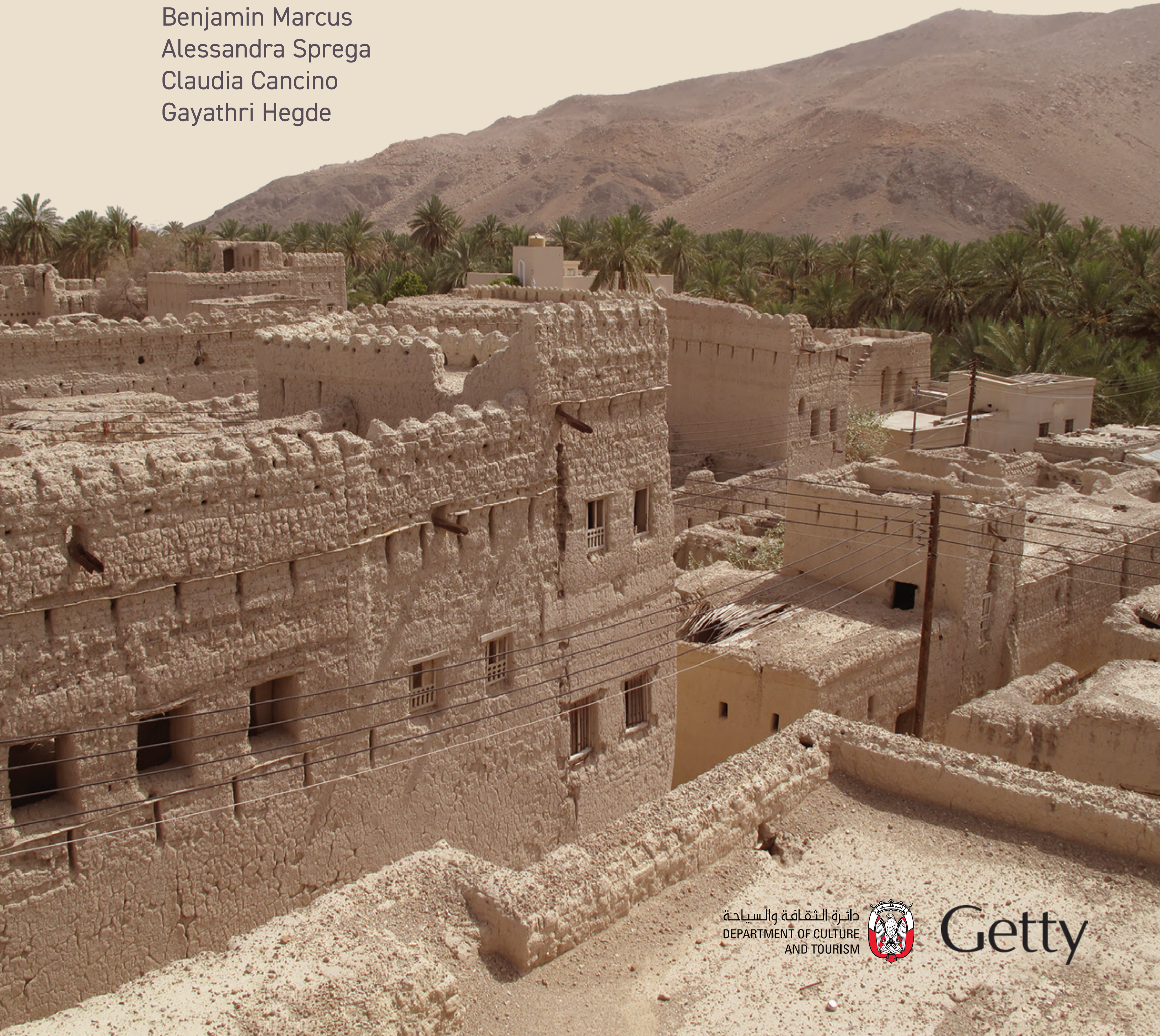
International Course on the Conservation of Earthen Architecture

ACCOMPANYING ESSAYS

Edited by
Benjamin Marcus
Alessandra Sprega
Claudia Cancino
Gayathri Hegde



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Cover: Earthen village of Al Ghafat, Ad-Dhakhiliyah, Oman. © J. Paul Getty Trust. Photograph by Benjamin Marcus.

The Getty Conservation Institute works internationally to advance conservation practice in the visual arts—objects, collections, architecture, and sites. The Institute serves the conservation community through scientific research, education and training, field projects, and disseminating information. In all our endeavors, we create and deliver knowledge that contributes to the conservation of the world's cultural heritage.

The Department of Culture and Tourism–Abu Dhabi drives the sustainable growth of Abu Dhabi's culture and tourism sectors by creating a diverse ecosystem that preserves, promotes and embodies the Emirate's heritage, innovative spirit and unparalleled hospitality.

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FOREWORD

Timothy P. Whalen

It is a great pleasure to present the publication *International Course on the Conservation of Earthen Architecture: Accompanying Essays*. This volume is the result of a fruitful collaboration between the Getty Conservation Institute (GCI) and the Department of Culture and Tourism–Abu Dhabi (DCT Abu Dhabi). The course was initially developed in 2017 to provide a regional training opportunity for conservation professionals working with earth in the Middle East, North Africa, and South Asia (MENASA). Its main objective is to build practical skills and a sound theoretical framework for conserving earthen heritage.

The GCI has a long-standing commitment to the conservation of earthen architecture, beginning in the 1980s with studies of protective coatings at Fort Selden, to collaborations with ICCROM and CRAterre on training for the conservation of archaeological sites, to work developing seismic retrofitting techniques for earthen buildings via the Getty Seismic Adobe Project (GSAP) and the Seismic Retrofitting Project (SRP) in Peru as well as rehabilitation plans for earthen ensembles in Morocco. The GCI also organized two International Conferences on the Study and Conservation of Earthen Architectural Heritage: Terra 2008 in Bamako, Mali, and Terra 2022 in Santa Fe, New Mexico, United States.

DCT Abu Dhabi works to record, protect, and conserve the significant heritage of historic buildings and archaeological sites in the Emirate of Abu Dhabi, including the Cultural Sites of Al Ain World Heritage Site, where the International Course on the Conservation of Earthen Architecture is held. DCT Abu Dhabi is the key partner in the design and implementation of the course, and the course is enriched by the wealth of case studies and best practice examples from Al Ain.

The essays in this volume cover the key themes and support the lessons and activities that have been taught over two iterations of the earth course in 2018 and 2022. It includes chapters on regional earthen architecture and archaeology, analysis of earthen materials, building with earth, documentation, conservation theory, building assessment, and structural diagnosis. Conservation treatment methods for earthen buildings and sites include sections dedicated to structural interventions, seismic retrofitting, roofing, the conservation of earthen archaeological sites, and finishes including earthen plasters and decorative surfaces on earthen substrates. It also describes adaptive reuse strategies, case studies, and master planning for conserving earthen settlements using historic cities in Oman as examples. All of these follow a sound methodology for the conservation of earthen architectural heritage.

We are grateful to the project team, particularly Benjamin Marcus, Claudia Cancino, and Susan Macdonald of the GCI and Amel Chabbi, Aqeel Ahmed Aqeel, and Felipe Gutierrez of DCT Abu Dhabi and their colleagues. We are also grateful to the many instructors who contributed to the course and this publication, including Peter Sheehan, Henri Van Damme, Wilfredo Carazas, Hossam Mahdy, Mario Santana, Christof Ziegert, Paulo B. Lourenço, Aqeel Ahmed Aqeel, Clemencia Vernaza, Gaetano Plumbo, Naima Benkari, and Soumyen Bandyopadhyay. This volume would not have been possible without the careful editorial work of Benjamin Marcus, Alessandra Sprega, and Gayathri Hegde. Finally, we would like to thank the Oman Ministry of Heritage and Tourism (MHT) for generously hosting the course workshop on the conservation of historic earthen settlements in the ancient cities of Manah and Nizwa.

We hope that this publication will not only serve as a valuable reference to course participants, but also contribute to disseminating the content of the course broadly as a resource for researchers, practitioners, and those interested in the conservation of earthen heritage.

Timothy P. Whalen
John E. and Louise Bryson Director
Getty Conservation Institute

FOREWORD

Rita Aoun-Abdo

Earthen architecture has a deep and significant history in the Arabian Peninsula and in many parts of the world dating back millennia. This is the shared legacy of humanity, and we must act quickly and decisively to preserve and protect this form of living cultural heritage.

It is the mandate of the Department of Culture and Tourism–Abu Dhabi (DCT Abu Dhabi) to protect, preserve, and promote the tangible and intangible heritage of the Emirate, and we implement an extensive conservation program to ensure that Abu Dhabi's ancient built heritage is safeguarded for generations to come.

Culture and heritage are a large part of our remit as we work to preserve vital elements of the United Arab Emirates' past. But our cultural vision extends far beyond our borders. We have a responsibility to contribute to the preservation of shared human history, and we feel a sense of duty to help conserve heritage from around the world.

This is why the International Course on the Conservation of Earthen Architecture is a strategic and long-term initiative to ensure that conservation professionals from around the MENASA region will be able to contribute to the preservation of this shared legacy of humanity. Collaborations and partnerships are essential when tackling cultural issues of this reach and magnitude, such as advancing conservation practice. It is only by working together and combining our knowledge and resources that we can make a long-lasting contribution to the field of heritage conservation. DCT Abu Dhabi is proud to have partnered with the Getty Conservation Institute over the years on this initiative.

The wealth of earthen heritage found here and the variety of conservation projects implemented by DCT Abu Dhabi over the past decade have served as invaluable touchstones for the course curriculum that is crystallized in this handbook. This series of essays reflects efforts to integrate and collate the varied and complex content of the curriculum taught in the International Course on the Conservation of Earthen Architecture. Since 2018, the project teams at GCI and DCT Abu Dhabi, along with the instructors, have honed and updated the course content after an evaluation of each edition as well as in response to new areas of focus such as climate change and disaster risk preparedness. From fundamental theories of conservation to innovative technology and research, these essays will hopefully serve as an essential reference for years to come.

Rita Aoun-Abdo
Executive Director of the Culture Sector
Department of Culture and Tourism–Abu Dhabi

INTRODUCTION

Benjamin Marcus and Amel Chabbi

This publication is a companion to the International Course on the Conservation of Earthen Architecture (EAC), a four-week training initiative organized by the Getty Conservation Institute (GCI) in partnership with the Department of Culture and Tourism–Abu Dhabi (DCT Abu Dhabi) with support of the Ministry of Heritage and Tourism (MHT), Oman. Held in Al Ain, UAE, and Nizwa, Oman, the course aims to improve the practice of earthen heritage conservation by providing training for midcareer professionals working in the Middle East, North Africa, and South Asia.

The course follows a strong methodological approach that guides the participants through the different phases of the conservation process. It covers practical methods contextualized within a theoretical framework for the conservation of earthen buildings, settlements, and archaeological sites, including topics such as conservation theory, material analysis, documentation, and diagnosis, as well as structural interventions, rehabilitation, and preventive conservation. The course is taught by a distinguished group of experts in the conservation of earthen buildings or related disciplines.

This publication, *International Course on the Conservation of Earthen Architecture: Accompanying Essays*, provides a selection of the key topics delivered by core instructors during the course. The inspiration for this volume grew out of a desire to provide participants with a more comprehensive repository of the course content. This series of essays is also a useful resource for those working in the region, given much of the content relates to earthen architecture typologies and conservation practices within the geographic area where the course is held.

The background essays follow the sequence of the four-week course, beginning with chapter 1 by Peter Sheehan, which provides an introduction to the history, archaeology, and earthen heritage of the World Heritage Site of Al Ain, where the course is hosted. In chapter 2 the properties and analysis of earthen materials are explored by Henri Van Damme and Wilfredo Carazas Aedo. Chapter 3 by Wilfredo Carazas Aedo discusses common construction techniques of earthen materials and their use around the world. After understanding the heritage of the region and earthen material performance and building techniques, chapter 4 by Hossam Mahdy provides an overview of the history and theory of conservation, with a particular emphasis on the regional context. This chapter also explains the different phases of a conservation project as part of the course's overall theoretical approach. Documentation and inventory of historic sites, with a focus on practices for the recording of earthen architecture, are discussed by Mario Santana in chapter 5. Next, chapter 6 by Christof Ziegert, Paulo B. Lourenço, and Peter Sheehan examines the assessment and investigation of earthen structures, including common deterioration patterns and their causes, structural investigation and seismic modeling, and archaeological investigation to produce a sound diagnosis of an earthen site. Chapter 7 by Christof Ziegert, Benjamin Marcus, Paulo B. Lourenço, and Aqeel Ahmed Aqeel discusses structural interventions including emergency conservation measures, structural repair and seismic retrofitting, and the preservation of traditional roofing in the Al Ain region as case studies. Chapter 8 explores finishes for earthen buildings, beginning with Christof Ziegert's overview of plaster types and application methods and concluding with a summary of the conservation of historic decorated surfaces by Clemencia Vernaza, including assessment, grouting, and consolidation treatments. Chapter 9 by Gaetano Palumbo focuses on the conservation of earthen archaeological sites, with an emphasis on typical deterioration phenomena, assessment methods, conservation interventions, and the site management planning process.

The remaining chapters cover the rehabilitation and reuse of historic earthen buildings. Chapter 10 by Benjamin Marcus and Aqeel Ahmed Aqeel explores the rehabilitation of earthen heritage for contemporary purposes and includes case studies of successful examples of adaptive reuse from the local region. Preventive conservation and maintenance of earthen structures, both pre- and postconservation, is the topic of chapter 11 by Aqeel Ahmed Aqeel, which presents a methodology for planning and implementing maintenance work on individual earthen structures and groups of buildings. The final chapter by Soumyen Bandyopadhyay is based on the Oman portion of the course—a workshop in the Nizwa region dedicated to the conservation of ancient earthen settlements. This chapter discusses the context of historic settlements within Oman's oasis cultural landscapes and references the Historic Urban Landscape (UNESCO 2011) methodology for conserving and managing historic settlements. It includes cultural heritage master planning and the development of policies and guidelines for conserving and reusing historic settlements. The chapter closes with a case study of rehabilitation and revitalization in the historic oasis village of Misfat al-ʿAbriyin. Bibliographies and additional references suggested by the course instructors are found at the end of each chapter, and a glossary of key terms used in the publication is provided at the end for reference.

It is the hope of the course organizers and the contributing authors that the *International Course on the Conservation of Earthen Architecture: Accompanying Essays* will benefit students of the course by providing a central resource for course materials while also serving the field more broadly as an enduring reference on the conservation of earthen heritage.

HISTORICAL CONTEXT

1

Overleaf: Al Daramka Tower, Al Ain, United Arab Emirates.
Source: J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.

1

HISTORICAL CONTEXT

Earthen Architecture and Archaeology of the Al Ain World Heritage Site

Peter Sheehan

"The Cultural Sites of Al Ain" (Hafit, Hili, Bidaa Bint Saud, and Oases Areas), inscribed on the UNESCO World Heritage List in 2011, is a serial World Heritage property that provides an exceptional testimony to the development of prehistoric cultures in the region and the management of water in a desert environment. This cultural landscape is characterized by a unique combination of natural- and human-made elements and consists of seventeen components grouped into four major assemblages (see figure 1.1): Jebel Hafit, with its early Bronze Age tombs; the Bronze

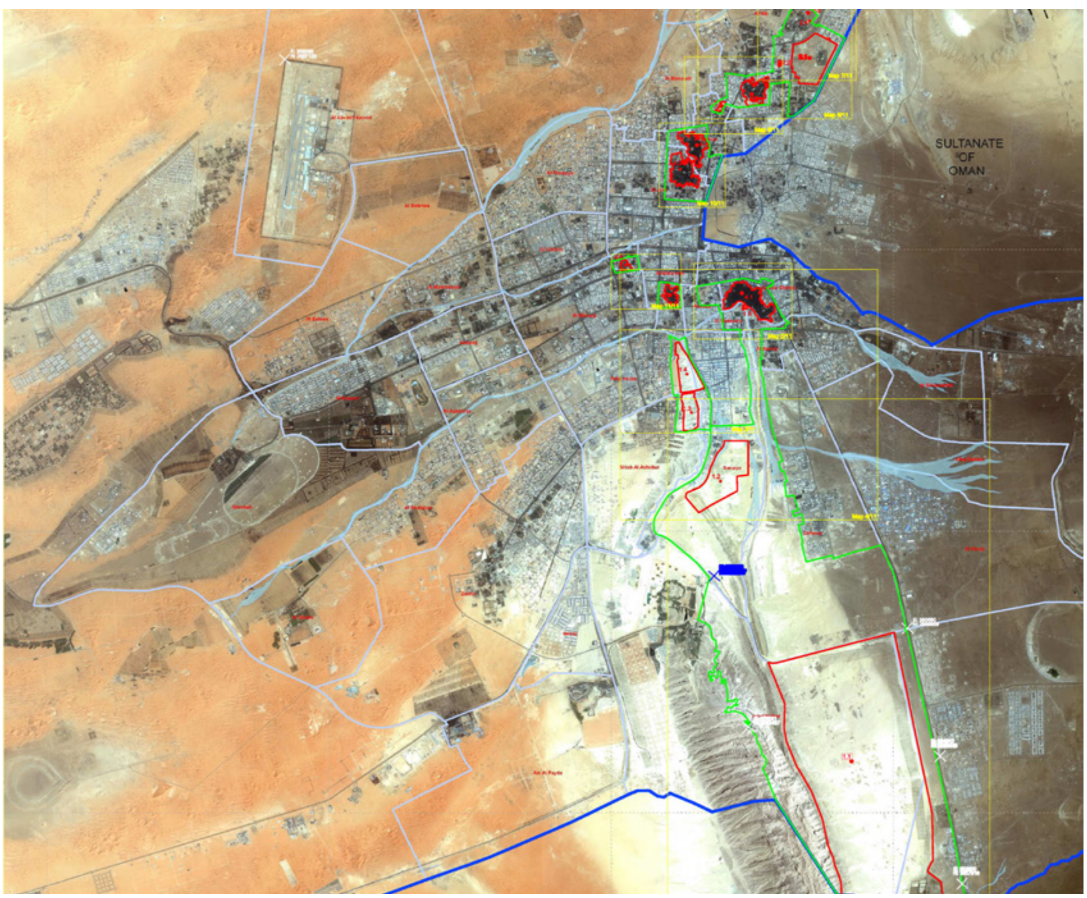

FIGURE 1.1. Google Earth view of the World Heritage Site of Al Ain showing the seventeen components of the serial site (in red), their buffer zones (in green) and the international border (in blue). *Source:* WHC UNESCO 2011.

and Iron Age sites, tombs, and earthen buildings of Hili and Rumailah; the outcrop of Bidaa Bint Saud with more Bronze and Iron Age graves and other features; and the six oases of the city—Al Ain, Qattara, Jimi, Hili, Mutaredh, and Muwaiji (UNESCO 2011).

1.1 The Natural and Cultural Landscape of Al Ain

Al Ain is located on a narrow, fertile alluvial plain bordered on the west by the desert region known as the Empty Quarter and on the east by the Hajar Mountains. The southern limit of this cultural landscape is marked by the distinctive mass of the Jebel Hafit formation (figure 1.2). This mountain rises more than 1,000 m above the surrounding plain and formed an important landmark on ancient land routes that connected Al Ain with Oman and the rest of the Arabian Peninsula, the Persian Gulf, and the Indian Ocean. The geology of the mountains has been key to past settlement in the plain, which benefits from runoff during rainstorms and access to the water resources stored deeper within the mountains.

Over the past five thousand years, settlement in Al Ain has been characterized by alternating cycles of settlement and abandonment, with periods of more intense activity essentially reflecting political and economic stability that allowed for a more successful exploitation of the two main natural resources of the landscape: water and copper. At different periods, settlements

FIGURE 1.2. Jebel Hafit, rising more than 1,000 m above the surrounding plain, dominates the cultural landscape of Al Ain. *Source:* Peter Sheehan, DCT.

and their associated agricultural systems shifted around within the wider oasis landscape zone at the foot of the mountain. There is archaeological evidence for Neolithic occupation (ca. 8000–4000 BCE) and for major periods of activity occurring in the Bronze Age, marked first by the Hafit tombs (ca. 3200–2700 BCE) and later by the tombs and towers of Hili dating from the Umm an-Nar period (ca. 2500–2000 BCE), which saw the extensive supply of copper to the contemporary civilizations of Mesopotamia and the Indus Valley. By the Iron Age (ca. 1100–300 BCE), the earlier wetter climate had given way to arid conditions similar to those of the present day, and the region saw a major expansion of settlement, apparently based on both organized irrigation agriculture and the continued copper industry (Potts 2012). The most recent discoveries have indicated a significant presence in the landscape during the pre-Islamic period (ca. 300 BCE–300 CE), and another sustained period of intense activity took place in the early Islamic period (ca. 800–1000 CE), for which there is also increasing archaeological evidence of settlement, agriculture, and a revival of the copper industry (Sheehan et al. 2022; Al Marzooqi, Nasser, and Sheehan 2023).

Ongoing archaeological research reveals that the present-day oases of Al Ain were formed over the earlier ancient landscape from the late seventeenth century onward (figure 1.3). Political stability, the availability of slave labor from East Africa, and access to the Indian Ocean and African markets via Oman helped form the various elements of this oasis landscape, which

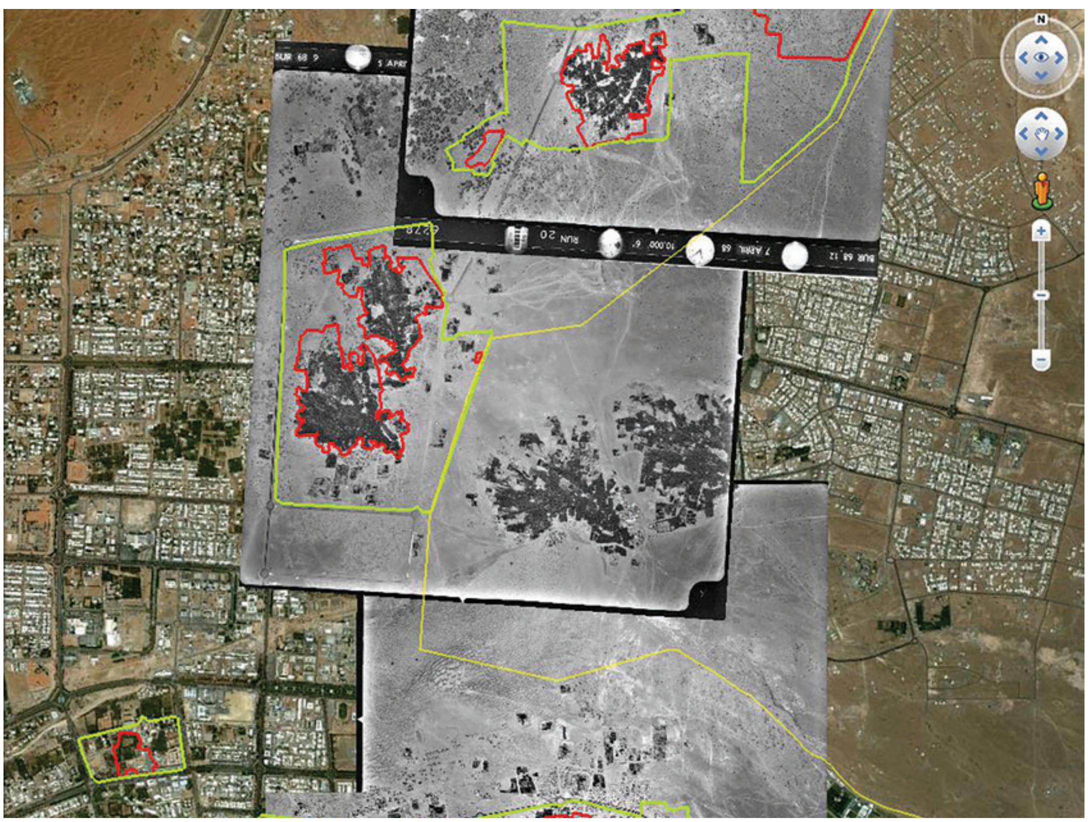

FIGURE 1.3. Google Earth image of Al Ain overlain by 1968 aerial views of the oases of Al Ain and Buraimi, showing the growth of the modern city in formerly open areas. *Source:* DCT Abu Dhabi.

FIGURE 1.4. Hili Oasis, an example of a historic Late Islamic earthen boundary wall preserved in the landscape. *Source:* Peter Sheehan, DCT.

was made up of three distinct concentric zones: an inner zone, a middle zone, and an outer zone (Power and Sheehan 2012).

The inner zone consisted of the palm garden oasis, essentially a sunken basin divided into numerous small plots. The earthen walls defining these individual plots display a range of construction and material typologies that constitute an important resource for understanding the chronological development of each oasis and the changes to its size and layout over time (figure 1.4). These plots contained palm trees that formed a canopy under which fruits and vegetables were cultivated. The main source of water for each oasis was a system of underground channels, or *aflaj* (sing., *falaj*), which tapped into the groundwater trapped at the base of the mountains and transported it, often over substantial distances. Upon arriving at the oasis, the water was then carefully distributed—following a complex system of traditional water rights—to the various plots via a series of surface channels (figure 1.5). These oases are still preserved today within the city and form individual core components of the World Heritage Site.

Around each oasis, the second agricultural zone was composed of an extensive network of fields watered by wells and seasonal rainfall. This middle zone also contained the settlements associated with each oasis so that most of the existing historic buildings in Al Ain are broadly contemporary with the development of the palm gardens. The third outer zone of this complex subsistence landscape included areas of seasonal natural vegetation used for grazing camels and goats.

(A)

(B)

FIGURE 1.5. Aflaj of Al Ain: (a) shows a falaj channel as it comes to the surface near the oasis of Al Ain in the 1960s, while (b) shows the interior of a stone-lined underground tunnel revealed during recent archaeological work. *Source:* Peter Sheehan, DCT.

Much of the nineteenth century saw the landscape of Al Ain contested between various regional powers. This struggle was eventually concluded toward the end of the long reign of Sheikh Zayed the First (r. 1855–1909). In the years around the turn of the twentieth century, the stability brought to Al Ain by the Abu Dhabi rulers was marked by the construction of a series of earthen forts—Jahili, Mezyad, Sultan Fort, and Qasr Al Muwaiji—at strategic, highly visible locations in the landscape (Power and Sheehan 2011b; Sheehan 2012).

1.2 Earthen Architecture of the Al Ain Region

The United Arab Emirates and Oman share a landscape, history, and climate that have shaped the cultural life of these countries and the forms of their traditional earthen architecture. Architecturally, these influences find major expression in the form of the mosque and the open prayer space, or *musalla*, oriented toward Mecca and providing a location for communal prayer and the focus of community life (figure 1.6). Historically, larger settlements were located on the coast and linked by the Indian Ocean and Red Sea trading networks. Away from the coast, rainfall over the high mountain ranges allowed settlement on the piedmont plains around oases fed by groundwater. Here in the mountains and in the oasis settlements on the outwash plain or near seasonal riverbeds, or *wadis*, earthen buildings predominate. The typology of these buildings includes forts, defensive towers, and

FIGURE 1.6. The traditional vernacular mosque at Jahili, shown during earthen conservation works related to the rehabilitation of the fort. *Source:* Peter Sheehan, DCT.

FIGURE 1.7. The Bin Biduwa House in Al Qattara Oasis, a fine example of the development of fortified earthen houses in Al Ain from the seventeenth century onward. *Source:* Peter Sheehan, DCT.

fortified houses like the Bin Biduwa House (figure 1.7), built to protect the inhabitants and their crops and supplies from raids by other tribes. Another significant cultural factor that affected the architecture was the need for reception rooms to be separated from those of the family, a requirement that was sometimes achieved by using a bent-axis entrance that prevented direct views into the private quarters of the house from outside (figure 1.8). The existence of large family groups and the tribal structure of society provided opportunities for communal building that were often related to seasonal activities (Bandyopadhyay 2011; Sheehan 2017).

All these buildings combine traditional materials and techniques that utilize the thermal qualities provided by thick earthen walls with limited small openings for light and air. Floors are made of beaten earth, and roofs of earth are laid over palm logs and palm mats (figure 1.9). Waterproof *sarooj* plaster is made by firing a mixture of clay and manure. In summer, cooling is achieved by opening windows at floor level to the night breezes and closing them during the day to let the hot air rise and escape through the small vents in the upper parts of the walls. Permanent dwellings are often supplemented by temporary structures using a range of palm-leaf (*arish*) typologies as well as the *bayt al-shaar*, a large portable tent made from animal hair.

The extraction and economical use of water is a priority. As mentioned earlier, the region is home to the ingenious system of aflaj that can tap both shallow wadi flows and deep aquifers. The climate and the water regime provide ideal conditions for the tolerant, ubiquitous date palm, a plant that has become an integral part of life in the region and provides a variety of materials used in traditional building practices. Date farming has even produced a specific regional

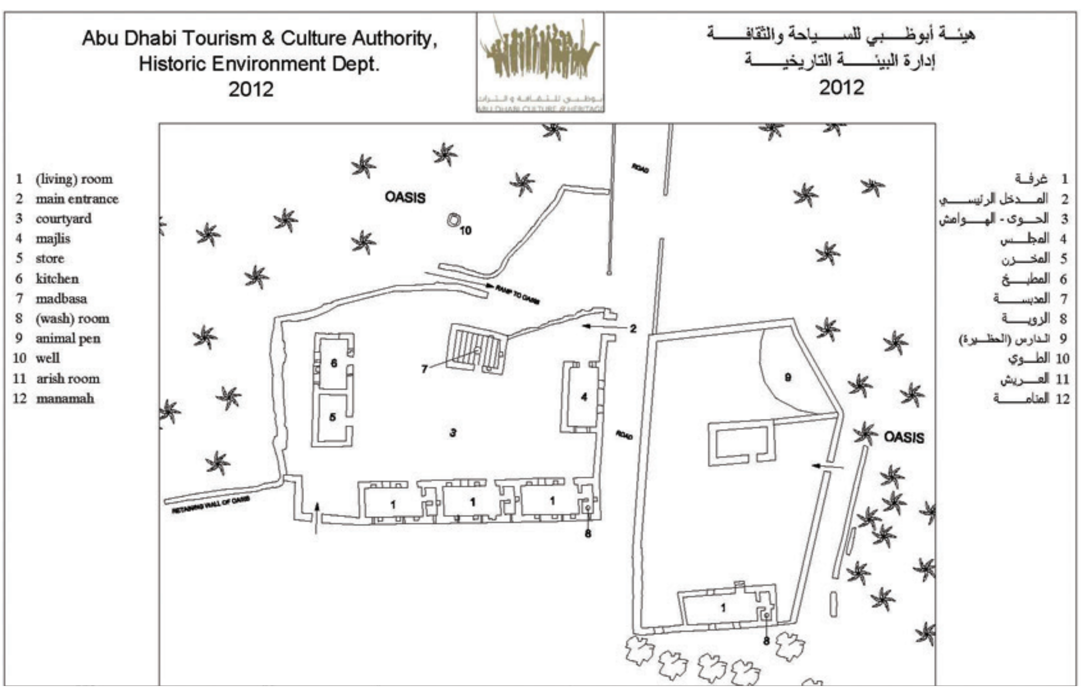

FIGURE 1.8. The typical layout of twentieth-century vernacular earthen buildings in Al Ain. *Source:* Peter Sheehan, DCT.

FIGURE 1.9. Earthen building production of palm-leaf mats for use in roofing. *Source:* Peter Sheehan, DCT.

FIGURE 1.10. An example of a *madbasa* (date press) revealed during archaeological excavations at the Bayt bin Ati. *Source:* Tim Power, DCT.

vernacular construction in the form of the *madbasa*, or date press, known from the second millennium BCE onward. In a date press, layers of the fruit are stored in a sealed room, and their juices (*al-dibs*) are allowed to trickle through a network of plaster channels set into the floor and collected in earthen jars.

1.3 Archaeology and the Cultural Landscape of Al Ain

Understanding the development of the wider cultural landscape forms part of ongoing archaeological research in Al Ain. This research continues to be informed by excavations and fieldwork (figure 1.10), observations during conservation work on historic buildings, research into historical sources and images, and the gathering of oral histories (McPhillips and Wordsworth 2016; Magee 2014; Sheehan et al. 2022; Sheehan et al. 2023).

Most historic earthen buildings in Al Ain date to those periods that are marked by more intense activity in the landscape. The range of surviving earthen buildings thus includes the enigmatic Bronze Age tower platforms of the Umm an-Nar period at Hili; the Iron Age villages of Hili 2, Hili, 17, and Rumailah; early Islamic earthen buildings from Buraimi and Oud Al Touba; and the historic buildings of the last three hundred years such as Bayt bin Ati (figure 1.11), Bin Biduwa House, Al Jahili Fort, and Qasr Al Muwaiji, many of which continued to be used through to modern times.

FIGURE 1.11. The basement of Bayt bin Ati following the excavation of a 5 m-deep archaeological sequence spanning more than three thousand years and encompassing the development of the cultural landscape from the Iron Age to the present day. *Source:* Tim Power, DCT.

Many of the alternating cycles of activity and abandonment within this cultural landscape are represented in the archaeological record revealed during the conversion of the Bayt bin Ati, a historic earthen building rebuilt in the 1980s and repurposed between 2009 and 2011 as Al Qattara Arts Center (Power and Sheehan 2011a). Works here revealed an archaeological sequence with 5 m of stratigraphy spanning more than three thousand years and encompassing the development of the cultural landscape from the Iron Age to the present day.

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EARTHEN MATERIALS

2

Overleaf: Conducting the Carazas Test during the Earth as a Building Material module of the EAC22 course in Al Ain, United Arab Emirates. *Source:* J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.

2

EARTHEN MATERIALS

Henri Van Damme and Wilfredo Carazas Aedo

Our earthen-built heritage is an extraordinarily diverse display of resourceful and frugal solutions to local material and environmental constraints. The intrinsically vernacular character of earthen architecture—to use what is locally available and recyclable to find locally optimized solutions—is brilliantly illustrated by the multiple forms that have sprung from the fertile minds of earth builders using the humblest of all materials: soil.

Pedogenesis, the origin and development of a soil, is the slow transformation of an often hard, rocky substratum into a softer, granular material through the action of water, temperature, wind, landscape topography, and the multiple forms of microbial, vegetable, and animal life. As a result of the physical action of the environment and the chemical action of water and organic acids, the bedrock disintegrates, and its primary mineral constituents dissolve. The dissolved ions and molecules migrate and precipitate down in the form of secondary minerals.

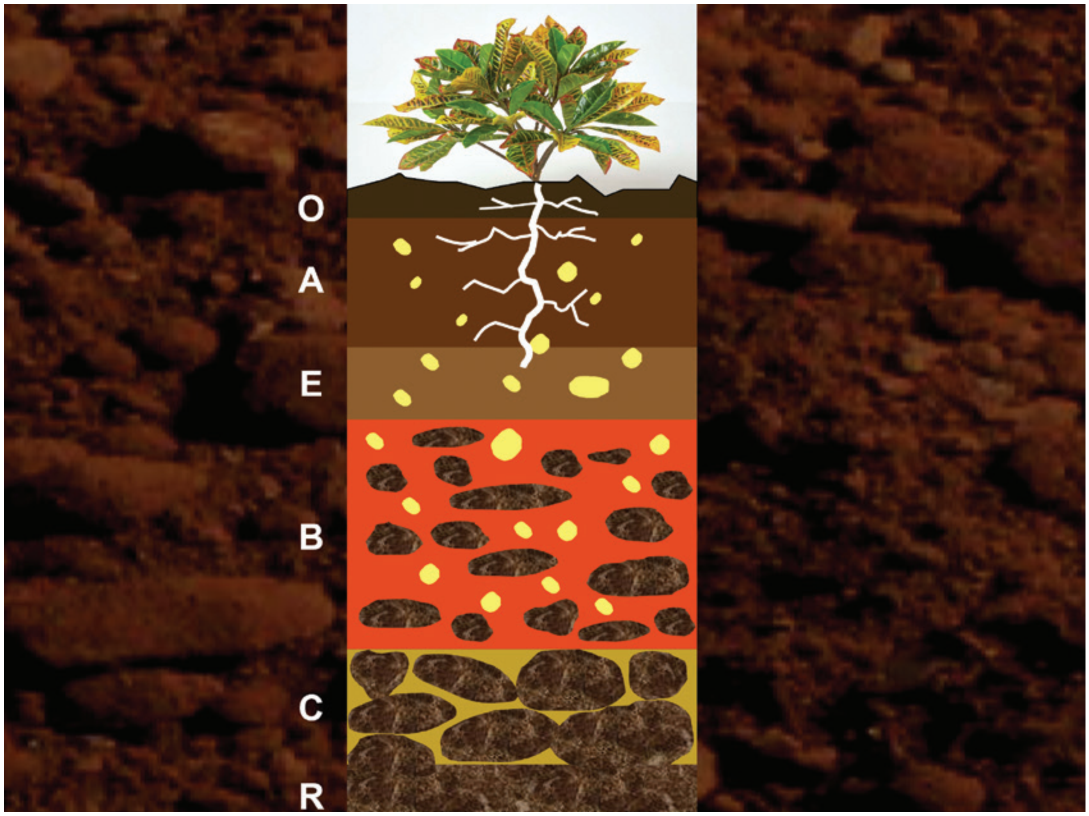
Over a few thousand years, the rock turns into a profile of superimposed layers called "horizons" (figure 2.1). The surface horizon *O* is a litter layer of plant residues in a relatively undecomposed form. The *A* horizon is a surface layer of mineral soil with mostly decomposed organic matter accumulation and soil life. This layer eluviates—or is depleted of—iron, clay, aluminum, organic compounds, and other soluble constituents. A lighter-colored *E* subsurface horizon forms at the base of the *A* horizon, where eluviation is pronounced.

The *B* horizon is a generally darker layer and accumulates iron, clay, aluminum, and organic compounds in a process referred to as illuviation. The *C* horizon is a transition layer between soil and bedrock (the parent material). It is the partially weathered, cracked, and broken surface of the bedrock and may accumulate more soluble compounds. The *R* horizon is an essentially unweathered and continuous layer of bedrock at the base of the soil profile. Unlike the previous layers, *R* horizons cannot be excavated by hand (USDA 2017).

According to the conditions and length of pedogenesis, the thickness of the soil profile from surface to bedrock may vary from a few centimeters to several hundreds of meters, and the development of the various horizons may exhibit vast differences. Each soil profile tells a unique story.

Early earth builders may have been unaware of the genesis of soil, but they knew how to use soil or how to select fractions of it as a building material. Digging essentially in the *E* and *B*

FIGURE 2.1. General structure of a soil profile. *Source:* Henri Van Damme and Wilfredo Carazas Aedo.



horizons (see figure 2.1), they proceeded to invent building techniques by adapting to what was available. In this chapter, we describe some of the most frequently used characterization and selection methods and link the properties of raw earth to its optimal usage conditions. In chapter 3, material properties will be connected to the main building techniques. More information can be found in Houben and Guillaud (2003), Röhlen and Ziegert (2011), and Schroeder (2016).

2.1 Earth as a Building Material

To understand how a material as basic as raw earth became the building material of choice for so many human cultures, the simplest analogy is to consider it a natural concrete or mortar (Fontaine and Anger 2009). Just like industrial cement-based concretes and mortars, the raw earth used in construction is a cohesive and porous mixture of solid particles of different sizes. Ranging from coarse to fine, these include stone, gravel, sand, silt, and finally, clay (figure 2.2). The difference in size is significant: a clay particle may be a hundred thousand times smaller than a gravel particle.

Like those of regular concrete or mortar, the particles of raw earth serve two functions. The first is to form a "skeleton" or "scaffold" able to withstand mechanical forces, particularly compression. This is essentially the primary function of the coarse particles—stone, gravel, sand, and silt.

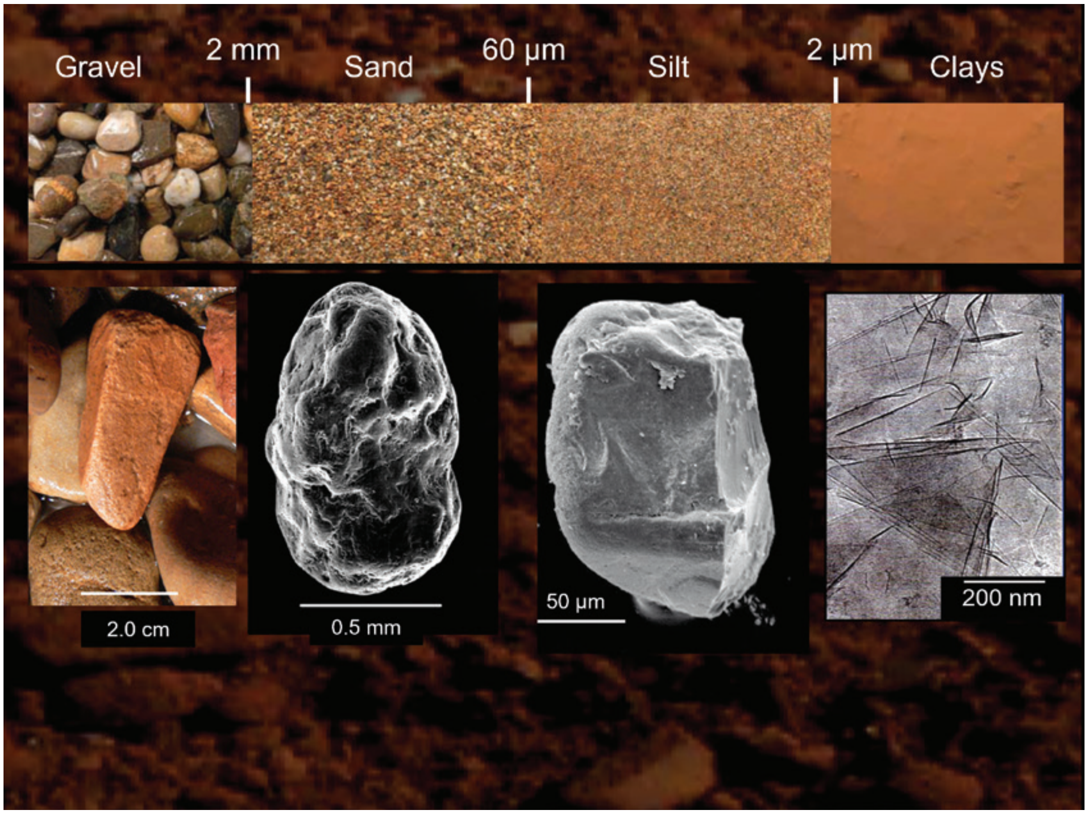


FIGURE 2.2. Each raw earth is a unique mixture of particles of different sizes, from stones (20 cm to 2 cm), to gravel (2 cm to 2 mm), sand (2 mm to 60 µm), silt (60 µm to 2 µm), and clay (less than 2 µm). *Source:* Fontaine and Anger (2009).

Their secondary function is to secure the adhesive link between the skeleton particles and to confer some cohesion to the whole system. In regular concrete, this is what cement does after reacting with water. In asphalt, it is the role of bitumen. In raw earth, the binder role is designated to the finest fraction: fine silt and, above all, clay. But neither silt nor clay would be able to strengthen without a critical amount of residual water and air in the pore space.

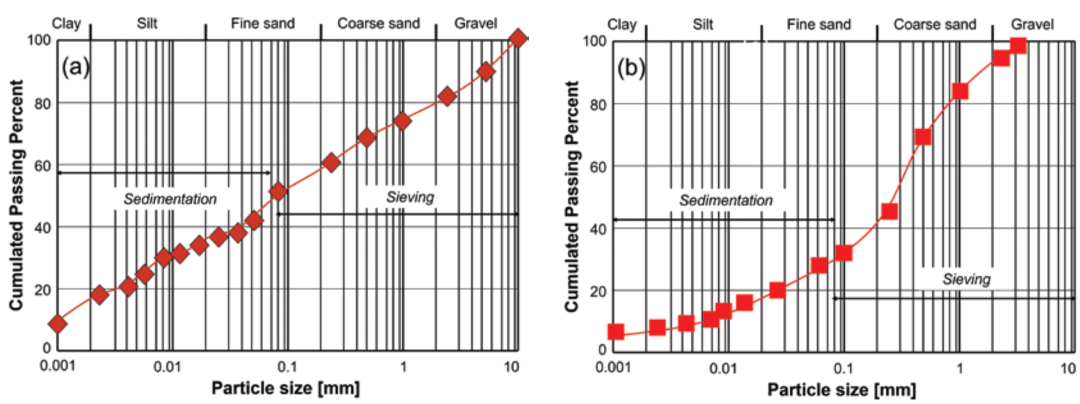
The analogy to concrete provides a clue as to what will follow. In section 2.1, we take a closer look at the granular skeleton. In section 2.2, we focus on clays and their special interaction with water and examine why they are key players in the dramatic changes in rheological and adhesive properties that take place during this interaction. Finally, in section 2.3, we attempt to understand why air, the last and seemingly inconsequential component of raw earth, is in fact very important during construction and why it is an essential contributor to strength and density.

2.2 Earth as a Granular and Frictional Material: Particle-Size Distribution

Like concrete and all granular materials, dry earth is primarily a collection of hard particles in sliding friction with one another. The shape of the particles, their surface state (smooth or rough), and more importantly, their size distribution are the three parameters that control their collective behavior in the dry state. These parameters determine how easy or difficult it is for the particles to slide and roll over one another as well as the maximum density that can theoretically be reached upon compaction. Ultimately, they are the keys to both flow and strength.

Whereas the shape and the surface state of the particles are a fact of nature, the particle-size distribution can be corrected and adapted to the chosen construction technique as needed. This is why particle-size distribution is one of the most important parameters to determine, at least semiquantitatively, when evaluating a type of raw earth material for construction. In practice, the distribution is generally determined in a broad range from small stones to clays—that is, from ~60 mm to less than 2 μm.

In order to understand the particle distribution of a soil, two main techniques are used: dry sieving on the coarse fraction from stones to fine sand (see box 2.1) and sedimentation on the fine fraction (see box 2.2; Teutonico 1988, 73–92). The final result is generally expressed as a curve connecting data points, each point giving, for a given particle size, the fraction (percentage) of total mass with the particle size below the test value. Two typical grading curves are shown in figure 2.3.



(A) (B)

FIGURE 2.3. Two typical grading curves obtained by coupling the sieving and sedimentation test methods. Curve (a) is typical of well-graded soils with a broad distribution of particle sizes, suitable for the rammed-earth technique. Each fraction is present in approximately equal amounts. Curve (b) is typical of fine-grained soils with a narrower distribution of particle sizes. It contains approximately 60% coarse sand and 20% fine sand. The clay fraction is only ~8%. This type of soil may be suitable for making adobe or coatings. *Source:* Adapted from Moevus-Dorvaux et al. (2016), redrawn by Henri Van Damme and Wilfredo Carazas Aedo.

Box 2.1. Sieve Analysis

In sieve analysis, the sample is first gently crushed (while trying to avoid breaking individual particles) and subsequently dispersed in a large volume of demineralized water or, preferably, in a solution of a dispersing agent such as sodium hexametaphosphate (NaHMP, 40g/l). This allows for complete separation of all particles, including the fine fraction that would otherwise remain agglomerated or attached to the surface of the coarse particles. The slurry is then filtered on a 60 μm size mesh sieve. The retained material is washed on the sieve, recovered, and dried in an oven. It is then ready for the sieving procedure, which is performed on a stack of sieves with calibrated mesh sizes, varying from larger to smaller from the top down (figure 2.4). The amount of sieved material should be such that no sieve gets overloaded. Overloading occurs when the layer of material retained is so thick that not all particles have the opportunity to reach an opening during sieve shaking (ASTM D6913/D6913M-17 2017).

At the end of the sieving operation (about ten minutes of shaking), the mass of material retained on each sieve, MR_N, is recorded (N is the order of the sieve, starting from the top). The cumulative mass retained on a sieve of order N, CMR_N, is obtained by summing all the sieves of a lower order: $CMR_N = MR_1 + MR_2 + \ldots + MR_N$. The cumulative passing percentage, CPP_N, is obtained using the following relation, where MS_d is the total mass of the sample that was sieved:

$$CPP_N = 100\,[1 - (CMR_N / MS_d)].$$

FIGURE 2.4. Sieve set used for the particle-size analysis of the coarse fraction of soils (gravel and sand). After sieving, the mass of material retained on each sieve is weighed, and the cumulated passing percentage is calculated. *Source:* Fontaine and Anger (2009). The inset shows a sieve set on a mechanical shaker. *Source:* Schroeder (2016).

Box 2.2. Sedimentation Analysis

Sedimentation analysis is based on the concept that larger, heavier particles will fall through a fluid faster than smaller, lighter particles. According to the equation known as Stokes's law, the terminal velocity v_s of a spherical particle of radius *r* falling through a stationary liquid is proportional to the square of the particle diameter: $v_s = (2/9)r^2(\rho_p - \rho_w)(1/\eta)$. In this equation, ρ_p and ρ_w are the specific gravity of the soil particles and the liquid, respectively, and η is the liquid viscosity. Therefore, particles are sorted by size in both time and position when settling in a container of liquid.

Figure 2.5 shows the process of sedimentation analysis. In practice, a well-dispersed and homogeneous slurry of the fine fraction of the soil specimen is placed in a large glass cylinder. A buoyant device called a hydrometer is used to measure the fluid density, which depends on the concentration of settling soil particles and the specific gravity contrast between the particles and the fluid. Thus, each hydrometer measurement at an elapsed time is used to calculate the percentage of particles finer than the diameter given by Stokes's law. The series of density readings as a function of time provides the distribution of material mass as a function of particle size (ASTM D7928-17 2017).

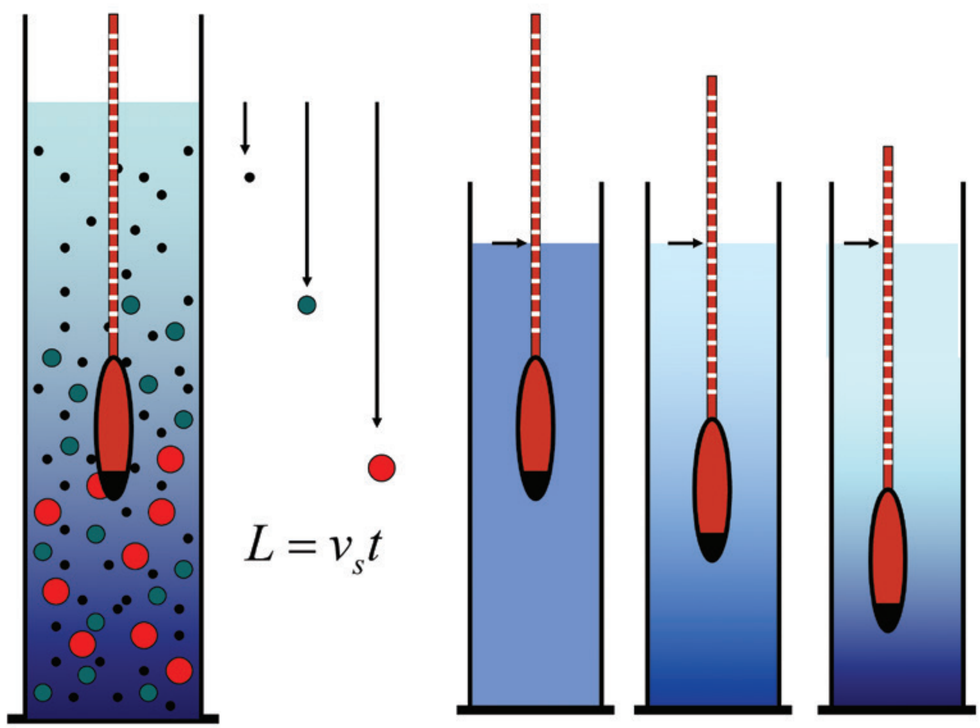


FIGURE 2.5. In the hydrometer or sedimentation analysis of soils, the size of soil particles is calculated from the speed at which they settle out of suspension from a liquid. After time *t*, particles of radius *r* are moved downward by a distance of $L = v_s t$. Therefore, after time *t*, the section of height *L* on top of the glass cylinder is free of particles larger than *r*. Simultaneously, at the bottom, the same amount of particles has settled down. As time passes, the suspension loses particles, buoyancy decreases, and the hydrometer sinks. *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

2.3 Earth as a Colloidal and Cohesive Material: Clays, Water, and Salts

The grading curve is an important piece of information but alone is not sufficient to allow for a correct assessment of a soil sample for construction due to the critical role played by the clay fraction in several properties, including cohesion, plasticity, and swelling or shrinking. We first examine what clays are and how they behave in the presence of water.

2.3.1 Clays and Water

Clays form a very broad family of aluminum or magnesium silicates with a layered atomic structure (Velde and Guillaud 2008). Clay particles differ from other soil particles in terms of size, shape—for example, fibrous, platelets, sheets (figure 2.6)—and in some cases, the presence of electric charges on the particle surface. Their very small size (≤2 μm) is responsible for a particular behavior, intermediate between that of macroscopic particles and that of atoms or molecules. Theirs is the world of the so-called colloids, particles so small that when suspended in water, they never stop moving.

The property that best materializes the unique character of clays is the specific surface area accessible to water, or S_w. By definition, S_w is the total surface area accessible to water molecules, developed by all the particles in one gram of material. For instance, in sand with supposedly

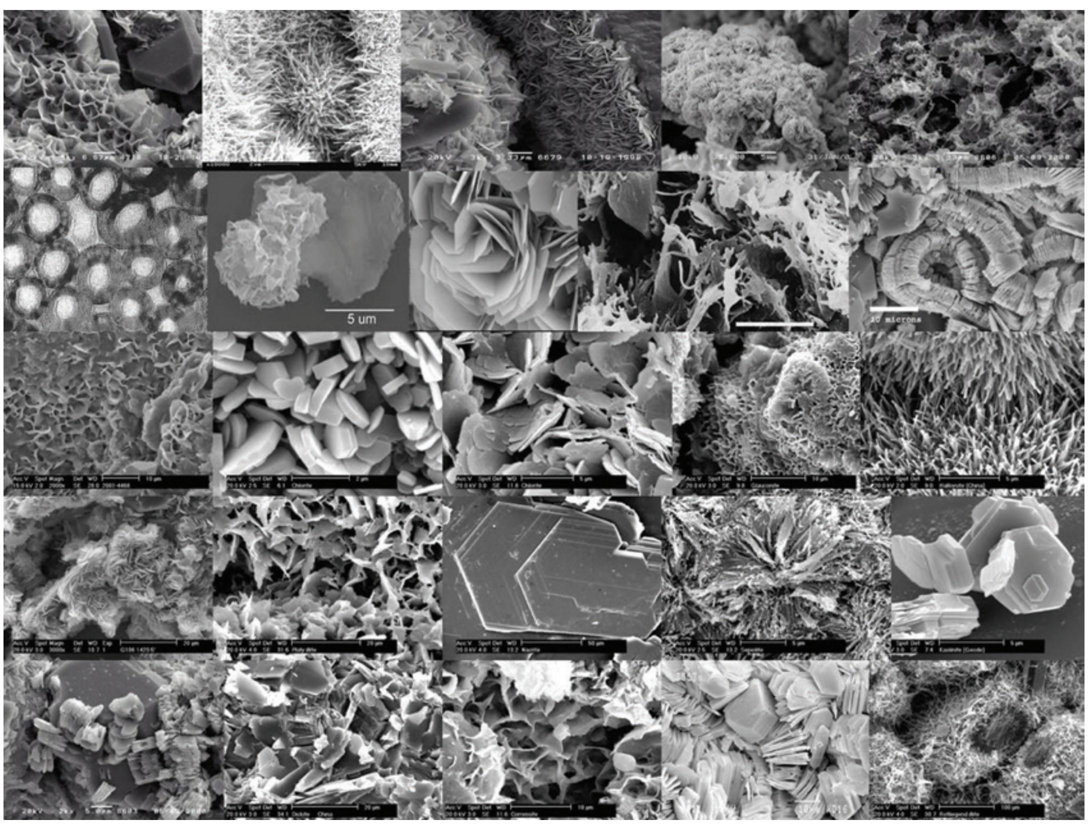
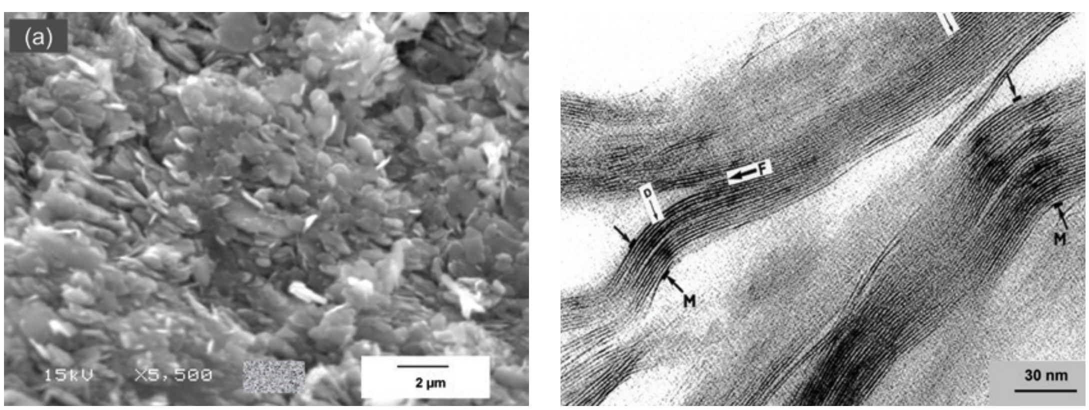


FIGURE 2.6. A selection of scanning electron microscopy (SEM) images of clay minerals that can be found in soils and sediments. *Source:* Clay Minerals Society.

spherical particles of 0.5 mm ($r = 2.5 \times 10^{-4}$ m), one gram of material contains approximately six thousand grains, and their total surface area (akin to removing the entire peel of an orange) is a few tens of cm^2, about the surface area of a credit card. In 50 μm silt particles ($r = 2.5 \times 10^{-5}$ m), the total surface area rises to a few hundreds of cm^2/g, similar to that of a few bank notes. Further, in platelets of kaolinite clay 50 nm thick ($t \cong 5 \times 10^{-8}$ m), the surface area reaches ~20 m^2/g (that of a typical bedroom floor; figure 2.7a). Top values are reached with clays of the smectite group, such as montmorillonite, which separate into electrically charged individual lamellae only 1 nm thick ($t = 10^{-9}$ m) when dispersed in water (figure 2.7b). Their surface area accessible to water approaches 1,000 m^2/g (that of a typical ballroom floor).

With surface areas in a range this high, clays have an enormous interaction potential with water. Even in a modestly humid environment—say, air with a low percentage of relative humidity—water molecules stick to the surface of most mineral particles (with some exceptions, including talc). This is called adsorption. Quite straightforwardly, the total amount of adsorbed water is directly related to S_w. This is particularly important in clays and especially in clays with electrically charged lamellae because the negative charge of the lamellae is compensated by positively charged ions (cations) located on their surface. These ions are very attractive spots for water molecules. Thus, in air with a relative humidity (RH) of ~70%, montmorillonite clay already contains more than 10% of its weight in water (figure 2.8). Yet it still looks and feels perfectly dry.

Simultaneously, with the adsorption of water, the volume also increases. This increase is modest in clay such as kaolinite, which has a relatively small specific surface area ($S_w \cong 20\ m^2/g$). The increase is higher in illite, which has a significantly larger surface area ($S_w \cong 150\ m^2/g$). Subsequently, the increase in montmorillonite ($S_w \cong 800\ m^2/g$) may be huge—enough to bring down buildings, as exemplified by figure 2.9.



(A) (B)

FIGURE 2.7. (a) Image of kaolinite clay by SEM. The kaolinite platelets are several tens of nanometers thick. Each platelet is a stack of many individual 0.7 nm–thick sheets firmly bound to each other. Water only has access to the external surfaces of the stack. (b) Image of montmorillonite clay by transmission electron microscopy (TEM). Each montmorillonite lamella is only one nanometer thick. Water molecules cover the total surface, including the narrow space between adjacent lamellae. *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

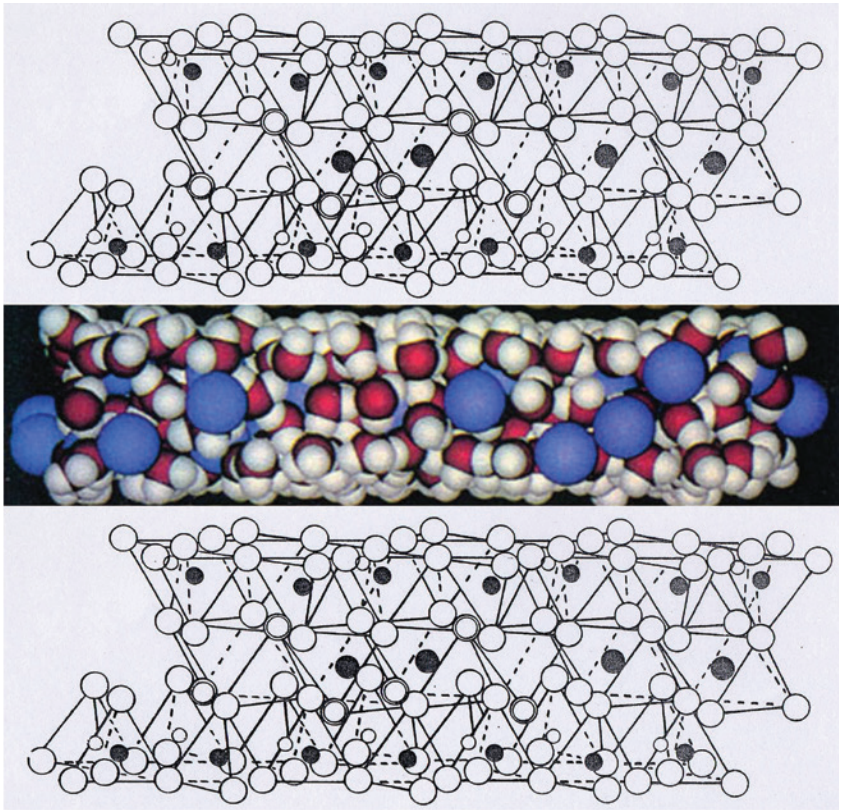


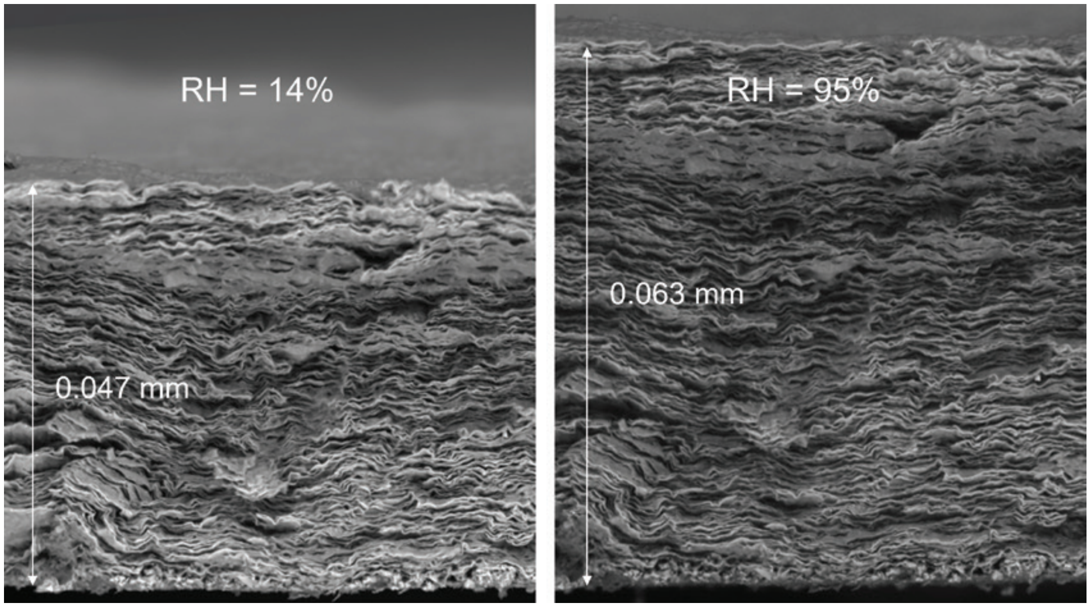
FIGURE 2.8. A computer-generated physically realistic model of the water layer between adjacent montmorillonite clay lamellae at an RH of ~70% (courtesy of A. Delville). Water molecules are in red (oxygen atoms) and white (hydrogen atoms). The blue spheres are potassium ions. The atoms of the clay lamellae are not at scale. *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

Relatively modest at low RH, adsorption of water greatly increases when humidity is approaching saturation—say, beyond RH = 90%—and rises even higher when liquid water is added. The clay then turns into a humid state, then a plastic state, and finally a liquid, muddy state. The larger the surface area, the larger the water content required to move from one state to the next. A comparison of the low surface area of kaolinite with the high surface area of montmorillonite is depicted in figure 2.10.

2.3.2 Clays in Earth

The behavior of clays summarized above is also observed in earth but in a "diluted" way, depending on the amount of clay in the material. However, the mineralogical analysis of clays in soil is not an easy task and requires relatively expensive laboratory equipment (X-ray diffraction). In practice, it is easier to perform simple benchtop tests related to consistency, a concept introduced in 1911 by the Swedish chemist and soil scientist Albert Atterberg (Schroeder 2016, 80–91). Four distinct states of consistency were identified by Atterberg: liquid, plastic, semisolid, and solid. The same soil sample passes through those four states as the amount of water it contains changes.

Mixed with a large amount of water, soil—at least its fine fraction—turns into mud, a viscous liquid that flows when it is sheared. The flow rate increases with the applied shear stress. However, not



(A) (B)

FIGURE 2.9. A thin deposit of montmorillonite clay has been pictured by SEM in moist air at a relative humidity of 14% (a) and 95% (b). The deposit thickness has increased by more than 30% due to the adsorption of water molecules in the space between individual clay lamellae. *Source:* Benoît Carrier.

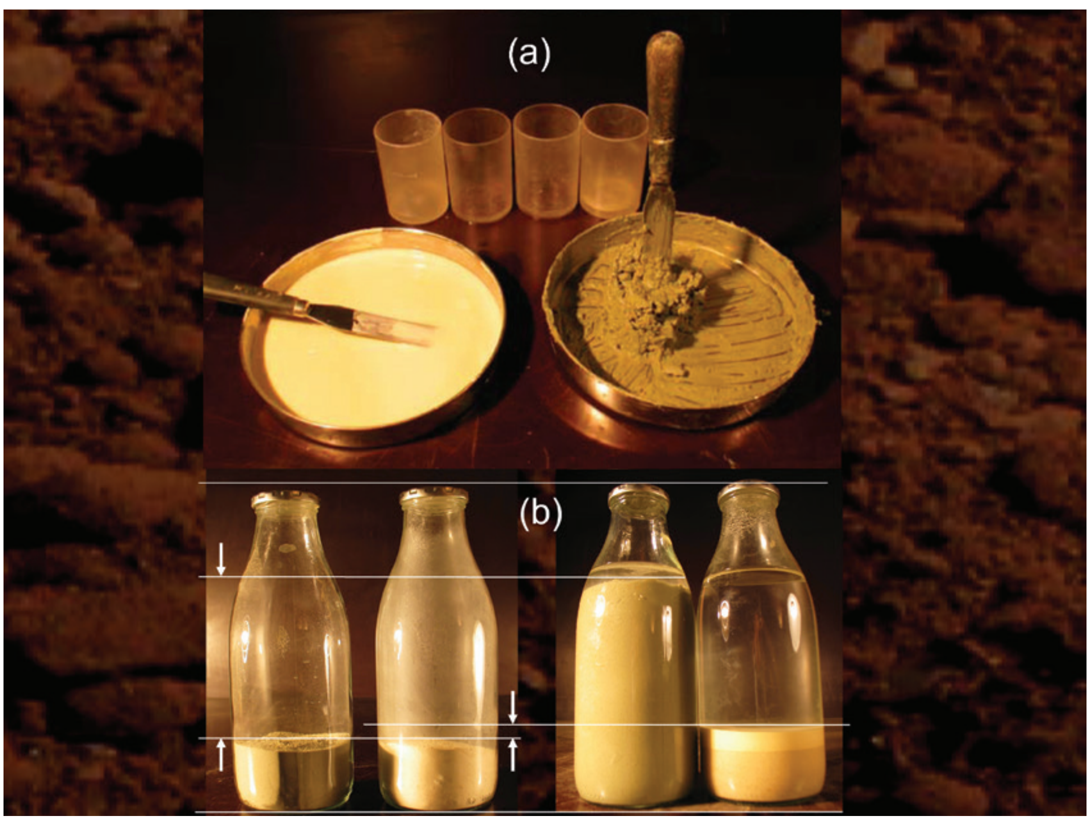


FIGURE 2.10. Two experiments performed with kaolinite and montmorillonite, respectively. In (a), a small amount of liquid water was added to kaolinite, a clay with a relatively low surface area (left), and to montmorillonite, a clay with a very high surface area (right). Kaolinite is already forming a liquid mud, whereas montmorillonite is still in the solid plastic state. In (b), a much larger amount of water was added to the same clays. The kaolinite is very moderately swelling, whereas the montmorillonite is experiencing a huge volume increase. *Source:* Laetitia Fontaine and Romain Anger.

all stress values produce flow. Even a very fluid clay or soil mud can withstand a small amount of shear stress before it starts to flow, similar to what can be seen in yogurt or toothpaste. This minimum stress is called yield stress.

As it loses water by evaporation, mud becomes stiffer and more viscous and has a larger yield stress, in addition to losing some volume from the evaporated water. As evaporation continues, mud turns malleable, not only able to be deformed without rupturing when stress beyond the yield stress is applied but also able to keep its imposed shape after removal of the applied stress. It is now in the plastic state.

If it lowers further, the water content becomes dangerous because the earth sample, while continuing to lose volume, is fragmenting instead of deforming continuously. It is now in the semisolid state according to Atterberg's classification. At an even lower water content, the semisolid body reaches a point where drying no longer leads to a decrease in volume. The granular skeleton has reached a point where it can no longer shrink. Any further loss of water has to be compensated by an inlet of air. The body is now in the solid state. To be shaped, it must be crushed and rewetted.

Conversely, starting with a dry, powdery earth sample and adding water, a rather abrupt increase in yield stress is observed as the material moves into the semisolid humid state and then the plastic state before collapsing as it reaches the liquid state (figure 2.11). The maximum of this yield stress versus water content curve corresponds to the point where the material has the highest wet cohesive strength and the highest adhesive strength ("stickiness").

Numerous tests were developed to characterize these complex behaviors. In practice, the most broadly used are the Atterberg limit tests, which establish the moisture content at which fine-grained soils transition between the liquid, plastic, semisolid, and solid states. The original tests were refined and standardized by Arthur Casagrande, an American civil engineer born in Austria-Hungary, in the early 1930s (see box 2.3).

Several secondary indexes were defined based on the previous Atterberg limits. One is the plasticity index (PI):

$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL}$$

Soils with a low PI react much faster to the addition of water than soils with a high PI, making them easier to work with. On the other hand, soils with a high PI and a high LL have a wide plastic range, extending up to a large moisture content. They are highly cohesive and sticky. The so-called wet cohesive strength can be assessed using a tensile strength test first proposed by the German engineer Richard Niemeyer in 1944 (see box 2.4).

The consistency of humid earth is very dependent on the aggregation state of the clay particles—in particular, the swelling clay particles. Attracted to one another by electric forces, they tend to form microscopic lumps, or "flocs," which increase the consistency of the mixture. The

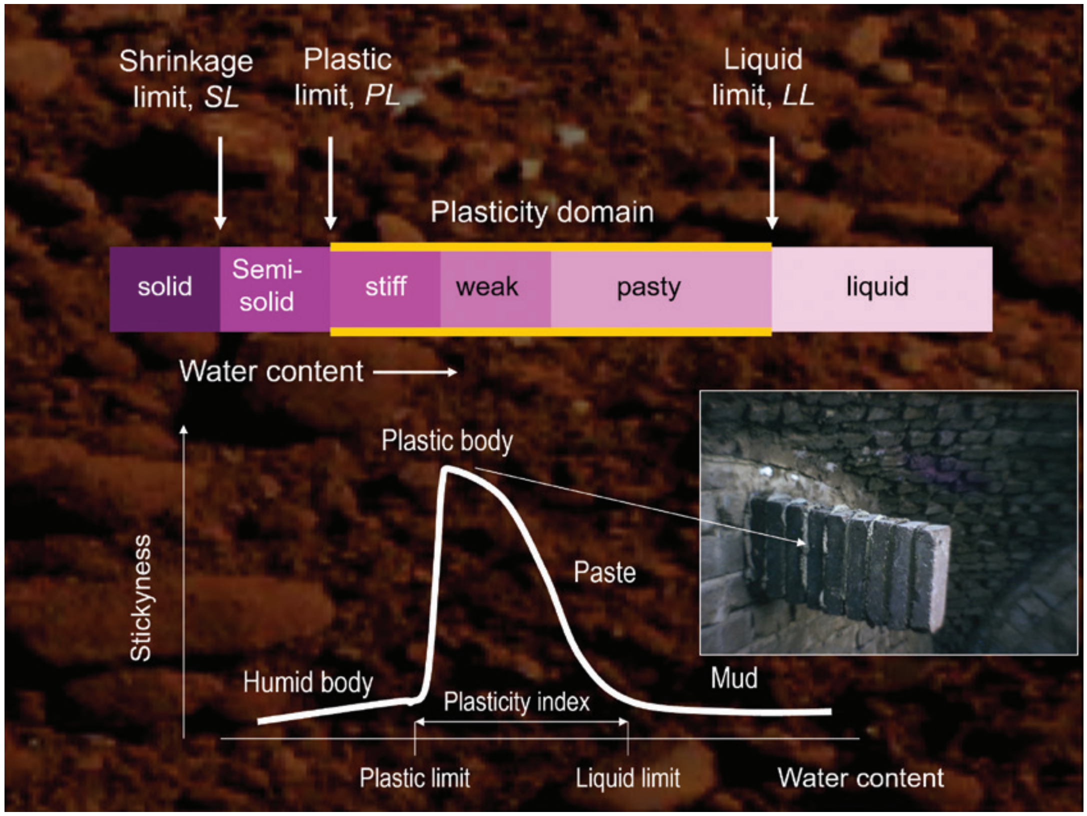


FIGURE 2.11. The shear strength of humid earth passes through a sharp maximum at the onset of the plastic domain. This maximum corresponds to the maximum of wet adhesive strength, as shown by the impressive horizontal pile of bricks held together by a layer of fresh earth (courtesy of CRAterre ENSAG). *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

attractive forces stem from the lamellae edges carrying a positive charge and the lamellae's large, or "basal," faces carrying a negative charge. The result is a highly porous house-of-cards structure that traps a large volume of water.

This situation can be avoided by inverting the charge on the lamellae edges thanks to the adsorption of a polyanion (an anion with multiple negatively charged sites). The hexametaphosphate (HMP) anion is a good example. (NaHMP is used as a dispersing agent in the pretreatment of soil samples prior to the sieve test; see box 2.1.) The surface of the clay particles is then entirely negative, and the particles repel one another, loosening the flocs and freeing the immobilized water. This process is illustrated in figure 2.16.

2.3.3 Salts

Soils contain variable amounts of soluble salts (Teutonico 1988, 56–69). Most often, these salts are sodium or calcium chlorides, nitrates, or sulfates. By increasing the concentration of Na^{+} or Ca^{2+} ions in the water layers around the clay particles, the swelling character of the particles is decreased. This is beneficial, but other effects render salts undesirable. Their hygroscopic character—the capacity to retain water and form brines—creates moisture-related problems in earthen walls and soils. Even more detrimental is the soluble character of salts, which allows them

Box 2.3. Atterberg Limit Tests

- The liquid limit (LL) is the water content (%) at which soil changes from a plastic to a liquid state when the soil specimen is just fluid enough for a groove to close when jarred in a specified manner (figure 2.12).
- The plastic limit (PL) is the water content (%) at which soil changes from a plastic to a semisolid state. This test involves repeatedly rolling a soil sample into a thread until it reaches a point where it crumbles (figure 2.13).
- The shrinkage limit (SL) is the moisture content (%) at which no further decrease in specimen volume occurs with further reduction in moisture (figure 2.14). At this point, the friction forces between the particles that form the granular skeleton can resist the shrinkage forces.

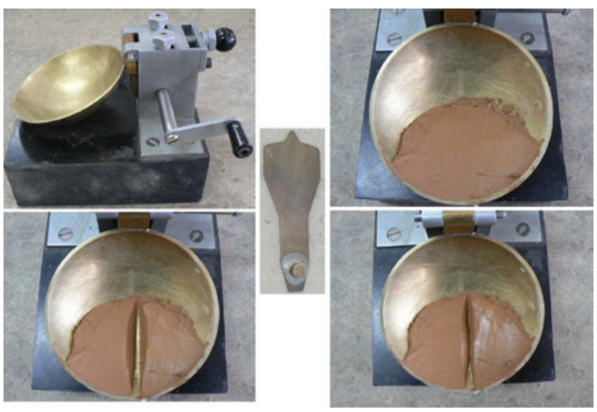


FIGURE 2.12. The LL is measured by spreading a portion of the earth sample in the brass cup of a Casagrande LL machine (max thickness: 1 cm) and dividing it using a grooving tool (center; width: 2 mm; min. groove length: 4 cm). The moisture content when the groove (bottom left) closes for at least 1 cm after twenty-five drops (bottom right) of the cup is defined as the liquid limit (LL; ASTM D4318). *Source:* RMS NSW (2015).

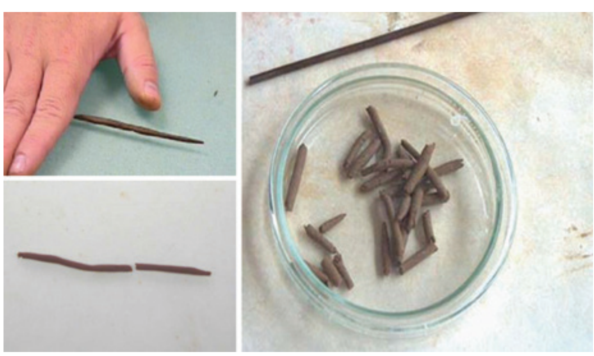


FIGURE 2.13. The PL is determined by remolding a small ball of moist plastic earth and manually rolling it out into a 3 mm thread (min. length: 5 cm). The PL is the moisture content at which the thread crumbles into 1 to 2 cm pieces before being completely rolled out (ASTM D4318). *Source:* Schroeder (2016).

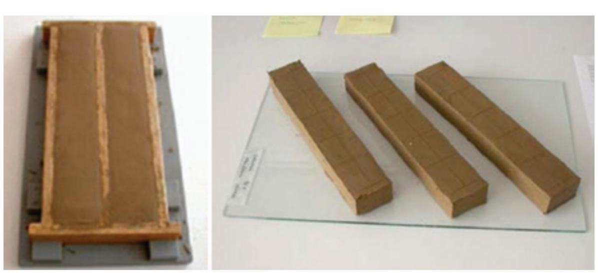


FIGURE 2.14. The SL is determined by monitoring the reduction in length of a standardized specimen. The earth is first prepared to standard consistency. It is then placed into a mold (220 × 40 × 25 mm). The mold is removed and the specimen is air-dried until its length no longer changes. *Source:* Schroeder (2016).

Box 2.4. Wet Cohesive Strength Test

The wet cohesive strength test, also called the figure-eight shape test, is a measure of the tensile strength of soil samples in the standard consistency state, which is a plastic humid state. To prepare the sample, a ball is made with 200 g of soil kneaded on a nonabsorbing surface. The ball is then dropped from a height of 2 m.

It is dropped again until standard consistency is reached when the ball flattens by 50 mm. The sample is then pressed into a wooden mold in the shape of a figure eight. After demolding, it is placed between two metal claws, and an increasing load is suspended on the lower claw until the sample ruptures in its narrowest section. The load at rupture is converted into a value of tensile strength (unit: pascal; i.e., newton/m^2). Elements of the test are shown in figure 2.15.

FIGURE 2.15. The wet cohesive strength test of soils and the mold used to shape the specimen. *Source:* Schroeder (2016) and ZRS, Christof Ziegert.

to migrate with water to the surface of structural elements, where they crystallize after the evaporation of water, ruining the cohesion of earth and provoking the scaling of coatings.

In the laboratory, the amount of soluble salts is determined by washing a weighed amount of dry soil. After washing, the sample is dried and weighed again. The difference is the soluble matter. More specifically, the presence of chlorides or sulfates in the wash is detected by adding silver nitrate ($AgNO_3$) and observing for a white cloud of silver chloride (AgCl) precipitate. Similarly, the presence of sulfates is detected by adding barium chloride ($BaCl_2$) and monitoring for a white barium sulfate ($BaSO_4$) precipitate. It is generally considered that in order to avoid problems, the total concentration of soluble salts should not exceed 0.12 mass % or, more specifically, 0.02 w% in nitrates, 0.10 w% in sulfates, or 0.08 w% in chlorides (DIN 18945:2024-03 2024; ASTM C1580-20 2020).

2.4 Earth as a Porous and Multiphasic Material

Up to now, we have been interested in two component phases of earth: the solid mineral particles and the liquid (adsorbed or capillary) water. To be comprehensive, there is a third phase to consider: air, which is a gas. Therefore, earth is a triphasic material containing solid, liquid, and gas. This is the state of earth in our built heritage. It looks like a dry,

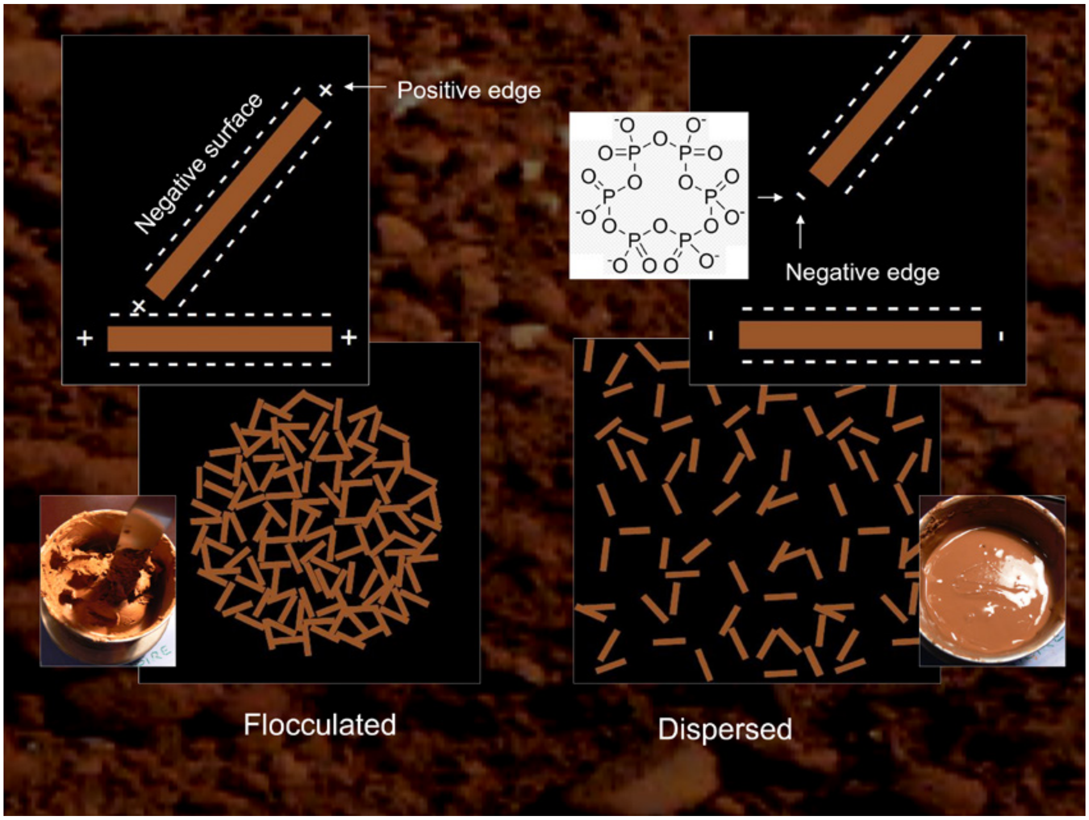


FIGURE 2.16. The edges of clay lamellae are positively charged, whereas their large "basal" surfaces are negatively charged. This leads to the formation of large house-of-cards-type aggregates and to a large viscosity increase via electrostatic attractions. Polyanionic dispersing agents—like HMP, for instance—invert the electric charge on the edges, preventing the formation of aggregates and fluidizing the mixture. In the field, a pinch of HMP is enough to fluidize humid earth without adding any water. *Source:* Laetitia Fontaine and Romain Anger.

porous solid, but in reality, it contains a small amount of water in equilibrium with the atmospheric environment.

We have seen that when mud dries, its volume diminishes to a point where the skeleton is no longer able to adapt to the shrinking forces. This is the so-called point of air entry. Any loss of water beyond this point must be replaced by the inlet of air. Up to the point of air entry, all void spaces between solid particles are full of liquid, and earth is said to be saturated. Conversely, beyond the point of air entry, earth is unsaturated.

Together, the three phases determine the two essential characteristics of earth: "dry" cohesion and density—or more precisely, the way density can be increased by compaction.

In terms of soil mechanics, raw earth is a cohesive-frictional material, which means that its properties are determined by the combined action of adhesion forces and friction forces. Cohesion is defined as the force (per unit of surface area) that attracts the particles to one another. Friction is the force (also per unit surface area) that prevents the particles from sliding on one another. These forces are intimately related. The friction force increases linearly with the intensity of the cohesion force when in contact.

There are numerous types of attractive forces in nature. It has now been established that cohesion in raw earth is essentially due to capillary forces. In other words, paradoxically, raw earth owes its “dry” cohesive strength to the tiny capillary bridges surrounded by air that form by condensation of atmospheric moisture (figure 2.17). Even more paradoxical, the attractive pressure generated by these capillary bridges—what soil scientists call suction—is all the more intense because the bridges are small and the surrounding humidity is low. This explains why raw earth becomes stronger as it dries and as the number of small particles (clays) it contains increases.

However, this rationale has obvious limits. In a totally dry material, there is no more water to form capillary bridges, and cohesion collapses. On the other hand, when there is so much water that every void is flooded (saturated state), there is no air-water interface, and capillary bridges can no longer exist. Again, cohesion collapses. Yet in this state, the material may remain so highly viscous that it behaves as if there was still some cohesion. This is the wet cohesive strength measured using the figure-eight test (see figure 2.15).

The final density that earth is able to reach at compaction is also dependent on the equilibrium between air and water. Not enough water, and friction prevents the particles from rearranging under the pressure of the rammer. Too much water, and an important part of the compaction effort is transmitted to water and not to the granular skeleton. In between, there is an optimum that depends on the texture of earth (i.e., its particle-size distribution and its type of clay) and the compaction energy. The Carazas test (see section 2.4.3) is an experiential exercise for understanding how earth responds to a compaction treatment according to its nature and its hydric state. It provides the basis for a rational choice of construction material and method.

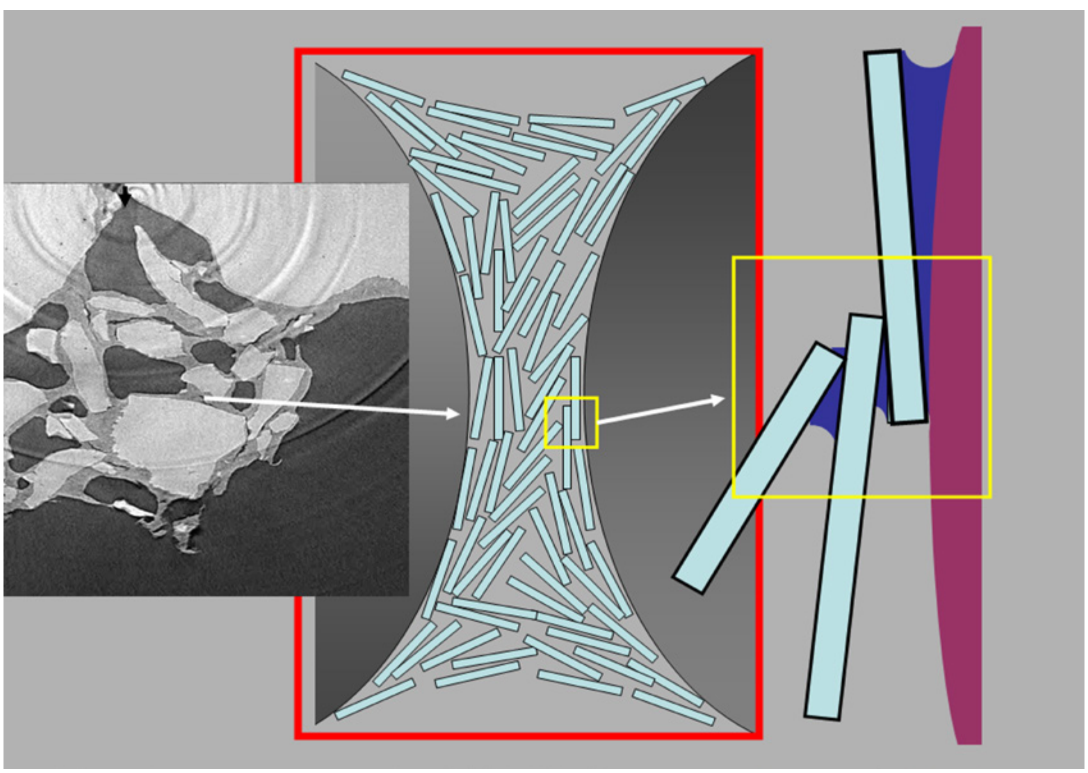


FIGURE 2.17. Graphic illustrating the mechanism of capillary cohesion in earth. *Left:* An X-ray scanner section in a lab-made earthen material obtained by drying sand-clay slurry. One can see the coating of clay (medium gray) around the sand grains (light gray). The dark-gray area is void space. *Middle:* Graphic showing the fabric of clay particles between two sand grains. *Right:* The tiny capillary bridges of condensed atmospheric humidity ensuring the cohesion of the material. *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

2.4.1 Particles, Water, and Hydration States: Correlations

As builders and conservators familiar with raw earth, we know that without water, we are totally disarmed. Water is fundamental to the material production and construction processes. By incorporating water into raw earth in different quantities (percentages), we obtain materials with different physical states that we call hydration states. A priori, an infinite number of hydration states may be considered, but for better control and understanding, we define only five: dry, humid (or moist), plastic, viscous, and liquid (figure 2.18). Both viscous and liquid are flowing states; the difference is a matter of viscosity and yield stress. Similarly, in well-aerated, powdery soil samples, the difference between dry and humid is often a matter of degree of water-induced aggregation. Most soil samples that look dry already contain some water on the clay particles and in narrow pores due to adsorption and capillary condensation of water vapor from the surrounding environment. Temperature and air relative humidity variations cause the water to adsorb or evaporate from the walls. Each hydration state has distinct mechanical properties that logically determine a specific use or activity in the construction process. For example, plastic earth can be molded into adobe bricks, whereas moist earth can be rammed between rigid walls to make a rammed-earth wall.

2.4.2 Particles, Air, and Voids: Correlations

Often neglected, air is on equal footing with water; both are essential components of raw earth as a building material. Yet most of the time, only the negative side of this important role is considered. Indeed, air-filled voids are generally considered detrimental to strength. This stems from the theory of brittle fracture, which states that voids in a solid material are places of stress concentration and crack-initiating defects. Though this is true, it neglects the fact that in raw earth, triple air-water-solid interfaces are required to generate capillary cohesion and strength (figure 2.19). Without some air, a water-saturated soil sample is but a viscous or liquid mud. Each raw earth preparation technique and each construction method require the proper amount of air in the mix and in the final material. Therefore, it is important to understand the role of air when preparing and using material for a specific construction technique.

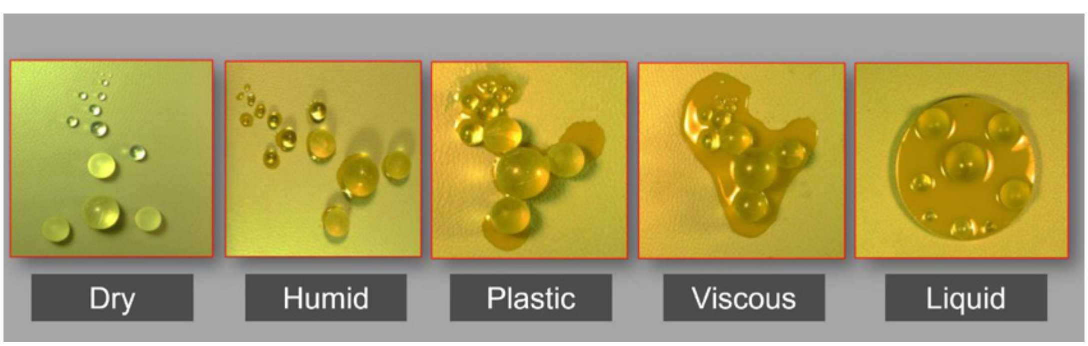


FIGURE 2.18. The five hydration states of raw earth. Depending on the water content, cohesion and consistency will vary. *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

In practice, the amount of air is controlled by mechanical action. For instance, reworking a pile of soil is a simple way to trap air. Conversely, applying gentle pressure or compacting the earth more vigorously will expel air (figure 2.20). A critical point is that the efficiency of both entrapping and expulsion of air is strongly dependent on the hydration state. Each construction technique is thus a unique blend of material composition, hydration state, and mechanical properties.

2.4.3 A Three-Phase Correlation Test: The Carazas Test

For a better understanding and assimilation of the triphasic nature of raw earth, a practical exercise has been designed by one of the authors of this text (Carazas Aedo, 2022). It is based on the search for cross-correlations between the solid variable (the granular composition of the soil sample), the liquid variable (the amount of water and the hydration state), and the gaseous variable (the amount of air and void space).

The Carazas test is based on a 5 × 3 matrix of samples corresponding, for each tested material, to the five hydration states (dry, humid, plastic, viscous, and liquid) and three mechanical actions (filling, packing, and ramming). A model of the matrix is shown in figure 2.21. Each sample is placed in a 15 × 15 × 15 cm = 3,375 cm^3 (3.375 L) dismountable mold. The required total amount of dry earth (15 × ~3.5 L ≅ 100 kg) is first prepared by sifting the raw material through a 2 mm sieve and letting it dry. Next, fifteen doses of the experimental material are prepared by pouring 3.375 L of dry earth into large bowls and mixing in the amount of water needed to reach the desired hydric state (no water is added to the three dry samples in the first column of the matrix).

The mold is placed on a matrix position and filled with the earth-water mix corresponding to that position, and the chosen compaction treatment is applied. In some cases, often in the humid state, if the earth is neither pressed nor rammed, there is more material than needed to fill the mold. This is due to air trapped in the material during the mix preparation—what soil engineers call soil loosening. The excess volume of earth is then estimated as a measure of the loosening

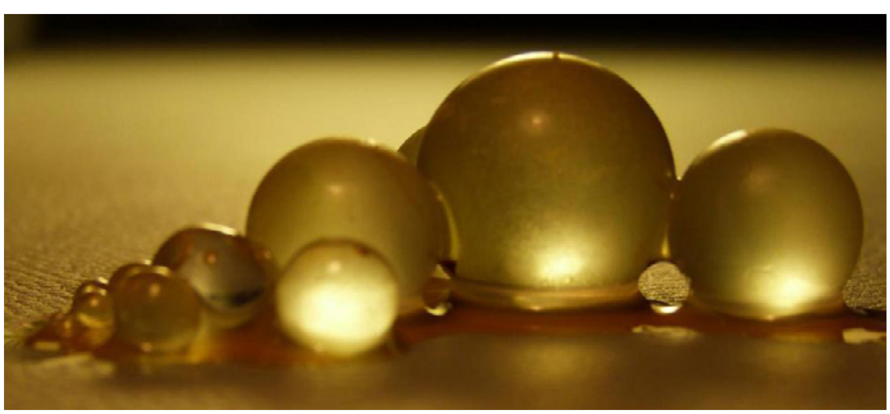


FIGURE 2.19. Raw earth owes its cohesion to capillary bridges. This requires triple interfaces between particles, water, and air. *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

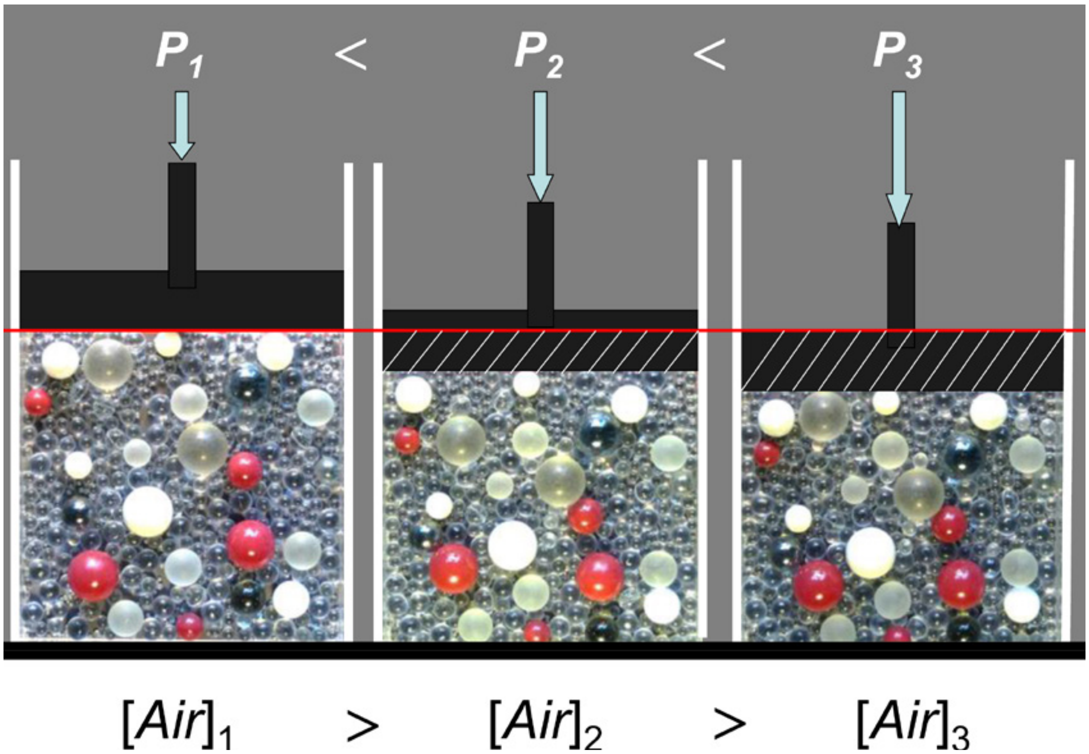


FIGURE 2.20. Graphic illustrating the effect of mechanical action (pressure or compaction, increasing from P_1 to P_3) applied to an unsaturated soil. Voids close, air is expelled (the striped areas), and particles adopt a denser structure. *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

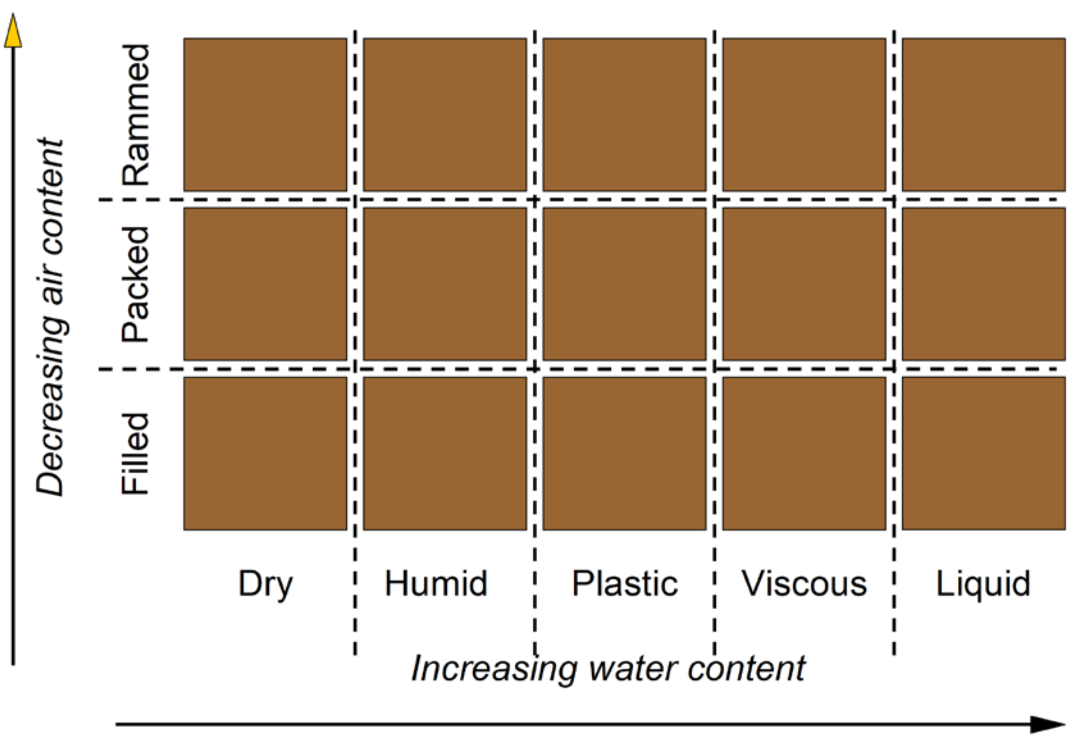


FIGURE 2.21. The pedagogical matrix of the "Carazas test," which allows for the detection of cross-correlations between the three phases of raw earth: the solid phase (type of soil), the liquid phase (hydration state), and the gaseous phase (air-filled voids). *Source:* Henri Van Damme and Wilfredo Carazas Aedo.

effect. In other cases, there is not enough prepared material to fill the mold, even without pressing or compacting. The final height of the material in the mold is then measured using a ruler. This determines the apparent loss of volume generated by replacing some air with water or by replacing some air with water and pressing or compacting the mixture. The shape of the unmolded sample and its defects are scrutinized for clues as to its durability (figure 2.22).

The Carazas test is the first hands-on approach to earth matter. It allows students to come into direct contact with earth and to observe several physical and mechanical phenomena. Students gain experience in formulating, researching, and testing a hypothesis, as well as the ability to obtain an instant reading of the phenomena they will encounter in their future endeavors in construction or conservation.

2.5 Check Your Skills for Soil Selection

Understanding the behavior of raw earth covers many aspects, some of which have been discussed in this text. We reviewed traditional tests that, together with the somewhat unconventional Carazas test, give us confidence in their use for particular types of earth. The following exercise expands on this and offers virtual practice in identifying earth materials for certain construction applications. While hiding the caption, study figure 2.23, which shows five soil samples that have each been sieved and portioned in five size fractions: stone, gravel, sand, silt, and clay. For each sample, looking at its particular composition, speculate as to what could be a good use for it. Then read the caption for the answers.

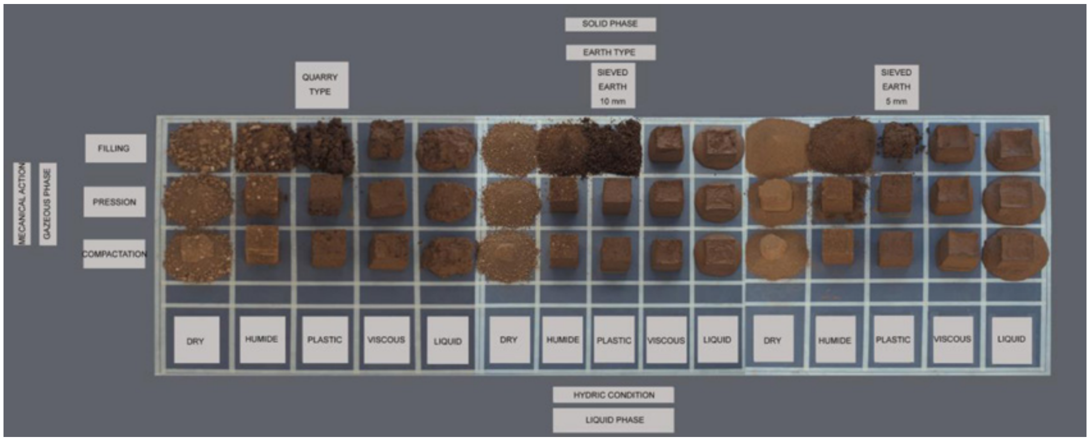


FIGURE 2.22. A look at the outcome of the Carazas test at the end of a test performed with three different soil samples, each sample having its own fifteen-box matrix. *Source:* Wilfredo Carazas Aedo.

FIGURE 2.23. Five soil materials considered for earthen construction. *Source:* Laetitia Fontaine and Romain Anger. Soil #1 is a well-balanced mixture of stones, gravel, sand, silt, and clay, all present in roughly equal amounts. After compaction, it becomes a real, natural, very hard concrete containing enough clay to be highly cohesive and enough coarse grains to be rigid and avoid cracking. This earth is good for rammed-earth construction. Soil #2 contains many fewer stones and gravel. It is easier to work and to model by hand. Yet the amount of sand is large enough to avoid cracking when the material is used in the plastic state. This earth is ideal for making molded bricks. It is good for adobe construction. Soil #3 is very fine earth. It contains almost no stones and gravel, and the sand fraction is very small. It is very sticky when wet, but it cracks when it dries. Mixed with straw and/or sand to avoid cracking, this type of earth may be used as a filling material in a wooden frame. It is good for cob construction. Soil #4 contains neither stone nor gravel. It contains sand, silt, and clay in well-balanced amounts, but the clay fraction is smaller than in adobe earth, whereas the sand fraction is larger. This prevents cracking even when the material is mixed with a lot of water. This is an ideal material for coatings and mortars implemented in the viscous state. Soil #5 is very fine. It contains no stone, no gravel, no sand, and very little clay. The clay content is too small to impart some cohesion to the mixture. Using this material would lead to strength problems. Do not use it as it is.

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EARTHEN CONSTRUCTION TECHNIQUES

3

Overleaf: Making adobe during the Earth as a Building Material module of the EAC22 course in Al Ain, United Arab Emirates. *Source:* J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.

3

EARTHEN CONSTRUCTION TECHNIQUES

Wilfredo Carazas Aedo

3.1 Introduction

Building with earth is a practice that has long been a part of human development, and numerous countries around the world can attest to the architectural quality of such constructions. Earthen buildings provide relevant and rational solutions to a given context and are built using the appropriate local materials and technologies, as demonstrated by the exceptional archaeological sites of Mari in Syria (third millennium BCE; figure 3.1), Mesa Verde in the United States, Paquimé in Mexico, and Joya de Cerén in El Salvador (figure 3.2), among many others. These major sites were home to civilizations with important cultural histories.

FIGURE 3.1. Mari archaeological site, Syria. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.2. Joya de Cerén archaeological site, El Salvador. *Source:* Wilfredo Carazas Aedo.

3.2 The Importance of Earthen Materials in the Selection of Building Techniques

To better understand earthen construction, it is important to examine the earthen material(s) used, including understanding their nature and properties. As explained in the previous chapter, earth is a material composed of three main elements or phases: liquid, solid, and gas. The interaction between these phases gives us both qualitative and quantitative variations that will determine characteristics suited to a particular constructive action or technique.

This process begins at the infinitesimal architecture of matter—from the first elementary grains that form the atom, to the adhered form of a crystal, to the sum of these crystals, which form rocks. From this matter, the earth is born, with all its characteristics and properties. It is the product of a slow process of the disaggregation of the mother rock by physical, chemical, and biological actions linked primarily to climatic conditions.

The process or transit of earthen material to architecture begins with the determination of the three phases that are intimately linked to—in other words, inseparable from—the extraction of the material to its permanent state as a building.

As explained previously, each phase has its own characteristics, which are described below:

- **The solid phase**. This phase is characterized by grains (silica, micas, quartz, and other elements) of different dimensions, textures, and mineralogical structures, generally with a significant presence of clay in relation to the other components. The dimensions and components are defined by granulometry, specific to the type of grains contained in the soil. A reading will also be necessary to determine the type and percentage of clay.
- **The liquid phase**. This phase is essentially water (H_2O), with proportions that will vary according to the origin and subsequent handling of the soil. These proportions are determined by the progressive water states: dry, wet, plastic, viscous, and finally liquid. Each of these water states is delimited by limits and indexes that are also determined by a constructive action.
- **The gaseous phase**. This phase is air (oxygen, nitrogen, and some rare gases) contained within the earthen material in different proportions or volumetric quantities. The volumetric variations, referred to as maximum porosity or minimum porosity, are variable depending on the mechanical action of the building technique—for example, filling, pressing, or compacting.

The interchange or interrelationships among these three phases determine the appropriate actions—the method or technique of producing an earthen material—that lead to a particular constructive system. For example, cob, made of earth in a plastic state, is piled up and then cut to form, whereas rammed earth, which is tamped down into a wooden form, requires only marginally moist and well-aerated soil, with the ramming action driving out the air and binding the grains through cohesion.

The scheme below (figure 3.3) shows the three phases of matter and how they relate to various actions or techniques in earthen building practice. These actions are also described in detail for the five most commonly used building techniques in the following section.

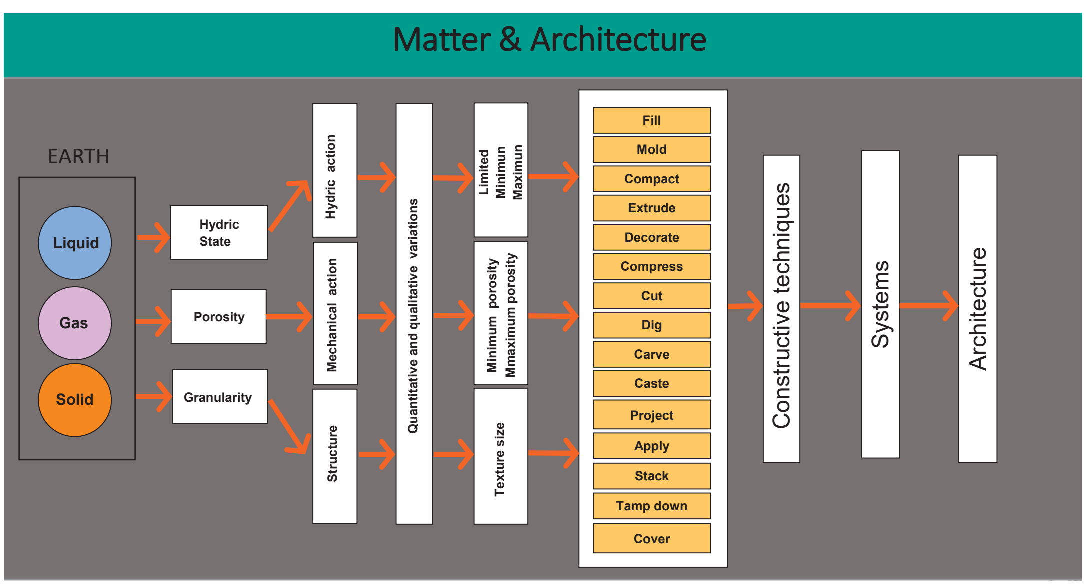


FIGURE 3.3. Linear process from the use of the material earth to architecture. *Source:* Wilfredo Carazas Aedo.

3.3 A Range of Building Techniques

We often describe earthen building techniques as the product of local builders who developed their approaches in different regions of the world and in parallel or consecutive ways. There is a wide variety of earthen building techniques that are adapted to soil quality, natural environment, and culture. Among these, five stand out as the most used techniques around the world: adobe (mud brick), rammed earth, mixed method or wattle and daub (*quincha* or *bahareque*), cob, and plaster finishes and decorations. These five techniques are described in detail in the following sections.

3.3.1 Adobe: Molded Earth

3.3.1.1 Introduction

Adobe is one of the easiest building materials to manufacture, requiring only a simple mold and proper clay preparation. Multiple adobe blocks are stacked to form physical structures (walls) that are joined together to construct beautiful buildings, from simple dwellings to grand palaces and mosques. Adobe is one of the easiest building materials to manufacture, requiring only a simple mold and proper preparation of the clay. Multiple adobe blocks are stacked to form physical structures (walls) that are joined together to construct beautiful buildings, from simple dwellings to large palaces and mosques (figure 3.4).

Also, populations affected by earthquakes learned to build housing adapted to that context, developing in response a simple and efficient building culture that employs walls with an acceptable slenderness ratio, which are wider at the base than at the top or have buttresses or perpendicular walls to resist out-of-plane failures.

FIGURE 3.4. The mosque of Mopti in Mali, built entirely of adobe, restored in 2006. *Source:* Wilfredo Carazas Aedo.

Notably, populations affected by seismic disruptions learned to build homes adapted to that context, developing a simple and efficient building culture in response that employs walls that are wider at the base than at the top or have buttresses or perpendicular walls to withstand out-of-plane failures.

3.3.1.2 Types of Adobe

Since humankind began building, adobe has been one of the most widely used techniques independent of period, era, or region. Over time, ancient populations and cultures followed the same general patterns and forms of design and construction, with certain variations in dimension and shape. In essence, however, all relied on the same technique: adobe masonry.

Many ancient civilizations used coniform, pyramidal, plano-convex, or parallelepiped adobe blocks, many of them molded by hand, as evidenced by fingerprints left behind in the adobe. We have numerous tangible examples of adobe building: in Jericho, in the Jordan Valley (800 BCE); in Peru, in the Sechin culture of the Casma Valley (3600–200 BCE; figure 3.5); and among other cultures that favored the technique, which is still used in certain regions of Africa.

Parallelepiped adobes are the most commonly encountered and come in varying forms, with dimensions and shapes corresponding to types and forms of production and construction. Notably, the dimensions of an adobe block—its width, length, and thickness—have a concordant geometric relation that allows the blocks to be tightly assembled, providing mooring and stability to a wall (figure 3.6). This geometry was used across many regions in different and independent ways.

3.3.1.3 Types of Molds: Formworks

There are various sizes and types of adobe molds, which can be made from wood, cane, metal, or other materials, but the molds most commonly used around the world are those made from wood. In adobe construction, formworks are also designed for specific uses—for example, for round columns, reinforced brick masonry, and plumbing and electrical systems (figure 3.7).

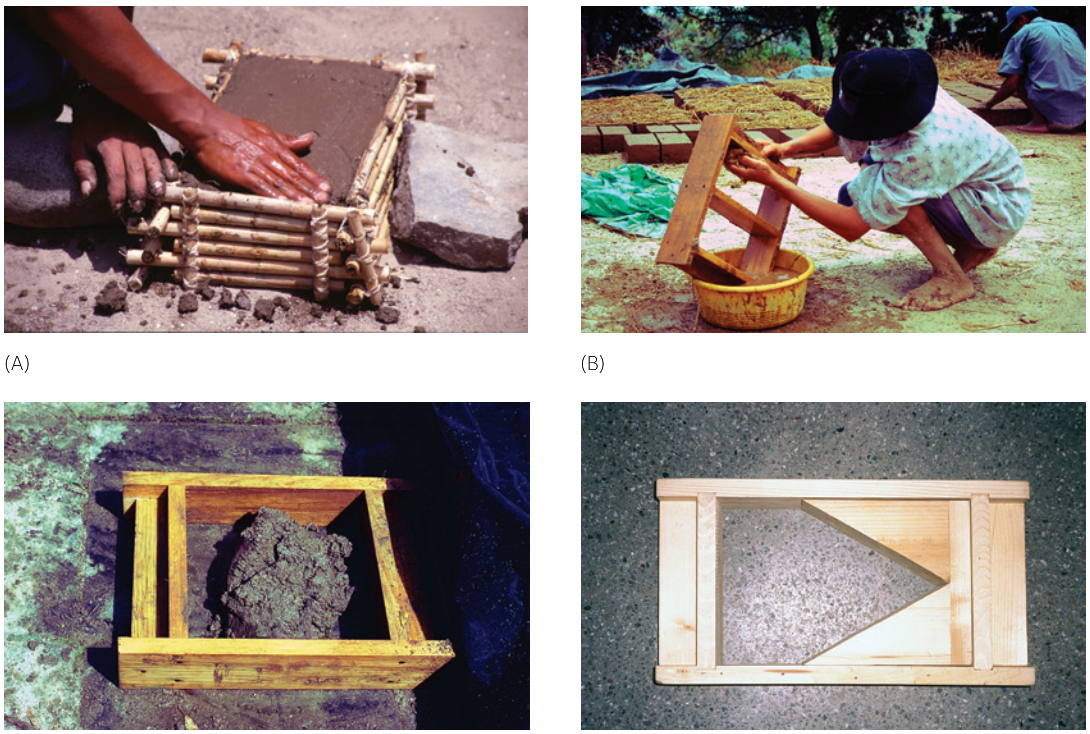
(A)

(B)

FIGURE 3.5. (a) Coniform adobe blocks and (b) their placement in a wall. This was a common building practice in Peru's Sechin culture. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.6. (a) Rectangular adobe blocks and (b) square adobe blocks. *Source:* Wilfredo Carazas Aedo.

(A) (B)



(A) (B) (C) (D)

FIGURE 3.7. (a) Cane mold, (b) double wood mold, (c) single wood mold, and (d) shaped mold. *Source:* Wilfredo Carazas Aedo.

For these elements, special formworks are made for adobes with preformed cutouts, notches, and special shapes that can receive, for example, electrical boxes, thus avoiding cutting into walls that are already built.

3.3.1.4 Production of Adobe

Adobe production methods vary according to the geological characteristics and the climatic conditions of a given region. One of the easiest forms of production involves the use of a simple mold (single-unit production) in which the entire extraction, preparation, and molding process is carried out using a minimum of tools and equipment (figure 3.8).

FIGURE 3.8. Individual artisan production of adobe. *Source:* Wilfredo Carazas Aedo.

Other forms of adobe production rely on the use of special tools and machinery, which allows for large-scale production of thousands of adobe blocks in a single day (figure 3.9). For example, in the US city of Albuquerque, New Mexico, there are industrial adobe production companies that serve regional demand.

3.3.1.5 The Adobe Production Process

After conducting preliminary field tests, the best soil is selected (see chapter 2). The production area is readied, and the soil is prepared by sifting or otherwise eliminating organic matter. The soil is then mixed with water until a state of hydric plasticity is achieved, and the material is left to set (ideally overnight). The final stage of preparation consists of mixing/homogenizing the material to obtain an ideal consistency, taking advantage (if necessary) of the inclusion of some type of plant fiber, which increases the adobe's cohesion and resistance to decay.

The molding and demolding begin immediately in the formworks. The adobe is then left to dry in the sun for the required number of days (a duration that varies with temperature and humidity). The drying process occurs in stages: after the exteriors are predried, the adobe blocks are placed vertically to allow for the cleaning off of excess mortar and the correction of deformities. Once the blocks have completely cured, they will be stored and are ready for use in construction.

A diagram of the adobe production process is shown in figure 3.10.

FIGURE 3.9. Industrial production of adobe. *Source:* Wilfredo Carazas Aedo.

3.3.1.6 Building with Adobe: Masonry

Adobe blocks are designed for use with a specific building technique known as simple masonry, or bricklaying, which employs blocks assembled using a viscous mud or clay mortar. Simple masonry involves assembling adobe blocks using a buttressing method, an interlinked layering system that creates structures with increased stability and resistance and helps determine the thickness of the walls.

A related technique known as reinforced masonry was developed in response to the need for structures to resist seismic movements. This form of construction was used by populations living in earthquake-prone regions, such as the Andean cultures (South America), who developed these efficient building systems, such as trapezoidal adobe walls, with an inward inclination of 10 to 12 degrees, all on wide and high lithic foundations, paying special attention to the connection of the corners.

In recent years, after extensive research and experiments conducted by universities, research centers, and other institutions around the world, new adobe building methods have been developed that enable structures to better withstand earthquakes. These methods are known as seismic-resistant adobe construction techniques and involve reinforced adobe masonry, which is adobe masonry that has been strengthened and made more compatible with the earth, giving it increased tensile strength (figure 3.11).

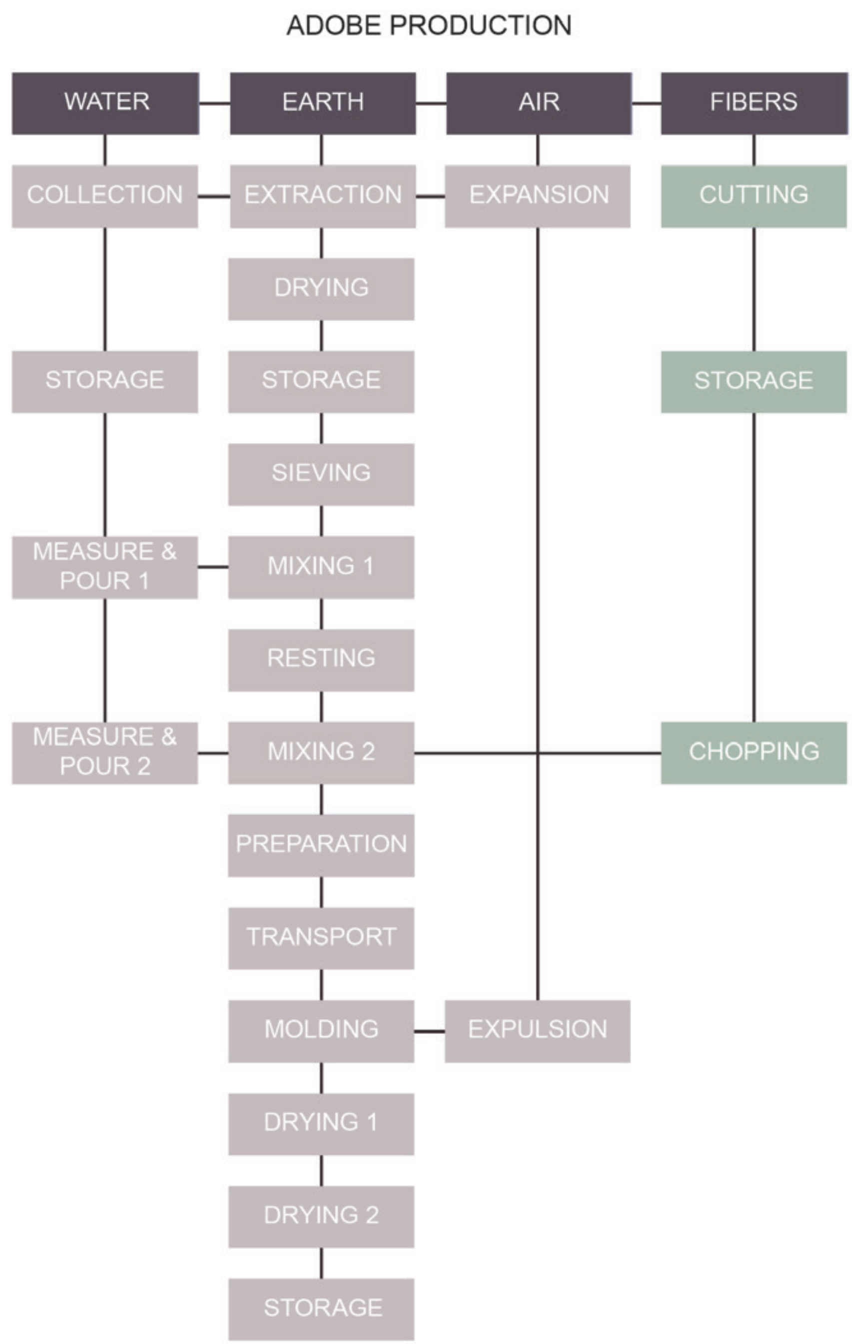


FIGURE 3.10. Diagram of the adobe production process, from raw material to storage of finished blocks. *Source:* Wilfredo Carazas Aedo.

In 1990, the Getty Seismic Adobe Project (GSAP) was established by the Getty Conservation Institute, in cooperation with Stanford University, to develop and test minimally invasive and easily implemented techniques to avoid the collapse of historic earthen structures during seismic events (Getty, n.d.-b). In 2009 the GCI initiated the Seismic Retrofitting Project (SRP) with the objective of adapting GSAP techniques to better match the equipment, materials, and technical skills available in many countries with earthen sites. Using four Peruvian historic earthen buildings representing typologies across Latin America, the GCI—in collaboration with the Ministerio

(A) (B)

FIGURE 3.11. (a) Adobe dwelling in Guatemala built using earthquake-resistant buttressing construction method. *Source:* Wilfredo Carazas Aedo. (b) Diagram of the buttressing adobe construction method using vertical reinforcement with bamboo. *Source:* Wilfredo Carazas Aedo.

de Cultura del Perú, the Escuela de Ciencias e Ingeniería of the Pontificia Universidad Católica del Perú, and the University of Minho, Portugal—is designing, testing, and implementing seismic retrofitting techniques and maintenance programs with locally available materials that will improve the structural performance and safety of earthen buildings while minimizing loss of historic fabric (Getty, n.d.-a).

3.3.2 Rammed or Compacted Earth

3.3.2.1 Introduction

Rammed earth is made using soil in a humid, hydric state. This soil is compacted into successive layers inside a formwork, with the aim of eliminating trapped air and thus obtaining cohesion by adherence and friction between coarse grains and clay. The compacted material is then dried in the open air, resulting in a strong, resistant wall.

This technique requires a solid formwork, which determines the width of the wall. The technique employed in making rammed earth was inherited from multiple sources dating as far back as ancient Phoenicia (Tyre, Lebanon) and Syria (Ugarit) and subsequently during the Roman era. Later, it was used around the world, mostly in parts of North Africa, Europe, and the Middle East, as well as in some regions of Latin America, especially during pre-Hispanic periods (figure 3.12). However, the ancient technique differs substantially in design and construction from its use in the modern era; specifically, the hydric state of the earthen material was more plastic, with a higher percentage of water, and required only moderate compaction (figure 3.13). Vestiges of this building method can still be observed today—for example, at the Oquendo Palace archaeological site, a former elite residence in the lower valley of the Chillón River, Peru, and at the Paquimé archaeological site in Mexico.

FIGURE 3.12. Rural dwelling, Isère, France. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.13. Modern-day dwelling, Picardy, France. *Source:* Wilfredo Carazas Aedo.

3.3.2.2 The Rammed-Earth Production Process

The soil used in rammed-earth building is naturally composed of a mixture of diverse coarse grains and clays, generally derived from alluvial sediment deposits created more than ten thousand years before the current era. One of the characteristics of the soil used in rammed earth is that it is made up of a balanced percentage of coarse grains and a maximum of 20% clay.

Generally, soil extracted from the quarry is already in a hydric state and contains moisture levels close to those required for compaction, thus streamlining the building process. It is always necessary, however, to verify the soil's suitability and to determine whether to increase the water content to reach an optimum hydric state for compaction.

A diagram of the rammed-earth production process is shown in figure 3.14.

3.3.2.3 Wall Construction

The first stage in constructing a wall using rammed earth is the extraction of optimal soil, which must then be stored in a suitable location, generally near the construction site. If the soil is too wet, it must be dried (using sun and air). If the soil is too dry, an additional amount of water must be added until the correct moisture content is obtained.

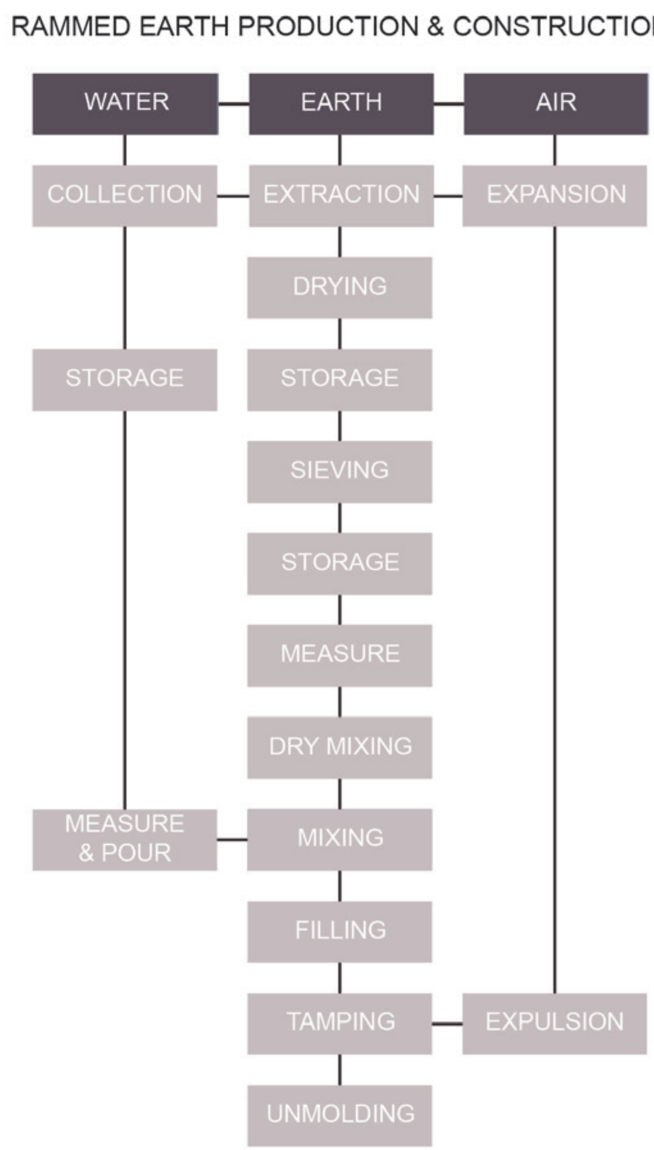


FIGURE 3.14. Diagram of the rammed-earth production process, from raw material to uncasing. *Source:* Wilfredo Carazas Aedo.

The tamping and compacting process begins by situating the forms/formworks in the place where the wall is to be built. A layer of moist earth material no more than 15 cm thick is added to the formwork and tamped and compacted with a manual "rammer" compactor to ensure uniform compacting. This process is repeated until the desired wall height is achieved, and the wall is built in successive, uniformly compacted layers.

3.3.2.4 Types of Formworks and Compacting Tools

Numerous kinds of formworks, from the simplest and most traditional to highly sophisticated, may be selected depending on the context and the capacities of the building site. Traditional formworks and tools are generally manufactured in an artisanal manner and employ a combination of wood and attachments such as ropes, tensioners, and certain metal components (figure 3.15). The ramming tool is typically wood but may be metal in some cases.

Today, there are metal and wooden formworks manufactured specifically for rammed-earth building, though many of these are repurposed formworks designed for use with cement and aggregates in conventional industrial construction (figure 3.16). Similarly, mechanized tools and implements, such as pneumatic compactors, mixers, conveyors, and lifters, are currently used in contemporary earthen building as well.

FIGURE 3.15. Traditional formworks use a combination of wood and attachment elements including metal anchors. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.16. Many formworks for rammed-earth construction are repurposed for use in industrial construction. *Source:* Wilfredo Carazas Aedo

3.3.2.5 Wall Assembly Techniques

One of the characteristics of rammed-earth construction is that the process of building and layering the wall is done in a continuous and consecutive manner, immediately disassembling the forms or formworks as the wall is erected, resulting in walls with monolithic characteristics. As a result of the action of compacting, a series of striations appears in the finished wall, indicating the consistency of the compaction; if the compacting is uniform, the striations will also be uniform.

Rammed-earth walls are easily recognized by the grooves and traces left from the formwork that was used during construction and, in some cases, from the seams joining each section of wall, both vertically and horizontally. For example, some traditional walls will have a seam of sand and lime mortar averaging about 2 cm. In other regions of the world, seam joints are made using small stones (5 cm average), although only between the horizontal layers.

3.3.3 Mixed Technique: Wattle and Daub

3.3.3.1 Introduction

Wattle and daub is defined as a mixed method because it uses a wood, bamboo, or other similar support structure filled with earth material that is in a plastic and hydric state. Pressure is applied to ensure adherence to the structure and to eliminate any empty space or trapped air;

the structure is then left to dry in the open air. The wattle and daub technique has several different names and subcategories depending on the region—for example, *quincha* in Peru, *bahareque* in Central America, *cuje* in Cuba, *pau a pique* in Brazil, and *fajina* in Uruguay.

Many civilizations have constructed buildings using this technique. Known as *torchis* in France, it has been used since ancient times. Some structures in Cuiry-lès-Chaurdades in Aisne are five thousand years old. The historic center in the French city of Troyes still features many houses built using this technique (figure 3.17a).

Numerous palaces in Asia were built using the technique, most notably in Japan. The art of assembling the vertical wood stakes and horizontal sticks, then filling and decorating them with earth material, allows for impressive structural quality. Many of these beautiful imperial palaces remain standing today. In Central America, there are remnants of pre-Hispanic structures built with wattle and daub, such as the Joya de Cerén archaeological site in El Salvador or the City of Caral in Peru, as well as in parts of the Middle East, such as the Syrian capital of Damascus

(A)

(B)

(C)

FIGURE 3.17. (a) Historic center of Troyes, France; (b) historic center of Damascus, Syria; (c) historic center of Lima, Peru. *Source:* Wilfredo Carazas Aedo.

(figure 3.17b), where some structures have also been preserved. From pre-Columbian times through the colonial period and into the present, due to its light weight and flexibility, this technique was also used across South America in areas and cities including Lima, Peru (figure 3.17c), proving suitable to a region located in the earthquake-prone Circum-Pacific Belt.

3.3.3.2 Soil Selection and Preparation

The soil required for wattle and daub has a granulometry similar to what is required in the formation of adobe. In many cases, it has a higher percentage of clay, and the coarse grains are generally less than

FIGURE 3.18. Diagram of the wattle and daub (mixed method) production process, from raw material to drying. *Source:* Wilfredo Carazas Aedo.

10 mm in diameter. Plant fibers are usually used in generous proportions, allowing for better adherence to the secondary structure. Examples of these fibers include wheat straw, along with wild straws, such as Andean straw found in South America, or zacate, a type of grass found in Central America.

A diagram of the wattle and daub (mixed method) production process is shown in figure 3.18.

3.3.3.3 Principles of Structure and Infill

Wattle and daub construction involves a structure and its infill material. The main structure, which ensures stability during construction (consisting of vertical and horizontal sticks or timbers), includes intermediary structures that define the internal and external spacing (smaller intermediary columns). The secondary structure is made of small, structurally complementary elements that are often thinner or more flexible and that support or hold the infill material. These can be made of bamboo, cane reeds, tree branches, or other materials.

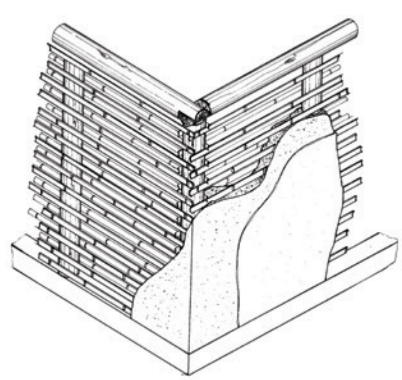
The infill material consists of mineral material, or soil, that serves to cover and protect the structure. Essentially, it is a mortar made of earth and water, with a generous addition of straw or other fibers (a ratio of five parts earth material to one part fiber).

Methods for infilling depend on the placement and type of structure as well as the kind of infill material used.

3.3.3.4 Types of Construction Methods

Several methods are used in wattle and daub construction. The relatively simple and economic framework method is used throughout the world and is popular in Latin America, Africa, and other regions, especially in rural areas (figure 3.19a). It uses rough-cut timbers (called *horcones* in Latin America) or thick, whole bamboo for the main corners and main support beams, which are reinforced horizontally with split bamboo or cane reeds (figure 3.19b). The infill is earth and straw, with stones sometimes placed between the horizontal supports.

(A)



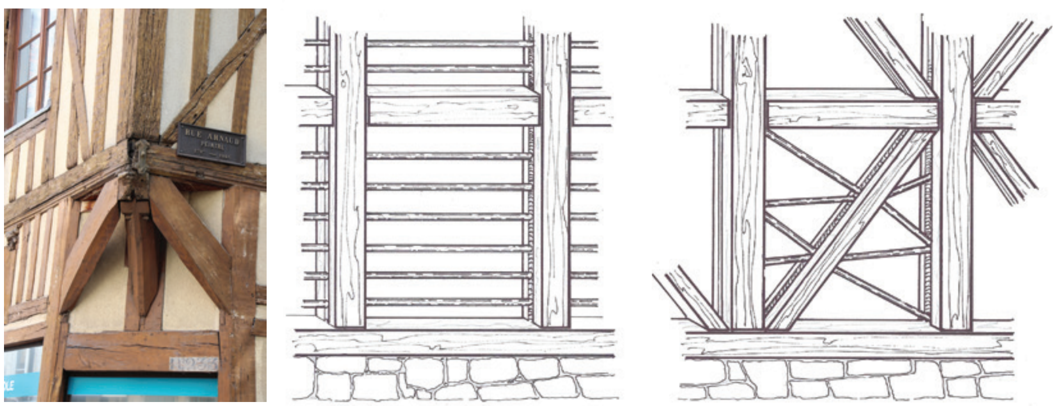
(B)

FIGURE 3.19. (a) Rural dwelling, Owando, Republic of the Congo, constructed using the framework method. (b) Drawing of the framework method. *Source:* Wilfredo Carazas Aedo.

The box method has been used across the European continent—in Germany and France, for example—especially during the Middle Ages (figure 3.20a). It relies heavily on wood of various dimensions, which is worked, or sculpted, into orthogonal shapes to make solid connections or joints (figure 3.20b). This allows for the construction of multilevel buildings.

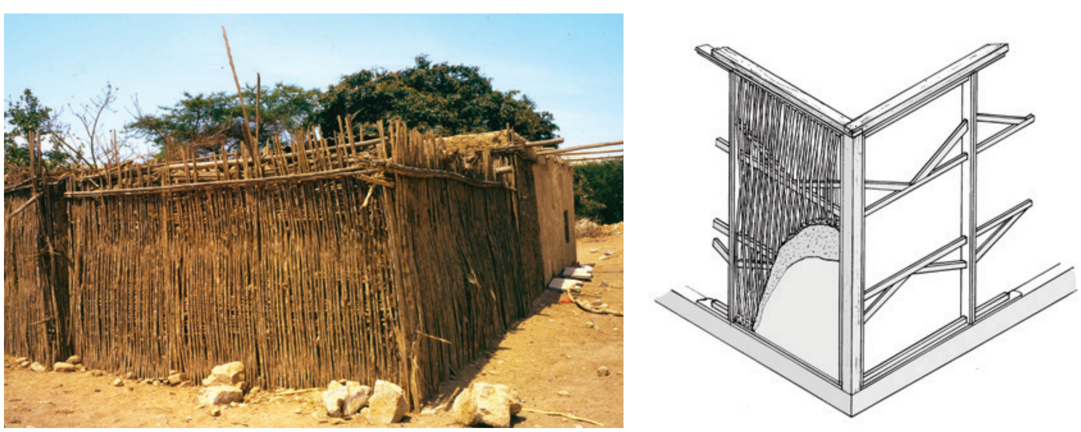
The latticework method relies on the use of sticks, cane reeds, or flexible bush branches, allowing for the creation of a latticework, or weaving, that is often tightly closed, thus increasing the structural rigidity of the walls. In some cases, intermediate or secondary structures may not be necessary due to the strength and rigidity that can be achieved by this type of weave.

This technique has been used since ancient times, especially in Latin America, where *quincha* has been used since the dawn of Andean civilization on the Peruvian coast (figure 3.21a). The method was later adapted and improved in urban regions during the colonial period and used in the construction of enormous manor houses (figure 3.21b). It includes the addition of fired bricks in the lower parts (called "citara") to allow better connection with the lower floor made of adobe.



(A) (B)

FIGURE 3.20. (a) Corner of a building in Provins, France, constructed using the box method. (b) Drawings of box method formworks using rough-cut timber and two types of latticework. *Source:* Wilfredo Carazas Aedo.



(A) (B)

FIGURE 3.21. (a) Rural structure in northern Peru built using the latticework method. (b) Drawing of *quincha* panels used in latticework in urban areas of Peru. *Source:* Wilfredo Carazas Aedo.

(A) (B)

FIGURE 3.22. (a) Partition method for interior subdivision. (b) Drawing of a panel constructed of cane reeds using the partition method. *Source:* Wilfredo Carazas Aedo.

A more recently developed technique, the partition method, has been improved over time to allow for the construction of lighter, thinner structures (figure 3.22). There are two versions. The first uses a fabric or plant-based mesh applied directly throughout a supporting structure, covering both sides of the load-bearing frame. The second uses “prefabricated” panels of similar dimensions, which are installed between load-bearing frames. After the panels are installed, an earthen mortar is used at minimum thickness to plaster the structure. The latter version is frequently used in regions of South America. It is also a popular building method in Chile.

3.3.4 Cob: Piled/Kneaded Earth

3.3.4.1 Introduction

Cob is a technique that uses earth in a plastic and hydric state—a dough or paste that can be modeled—which is then piled and compacted using a large mallet and finished by sculpting the outer surface to define the wall and its thickness. Cob was a popular building technique in Europe, especially in the Pays de la Loire in the north of France. In Brittany, France, it was known as *bauge*, and in Devon, England, the technique was given the name *cob*.

FIGURE 3.23. Al Murabb'a Palace, the Kingdom of Saudi Arabia. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.24. Batammariba dwellings, Benin. *Source:* Wilfredo Carazas Aedo.

Today, we find large, magnificent buildings using cob (figure 3.23). Yemen and Saudi Arabia offer remarkable examples of the technique, including cob buildings featuring multiple levels. We also find examples in certain parts of the African continent, such as in the region surrounding Ghana, Burkina Faso, and Benin, where we find the famous Batammariba, or Tata Somba, houses (figure 3.24).

In Latin America, adobe construction was used in pre-Columbian times, as evidenced by archaeological ruins on the Peruvian coast, such as the archaeological complex of Cerro Respiro in Callao, Peru (Torres 2021). The structures of these archaeological complexes are often confused with buildings constructed using the rammed earth technique, but the finished walls have characteristics more similar to those of cob construction (figure 3.25).

The technique is currently being recovered for use in modern building construction. Contemporary builders have adapted the method for use with modern tools and equipment, like mechanical mixers or prefabricated walls that are small enough to be transported—a technique that lies between *adobón*, or large brick adobe, and rammed earth with prefabricated formworks.

3.3.4.2 Production Process and Wall Construction

In selecting and preparing earth matter for cob construction, the granulometry should be between what is used in adobe and in rammed-earth building and should include between 15%

FIGURE 3.25. Wall of warehouses of the archaeological site Cerro Respiro, Callao, Lima, Peru. *Source:* Henri E. Torres.

and 20% clay. The soil is mixed with water, typically one day before beginning the wall construction process. In many cases, to achieve greater strength and less weight, a plant fiber such as straw, rice husks, or a similar fiber, depending on context, is mixed into the soil.

First, the soil is prepared for transport to the construction site. The simplest way to accomplish this is to knead the material into balls that are small enough to be transported by hand. It can then be carried or even tossed to the person stacking the cob. The balls are piled or dropped with some force into the wall frame, and the earthen dough is then pounded, or compacted, with a wooden mallet in order to improve cohesion by eliminating empty space or trapped air and to achieve a uniform mass.

Finally, the cob is sculpted, which is to say, the wall is given a specific verticality and thickness. To accomplish this, a type of flat shovel, machete, or similar agricultural implement is used.

The cob wall construction process is unique in that it is done in stages, with certain height restrictions: layers average 50 cm in height, which gives the wall a degree of stability in its plastic state and allows it to dry quickly in order to receive the next layer (figures 3.26 and 3.27). It also enables the builder to stand on top of the wall while working on it.

The construction process is determined by the drying time of each layer or level, which is why the entire perimeter of the structure is generally "stacked." This establishes a uniform drying process and achieves a rhythm of sustained horizontal progress, thus creating a finished wall that has the proper thickness and monolithic characteristics.

A diagram of the cob construction process is shown in figure 3.28.

FIGURE 3.26. Traditional cob construction, West Africa. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.27. Traditional cob wall, Europe. *Source:* Wilfredo Carazas Aedo.

3.3.5 Plaster and Decorated Surfaces: Mudding and Troweling

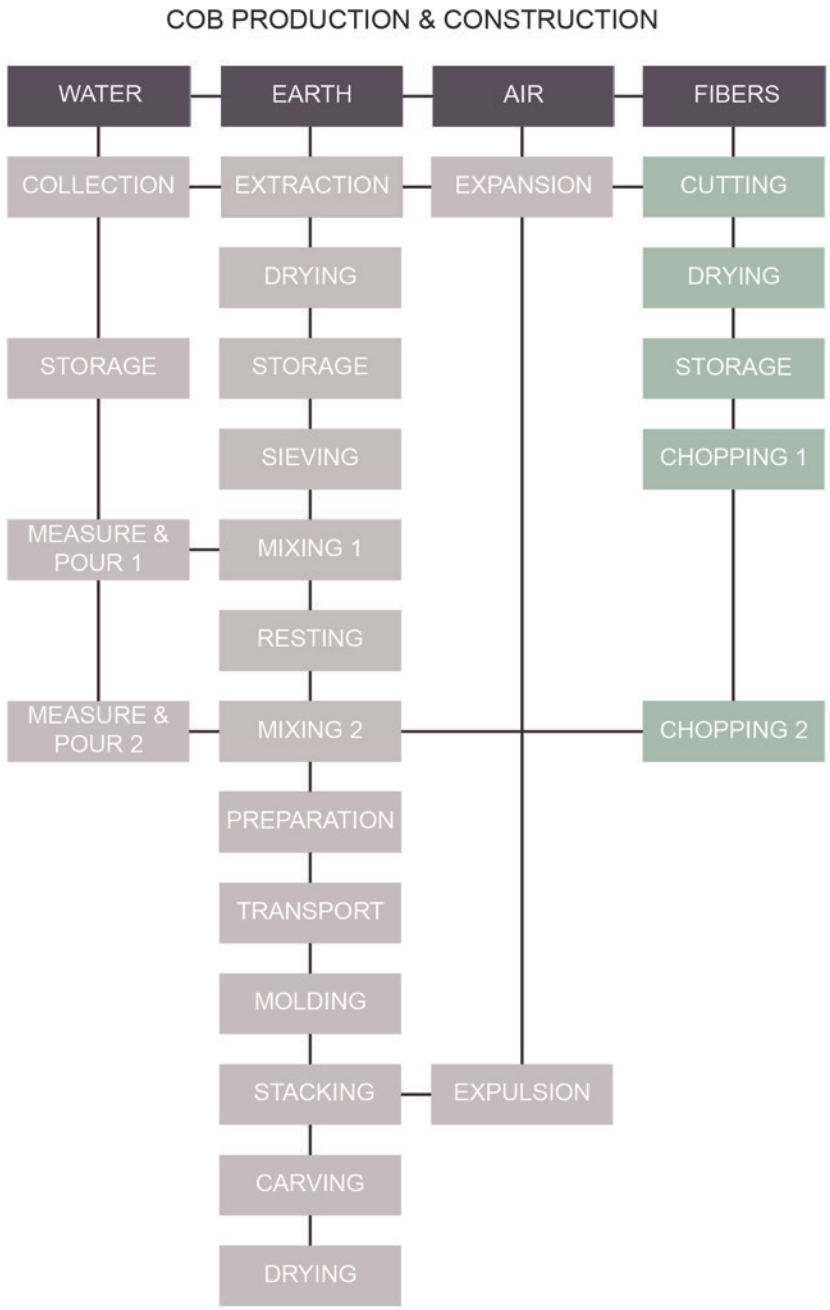
3.3.5.1 Introduction

The decorative plaster technique uses earth matter in a hydric and viscous-plastic state that is pressed and spread over an earthen wall with the help of a tool or simply by hand. The earthen mortar can be mixed with additives or natural stabilizers, such as plant or other fibers.

Earth plastering and decorative finishes (see chapter 8) have existed since the dawn of humanity. Humans have always sought to beautify their dwellings by drawing figures, lines, and colors as an expression and an enhancement of their daily lives. With the emergence of more consolidated urban areas, this desire to beautify living spaces became increasingly precise, reflecting collective cultural and environmental realities. In short, throughout history, humans have always sought to leave traces of their culture, whether on the walls of a simple room or a magnificent palace.

In Africa, we have examples of the Kassena painted dwellings in Tiébélé, Burkina Faso (figure 3.29), and the sculptures and decorative murals in the dwellings in Agadez, Niger. In Latin America, there are many decorative finishes dating from the ancient period to the colonial era. In Trujillo, Peru, numerous examples are found in the Moche culture (100 to 700 CE), including at the El Brujo archaeological site and at the Huaca de la Luna and the Huaca del Sol temple

FIGURE 3.28. Diagram of the cob construction process, from raw material to drying. *Source:* Wilfredo Carazas Aedo.



complexes. To the south, in Cusco, is the rich baroque ornamentation of the seventeenth-century churches of Andahuaylillas and Canincunca (figure 3.30). In northern Latin America, in Mexico, the ancient citadel of Tajín (300–1200 CE) has beautiful decorative murals made with natural pigments on lime plaster.

Decorative earth plaster is currently experiencing a resurgence as Japanese masters incorporate the aesthetic qualities of the technique in contemporary building; many in Europe are following a similar path.

FIGURE 3.29. Painted houses in the *cour royale* (royal court) complex of Tiébélé, Burkina Faso. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.30. Interior of Canincunca Chapel, Cusco, Peru, showing baroque ornamentation. *Source:* J. Paul Getty Trust.

FIGURE 3.31. A chromatic variety of earth materials used in construction. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.32. Natural colors extracted from plant pigments. *Source:* Wilfredo Carazas Aedo.

3.3.5.2 Earth Colors

Earth material comes in a wide variety of colors that can range from white to yellow, red, green, ocher, gray, and black. Each material has its own unique geological origin; these origins together may go unnoticed but nevertheless exist all around us. Masters and connoisseurs take advantage of the earth's color palette and its infinity of textures to create their works (figures 3.31 and 3.32).

3.3.5.3 Aggregates and Stabilizers

In addition to using a limitless variety of different colors and textures, decorative plastering employs a variety of stabilizers and aggregates. These have properties necessary to fix, bind, and help increase the abrasion resistance of a structure when added to the mass or mortar used to plaster the wall. Some stabilizers are organic, including cellulose, starches, caseins, animal excrements, and those with mineral origins, such as lime and plaster; others, such as cement, are artificial or are chemical products like silicates.

3.3.5.4 *Production and Application Process*

Similar to the construction techniques discussed above, building with plaster requires careful selection and preparation of the soil, or earth matter. In addition to being aesthetically pleasing, the material used for plaster should have qualities that allow it to adhere well to the structure or wall, to resist climatic and other environmental degradation, and to resist cracking or detachment from the structure. A thorough understanding of ideal building conditions, as well as knowledge of the material and its applications, is crucial.

In preparing the wall, regardless of its type or characteristics, it must be conditioned to ensure proper adhesion of the plaster. Loose particulates (dust) must be cleaned off, roughness or protrusions must be eliminated, cavities are to be filled, and moisture must be applied to the wall if it is dry.

The next step is applying the layers of plaster. Every region or culture has its own approach and procedure for building with plaster. In some regions, only a single layer is applied, while in others, up to seven layers of progressively decreasing thickness are used. Japanese masters, for example, use a multilayering technique. As a general rule, however, there are two main layers.

The first serves as the base and involves creating a smooth, uniform surface with a thickness of 0.5 to 2 cm (figure 3.33a). This layer is generally covered by a thinner second, refining layer that varies between 0.5 and 2 cm thick.

For the second layer, the surface quality can vary from a simple monochromatic layer to one that uses elaborate colors and textures; generally, the thickness is very thin, from 1 to 3 mm (figure 3.33b).

(A) (B)

FIGURE 3.33. (a) A technician creates an initial base layer of earthen plaster on a wall. (b) Technicians apply the second, refining layer of plaster to a wall. *Source:* Wilfredo Carazas Aedo.

At this stage, both the protective qualities of the plaster and the aesthetic criteria (decorations) are considered.

A diagram of the decorative plaster and finishing process is shown in figure 3.34.

3.3.5.5 Types of Decorative Plaster

Decorative plaster is used to embellish a dwelling or structure through color, texture, and shape. Many different application techniques exist; several of the more notable ones are defined below.

- **Painting**. There are various ways of painting plaster, including fresco, which combines lime and plant or mineral pigments, and tempera (figure 3.35), a process that uses natural fixatives.
- **Engraving**. The engraving method entails creating shapes or figures using simple, sharp tools applied with pressure to etch into plaster that is still fresh (figure 3.36).
- **Reliefs**. Reliefs are designs or figures that protrude from the wall surface. They are made by first increasing the thickness of the earthen plaster to an average of 2 cm, then carving or cutting away the mortar in the shape of the desired figure (figure 3.37).
- **Sculpting**. Sculptural forms, generally anthropomorphic, that protrude from a wall require some type of support to remain stable (figure 3.38).
- **Carving**. In this method, figures are carved into a wall or into the thick layer of mortar base (figure 3.39).
- **Stamps**. Stamps involve the use of a stamp pad or similar tool and a template, which are used to create a figure on the surface of a finished wall (figure 3.40). After a figure or decoration is drawn onto a base medium, the positive aspects of the desired shape are cut away. This technique incorporates some of the materials used in fresco and tempera painting.

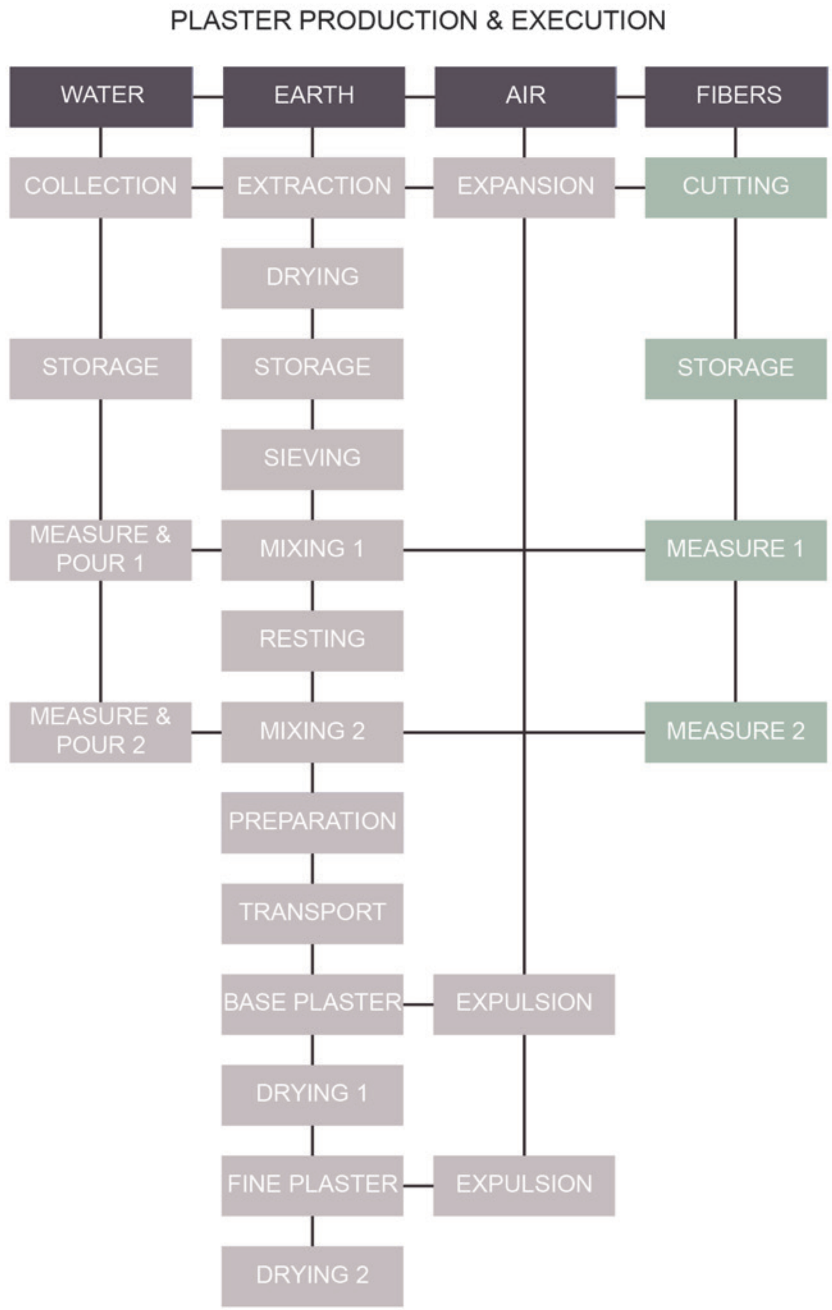


FIGURE 3.34. Diagram of the decorative plaster and finishing process, from raw material to drying. *Source:* Wilfredo Carazas Aedo.

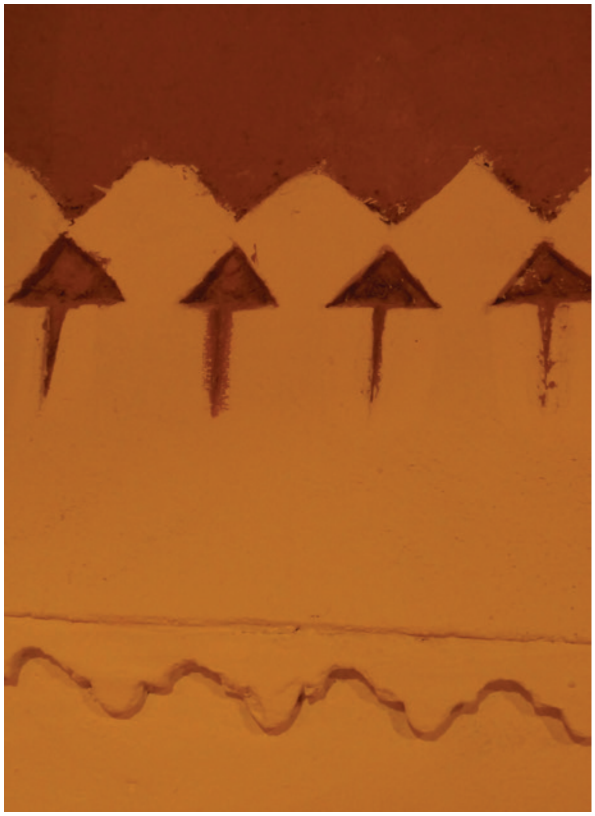
FIGURE 3.35. Fresco painting over lime surface. Gadhames, Libya. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.36. Engraving on an earthen plaster wall. Bétamaribes, Benin. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.37. Carved reliefs (thickness 10 mm) in a wall surface. Grenoble, France. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.38. Sculpture inside a dwelling. Agadez, Niger. *Source:* Wilfredo Carazas Aedo.

FIGURE 3.39. Figures carved into a wall and painted. Riyad, Saudi Arabia. *Source:* Wilfredo Carazas Aedo.



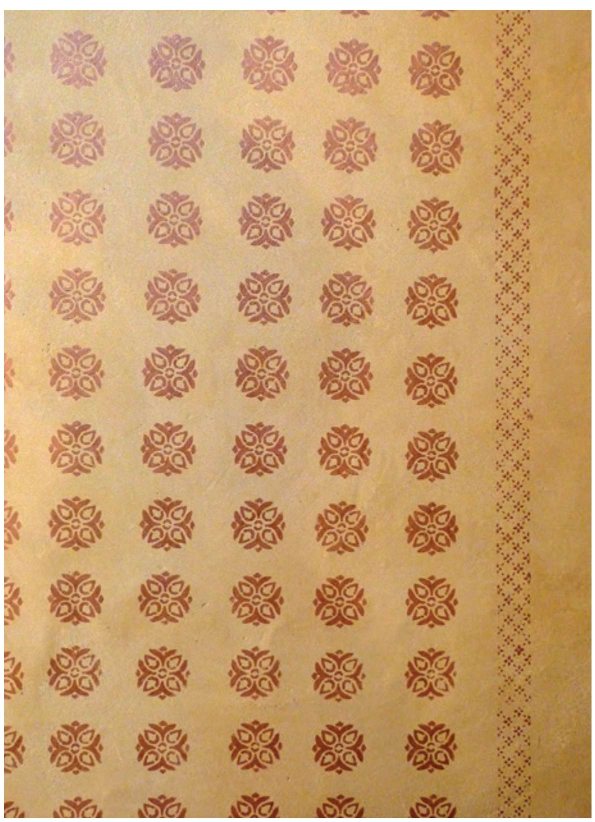


FIGURE 3.40. Stamp decorations applied using paint on an earthen wall. Corbelin, France. *Source:* Wilfredo Carazas Aedo.

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HISTORY AND THEORY OF CONSERVATION

4

Overleaf: The House of Sheikh Ahmed bin Hilal Al Dhahiri, Al Ain, United Arab Emirates.
Source: J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.

4

HISTORY AND THEORY OF CONSERVATION

Hossam Mahdy

4.1 Conservation History

Conservation of cultural heritage, as practiced in modern times, is rooted in European ideals of modern archaeology that date back to fifteenth-century Rome and the time of the Renaissance. During this period, interest in ancient ruins and classical literature, arts, and culture was "reborn." Collecting antiquities became a social status symbol, and the study of the aesthetics and proportions of ancient remains inspired the art and architecture of the time. The period from the sixteenth to the nineteenth century could be called the age of reason, when new concepts of science, history, and cultural heritage emerged, including that of authenticity, which was formulated in the eighteenth century concerning the remains of classical civilizations. The art and architecture of antiquity were considered the height of human achievement (Jokilehto 2018).

The birth and evolution of modern conservation movements and practices unfolded in nineteenth-century Europe, particularly England and France. Advances in science led to the development of archaeology as a scientific discipline, which in turn led to the practice of restoration of historic buildings. Differences in philosophies led to the creation of different approaches. While restoration was widely practiced and justified in France, as exemplified by the architect Eugène Emmanuel Viollet-le-Duc, preservation was the norm in England, with antirestoration arguments strongly made by John Ruskin (Stanley Price, Kirby Talley, and Vaccaro 1996).

The recognition of historic buildings and sites as a common heritage of humanity grew in significance after the First World War as collective concerns over conservation sparked the international conservation movement. In 1933, the Athens Charter was issued by the International Congresses of Modern Architecture (Congrès Internationaux d'Architecture Moderne, or CIAM). It favored conservation of the different historic layers of a monument over stylistic restoration. The Convention for the Protection of Cultural Property in the Event of Armed Conflict, known as the 1954 Hague Convention (UNESCO 1954), was drafted and adopted by many countries because of the huge losses brought on by the massive destruction of cultural heritage during the Second World War. It was the first international convention to address the protection of cultural heritage.

International efforts in the protection and conservation of cultural heritage further intensified in the ensuing years in response to the issues surrounding postwar reconstruction. The International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) was established in 1956. In 1964, the Venice Charter was adopted by the Second Congress of Architects and Specialists of Historic Buildings. The charter laid the foundations for the conservation of built heritage that remain valid today, even in the wake of the many charters, documents, and declarations that stemmed from it and tackled particular notions or aspects. In 1965, the International Council on Monuments and Sites (ICOMOS) was established.

In 1972, the UNESCO World Heritage Convention took this international collaboration to a new level by holding state parties (countries signatory to the convention) accountable for the conservation of heritage for the whole of humanity and establishing a mechanism for technical and financial assistance for this purpose. The convention also linked cultural and natural heritage. UNESCO named ICOMOS and ICCROM as its advisory bodies for cultural heritage and the International Union for Conservation of Nature (IUCN) as its advisory body for natural heritage. The Venice Charter and other ICOMOS doctrinal documents guide the implementation of the convention and management of World Heritage Sites.

Although conservation of cultural heritage was known to different peoples in different parts of the world, the knowledge of these practices was limited to their geocultural contexts. As such, practices in these areas did not influence the ideology of the modern conservation movement in the same way that European practices did. For example, Shinto shrines in Japan, particularly and famously the Ise Shrine in Mie Prefecture, were conserved for centuries through a ritualized practice of reconstruction. The entire shrine complex had been reconstructed every twenty years since its inception in the seventh century. Each time, this was carried out according to a notion of authenticity that was influenced by intangible aspects and traditions, not by the built fabric of the buildings. This raised very pertinent discussions about the concept of "authenticity," as there was no doubt that the Ise Shrine was an important part of Japan's cultural heritage. Nonetheless, the shrine was not inscribed on the World Heritage List at the time because it did not fulfill the authenticity requirements set by the World Heritage Committee, which followed a Eurocentric emphasis on authenticity of the historic fabric. These discussions led to the adoption of the Nara Document on Authenticity by ICOMOS, UNESCO, and other international organizations (more on this below; Stanley Price and King 2009).

In sub-Saharan Africa, spiritual values motivate the protection of sites and their maintenance by social organizations rooted in local communities. Conservation interventions are often implemented during special events that aim to reinforce the cohesion of a community or the positive relationships between communities. At Terra 2008, the International Conference on the Study and Conservation of Earthen Architectural Heritage, held in Mali, the imam of Mali's Great Mosque of Djenné was asked why the huge earthen mosque had not been replaced with one of modern, reinforced concrete. After all, if this were done, the entire village would no longer need to come out and work every year on the mosque's traditional pre–rain season maintenance. The imam answered, "But then, what would bring the community together?" His reply revealed that it was the annual collective maintenance event that brought the community together, not the structure itself, as an outsider might assume (Joffroy 2005).

In Muslim-majority communities, *waqf* is an endowment system that has a significant impact on cultural heritage. The aim of *waqf* is to sustain acts of charity and community service so that they outlive the life spans of their patrons. A *waqf* arrangement is initiated when a patron allocates funds for both a charitable institution and a commercial investment. The revenue from the commercial investment is put toward running the charitable institution, including maintenance and repairs. Although in premodern times, there were no terms for these notions of conservation and sustainability as we know them today, the *waqf* system ensured the sustainable conservation of the built heritage in Muslim-majority cities, as many of the buildings were either an investment or a beneficiary within a *waqf* legal arrangement (Mahdy 2017).

The Burra Charter was adopted for the first time by ICOMOS Australia in 1979 and reviewed multiple times, as explained later in this chapter. Based on the general philosophy of the Venice Charter, this charter addressed issues particular to Australia, such as the cultural heritage of the country's native peoples. It signaled a move from the concept of a historic monument to the concept of a place of cultural significance and from restoration to the conservation of cultural significance.

The Nara Document on Authenticity was drafted in 1994 by experts from UNESCO, ICCROM, and ICOMOS by invitation of the Japanese government. It recognized the diversity of cultural heritage around the world and that values and authenticity are culture specific. A revised document, Nara + 20, was issued in 2014 and reiterated and elaborated on the principles of the earlier document.

In 2011, UNESCO adopted the *Recommendation on the Historic Urban Landscape* (HUL; UNESCO 2011b). HUL defines an approach and offers a tool kit for integrating the conservation and management of cultural heritage in cities and settlements with the policies and practices of sustainable urban development.

In 2015, the United Nations identified the Sustainable Development Goals (SDGs) to achieve a better world by 2030. These goals require universal cooperation to combat threats to the whole of humanity, including poverty, inequality, and climate change. ICOMOS has established the SDG Working Group to develop guidance to ensure that cultural heritage conservation and management contribute toward achieving the SDGs in an indirect way for all goals and in a direct way for some of the goals, such as SDG 11, "Sustainable Cities and Communities," and SDG 13, "Climate Action," for which the General Assembly of ICOMOS in 2020 declared a climate and ecological emergency.

4.2 Values in Conservation

The designation of a historic building as part of the local, national, regional, or universal heritage is based on its significance. Therefore, all conservation and management policies and actions affecting a historic building should be informed by that structure's significance. As "relative degrees of cultural significance may lead to different actions at a place" (Australia ICOMOS 2013, article 5.2), the significance of a historic building varies greatly on the basis of the building itself and on the views and interests of its stakeholders. The values of a building or a site could be historical, commemorative, functional, aesthetic, associative, symbolic, scientific, social, spiritual, political, educational, recreational, and/or economic.

That same building may be valued differently by different stakeholders. For example, two separate ethnic groups may see the associative and symbolic values of the same building from different perspectives. Similarly, developers and local businesses may appreciate economic values in a historic building, whereas the local community may see associative and symbolic values in the same building. Furthermore, the users of the building may consider its functional and social values as the most important. The identification of a building's significance requires negotiations with all stakeholders to reach a common, unbiased statement of significance that will guide all conservation and management decisions for the building. The role of the heritage professional is to initiate, facilitate, inform, and guide discussions of values and secure the inclusion of all stakeholders (Myers, Smith, and Ostergren 2016).

Extra care should be taken to understand the value systems that different stakeholders may reference. This is particularly important in regions outside the West. Although international conservation thought is continuously moving away from its European roots, the broader rationale for contemporary conservation theory remains Eurocentric, as it is based on the worldview and value systems developed in Europe from the Renaissance to the present day. The question of language is another aspect to be considered. Most international charters, conventions, and declarations that define best practices for the conservation and management of the built heritage were initially developed, discussed, and drafted in English or French. Even though these doctrinal documents have been translated into non-European languages, certain aspects may remain ambiguous, unclear, or imprecise due to linguistic, cultural, or religious differences in worldviews. For example, there is no word in Arabic for "landscape," as the notion did not exist in Arab communities before their encounters with the West in modern times. This makes the task of communicating the concept in Arabic difficult and often unsatisfactory, and attempts to explain relevant composite ideas such as "cultural landscape," "historic urban landscape," and "rural landscape" become even more complicated.

Authenticity and integrity are the foundation on which the significance of the built heritage stands (Jokilehto 2006). According to the Nara Document, authenticity depends on the cultural context. Attributes of authenticity may include the following:

- form and design
- materials and substance
- use and function
- traditions, techniques, and management systems
- location and setting
- language and other forms of intangible heritage
- spirit and feeling
- other internal and external factors

Integrity is a notion that has recently been added to the field of cultural heritage conservation. The concept is rooted in natural heritage conservation and the preservation of biodiversity (Fadaei Nezhad, Eshrati, and Eshrati 2016). The inclusion of both cultural and natural heritage in the World Heritage Convention brought the concept of integrity into the field of cultural heritage. Integrity ensures that the heritage resource

- includes all elements necessary to express its values,
- is of adequate size to ensure the complete representation of the features and processes that convey the resource's significance, and
- does not suffer from adverse effects of development and/or neglect (UNESCO 2011a).

The protection, conservation, and management of the built heritage are essential to secure the retention of its significance. For a property to be inscribed on the World Heritage List, it should have Outstanding Universal Value (OUV), which is based on three pillars, or conditions, that must be met:

1. The values of the property should fulfill at least one of the criteria defined by the World Heritage Conventions (six cultural and four natural criteria).
2. The property should meet the conditions of integrity and authenticity.
3. The property should be legally protected and managed satisfactorily according to a carefully developed and implemented management plan (UNESCO 2011a).

Even if the built heritage is not of OUV, its protection, conservation, and management should be based on its values, with the aim of retaining its cultural significance. It is therefore essential to identify the attributes that manifest the values of the heritage so that conservation and management policies and strategies may be designed to protect and conserve these attributes. For example, interventions to the authentic parts of a historic building that manifest its archaeological values should ensure retention of the authenticity of the archaeological fabric. On the other hand, interventions to previously reconstructed functioning parts of a historic building that manifest its utilitarian values should ensure the continuation of the function of these parts.

4.3 Conservation Planning

Conservation of the built heritage should be sustainable. Thus, all factors that impact the building in question should be managed in a way that prevents and mitigates any negative impact on the historic fabric of the building. These factors include the impact of large numbers of visitors as well as the impact of the urban and environmental context on a building's conservation and presentation. Preparation of a conservation management plan must also consider the diversity of stakeholder groups and their potentially conflicting values and interests in the building. Conservation should be managed as a dynamic, continuous, and multidisciplinary process that engages all stakeholders and adapts to the context. Mutual agreement is therefore needed on the plan as the reference document for all interventions and decisions regarding the heritage.

According to the series of publications by the GCI on values-based conservation (Avrami, Mason, and de la Torre 2000; De la Torre 2002), the planning process is carried out in three phases that partially overlap (figure 4.1):

1. *Identification and description*. A full documentation of the historic building is carried out and a full set of records is prepared. All existing information is collected, including historical documents, characteristics of materials, environmental context, and management context (e.g., stakeholders, legal protection tools and mechanisms, local community, visitors, tourism operators, and personnel engaged in management, maintenance, and security).
2. *Assessment and analysis*. The collected information is assessed and analyzed according to the following three categories prior to being synthesized and integrated:

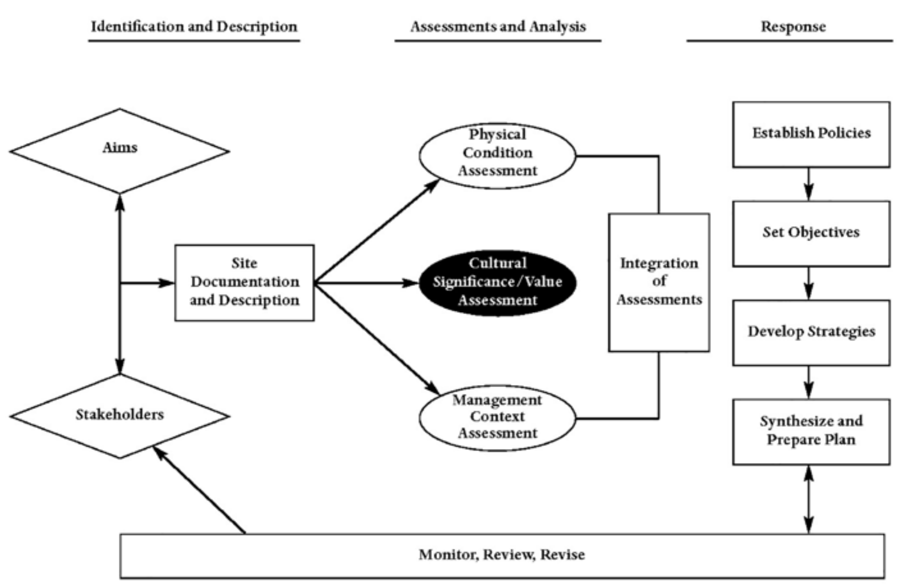


FIGURE 4.1. Chart showing the three phases of the planning process methodology (identification and description, assessments and analysis, and response) for conservation management, after Randall Mason. *Source:* de la Torre (2002, 6).

   a. *Value assessment*. Identification of values is made with the participation of all stakeholders. A statement of significance should be negotiated with stakeholders to incorporate all values. Values should be connected to the physical properties and resources of the site (the attributes).
   b. *Physical condition assessment*. Threats should be identified and categorized in relation to the statement of significance and its physical attributes. Examples of threats are environmental factors, vandalism, neglect, poor management, and development pressures.
   c. *Management context assessment*. Assessment is made of the capacity of people and organizations responsible for the conservation and management of the building, financing, institutional structures, legal frameworks, political factors, and any other aspects that may influence the management of the building. Issues related to visitor management and building function also should be assessed.
3. *Response*. In light of the two previous phases, policies should be formulated to guide all actions pertaining to the protection, management, and conservation of the building. Accordingly, a set of strategies and/or an action plan should be created to address ongoing and pressing needs and achieve conservation and management goals, including prioritization of actions, a monitoring regime, periodical maintenance, and identification of different personnel and organizations and their specific responsibilities (Avrami, Mason, and de la Torre 2000; De la Torre 2002).

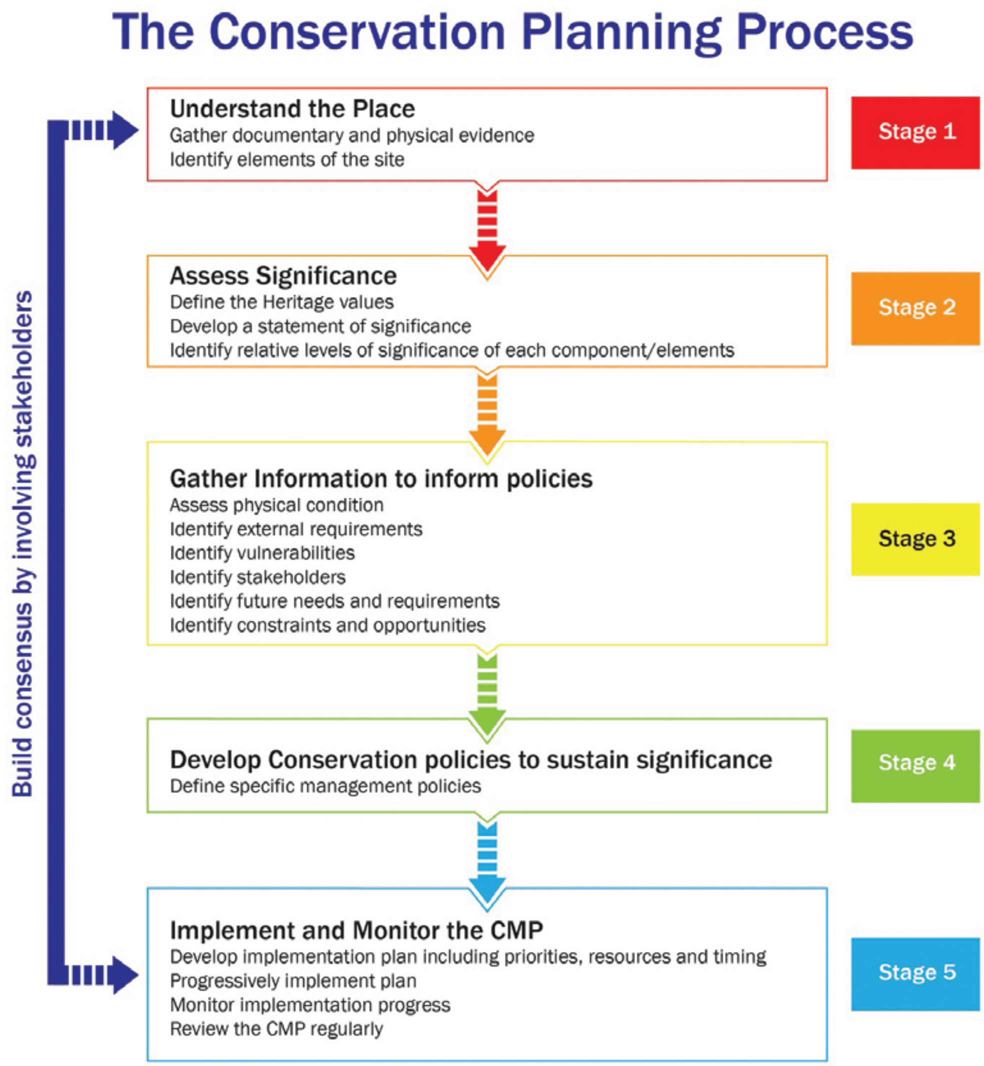
The output of the planning process is a document, or conservation management plan, that should be the guide and reference for all decisions and actions concerning the relevant building. It should be updated regularly and/or when any previously unforeseen changes occur.

The 2013 Burra Charter review provides another model for the planning process, which is divided into three main steps (Australia ICOMOS 2013):

1. Understand the significance.
   a. Understand the place.
   b. Assess cultural significance.
2. Develop policy.
   a. Identify all factors and issues.
   b. Develop policy.
   c. Prepare a management plan.
3. Manage in accordance with policy.
   a. Implement the management plan.
   b. Monitor the results and review the plan.

The GCI has used an adapted version of the Burra Charter methodology in its work for decades and has applied the process to its multiple conservation courses, including the International Course on the Conservation of Earthen Architecture (see figure 4.2).

FIGURE 4.2. Chart showing conservation planning process used by the GCI, adapted from the Burra Charter. *Source:* J. Paul Getty Trust.



4.4 Case Study: Al Ain

An interesting case study for values-based conservation involves the earthen structures that compose the serial property of the Cultural Sites of Al Ain in Abu Dhabi, United Arab Emirates (UAE). This serial property nomination was inscribed on the World Heritage List in 2011 based on criterion (iii) "to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared"; criterion (iv) "to be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history"; and criterion (v) "to be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment" (UNESCO 2023). Despite being component parts of one World Heritage Site, different approaches are adopted for different earthen structures according to their values (Chabbi et al. 2012).

For example, Rumailah at Al Ain is an archaeological site of an Iron Age settlement that was one of the first to have been excavated in the UAE (figure 4.3). The site is of very high cultural, historical, and anthropological value, as it contributes to an understanding of the early history of Al Ain and its cultural, economic, and political roles in the region. Some of the excavated houses have interesting architectural features worth preserving to ensure the OUV of the site. The unexcavated houses are of great scientific potential and may shed light on conditions in the region during the Iron Age. A conservation management plan was prepared for the site in 2012 developing policies to preserve the features that contribute to overall significance of the site. The highest priorities were given to the documentation and stabilization of the archaeological fabric with great attention to the retention of the authenticity of the earthen materials and the reversibility of all interventions. The conservation, management, and presentation of the site were planned with the highest priority given to its scientific values.

Another structure within Al Ain is Al Qattara Fort, or Bayt bin Ati Fort, which was conserved, presented, and managed according to its high social and political values. In a tribal society, the fort was key in protecting the community and its sources of water as well as in asserting the authority of the ruler. Al Qattara Fort is the most prominent vernacular building in Al Qattara Oasis and comprises a defensive structure encased in some areas by walls and a square tower. The fort was reconstructed in the 1980s and used to accommodate traditional builders.

In March 2011, a section of the fort was rehabilitated and repurposed as Al Qattara Arts Center. This project combined new and traditional construction materials and techniques. A new building was constructed at the corner of the fort to hold classrooms, while rooms in the extant external fortification wall were turned into offices (figure 4.4). Insulation and service networks were installed under a new sacrificial layer of mud, either below ground or below the surface of the walls. The newly added building was intentionally designed to be modern, in contrast with the traditional building. During the project, archaeological remains from the Bronze Age were discovered while workers were digging the foundations for the machine room (figure 4.5).

FIGURE 4.3. Photo of Rumailah archaeological site at Al Ain, UAE, a case study for conservation management according to scientific and educational values. *Source:* DCT Abu Dhabi.

FIGURE 4.4. Photo of the courtyard of Al Qattara Arts Center, Al Ain. The new building at left houses classrooms; the rooms in the external fortification wall in the background and to the right have been repurposed as offices. *Source:* DCT Abu Dhabi.

The rare nature of this discovery, which clearly linked the Islamic-period fort to the Bronze Age, led to modifications in the new building's design. It was decided to incorporate and display the remains in the basement of the arts center (figure 4.6). While the overall approach to the conservation of the building was based on its political and social values, the archaeological elements that were uncovered during the works are being conserved, presented, and managed according to their scientific and educational values (Chabbi et al. 2012).

Khumaysani Mosque is another earthen vernacular building within Al Ain that represents a high social value. Also of high religious and spiritual value, it is, most importantly, living heritage. Its original function remains as relevant today as it was at the time of its construction and during its history. Khumaysani is one of the few surviving nineteenth-century mosques in Al Ain. Located to the north of Al Qattara Oasis, it was reconstructed in the 1990s and continues to be used for the five daily prayers. It is a typical example of Al Ain mosques built of mud brick with a palm-beam roof. An arcaded patio leads to the prayer room. The building is enclosed by a low boundary wall with a small gate. The approach to conservation is to ensure the mosque's sustained use while monitoring and maintaining the historic fabric. Accordingly, service installations were upgraded, including the air-conditioning unit, water tank, ablution facilities, and other practical utilities (figure 4.7). Although these additions impact the aesthetics of the building and the material fabric, they were installed in a minimally invasive way and were necessary to ensure that the mosque remains in use. The mosque is being conserved and managed according to its social, religious, and functional values.

FIGURE 4.5. Photo depicting the archaeological features from the Bronze Age discovered during the dig for the foundations of the new structure at Al Qattara Arts Center, Al Ain. *Source:* DCT Abu Dhabi.

FIGURE 4.6. Photo of a segment of the uncovered Bronze Age archaeological features, displayed in the basement of Al Qattara Arts Center, Al Ain. *Source:* DCT Abu Dhabi.

FIGURE 4.7. Photo of the interior of Khumaysani Mosque, Al Ain, showing air-conditioning and ceiling fan upgrades necessary to ensure its status as a functioning mosque. *Source:* DCT Abu Dhabi.

The Cultural Sites of Al Ain include many other buildings and places that vary in nature and values. They span a long period of time, from around 2500 BCE to the 1960s. The conservation, presentation, and management of each building or site are based on the values of each while preserving their significant features. Within a single building, conservation approaches may differ according to the different values of certain parts of the building, as in the case of Al Qattara Fort.

4.5 Notes on Conservation Terminology

The categorization of heritage types is useful in applying appropriate methodologies and techniques. However, this categorization should be carefully and critically considered. For example, an "earthen building" often includes other building materials, such as wood for ceilings, doors, and windows and stones for foundations. A defensive building may include residential and religious structures.

While the movable and immovable attributes of heritage are useful for studying each type, they are often strongly connected and should not be considered in isolation. For example, historic lamps, chairs, and books are movable heritage; however, they may be associated with particular historic buildings or sites. Therefore, these objects, as well as the relevant buildings or sites, should not be studied, conserved, and managed in isolation. The same is true for the divisions of tangible-intangible heritage and cultural-natural heritage.

The concepts of *cultural landscape* and *historic urban landscape* are more inclusive and respectful to local traditions and values, as is the use of the term *place of cultural significance* by the Burra Charter rather than the more commonly used *monument*, *historic building*, or *heritage site*. Terms for interventions should be used with the hierarchy of said interventions in mind. For example, *restoration* should be used with the view that it indicates more changes to the heritage fabric than the term *conservation* and less than the term *reconstruction*. In most conservation works, more than one level of intervention is applied. For example, the overall intervention for a historic building may be *rehabilitation*, but for a more archaeologically valuable part of the building, the intervention would be *preservation*, as in the case of the abovementioned Al Qattara Fort and the Bronze Age remains that were found during construction. The following is the hierarchy of possible interventions, arranged from least intrusive to most intrusive to the heritage fabric:

- preservation
- conservation
- consolidation
- restoration
- rehabilitation
- adaptive reuse
- reconstruction

An intervention that does not sustain the cultural values, integrity, and authenticity of the heritage would defeat its purpose. Therefore, certain conservation criteria should be respected, such as minimum intervention, reversibility, and differentiation of the authentic heritage fabric and newly introduced materials (Muñoz-Viñas 2011). Other management and presentation criteria should also be respected, such as inclusion and active participation of local communities as well as all stakeholders and contribution to the Sustainable Development Goals.

For reference, these and other key terms are defined in the glossary located at the end of this publication.

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RECORDING, DOCUMENTATION, AND INFORMATION MANAGEMENT FOR HISTORIC EARTHEN SITES

5

Overleaf: Documentation of the Bin Jabr Al Suadi house using a total station during the Recording and Documentation module of the EAC22 course in Al Ain, United Arab Emirates.
Source: J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.

5

RECORDING, DOCUMENTATION, AND INFORMATION MANAGEMENT FOR HISTORIC EARTHEN SITES

Mario Santana Quintero

5.1 The Role of Documentation in Conservation

Recording the character-defining features of historic places is a cornerstone of monitoring, preventive maintenance, and conservation. The data and information produced by such documentation aid decision-making by property owners, site managers, public officials, and conservators. Rigorous development and application of digital workflows may also serve a broader purpose: over time, the resulting products, equipment, and information become the primary means by which scholars and the public can interpret a site that has changed radically or is no longer extant.

The growth of the field of conservation has yielded vast quantities of heritage information using various techniques, from long-established practices such as photography and sketching by hand to emerging technologies, including building information modeling (BIM), machine learning, and digital fabrication (figure 5.1). Documentation plays a vital role in defining a heritage place's significance, integrity, and spatial extent, as well as identifying potential threats, and is crucial to understanding, protecting, and managing the place. Heritage professionals must understand the various recording techniques that are available to them, along with their applications and expected products.

This chapter articulates the challenges and opportunities that digital workflows provide in heritage conservation, in particular with earthen architecture sites. It outlines a relevant and consolidated digital workflow and discusses creating permanent digital records that will be of use in the future.

The concept and role of recording, documentation, and information management lie at the core of all major international statutory documents devoted to the conservation of heritage places. Historically, the purpose of recording has undergone a paradigm shift from identifying archaeological and scientific relevance to enhancing the significance and understanding of heritage places in their tangible and intangible expression. Therefore, the discipline of recording has become paramount within the conservation process, contributing to safeguarding the authenticity and integrity of cultural heritage and facilitating its interpretation and management.

FIGURE 5.1. A technician photographs historic decorated surfaces of the interior of the church of Santiago Apóstol de Kuñotambo, Cusco, Peru. *Source:* Mario Santana Quintero.

In response to the need for the extensive reconstruction of monuments and urban areas severely damaged during the Second World War, the Venice Charter clarified the notion of the "documentation" of heritage places. This documentation requires a high level of quality, ensuring a precise reproduction of the object and its context. Article 16 of the charter emphasizes the importance of documenting all restoration and conservation work. In particular, "precise documentation" is recommended in terms of techniques that can capture the geometry and texture of the building and the context with precision and integrity. This is complemented by "analytical and critical reports" that include assessments of the object's actual condition, especially regarding the quality of the measured data set of geometry and texture for thematic mapping (ICOMOS 1964, 4).

Building on the Venice Charter, the publication "Principles for the Recording of Monuments, Groups of Buildings and Sites" (ICOMOS 1996) laid the groundwork for the actual recording of historic buildings, highlighting the main responsibilities and contents of conservation records, including their management and dissemination. *Recording* is defined there as an essential activity to provide an understanding of cultural heritage and its related values. The *Operational Guidelines for the Implementation of the World Heritage Convention*, adopted by UNESCO (2019), also underline the importance of recording to support the nomination of World Heritage places and define their Outstanding Universal Value (OUV). These guidelines suggest the use of detailed maps to identify the boundaries of the area nominated, including photographic documentation, 35 mm slides, and image inventories.

Another significant publication is the two-volume *Recording, Documentation, and Information Management for the Conservation of Heritage Places* (Letellier, Schmid, and LeBlanc 2007; Eppich and Chabbi 2007), a product of the Recording, Documentation & Information Management Initiative (RecorDIM, 2003–7, https://www.getty.edu/projects/recording-documentation-information-management-initiative/). This work assists conservation professionals in improving the practice of collecting, processing, and managing information for the conservation of architectural heritage. In particular, the results presented in these two manuals show the use of technology explicitly for documenting our cultural heritage and serve as a reference source for applying metric survey tools to the conservation of architectural heritage. Similarly, Historic England provides several publications that guide many aspects of heritage surveying and recording. Notably, the Metric Survey Specifications (Historic England 2015) present practical standards and guidelines related to surveying tools and methods.

Digital and technological advancements in the field of cultural heritage documentation have led to the ratification of "The Seville Principles: International Principles of Virtual Archaeology" (International Forum of Virtual Archaeology 2011), adopted by ICOMOS in 2017. This has provided a scientific framework for the digital reconstruction of heritage, stressing the importance of interdisciplinary teams of professionals and complementary methods for integrating traditional heritage records and improving the understanding of archaeological heritage.

Along with the adoption of international charters and guidelines related to cultural heritage documentation, the development of an ethical framework is vital. This framework can be used to benefit the public by informing documentation specialists' conduct and professional practices and outlining their responsibilities. The "ICOMOS Ethical Principles" (ICOMOS 2017) and the code of ethics of the Canadian Association of Heritage Professionals (CAHP 2019) cover the main ethical issues related to conservation practice. While the CAHP code establishes guidelines relative to professional conduct focusing on the relationship between clients and colleagues, the "ICOMOS Ethical Principles" provide an overview of the responsibility of members toward cultural heritage as well as the general public and local communities. Improving the work of heritage recording specialists allows for better planning, recording, processing, and disseminating of digital workflows for the conservation of historic places. Furthermore, the digital products of this ethical framework provide a way to share and preserve records among heritage organizations around the world.

5.2 Site Recording

The objective of site recording is to produce a technical heritage record that provides the basic information necessary for conservation and monitoring activities and posterity records for public archives (Letellier, Schmid, and LeBlanc 2007, 120). When recording heritage places, the following principles should be considered:

- The heritage place is the primary source of information, and the secondary source is historic documents and iconography.
- Interdisciplinary collaboration and partnership are crucial to developing approaches for maintaining and protecting the heritage's integrity.
- It is essential to analyze the why, when, where, and what in order to design and implement a workflow (the how) to acquire the information accordingly.
- Appropriate, timely, and sufficient information allows informed decisions.

The heritage record usually includes measured representations, such as a site plan, an emplacement plan, feature plans, sections, elevations, construction details, and three-dimensional models. Records are produced at different graphic scales and with desired levels of information for conservation actions, including condition assessments, rehabilitation interventions, and conservation and management plans. Furthermore, the records should identify the site location (geographic centroid, boundaries, elements, features, and buffer zone).

Records should also include a complete set of record photography depicting interior and exterior character-defining elements and the condition assessment of the site. The relevance of these photographs is fundamental to conducting an accurate analysis of the site's significance and condition. According to Peter Dorell, "The essentials to be recorded are: the shape of the building from all elevations; the ground plan (insofar as this can be recorded without aerial photography); methods of construction and rebuilding, where evidence for these can be seen; materials of construction; interior features; and the setting of the building in its surroundings" (1994, 96). Photography can be in the form of still photos, panoramic pictures, time-lapse photos, and videos.

When recording, it is important for the specialist to bear in mind the following:

- Remember that nothing is straight, square, or horizontal; this means that assumptions are not acceptable when recording heritage places.
- Record as-built condition (i.e., record only what can be seen and not what can be assumed based on a "logical" way of fabric).
- Record elements from large to small; this minimizes cumulative errors in recording.
- Record and provide provenance information.
- Create a basis and control system that can rely on local coordinates or other geographic reference systems, such as Universal Transverse Mercator (UTM; procedures for setting up a local or geographic coordinate system are explained in section 5.4.5).

This list is particularly relevant when working with earthen architecture due to the nature of this organic, irregular construction material. The application of solid procedures will help guarantee the accuracy of the records produced.

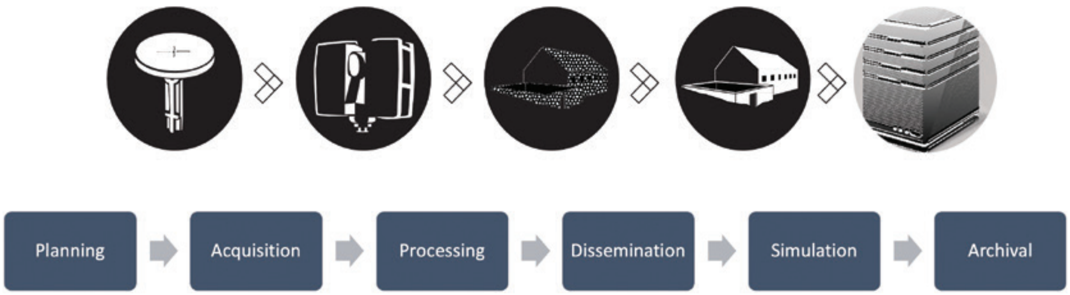

FIGURE 5.2. An example of the potential phases of a digital workflow when compiling and producing a heritage record of a historic place. *Source:* Carleton Immersive Media Studio.

As illustrated in figure 5.2, the creation of a heritage record involves a number of phases, from planning to archiving. Planning involves setting up and providing technical assistance to the project team as well as organizing workflow and equipment, reviewing materials, and preparing a presentation for the potential client. The acquisition, processing, and dissemination of information allow the advancement of archaeological hypotheses or conservation interventions based on the data collected. Simulation from the produced records includes energy performance simulations and discrete element modeling for structural evaluations. In the final, archival phase, the records are deposited into physical or electronic archives.

5.3 Developing a Strategy and Digital Workflow

A successful strategy involves close communication between the conservation team and the heritage recording specialists in order to produce relevant records.

First, the scope of the project should address why the records are necessary. For example, different graphic types can be made to accomplish specific actions or tasks, such as preparing an inventory, designing a conservation strategy, or preparing a site management plan, maintenance plan, or risk preparedness strategy. Key considerations in defining the needs of the project should address the time available to produce the records, the level of detail required, the extent of the site, and the financial resources available to complete the work. The beneficiary organization's institutional capacities for using the records for conservation should also be assessed. Recording techniques require specific infrastructure and personnel skills to be used cost-effectively; this is a critical variable often neglected in many projects.

For consistency, the digital workflow should follow rigorous accepted technical requirements (e.g., standards, guidelines, protocols, and best practices) that yield records with adequate quality, sufficient provenance information, and digital formats that allow continued use.

In terms of fieldwork, the condition and accessibility of the heritage place should be considered. A recording project will be impacted by the amount of time needed to record on-site; this has a direct relation to the permitted (legal) time available, access to the site, height and extension of the site, and climatic conditions. Also, it is imperative to adopt health and safety protocols to help protect the team as they conduct the work.

Assembling the team and the equipment requires having sufficient knowledge of the strengths and limitations of recording techniques. The following aspects should be considered:

- Speed: time needed to record an asset
- Precision: accuracy factor of the surveying equipment
- Measuring range: range of measurement depending on distance and other environmental constraints
- Field operability: constraints concerning the fieldwork
- Robustness: the strength to withstand adverse weather conditions and impact
- Portability: capability of transport to remote sites, requirements of transport, availability of power sources, and other factors
- Adjustment and corrections: processes required to obtain accurate results
- Occlusion: response to shadows, obstacles, and material-related constraints (reflectivity)
- Price: rental and purchase of the sensor equipment

An effective documentation strategy should establish a workflow that employs different recording techniques and tools to capture shape, color, spatial configuration, and current conditions of the heritage place.

5.4 Overview of Heritage Recording and Documentation Tools

A common approach to classifying heritage recording and documentation tools relies on the required level of engagement to capture data, technical heritage recording skills, and interaction with the fabric from the site being studied. First, the level of engagement relates to the time necessary to record on-site and process the data off-site. To produce a floor plan using field notes takes substantial time on-site to measure distances using trilateration and other hand survey tools compared to using a 3D scanner that requires pressing a button and waiting for the data to be captured.

Next, technical heritage recording skills rely on the operator's knowledge to utilize the devices correctly and determine what type of digital resolution is required. For example, to capture the decorative motifs of historic earthen architecture buildings, a 3D scanner should use a very detailed resolution. The ground sampling distance parameters should allow for sufficient details in the photographs to draw these essential character-defining elements using photogrammetry.

Finally, interaction with the fabric is associated with physical action. When taking photographs, there is passive contact with the asset; this is an example of the use of a passive sensor (figure 5.3). When using a total station, a laser beam is deflected to the surface to obtain a

FIGURE 5.3. Technicians use an engineer's streetlight repair lift to photograph the site context for photogrammetric recording at the Kasbah of Taourirt, Ouarzazate, Morocco. *Source:* Mario Santana Quintero.

measurement; this is an active sensor. Understanding this interaction is essential. In addition, survey instruments should cause no harm to the integrity of the heritage place.

5.4.1 Global Navigation Satellite Systems

The role of Global Navigation Satellite Systems (GNSS) is to provide accurate geolocation of heritage places for establishing the basis and control system as mentioned in section 5.2 (figure 5.4). These devices operate by capturing signals from different segments: satellites, users, corrections from antennas, and control stations (Barazzetti 2020). Signals from space are emitted by different satellites in GNSS constellations (e.g., GPS, QZSS, BEIDOU, GALILEO, and GLONASS) and are captured by the user segment using antennas. The control segment involves one master control station and five monitoring stations. GNSS technology is used to produce maps at different scales and accuracy to record landscapes especially (Historic England 2015, 11–13)

5.4.2 Digital-Record Photography

A photographic portfolio for a heritage place is used to document the current conditions of various contexts throughout the site. It is a quick, reliable way to capture the geometry, texture, shape, and color of subject matter with various levels of detail (figure 5.5). Photography is an efficient method for visually recording various character-defining elements that compose a site and providing clarity for other types of records, such as field

FIGURE 5.4. In site documentation, a GNSS device is used to record coordinates to georeference a survey network at the Tha-mu-ti-hpaya temple (Bagan World Heritage Site, Myanmar). *Source:* Mario Santana Quintero.

notes and digital surveys. Photographs can also be used for future study and comparison through monitoring practices.

For a photographic portfolio to be useful, the photographs must show a variety of views and contexts. Not every context is appropriate for every site; however, a complete, thorough portfolio should consist of photographs taken with varying levels of detail and scale that best capture the

FIGURE 5.5. Example of context photography capturing geometry, texture, shape, and color at the Kasbah of Taourirt, Morocco. *Source:* Mario Santana Quintero.

qualities of the historic place. These views and contexts are achieved by changing magnification levels and how the image is framed. Portfolios should include the following:

- *Contextual images.* A contextual image captures the building's relationship to its surroundings and the qualitative characteristics of its setting.
- *Perspective images.* A perspective image captures two or more plans of view, depicting how height, width, depth, and position relate to one another.
- *Elevations.* An elevation is an image taken straight-on of a 3D object, capturing only one side or elevation. It is a standard orthographic projection that helps one understand the nature of a surface, either interior or exterior.
- *Interior views.* Both perspective and elevation views can be taken in interior spaces to capture the relationship between various character-defining elements, orthographic representations of specific walls, and the space's overall atmosphere.
- *Details.* Photographs are taken of specific character-defining elements, exposing their various attributes. The detail should take up the entire frame, while the lighting conditions and techniques should highlight specific attributes. An additional, lower-magnification image should accompany each detailed image to document its context within the heritage place.
- *Condition images.* A condition photograph is often used in historic site recording where there is evidence of damage and deterioration. The damage is documented, and these records are used for future interventions and monitoring.

Depending on the type of photo being taken, various techniques can be used to capture the desired subject matter more effectively:

- Panoramic images have a wide aspect ratio distributed across a field of view that is much wider than that of standard photographs. The resulting photographs mimic how the world is seen through the human eye by stitching two or more consecutive images along the same plane. This technique is best used for contextual and general interior views.
- High dynamic range (HDR) is a process that merges multiple photographs of a high-contrast scene into a single image (figure 5.6). This technique yields an image that contains additional details by exploiting highlights and shadows through exposure bracketing. HDR can be implemented in all photographic contexts, depending on the nature of the subject matter.

5.4.3 Conventional Recording Tools

5.4.3.1 Hand Survey for Producing Field Notes

Field notes are used as a preliminary method of evaluating a site, allowing conservators to become familiar with the heritage place's more subtle aspects. They involve manually drawing and measuring sites using plans, sections, elevations, and details. This process can be labor intensive. Today, field notes are typically digitized using computer-aided design and drafting (CADD).

FIGURE 5.6. Example of an HDR image of the exterior of the Kasbah of Taourirt, Morocco, merging multiple high-contrast images into a single image showing additional details. *Source:* Mario Santana Quintero.

FIGURE 5.7. Technicians conduct a hand survey to prepare a field note using trilateration at a historic building in Liège, Belgium. *Source:* Mario Santana Quintero.

To produce an accurate field note, an optimal level of plan has to be chosen. Also, the use of trilateration is highly recommended (figure 5.7). This method is carried out by measuring diagonals to record irregular spaces; the distances should be clearly and systematically annotated on the drawing. For linear measurements, running dimensions is recommended, as is checking leaning or irregular walls using a plumb bob.

Freehand sketches are instrumental in depicting contexts and interactions between building elements. Sketches are useful when combined with measured data from other sources. It should be remembered that, like all survey techniques, sketching will benefit from a consistent, systematic approach. Profiles are irregular details within the site that require notation based on their significance. The most accurate way to depict these details is by using a profile gauge to capture the irregularities accurately. Once the profile is taken, it is traced, dimensioned, and hatched to produce a 1:1 detail drawing that can then be digitized.

Today, field notes are typically used in conjunction with other techniques to produce digital records in the form of CAD drawings, digital models, and orthophotography and as a reference in future projects. To that end, field notes must be documented as accurately as possible to ensure that the resulting documents are precise.

5.4.3.2 Total Station

A total station measures vertical and horizontal angles and distances and combines them to determine a 3D coordinate (figure 5.8). The distances are measured by transmitting a beam from

FIGURE 5.8. A technician conducts a total station measurement in the interior of the Kasbah of Taourirt, Morocco. *Source:* Mario Santana Quintero.

the station toward a prism, target, or object and calculating the distance using the time it takes for the light to bounce back to the instrument. The vertical and horizontal angles are measured with a built-in theodolite, using a horizontal azimuth and the vertical distance as references. The telescope used for orienting the device is attached to a graduated electronic horizontal circle for measuring the angle of rotation (horizontal) and a vertical circle to measure the angle of inclination (vertical). The instrument's height above the ground and the height of the reflector or target above the ground may also be required. Once the measurements have been obtained, trigonometry is used to determine the unknown measurements needed to complete the survey.

Currently, this device is used for setting the control network along with GNSS devices. The GNSS is used to determine the geographic location, while the total station is used to measure control points for combining data obtained from 3D scanning, photogrammetry, and field notes.

For correct use, a total station should be stable and safe, horizontally leveled, and vertically centered over a control point. A second known control point is required to calculate the orientation angle in relation to the azimuth to orient the total station.

To increase the accuracy of the control network, a traverse is used to refine the precision of the surveyed points relative to each other. This method establishes control networks by using previously surveyed points as a backsight for the subsequent points, allowing the obtained data to be placed correctly relative to each station. To establish a traverse, an identified starting point and an orientation are required.

5.4.4 Imaging Recording Tools

5.4.4.1 Rectified Photography

Rectified photography is the process of combining the surface of an object and the plane of an image to remove perspective and distortion. This is an inexpensive and efficient tool that creates a measurable image. Image rectification can be carried out with or without measured control points. If control points are required, they can be measured using a tape measure or survey instruments such as a total station. These measured distances correct the angle or tilt in the original image while retaining the building's correct proportions.

Several constraints are involved in producing an accurate rectified photograph. First, photo rectification is only possible for flat, regular surfaces. Additionally, each rectification needs to be limited to one plane or surface. The process requires good photography and accurate controls to be successful.

5.4.4.2 Photogrammetry

Photogrammetry can be defined as "the art, science, and technology of obtaining reliable information about physical objects and the environment through the processes of recording, measuring, and interpreting photographic images" (Wolf, Dewitt, and Wilkinson 2014, 1).

This technique follows geometric and mathematical principles based on the assumption that photographic images are in perspective and generated from a centrally projected system. Photogrammetry can be used to obtain information about 3D objects such as statues, buildings, sites, or earthen surfaces. When the images are clear and captured at a high resolution, they can be extremely accurate and produce high-quality 3D models and orthophotos.

It is impossible to define the position in the space of a certain point with only a single image. However, using two perspectives or two photographs taken from unique points allows for calculating spatial conditions from a set of images. According to this scenario, there should be enough information to assess the spatial position of all points visible in both images. The intersection of the two projective bundles can then be determined when a particular measurement is taken using a total station from two different positions. Photogrammetry extends this principle to a generic number of images. A sequence of overlapping and oblique images is captured from the scene or subject at the same distance.

Photogrammetry permits the reconstruction of the position, orientation, shape, and size of objects merely by using photographs. It is useful when information is required from large facades without extensive details. There are two types of photogrammetry: terrestrial and aerial. Terrestrial photogrammetry, also known as close-range photogrammetry, uses a camera in a stationary position to record buildings and their condition (figure 5.9). Aerial photogrammetry involves taking photographs of the ground from an elevated position. The most common practice in heritage recording is the use of remotely piloted aircraft systems (RPAS), or drones, as

FIGURE 5.9. A technician photographs the exterior of the Kasbah of Taourirt, Morocco. *Source:* Mario Santana Quintero.

FIGURE 5.10. A technician operates a drone while conducting aerial photogrammetry at the church of Kuñotambo, Peru. *Source:* Mario Santana Quintero.

FIGURE 5.11. Example of terrestrial and aerial targets to record a historic site that are measured using a total station, GNSS, correction services, and RTK networks to produce more accurate photogrammetric results (Tha-mu-ti-hpaya temple, Bagan World Heritage Site, Myanmar). *Source:* Mario Santana Quintero.

they are commonly known. RPAS have revolutionized heritage recording. These devices allow quick, reliable site inspections, cinematography, and presentation of the site and probably the most critical comprehensive photogrammetric survey to date (figure 5.10).

A site inspection can be conducted by taking aerial views of the heritage place to assess the condition of rooftops, understand the ancient city wall of an archaeological site, or assess the extent of damage from an earthquake. Correction services and real-time kinematic (RTK) networks are used to improve the accuracy of RPAS devices. This allows subcentimeter points to be produced from the measured features. The geographic coordinates are commonly used to measure other control points to reference data collected through photogrammetry and 3D scanning using a total station (figure 5.11).

Drone footage can be incorporated into videos to show aerial views and provide quick "tours" of the site under study. In photogrammetry, drones can capture multiple overlapping views to create 3D meshes of the site, context, and topography. However, these devices fall under legal safety frameworks to protect the community and the integrity of the heritage fabric of sites. Drone operators must follow rules regarding safe flight altitudes, advised payloads, accepted radio transmissions, and controlled airspace. The equipment must not be flown near airports or over bystanders, wildfires, or outdoor concerts and parades. It is advisable to invest time in researching these legal frameworks, as well as third-party insurance requirements, licensing, and permits, before adopting this useful tool for a heritage recording project.

FIGURE 5.12. A laser scanner is positioned for site recording at the Kasbah of Taourirt, Morocco. *Source:* Mario Santana Quintero.

Responsible planning for RPAS use involves defining the area to be studied and the level of detail and graphic scale needed to produce the resulting measured products. Assessment of optimal outdoor light conditions, site conditions, and adequate weather forecasts for flying must also be taken into consideration.

5.4.4.3 Scanning Recording Tools (3D Scanning)

Laser scanning is a method that mass captures 3D data by using laser technology (figure 5.12). It measures the X, Y, and Z coordinates of a large number of discrete points and other values such as intensity and color to produce a point cloud. Various by-products can be created from the point cloud data, including 2D drawings and 3D models.

This tool can capture a large amount of data rapidly with predictable precision. It can gather descriptive surface information that cannot always be obtained through photogrammetry. It is, however, not suitable for important edge definition. To have details appear in the scan, the point density should be at least half the smallest feature size.

There are two types of laser scanning: dynamic and static. Dynamic laser scanning captures data in motion, such as that from cars, drones, or planes. Static laser scanning can only capture the amount of information within the range of the instrument. A midrange scanner, which has a range between 1 and 350 m, is typically used when recording a historic place.

Laser scanning uses one of three possible systems appropriate for different results and processes. Triangulation is used for close-range objects to obtain submillimeter accuracy. Time-of-flight and phase-comparison systems are used for larger objects, which require a better range. Time-of-flight systems calculate distances by recording the time it takes light to travel from the instrument to the object and back. Phase-comparison systems calculate distances by analyzing the variation in the phased pulse of light sent and received by the scanner.

With this method, an immense number of points can be recorded with high accuracy in a relatively short amount of time. It requires no direct contact with the object, which permits long-range recording of an inaccessible target, and is similar to taking a photograph that contains depth information. Laser scanning could be considered five-dimensional because it can provide values for the X, Y, and Z coordinates; intensity; and RGB color information.

Despite its ample benefits, laser scanning does have its disadvantages. It requires expensive equipment, including hardware and software that can handle a large amount of collected data. Intense external illumination can result in errors, while motion can distort the data. Temperature and surface reflectiveness can also affect the calculation of distances. Furthermore, complete coverage requires multiple scan positions and a clear path between the scanner and the object. Without these conditions, unreadable holes in the data can result.

A closely related technology, LiDAR (Light Detection and Ranging), is a remote sensing technology that uses laser pulses to measure distances between a sensor and objects on the Earth's surface. By emitting laser beams and analyzing the time it takes for them to bounce back from the target, LiDAR creates highly accurate, three-dimensional maps of landscapes, structures, and other features. This technology is widely used in various fields, including archaeology, forestry, urban planning, and autonomous vehicles, as it allows for precise mapping and analysis of environments, even through dense vegetation or in areas with complex topography. In heritage conservation LiDAR has useful applications for mapping archaeology and other features hidden by tree cover or other dense foliage, which would not be easily recorded through other means.

5.4.5 Processing and Dissemination Tools

5.4.5.1 Geographic Information Systems

A geographic information system (GIS) is a computer-based system capable of capturing, storing, analyzing, and displaying geographically referenced information—that is, data identified according to location. Over the last few decades, this tool has become progressively implemented in urban planning and design practices. GIS technologies integrate a wide range of geographic information into a single analytical model, allowing diverse data to be georeferenced to cartographic projections.

Implementing GIS as an information system allows a large amount of information to be easily stored and updated to build a database that combines digital data from various gathering techniques. Once implemented, it is possible to magnify sections of the displayed data to allow analysis of both attributes and entities.

Open-source GIS-based information systems include platforms such as Arches, a software system for cultural heritage in inventory and management developed by the GCI and the World Monuments Fund and widely used by the heritage sector (GCI 2021). The need for functional heritage inventories has grown over the past few decades, accompanied by the rise of global awareness of the importance of heritage management. Nevertheless, inventories remain complicated to establish and maintain and frequently rely on costly proprietary software. Arches attempts to provide a common platform that is easy to use and customize yet takes advantage of the latest available technology to allow users to create and manage heritage information in all its richness and diversity.

5.4.5.2 Information Sources and Data Representation

GIS information is presented in two forms of data: vector and raster. Vector information represents all geographic features expressed as geometric typologies. These features are generally expressed as points, polylines, and polygons. Raster information is a type of digital image that is represented by reducible or expandable grids or pixels and includes aerial photographs, satellite images, and digital elevation models. Projections can be additionally implemented in algorithms that translate the spherical Earth into a flat map or screen. This form of information always contains distortion (direction, area, shape, and distance).

Once combined, GIS data depicts real objects such as roads, parcels, historic districts, zoning areas, topographic contour lines, trees, and waterways as part of an overall system.

5.4.5.3 Computer-Aided Design and Drafting

Computer-aided design and drafting (CADD), widely used to produce line drawings, is a software in which measurements, data, and images from multiple tools and methods can be combined (Eppich and Chabbi 2007, 61). In most heritage projects, an accurate base record of 3D point clouds and ortho-corrected photos is produced from 3D scanning and photogrammetry data.

The resulting point clouds are imported directly into CAD together with orthophotos to produce the drawings. The 3D point clouds are sliced using sophisticated visualization, and CAD manipulation features and drawing commands are used to trace the plans and sections (figure 5.13).

For elevations and projected surfaces in cross sections, ortho-corrected photos are used. They are attached to the CAD environment and traced in order to produce two-dimensional line drawings. This approach is replicated for all the elevations, floor plans, cross sections, and roof plans to produce line drawings.

FIGURE 5.13. A measured line drawing of the floor plan of the Kasbah of Taourirt, Morocco. This record has been produced with total station survey, photogrammetry, and CAD. *Source:* Carleton Immersive Media Studio.

5.4.5.4 Building Information Modeling

Building information modeling (BIM) is a digital representation of the physical and functional characteristics of a heritage place that extends beyond a typical 3D representation. After the three primary spatial dimensions (width, height, depth) are defined, attributes such as time and cost, spatial relationships, light analysis, geographic information, material quantities, and various properties can be considered. Once combined into a single model, these factors can give insight into planning, designing, constructing, and managing buildings and infrastructure.

One of the significant applications for BIM in the heritage field is to create accurate representations of physical and functional building characteristics, which can be exported as three-dimensional representations, two-dimensional images, and details. Building schedules for maintenance and monitoring purposes can be extracted for overall site management. In addition, BIM can be used to develop hypothetical scenarios to determine possible uncertainties or outcomes. A practical example of this application is modeling various elements to determine energy performance or structural capabilities using simulation software, as shown in the Revit model of Loka-Hteik-Pan temple in Bagan, Myanmar, in figure 5.14.

As a comprehensive digital model, BIM integrates various data types, making it useful in heritage conservation for management, monitoring, energy retrofitting, and disseminating information regarding building technology. Due to its parametric and customizable capabilities, BIM can depict and organize high levels of detail, such as wall compositions and deformities.

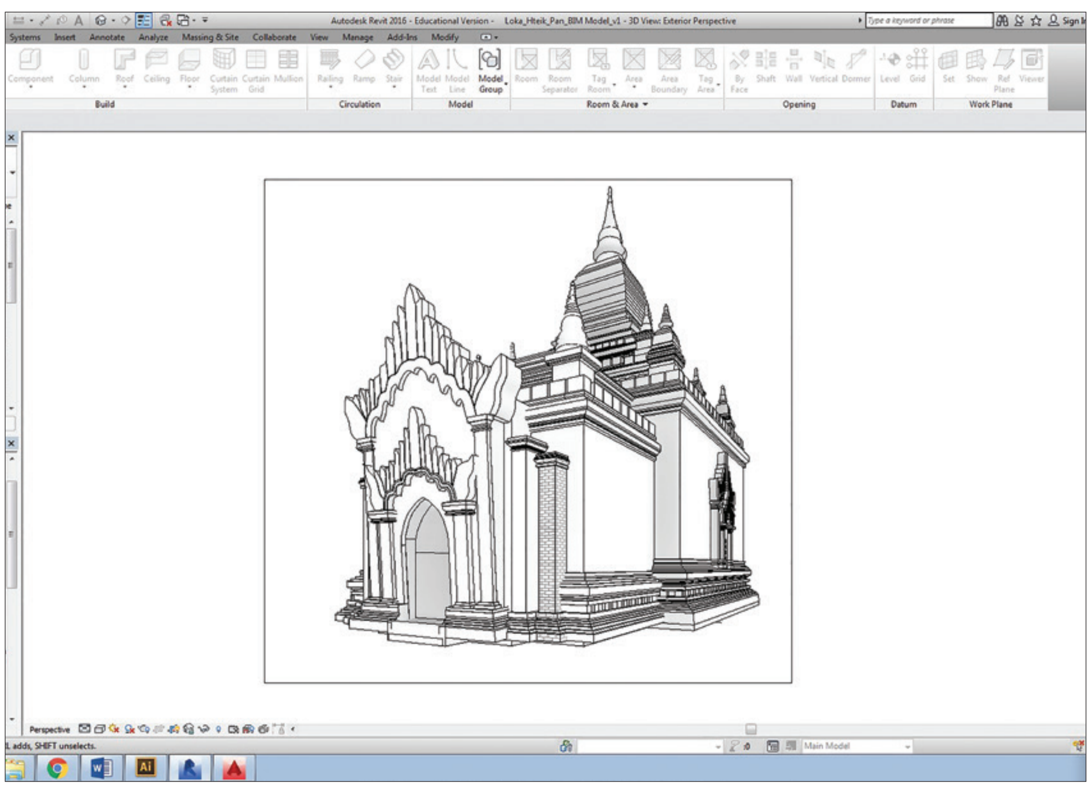

FIGURE 5.14. Revit model of the Loka-Hteik-Pan temple, Bagan, Myanmar. The record has been created using 3D scanning and photogrammetric data to produce a BIM for the research of the temple. *Source:* Mezzino et al. (2017, 148).

Though BIM can depict a high level of detail, this approach tends to resort to standardization, which opposes the irregularity of details in heritage buildings. It is also challenging to adapt the modeling process to building materials and construction methods typically found in heritage buildings that are no longer standing in the building industry, such as log construction and rubble-stone foundations. Complete BIM modeling requires significant collaboration among project team members in dealing with complications due to a lack of international industry standards.

5.4.6 Other and Emerging Tools

Other important categories are of note but are not discussed in this chapter. These include digital storytelling (e.g., virtual, augmented, and mixed reality), digital simulation (e.g., finite element modeling and energy performance), and digital fabrication (e.g., 3D printing and replication).

As new sensors such as LiDAR are adapted for use in smartphones, these devices will be able to capture data faster and with increasingly higher quality.

It is also important to keep in mind the emerging use of crowdsourcing and machine learning algorithms in achieving a certain level of automatization in recording activities in the area of cultural heritage, such as semiautomatic detention of weathering forms from thermal images, three-dimensional modeling of attributes (e.g., walls, columns), and the identification of stolen cultural assets from social media photographs.

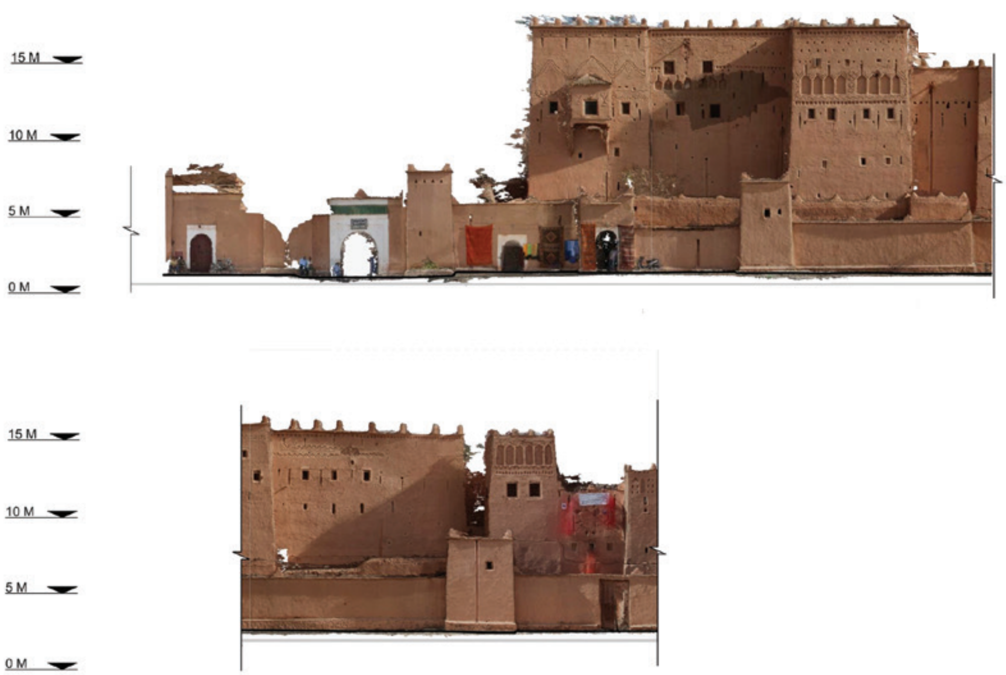

FIGURE 5.15. Ortho-corrected image produced using total station survey and photogrammetry aimed at recording the complex and irregular elevation of the Kasbah of Taourirt, Morocco. *Source:* Carleton Immersive Media Studio.

5.4.7 Dissemination: Measured Drawings, Ortho-corrected Images, and 3D Models

The approach to producing measured drawings and 3D models involves the use of photogrammetry, CAD, and portable document format (PDF) files.

In photogrammetry, dense point clouds and ortho-corrected images are used in the preparation of the line drawing for the site recording of a heritage place (figure 5.15).

For the creation of line drawings, the recording and description of a monument are entirely separate from the interpretation of it: the former is intended as an accurate statement (within limits established for the survey) of the current form of the archaeological structures, while the latter may change (quite correctly so) in light of developments in the wider study of sites (Howard 2007, 7).

5.5 Case Study: Documentation of the Church of Santiago Apóstol de Kuñotambo, Cusco, Peru

The GCI's Seismic Retrofitting Project (SRP), in collaboration with Peru's Ministry of Culture, selected the seventeenth-century adobe church of Kuñotambo in Peru as an important prototype for the design and implementation of "high-tech methodologies" and to "test easy-to-implement seismic retrofitting techniques and maintenance programs to improve the structural performance and safety of earthen buildings while minimizing loss of historic fabric" (GCI 2016).

Under the framework of the SRP, a team from the Carleton Immersive Media Studio (CIMS) at Carleton University recorded the state of conservation after rehabilitation of the church for further monitoring. For this project, a robust digital workflow was established that acquired data in a relatively short time with the appropriate level of detail and given the physical constraints of the church's remote location. This approach involved the use of 3D scanning and both aerial and terrestrial photogrammetry.

With regard to photogrammetry, CIMS employed software equipped with strong structure-from-motion (SfM) algorithms that, according to Westoby et al. (2012), operate under the same basic tenets as stereoscopic photogrammetry—namely, that 3D structures can be resolved from a series of overlapping, offset images. However, this method differs fundamentally from conventional photogrammetry in that the geometry of the scene, camera positions, and orientation are solved automatically without the need to specify, a priori, a network of targets that have known 3D positions. Instead, these are solved simultaneously using a highly redundant, iterative bundle adjustment procedure based on a database of features automatically extracted from a set of multiple overlapping images (Westoby et al. 2012, 300). Photogrammetry is an excellent tool for recording earthen architecture; given the fabric's organic nature, the SfM algorithms can produce excellent point clouds.

A measured and graphic dossier for the church of Kuñotambo submitted to the GCI to meet the requirements was created, including the following:

- a final technical dossier that includes site plans, floor plans, elevations, and cross sections of the church for posterity after the restoration in CAD and PDF formats
- a record of ortho-corrected photographs of internal elevations, ceilings, and pavements of the decorated surfaces of the church of Kuñotambo, integrating suggestions and input from GCI wall paintings conservators in CAD and PDF formats
- feedback to develop parameters for the monitoring and evaluation of the wall paintings at the church following an accurate measurement workflow
- a presentation for GCI management on-site on how to use the data acquired for the monitoring of the wall paintings
- per GCI specifications, a set of ortho-corrected photographs of internal elevations of the decorated surfaces of the church in CAD and PDF formats

To prepare the line drawings, an accurate base record should be produced from the photogrammetry and 3D scanning. This limited the degree of interpolation needed between the site and readable measured drawings that reflected the requirements of the GCI and the stakeholders, which involved the plotting of PDF drawings to annotate potential deterioration patterns that appear in the building's fabric using regular condition assessment inspections.

The final technical dossier included relevant measured drawings done at different scales, including floor plans, roof plans, inverse ceiling projections with ortho-corrected images (including site context), elevations (including site context), and longitudinal and transversal sections (figures 5.16–5.19). Ortho-corrected photographs were also produced for the interior surfaces of the church's main spaces and decorated surfaces and ceilings (figure 5.20).

FIGURE 5.16. Contextual image of the site of the church of Kuñotambo, Peru. This record has been produced with aerial photography and photogrammetry to produce an ortho-corrected image of the site. *Source:* Miquel Reina Ortiz and Mario Santana Quintero, Carleton Immersive Media Studio.

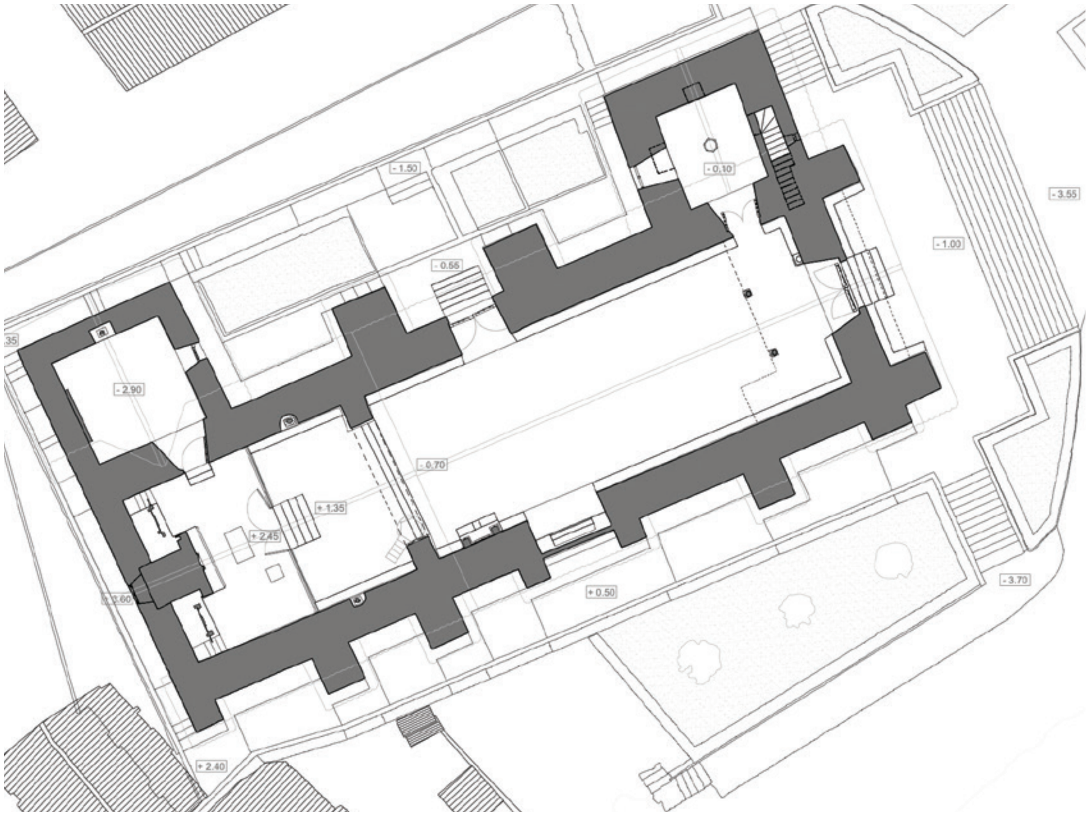

FIGURE 5.17. This measured drawing of the floor plan of the church of Kuñotambo (Peru) has been produced from the total station survey, 3D laser scanning data, and photogrammetry. *Source:* Miquel Reina Ortiz and Mario Santana Quintero, Carleton Immersive Media Studio.

FIGURE 5.18. A measured drawing of the north elevation of the church of Kuñotambo, Peru. This record has been produced with the total station survey, aerial photography, and photogrammetry to produce an ortho-corrected image, which has been traced using CAD. *Source:* Miquel Reina Ortiz and Mario Santana Quintero, Carleton Immersive Media Studio.

FIGURE 5.19. A measured drawing of the cross section of the church of Kuñotambo, Peru. This record has been produced with the total station survey, 3D scanning data, and photogrammetry to produce an accurate record. CAD has been used to trace and produce the line drawing. *Source:* Miquel Reina Ortiz and Mario Santana Quintero, Carleton Immersive Media Studio.

FIGURE 5.20. An ortho-corrected image of the decorated surfaces of the church of Kuñotambo, Peru. This record has been produced with the total station survey, 3D scanning data, and photogrammetry to produce an ortho-corrected image, which has been traced using CAD. *Source:* Miquel Reina Ortiz and Mario Santana Quintero, Carleton Immersive Media Studio.

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EARTHEN BUILDING ASSESSMENT AND INVESTIGATION

6

Overleaf: **Condition assessment of Qattara East conducted during a Graphic Condition Recording field exercise at the EAC22 course in Al Ain, United Arab Emirates. Source: J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.**

6

EARTHEN BUILDING ASSESSMENT AND INVESTIGATION

Christof Ziegert, Paulo B. Lourenço,
and Peter Sheehan

This chapter discusses the assessment and investigation of earthen buildings, from understanding deterioration patterns and their causes to structural inspection, seismic testing and modeling, and archaeological investigation. In sections 6.1 and 6.2, Christof Ziegert summarizes typical deterioration observed in earthen structures and describes the most common causes of decay. In section 6.3, Paulo B. Lourenço provides an overview of the structural assessment of earthen buildings, including visual inspection, nondestructive and minimally invasive testing, and seismic modeling. Archaeological investigation of earthen buildings is also a critical part of building assessment and is described in section 6.4 by Peter Sheehan along with case studies from the Al Ain region.

6.1 Deterioration of Earthen Buildings

6.1.1 Introduction

The purpose of this section is to provide an overview of the most common decay mechanisms affecting earthen structures and their causes of deterioration. Damage to earthen architecture can be caused by a variety of external factors, from natural and human disasters to environmental factors. Moisture from various sources, including rising damp, drainage problems, and direct precipitation, is particularly damaging. This section will provide descriptions of common decay mechanisms, including material and structural damages, and will cover the most common causes of deterioration, including environmental and the impacts of natural and human disasters.

For simplicity, this overview of decay mechanisms in the earthen substrate and surface will be divided into structural and nonstructural ones. Nonstructural damages include surface conditions such as delamination, erosion, efflorescence, biological growth, and so on, while structural damages are generally related to failure of the wall construction, including structural cracking, basal erosion, out-of-plane movement, displacement or in-plane movement, missing parts or major loss of structural elements, due external impacts to the structure (seismic damage, floods, inappropriate interventions, etc.).

6.1.2 Nonstructural Damages

6.1.2.1 Detachment

Detachment is the lack of adhesion between the render and the earthen building material substrate (figure 6.1a). There are several factors that will cause this, but the most common one is when the top layer of render is too hard or of a different composition, such as cement-based renders or earthen plasters with significantly differing composition from the earthen substrate. Due to thermal stress, the firmer render then detaches from the substrate. However, the damage pattern can also be caused by salt transport and salt crystallization in the transition layer from the substrate to the top render. The damage mechanism can often be detected by tapping on hollow areas.

6.1.2.2 Delamination

Delamination is the lifting, separation, and partial loss of surface layers, resulting in an uneven, irregular contoured surface. Delamination can also be a planar detachment of the earthen substrate.

6.1.2.3 Disaggregation

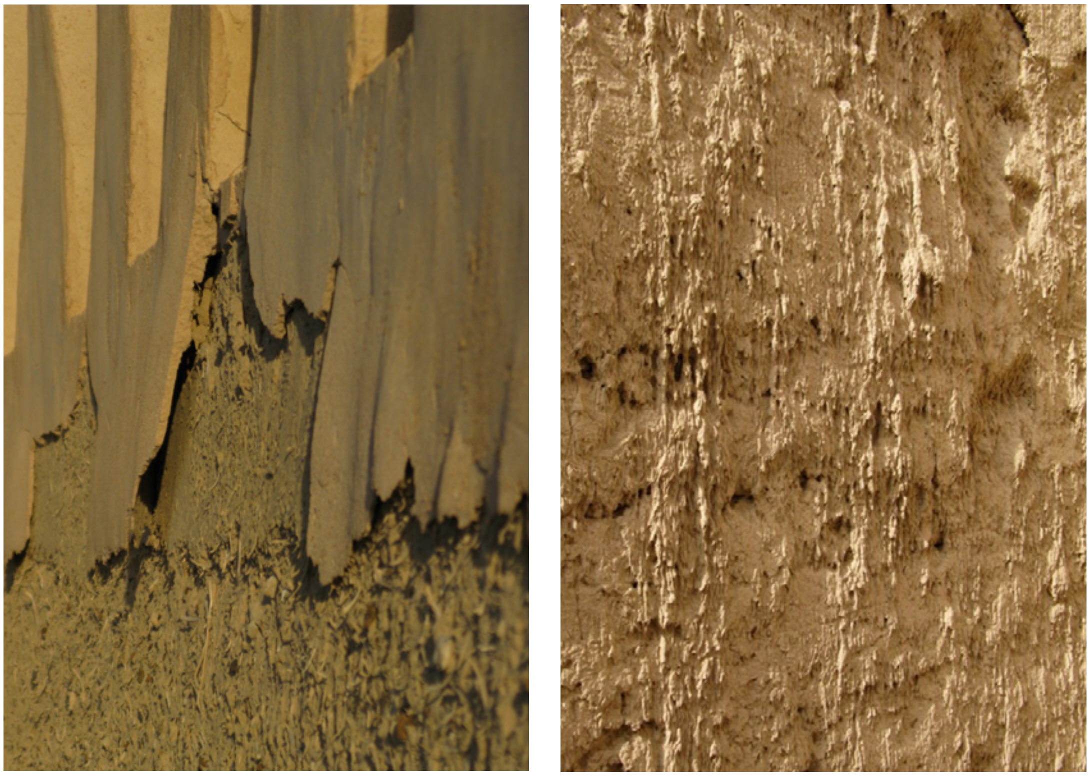
A disaggregated surface is friable to the touch, and the surface cohesion of the earth grains has been lost. This can also be considered as granular disintegration and is mostly due to lack of the material cohesion forces under constant wetting/drying cycles. Material loosened by rain from upper wall areas runs over the surface of loose areas below and forms stripy deposits (as shown in figure 6.1b) or flat crusts.

6.1.2.4 Flaking and Blistering

Flaking is small-scale thin lamellar loss of the surface finish(es) or substrate material, often caused by salt crystallization but also by freeze/thaw cycles in wet conditions or wetting/drying cycles in arid conditions. Flaking can also occur when runoff material (see figure 6.1b) solidifies on salt-induced microdelaminated areas (see figure 6.2b).

6.1.2.5 Cracking (Nonstructural)

Nonstructural cracking is a fracture of variable length and orientation, with or without associated planar displacement of the finish, and is differentiated by depth and pattern. A network of superficial cracks can be formed with different or identical patterns in the different plaster layers (see figure 6.3a). This is usually caused by layers of plaster that have cracked due to shrinkage and either have been covered with the next layer or have only been sealed with a slurry in the upper layer.



(A) (B)

FIGURE 6.1. (a) Detachment of plasters from an earthen wall, Al Jahili Fort, Al Ain, United Arab Emirates (UAE). (b) Disaggregation of the earthen surface, Uruk, Iraq. *Source:* ZRS, Christof Ziegert.

(A) (B)

FIGURE 6.2. (a) Planar detachment and flaking on a mud-brick wall. Hili 17, Al Ain, UAE. *Source:* Benjamin Marcus (b) Archaeological site of Uruk, Iraq. *Source:* ZRS, Jasmine Blaschek.

Changes in temperature and humidity over the course of years and even centuries will naturally cause expansion and contraction of the earthen materials. Shrinkage due to drying of the original materials also introduces a decrease in the length or volume of an earthen wall, often leading to cracking. Both phenomena can manifest as network cracks on the surface and as cracks within the masonry of the walls. These are generally hairline or fine cracks, not structural cracks, but over time, they can lead to larger fissures.

6.1.2.6 Alveolization

Cavities, or alveoles, can form on the surface of earthen material and may be interconnected and have variable shapes and sizes. While alveolization refers to cavities caused by wind and dust, in figure 6.3b, there is also damage caused by insects. Bees and wasps commonly occupy the area near the surface (up to 5 cm deep), while termites can also be found over the entire thickness of the wall if the earth building material contains such a high proportion of organic additives that it becomes interesting as food. In the author's experience, this is possible below a bulk density of 1,400 kg/m^3 of earth building material.

6.1.2.7 Surface Deposit

Deposition of black soot due to the burning of organic materials is referred to as carbon deposit. Deposition of animal or bird excrement can also cause damage to earthen materials (see figure 6.4).

6.1.3 Structural Damages

6.1.3.1 Structural Cracks

Structural cracks are generally deep fissures that affect the stability of the structure. The term *structural crack* also applies to diagonal or shear cracks and to through-wall cracks with variable thickness. Often multiple causes create a structural crack (figure 6.5a). When earthen walls are not properly connected during, for example, a seismic event, they are free to move individually, leading to structural cracking. The presence of cracks radiating from the corners of the windows or doors are normally caused by absence of lintels. Additionally, soil settlements can create foundation problems that impact the stability of the wall creating cracks The damage caused by basal erosion described below weakens the most heavily loaded area of the walls, causing them to settle and sometimes tilt.

6.1.3.2 Basal Erosion

Basal erosion is the result of the combination of water in contact with the lower part of the wall, soluble salts rising from the ground or the surrounding materials combined with wetting/drying cycles and wind erosion. The outcome is deep erosion at the wall base, often on both sides. In this case, the typical section is referred to as a "wine-glass profile" (ISCEAH Glossary) (figure 6.5 a). Basal erosion can ultimately lead to the complete or partial collapse of a wall.

6.1.3.3 Out-of-Plane Movement

Out-of-plane movement is the shifting of masonry from its original vertical orientation. Walls can lean if not connected to other walls, if they have no lateral restraint or when foundations are not properly constructed. This can ultimately lead to complete or partial collapse of the wall, especially if the center of gravity moves outside the middle third of the wall, thus introducing tensile stresses (figure 6.6).

(A)

(B)

FIGURE 6.3. (a) Plaster cracking in an earthen house in Bahla, Oman. *Source:* ZRS, Christof Ziegert. (b) Alveolization of a wall at Hili 17 archaeological site, Al Ain, UAE. *Source:* Benjamin Marcus.

(A)

(B)

FIGURE 6.4. (a) Carbon deposit on walls, Bahla, Oman. *Source:* ZRS, Christof Ziegert. (b) Birds nest over an earthen wall, El Badi Palace, Marrakech, Morocco. *Source:* Elena Macchioni.

6.1.3.4 In-Plane Movement or Displacement

The movement and cracking of the wall often result in the shifting of the wall surface significantly beyond the normal irregularities of historical wall surfaces out of plane. The resulting significant deviation from the plane of the wall and its surface is usually associated with mechanical failure of the wall and/or finish (figure 6.7a).

Settlement due to uneven foundation soil can cause out-of-plane movement. However, they can also provoke that part of the building located on softer soil to settle and separate from other parts of the wall located on more solid ground, creating in some cases in-plane movement.

6.1.3.5 Missing Part / Major Loss

Partial or major loss of earthen walls are commonly caused by the damage or failure of other structural elements (such as lintels, beams, roofs, etc.) or deterioration of the material itself (figure 6.7b). A major loss is when the area lost is greater than approximately half a square meter and at least around 10 cm in depth, as measured from the present plane of the wall surface.

6.2 Causes of Deterioration

6.2.1 Environmental Factors

As explained in the introduction of this chapter section, deterioration mechanisms of earthen sites come from many sources including environmental factors, the impact of humans, and natural disasters such as earthquakes.

The primary agent affecting the sites located in the MENASA area is environmental. *Precipitation*—even occasionally—and the resulting wetting of the ground cause significant damage to earthen sites, especially those that are not well protected by a roof or stone foundation.

Wind impacts earthen sites by driving blown precipitation or sand in arid environments, which can erode the surface of walls that face prevailing winds. For example, in the sites of Al Ain, northern and northwestern facades often face much higher rates of deterioration than south-facing walls due to the presence of windblown sand and rain driven by wind (see figure 6.8a).

The combination of *humidity and salts* is a major factor of deterioration in most places. Moisture in the ground or drainage issues in the site can combine with salts to create conditions favorable to basal erosion. If moisture rises by capillary action through the foundation and the lower walls of the building, when it comes in contact with the air above the ground, the moisture evaporates through the building surface, and salts crystallize during this evaporation process, leading to subsurface salts, or efflorescence. In earthen buildings, efflorescence and moisture, combined with wind and other deterioration factors like precipitation, can lead to rapid loss of wall thickness. When a wall that is 80 cm thick has lost 20 to 30 cm of its base near ground level, it can

(A) (B)

FIGURE 6.5. (a) Structural crack at a cob barn in eastern Germany. (b) Basal erosion (coving) of an earthen building in Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

(A) (B)

FIGURE 6.6. (a) Drainage issues and cracking lead to out-of-plane movement, Babylon, Iraq. (b) Out-of-plane movement of a courtyard wall, Al Jahili Fort, Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

(A) (B)

FIGURE 6.7. (a) Deformation of earth block masonry due to improper conservation measures with cement-based materials, Al Jahili Mosque, Al Ain, UAE. *Source:* Louise Cooke, Enrico Fodde, Sandeep Sikka, and Julio Vargas-Neumann (2012). (b) Missing masonry, House of Saif and Khalfan Bin Abdallah Al-Zhahiri, Jimi Oasis, Al Ain, UAE. *Source:* Benjamin Marcus.

be considered structurally compromised, and this can quickly become a priority or emergency condition (see figure 6.8b).

Vegetation or biological growth is typically more of a factor in northern climates where moss, lichen, algae, and higher plants may affect earthen structures. In arid desert climates earthen architecture is rarely directly impacted by biological growth. However, the watering of oasis plants or other plant life too close to an earthen site can have a significant impact on nearby sites (see figure 6.9a). Similarly, changes in the water table due to nearby agricultural activities can affect earthen buildings. Lowering water tables can cause settlement of structures, while increasing water tables can lead to capillary rise of moisture, undermining the walls in the ground floor of earthen buildings.

Earthen material can be directly affected by the *presence of insects* such as wasps and bees, which make their homes in earthen walls (see figure 6.9b). Termites can also indirectly affect the structural stability of buildings by destroying elements such as lintels, roof beams, and timber structural ties.

6.2.2 Human and Natural Factors

The impact of human activities such as abandonment and incompatible interventions, among others, affects earthen sites. Similarly, the impact of natural disasters such as earthquakes or floods can be detrimental for the survival of earthen sites.

6.2.2.1 Abandonment

One of the largest single causes of damage to earthen architecture is the abandonment of structures. Changes in the lifestyle of populations moving from traditional agricultural societies into urban areas and the perception of earth as a poor or unsafe material frequently cause entire settlements to be abandoned. Once abandoned, the buildings are no longer maintained, and with roof failure and precipitation, they can quickly collapse. An abandoned earthen settlement can go from intact structures to rubble within a period of decades (see figure 6.10a). Abandonment and the lack of reuse options as well as the economic feasibility of using earthen buildings are the main causes of the loss of earthen heritage in many countries.

6.2.2.2 Demolition

Intentional demolition of earthen structures is another main cause of the loss of earthen heritage. Development pressures within historic urban cores and larger village settlements cause earthen buildings to be demolished in favor of so-called modern materials such as concrete. Again, the perception of earth as a nonmodern material and as poor or unsafe means that many governments do not see earthen buildings as priorities and only focus on those structures associated with famous historical figures or military defense such as fortifications, while regular

(A) (B)

FIGURE 6.8. (a) Wind erosion at an early Islamic city wall near Al Ula, Saudi Arabia. (b) Salt damage. *Source:* ZRS, Christof Ziegert.

(A) (B)

FIGURE 6.9. (a) Vegetation/biological decay. (b) Insect attack. *Source:* ZRS, Christof Ziegert.

housing often falls under the bulldozer. However, there is also a noticeable change in awareness that earthen buildings are an important part of the architectural tradition, offering indoor climate comfort and sustainability benefits.

6.2.2.3 Lack of Maintenance

For houses that are inhabited, the loss of traditional building knowledge and understanding of maintenance practices needed to preserve earthen buildings leads to failure of the building system. Examples are drainage problems; the introduction of inappropriate windows or plasters, which may structurally compromise the building envelope; inappropriate roof treatments such as cementitious coatings that lead to failures; and other maintenance issues.

6.2.2.4 Original Construction Techniques

Many earthen buildings are constructed without any sort of ring beam, shallow foundations, long and slender walls or not properly connected structural elements.

A ring beam may be as simple as a timber sill plate that goes around the top of the wall to anchor the roof in place or may include timber inserted into walls to strengthen them. But most earthen structures in the region of MENASA do not have timber ring beams, leaving their corners and long wall lengths vulnerable to out-of-plane movement, leading to cracking, settlement, and possible collapse.

A similar fault in original construction techniques is the lack of deep and strong foundations, with shallow foundations more common in the region. Surprisingly, earthen sites located in seismic areas, probably due to constant collapse of their structures, have wooden ring beams and strong foundations, among other seismically resistant techniques. As explained in section 6.1.3.4, shallow foundations and settlement can generate out-of-plane damage.

Long wall lengths in earthen structures (e.g., barns) can be vulnerable to localized settlement or out-of-plane movement caused by an uneven distribution of weight within the wall length. This can lead to bulging or bowing of the wall and even localized collapse. Additionally, the presence of multiple windows or doors, especially when not properly supported with lintels.

Many earthen structures are constructed without adequate connections between corner walls, often due to different phases of construction or simply inadequate bonding of brickwork. As explained in section 6.1.3.1, this is often manifested in cracks at the corners of the building or in the connections between perpendicular walls.

6.2.2.5 Inappropriate Intervention

The addition of incompatible materials to earthen buildings, especially in seismic zones, can result in damage or even collapse of the structure (see figure 6.10b). Additions such as concrete

(A) (B)

FIGURE 6.10. (a) Abandonment, Bahla, Oman.
(b) Removal of a cement plaster as an inappropriate intervention. *Source:* ZRS, Christof Ziegert.

FIGURE 6.11. Cracks in solid earthen walls caused by different stiffness of materials and earthquakes. *Source:* ZRS, Christof Ziegert.

ring beams, columns, or block insertions are incompatible with earth and will respond inadequately to changes in humidity, temperature, or even seismic movement (see figure 6.11).

6.2.2.6 Armed Conflict

Armed conflict is a common cause of the destruction of earthen heritage, among others. In countless examples, from Afghanistan to Yemen to central Africa, earthen heritage is often affected by war. In Mali, for example, historical libraries were attacked, and earthen sites such as religious structures and mosques were recently intentionally destroyed. In Iraq, earthen archaeological sites such as the famous city of Babylon were used as staging grounds for troops. In this case, the destruction, while not actively from violence, is a by-product of the occupation of the site and a lack of understanding of the significance of individual structures and remains. In addition, looting of artifacts from archaeological sites causes direct destruction of earthen building remains.

6.2.2.7 Natural Disasters: Earthquakes and Floods

An earthquake, also referred to as a tremor or temblor, occurs due to a sudden release of energy within the Earth's crust, generating seismic waves. These seismic events are measured using instruments called seismometers or seismographs. The magnitude of an earthquake is typically quantified using the moment magnitude scale (MMS or MW) or the Richter magnitude scale (ML), though Richter's scale is mostly outdated.

The impact of earthquakes on the Earth's surface includes shaking and potential ground displacement. In cases where the epicenter of a significant earthquake is offshore, the displacement of the seabed can lead to the formation of tsunamis.

Causes of earthquakes include the following:

- **Rupture of geological faults**. Most earthquakes are caused by the sudden movement along faults in the Earth's crust.
- **Volcanic activity**. Earthquakes can result from volcanic processes, such as magma movement and volcanic explosions.
- **Landslides**. Large landslides can generate seismic waves similar to earthquakes.
- **Human activities**. Activities like mining explosions and nuclear experiments can also induce seismic events.

Tolles et al., in 1996, stated that the *extent* of earthquake damage to an adobe structure "is a function of (a) the severity of the ground motion, (b) the geometry of the structure, i.e., the configuration of the adobe walls, roof, floors, openings, and foundation systems, (c) the existence and effectiveness of seismic retrofit measures, and (d) the condition of the building at the time of the earthquake." A few databases of earthquake damage have been developed in the field of conservation engineering and have helped to understand the structural performance of earthen sites in seismic areas (Tolles et al. 1996, 17; Cancino 2011).

The following section (6.3) discusses methods for non- and minimally invasive evaluation of earthen buildings aimed at assessing earthquake damage and the methodology and information required for structural modeling of earthen buildings, with the aim of retrofitting. Retrofitting is the addition of technology or features (traditional or new) to existing structures to improve their performance in general. Seismic retrofitting of an existing earthen site should improve the site's structural capacity to withstand an earthquake. Repair is the action to recover the original structural configuration and performance of a building or material (Roca et al. 2019, 13–14).

Floods are overflow events where water inundates land that is typically dry. They occur due to various reasons such as heavy rainfall, river overflow, storm surges, or the failure of dams and levees. Floods can vary in scale from minor waterlogging to catastrophic events that cause significant damage to infrastructure, agriculture, and ecosystems, as well as posing serious risks to human life.

In the last few years, the intensity and quantity of floods have increased all over the world and have also damaged communities living in earthen sites as well as heritage. The exposure to huge amounts of water at once can severely impact earthen archaeological sites, historic buildings and urban settlements. There is a need for systematic collection of data on how floods impact cultural heritage in general and earthen sites specifically, due to the nature of the material (Arrighi 2023).

6.3 Structural Assessment of Earthen Buildings

This section describes methods for non- and minimally invasive evaluation of earthen buildings aimed at assessing the condition of the structure. It also describes the methodology and information required for structural modeling of earthen buildings, with the aim of strengthening their resistance to earthquakes (retrofitting).

According to principles and recommendations from the International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH) of the International Council on Monuments and Sites (ICOMOS), the design of interventions in built heritage must consider safety evaluation and requirements, compatibility between original and newly added materials and components, and issues addressing invasiveness, durability, reversibility, and controllability (ICOMOS 2003; ICOMOS and ISCARSAH 2003).

From an operative point of view, the ISCARSAH recommendations propose an approach based on the following phases, in sequential order: (1) diagnosis (identify causes of damage and decay), (2) safety evaluation (determine acceptability of safety levels by analyzing the present condition of structure and materials), and (3) design of remedial structural measures (conduct repair or retrofitting actions to meet the required safety levels; ICOMOS 2003). Phases 1 and 2 are determined by the actual need for and extent of the treatment measures. If these phases are carried out incorrectly due to poor judgment, the result may be heavy-handed conservation measures or inadequate safety levels. On the other hand, actions that are too much on the safe side and too invasive may have a significant impact in terms of loss of cultural value and authenticity because of alterations to or transformations of the structure. Therefore, a thorough scientific investigation of the building under consideration is needed.

6.3.1 Sampling and Preliminary Field Tests

Adequate knowledge of the building is essential for understanding its structural behavior. The investigation should highlight possible localized defects in the original construction—for example, a construction joint with no connection between parts, basal erosion, or cracks that show subsequent deterioration. These defects are particularly frequent in earthen constructions, where safety assessments should consider both local and global failure mechanisms. Local failure mechanisms involve deficiencies that affect the capacity of the structural element itself or the connections between elements. Typical cases include the presence of shafts, niches, and openings with no lintels and walls properly interconnected between them or with no other structural elements like foundations or roofs, which may lead to local failures in the building.

Only when local failure mechanisms are prevented is it possible to discuss global failure mechanisms involving the entire building. Indeed, the definition of a global and accurate structural analysis model represents one of the most complex phases in the entire procedure. This is particularly relevant in the case of earthen constructions, where the uncertainties related to the current internal force distribution, material properties, degree of element interconnection, and internal morphology play a significant role.

During the process of assessment and investigations, the information gathered should include the following:

- description of the structure, including design drawings or any survey drawings, if existing
- historical information about the building's construction and any changes to it and its behavior over its lifetime, including old inspection reports or past interventions
- necessary means of access and possible measures to restrict the use of the structure during the detailed inspection tasks
- possible removal of elements that prevent adequate visual access
- required inspection equipment
- required competencies and responsibilities for the professional team

The equipment required for an initial inspection at the site should include light equipment for cleaning and removing materials. This can include brushes, pointers, and hammers for plaster and chisels for wood and visual aids such as binoculars, lenses, and flashlights. Simple measurement equipment can include tape measures and laser distance meters. Assessment forms and photographic images can be used for data collection. Safety equipment can include first aid boxes, harnesses, helmets, safety shoes, gloves, and ladders. Crack width gauges, markers, and photo scale labels are examples of auxiliary equipment.

The team of professionals should consist of structural and mechanical engineers, architects, and conservators. The inclusion of an architectural historian or archaeologist has proven to be beneficial while trying to understand the site's evolution over time.

During the preliminary inspection, attention should be paid to aspects such as verification of the information obtained before the field visit, like appearance and pattern of cracks and moisture, water leakage and infiltration, biological activity (fungi, lichens, vegetation, etc.), excessive deformation, surface deterioration of materials, previous protective treatments, paintings and impregnations, signs of spalling, and corrosion of any metallic elements. The identification of conditions as part of a glossary will make the field inspection more productive and will allow monitoring in the future.

6.3.2 Inspection and Diagnosis

Visual inspection alone, despite its importance in the evaluation process, cannot provide complete information about the materials and the invisible aspects of the structure. Therefore, complementary means of diagnosis, including nondestructive testing (NDT) and slightly destructive testing (minor destructive testing, or MDT), are essential in obtaining additional information on the characterization of materials and structures. Load tests and dynamic tests, which involve global tests on the structure, should also be considered. These ascertain stiffness, strength, structural behavior, and likelihood of damage in full and not at the material level.

An inspection plan can be formed during the initial site visit. The factors that determine the appropriate knowledge level (KL) of the structure are as follows: (1) geometry (i.e., dimensions) of structural and nonstructural elements (as these may affect the structural response), (2) details such as the morphology of earthen construction or connections between timber members, and (3) material characterization—that is, the mechanical properties of the constituent materials.

There are three KLs that can be achieved (EN 1998-3 2005). The first is *limited knowledge*, which includes historical analysis, complete geometric survey, limited inspections of construction details, and limited testing of the mechanical characteristics of the materials. The geometric survey is based on visual inspections of earthen elements and, at least locally, of the construction techniques, as well as the characteristics of the components behind the plaster and across the thickness of the walls. The aim is to define the cross section of the wall, the degree of connection between orthogonal walls, the characteristic of the floor supports, and possible ties. The entire building should be investigated to detect possible cracks and degradation phenomena. Adjacent buildings that potentially interact with the building under consideration should also be examined. For mechanical characterization of materials in general, a less detailed inspection is required, based mainly on visual assessment of earthen element constituents; this may require local removal of plaster in select locations that are not historically significant. Using historical-critical analysis, the investigation should assist in classifying structural elements in areas that can be considered homogeneous. The objective is to identify earthen element typologies, such as rammed-earth or fired brink areas versus adobe areas, or adobe of different sizes or periods, that can be used as a reference when evaluating the related mechanical properties.

Extended knowledge, the second level, includes historical analysis, complete geometric survey, extensive inspection of construction details, and extensive testing of the mechanical characteristics of the materials. Here, the geometric survey should address the requirements of the first KL but should be more extensive and widespread for an adequate characterization. For the mechanical characterization, extensive visual and systematic inspections, accompanied by localized, deeper inspections, should be conducted. These should examine both the exterior and the thickness of earthen elements, incorporating endoscopic inspections to evaluate constitutive materials, internal morphology, possible homogeneous areas, transversal connections (through bricks, timber reinforcement, or other systems), and any existing damage or deterioration. The analysis of mortars (and of units, if relevant) using nondestructive diagnostic techniques (penetrometric, sclerometric, sonic, thermographic, radar, etc.) and possibly moderately destructive techniques such as flat jacks in areas where reconstruction will be implemented should allow more accurate classification of the typology and quality of the structural elements.

The third KL is *comprehensive knowledge*, which includes historical analysis, complete and accurate geometric survey, comprehensive inspection of construction details, and comprehensive testing of the mechanical properties of the materials. To achieve this level, the availability of original construction documents can be considered as good as the complete geometric survey with exhaustive knowledge of the construction details (to be checked appropriately in their completeness and correspondence to the real situation), even if these documents rarely exist for earthen architecture. In this case, the geometric survey must be systematically extended by means of additional inspections. The analyst should form a clear idea of the morphology and quality of earthen elements (for both surface and cross section), the efficacy of the connection between orthogonal walls, the characteristic of floor supports, and possible ties. For the mechanical characterization, in addition to the requirements for the second KL above, the constitutive materials should be tested to evaluate their mechanical properties. The analyst must define test typologies and quantities according to the KL desired concerning the earthen elements' morphology. These typologies may influence, for example, the choice of how to investigate the shear strength of a given wall. The tests must be performed either in situ or in the laboratory on undisturbed samples and may include, if applicable, compression tests (e.g., on test walls or using double flat jacks) and shear tests (e.g., compression and shear, diagonal compression, or direct shear on joints). They should consider the homogeneous construction typologies defined by the visual inspection or at least the typologies related to the elements that are significant for the safety assessment based on a preliminary sensitivity analysis. The material properties used for the structural analysis should combine the average and/or expected values and the test results (according to the reliability of the test method). Instead of conducting direct tests on a specific building, test results from other buildings in the same area can be considered, if these correspond in terms of typology, materials, and morphology.

According to the European standard EN 1998-3 (2005), the classification of the levels of inspection and testing depends on the percentage of structural elements that must be checked for details as well as on the number of material samples per floor that must be taken for testing (table 6.1).

6.3.3 Nondestructive Testing and Minor Destructive Testing

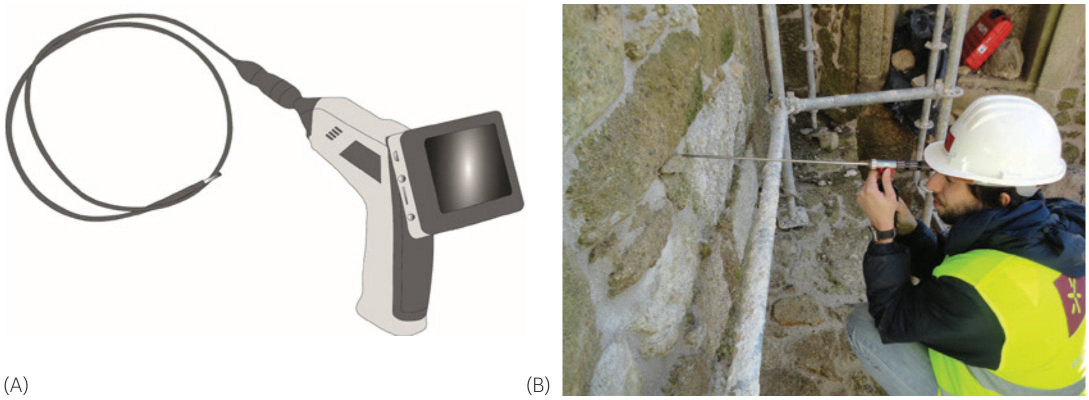
Different equipment is available for the geometric characterization of a structure that can detect aspects not visually identifiable, such as internal timber reinforcements or infilled openings under plaster. As explained in the previous section, a series of tests can be carried out in situ or in the laboratory to characterize the materials. These tests can be NDT, MDT, or destructive; those considered more relevant to professional practice are described below. Additionally, structural tests should be carried out in situ to analyze the overall behavior of the structural system or its elements, such as floors or beams, to supplement the characterization of the materials that compose them.

6.3.3.1 Structural Characterization Tests

Endoscopes may be used to access the inside of walls or under floors, among other hidden parts of the structure. The endoscope's probe (flexible or rigid) may be inserted into a small hole created for inspection purposes or into an existing crack or opening to detect any voids, defects, or biological infestations (figure 6.12).

Table 6.1. Recommended minimum requirements for different KLs of inspection and testing per European standard EN 1998-3 for each structural element (e.g., beam, column, or wall)

Level of inspection and testing	Percentage of elements checked for details	Material samples per floor
Limited	20	1
Extended	50	2
Comprehensive	80	3



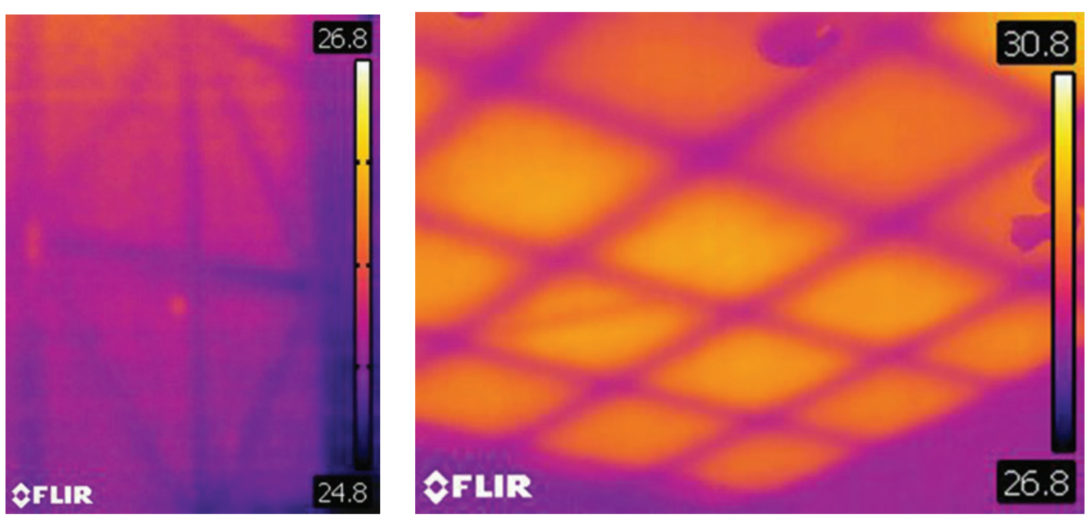
(A) (B)

FIGURE 6.12. (a) Endoscope with a flexible probe. (b) A worker inserts an endoscope with a rigid probe into a wall. *Source:* University of Minho.

Thermography allows the identification of existing discontinuities in structural elements, such as cracks and old repairs. It is a particularly useful method in plastered walls for the detection of hidden elements; for example, in mixed timber-earth walls, thermography can reveal the geometry of hidden structural elements embedded within the walls as well as floors and roofs (figure 6.13).

Every material has different thermal characteristics, and thermography is based on the emission of that radiation. A thermographic camera is sensitive to infrared radiation and detects the surface temperature of the material. The quality of the results depends on the temperature difference between each material and on the time of the day the test was conducted. Early morning or end of day are generally recommended as the best times because they provide the greatest contrast between ambient temperature and that of building materials.

Ground-penetrating radar (GPR) is a test method based on the electromagnetic radiation of pulses generated through a transmission antenna, which are then reflected in the interfaces of materials with different dielectric properties. These reflected pulses are registered by an antenna along a chosen profile on the surface of the element to be tested. GPR can detect deep



(A) (B)

FIGURE 6.13. Detection of hidden structural elements using thermography: (a) infrared image revealing timber structure of a mixed wall; (b) infrared image showing a grid of timber beams inside a floor. *Source:* University of Minho.

structural ties or reinforcement elements as well as voids, depending on the antenna used and the respective frequencies. It is also widely used in earthen construction to assess the consistency or thickness of walls (figure 6.14).

Inspection pits are used to check the depth of a building's foundation and to assess its typology and dimensions (figure 6.15). If significant changes are expected in the vertical actions of the building due to a change of use, or if there is doubt about the foundation's capacity to resist seismic action, geotechnical characterization of the terrain must be determined. This is usually done through standard penetration tests, dynamic or static penetration tests, plate tests, or soil sampling.

6.3.3.2 Material Characterization Tests

Ultrasonic tests measure the speed of propagation of elastic waves (frequencies of 20 to 150 kHz) through a solid medium. This test can detect detachments between multiple wythes in an earthen wall as well as voids, areas with deterioration, and cracks within the material. The speed of the waves can be related to the modulus of elasticity of the material. Ultrasonic testing is used in various materials, including earth, concrete, stone, and wood.

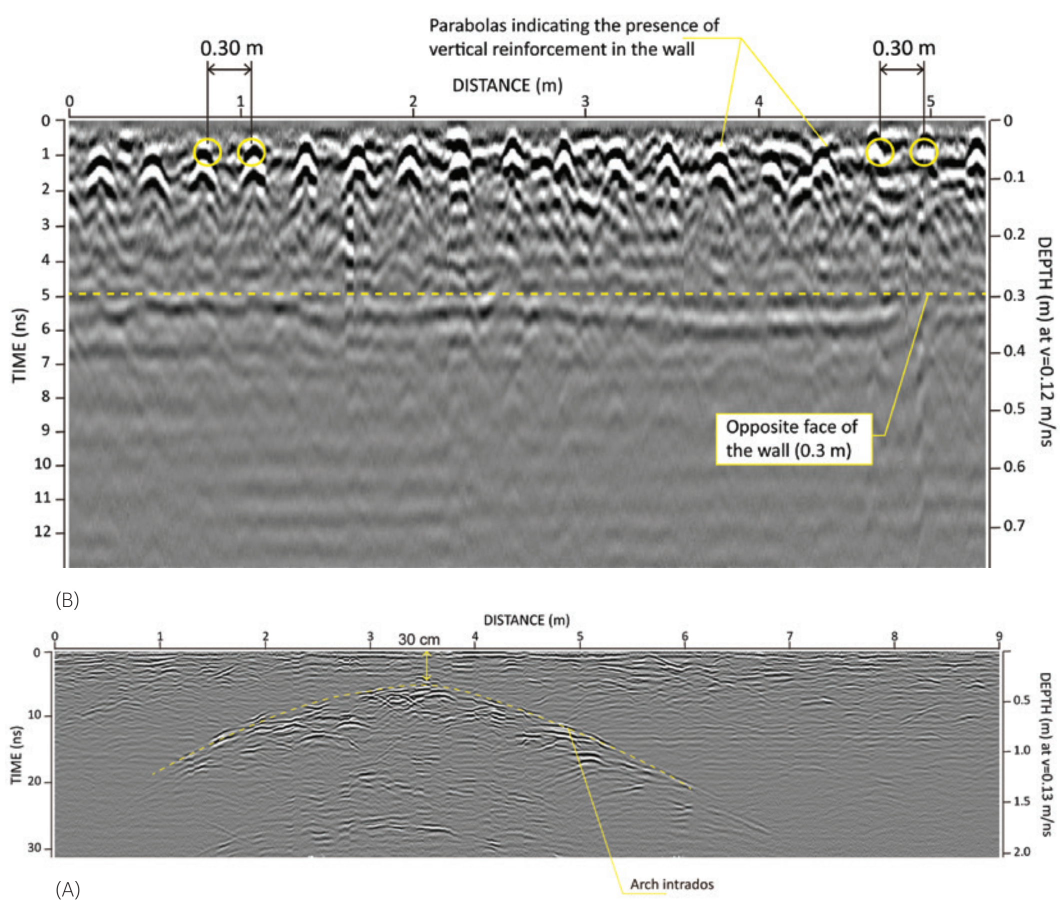
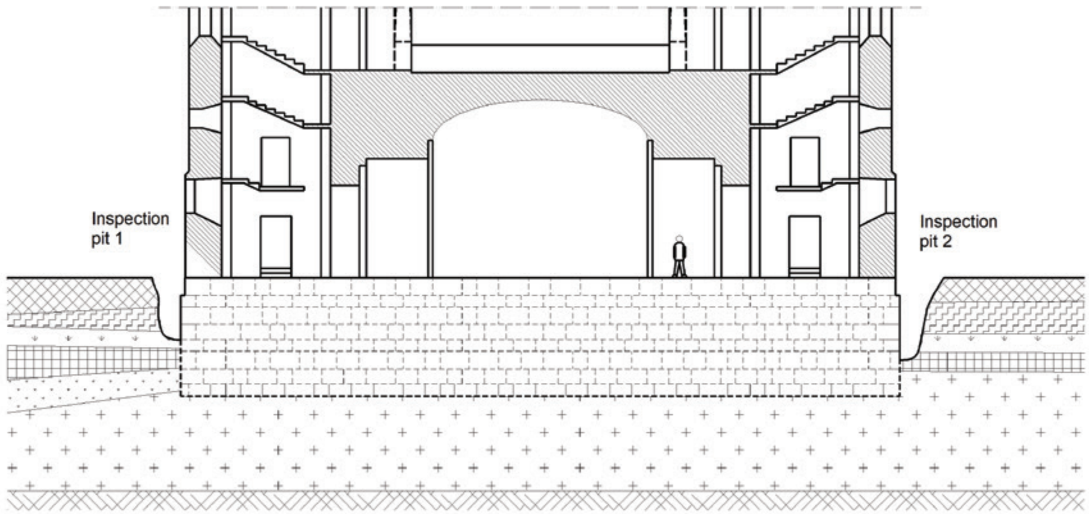


FIGURE 6.14. Sample radargrams of GPR applications: (a) radargram showing the presence of spacing (in yellow) vertical reinforcements in a wall and (b) radargram detecting the intrados (interior curve) and thickness of a vault. *Source:* University of Minho.

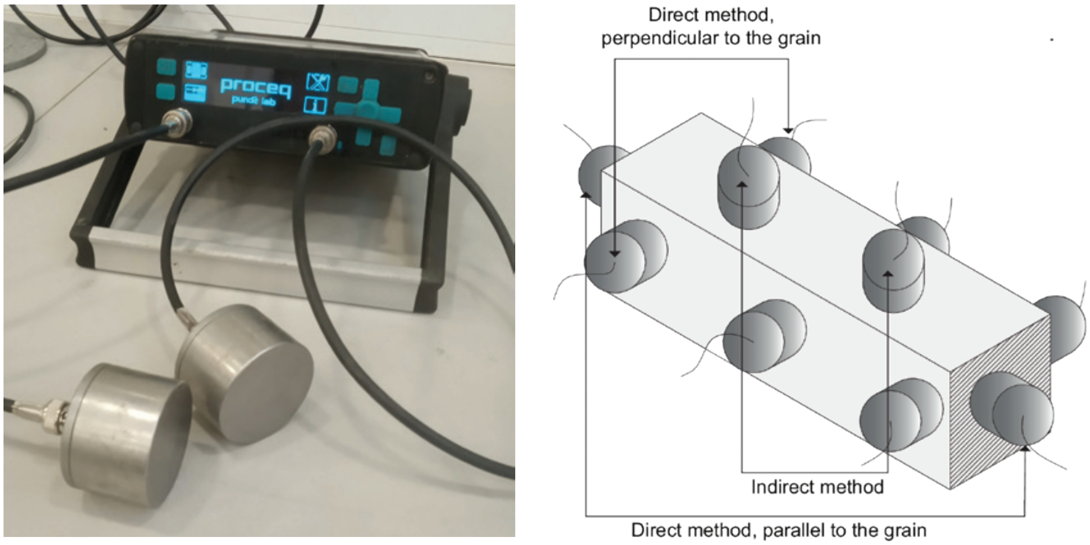
FIGURE 6.15. Inspection pits are used to assess the depth, typology, and dimensions of a structure's foundation: (a) cross section of a foundation showing the location of two pits; (b) an open inspection pit. *Source:* University of Minho.



(A)

(B)

Different configurations of this equipment exist depending on the position of the two probes (figure 6.16a). The direct method consists of placing the probes opposite each other, either on parallel faces or on perpendicular faces. In the indirect method, the probes are placed on the same face as the element; this is commonly done when it is not possible to access all faces of the element (figure 6.16b).



(A) (B)

FIGURE 6.16. Ultrasonic testing detects detachments, voids, cracks, and areas of deterioration in a wall: (a) test equipment, including probes; (b) diagram showing direct and indirect configurations of the probes. *Source:* University of Minho.

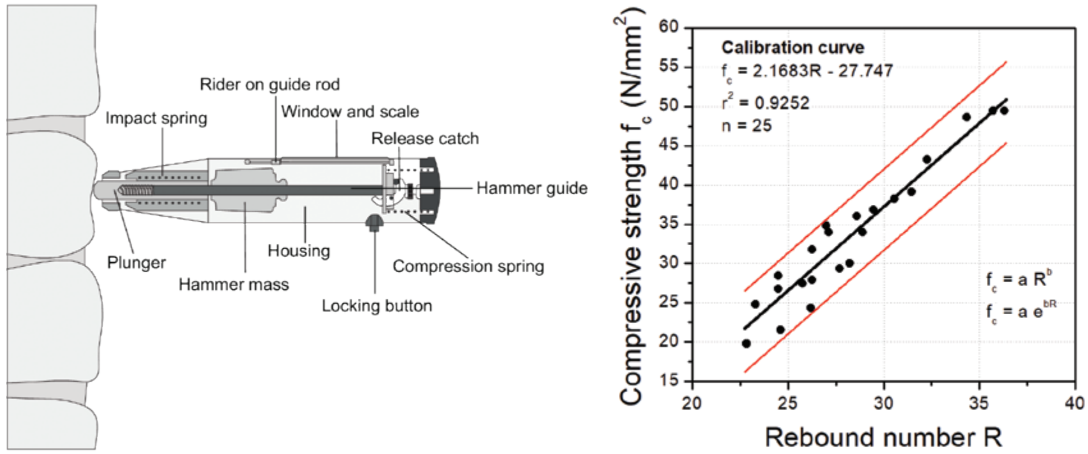
Table 6.2. Typical elastic wave propagation velocities for different materials

Material	Velocity (m/s)
Concrete	4,200–5,200
Masonry and earthen construction (ancient)	200–2,500
Masonry and earthen construction (new)	1,000–3,000
Steel	5,800
Stone	2,000–5,000
Wood	3,500–6,000

Typical wave propagation speeds for different materials are shown in table 6.2. The measurement of wave propagation speed is influenced by factors such as frequency, the pressure applied by the user, the contact between transducers and elements, and the nature of the coupling material. In the case of earthen buildings, this test can be advantageously replaced by sonic tests (frequencies of 20 Hz to 20 kHz) using a hammer and accelerometers.

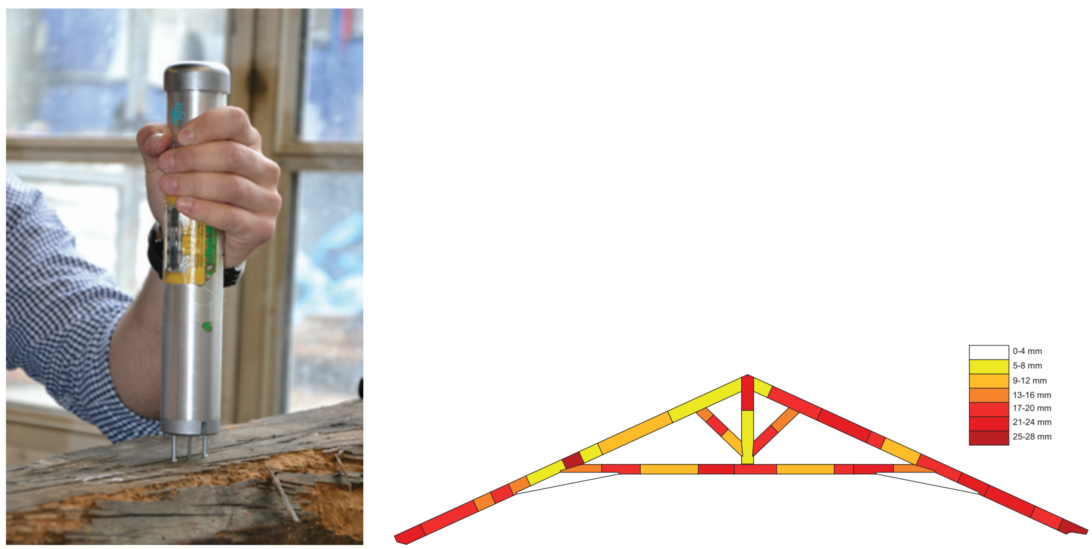
Surface hardness tests are based on the relationship between the hardness of the surface and the compressive strength of the material. A Schmidt hammer, or rebound hammer, is used in place to assess the quality of a masonry surface. The method measures the rebound of this hammer on the surface to be tested (figure 6.17). Because surface hardness is only representative up to about 5 cm in depth, the surface must be free of plaster, deterioration, and high irregularities. Although correlation curves are available for concrete and various types of stone, the assessment of mechanical characteristics usually requires core extraction and destructive laboratory tests to allow for proper calibration. There are also pendulum sclerometers

FIGURE 6.17. Surface hardness testing assesses the quality of masonry: (a) cutaway illustration of a Schmidt hammer, used to record rebound on a test surface; (b) graph showing the relationship between the rebound number and the compressive strength of a material. *Source:* University of Minho.



(A) (B)

FIGURE 6.18. The Pilodyn test, another method of assessing surface hardness: (a) equipment; (b) damage map of a wooden roof truss. *Source:* University of Minho.



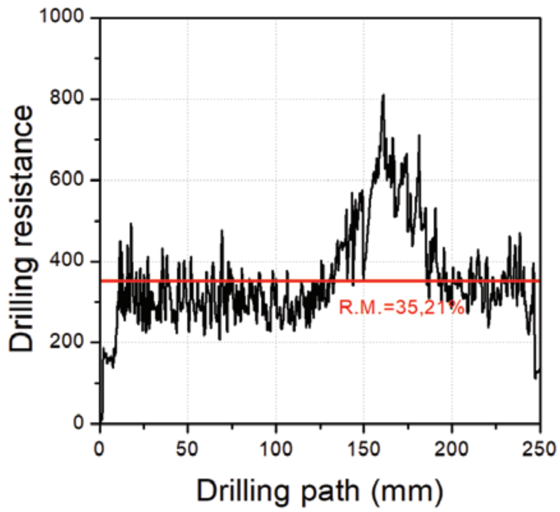
(A) (B)

for mortar joints and other surface hardness tests with lower energy, which can be used for earthen materials.

Another surface-hardness-testing instrument, like the Schmidt hammer, is the Pilodyn. In this nondestructive test, resistance to penetration is measured by releasing a metal pin with a predefined diameter against a wooden surface through a dynamic force (figure 6.18). The depth of penetration, being inversely proportional to the density of the element, gives an indication of the quality of the wood. This test also allows for local and superficial assessment. Pilodyn can indicate the presence of damage to elements and assist in the qualitative mapping of element damage.

The Resistograph is used to detect cracks, voids, and biological deterioration through controlled drilling of wood, a material that commonly interacts with earth. This instrument employs

(A)



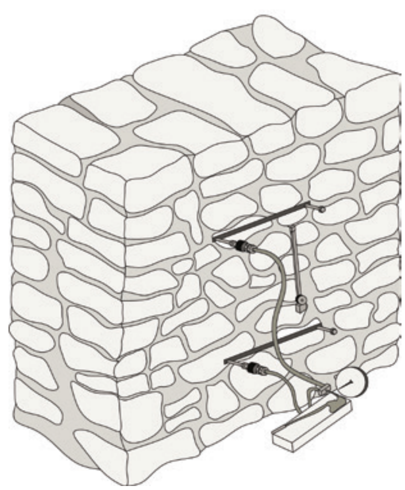
(B)

FIGURE 6.19. A Resistograph measures resistance to determine the presence of cracks, voids, and other defects in wood elements: (a) the drill bit being applied to wood material; (b) typical result showing inconsistencies in a wooden element. *Source:* University of Minho.

a small-diameter drill bit to penetrate a surface and record the material's resistance; a low resistance implies the presence of defects or weakened material (figure 6.19). It is usually used on wood to determine sections of the elements that are usable, and it may be used, in a different version of the equipment, on masonry to test the effective depth of the consolidation treatment.

Flat jacks can be used to determine the compressive stress level in earthen walls (single flat jack test) and the compressive strength and elasticity modulus of the material (double flat jack test; see figure 6.20). A flat jack consists of a thin metal pad equipped with two holes—an inlet and an outlet—that allow pressurization of oil through a hydraulic system. Cuts are made in the walls to be tested, and the jack is then positioned and pressurized. The single flat jack test is based on the principle of partial stress release and involves a horizontal cut, followed by controlled stress compensation (see figure 6.20a). The double flat jack test is like a uniaxial compression test (see figure 6.20b).

(A)



(B)

FIGURE 6.20. Flat jacks are used to measure compressive stress levels: (a) execution of a single flat jack test; (b) diagram showing an in situ setup for a double flat jack test with horizontal jacks, removable extensometer for reading displacements, and oil pump. *Source:* University of Minho.

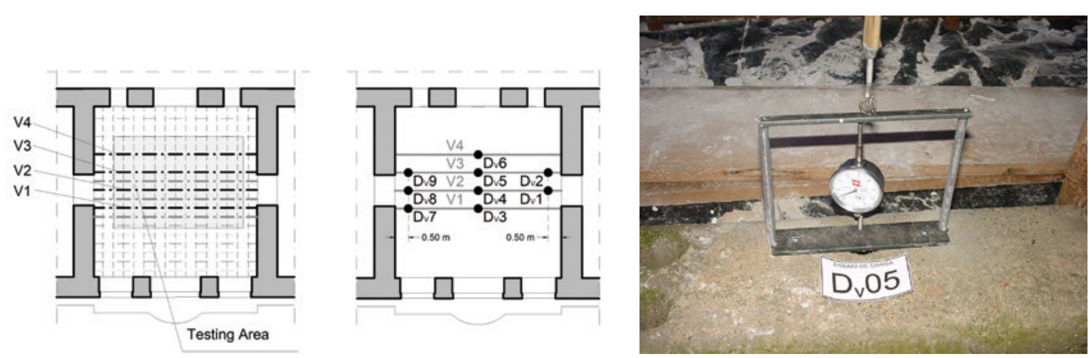
6.3.3.3 Structural Load Tests

Theoretical models of structural behavior of historic buildings in general may be unsuccessful in re-creating the conditions found in situ. A load test considers the real conditions of structural response, allowing verification of displacements and rotations, settlements, and formation or opening of cracks.

The load test must be carried out safely. This involves isolating and monitoring the structure to be tested. Prior to the test, an analysis of the structure is necessary, including a geometric survey, visual inspection, estimation of the mechanical properties of the materials and the actions to be considered, and a safety assessment that provides the displacements expected. Other requirements include a definition of the value and location of the load to be applied, fractionation of the load application in phases, and duration of each load phase, as well as the position of the displacement measurement equipment (figure 6.21).

The load can be applied under different processes, depending on the type of structure and access to it. The load must be easy to measure (e.g., the volume of water), it cannot create a structural change that affects the load capacity (e.g., arching effect to the supports), and it must be distributed over the relevant area. It is customary to use drums or reservoirs filled with water and other materials such as concrete block pallets, sandbags, or cement bags, provided they are spaced and allow free deformation of the supporting structure. The load is applied in phases, and a certain load level is maintained until the parameters to be stabilized are met. The safety assessment criterion is based on recovery from deformation (see figure 6.22).

Dynamic identification tests assist in identifying natural frequencies, modes of vibration, and damping of earthen structures. The elastic properties of earthen materials, which are directly related to the mechanical and structural characteristics (namely, stiffness, mass, connection between elements, and boundary conditions), allow for a better interpretation of the behavior of structural systems. Further, dynamic identification tests allow calibration of structural analysis models and aid in understanding the existing damage. In traditional earthen constructions, environmental vibration due to wind, traffic, and other origins is normally considered excitation.



(A) (B)

FIGURE 6.21. Load test: (a) plan for load placement; (b) example of measurement with a mechanical extensometer. *Source:* University of Minho.

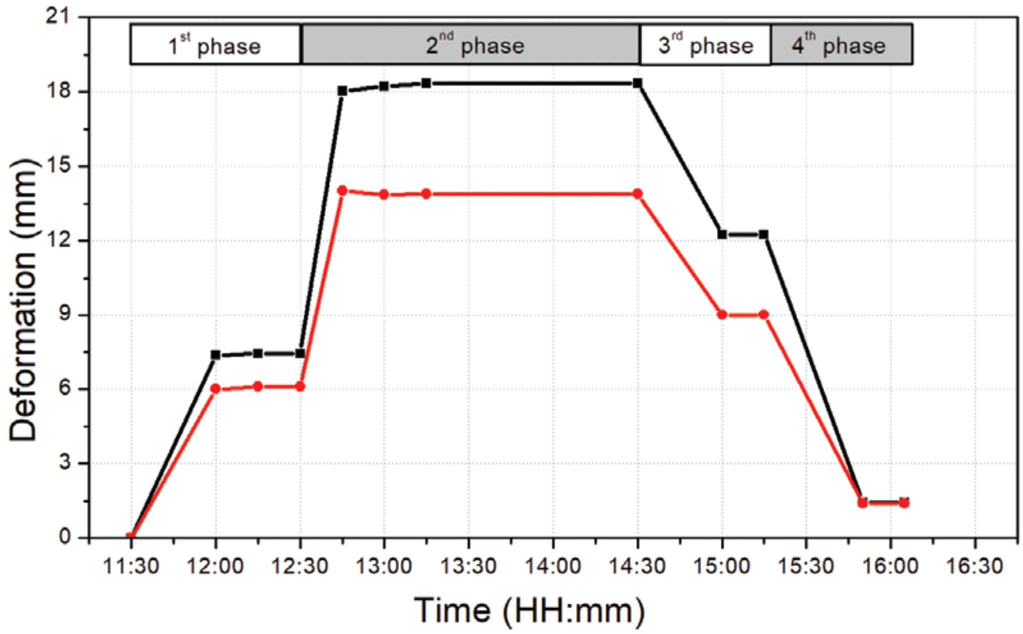
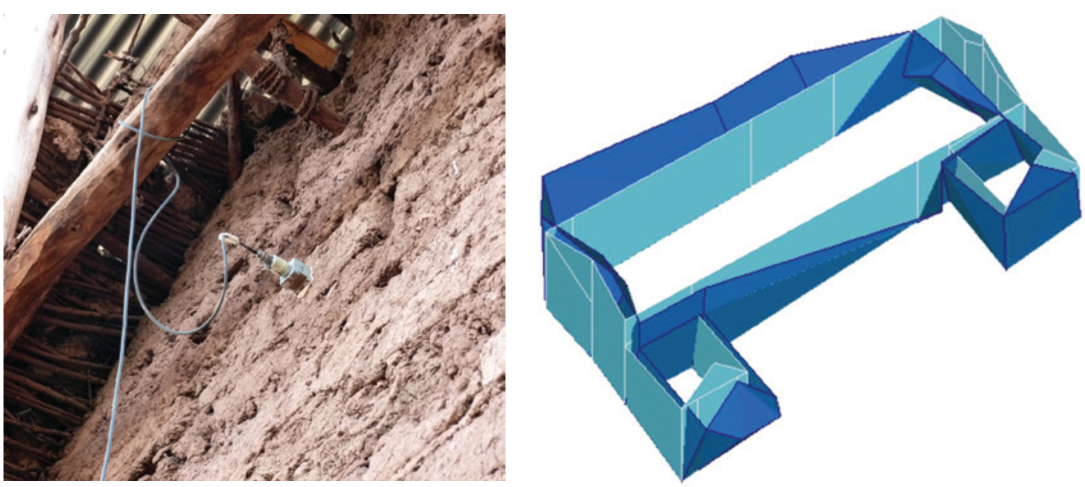


FIGURE 6.22. Example of a load test result. *Source:* University of Minho.

The identification methods can be in the frequency domain, which is easy to use and faster to process, or in the time domain, which is more complex and usually more accurate. The proper equipment includes a set of accelerometers and a signal acquisition system (figure 6.23).

6.3.4 Structural Analysis: Seismic Testing and Modeling

Structural analysis is an important tool widely adopted in the diagnosis, safety assessment, and retrofitting design phases of interventions in the built heritage. Its implementation requires understanding the following conditions of the building:



(A) (B)

FIGURE 6.23. Dynamic identification test: (a) testing equipment in place at the church of Kuñotambo, Peru; (b) the church's vibration mode obtained experimentally, showing areas of potential extreme movement in dark blue. *Source:* University of Minho.

- geometry and morphology (structural form, internal composition, connections between the structural elements, etc.)
- material properties
- actions (mechanical, physical, chemical, etc.)
- existing alterations and damage (cracks, mistakes in construction, disconnections, crushing, leaning, etc.)
- interaction with the soil (except where determined to be irrelevant)

The conceptual process that leads the analyst to understand, define, quantify, visualize, and simulate the effects of these conditions is referred to as modeling. A model approximates reality and represents a limited number of what are assumed to be the most influencing features, reaching a compromise between realism and cost. The process is both conceptual and hypothetical (e.g., the description of the actions as well as mechanical, geometrical, and morphological properties). Thus, calibration and validation are needed, which the analyst can perform through observation and empirical or experimental information. Only when the process is completed—that is, when the results correctly simulate the observation—can the model be used for safety assessments and evaluation of retrofitting measures.

Next, the methods recommended for seismic analysis of earthen buildings are briefly introduced. From recent observations, seismic capacity can be analyzed based on a local or global model, but actions to prevent the disintegration of walls in case of a seismic event need to be considered in addition to seismic analysis (figure 6.24). If the masonry is of poor quality, material consolidation measures must be considered, in addition to other measures according to the structural analysis findings (see chapter 7).

The most common damage mechanisms in an earthen masonry building when subjected to seismic action are shown in figure 6.25. Two distinct behaviors can be considered, depending on the mobilization of the overall behavior of the structure. Figure 6.25a illustrates the behavior of a building in which the vertical and horizontal elements are well connected, commonly referred to as "box," or integral, behavior. Figure 6.25b shows the behavior of a building in which the floors and walls are poorly connected or lack integral behavior. The failure mechanisms of

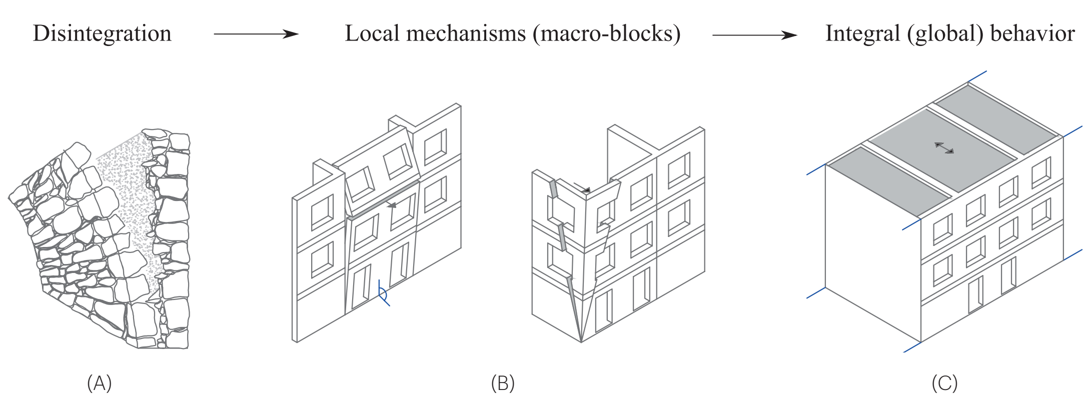


FIGURE 6.24. Modeling of masonry structures and vulnerability hierarchy according to collapse modes: (a) disintegration of the wall or separation of leaves; (b) macroblocks for the study of local mechanisms; (c) model for integral behavior. *Source:* University of Minho.

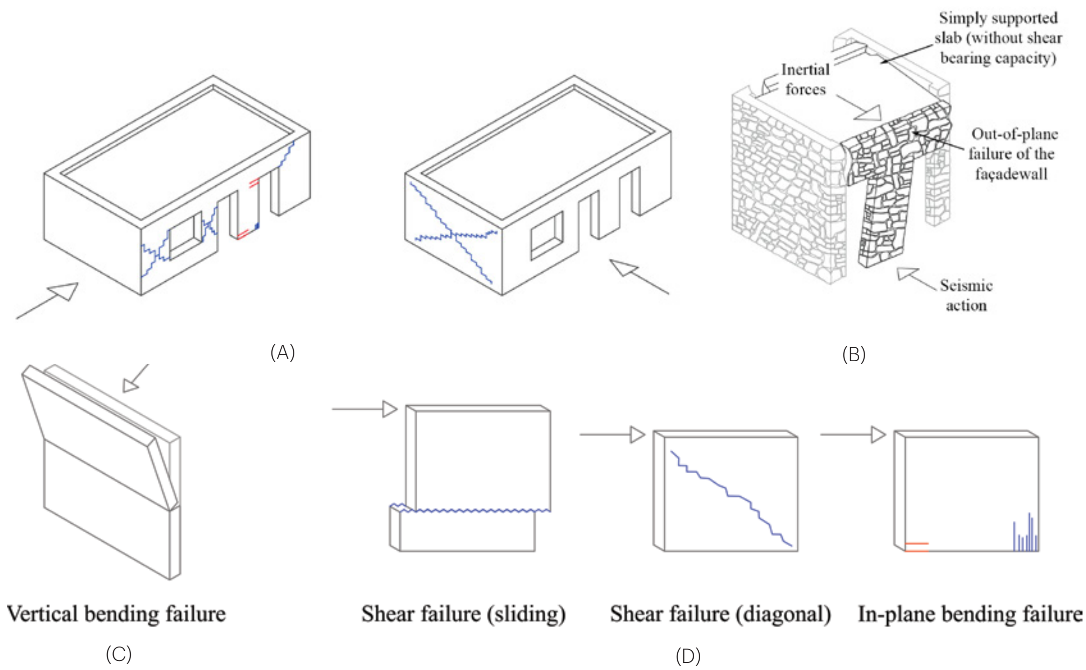


FIGURE 6.25. Collapse mechanisms in masonry structures considering the direction of the seismic action: (a) with "box," or integral, behavior of the structure; (b) without integral behavior of the structure and in walls; (c) out of plane; (d) in plane. *Source:* University of Minho.

walls can be out of plane (figure 6.25c) or in plane (figure 6.25d). Out-of-plane mechanisms are directly related to the low tensile strength of the material. These mechanisms essentially occur when connections are weak between walls and floors and/or the roof. In-plane mechanisms occur when connections are adequate between walls and floors and/or the roof, whether in modern buildings or in traditional buildings that are sufficiently retrofitted. The response of walls in plane is characterized by stiffness, an energy dissipation, and a capacity much higher than those for out-of-plane mechanisms.

A global structural analysis model may be formulated based on the finite element method (FEM), which subdivides each structure into smaller, simpler parts called finite elements, or on methods that represent individually each pier, spandrel, and other structural component, such as the equivalent frame method (EFM). Examples of a model for an earthen building are shown in figure 6.26.

A local analysis model can be formulated based on the kinematic method using macroblocks, often referred to as limit analysis (figure 6.27). For earthen buildings, the seismic response must be governed by in-plane collapse modes. In this case, a 3D model is recommended based on EFM or FEM, which encompasses the behavior of all walls in the overall response of the structure. A global analysis can be considered only if it is guaranteed that the local collapse mechanisms are not activated before the failure regarding the global response occurs.

If corrective measures cannot be taken to ensure that the response of the structure is governed by collapse modes in plane, the analysis of traditional simple earthen buildings must integrate the identification and assessment of collapse mechanisms using a limit analysis strategy. In the case of existing structures without global behavior and with strong irregularities in plan or in elevation, such as monuments or traditional complex buildings, the analysis must include the

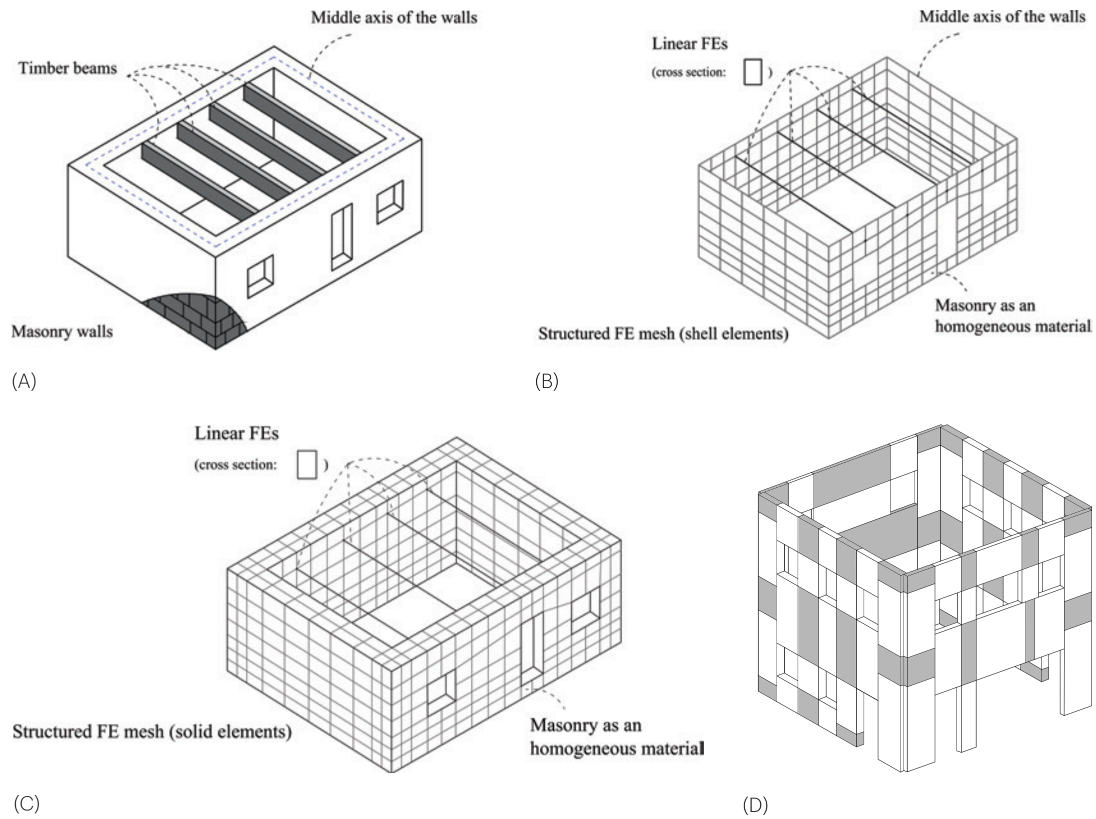


FIGURE 6.26. Global structural analysis models for (a) an earthen building with integral behavior based on (b) FEM and shell elements for the walls, (c) FEM and volume elements for the walls, and (d) EFM for piers and spandrels. *Source:* University of Minho.

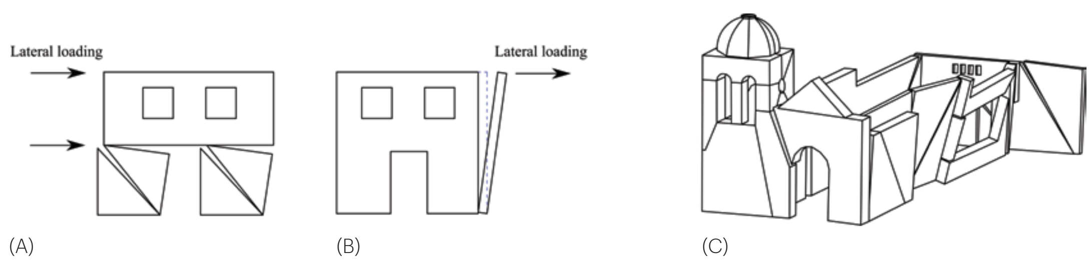


FIGURE 6.27. Local structural analysis model using limit analysis in which macroblocks, or collapse mechanisms, are defined: (a) load factor in plane, (b) load factor out of plane, and (c) three-dimensional model. *Source:* University of Minho.

identification and assessment of collapse mechanisms using limit analysis and overall analysis of the structure using FEM.

All computer models need validation. They must be able to explain past or present observations but also predict future observations or be disproved if the level of confidence is insufficient. The results of structural analysis are valuable to achieving multiple objectives, the most evident being safety assessment, which assists in making decisions regarding strengthening actions. In addition, the model contributes to diagnosis under different possible loads, based on comparison with past or present observations, and aids in the design of remedial measures by implementing them in the model and verifying their impact on safety.

6.4 Archaeological Investigation of Earthen Buildings

While condition survey, structural investigation, and modeling help us to understand an earthen building's condition and structural behavior, archaeological investigation can provide a wealth of information critical to supporting conservation decisions. This section describes the important role that archaeological investigation plays in the conservation of earthen buildings.

Given the relative paucity of historical sources, much of our understanding of historic earthen buildings, in the Arabian Peninsula at least, is derived from information obtained through archaeological investigations. Conservation of cultural heritage is rooted in the values attributed to it, which may be different in other parts of the world. Therefore, our ability to identify the value of cultural heritage depends on the degree to which the information we have relating to cultural heritage may be understood as credible or truthful. This, in turn, depends on the quality of the archaeological investigations, an essential part of the conservation and management cycles. The current state of understanding of a building or site informs the approach to conservation interventions, which result in further understanding and thus further conservation.

6.4.1 Archaeological Methodology and Recording

Archaeological investigations seek to identify and record the nature and extent of the available evidence. This evidence may include distinct archaeological layers, or "horizons," of activity; the ceramics and other finds across a site; written historical sources; maps; and archival photographs (figure 6.28). In earthen structures, important evidence often lies in the key stratigraphic

FIGURE 6.28. Louis Wilkes's aerial view of al-Jahilī fort from the north in the 1960s when the eastern enclosure (left) of the fort was used for helicopter landings. The photograph shows the buildings of the "administrative courtyard" (right) and the vehicle yard behind this, with the western (Sanaiya) ridge of Jebel Hafit in the distance. *Source:* Louis Wilkes.

relationships between different elements of the structure, which can reveal their relative chronology and the development of the building over time.

The evidence is then recorded and interpreted using a range of complementary processes and techniques that represent a holistic approach to understanding the past. A staged approach is often adopted for archaeological investigations involving desktop study, field survey, evaluation trenches and "opening-up works," excavation, and postexcavation analysis, followed by publication and presentation to the public.

There are choices of what and how to record, with four broad levels of recording depending on time and resources and the significance of the building or site. Level 1 is essentially a basic visual record. Level 2 is a descriptive record made under circumstances like those of level 1 but provides more information, such as the exterior and interior views, detailed descriptions, and photographs. Level 3 is an analytical record comprising a systematic account of the building's origins, development, and use. Level 4 provides a comprehensive analytical record and is appropriate for buildings of special importance (Lane 2016, 64)

In recent years, archaeological research has focused increasingly less on individual sites and buildings and more on wider cultural landscapes and the historic environment. A modern archaeological approach is based on three key complementary elements:

1. Methodology—that is, the techniques and processes of stratigraphic excavation and recording initially developed on large urban rescue projects in Europe from the 1970s onward
2. Advances in archaeological science and technology
3. Archaeological theory

Stratigraphic approaches to archaeology are based on the identification and recording of single events or actions—the so-called archaeological context—and lead to an understanding of the relative chronology of these events and their stratigraphic relationships over time.

Descriptions of the context are based on a standardized, consistent pro forma approach and on conventions that assist in the identification of the different phases of activity at a site or building. Recording the outline of individual contexts in a plan allows testing of stratigraphic relationships by overlaying the contexts to determine their sequence (Museum of London Archaeology Service 1994).

In recent years, advances in science and technology have revolutionized both the scale and scope of archaeological recording and investigations. Surveys and excavations now routinely make use of satellite and aerial imagery and employ a range of modern technologies including unmanned aerial vehicle (UAV) drones, 3D scanning, and digital photogrammetry, as described in chapter 5. Depending on the nature of the burial environment, non-invasive archaeological geophysical techniques such as GPR, resistivity, and magnetometry can be used to reveal the extent of buried structures. Additionally, as explained in the previous section of this chapter, thermal imaging can help identify features and decorations hidden behind later layers of plaster. Huge advances in understanding past landscapes have been made possible through the integration of environmental sciences into the multidisciplinary approaches of landscape archaeology and geoarchaeology. In the laboratory, the establishment of absolute dates to complement the relative chronology provided by stratigraphic excavation has been realized using radiocarbon dating techniques and optically stimulated luminescence (OSL). Meanwhile, advances in the study of DNA continue to transform our understanding of the past societies that created our cultural heritage.

6.4.2 The Importance of the Archaeological Approach

Archaeological research is driven by the desire to understand sites, buildings, and landscapes in the most complete manner possible. Thus, it is essential that our approach to recording or documenting earthen buildings must be an archaeological one. It is not just about what we find; but rather how this contributes to our understanding. At the outset of investigations, we need to ask ourselves how we know what we think we know (and how we can demonstrate having this understanding), then direct our focus toward finding out what we do not already know. Archaeology is the epitome of a work in progress, in which even a fragment of new information may transform our understanding of a particular site or period.

In recent years, building archaeology has become a specialized activity. The building archaeologist is often tasked with informing the conservation process, although the approach to recording standing buildings with "vertical stratigraphy" is no different from the approach to those parts of the archaeological sequence that are preserved only below ground. In both cases, understanding the upper layers or most recent actions is crucial to understanding what happened before. Interpretation of the development of sites and buildings is aided by identifying the different site formation processes at work and grouping them into episodes of construction, use, and disuse (figure 6.29). Taphonomy looks at how elements of the cultural landscape arrived at their current state and the processes that take place when they begin to decay or fossilize. The hermeneutic cycle, in which we understand the part by examining the whole and vice versa, underlines the importance of linking our understanding of individual buildings to wider typological approaches.

Archaeological theory has always been an important component of the search to explain the present by studying the past. The New Archaeology movement, which emerged after World War II, sought to establish objectivity based on exploring hypotheses through scientific methods and processes. This intellectual movement has since been challenged by influential post-processual thinkers who have argued for the acceptance of personal biases and agendas in every interpretation.

FIGURE 6.29. (a) Bin Ati al Darmaki Mosque (West), showing a series of superimposed mihrabs created by successive rebuilding of the mosque over time. (b) Excavations at Bin Ati in the Al Qattara oasis showed the stratigraphic sequence on the site. *Source:* DCT Abu Dhabi.

(A)

(B)

6.4.3 Archaeological Survey in Al Ain and Buraimi

From 2009 to 2024, archaeologists from DCT Abu Dhabi have been surveying and investigating earthen buildings and the wider historic oasis landscape of Al Ain, UAE, and Buraimi, Oman (Power and Sheehan 2012; Power et al. 2015; Sheehan et al. 2022; Sheehan et al. 2023). A variety of survey techniques have been used in the investigation of earthen buildings. Desktop research was followed by both intensive and extensive surveys employing different levels of recording. Analysis of satellite imagery and aerial photographs taken by the Royal Air Force in 1968 provided a wealth of archaeological data on these landscapes before the rapid urbanization of the past fifty years (figure 6.30). Comparison of these photographs with modern satellite images allowed us to establish the location of several "lost" buildings, including the historic Qasr Al Sudairi in Buraimi. At ground level, archival photographs of Al Jahili Fort taken before, during, and after its use by the Trucial Oman Scouts, a paramilitary force maintained by the British government from 1955 to 1971, revealed the form and condition of the original buildings and the modifications carried out during that period (Sheehan 2012).

At Buraimi, the initial desktop study of satellite and aerial images was followed by intensive fieldwork composed of high-resolution topographic surveys and targeted remote sensing using both GPR and magnetometry. It was supplemented by a program of gridded fieldwalking in which surface ceramic material was picked up systematically (Power and Sheehan 2011a). Historic earthen boundary walls in the oases of Al Ain were the subject of an extensive low-resolution survey and single-class assessment carried out by DCT Abu Dhabi in collaboration with students

FIGURE 6.30. Extract from Royal Air Force (RAF) aerial photography of Al Ain taken in 1968, showing the final form of Al Jahili Fort toward the end of its use by the Trucial Oman Scouts. Note the evidence of a number of earlier field walls that were still visible at that time to the southwest of the fort (north is at the bottom of the picture). *Source:* Sheehan (2012).

from Zayed University, Abu Dhabi. The Al Ain Oases Mapping Project (2013–17) documented the oasis landscape and identified surviving historic components (figure 6.31). Systematic documentation of the individual oasis plots was used to help develop a comprehensive conservation plan for the boundary walls (Sheehan et al. 2017).

Since 2007, several DCT projects carried out in Al Ain have focused on combining the rehabilitation and conservation of large historic earthen buildings with their adaptive reuse for cultural purposes. Written historical records for these buildings are relatively rare, so the archaeological investigation has been key to understanding the site context and development of the structures over time, as well as providing much of the subsequent educational and interpretive content. These projects began with the rehabilitation of Al Jahili Fort from 2007 to 2008. This fort was built by Sheikh Zayed the First at the end of the nineteenth century. In 2008, another major project was launched, this time to conserve Qasr Al Muwaiji, a fort built in the early twentieth century by Sheikh Khalifa bin Zayed bin Khalifa, son of Sheikh Zayed the First. From 1946 to 1966, it served as the *diwan* (seat of government) of Sheikh Zayed bin Sultan Al Nahyan (Power and Sheehan 2011b; El-Masri and Sheehan 2009; Sheehan 2012) (figure 6.32a).

In major conservation projects such as these, the role of the archaeologist includes establishing survey methodologies that will allow the compilation of drawn, photographic, and written records. These records will, in turn, allow stratigraphic analysis and the definition of historic phases through interpretive drawings. An initial consultation to establish aims, objectives, and research priorities is followed by the definition and prioritization of the sequence of archaeological works and the level of response. Later, the evaluation stage of the investigation is composed of visual inspection, nondestructive surveys, and selective interventions. The formulation of the project should quantify the number of interventions and the level of recording and ensure the integration of archaeological considerations into work specifications and schedules. During implementation, the focus shifts to recording newly exposed fabric, monitoring interventions to minimize impact, and maintaining the as-built records (Wood 1994).

Throughout the conservation process, the aim is to identify evidence of phasing and record key physical and stratigraphic relationships at the building or site. Evidence of architectural styles, surviving or modified plan elements, decorative schemes, fixtures, fittings, and other details help date the building or its various stages of evolution. Documentation and analysis are needed to adapt to new information and may change the scope or inform the next cycle. Once the works begin, the archaeological emphasis shifts toward maximizing the information gained during the window of opportunity opened by the works. This includes allowing recording during conservation, defining the limits of any impact on the historic fabric, and improving methodologies for recording.

The same general principles have been applied to selective investigations undertaken during limited emergency conservation at several other historic earthen buildings at Al Ain, including the Bin Biduwa House in Al Qattara Oasis and the Bin Hadi House in Hili Oasis (Sheehan et al. 2017) (figure 6.32b). The identification of archaeological horizons and key relationships proved to be a major source of information for understanding the development of these buildings. The baseline survey, desktop study, and visual inspection, followed by the careful location of test pits and opening-up works, formed the key interface between archaeology and conservation interventions, allowing us to facilitate repairs and increase our knowledge of the buildings.

FIGURE 6.31. This madbasa or date-press was revealed during excavations at the house of Rashid Al Dhaheri in the historic village of Khrays on the southern edge of Jimi Oasis in Al Ain. *Source:* Peter Sheehan.

(A)

(B)

FIGURE 6.32. (a) Qasr Al Muwaiji, evidence of multiple construction phases revealed by archaeological investigation. (b) Bin Hadi Field School. *Source:* DCT Abu Dhabi.

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EMERGENCY INTERVENTIONS, REPAIRS, AND SEISMIC RETROFITTING

7

Overleaf: **Structural repairs on a traditional timber roof photographed during an Emergency Interventions field exercise at the EAC22 course in Al Ain, United Arab Emirates. Source: J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.**

7

EMERGENCY INTERVENTIONS, REPAIRS, AND SEISMIC RETROFITTING

Christof Ziegert, Benjamin Marcus, Paulo B. Lourenço, and Aqeel Ahmed Aqeel

This chapter explores various types of conservation interventions for earthen buildings and provides illustrative case studies. In sections 7.1–7.3, Christof Ziegert and Benjamin Marcus describe emergency conservation measures for earthen buildings and various structural and nonstructural repair approaches, with several case studies from Al Ain. The repair and restoration of traditional roofing, explained by Aqeel Ahmed Aqeel in section 7.4, are also an integral part of the conservation of an earthen building. In section 7.5, Paulo B. Lourenço provides an overview of seismic retrofitting methodologies with a case study from Peru.

7.1 Emergency and Priority Conservation

7.1.1 Introduction

Emergency conservation involves a systematic approach to address structural issues that pose threats to human safety and the integrity of historical monuments. Initially, it involves identifying the need for interventions through investigations and assessments. Subsequently, these identified issues are prioritized to determine the most urgent interventions. Once priorities are established, various intervention options are evaluated.

The process then progresses to a safeguarding stage, where measures are taken to stabilize and protect the monument or structure from further deterioration. The goal of this work is to maintain the structure's stability for a certain duration or until comprehensive rehabilitation can be undertaken, thereby preserving the monument's historical authenticity and ensuring the safety of those in or around it.

Cycle planning is introduced in emergency conservation as a systematic approach for managing multiple sites. It begins with rapid assessments, followed by listing and grouping conservation tasks. Tasks are then prioritized, with detailed planning for time, personnel, and resources, concluding with implementation monitoring and evaluation.

7.1.2 Methodology

The goal of emergency conservation is to stabilize a building or group of buildings at risk of serious structural decay, to remove safety hazards, or to eliminate dangers to the monument itself. This begins with a structural assessment of the building or a group of buildings (figure 7.1). The goal of this assessment is to determine the level of threat from collapse and prioritize the necessary interventions. Interventions are prioritized by risk level according to the following scheme:

AA = Immediate measures necessary due to direct threat to publicly accessible areas

AB = Immediate measures necessary due to the lack of stability (building in danger of collapse) or irreversible structural changes without direct threat to public space

B = Safeguarding measures necessary to rule out any safety-relevant damage from occurring in the longer term

In the case of Al Ain, this emergency conservation work went hand in hand with a documentation survey and analysis of the site's context, history, significance, and so on—all conducted as part of the Al Ain World Heritage Site's management plan.

FIGURE 7.1. Structural assessment of a threatened earthen building with a serious crack directly on a public area, Al Ain, United Arab Emirates (UAE). *Source:* ZRS, Christof Ziegert.

7.1.3 Emergency Conservation Planning for Multiple Sites

Methods for emergency conservation seek to stabilize threatened earthen buildings using traditional vernacular construction techniques with modern conservation practices and should emphasize the retention of authenticity and minimal intervention. Treatments are intended to address immediate structural threats, including basal erosion, leaning walls, cracks, and deteriorated structural elements including lintels and roofing. While the primary response to these is typically shoring and support with scaffolding, minimal repairs—for example, to wall bases or cracks—must also be made using local earthen materials for interventions. Materials analysis, discussed by Henri Van Damme and Wilfredo Carazas in chapter 2, must be carried out to ensure the compatibility of the new earth with historic construction materials.

To effectively address numerous sites concurrently, such as in a ruined earthen village, we identify the conservation task itself as the program's central element rather than focusing on individual buildings or sites. This approach enables conservation teams to address recurring issues across multiple buildings—for example, supporting collapsing roofs, removing vegetation and debris, resolving immediate structural concerns, and supporting collapsed window and door lintels, among other challenges. This has led to the conservation cycle plan, which involves rapid site assessments followed by inventorying of tasks in a structured spreadsheet, prioritizing them based on importance. Tasks are integrated into the main cycle plan and scheduled considering site significance, urgency level, location, type, and anticipated challenges. Each task is assigned a unique ID for tracking. The cycle allows for flexibility to accommodate unplanned tasks, with four working teams operating concurrently and a spare team addressing unforeseen issues, thereby ensuring efficient conservation efforts.

Using this task-based methodology, it is necessary to assess priority (AA) conditions across multiple structures—for example, twenty-nine buildings in the first cycle of the Al Ain Emergency Conservation program, with a primary focus on identifying the hazardous conditions (Aqeel et al. 2016) (figure 7.2). It is advisable to work with a multidisciplinary team or at least with a specialized earthen construction engineer to pinpoint areas most susceptible to structural failure. Subsequently, recommendations for shoring or reinforcing these areas are proposed (figure 7.3). Simultaneously, conditions are identified that, although severe, do not pose an immediate human safety threat (AB) and can be addressed after (AA) conditions. Finally, works are planned that are considered more medium-term or long-term issues (B) once the buildings are stable.

With this defined list of conservation tasks across multiple buildings, the work force and materials can be divided into teams to address multiple sites simultaneously. In the case of Al Ain, these teams consisted of a conservation supervisor, a lead craftsman, and two to three assistants. This approach fosters a flexible and controlled program, allowing multiple conservation teams to transition seamlessly between tasks and sites. Consequently, parallel tasks can be completed within a condensed time frame. This approach emphasizes the most critical conditions among the list of sites, categorizing task types, providing specialized training for addressing specific

FIGURE 7.2. Examples of buildings addressed during emergency conservation works in the Al Ain World Heritage Site. *Source:* DCT Abu Dhabi.

FIGURE 7.3. A team carrying out emergency shoring and basal erosion repair. *Source:* Benjamin Marcus.

conditions, and effectively managing conservation resources such as scaffolding, tools, mud brick, and plaster.

7.1.4 Emergency Conservation Case Study: Abdullah Bin Salem Al Dhaheri House

As part of the emergency conservation program for the historic buildings in Al Ain undertaken by the DCT Conservation Department, temporary wooden frame supports were installed around Abdullah Bin Salem House in Al Qattara Oasis. This multistory tower house, thought to date from the seventeenth century, is located on the edge of a secondary road next to the oasis; because of this location, and as the main tower of the house was suffering from serious structural problems, the safety of pedestrians and nearby residences was at risk. The main structural problems were the separation of the corner joints of the tower walls, severe basal erosion and debris accumulated at the bottom of the tower putting pressure on the walls, and the absence of structural elements connecting the main walls of the tower (figure 7.4a). After analyzing the structural condition, it was recommended by structural engineering consultants to shore the main tower and other walls, repair the basal erosion to ensure that the walls did not subside further, and reestablish the connection of the upper walls of the tower (figure 7.4b).

The works began with the construction of timber shoring to support the walls during repair works. One of the main logistical challenges was closing the secondary road in front of the house, which was necessary as a safety measure and to secure some space for the shoring frames. It was agreed with the Al Ain municipality to close half the road, and safety signs were installed on the site for both vehicles and pedestrians.

Carried out by DCT's team of conservation craftsmen and supervised by the structural engineer, basal erosion and crack stitching repairs were completed in a minimal way that preserved the ruined appearance of the structure while strengthening it against further collapse (figure 7.4c). A system of reversible timber and steel tie beams was installed to provide structural connection to the upper walls instead of fully reconstructing the roof, which would have been conjectural. Finally, the timber shoring was removed, leaving the structure in a stable state while preserving its authenticity and ensuring the safety of the building and surrounding site.

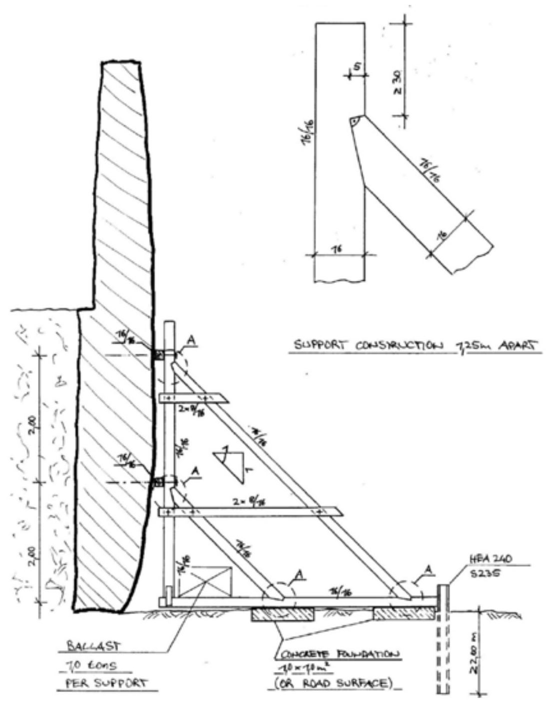
7.2 Repair of Earthen Sites

7.2.1 Introduction

This section will address structural and nonstructural repair techniques for earthen buildings. This includes interventions to damaged walls, the repair of the wall base, and specific techniques for repairing cracks and stabilizing the integrity of a building's overall structural system, including

FIGURE 7.4. Abdullah Bin Salem al Dhaheri House: (a) before intervention, (b) shoring design, and (c) following shoring and emergency stabilization works. *Source:* ZRS, Uwe Seiler.

(A)



(B)

(C)

grouting, stitching, wrapping, anchors and anchoring systems, ring beams, and shoring and buttresses. Methods for straightening inclined walls will also be described.

In section 7.3, case studies of the repair of earthen buildings are illustrated. While many of these techniques are universal, the examples shown here are based on work carried out in the region of the course.

7.2.2 Material Compatibility

In deciding the repair technique, it is important to consider certain factors for an effective conservation intervention. For example, heavily deteriorated masonry, except in archaeological contexts where it can be carefully repaired, where valuable wall paintings are present, or where the plaster is considered a significant feature, must often be removed and replaced. The conservation material used for repair/replacement should be adapted to the existing material and be slightly softer to ensure compatibility and prevent further damage to the original fabric.

Table 7.1 illustrates the often-diverging strength of historic materials versus those used in conservation. It shows that some earthen building materials—for example, those produced industrially for contemporary uses—do not have the right strength level for conservation works in earthen architectural heritage. It is worth noting that cementitious materials and steel are generally not recommended for these purposes.

Table 7.1. Strength of historic materials versus those used in conservation.

Compressive strength of	Modern Earthen Building Materials N/mm^2	Historical Earthen Building Materials [Empirical Values ZRS] N/mm^2
Rammed earth	2-4	1
Cob	1	0,6-1,3
Earth blocks (load bearing)	2-6	1,5-2,5
Light earth blocks	1-2	-
Earthen plaster mortar	1,5-4	0,5-1,5
Earthen mortar for masonry	1-4	1-2

7.2.3 Wall Repairs

The process of repairing structurally damaged walls requires the removal of any nonrecoverable original render and substrate to create a new section adhering new adobes and/or earthen mortars (figure 7.5a). To identify the material in good condition, the color of the straw can be a good indicator as well as the material consolidation. Mud bricks in good condition will usually have straw with yellow coloration and will not show erosion, while the straw in deteriorated adobes will have turned a dark-gray color and will disintegrate in contact with the hand. By carefully removing the damaged mud bricks—using some shoring when needed—the underlying sound material can be exposed and can provide a sound base for the process of reconstructing the wall. The replacement of the new mud bricks and mortar should be done carefully, working only in small sections of the walls of up to a meter in length.

The repair of damaged wall surfaces involves a step-by-step process. First, the deteriorated plaster or render is carefully removed (figure 7.5b). Any loose components are then swept away, and the surface is blown off to remove any remaining debris. For missing surfaces deeper than approximately 7 cm, earthen blocks are used to re-create missing parts of the wall. Earth plaster can then be added, with a maximum of 2 cm of depth for each layer.

Finally, the repair is completed with a finishing layer of earthen mortar, lime wash, or lime plaster, depending on the historical precedent (see chapter 8 for a complete overview of earthen plasters and finishes). Figure 7.6 illustrates these various phases, including the prepared historic material (rough surface), deep repairs (blocks), and an initial test of the new plaster layers.

(A)

(B)

FIGURE 7.5. Delaminated surface of an earthen building, Saxony, Germany (a). Section of wall showing sound surface after removal of delaminated surface. Note the yellow straw (b). Saxony, Germany. *Source:* ZRS, Christof Ziegert.

FIGURE 7.6. Muwaiji Fort, Al Ain, after removal of damaged plaster, preparation of the surface, and reintegration of losses. *Source:* ZRS, Christof Ziegert.

7.2.4 Foundation and Wall Base Repairs

Basal erosion, at the subsurface foundation level and at the base of the wall, is a common problem in earthen buildings that can lead to collapse. As described in chapter 6, the combination of rising damp, soluble salts, and pooling water can undermine the strength of the wall, causing basal erosion, slumping, leaning walls, and possible collapse.

The repair of eroded foundation or the base of the wall aims to fill the deteriorated area with new earthen material to restore the wall's structural integrity. To accomplish this, the repair must span both the foundation and the lower wall and often requires excavation to expose the eroded part underground level. These excavations and consequent repairs must be staggered, implemented meter by meter. In this scenario, only a meter of the wall base is excavated at a time and repaired with new mud bricks. The next meter of wall is left unrepaired to maintain structural stability, and the meter after that is repaired only after the first repair has dried (figure 7.7).

To ensure proper load transfer, the existing historical material upon which the repair bricks will be placed should be cut out in a rectangular shape, which gives the new mud bricks a sound base. For the best connection, the mud bricks should be properly bonded, with headers and stretchers in the different layers and the brick header (those placed perpendicular to the wall) inserted deeply into the wall. The bond with the best structural stability is the so-called cross bond, in which the stretcher layers are offset by half to the previous stretcher layer. The so-called English bond, in which the stretcher layers are on top of each other, has a higher risk of cracking (figure 7.8). The proper bond allows for a secure and stable connection between the new earth block masonry and the remaining wall base, providing the necessary structural integrity for long-term stability. If the repair is to a rammed-earth or cob wall, the bond of the repair masonry is less significant as there is less risk of cracking.

One must work with mud bricks of the same size as the original to repair masonry walls. It is not necessary that each mud brick be anchored deep into the historic masonry, so long as the repair is anchored into the wall at regular intervals. Ultimately, a compromise must be found between the necessity of interlocking the repaired section and the guiding principle of minimal intervention.

During this incremental replacement process, repaired sections should never be placed directly adjacent to a newly repaired section so that the load transfer and overall stability of the structure can be maintained. Staggering the sections helps distribute the stresses evenly and prevents any concentration of weakness in one area (figure 7.9). It is an important step to prevent undermining the structure and to ensure that the repaired base or wall remains structurally sound and capable of withstanding loads over time. Equally important is the techniques of execution, including proper cleaning and wetting of repaired areas (figure 7.10, 7.11). Depending on the geometric conditions, such as wall thickness and distance between the transverse walls, the wall to be repaired must also be supported laterally (figure 7.12, 7.13).

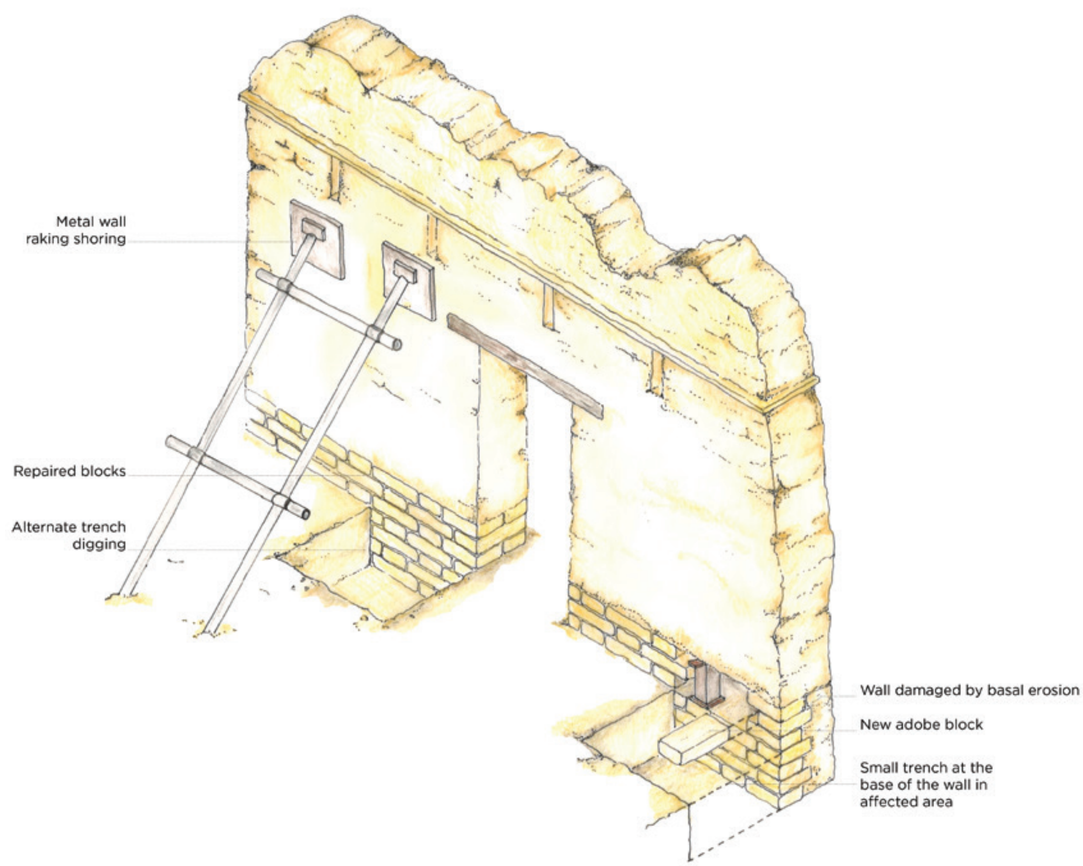
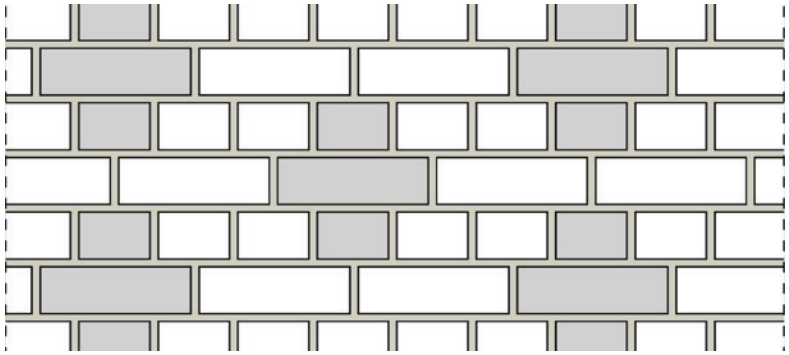
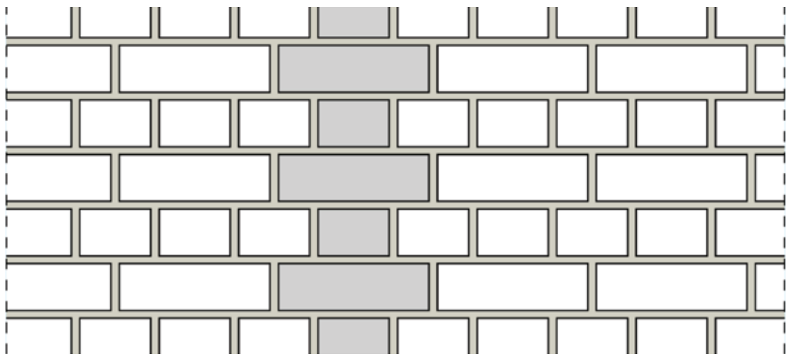


FIGURE 7.7. System of basal erosion repair, including shoring support, archaeological excavation in alternating trenches, and insertion of new mud bricks to reinstate the load-carrying capacity of the wall. *Source:* Alessandra Sprega for the J. Paul Getty Trust.



(A)



(B)

FIGURE 7.8. (a) So-called cross bond and (b) block or English bond. *Source:* Kalksandstein-Dienstleistung GmbH.

(A)

(B)

FIGURE 7.9. Al Muwaiji Fort, Al Ain, with stepped removal of damaged material (a). Al Jahili Fort courtyard wall, Al Ain, with area of eroded wall base removed at right angles and partial repair in place (b). *Source:* ZRS, Christof Ziegert.

FIGURE 7.10. Regularly incorporated interlocks, where headers are inserted in the existing earth block masonry. *Source:* ZRS, Christof Ziegert.

(A)

(B)

FIGURE 7.11. In addition to interlocking, (a) vigorous blowing off of the dust and (b) subsequent repeated gentle wetting are basic requirements for good bonding between the existing and supplementary masonry. *Source:* ZRS, Michelle Härder.

FIGURE 7.12. Small residential building in Germany in which the damaged plinth in the splash water area (up to 30 cm above ground level) was replaced with mud bricks. *Source:* ZRS, Christof Ziegert.

(A)

(B)

FIGURE 7.13. Muwaiji Fort, Al Ain, with replacement of the material over the entire cross section and installation of a horizontal moisture barrier. *Source:* ZRS, Christof Ziegert.

7.2.5 Crack Repairs

Repair of cracks is a crucial step for strengthening the structural system of an earthen building. This is accomplished through various means, including injection with grout and physical repair through stitching with various materials, such as mud bricks (figure 14), geomesh, wood, fiberglass rods, and many others.

Grouting generally involves injecting a fluidlike material into cracks or voids within structures to improve the strength of the wall. Such grouts typically include clay or local earth as the primary binder or fine aggregates like sand or crushed stone for added strength and may incorporate pozzolanic additives such as volcanic ash to enhance durability. While some grouts employ stronger additives such as hydraulic lime, a simple liquid earthen mortar is often sufficient to fill a crack and unify a wall, especially in buildings built primarily in mud brick.

However, it can be challenging to develop earthen mortar with minimal shrinkage. The consistency of the mortar used generally depends on the width of the crack being addressed, with wider crack widths requiring larger aggregates to reduce the potential for shrinkage.

Grouts can be applied to earthen walls either through a gravity system, in approximately 30 cm lifts, or through pressure grouting from below (figure 7.15). Each lift should be given sufficient drying time before the next injection of grout. In each case, the crack must be sealed from the outside with earthen mortar to prevent the loss of the liquid grout (figure 7.15). The choice of grout should be compatible with the specific earthen material used in construction. Regular maintenance and inspection of the cracks are also necessary. The term stitching means physically connecting two sides of a crack by inserting a material that spans the crack, rejoining the two parts of the wall. Cracks in earthen walls can be stitched with a variety of materials, including new earthen blocks, wood, or textured fiberglass rods (figure 7.16). In Al Ain, new

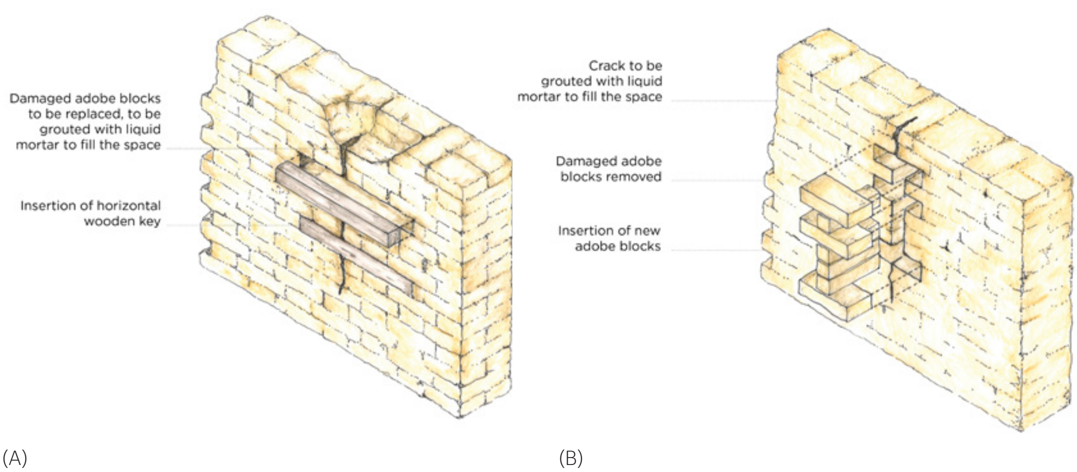


FIGURE 7.14. Examples of two stitching methods: (a) one using treated wooden beams inserted with earthen mortar and (b) the other using earth blocks to stitch the crack. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

FIGURE 7.15. Example of gravity-fed grouting of an earthen wall using an earthen grout with sand aggregate. *Source:* Benjamin Marcus.

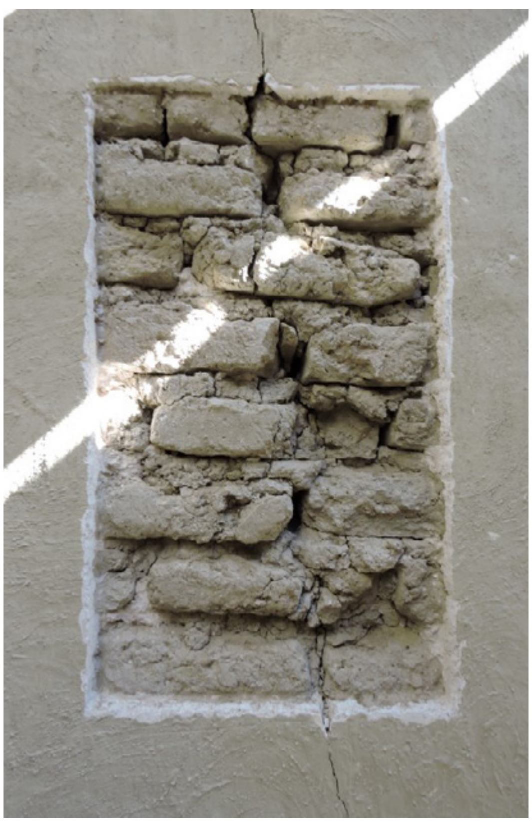


FIGURE 7.16. Stitching of cracked earth block masonry with earth blocks at the Murabb'a Fort Tower, Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

earthen blocks are generally used for stitching. In this case, the cracked earth blocks are to be replaced with a new, whole block. Following this, the crack is grouted with liquid mortar to fill the space.

In other contexts, such as in southern Morocco, where buildings are generally constructed in rammed earth, cracks are often stitched with timber elements. These wooden elements are made from a hard wood resistant to decay and insects and may be wrapped in fabric or formed into an "I" shape so that the stitch can hold both sides, because the cohesion between the wood and earthen building materials is often not sufficient.

Needling is another stitching technique that can be used to increase the connection between the two sides of a crack in an earthen wall. This involves cutting slits about 5 cm wide and 10 cm deep perpendicular to the crack banks and inserting fiberglass rods embedded in hydraulic lime mortar (figure 7.17). Fiberglass needles have a low thermal expansion coefficient and a low Young's modulus (how easily a material can stretch or deform), making them more compatible with earthen material than metallic rods such as stainless steel, for example.

Properly set into the wall with mortar, the needles provide additional reinforcement, helping to stabilize the structure and prevent further cracking. For corner cracks, a combination of needles with end anchors may be necessary. This is because the separated corner may not provide sufficient anchorage length for the needles alone. By combining fiberglass rods with a surface anchor, the structural integrity of the corner can be restored effectively. Needling is a mostly nonreversible intervention and should be used only if other options for strengthening are not possible or not appropriate.

FIGURE 7.17. Stitching of cracked earth block masonry with fiberglass bars (a). The arrangement of the needles should be staggered (b). *Source:* ZRS, Christof Ziegert.

7.2.6 Wrapping

In cases where grouting, stitching, and other crack repairs mentioned previously are not effective—for example, where the masonry is too weak for such an intervention but strengthening is still necessary—wrapping with anchored structural mesh can be an effective solution. This method is generally used for buildings where new plaster will be applied. By wrapping the affected area with a structural mesh, such as polypropylene, fiberglass, or basalt mesh, the structural integrity of the damaged section can be reinforced. Structurally effective steel nets are too stiff and create cracks in the plaster.

The mesh is anchored into sound masonry at two ends so that it binds the masonry tightly. Anchoring of the mesh can be done with steel bars and screws or bolts to fix the assembly in place. This technique provides an additional layer of support, helping to distribute forces and prevent movement. A mesh wrapping intervention was carried out at the southern gate of Muwaiji Fort, Al Ain, to stabilize the intersection of earth block masonries of different periods. The nineteenth-century masonry and a 1980s restoration were not well joined, and the mesh wrap ensured that the two masonry zones acted as one structural unit (figure 7.18). After the wrapping, the area was covered in earthen plaster.

Additionally, in some instances, horizontal reinforcement using geomesh can be employed to further enhance the strength of the structure (figure 7.19). This is useful, for example, for geometrically difficult additions to existing structures or to improve earthquake resistance, as explained later in this chapter.

FIGURE 7.18. A polypropylene geomesh wrap is anchored to an entrance at Muwaiji Fort, Al Ain, to strengthen the union of original nineteenth-century masonry and earth blocks added later during restorations in the twentieth century. *Source:* ZRS.

FIGURE 7.19. Horizontal reinforcement of the joints with geomesh strips. The positioning follows possible tensile stress orientations. The material is spread into the joint mortar. Protective masonry reinforcement at the White Temple in Uruk, 3500 BCE. *Source:* ZRS, Christof Ziegert.

7.2.7 Anchors and Anchoring Systems

In cases where walls require strengthened connection and higher tensile forces are expected, systems of anchoring may be necessary. This can involve re-creating the boxlike structural stability of a building through a series of long timber or metallic anchors fixed in place with a perpendicular end such as a wooden or metal plate. This system is often used to strengthen wall connections where the existing floor beams are not adequate to do so or when the floors or roofs have been lost and the structure will be stabilized as a ruin (figure 7.20).

7.2.8 Ring Beams

Ring beams are a structural reinforcement for the load-bearing system including the system of walls, roof beams, and roof elements that make up a building. Ring beams in earthen architecture are traditionally timber elements along the tops of walls that connect at the corners and provide support for the beams of the roof.

Often these traditional ring beams are rotten or eaten by termites and other insects and must be replaced. Because this is almost impossible when the ring beam is located between the floors of a multistory building, it can be replaced by narrower systems such as fiberglass rods and the remaining cavities are filled (figure 7.21).

FIGURE 7.20. Various examples of timber and metallic anchoring systems used to create or restore the connection between walls. *Source:* ZRS, Christof Ziegert.

FIGURE 7.21. A ring beam in fiberglass to be filled in with lime mortar. Old Palace, Doha, Qatar. *Source:* ZRS, Christof Ziegert.

In more modern times, many earthen buildings have been altered with concrete ring beams, which are heavy and brittle and do not perform well in seismic conditions. Timber is often used as a replacement for concrete ring beams. Timber ring beams play a critical role in distributing the load from the roof, upper floors, or other loads down to the supporting walls. They also help resist horizontal forces like wind or seismic forces, adding lateral stability to the structure. Timber beams are securely attached to the top of the supporting walls, often through bolting, notching, or using specialized connectors to ensure a strong connection.

7.2.9 Shoring and Buttresses

For structural interventions, stabilization of the building system via external or internal shoring is a high priority. This provides temporary protection from further damage or collapse while the building is undergoing repairs. Shoring materials can range from simple wooden single-beam supports (figure 7.22) to more sophisticated systems made from steel or wood (figure 7.23). Buttresses are often added as a permanent structural solution for walls that lack lateral stability and support or are in seismic zones and are vulnerable to collapse during a seismic event. Buttresses significantly change the visual appearance of a structure, so they must be carefully considered as a modern solution for permanent structural support (figure 7.24).

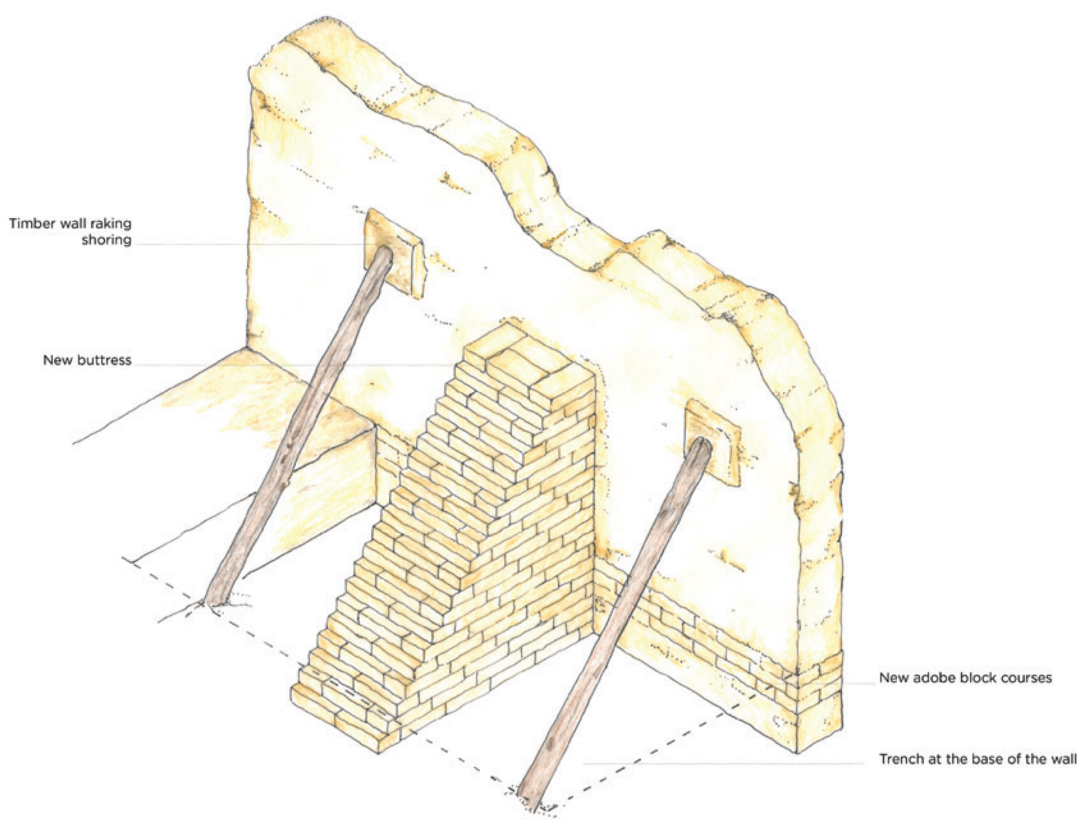


FIGURE 7.22. Diagram showing the application of a buttress as a permanent supporting measure for a leaning wall. New buttresses may be distinguished from the historic material by a separation layer such as geotextile. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

FIGURE 7.23. Timber system for an unstable earthen wall in Germany. *Source:* ZRS, Christof Ziegert.

FIGURE 7.24. Historic mud-brick masonry buttresses at the North-West-Tower of the Muwaiji Fort, Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

7.3 Case Studies of the Repair of Earthen Buildings from the Al Ain World Heritage Site

7.3.1 Bin Biduwa House

Bin Biduwa is significant as one of the largest fortified houses in the Al Ain World Heritage Site. The now roofless building dates to the seventeenth century based on its architecture and pottery record. The aim for Bin Biduwa House was to conserve the building as a ruin and to ensure that the building could stand safely without external support. This would allow visitors to explore the site without life safety risks.

The building had long suffered from rising damp and basal erosion due to active irrigation around its foundation. Once the irrigation was stopped, archaeological investigation confirmed the age and construction chronology of the structure as well as revealed deep basal erosion that affected both sides of the foundation (figure 7.25), severely reducing the wall profile and the structural stability of the massive walls.

To restore the building, a system of temporary steel shoring was installed to vertically support the door openings while work progressed on the foundations. The masonry cross section of the lower wall was restored by filling in adobe. While more resistant materials such as natural stone for the foundation and a horizontal moisture barrier were considered, it was decided to employ the traditional materials and construction techniques of the Al Ain region, which did not historically have stone in foundations, instead using mud-brick foundations.

In some areas, reconstruction of lost components was carried out to structurally support the remaining original components. This measure had to meet the condition that historical geometry could be achieved again without conjecture, based on historical photos and archaeological evidence of the foundations. The added components were finished with a smoother earthen plaster to be differentiated from the original components (figure 7.26a and b).

One notable example of the reconstructed components was the main old gate. The gate had partially collapsed, and the adjacent walls suffered from some structural instability. An approximately 20 m^2 section of wall, which had to be supported by shoring due to its extreme inclination, was straightened gradually in one day (figure 7.26c and d). The special challenge here was that the wall needed to be pressed up evenly over the entire surface to prevent it from breaking into several pieces. Once straightened, the walls were reconnected with new mud brick and earthen grout to rejoin the wall to the larger structure.

Prior to this, a variant analysis was carried out in which the option of securing the wall in its inclined position with buttresses was also considered, but this would have entailed the construction of a nonhistoric element that would have disrupted the original plan of the structure.

FIGURE 7.25. Bin Biduwa House in its former state, close to collapse. Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

(A)

(B)

(C)

(D)

FIGURE 7.26. (a) Stages of repair and (b) in the safe stage, able to stay without support and without hazard for the visitors. (c) Straightening of a wall section of 20 m^2. (d) pushing the wall back into alignment using shoring, jacks and counterweights. Bin Biduwa House, Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

The building, now safe for visitation, functions as an open-air ruin, and its courtyard is used for community activities related to traditional building and the nearby historic *souq*, such as making the traditional palm-leaf roofing building material known as *arish* or basket making.

7.3.2 Murabb'a Fort Tower

The main structure of the Murabb'a Fort, in the city center of Al Ain, is its tower. Built of earthen blocks, the tower is one of the few three-story earthen block buildings in the UAE (figure 7.27a). The tower has historic value as the first police station in the region. The building is to be made accessible to the public again. For this, stability needed to be reestablished, and an appropriate level of safety needed to be achieved.

A part from the stabilization of the north wall, it was urgently required to strengthen the staircase column to prevent a collapse (figure 7.27b and c). The following options were considered:

- dismantling and rebuilding the pillar
- anchoring
- strengthening by means of wrapping
- strengthening by means of stitching/needling with fiberglass rods

The needling option was chosen, as it was the least destructive choice and maintained the authenticity of the historic elements while preserving historically significant fabric (figure 7.27d).

For needles to be laid transversely and diagonally, access channels were drilled out. The mortar, prepared in a liquid state, was filled in the access channels to flow in by gravity prior to the insertion of the needles. Once inserted, each fiberglass stitch was mortared in place and covered with earthen plaster (figure 7.28).

The intervention was successful. Regular monitoring has shown that several years after the intervention, the cracks have not reopened, and no new cracks have appeared. Meanwhile, the east, north, and west facades are reconnected to the outer and inner cross walls by stitching/needling, ensuring structural stability of the wall connections and the integrity of the overall structure.

7.3.3 Al Qattara Souq

Al Qattara Souq and Al Qattara Arts Center are the cultural heart of the Al Qattara Oasis in the northern part of Al Ain, frequented by the local community and visitors. Some of the DCT staff also have their offices in the authentic earthen section of Al Qattara Arts Center. Al Qattara Arts Center also hosted the International Course on the Conservation of Earthen Architecture organized by the Getty Conservation Institute (GCI) and DCT and attended by students from the Middle East, North Africa, and South Asia (see figure 7.29).

(A)

(B)

FIGURE 7.27. (a) Murabb'a Fort Tower, Al Ain. (b and c) Structural cracking was prevalent throughout the building, risking potential collapse. (d) View of Murabb'a Fort exterior showing structural interventions before being replastered. *Source:* ZRS.

(C)

(D)

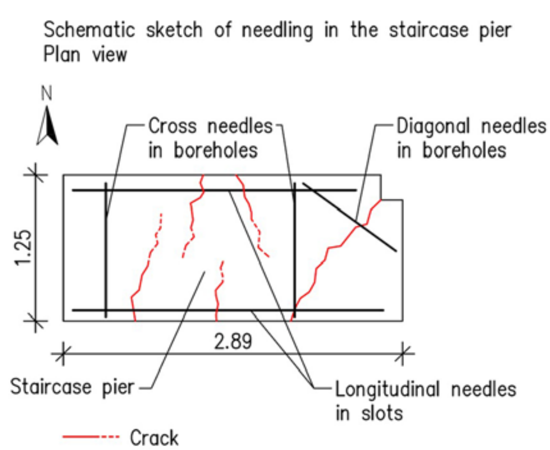


FIGURE 7.28. Insertion of fiberglass needles across critical cracks. *Source:* ZRS, Christof Ziegert.

In 2018, without any external influences, settlement and cracks were noticed on a column between the shop windows, and a shell of earth block masonry fell into the interior of one of the shops. The building investigation showed that there were wooden lintels over a former window opening from an earlier construction phase and that these beams had been completely undermined by termite infestation and had lost their structural integrity (figure 7.30).

As a result, compression had occurred at the height of the beams, which led to the settlement of the upper section of the column and the roof, as well as the formation of cracks in the adjacent transversal wall. The wall was significantly weakened and, because of its function as a central load-bearing pillar, required careful structural intervention to strengthen it and support the weight of the wall and roof above.

To preserve and present the wall section of the earlier building phase and especially the wooden lintels as comprehensively as possible, the following strategies were studied:

- replacing the wooden beam layer in combination with strengthening the masonry
- stabilizing the remains of the wooden beam layer by injection and strengthening the masonry
- installing a wooden frame for the load-bearing function and minimally stabilizing the masonry
- installing a metal frame for the load-bearing function and minimally stabilizing the masonry

The last of these options, which was able to structurally support the load and resist termite damage, was chosen and successfully implemented (figure 7.31). Visitors can now experience the different building phases of the building at this point, and its stability has been reestablished.

(A) (B)

FIGURE 7.29. (a) Al Qattara Souq and (b) Al Qattara Arts Center. Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

FIGURE 7.30. Collapsed masonry because of a flattened damaged lintel. Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

FIGURE 7.31. The slimline frame integrated for support blends in visually with the doorframe system. Al Ain, UAE. *Source:* ZRS, Christof Ziegert.

7.4 Maintenance of Traditional Roofing

7.4.1 Traditional Roofing in Regional Vernacular Buildings

Of all the parts of an earthen building, the roof is perhaps the most crucial because it needs to insulate the building from the extreme heat of desert environments and ensure that the interiors are dry during seasonal torrential downpours. A roof also responds to structural challenges such as how to span a room while resisting the force of gravity or how to resist the forces of winds or seismic movements.

The roofing system is an essential aspect of the vernacular character of traditional buildings, particularly in the Al Ain region, where the following examples originate. Such roofs not only reflected a full understanding and appreciation of the impacts of the environment on the buildings but also addressed their functions in a highly efficient, economic, and beautiful manner.

Since the Bronze Age (circa 3000 BCE), the ubiquitous construction materials for roofing in desert areas of the region have been earth and palm trees. And so, naturally, most of the vernacular buildings in the seven oases of Al Ain were historically built of mud-brick masonry and mud mortar and made use of the palm tree trunk, the palm fronds or branches, and the palm leaves to construct the roofs (figure 7.32).

Traditional roofing systems constructed of palm tree trunks usually lasted around twenty-five to thirty years, with a subsequent partial or complete replacement needed. Several factors

FIGURE 7.32. Stored roofing materials, including woven mats and palm trunks. *Source:* DCT Abu Dhabi.

contribute to their failure. Although precipitation is infrequent in the region, the occasional monsoon rains can dramatically affect the performance of these roofs. Most widespread damage comes from termite infestation of the wooden elements. This can be quite dangerous, as the roof may appear sound visually, but the beams are in fact entirely compromised. In the past two decades, a nylon membrane has often been placed on top of the palm fronds and below the top mud layer. While nylon may prevent water infiltration, over time it loses its plastic qualities, dries out, and eventually tears. This impacts moisture penetration and consequently speeds up deterioration of the entire roofing system, which can result in collapse.

7.4.2 Traditional Roof Construction

The palm-beam construction method has been found to be generally similar throughout the Al Ain and Oman regions and perhaps much of the Arabian Peninsula, and conservation methods follow this historical precedent. In the layering of materials that form traditional roofs, first are the beams, which are cut from palm tree trunks and make up the structural support for the roof (figure 7.33). The root segment (lower 20–30 cm of the trunk), which is completely dry and unusable, is removed from the tree. The leafy top part, where dates grow, is too soft, so it is also removed.

Beams are made by quartering the round tree trunk. Once dried and treated (figure 7.34), these quartered beams are placed on top of the load-bearing wall with at least 25 cm overlap

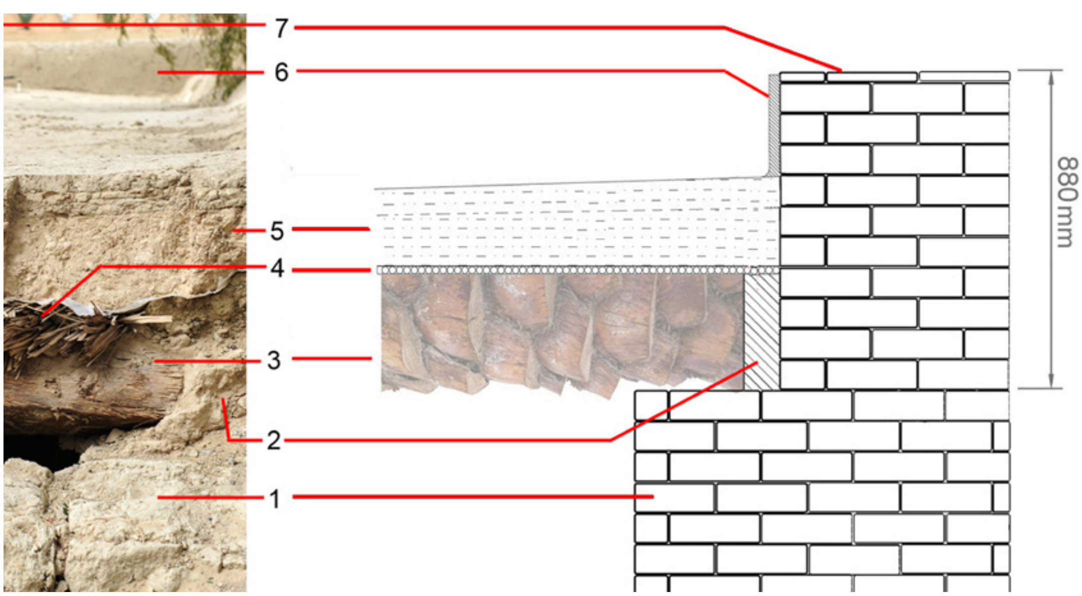


FIGURE 7.33. The anatomy of a traditional roof: (1) load-bearing wall, (2) filled area, (3) palm beam, (4) palm frond (+ nylon), (5) sloping mud layer, (6) plaster, (7) parapet wall. *Source:* Aqeel Ahmed Aqeel, DCT Abu Dhabi.

(figure 7.35). The beams are laid alongside each other, about 25–30 cm apart and in opposite directions to counterbalance the strong and weak points of the trunk and evenly distribute the weight of the roof. The beams' ends are generally encased by the masonry (figure 7.36), which continues about three mud-brick courses (50–80 cm) above the level of the beams.

The second layer in the roofing system insulates and waterproofs the structure. It can be made of either palm fronds or tightly woven mats of palm leaves. Mats woven with palm leaves have greater strength than fronds even though they are much thinner.

Mud is the final top layer of the roofing system. The mud layer reaches up to 20 cm in thickness, has a smooth finish, and is sloped to facilitate drainage through waterspouts carved from palm tree trunks. The waterspouts are in openings along the parapet. They are traditionally spaced to evacuate water efficiently while enhancing the aesthetics of the facade and project far enough to evacuate rainwater away from the base of the mud wall.

In some regions, a final layer of harder render—for example, lime or mud with organic additives such as soap—is added to create more waterproof protection. In the Al Ain region, *sarooj*, a fired clay-based mixture with water-resistant properties, is often used to cover drainage areas and spouts. *Sarooj* is made of natural clay and organic materials such as straw or animal dung. The clay is mixed with water to form cakes, which are then dried and burned over a long period using palm wood as fuel. Following the burning process, the cakes are ground to a powder that

FIGURE 7.34. Traditional method of preparing palm beams at the DCT workshop: palm trunks are usually sourced from old trees, dried over a period of three to six months, cut down to size, and stored until needed. *Source:* DCT Abu Dhabi.

FIGURE 7.35. A closer look at the layers of the roof at Al Jahili Fort before restoration: after removing the layer of mud and palm branches, the beams were exposed. The rectangular opening leading to the water spout can be seen in the background. *Source:* Aqeel Ahmed Aqeel, DCT Abu Dhabi.

FIGURE 7.36. Looking up at the ceiling in Al Jahili Fort, showing the palm beams from the interior. *Source:* Aqeel Ahmed Aqeel, DCT Abu Dhabi.

is then mixed with water, beaten, and applied by hand to form a hard, water-resistant surface on masonry.

Understanding which tree species is best to use and how best to treat it, dry it, or store it enhances the effectiveness of the repair while respecting the authenticity of the traditional method. One of the workshops set up in Al Ain ensures the production of palm beams for roof restoration and repairs. All the stages of production, from sourcing the palm tree, to cutting and preparing, to storing and treating, follow the traditional method but are technically monitored, tested, and analyzed by the Department of Conservation to guarantee the quality of the wooden materials.

Systematic monitoring of building conditions and regular maintenance are essential to curb the deterioration of wooden elements and ensure the structural integrity of the vernacular buildings of the Emirate. Monitoring should involve not only identifying decayed elements that need to be replaced but also understanding the reasons for their deterioration and mitigating them.

7.4.3 Restoration and Maintenance of Traditional Roofs

All buildings, whether contemporary or historic, deteriorate with the passage of time. Deterioration factors include the impact of climate and geography; the effects of human intervention in constructing, using, and transforming the building; and the natural behavior and weathering of building materials over time. Slowing down the deterioration of buildings depends on regular maintenance and appropriate interventions that are compatible with the properties of the materials being repaired and that respect traditional methods (figure 7.37a).

Different building materials decay at different rates. Wood, for example, deteriorates more rapidly than brick, stone, or mortar. In traditional buildings of the Emirate of Abu Dhabi, palm, teak, and mangrove were used to make doors, windows, and roof beams; in Al Ain, palm was particularly prevalent, despite its lack of long-term durability. Causes for the deterioration of wooden elements can be split into two categories: natural and nonnatural.

Palm beams can provide sound structural support for a roof for around twenty-five to thirty years and up to forty years if the wood was treated against termites prior to construction. This natural "life span" depends on the type of palm species, where the trees were grown, and how the beams were prepared. In historic buildings of the region, particularly Oman, palm beams can be hundreds of years old; however, often they have lost their primary structural role.

There are also many environmental factors that affect the beams' rate of deterioration. Hazards such as earthquakes, floods, and severe storms can affect the structural soundness of beams and destroy historic buildings. Termites are the primary cause of the deterioration of wooden elements in the traditional buildings of the region. They thrive in dark and humid environments such as wooden beams, and their effects can be quite dangerous, as a perfectly healthy-looking beam could be destroyed within (figure 7.37b).

The degree of infestation is a function of the site environment, the type of wood substrate, and the size of the nests and their location with regard to the building. Not only can termite nests be unsightly to the appearance of the building, but the burrowing nature of these insects can rapidly affect the structural integrity of the infested elements, with the risk of losing original and historical fabric. Termite infestation must be professionally assessed, including the extent of the infestation and degree of damage, identification of termite species and wood species, and proposed solutions that are compatible with conservation aims and methodology.

An environmentally friendly solution is an important criterion; therefore, a range of solutions were tested in Al Ain, from chemical pretreatments of replacement beams through trenching and pesticide injection to noninvasive solutions such as laying termite baiting stations along the perimeter of the building. A termite baiting station is a system with containers buried in the ground around a property and filled with wooden bait that contains a pesticide or growth inhibitor. Termites find and feed on this bait, taking it back to their colony and gradually reducing their population, leading to termite control. Regular inspections and bait replenishment are essential for long-term effectiveness.

(A) (B)

FIGURE 7.37. (a) A building without its roof: the round cavities in the walls of Bin Jaber House used to hold the roof beams. The absence of a roof led to the deterioration of the mud-brick walls. *Source:* A. Malekabbasi, DCT Abu Dhabi. (b) Severe termite infestation caused the beam above the door in Bin Hilal Fort to sag. *Source:* DCT Abu Dhabi.

1

2

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5

6

FIGURE 7.38. Prior to installation in a building, the wooden elements are chemically treated to prevent termite infestation: they are first soaked in a chemical bath for a day and then dried for about three weeks depending on climatic and environmental conditions. *Source:* DCT Abu Dhabi.

Chemical pretreatment of beams includes borate-based treatments such as disodium octaborate tetrahydrate, and these are commonly used to protect wood against termites. These chemicals are effective at deterring termite infestations and can be applied as sprays or absorbed into the wood via a soaking tub (see beam treatment process, figure 7.38). In all cases, a monitoring regime is necessary to check the effectiveness of the implemented methods.

Inappropriate past interventions can also affect the life span of a roof. Traditionally, roofs were seasonally maintained by applying a fresh layer of mud on top of the previous one; over time, the accumulation of mud often makes the roof too heavy for the beams to support it any longer, resulting in partial or full collapse; sometimes, however, the effects can be imperceptible to the eye, with beams only exhibiting fine cracks and gentle sagging. These conditions need to be inspected regularly to ensure that the structure remains safe.

7.5 Seismic Retrofitting of Earthen Buildings: Methods and Case Studies

The complexity of seismically retrofitting earthen buildings requires careful planning and preparation. This section will discuss the special requirements of seismic retrofitting interventions. Any decision made regarding intervention on a building must be based on knowledge of the building's materials and construction systems, as well as on the understanding of its structural behavior. Bearing in mind that interventions on existing buildings may affect their equilibrium and are likely to involve high costs and a considerable amount of disturbance to users, the intervention must be as minimal as possible to achieve the established objectives. The causes of the damage should be addressed, not the symptoms. Finally, the materials used must respect the principle of compatibility (chemical, physical, and mechanical) with the existing materials to ensure adequate performance and durability.

For this chapter, we have organized the sections based on the objectives of avoiding in-plane failure (the general improvement of the structural behavior) and avoiding out-of-plane failure during a seismic event.

To significantly enhance the postelastic, in-plane performance of a wall, ensuring in-plane continuity along its length is crucial. When cracked wall sections are held together by continuity elements, large amounts of energy can be dissipated within the walls. These elements allow sections to move and dissipate energy through friction while preventing the wall from deteriorating. Adding in-plane continuity elements can greatly improve the ultimate capacity of shear walls.

The most critical aspect of retrofit design is controlling out-of-plane wall displacements. This is because out-of-plane collapse, or overturning, is a costly, catastrophic, and life-threatening failure. In order to avoid that, an improved overall behavior of the building needs to be achieved using techniques to improve connections between structural elements and walls.

7.5.1 Avoiding In-Plane Failure Mechanisms

7.5.1.1 Wall Strengthening

Walls play a key role in the structural response of earthen buildings to earthquakes. Typical repair methods include those discussed in the previous section, such as crack repair, basal erosion repair, and local reconstruction.

Experimental results by Tolles and Krawinkler (1990) demonstrated that walls with in-plane continuity outperformed those with twice the "shear area" but without this feature. Center-core rods have been provided in the past to improve the performance of shear walls by raising the damage threshold level, reducing cracking during extended shaking, and increasing the ductility of the structural element. However, the implementation of this technique has proven to be quite invasive and damaging to the original material.

If a wall is heavily damaged or if its seismic-resistant characteristics need significant improvement and its plaster is not significant and can be removed, the application of a reinforced render on one or both sides of the wall is an effective solution that has been tested against even strong earthquakes. The new reinforced render can be applied locally or over the entire surface. This solution involves relatively high costs, affects the material authenticity, and must be carefully considered.

The process begins with removal of the existing render, followed by application of a first layer of earth-based plaster. A reinforcement mesh is then positioned and anchored using mechanically tightened connectors (rods inserted in previously drilled holes). After ensuring that the connection between the mesh and the connectors is secure, a second layer of render is applied (figure 7.39). Compatible solutions on the market include meshes of fiber-reinforced polymer (FRP) and prestressed polymer grids. The reinforced render technique usually needs to be combined with interventions in the floor and roof structures to improve the overall behavior of the structure.

7.5.1.2 Strengthening of Foundations

The need to consolidate and strengthen the foundations of a structure may arise for several reasons. A building's rehabilitation or change of use may place additional loads on the foundation. Any change to the condition of the soil underneath—due to soil erosion or change in the water table level, for example—can undermine the foundation, or the foundation itself may deteriorate. It is possible to improve the ground, such as by injection, or to improve the capacity of the foundation, such as by using piles or micropiles.

A simple intervention is to consolidate the foundation base in a traditional manner, which involves enlarging the foundation and/or increasing its depth (figure 7.40). These operations usually imply partial shoring and partial load transfer, opening successive trenches by section, and filling them with masonry.

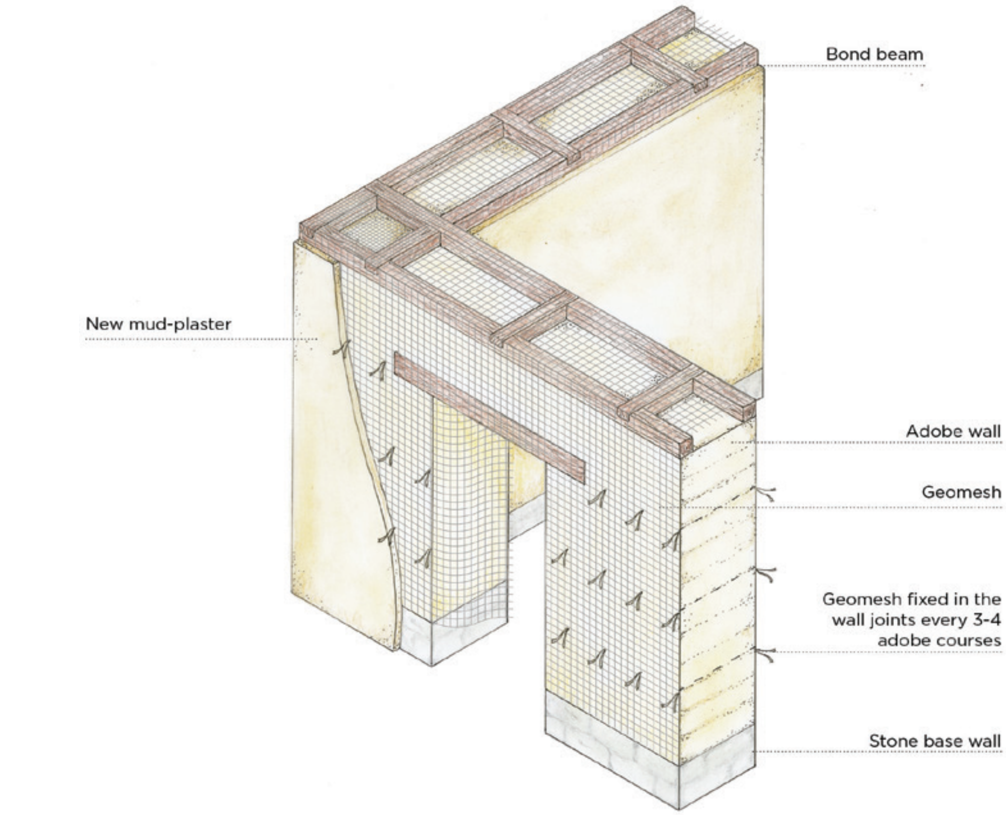


FIGURE 7.39. A wall reinforced with render and the insertion of a geomesh. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

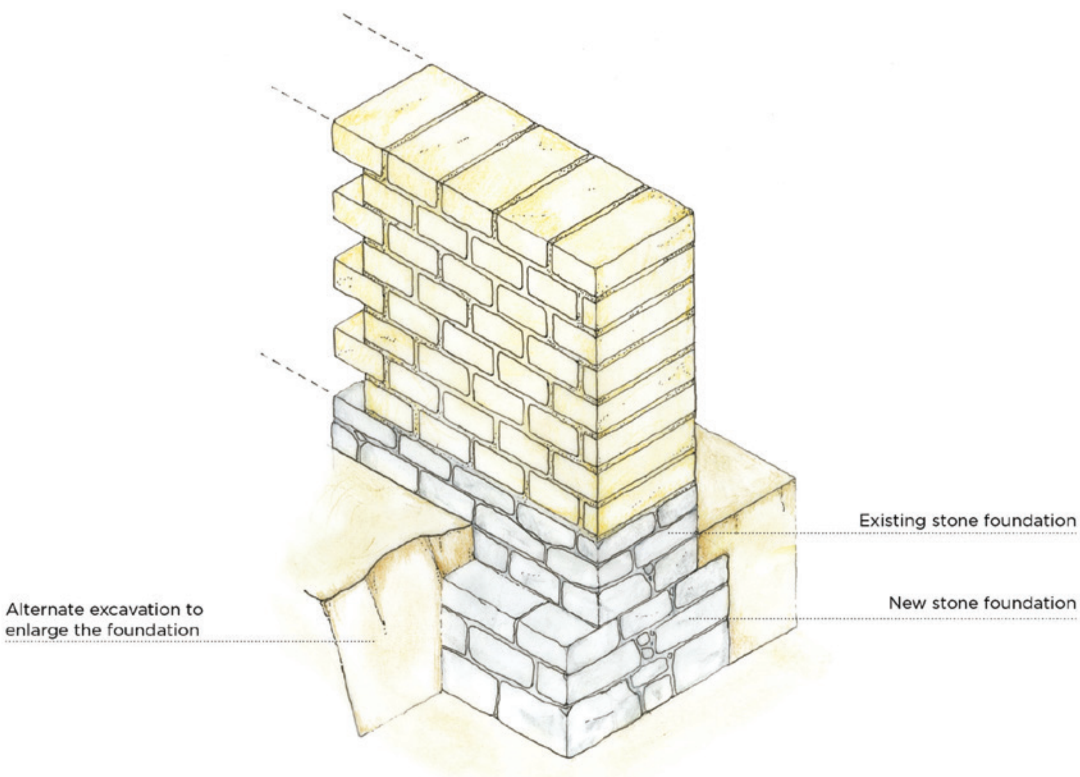


FIGURE 7.40. A traditional intervention of consolidating a foundation base through enlargement and increase of depth. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

7.5.1.3 Timber Element Repair

Timber elements play a fundamental role in the structural behavior of earthen buildings. Wooden lintels, for example, are important elements that stop cracking propagation. Reasons for intervention of wooden elements may include wood deterioration or adaptation of the building to a new use (such as that of higher loads). The two main types of interventions in wooden structural elements are reconstitution of the original sections and strengthening of the timber by adding new material.

Partial replacement or reconstitution of the timber sections may be carried out by removing the damaged area—for example, a floor-beam support—and replacing it with new material joined to the historic element (figure 7.41). This is especially carried out when the historic wooden element is considered historically significant. Alternatively, new wooden (or metal) elements may be placed on either side of the existing beam without removing it, followed by the addition of transverse connectors. Another possibility is to reconstitute the affected areas with injection or application of epoxy resin. Bonding is achieved by mixing wood with resin and improving adhesion by incorporating steel or FRP dowels.

In situations where the timber elements have insufficient strength or stiffness or where inadequate bracing is found, the structure can be strengthened by adding new materials in the connections, in the elements themselves, or in the structural system. These materials are typically plates or profiles in stainless steel (figure 7.42). Metal cables can be added to increase the stiffness of wooden elements, or new timber elements may be added to the structure for bracing.

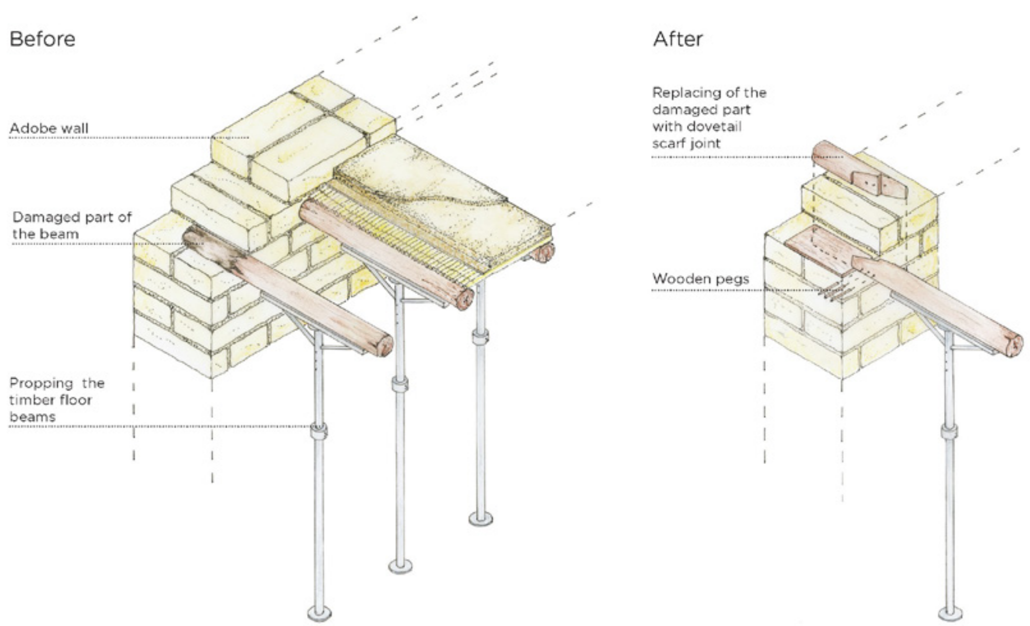


FIGURE 7.41. Repair of a support beam of a floor, before and after intervention. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

7.5.2 Improving the Overall Behavior of the Building

To take full advantage of the strength and energy dissipation capacity of earthen structures in the event of an earthquake, it is necessary to ensure a structure's integral behavior as a unit and to prevent out-of-plane movement of its walls. This is often referred to as "box behavior." The installation of ties (subjected to tension) and struts (subjected to compression) allows the connection of walls between opposite facades. Usually placed under the floor or at roof level, these ties are typically made of timber (figure 7.43).

One factor most affecting the seismic response of a building is the efficiency of the connections between the horizontal diaphragms (floors and roofs) and the walls, as well as the stiffness of those diaphragms. The adoption of heavy reinforced concrete floors may require strengthening of the foundations. Because of the resulting large mass of the floors and the difficulty in ensuring proper connections, this method may yield poor behavior in the event of an earthquake. If the original timber floors are maintained, the connections between the floors and walls should be improved. The diaphragms can be strengthened using timber, for example, with new boards orthogonally placed over the existing ones or with the placement of additional wooden beams or steel profiles, forming a truss (figure 7.44).

The attachment of a wall to an upper-wall element or roof system using compatible materials is critical to the design. A stiff upper-wall element (such as a concrete bond beam) may transfer a very large portion of the lateral load into the transverse walls, thus overloading these walls and causing in-plane shear damage that would be difficult to repair.

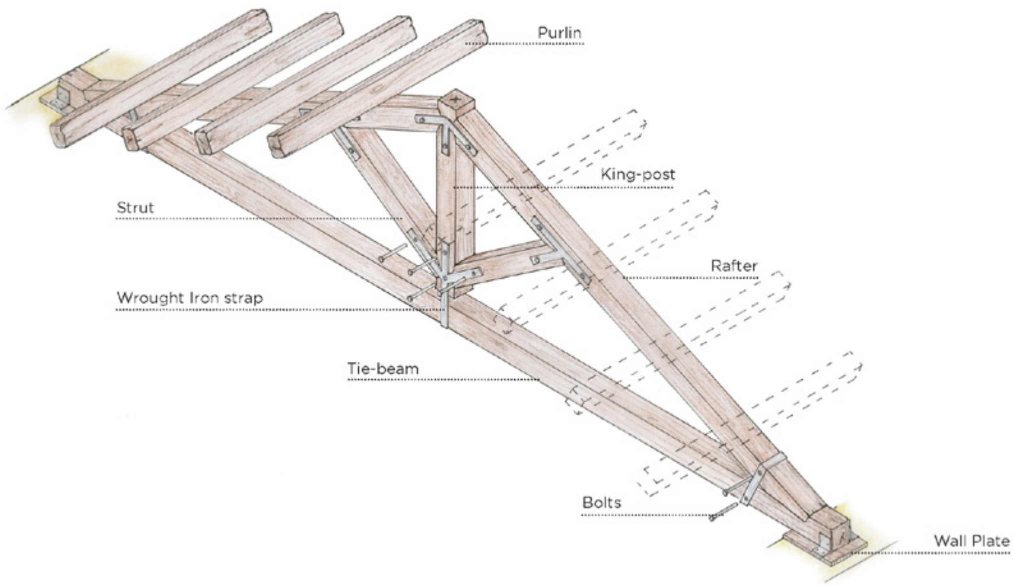
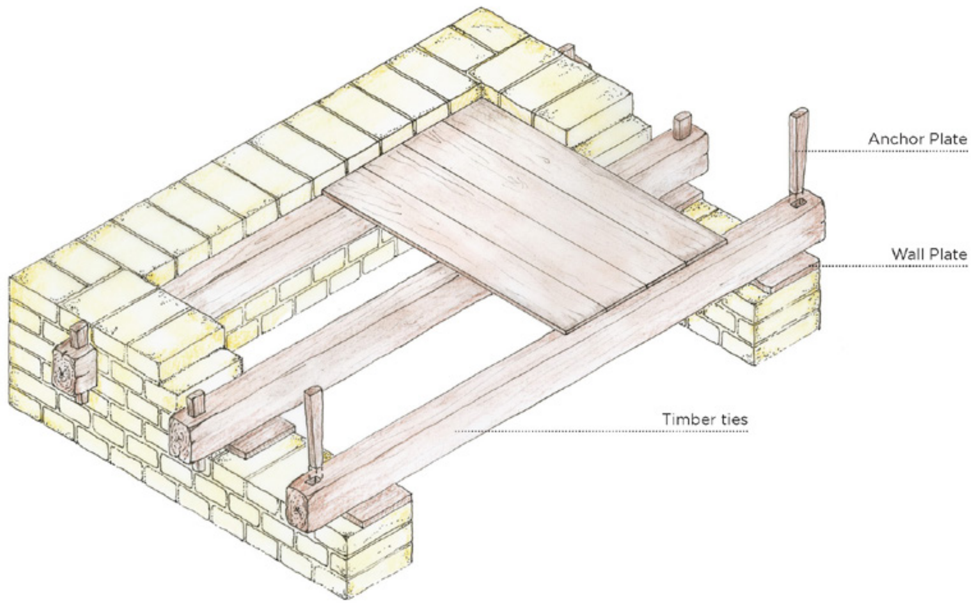


FIGURE 7.42. Strengthening of a timber truss and timber joints with plates or profiles in stainless steel. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

FIGURE 7.43. Timber ties installed through beams protruding from the masonry and anchored to the wall by a wooden anchor plate. *Source:* Alessandra Sprega for the J. Paul Getty Trust.



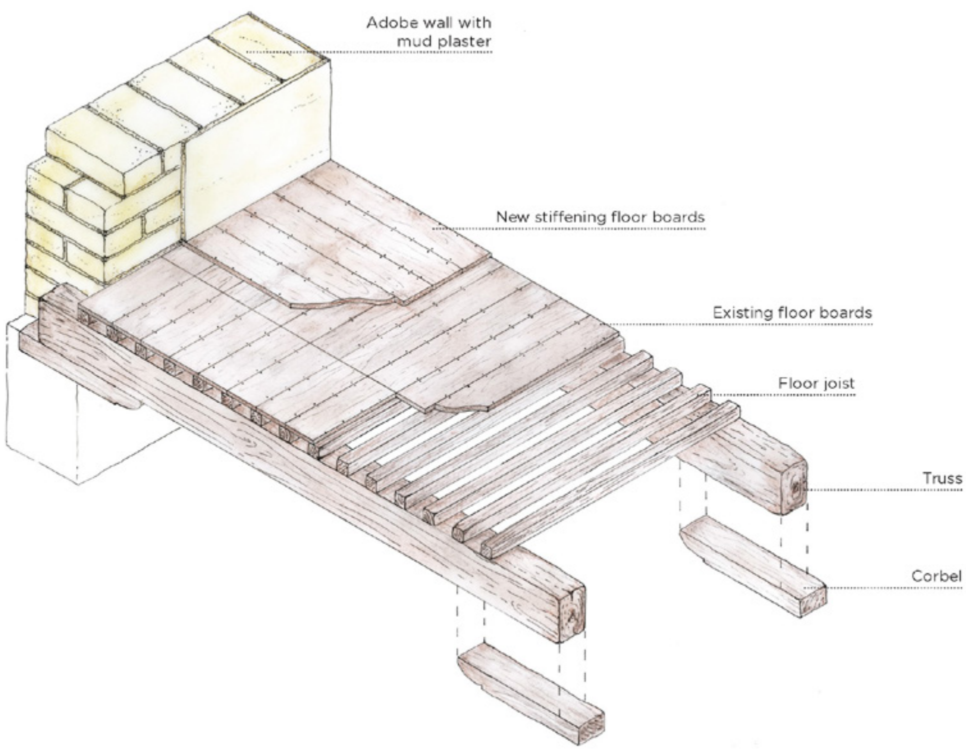


FIGURE 7.44. Orthogonal placement of new wooden boards for the strengthening of existing original timber floors. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

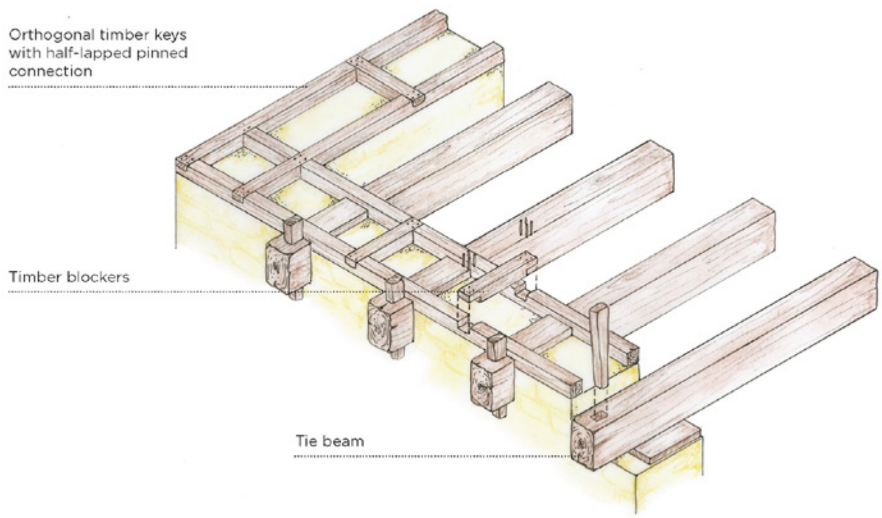


FIGURE 7.45. Addition of timber bond beams for improvement of the connection between wall and roof. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

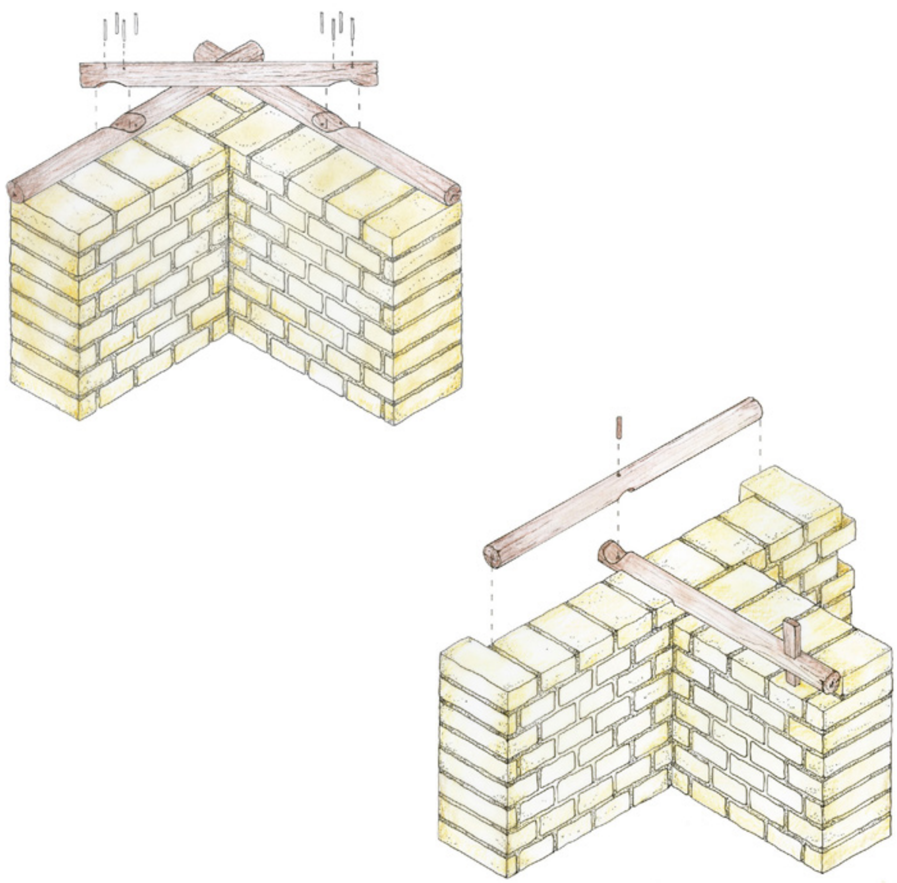


FIGURE 7.46. Application of timber keys or connections to strengthen wall corners. *Source:* Alessandra Sprega for the J. Paul Getty Trust.

Tolles and Krawinkler (1990) demonstrated that only minimal forces are needed to prevent the out-of-plane displacement of moderate to thick adobe walls. Anchoring the tops of these walls to the roof rafters or to perpendicular walls with corner keys effectively prevents their collapse.

For both thinner and thicker walls, the implementation of a collar bean to induce box behavior during an earthquake is recommended. On the top part of walls, bond or ring beams may be added in the connection to the roof to ensure the integral behavior of the building when subjected to seismic actions and prevent out-of-plane failure (figure 7.45).

Finally, an efficient way to strengthen corners and secure the connection between perpendicular walls is to use timber keys or connections (figure 7.46). This can be done by inserting timber elements inside the walls or applying them on the exterior.

In the event of collapse, nonstructural elements can cause significant damage to structural elements that can threaten life safety. As an intervention, chimneys and parapets can be strengthened by using reinforced render to provide proper anchoring to the structure, by stitching the elements with metal anchors, or by installing an external steel structure. Roof tiles, for example, must be properly anchored to a supporting backing structure.

7.5.3 Case Studies: The Church of Kuñotambo and the Cathedral of Ica

Two case studies of the seismic retrofitting of monumental earthen buildings in Peru are described in this section. The first involves the strengthening and rehabilitation project for the church of Santiago Apóstol de Kuñotambo in Acomayo, Cusco, Peru, implemented by the Ministry of Culture of Peru in collaboration with the GCI (Cancino et al. 2016). The seventeenth-century structure, featuring exquisite wall paintings, underwent a program of seismic retrofitting including structural modeling and conservation of its roof, exterior, and wall paintings. Based on the results of the finite element modeling analysis carried out by University of Minho, three new adobe buttresses with rubble-stone bases were designed for the south lateral wall of the church's nave. For each buttress, horizontal timber keys were placed in three elevations and inserted halfway through the thick lateral walls (figure 7.47).

The buttresses were also reinforced with horizontal geomesh sheets to better connect them with the existing walls. Additionally, timber-embedded elements were placed on the top eaves of the walls using continuous orthogonal bond beams and in the wall connections using corner keys. Adobe courses were removed to allow insertion of the elements. The elements are composed of two sets of timber beams connected transversally with timber blockers. Finally, a system of tie beams, bond beams, and double vertical anchors attached to the interior and exterior wall surfaces provides lateral restraint. To increase anchoring and pullout capacity, the tie beams were connected to the overlying bond beams.

Due to the addition of the new buttresses and timber frames, the structure presents a stiffer response. Nonlinear pushover analyses were performed in the principal directions and

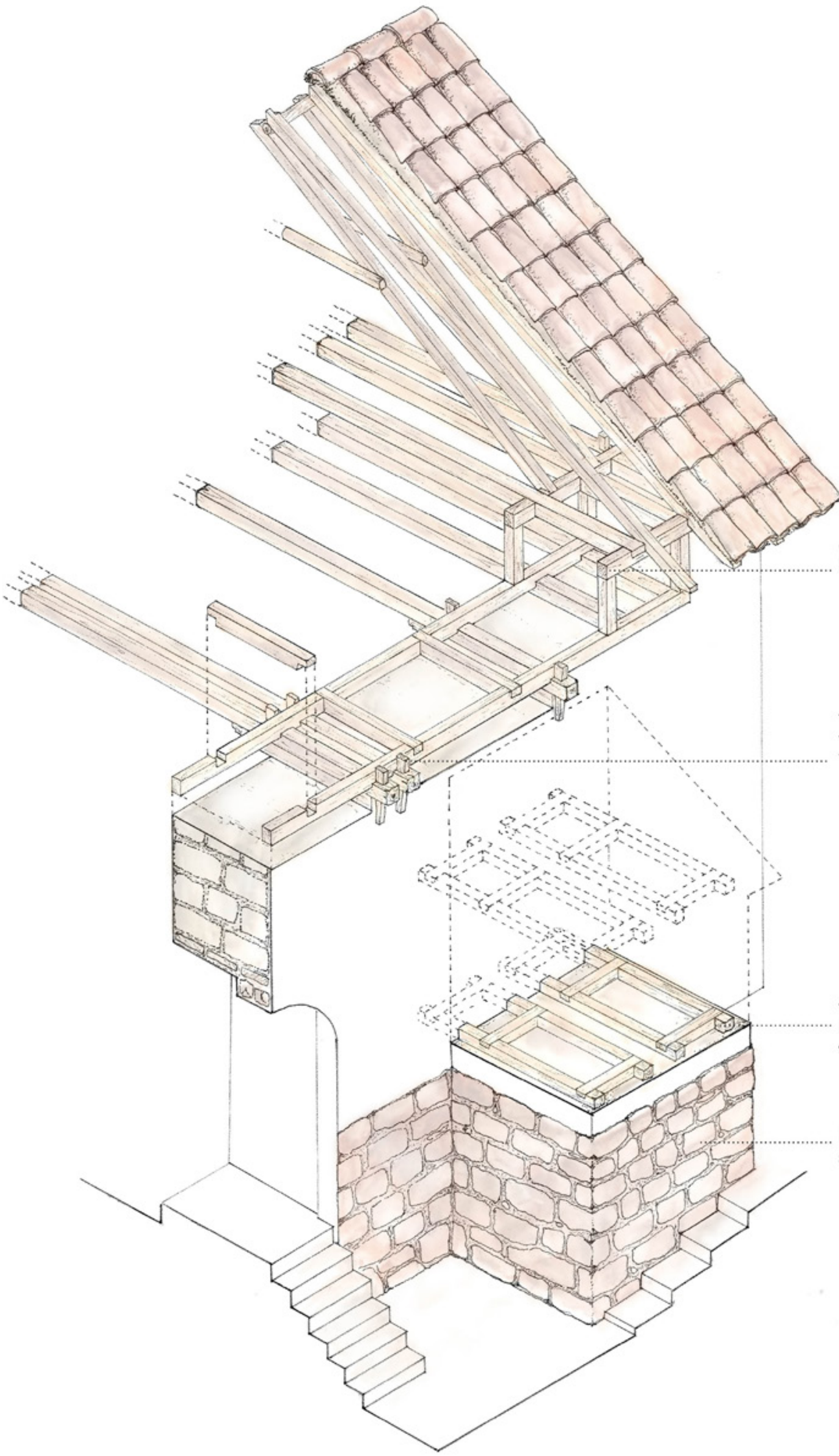
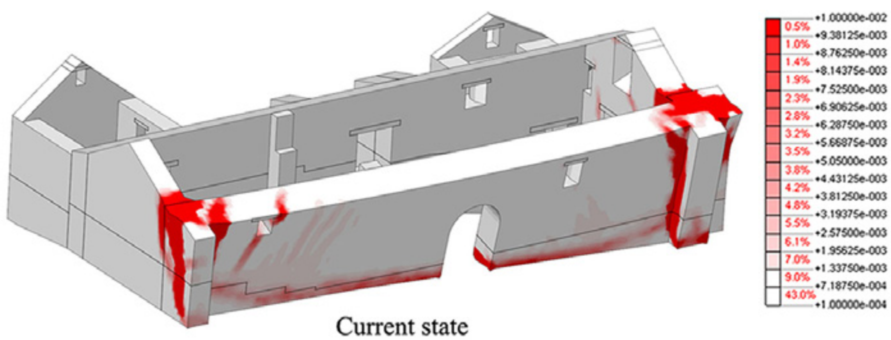


FIGURE 7.47. Traditional strengthening techniques implemented at the church of Kuñotambo: new buttress, showing horizontal timber keys between buttress and wall, new interlocking, geomesh; detail of timber key with vertical anchors to enhance connectivity; bond beam on the top eave, with corner keys in elevation; *Source:* Alessandra Sprega for the J. Paul Getty Trust.

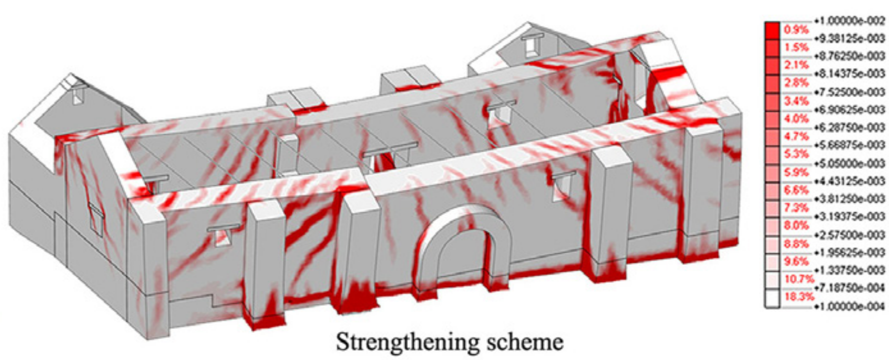
FIGURE 7.48. Images from the strengthening and rehabilitation project at the church of Kuñotambo: (a) integration of timber keys in new adobe buttress; (b) workers implementing the system of tie beams and bond beams into the church walls. *Source:* University of Minho for the J. Paul Getty Trust and Ministry of Culture.

(A)

(B)



(A)

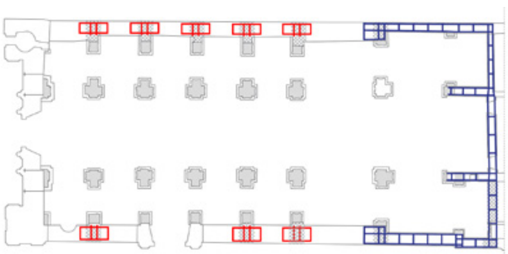


(B)

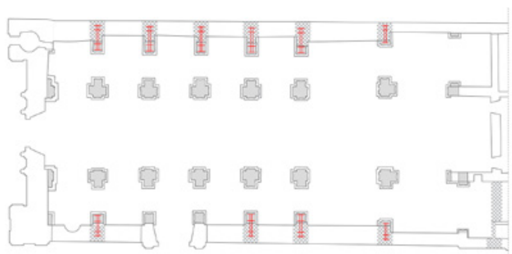
FIGURE 7.49. Cracking patterns (in red) at ultimate load at the church of Kuñotambo: (a) before and (b) after retrofitting. *Source:* University of Minho for the J. Paul Getty Trust and Ministry of Culture.

determined that overall performance greatly improved. Redistribution of seismic loads between transverse and longitudinal walls is ensured, and capacity has increased. An evident change in the failure mechanism occurs from the out-of-plane overturning of the entire south wall. The tie beams, bond beams, corner keys, and buttresses increase stiffness and allow the lateral walls to deform in out-of-plane bending while activating the transverse walls (figure 7.48). The cracking pattern exhibited at simulated collapse is more widely distributed, with small crack widths (figure 7.49).

The second case study involves the seismic strengthening project at the Cathedral of Ica in the coastal city of Ica, Peru. The eighteenth-century church suffered from extensive damage during



(A)



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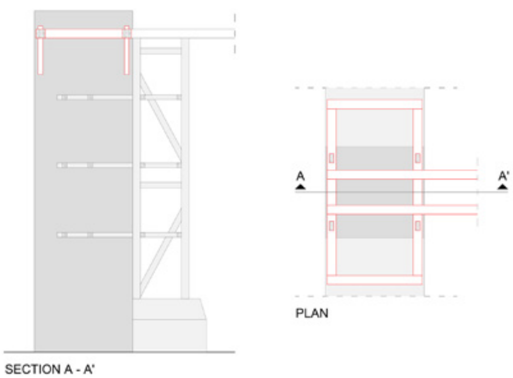

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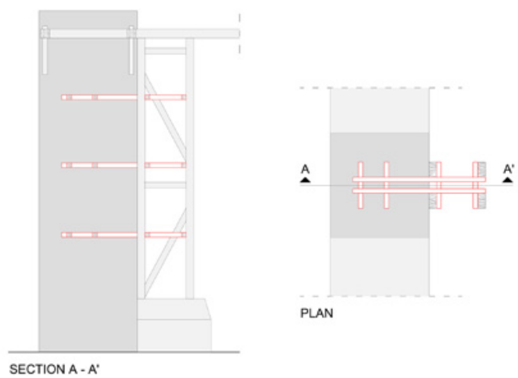

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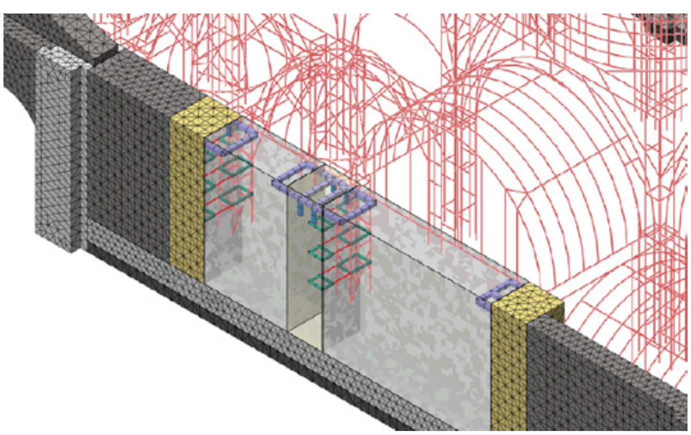

(E)

FIGURE 7.50. Diagrams detailing traditional strengthening techniques implemented at the Cathedral of Ica: (a) U-beam at top eaves in parts with low out-of-plane resistance, a configuration with two longitudinal timber beams and transverse timber blockers (in blue), and upper anchoring system in the lateral wall of the nave (in red); (b) lower anchoring system in the lateral wall of the nave (in red); (c) connection between masonry wall and timber floor and tying system with tie beams, vertical and horizontal timber anchors; (d) connection between masonry wall and timber pillar with horizontal timber anchors; (e) 3D view showing the configuration of embedded timber strengthening elements. *Source:* University of Minho for the J. Paul Getty Trust and Ministry of Culture.

the 2007 Pisco earthquake. A project of the Ministry of Culture, the Getty Conservation Institute, and the Catholic University of Peru, a program of seismic testing and modeling was carried out and specifications for the building's retrofit completed. The replacement of new adobes on part of the northwestern corner of the structure was proposed, connected to the adjacent existing walls by proper interlocking. New adobe sections were added along the cathedral's longitudinal walls at the location of each connection between the internal timber structure and the masonry envelope. Embedded in these columns were timber anchoring systems intended to improve the connection between the two substructures. As shown in figure 7.50, each timber anchoring system is composed of keys and ties connected using half-lap joints with nails and located at four levels along the height of the walls.

To improve the resisting mechanism, vertical keys embedded downward in new brick masonry were also proposed at the uppermost level of the anchoring system. A U-shaped timber collar beam is located at the back of the structure. Finally, a steel anchoring system was also proposed to improve the connection between the front facade and the internal timber structure.

The failure mechanism in the transverse direction is identified by the out-of-plane overturning of only the southern bell tower, replacing the out-of-plane overturning of the whole front facade, including the bell towers that was observed for the model without strengthening. As a result, the implemented strengthening techniques mostly improve the quality of the connections between the two substructures, effectively reduce the out-of-plane vulnerabilities, and increase the structural capacity of the structure (see figure 7.51).

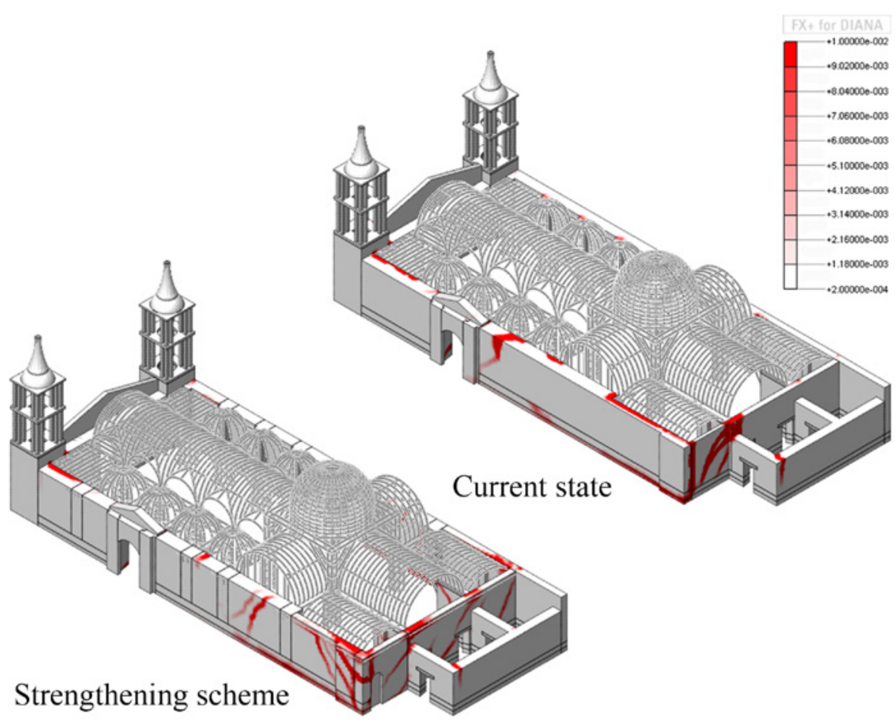

FIGURE 7.51. Cracking patterns at ultimate load (in red) at the Cathedral of Ica: (a) before (current state) and (b) after retrofitting (strengthening scheme). *Source:* University of Minho for the J. Paul Getty Trust and Ministry of Culture.

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EARTHEN PLASTERS AND THE CONSERVATION OF DECORATED SURFACES

8

Overleaf: **Grout testing for decorated earthen surfaces during the Conservation of Wall Paintings module of the EAC22 course in Al Ain, United Arab Emirates. Source: J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.**

8

EARTHEN PLASTERS AND THE CONSERVATION OF DECORATED SURFACES

Christof Ziegert and Clemencia Vernaza

This chapter discusses typical finishes for earthen buildings and their conservation. In section 8.1, Christof Ziegert describes the components of historical plasters as well as requirements, standards, and techniques for plaster application on existing earthen buildings. This is followed by a discussion of protective measures for earth plasters, such as lime washes and renders, with a discussion of the materials and methods of application.

In section 8.2, Clemencia Vernaza explores the conservation of decorated surfaces on earthen substrates, including the function and stratigraphy of decorated surfaces, causes of deterioration, intervention criteria, and stabilization of detached decorative layers with earth-based grouts. Section 8.2 concludes with an overview of consolidants for decorated surfaces.

8.1 Plaster Finishes for Earthen Architecture

8.1.1 Properties of Earthen Plasters

As explained previously in chapter 3, earthen plasters consist of clay, aggregates, and where appropriate, certain additives such as fibers to control the plaster properties. Aggregates must be sufficiently added to clay with a high binder content to reduce shrinkage cracking. Aggregates can be of a vegetable or mineral nature. Plaster quality is defined by good adhesion and good mechanical strength combined with minimal shrinkage and cracking. Earthen plasters should not be stronger than the substrate to which they are being applied.

Earthen plasters can be made from naturally occurring earth, taken directly from the ground, or made from dried and processed clay that is wetted and combined with other ingredients. The plaster mixture must be sufficiently bound, containing an adequate quantity of clay binder. In addition, a favorable mineral structure has a considerable influence on the plaster quality. Different clay minerals play a crucial role in the performance and durability of earthen plasters. The type and proportion of clay minerals, such as kaolinite, illite, and smectite, influence the plaster's plasticity, shrinkage, and binding strength. For instance, smectite clays, which have high swelling capacity, can increase the plaster's plasticity but also lead to greater shrinkage and cracking as it dries. Kaolinite, on the other hand, offers lower plasticity but contributes to a smoother finish and less shrinkage. The balance of these clay minerals affects the workability of the plaster, its adhesion to substrates, and its resistance to environmental factors like moisture and temperature changes.

An earthen plaster's properties are also influenced by the type and shape of the aggregate grains and the mixing ratio. Sufficiently coarse-grained mixtures have better properties in terms of shrinkage and durability than do fine-grained mixtures, especially for thicker coats. Plant fibers are particularly useful for the internal cohesion of the microstructure. As reinforcement, they can absorb stress from problematic substrates, thick layers, and other stresses (e.g., from thermal differences). In the case of thermal expansion, they improve the plaster performance, avoiding cracking. Mixtures without plant fibers usually have a higher sand content and, as a result, less favorable mechanical properties. The adsorption capacity can also be reduced.

Water vapor adsorption is defined by the capability of a building material to absorb and discharge moisture. Earth building materials have a remarkably high degree of water vapor transmission. This means that with high humidity, moisture is absorbed and stored in the building material and is released with decreasing humidity. Earth building materials show a higher adsorption than other mineral construction materials. For example, earthen plasters have a four- to sevenfold adsorption rate compared with gypsum plasters. The high adsorption capacity of earth building materials ensures a pleasant indoor climate as well as a reduced risk of mold formation due to the ability to buffer the humidity spikes.

8.1.2 Historical Earthen Plasters

8.1.2.1 Composition

Historically, local earth was rarely used directly as a plaster without amending the composition, as it would crack in most cases. Shrinkage was usually countered with lean sands or reinforcing fibers. While fibers can often still be identified in earthen plaster samples after thousands of years, it is sometimes unclear whether sand was present naturally in the original soil used for construction or if it was an intentionally added component.

In most cases, historical earthen plasters are reinforced with fibers. A variety of fibers available regionally were used; however, the most common is finely chopped straw from wheat. The thinner the plaster layer was intended to be, the finer the fibers used—for example, flax fibers were used in some regions. Animal hair is rarely found in clay plasters, as it is chemically better suited to lime plasters.

8.1.2.2 Aggregates and Reinforcements

Historic earthen plaster consists of suitable earth—in some cases, aggregates including larger grained gravel—and fibers (figure 8.1). However, mixing additional gravel into historic earthen plaster was not a common practice, as sand was more expensive. Additional gravel reduces the shrinkage ratio of earthen plaster and increases water resistance. However, it also influences workability and visual appearance (figure 8.2). Traditionally, various additives, such as cow dung and cactus juice, were also added to earthen plasters to increase water resistance. Soaking an earth-straw mixture over a period of days to weeks causes fermentation, resulting in a workability similar to adding cow dung. Adding cement, lime, or gypsum to earthen plasters—to shorten curing time—is not recommended, as these binders dominate the behaviors of the plaster, and the resulting mixture is more of a stiff cementitious plaster rather than an earthen plaster.

The amalgamation of plant fibers and mineral aggregates is pivotal in enhancing the structural integrity of this material (figure 8.3). This composite proves effective in reducing the impact of shrinkage by absorbing tensile forces. Moreover, the introduction of plant fiber aggregates serves a dual purpose: they facilitate improved processability, particularly evident in the material's heightened suppleness, with cellulose fibers demonstrating exceptional efficacy in this aspect. Additionally, these fine fibers play a crucial role in bolstering water retention capacity. As reinforcements, they adeptly absorb tensile forces, effectively managing stress stemming not only from subsurface pressures but also from temperature-induced fluctuations.

FIGURE 8.1. Historical earthen plaster made of earth and fiber. *Source:* ZRS, Christof Ziegert.

FIGURE 8.2. Earthen plaster with additional gravel. *Source:* ZRS, Christof Ziegert.

FIGURE 8.3. The different fibers of the base and top plaster can be seen in the core drilling. While the base coat contains coarser straw fibers, fine flax shives are visible in the top coat. *Source:* ZRS, Christof Ziegert.

For continental and arid climates, earth mortars mixed with additives serve as appropriate plasters for earthen sites. Lime plasters with a strength ≤ 1,5 N/mm^2 are also used. Cement mortars and mortars of high hydraulic limes, with high strength and low elasticity, are not appropriate. Resin-bonded plasters are also inappropriate.

Earthen plaster in outdoor applications needs regular maintenance. The sequence of maintenance depends on the composition of earthen plaster as well as the influence of rain, wind, and frost. The maintenance cycle should take place, at the latest, when the load-bearing substance is affected—for example, when the earth block is visible (figure 8.4).

Modern earthen plasters are also used as a sacrificial layer for archaeological findings as a complete or partial protection capping to reduce exposure to weathering (figure 8.5 and 8.6a).

8.1.2.3 Lime-Based Plasters

Earthen plasters on historic buildings are often covered and protected with lime wash or thin lime-plaster layers to increase their weather resistance (figure 8.6b). Lime mortars should be soft and elastic. The choice of lime, however, only partially determines the plaster properties; the type of aggregates and the mixing ratio are equally important. Depending on weather conditions, lime wash should be reapplied after five years. Lime wash is light and flexible and allows for easy and fast application on earthen structures. However, it offers only limited weather resistance. If it is not maintained properly, imperfections may occur, causing the coating to look unattractive and become counterproductive, as water can penetrate the cracks. No or minimum hydraulic additives should be used in lime plasters; otherwise, the plaster will become stiff and separate from the substrate.

For the renovation of historic earthen structures or the building of new earthen structures where significant weathering may be a factor, a two-layer exterior lime plaster of approximately 15 mm thickness should be used. In the case of sheltered exterior walls or areas with weak weathering—partially intact surface layers or only minor damage to the straw loam substrate—a single-layer exterior lime plaster of approximately 3 to 5 mm thickness based on a historical model may be advisable.

8.1.3 Application of Plaster

8.1.3.1 External Masonry

Before a lime plaster is applied, the earthen plaster substrate layer should be scored or combed to create a rough texture (figure 8.7). The plaster must be applied on a wet substrate and must be treated following application with water sprayed on a jute mesh. For a thin single-layer lime exterior plaster, the defects are repaired with lean straw earth or straw-containing earthen plaster mortar. Then the area is carefully wetted. Thinly prepared straw-containing earth plaster mortar is worked into the damp surface; hard sponges or felt boards are suitable for this

FIGURE 8.4. The earth plaster has weathered to such an extent that the structure of the earth blocks is visible. Further rainfall would erode the earth blocks. This is therefore a critical time to apply a new layer of plaster. *Source:* ZRS, Christof Ziegert.

FIGURE 8.5. Earthen plaster sacrificial coating and capping on an archaeological site. The different color tones of the wall and the capping are problematic. With erosion, the color of the supplementary mortar will become mixed with that of the existing material. *Source:* Alessandra Sprega.

(A) (B)

FIGURE 8.6. (a) Earthen plaster as capping on an archaeological site. The embedded ceramic shards significantly increase the weather resistance. *Source:* ZRS, Jasmine Blaschek. (b) Layer of lime wash over earthen plaster. *Source:* ZRS, Christof Ziegert.

(figure 8.8). The final coating, a lime and sand slurry, must contain sufficient binder; otherwise, the bond with the substrate will be insufficient. The slurry application must be protected from "burning," meaning drying too fast without proper carbonation. This can be achieved with moderate prewetting and covering with a wet fabric or jute cloth, with regular wetting over a two- to three-week period to ensure proper carbonation.

8.1.3.2 Internal Masonry

Before plastering a historic earthen wall, plaster residues or void fillings from past coatings such as lime or cement mortar must be removed. Earthen parts that can easily be loosened by rubbing with the palm of the hand must be removed. Contact surfaces must be swept free of dust and carefully wetted. Afterward, coarse-grained earth plaster slurry or a not-too-stiff earthen mortar is applied with a float or trowel depending on the thickness. Historic earth plaster surfaces are prepared in the same way before the application of new layers. The same material is used for the preparation of plaster in interior masonry surfaces as external ones. The top layers for these plasters often include fine fibers, to achieve a more finished look. Special aggregates and surface treatments determine the appearance of the plasters. Special clay resources may be used to give a particular color to the plaster. Use of artificial pigments is not advisable.

FIGURE 8.7. Combing of earthen plaster substrate layer before plaster application. *Source:* ZRS.

FIGURE 8.8. Application of earthen plaster on a masonry wall. *Source:* ZRS.

8.1.4 Plaster on Earth Block Masonry Substrate

The following are typical steps for applying earth plaster to existing earthen block masonry:

1. The delaminated surface is removed, and at least 1 cm thickness of the undamaged material is further processed with a mason hammer.
2. Voids deeper than approximately 7 cm should be filled with earth blocks. These adobes should have behaviors similar to the existing masonry.
3. Wooden nails are used within the deeper flaws to anchor the new repair material during plaster-like application. Voids up to approximately 7 cm should be replenished in layers.
4. The weathered substrate is prepared by removing loose pieces and dust.
5. All loose components are swept with a medium-hard wire brush.
6. The surface is moistened.
7. A slurry of sufficiently binding earth is inserted.
8. Sharp sand is applied with a hard brush.
9. A leveling course with multilayered earth mortar is applied with sharp sand and is reinforced by chopped straw; each layer should be no thicker than 2–3 cm.
10. Before applying the next layer, the formation of cracks in the lower layer should be finished.

FIGURE 8.9. Earthen plaster in an indoor application. *Source:* ZRS, Christof Ziegert.

FIGURE 8.10. Detail of earthen plaster layer in an indoor application. The long straw in the plaster base can also be used to bridge wider timbers in the plaster base. *Source:* ZRS, Christof Ziegert.

8.1.5 Substrate for Earth Plaster

As is the case with all paints and plasters, the substrate for earthen plasters must also be solid, nonslip, sufficiently absorbent, and dry. It must not be contaminated by impurities, dust, penetrating substances, salts, or frost. Depending on the desired uniformity of the plaster thickness, the substrate must also be sufficiently level. In the case of overhead plaster applications, the requirements for the mechanical suitability of the substrate are greater than for walls.

A sufficiently large work sample is always decisive for the evaluation of the substrate. The fault tolerance of different earthen mortars regarding substrate quality can be very different. In accordance with the *German Construction Contract Procedures (VOB)—Part C: General Technical Specifications in Construction Contracts (ATV)—Plastering and Rendering* (DIN 18350), "Unsuitable condition of the substrate may include, e.g. coarse impurities, efflorescence (e.g. apparent salt contamination), excessively smooth surfaces, oily surfaces, unevenly absorbent surfaces, frozen surfaces, various substrate substances such as too high building noise, greater unevenness, and insufficient adhesion in the substrate itself."

8.1.6 Strength Requirements for Substrate

The strength needed for the substrate when using earth mortar is not higher than that required for other types of plaster. Earth mortar forms soft and tension-free surfaces, making it suitable for even very soft mineral plasters. To ensure proper adhesion of coatings, it is advised to remove loose stones, plaster layers, and any hollow-sounding plaster from the substrate. While most historic building interiors will utilize only simple layers of earthen plasters or earth-based paints, some rehabilitation projects may incorporate more complex wall systems such as earth construction panels that provide insulation or in-wall radiant heating or cooling systems (see case study in chapter 10.3.1, “Al Jahili Fort, Al Ain, United Arab Emirates [UAE]”).

For earthen construction panels, it is recommended to lay them in an even bond and a flat manner, conducting a thumb-pressure test to ensure secure fixing without any movement. The adhesion of earth mortar relies on mechanical attachment, so a good grip on the substrate is crucial. Thicker coats or those with special tensions (e.g., for wall-heating systems) may require improved grip surfaces. Consideration may be given to a preparatory spray cast with liquid earth mortar for better adhesion.

In the case of single-layer earth plasters, it is essential to have even and homogeneously absorbent substrates to prevent uneven drying and surface marks. To address unevenness and achieve uniform suction characteristics, a preparatory prespray on a small surface area can be a compromise solution.

8.1.7 Repair of Shrinkage Cracks

Smaller shrinkage cracks can be closed with material from the surrounding areas when the surface is wet. Larger shrinkage cracks must be closed with additional material; otherwise, they will appear again after the repair has dried. It is problematic if the plaster mortar used is so coarse that it is not suitable for closing the cracks: one must either open the cracks sufficiently or fill them with a finer mortar mass. However, the finer mass may then stand out due to its different surface texture. Mock-up samples are highly recommended for assessing the expected quality of the repair.

In the worst case and when plasters are not highly significant, entire surfaces must be plastered again with a thin mortar coating. It is difficult to repair cracks that have formed in a flush-mounted surface that was not sufficiently dry at the time of the topcoat. Once the surface has appeared, in many cases only a new plaster coating on the entire surface is recommended, if necessary, even with a reinforcement mesh inlay.

8.1.8 Reinforcement Mesh

In historical plasters, fibers took over the reinforcement function and prevented cracks. However, as fibers are not always evenly distributed or ideally aligned, safe systems of plaster reinforcement with fabrics are often preferred today. The fabrics used in earthen plasters are often made of flax fibers or jute (figure 8.11). However, plastic or fiberglass fabrics are also used.

8.2 Conservation of Decorated Surfaces on Earthen Architecture

Decorated surfaces is the term for all coatings that complement architecture, ranging from plain color to illusionistic trompe l'oeil. These types of surfaces have been used in the architecture of nearly all cultures since ancient times. A decorated surface surrounds and immerses the observer, transforming one's perception of a building and, at the same time, modifying the space through the creation of textures, colors, building materials, architectonic elements, scenes, and so forth.

The more traditional term *wall painting* has been replaced in recent discourse by *decorated surfaces*, as such surfaces are not limited to walls but exist on many architectural elements, including ceilings, arches, and columns. However, the term *decorated surface* itself can be misleading, as its function not only is decorative but also serves as a form of cultural expression.

FIGURE 8.11. Insertion of flax fiber mesh. *Source:* CLAYTEC.

8.2.1 Stratigraphy of Decorated Surfaces

As shown in figure 8.12, the minimal stratigraphy of a decorated surface is formed by the substrate, the plaster, and the paint layer. In earthen architecture, the substrate can be made of adobe, rammed earth, cob, wattle and daub, or poured earth. The plaster is normally earth based, but lime-based and gypsum plasters are also common. Variations of this typical stratigraphy can include an intermediate layer called fine plaster, traditionally made of earth, gypsum, or lime, which provides a smooth surface to receive the paint layer.

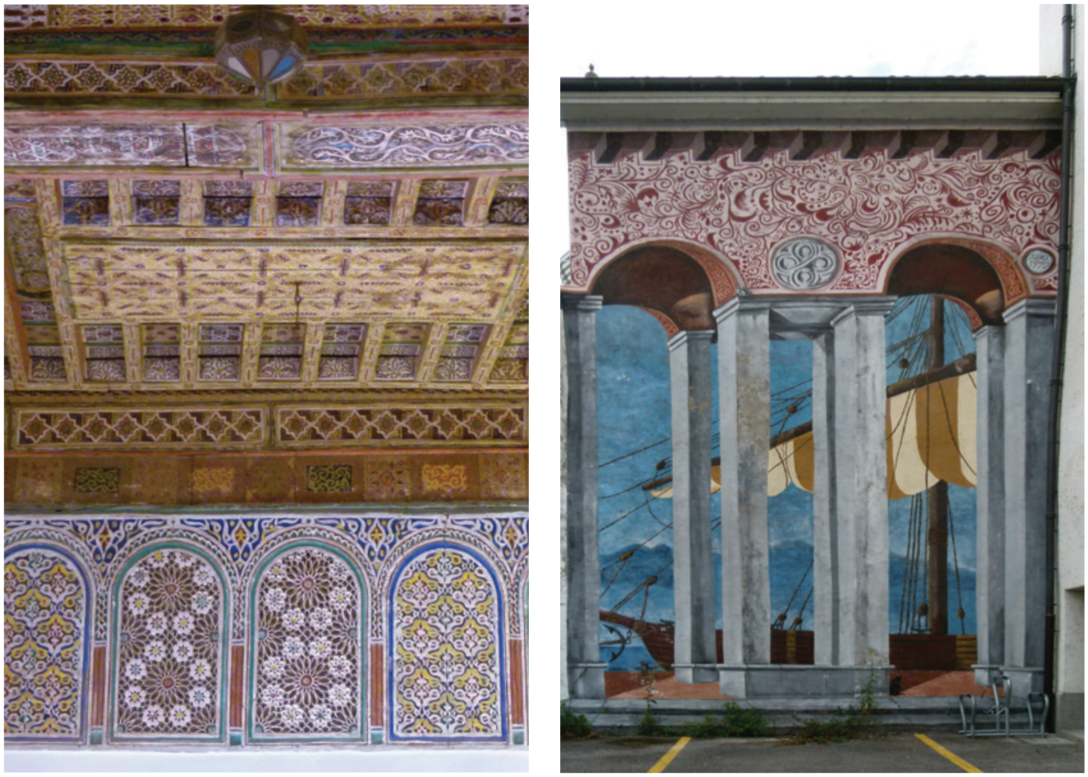
8.2.2 Functions of Decorated Surfaces

Decorated surfaces have diverse functions, and different types of surfaces achieve specific architectural modifications (Mora, Mora, and Philippot 1984). Examples of these modifications include the following: walls and ceilings transformed by new textures and fake arches (figure 8.13a); painted elements and materials used in a facade to simulate brick patterns, stone elements, pilasters, and arches, creating an illusionistic effect that appears as real as the materials themselves (figure 8.13b); or painted elements used to establish a different type of illusionistic effect, this one of architectural elements that give way to an exterior landscape or vista (figure 8.14a).

Another important function of decorated surfaces is to define the architectural space using iconographic elements. For example, by employing calligraphy and carved stucco, a building can be recognized as a religious and sacred space (figure 8.14b).

FIGURE 8.12. Stratigraphy of a decorated surface, showing (1) support, (2) render, and (3) layer of paint. *Source:* Clemencia Vernaza.

FIGURE 8.13. (a) Architectural modification involving the use of fake arches to imitate latticework inside the Kasbah of Taourirt, Ouarzazate, Morocco. (b) Architectural modification achieved by using painted elements and materials to imitate stone, brick, pilasters, and arches on the facade of a private home in Lausanne, Switzerland. *Source:* Clemencia Vernaza.



(A) (B)

(A) (B)

FIGURE 8.14. (a) Architectural modification involving painted elements used to simulate architecture and an exterior landscape view or vista on a building in Morges, Switzerland. (b) Architectural modification using calligraphy and carved stucco on the mihrab at Al-Masjid ash-Sharah, Harat al-Hilad, Oman, identifying it as a religious space. *Source:* Clemencia Vernaza.

8.2.3 Conservation Issues Related to Stabilization of Decorated Surfaces

Because decorated surfaces and architecture are closely connected, they share the same conservation issues. These include all conditions that impact the entire stratigraphic system. Another conservation problem involves the quality of materials, from the substrate to the paint layers, and the execution technique of those materials.

8.2.4 Causes of Deterioration

When deterioration is a consequence of poor materials and/or techniques, the causes are intrinsic and normally lead to a lack of adhesion between layers, poor cohesion within layers, stains, and changes in surface color.

Intrinsic lack of adhesion is in general a consequence of a poor keying system in which an overly smooth surface does not provide the anchoring needed for the material, causing failure of the system. Inadequate mortar preparation due to poorly chosen materials can also cause intrinsic deterioration. Renders containing too much clay can form fissures, resulting in failure of the system by contraction; conversely, an insufficient amount of clay can cause failure through a lack of bonding capacity. Materials of poor quality can yield by-products such as salts, which in time can cause system failure through solubilization and crystallization cycles.

Extrinsic deterioration can be the result of environmental, human, or building-related factors on the substrate. Such external problems should be fixed before any intervention is carried out on the decorated surfaces. Examples of external causes include the following:

- material deterioration of the substrate
- humidity infiltration
- dryness
- man-made damage

Lack of adhesion can occur due to internal or external factors and can appear between two layers: between support and plaster, between two plasters, or between fine plaster and paint layer (figures 8.15 and 8.16a). To repair, it is necessary to reconnect the layers by means of an adhesive. Stabilization of decorated surfaces refers to correcting the failure in the system caused by lack of adhesion and/or lack of cohesion.

Up until the 1980s, this often involved completely detaching the decorated surface from the support, resulting in the loss of the original surface. Today, however, this intervention is performed in situ through grouting, thus preserving the surface's physical and aesthetic characteristics and functions. Lack of cohesion occurs when aggregates lose their bonding capacity, leading to failure of stabilization within the layer. The layer becomes powdery, losing consistency and bonding characteristics (figures 8.16b and 8.17). To address this, it is necessary to bond particles within the layer by means of a consolidant.

8.3 General Criteria for Interventions

Intervention criteria for decorated surfaces do not differ from general conservation criteria for other cultural heritage sites. However, due to the specificity of materials used, some criteria need to be developed.

The first and most important is *minimum intervention* (Australia ICOMOS 2013), in which intervention should be limited to the recovery of a decorated surface's values. To achieve this goal, it is necessary to fully understand the context of the decorated surfaces, including their relation to the architecture, and to understand the conservation issues by conducting a comprehensive survey. Minimum intervention ranges from doing nothing to the reconstruction of decorated surfaces, and the decision regarding the level of intervention is based on the results of the comprehensive survey.

Reversibility (Petzet 2004) is an important criterion in all conservation intervention; however, it is unachievable here, as decorated surfaces are porous systems in which any liquid material penetrates without the possibility of removal. It can be replaced by the criteria of *compatibility* and *use of materials*, which will not interfere with future conservation treatments. Compatibility implies the use of materials that are harmonious with or complementary to the original. Decorated surfaces are heterogeneous systems, so interventions must consider chemical and physical compatibility within all existing materials. In addition, decorated surfaces are often already subject to interventions, in which case compatibility must be extended to all materials used.

FIGURE 8.15. Locations of lack of adhesion, or detachment (in red), between support and render and between render and paint layer. *Source:* Clemencia Vernaza.

(A) (B)

FIGURE 8.16. (a) Detachment between render and paint layer on a wall at the Kasbah of Taourirt, Ouarzazate, Morocco. (b) Photoshop montage from an adobe building in Peru and mural painting from Kuñotambo. *Source:* Clemencia Vernaza.

FIGURE 8.17. Detail of figure 8.20 showing the lack of cohesion of a weathered wall from a private house in Peru. *Source:* Clemencia Vernaza.

The criterion of *no interference with future conservation treatments* (ICOMOS 2003) means that materials and techniques used for stabilization should not prevent any future intervention, either with the same materials and techniques or with different materials and techniques.

8.4 Stabilization of Decorated Surfaces

Grouting is a bulked fluid material that can be injected behind stuccos, wall paintings, or mosaics to fill cracks and voids and to reestablish adhesion between delaminated layers and is used to stabilize decorated surfaces when detachment has appeared between the plaster and the substrate and/or between plasters. Injection grouts are composed of one or more binders, aggregates, and admixtures and a fluid—typically water (Biçer-Şimşir and Rainer 2013)

8.4.1 Grouting Criteria

Grouting formulations should meet the following criteria:

- Compatibility with all materials within the decorated surface system.
- Adequate fluidity to allow injection without clogging.
- Minimal separation of components during injection and drying. Separation of components will create unwanted differential behavior within the grouting material.
- Lowest shrinkage possible during drying. If the passage from paste to solid material presents shrinkage, contact between substrates will not occur and the adhesion will fail.
- Minimal salt content. It is important to avoid the introduction of any soluble salts, as they will cause damage through different mechanisms, leading to a lack of cohesion.
- Similar mechanical properties between dry grouting paste and the original. In the case of different behaviors, the mechanical properties of dry grouting paste should be weaker. This will ensure that the original will be preserved if the system fails.
- Porosity, in terms of water adsorption capacity, similar to the original. Open porosity defines the system's humidity behavior, which should remain unchanged.
- Preservation of free water passage in liquid and vapor phases throughout the system. Barriers to water cause damage to the original through mechanical tensions created by water movement toward the evaporation surface.
- Capacity to bond detached layers after drying. The main objective of grouting is to bond substrates, so the capacity to bond is of utmost importance.
- Tacking capacity in paste form. When grouting, it is important for grouting to have an initial adhesive capacity to bond the substrates until final drying is achieved.
- Lowest wet density possible. Grouting involves a liquid, normally water, so the initial weight of the paste is higher than the final weight of the solid. It is important to keep the initial weight as low as possible to avoid detachment.

- Lowest dry density possible. In the solid phase, grouting needs to be as light as possible to ensure that its weight will not cause future failure of the system.

8.4.2 Choice of Grouting Materials

It is important to understand that grouting formulation is always tailored to specific needs and that no universal recipe can be reproduced in all cases. This chapter covers only decorated surfaces in earthen architecture; consequently, the range of materials is limited to those used for earthen supports. Materials should be selected according to the criteria mentioned earlier and based on an overall understanding of the execution technique, conservation issues, and previous interventions on the decorated surface. In earthen architecture, layers are generally earth based. Nevertheless, mixed systems can be found that incorporate materials such as lime or gypsum. For grouting formulation, the use of original materials will provide the best possibility of accomplishing compatibility criteria, but these materials do not always perform in the appropriate way, and additives should be considered to improve grouting behavior.

8.4.2.1 Choice of Binders

The binder par excellence for earth-based grouts is clay, which is the most compatible material in all aspects. Experiments have been carried out using ethyl silicates as a binder and avoiding the use of water, but these were not conclusive (Dolph 2014). Personal tests conducted by one of the authors (Vernaza) have found that grouting material tends to separate.

8.4.2.2 Choice of Aggregates

Aggregates are materials added to a grout to control clay shrinkage and alter grouting density. As explained previously in chapters 2 and 3, soils used in earthen architecture often naturally include aggregates, though not always of the correct quantity or quality. Because soil for the execution of original decorated surfaces was often quarried from a location near the building site, testing local materials will usually reveal a good starting choice for grouting formulation.

When soil shrinkage behavior needs to be modified, aggregate plays an important role, as its addition changes the proportion of the clay content. The range of aggregates is large, and selection depends on availability and desired performance. There are many suitable aggregates, including pozzolanic earth, powdered brick, marble powder, and almost all finely ground inert aggregates. If the aim is to reduce wet and/or dry grouting density, aggregates play an important function, as they determine the weight of a grout.

Currently, void glass microspheres, which are inert and exceptionally light, are used to control shrinkage, reduce wet and/or dry grouting density, and modify rheological properties.

8.4.2.3 Choice of Additives

Often aggregates and binders are not enough to modify soil properties, and thus the use of additives is needed. Additives modify rheological properties and adhesive properties or reduce water content and can be classified as follows:

- *Bonding enhancers*. When the clay content of soil does not reach the desired bonding power during grouting (preliminary adhesive power) or after drying, an additive can be used to modify its behavior.
- *Rheology modifiers*. The property of grouting flow can be modified by adding different materials.
- *Deflocculants*. Flocculation is the natural property of clay particles that causes them to be attracted to one another. In an alkaline environment, clay particles repulse one another in a state called deflocculation and remain in suspension as single units. In a deflocculation state, viscosity is reduced; in a flocculation state, particles form structures that increase viscosity (Tozzi, n.d.). Deflocculants are chemicals that can drastically lower the viscosity of a suspension and are normally needed for earth-based grouts. The most common deflocculant is sodium hexametaphosphate.
- *Wet and dry density behavior modifiers*. Foaming agents improve wet and dry density by introducing voids in the grouting paste and final solids, which reduce the amount of grouting material.
- *Water reducers*. The amount of water in the grout plays an important role in shrinkage behavior and wet density. Too much moisture can impact sensitive decorated surfaces. It is always advisable to use as little water as possible.

Many possible additives can be tested. Some of the most common additives for earth-based grouts are the following:

- Egg white, whipped into an airy foam, is added to the grout, creating bubbles to produce a more voluminous paste with lower density. The rheology is also modified as the egg lubricates the paste, increasing the initial tackiness of the paste and improving final adhesion. In addition, the water content of the paste can be reduced. Nevertheless, it is important to bear in mind that this is an organic material, prone to develop microorganisms that can affect decorated surfaces.
- Synthetic polymers perform better when whipped to form a foamy material that changes the density, rheology, tackiness, and adhesive properties of a grout while reducing the amount of water in the paste.
- Methyl cellulose can enhance tacking and final adhesive power as well as rheological behavior.
- Mucilage from cacti has been used as an additive, though its function has not yet been fully studied and understood.

8.4.3 Grouting Fluid

The most common fluid used in grouting is water. In some cases, the water content can be reduced by replacing a portion of it with alcohol. It is essential to formulate the grout with a specific amount of fluid and the exact amount tested. Fluid plays a primary role in grout shrinkage, and even small variations can change the behavior of the grout.

8.5 Methodology for Grouting Formulation

Preliminary grouting tests should be carried out in the same location where the grouting will take place to ensure that changing environmental conditions do not cause variations in grout behavior. However, it is possible to start testing in the laboratory and make final choices of grout formula in situ.

The tests here described are based on the Getty Conservation Institute's publication *Evaluation of Lime-Based Hydraulic Injection Grouts for the Conservation of Architectural Surfaces: A Manual of Laboratory and Field Test Methods* (Biçer-Şimşir and Rainer 2013) and have been modified for earth-based materials.

Procedures used in the preparation of the grout affect workability and final performance characteristics. For example, the stirring method and mixing time have a critical impact on consistency, and these methodologies should be recorded and reproduced once their efficacy is proven. In general, grouting mixed at high speed for several minutes produces a paste with better injectability and penetration and less separation of liquids and solids.

As noted, water is an important factor that can modify flow, shrinkage, and bonding. The amount of water used should be consistent and accurately measured while mixing the grout. A good practice is to convert volume ratios into weight ratios to minimize measurement errors when preparing the final mixture.

Data for all test results, compiled into a chart for comparison, is essential in selecting the final grouting formula. An example of a comparative chart can be found in table 8.1.

8.6 Consolidation

Consolidation is an intervention on decorated surfaces that restores cohesion between particles of a layer when failure of the binder causes powdering or loss of material. The criteria for this type of intervention do not differ substantially from the criteria discussed above. In consolidation, however, a key difference lies in the significance of two criteria: no interference with other treatments, either with the same material or with new material, and keeping the aesthetic aspect of the surface unchanged.

Prior to any consolidation treatment, it is necessary to study the original materials and techniques of the system, the history of previous interventions and materials used, and the physical history and decay of the decorated surfaces and to evaluate the risk of intervention versus non-intervention. This information is important for guidance on the choice of materials and techniques for consolidation treatment.

Consolidants are divided into two main groups: inorganic and organic. Inorganic consolidants are substances that react chemically with the substrate, forming new compounds and improving cohesion through a chemical reaction. According to their general properties, inorganic consolidants act through a chemical reaction, last longer than organic consolidants, and are irreversible but allow new intervention with the same product or a new product.

Examples include ethyl silicates, nanosilicates, and ammonium phosphate, as well as several others in common use, and new products are continuously being developed, primarily for lime-based systems.

Organic consolidants normally are film-forming substances and can be natural or synthetic. According to their general properties, these consolidants have the following properties:

- act, or cure, through evaporation of the solvent;
- have a life cycle shorter than that of inorganic consolidants;
- are mostly reversible, but not necessarily in a porous system;
- form films that can change the porosity and surface appearance of decorated surfaces;
- normally prevent subsequent intervention with inorganic products and certain organic consolidants; and
- are prone to attack by microorganisms that can cause damage to decorated surfaces.

Organic consolidants were the first materials used to address a lack of cohesion. They were shown to result in damage mainly due to instability caused by humidity and biodeterioration and by the creation of water barriers. Nevertheless, some organic consolidants can be a good option for intervention when conditions allow.

The most commonly used natural organic consolidants throughout history are wax, casein, animal glue, Jun Funori (red algae glue), and mucilage. The most common synthetic organic consolidants include soluble nylon, vinyl emulsions, acrylic emulsions, cellulose esters, and polyacrylic acid. There are also temporary consolidants, including cyclododecane and menthol, that have a remarkably interesting behavior, as they sublimate and disappear over time.

No formula exists to determine whether the use of inorganic consolidants is more effective than the use of organic consolidants or if natural consolidants are superior to synthetic ones. The choice of consolidant depends on circumstantial factors such as environmental conditions, conservation requirements, previous interventions, and the physical history of the decorated surfaces.

Table 8.1. Data comparison table for grouting test results

Final notes																		
Hardness	+				–					+					++			
Final setting time	–				–					++					++			
Bonding power	–				–					+					+			
Tacking behavior	–				–					+								
Drying shrinkage	+				–					–					–			
Dry density	0.77				0.57					0.90					0.9375			
Wet density	1.12				1.15					1.15					0.91			
Segregation, expansion, and bleeding	+++				++					–					++			
Flow on mock-up	++				+					+					–			
Flow-through cannulas	++				+++					+++					++			
Weather remarks	Rainy day				Rainy day					Sunny day					Rainy day			
Temperature (°C)	14				19					21					14			
Relative humidity	63.7				66					45					63.7			
Proportion	2.0	3.0	1.0	0.5	2.0	3.0	1.0	0.5	0.8	2.0	3	1	2	0.5	2	3	1	2
Particle size	250 µm	K20 + K46	250 µm	N/A	250 µm	K20 + K46	250 µm	N/A	N/A	250 µm		250 µm	N/A	N/A	250 µm	K20 + K46	250 µm	N/A
Grout composition	Tuff powder	Microballoons (3M)	Earth local	Sodium hexametaphosphate (0.4%)	Tuff powder	Microballoons (3M)	Earth local	Egg albumin	Sodium hexametaphosphate (0.4%)	Tuff powder	Microballoons (3M)	Earth local	Distilled water	Egg albumin	Tuff powder	Microballoons (3M)	Earth local	Distilled water
Date	March 26, 2019				March 27, 2019					March 28, 2019					March 29, 2019			
Test number	1				2					3					4			

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CONSERVATION OF EARTHEN ARCHAEOLOGICAL SITES

9

Overleaf: **Application of a sacrificial coating in Hili 2 archaeological site, Al Ain, United Arab Emirates. Source: J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.**

9

CONSERVATION OF EARTHEN ARCHAEOLOGICAL SITES

Gaetano Palumbo

9.1 Deterioration of Earthen Archaeological Sites

Conserving earthen archaeological sites presents a challenge to the established parameters in conservation ethics and standards, especially when such sites are to be preserved for public presentation (Correia 2016; Oliver 2008). This chapter is an introduction to the topic of conserving earthen archaeological sites. It addresses the deterioration factors that affect these sites, exploring conservation and management solutions that maintain their authenticity, investigating solutions to provide for their long-term preservation, and finally, examining approaches to public presentation and interpretation. Two case studies conclude the chapter.

Deterioration of an earthen archaeological structure begins immediately after its excavation. Once exposed to the elements, earthen archaeological features start to show different types of damage, depending on the type of environment surrounding the structure. In a dry environment, exposure causes the rapid loss of material due to wind erosion and the drying up of the layers closer to the surface (figure 9.1). This poses a special challenge if the excavated site has original plaster coatings or decorations such as surface paint or other details preserved on its surfaces.

Other examples of deterioration and damage include peeling of the coatings, crumbling of the material, and formation of deep cracks in the exposed masonry (figure 9.2). This is caused by sudden excessive loss of water content and the varying rates of water loss between layers that are closer to the surface of the structure or between a coating and its substratum. Winds carrying sand particles may create a sandblasting effect on the exposed surfaces. Insects, birds, and small reptiles may burrow through the resulting cracks and crevices and into the core of the walls to build nests (figure 9.3).

Although rare and infrequent, rainfall does occur in dry environments and is often characterized by brief but very intense phenomena. In a desert environment, it is not rare for most of a year's worth of rain to fall within only a few minutes. This creates a situation of high risk for the exposed ruins, as stormwater flow may penetrate the cracks or undercut the walls, resulting in their collapse (figure 9.4). In addition, mechanical stress on the exposed masonry may be caused by the different rates of moisture present in the air between day and night. The masonry would absorb

FIGURE 9.1. View of a portion of the exterior wall of the ancient city of Nisa, Turkmenistan, showing evidence of wind and water erosion. *Source:* Gaetano Palumbo.

FIGURE 9.2. View of Hili 2, Al Ain, an Iron Age archaeological site, showing a vertical separation in the wall of a residential building. *Source:* Gaetano Palumbo.

FIGURE 9.3. Portion of a wall at Nisa, Turkmenistan, showing cracks and holes in the exposed surface in which birds have nested. *Source:* Gaetano Palumbo.

water at night and release it during the day, possibly causing the separation of the more superficial layers from their core.

In a wet environment, water and vegetation are the main causes of deterioration of an earthen site. Frequent rain causes the structure to absorb water, weakening its core. If the structure is close to the sea, humidity carries salts that are absorbed by the earthen fabric. This may also happen if the water table is high or if water stagnates frequently at the base of a wall. In this case, salts may be absorbed at the foot of the structure and then migrate to the surface during the crystallization process. Stagnant water may progressively undercut the base of the wall, as shown in figure 9.5. In another example, at the archaeological site of Merv in Turkmenistan, the rise of the water table due to agricultural irrigation has caused extensive damage.

Animal burrowing is also frequent in this environment, as is the growth of vegetation at the base of the walls or of lichens and mosses on their surfaces (figure 9.6). Roots either within or at the base of walls may weaken the entire structure as the plant grows (figure 9.7). If dead, the rotting vegetation will leave voids into which water may penetrate, further weakening the core of the structure.

Freezing/thawing processes are especially damaging, as freezing water breaks up the earthen material, creating cracks and voids once the water returns to its liquid state. Earthquakes are

FIGURE 9.4. View of a structure at Hili 2, Al Ain, United Arab Emirates (UAE), showing a collapsed wall following a heavy downpour. *Source:* Aqeel Ahmed Aqeel, DCT Abu Dhabi.

FIGURE 9.5. View of a structure at Hili 2, Al Ain, UAE. The bottom of the wall has been undercut by stagnant water and rising damp. *Source:* Gaetano Palumbo.

FIGURE 9.6. Portion of a structure at the archaeological site of Merv, Turkmenistan, showing vegetation growth at the base and from within a wall. *Source:* Gaetano Palumbo.

FIGURE 9.7. Roots embedded in a wall at Hili 17, Al Ain, UAE. As the vegetation continues to grow, the roots may weaken the entire structure. *Source:* Gaetano Palumbo.

FIGURE 9.8. View of the earthen citadel at Arg-e Bam in Bam, Iran, showing extensive damage following a powerful earthquake in 2003. *Source:* Gaetano Palumbo.

particularly disastrous for archaeological ruins, which have lost the capacity to withstand the motion caused by seismic waves and thus behave as freestanding structures (figure 9.8).

Finally, damage to an excavated archaeological site is frequently brought on by human actions, such as vandalism, botched conservation interventions, or trampling by visitors unaware of the weakness of the structure (figure 9.9). The use of incompatible materials during the conservation process may cause further deterioration, as these may affect the overall stability of the structure or accelerate the loss of surface layers (figure 9.10).

Although war and armed conflict have also emerged as a dramatic factor in the loss of heritage, the most significant factor in the deterioration of excavated archaeological earthen structures is neglect. Neglect sums up an entire range of inactions that may derive from a lack of specialized human resources, lack of funding, absence of maintenance, or lack of an overall conservation strategy.

Neglect may also be caused by insufficient or absent management, delayed responses to problems affecting the heritage, and the lack of specific knowledge of material behavior and research on the causes of deterioration and possible remedies.

Often the sheer size of the excavated remains or standing structures makes the preservation of these ruins an almost impossible task. The site of Merv in Turkmenistan alone has almost

FIGURE 9.9. Visitors stand on a mud-brick wall in the excavation area of the buried city of Kazakl'i-yatkan, Uzbekistan. Damage to an archaeological site is often caused by human action and a lack of awareness of the fragility of earthen structures. *Source:* Gaetano Palumbo.

FIGURE 9.10. View of damage at Arg-e Bam, Iran. The outer layer of this tower, a modern addition, collapsed following the 2003 earthquake. *Source:* Gaetano Palumbo.

FIGURE 9.11. Portion of the walled city of Abdullah Khan Kala, Merv, Turkmenistan, showing damage to the foundation at the base of the wall caused by rising damp. *Source:* Gaetano Palumbo.

1,000 hectares of earthen architectural remains, both excavated and unexcavated. These include structures that are above ground and whose decay has been accelerated due to changes in the height of the water table, affecting their foundations (figure 9.11). Other sites, such as Dura-Europos in Syria or Pendjkent in Tajikistan (figure 9.12), have been extensively excavated over the last century but were never structurally consolidated and are now a mass of indistinguishable ruins. Not only is the physical fabric of these structures being lost, but also the scientific information they hold, as well as their potential to be a vehicle for social and economic growth at the local and regional level.

9.2 Conservation and Management of Earthen Archaeological Sites

Avrami, Mason, and de la Torre write, "The ultimate aim of conservation is not to conserve material for its own sake but, rather, to maintain (and shape) the values embodied by the heritage, with physical intervention or treatment being one of many means toward that end" (2000, 7). Furthermore, conservation is not an objective process, as it is biased by the values and perspectives of various individuals and interest groups. Over the past twenty years, a broader and more dynamic conceptualization of heritage values has been researched by various scholars (Avrami,

FIGURE 9.12. View of the archaeological site of Pendjkent, Tajikistan. Lack of consolidation following excavation has rendered the structures unrecognizable. *Source:* Gaetano Palumbo.

Mason, and de la Torre 2000; de la Torre 2002; Mathers, Darvill, and Little 2005; Golinelli 2015; Avrami et al. 2019; see chapter 4 in this volume for further discussion). It is important to note that a values-based approach ensures a transparent decision-making process with shared principles and procedures.

In archaeological site management, and especially in the case of earthen sites, no one-size-fits-all solutions can be adopted, as there are too many variables at play. These have to do with local capacities; with the availability of human, financial, and technical resources; and with the overall conditions of the site, the extent of the excavated remains, and the factors affecting its conservation. While a methodological approach can be traced, each site has its own characteristics and issues that require local, tailor-made solutions.

The methodological approach to the preparation of a management plan for earthen archaeological sites is similar to plans commonly developed for other categories of sites. In recent years, this process has become more participatory, including the direct involvement of local communities in many planning exercises around the world (Wijesuriya, Thompson, and Young 2013; Egloff 2019). For earthen archaeological sites, participatory planning is essential given the fragile nature of such sites. It creates a stewardship role for the local community while offering the opportunity to derive economic benefits from eventual tourist exploitation of the site. However, even in the case of sites that may attract few visitors in the future, the benefit of involving local communities in the presentation and interpretation process has proven to be positive (Grimwade and Carter 2000).

For sites that have suffered years of neglect and have lost a significant portion of their original features, there are some challenging questions to be asked in order to interpret and present these sites while respecting their authenticity:

- To what extent can the documented but lost features be repaired or rebuilt?
- Is it still possible to conduct research on a site heavily modified by modern intervention?
- Is physical intervention (either direct or indirect) necessary?

Conservation and planning activities conducted in the past twenty years at sites such as Chan Chan (Hoyle and Castellanos 2000), Huaca de la Luna (Morales Gamarra 2011), Joya de Cerén (Descamps and Castellanos 2011), and Al Ain (DCT 2018) have shown that values-based, holistic approaches have positive outcomes for such fragile sites and that public participation, educational activities, and site interpretation and presentation must be part and parcel of a comprehensive strategy that empowers local communities by making them active participants in the process.

9.2.1 Interventions

Any intervention on archaeological earthen fabric must balance the needs of physical conservation with the imperative of preserving the authenticity* of the ruin and its scientific value. For this reason, any physical intervention must be carefully assessed before putting it into practice. When faced with the conservation of an earthen archaeological ruin, some questions must be answered in order to determine the course of action that is least invasive and most respectful of the authenticity of the site and its values:

- What scientific information can still be derived from the study of the site and its material composition before any conservation intervention is put into practice?
- Would this information be altered or hidden by the conservation intervention?
- For a site that is extensively studied and excavated, is research still a priority?
- Is the scientific value of the site so high that it overrides the site's educational, social, or economic values?

Research and conservation have notoriously different time scales: archaeological research requires the painstaking analysis of all findings to obtain credible and verifiable information that is then used to interpret the remains and establish their scientific significance. It is not rare for archaeologists to find it difficult to perform excavation work while conservation activities are

* We follow here the concept of authenticity as discussed by Giovanni Boccardi, where *authenticity* is defined not by a judgment of the cultural significance of an object but by the coherence of the statements made about such significance (2019, 15).

FIGURE 9.13. Partial reburial of House 1, Rumailah Iron Age archaeological site, Al Ain, UAE. Temporary conservation solutions such as this may be carried out to minimize exposure of the site. *Source:* Gaetano Palumbo.

taking place simultaneously, as conservation activities may be considered an obstacle to the correct interpretation of scientific data. It is also true, however, that decay commences immediately after the site is exposed to the elements. As such, balancing scientific rigor and conservation imperatives may be a challenge. In some cases, temporary conservation solutions may be adopted, such as partial reburial (figure 9.13), to minimize the effects of exposure while avoiding the introduction of new materials or direct interventions on the excavated ruins. Typical layers in an archaeological reburial include a geotextile or permeable membrane placed directly over the archaeological remains to prevent direct contact with the soil followed by a layer of clean, fine sand to provide cushioning and drainage. This is often topped with a thicker layer of soil or gravel, which acts as a protective cover, stabilizing the area and shielding it from erosion and environmental factors. In other cases, the remains may be so fragile that they require immediate attention by conservation specialists, who in turn will have to stabilize the archaeological remains by either introducing external supports, improving drainage, or using consolidation interventions.

It is wrong to assume that archaeologists and conservators are in competition or that the scope of their work is divergent. Let us take the example of material composition analysis. To an archaeologist, this analysis will have research objectives, as it may provide information on the technology of earth construction over a determined period, allow the identification of the sources of this material, or even contribute to the precise dating of the site. Changes in the composition of earthen materials may provide clues to understanding different construction phases within the same site.

To a conservator, these analyses will help in identifying the composition of conservation materials that are compatible with the original or may provide information on the causes of decay observed on-site. This example shows that coordination among research and conservation specialists is essential in order to establish an effective research program that will benefit both scientific and conservation needs.

This comparison suggests that the design of a research project should include a clear understanding of the final outcome of the project. If the intention is ultimately to have the site presented to the public, the plan should provide temporary protection measures while scientific investigations are being carried out. If there are no immediate plans for public display, then more permanent types of protection should be considered, such as total reburial.

For sites that are already excavated, new documentation of the remains that are left exposed may be required, as well as an assessment of the scientific values the site may retain. Such assessment would then be balanced against the need either to prepare the site for visitation or to rebury it to avoid further decay. Regarding sites that are left exposed and will be presented to visitors, interventions must be substantial and should include long-term conservation plans, taking into consideration the need for regular maintenance and periodic interventions on both the archaeological features and their surroundings. Interventions range from the consolidation of the earthen materials using various methods (see chapters 7 and 8 in this volume), to the application of sacrificial layers or the capping of walls, and also include the provision of effective drainage to avoid water pooling in the site as well as the construction of protective shelters (figures 9.14 and 9.15). The latter represents a solution that in many cases avoids the need to apply consolidants or modern materials to the archaeological fabric. However, the introduction of an object that has a visual impact on the site and that modifies the environment in which the site exists creates other problems in terms of conservation and management of the archaeological features (Aslan et al. 2018). In fact, shelters themselves require their own regime of maintenance, while the protected features need constant monitoring to ensure that the sheltering does not add new conservation challenges.

9.2.2 Presentation and Interpretation

Presenting and interpreting an earthen archaeological site gives rise to challenges in addition to those commonly faced by archaeologists and interpretation specialists. This is because of the fragile nature of earthen remains and the fact that they often have already lost many of their recognizable features due to erosion and decay. Although the following questions may apply to any archaeological site, they are particularly appropriate in the case of earthen sites:

- Is the reconstruction of at least parts of a site an alternative to consider in order to facilitate interpretation and presentation?

FIGURE 9.14. Temporary shelter erected over an excavated house at Hili 2, Al Ain, UAE. *Source:* Gaetano Palumbo.

FIGURE 9.15. Permanent shelter constructed over the Bronze Age gate at the archaeological site of Tel Dan, Israel. *Source:* Gaetano Palumbo.

- To what extent may partial reconstructions or the application of coatings or sacrificial layers modify the authenticity of the site? Are the site values improved or diminished by such interventions?
- When interpreting a site for the public, who guides the narrative? Who decides what should be presented and how?

Physical reconstructions must be guided by a rigorous process in which conservation meets archaeological interpretation. Graphic reconstructions and illustrations can be used to help the public better understand how a site looked and guide them to better appreciate the remains in front of them. Moreover, it may be difficult to explain why a site has changed so significantly from the time of excavation. Interventions that put an "envelope" around the monument may be counterproductive, as they may hide, more than enhance, the monument itself.

Sheltering may also be problematic in some cases, especially when the link between the site and its landscape is broken by the presence of a modern structure. On the other hand, shelters can help demonstrate to the public the fragile nature of these sites and the impact that the process of excavation to conservation and presentation has on them.

Digital technologies may assist with the interpretation and presentation of earthen archaeological sites, although there are obstacles to their deployment, such as the cost to purchase equipment and produce digital models of the site and the rapid aging of the software and hardware used for such projects. In an ideal scenario, 3D models of single-site components or an entire site can be easily generated and provide visual support for presentation in a museum or visitor center environment or through apps installed on visitors' smartphones or tablets (figure 9.16).

FIGURE 9.16. A 3D model derived from the laser scanning project conducted at the site of Hili 17, Al Ain, UAE, in 2011. *Source:* DCT Abu Dhabi.

As presentation strategies grow more digitally sophisticated and as our approach to interpretation evolves to include stakeholders in the formulation of narratives, the possibilities to engage the public become greater. We could improve public perception of earthen architecture not as a poor substitute for other, apparently more solid construction materials but as a sophisticated architectural system perfectly adapted and appropriate to the local environment.

9.3 Case Studies

Two case studies are presented here to illustrate the issues discussed in this chapter. The first is the ancient city of Merv (figure 9.17), in southern Turkmenistan, a vast site that has suffered from rapid decay over the past sixty years, where partial reburial was experimented with to conserve the trenches left open by previous research projects. The second is Rumailah, in Abu Dhabi, UAE, where a management planning exercise was conducted to address the long-term conservation and use of the site.

The World Heritage Site of Merv is one of the largest earthen architecture archaeological ensembles in the world and is characterized by a series of fortified towns built adjacent to one another over the past four millennia (Herrmann 1999; figure 9.17). A research, conservation, and site management project was conducted over several seasons (Williams et al. 2002; Williams and Kurbansakhatov 2003). In 2002–3, the field activities included a pilot project to address the pressing issue of the numerous trenches left open by previous excavations. The harsh environmental conditions of the site, where very high temperatures in summer yield to extremely frigid conditions in winter, have exerted a toll on the conservation of many structures that were either

FIGURE 9.17. The archaeological site of Merv, Turkmenistan. *Source:* Gaetano Palumbo.

visible on the surface or revealed by excavation activities. Moreover, the development of irrigation agriculture in the region surrounding the site caused the water table to rise to levels never reached in the history of the site. In fact, some areas of the site remain constantly wet, even in summertime. This has caused visible decay at the bases of most of the walls of the extant structures due to either water stagnation or salt accumulation following capillary action, in which salts migrate from the ground to the walls (see figure 9.11).

This pilot project involved the documentation of a trench and the design, implementation, and monitoring of its partial reburial. Louise Cooke identified problems that were very difficult to overcome in structures situated under the surrounding ground level for the most part. These problems included water stagnation and the inability to provide for proper drainage, the limited significance of structures gravely compromised by decay, and the cost and usefulness of more radical solutions such as the building of shelters (Cooke 2007, 100). Cooke's study identified ideal characteristics in planning reburial:

- quick implementation after excavation
- use of compatible fill material (preferably the same soil excavated from the trench, made free of cultural material through screening)
- reversibility (clearly showing the separation between excavated and unexcavated areas)
- compaction of the fill material
- proper drainage
- treatment of the spoil heaps to avoid changes in the natural drainage (100–102)

Since the pilot project for Merv was conducted under less than ideal conditions, the monitoring of the backfill exercise revealed obstacles due to the difficulty of reestablishing proper drainage, the presence of insect activity (insects were attracted to the moist new soil introduced into the trench), the high maintenance required for those structures emerging from the trench that had to be protected with sacrificial mud layers, and the ethics of using an expensive geotextile material in the reburial operation at a site where local capacities will not allow access to similar materials in the future.

The second case study concerns the archaeological site of Rumailah, which is one of the serial components characterizing the World Heritage Site of Al Ain. It preserves the remains of an Iron Age village. Some of its features were excavated between the 1960s and the late 1990s by various missions. No conservation was ever conducted on the site, and the Al Ain site management plan does not consider visitation as an option in the long term. For this reason, a limited site management planning exercise was carried out by a team from the Abu Dhabi Authority for Culture and Heritage (now known as the Abu Dhabi Department of Culture and Tourism; Palumbo et al. 2014).

The scope of the project was to develop a methodology for the preparation of in-house site management planning dedicated to "invisible" sites—that is, relatively "minor" sites for which

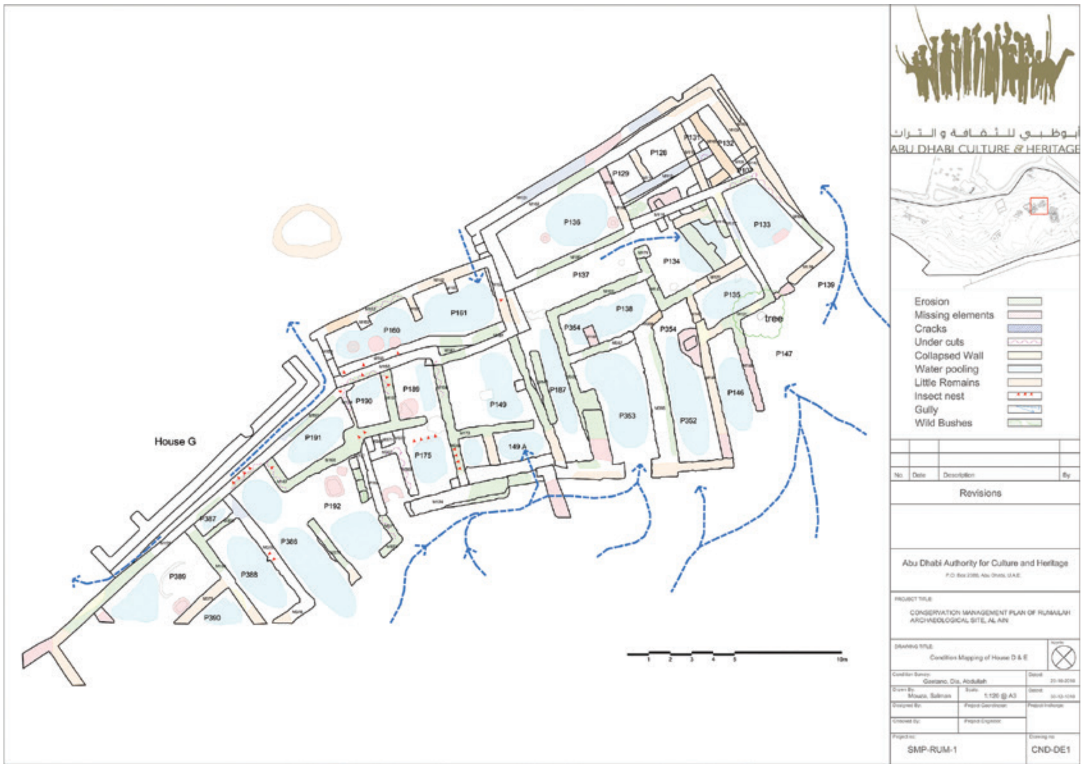

FIGURE 9.18. Condition assessment of the site of Rumailah, Al Ain, UAE, showing water movement and various deterioration conditions. *Source:* DCT Abu Dhabi.

no immediate development programs were envisaged but that still retained values that could, on the one hand, benefit the education of new generations of archaeologists and conservators in the country and, on the other hand, still contribute to understanding the cultural landscape of the Emirate. Documentation conducted on-site revealed the decay that had affected the exposed masonry over the years (figure 9.18). This condition assessment aided in the identification of the causes of the decay and possible remedial actions.

The process helped prioritize actions to protect the site from selective reburial to limited repairs while allowing the option of adding any new data to the body of knowledge derived from previous projects. Besides becoming a training ground for archaeology students nationwide, the site may also be a place where conservation practices can be taught and new techniques tested (Palumbo et al. 2014, 159–60). Scientists and researchers worldwide could potentially be involved as well.

9.4 Conclusions

The fragility of earthen archaeological sites is such that many of them have been lost after excavation. But this should not be their destiny. Advances in our knowledge of earthen materials have made it possible to intervene and prevent damage before it occurs or to limit the effects of weather and human activities.

Archaeologists are more aware today than in the past of their ethical responsibility to site preservation. Solutions are available to preserve the archaeological records even when a site will not be shown to the public, with reburial being the most common and cost-effective solution for the long-term preservation of such structures. Values-based site management planning has demonstrated its usefulness in the case of earthen sites, and alternative approaches to public display or reburial can also be adopted. As for the many sites that have been left to decay, while reburial will remain the preferential treatment, consideration should be given to using them to train new generations of archaeologists and conservators or to experiment with conservation treatments in programs that may involve researchers on a global scale.

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REHABILITATION AND ADAPTIVE REUSE OF EARTHEN BUILDINGS

10

Overleaf: **Rehabilitation and adapted reuse of Jahili Fort, Al Ain, United Arab Emirates. J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.**

10

REHABILITATION AND ADAPTIVE REUSE OF EARTHEN BUILDINGS

Benjamin Marcus and Aqeel Ahmed Aqeel

10.1 Adapting Earthen Heritage Buildings

This chapter discusses the rehabilitation of earthen buildings, specifically the adaptation of earthen heritage sites for contemporary use. While the use and reuse of earthen heritage buildings is necessary for their long-term survival, there are many obstacles, including the negative perception of earth as a material for the "poor," the loss of traditional building knowledge to conduct compatible repairs, the challenges of adapting historic living spaces to modern requirements, and the lack of financial resources and/or incentives available for restoring such sites. Reuse is the only way to sustain an earthen building and provide new economic opportunities, which can in turn be a catalyst for revitalizing the structure itself, the building context, and the surrounding community. However, such adaptation requires significant investment and must generate enough financial, social, or cultural value to cover the costs of rehabilitation and maintenance while preserving the historic fabric and values of the site.

Creating a plan for the rehabilitation of an earthen heritage place involves a values-based approach (see chapter 4). In this chapter, we examine the rehabilitation process, including the information gathering necessary for understanding the building and formulating a plan, the evaluation of significance, the definition of attributes, and the tolerance for change, as well as design and operational principles and guidelines for a rehabilitated historic site. The rehabilitation of the Kasbah Taourirt project in Ouarzazate, Morocco is used to better explain each case. The chapter ends with two case studies of rehabilitation projects for earthen heritage buildings and sites in the region.

10.2 Rehabilitation Planning

The preservation of historic and architectural values is outlined in the Venice Charter (ICOMOS 1964), which states that "the conservation of monuments is always facilitated by making use of them for some socially useful purpose. Such use is therefore desirable, but it must not change the layout or decoration of the building. It is within these limits only that modifications demanded by a change of function should be envisaged and may be permitted" (article 5). The US Secretary of the Interior's *Standards for Rehabilitation* define rehabilitation as "the process of returning a property to a state of utility, through repair or alteration, which makes possible an efficient contemporary use while preserving those portions and features of the property which are significant to its historic, architectural, and cultural values" (Morton et al. 1992). The Burra Charter (Australia ICOMOS 2013) outlines key guidelines aimed at preserving significant values, including the tenet that a place should have a compatible use (article 7.2, 4), that adaptation is acceptable only where it has minimal impact on the cultural significance of the place (article 21.1, 7), and that adaptation should involve minimal changes to significant fabric, achieved only after considering alternatives (article 21.2, 7). Also critical is assessing the significance of the place to stakeholders who may currently use or value it (figure 10.1).

Guidelines for planning the reuse of historic buildings have appeared in previous publications (see Kerr 2013; Heritage Office and RAIA 2008). These guidelines include practical and clear directives, the focus of which includes understanding the significance of the place, finding a use compatible with that significance, and determining the level of change appropriate to it (Heritage Office and RAIA 2008). Also addressed are management concerns such as providing for the reversibility and maintenance of the rehabilitation, conserving the setting and views of the place, and revealing and interpreting the significance of the building. In this chapter, the previously mentioned steps in the conservation and rehabilitation process are discussed within the context of earthen heritage.

10.2.1 Understanding the Building and Its Evolution

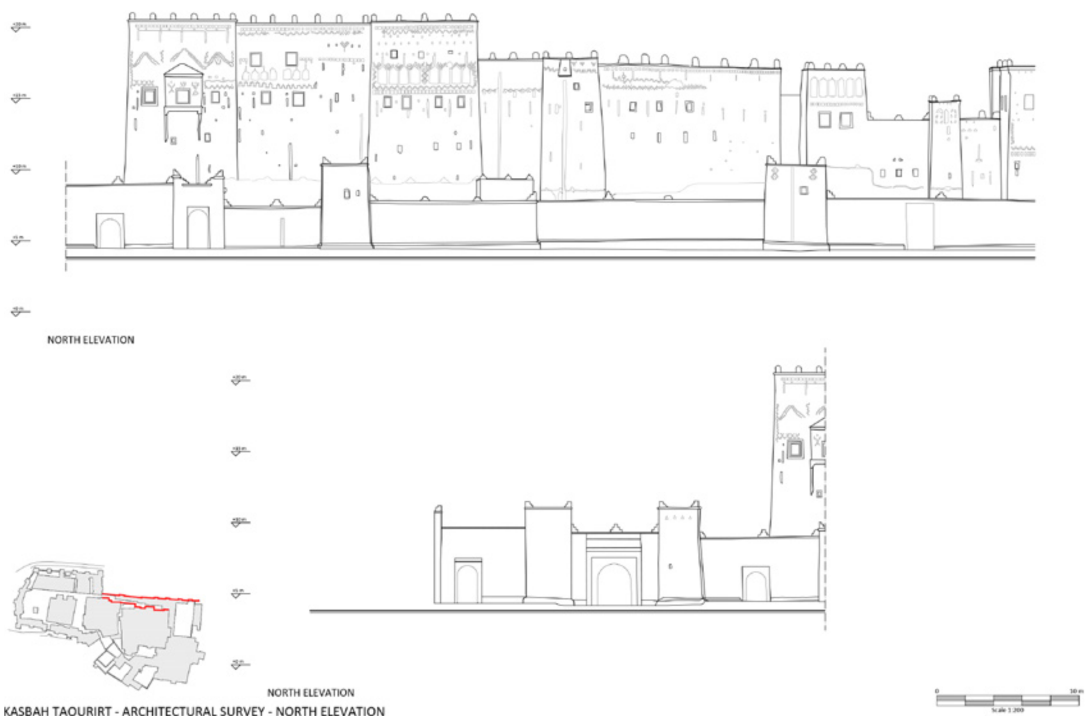
Rehabilitation projects require understanding the physical layout of a building, its major features, and its historic and current significance. This information-gathering process includes complete documentation of the site, including plans, sections, elevations, and photography or scanning data (figure 10.2). In order to record the history and significance of the building, archival data such as historic photos, aerial images, building records, and other historical sources should be consulted.

For earthen heritage, original construction documents and building records were rarely produced, much less preserved. In these cases, oral history is an important tool for determining the historical occupants of a building, the use of its spaces, and its significance to the community (figure 10.3). Historic images (paintings and/or photographs) and written descriptions and accounts are often also available and provide rich information on past condition and use. Archaeological excavation is also a critical source of information, particularly for structures built in areas with centuries of continuous occupation. Limited exploratory test pits at the foundation level carried out by an archaeologist can reveal information on the previous occupation, use of space, and approximate dates of construction or alteration based on horizons present and the dating of ceramic, metal, and organic artifacts.

Historic aerial photographs, available for many regions with earthen architecture starting in the early twentieth century, can also provide important information on previous alterations to

FIGURE 10.1. Kasbah Toaurirt, an earthen monument and settlement with a living community. *Source:* Scott Warren for the J. Paul Getty Trust.

(A)



(B)

FIGURE 10.2. (a) Kasbah Tourirt, Ouarzazate, Morocco. (b) Base documentation showing the elevations of the complex. *Source:* Carleton University CIMS for the J. Paul Getty Trust.

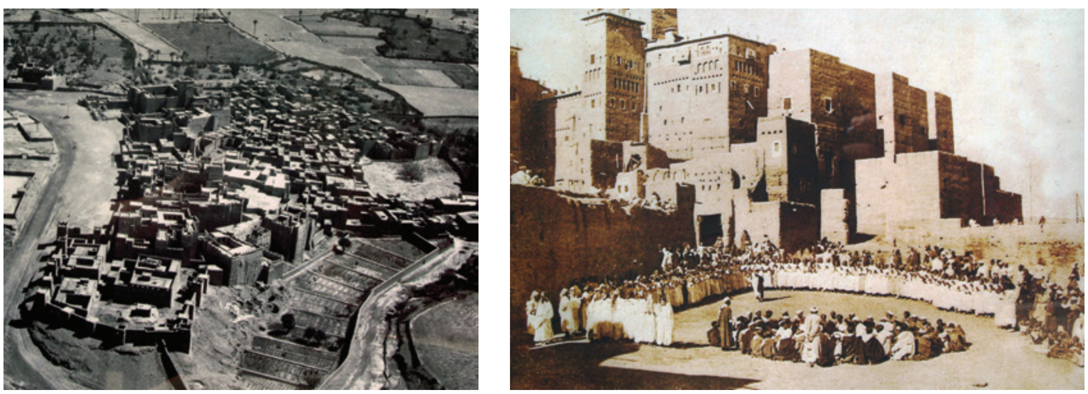
building plans, roads and circulation routes, evidence of abandonment through collapsed roofs, and past restorations (figure 10.4).

From these combined data sources, one can understand the building's history and its construction phases, past uses, and associations with historic persons and events.

10.2.2 Determining Significance, Attributes, and Tolerance for Change

Rehabilitating or conserving an earthen structure often requires significant change, even if the goal is simply to protect the structure against deterioration. Often, the reuse of an earthen building implies restoring or strengthening roofs, drainage, and exterior plasters; adding services

FIGURE 10.3. Oral history interviews conducted to document the traditional use of space in the kasbah. *Source:* J. Paul Getty Trust.



(A) (B)

FIGURE 10.4. Historic aerial photographs and images provide vital information necessary for understanding building use and conditions over time. *Source:* CERKAS.

such as plumbing, electricity, and climate control; installing lighting, doors, and windows; and even altering spatial arrangements to meet use requirements. These changes should be based on a sound understanding of the building's significant features.

According to the Burra Charter (Australia ICOMOS 2013), this process begins with an assessment of a building's overall significance by its stakeholders, taking into account aesthetic, historic, scientific, cultural, and other common values. Before any project planning, a statement of significance outlined for the building should articulate these values and reflect the building's meaning both for its stakeholders and for the wider community.

The next step is to understand what physical aspects of the building represent these values, sometimes referred to as attributes. Attributes are the physical embodiment of the identified values; for example, historic decorative features may have aesthetic value, a defensive tower can represent historic value, and common spaces may embody social value. The goal is to identify the aspects of the building that are highly significant and therefore cannot be changed (e.g., decoration, form, openings) versus features of lesser significance that may be altered without losing the authenticity and significance of the building.

An example of this process was carried out at the Kasbah of Taourirt in Ouarzazate, Morocco (figure 10.5). Stakeholders in that project, including the Ministry of Culture, the Municipality of Ouarzazate, and the project team members, identified the values of the site, drafted a statement of significance, and then mapped these values using documentation of the site to determine which elements were most significant decorative features, forms, circulation, etc. (Marcus, Cancino, and Boussalh 2017).

10.2.3 Developing Conservation Policies

Conservation policies are a set of directives that define specific actions taken to preserve the significance of a heritage place. Policies can guide both the design phase of a rehabilitation

FIGURE 10.5. Mapping of values at the Kasbah of Taourirt, Ouarzazate, Morocco. *Source:* Elena Macchioni for the J. Paul Getty Trust.

project and the operational phase, or work that is carried out to maintain or run a historic property. Kerr (2013) defines conservation policies as rules that guide the future care and development of a place. The main goals of conservation policies are to:

- retain or reveal significance,
- identify feasible and compatible uses,
- meet statutory requirements,
- work within procurable resources, and
- anticipate opportunities and threats (Kerr 2013).

Policies often define a vision for reuse based on retention of significance, treatment of specific elements intended to reduce the intrusion of new systems and services, and retention of the setting and associations of the buildings, including views and natural spaces.

Design and operational policies were developed for the Kasbah of Taourirt in Morocco. Activities carried out as part of these policies included the following:

- holding community stakeholder meetings to discuss priorities for preservation and use of the kasbah
- identifying the values of the site, negotiating a statement of significance, and mapping relative levels of significance and character-defining features in order to guide the rehabilitation proposal and ensure appropriate uses of significant historic spaces
- carrying out a condition assessment of the kasbah
- developing overarching policies to guide the rehabilitation that respect international standards and take into account the condition, significance, and values of the site
- defining physical intervention strategies, including practical conservation approaches and programming for future use of the structures and public areas
- developing operational guidelines for maintenance of the site

10.3 Rehabilitation of Earthen Buildings: Case Studies from Al Ain

10.3.1 Al Jahili Fort, Al Ain, United Arab Emirates (UAE)

10.3.1.1 Background

Al Jahili Fort has come to symbolize Al Ain and its historic past. Due to its prominent and central location in this oasis city—a World Heritage Site—the fort has become a visual landmark and distinguishes itself from other such structures through its round, terraced tower; large number of rooms; and vast number of enclosed spaces (figures 10.6 and 10.7). It is a source of pride for the Al Ain community. The iconic shape of its tower can be seen in logos for the local football club, on water-bottle labels, and on other urban landmarks.

FIGURE 10.6. Exterior view of Al Jahili Fort, Al Ain, UAE. The shape of its iconic, terraced tower, at left, has been incorporated into logos for local organizations and other landmarks. *Source:* DCT Abu Dhabi.

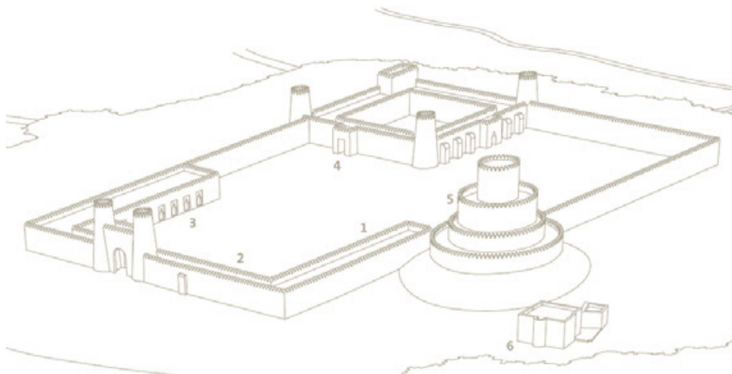


FIGURE 10.7. Isometric view of Al Jahili Fort. *Source:* DCT Abu Dhabi.

The fort was built in the 1890s by Sheikh Zayed the First, who is considered one of the most successful of the Al Nahyan rulers at that time. Intended as a symbol of power and political stability, the fort was also used as a summer residence (Sheehan 2012). From the 1950s to the 1970s, the building was used as an army base, and modifications were made to its layout and appearance. Although some major restoration activities took place in the 1980s, the fort remained closed, and visitors were restricted.

10.3.1.2 Rehabilitation Project

Because of its high political and symbolic significance, Al Jahili Fort was the subject of the first comprehensive rehabilitation project by Abu Dhabi's Department of Culture and Tourism (DCT), which began in 2007 (Chabbi et al. 2012). The objective of the project was to adaptively reuse the fort and open it to the public. Conservation was aimed at preserving the historical layers while designing modifications for the building to host a visitor center and two exhibition wings.

An innovative high-tech cooling system was implemented to provide a controlled environment for the collection while being sensitive to the building's historic fabric (El-Masri and Sheehan 2009). This system takes advantage of the thermal insulation characteristic of the earthen walls and improves upon it by cooling the walls, which eventually cools the spaces (figure 10.8). This cooling system was necessary given the extreme climatic conditions and offered the added benefits of quiet and consistent climate control that did not require intrusive air ducts or vents. The modifications to the fort have retained the historic character of a traditional earthen building while enhancing its functionality for modern use (figure 10.9).

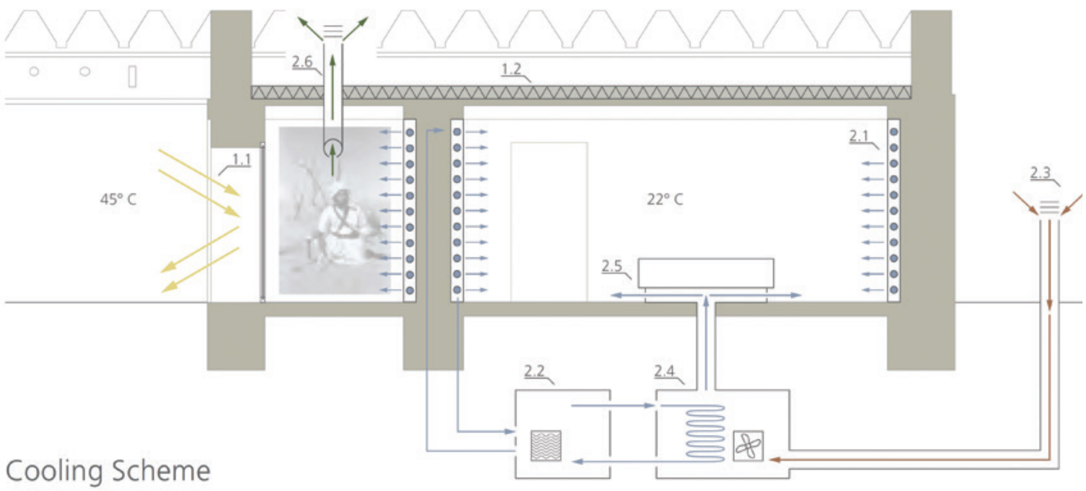


FIGURE 10.8. The schematic design of a network of chilled water pipes laid beneath the mud plaster that form an energy-efficient radiation cooling system introduced to provide a controlled environment at Al Jahili Fort. *Source:* DCT Abu Dhabi.

FIGURE 10.9. View of an area of the visitor center at Al Jahili Fort after completion of the rehabilitation project. The historic character has been retained and showcased in the basement floor by indicating the different archaeological stratifications and presenting the material history of the place across the timeline. *Source:* DCT Abu Dhabi.

A multidisciplinary team was involved in the project. Architects developed construction drawings to restore the buildings and redesigned the interiors, a curator oversaw the cultural content, an archaeologist advised on the archaeological significance of the building, and a conservator was responsible for the preservation of the building's fabric. In addition, traditional craftsmen were brought on who had experience working with local materials. Now serving as a visitor center featuring exhibitions and public events, the fort is again a center of social and cultural significance for the community of Al Ain.

10.3.1.3 Implementation Overview

The project began with site investigations that included archaeological, material, structural, termite, and condition assessments. Although good photographic archives and oral histories were available, archaeological investigation was instrumental in gaining a detailed understanding of the original fabric, which in turn informed the site's works and design. After removing the first nonsignificant layers of plaster from the original walls, a thorough documentation of the layers underneath was carried out. In addition, archaeological excavations brought to light more precise information that helped in the design of the mechanical, engineering, and plumbing (MEP; figures 10.10 and 10.11).

Structural assessments were made to understand the building's structural behavior, indicating any issues and responding with the proper solutions. These solutions were implemented using a minimal intervention approach while taking into consideration the historical and archaeological importance of the fabric. Examples of these solutions included reinforcing the foundations of

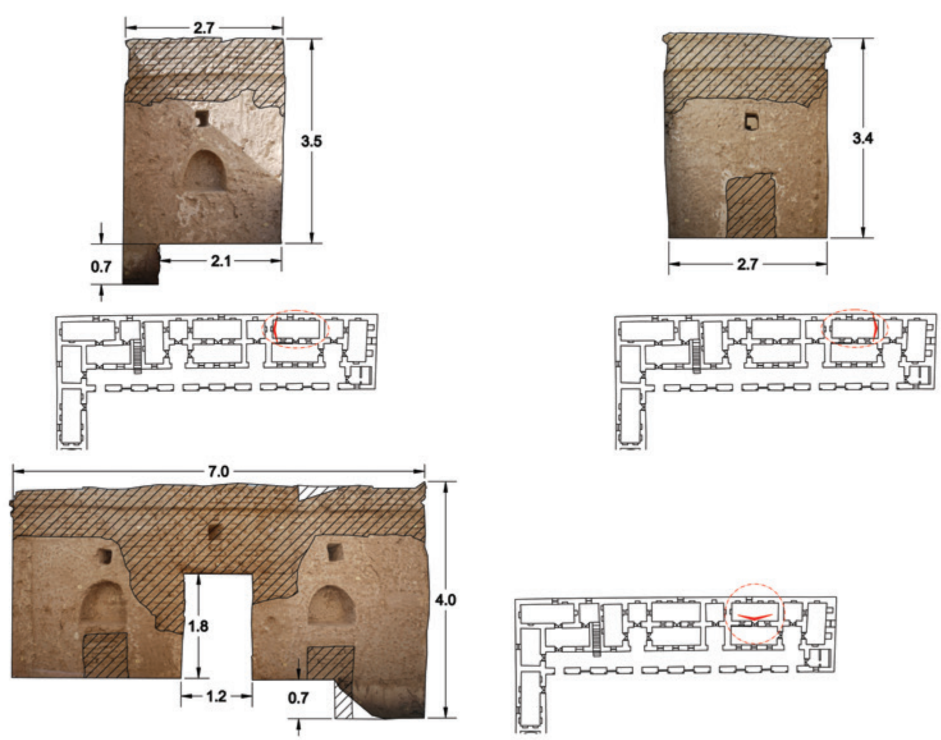


FIGURE 10.10. Documenting the different phases of the wall fabric. *Source:* DCT Abu Dhabi.

FIGURE 10.11. Building investigation after removing the first layer of plaster. *Source:* DCT Abu Dhabi.

the building's corners, installing wooden beams in long-spanned spaces, and maintaining regular shoring of the walls during construction (figure 10.12).

Following the assessments, the site works consisted of several major tasks that began with the dismantling of the roof and proceeded with the removal of 1980s nonsignificant plaster; excavation of service trenches for MEP; material preparation; treatment and installation of wooden elements; installation of the modern cooling system; application of new plaster; flooring; laying of the roofs, including the waterproof layer; sitewide enhancement; exhibition installation and wayfinding; replacement of the fixtures; activation of the spaces; and finally, opening it to the public. To illustrate, three of these stages in the fort's temporary exhibition space are shown: installation of the cooling system and MEP (figure 10.13); application of the first layer of plaster, backfill, and roof (figure 10.14a); and the space after placement of the final plaster, fixtures, doorways, and flooring (figure 10.14b).

The fort officially opened in the fall of 2008 (figure 10.15). Since then, it has hosted many events and welcomed visitors to Al Ain from around the world. In 2010, Al Jahili Fort received the International Architecture Award from the Chicago Athenaeum Museum of Architecture and Design and the European Centre for Architecture Art Design and Urban Studies in Dublin. The complex went on to win the Terra Award in 2016 in the category of Interior Layout and Design.

FIGURE 10.12. Photo of the south wing of Al Jahili Fort. Supports were installed to stabilize the corner walls while the foundations were reinforced underground. *Source:* DCT Abu Dhabi.

FIGURE 10.13. View of the temporary exhibition space at Al Jahili Fort during installation of the cooling system and MEP. *Source:* DCT Abu Dhabi.

(A) (B)

FIGURE 10.14. (a) View of the temporary exhibition space at Al Jahili Fort after application of the first layer of plaster, backfill, and roof. (b) View of the temporary exhibition space at Al Jahili Fort following placement of the final plaster, fixtures, doorways, and flooring. *Source:* DCT Abu Dhabi.

FIGURE 10.15. Opening ceremony at Al Jahili Fort in 2008. *Source:* DCT Abu Dhabi.

10.3.2 Muwaiji Fort, Al Ain, UAE

10.3.2.1 Background

Muwaiji Fort (Qasr Al Muwaiji) is located in Muwaiji Oasis, one of the six oases in Al Ain and a subcomponent of the Al Ain World Heritage Site. It was built by Sheikh Zayed the First in the early twentieth century, after Al Jahili Fort. A mud-brick structure, Muwaiji Fort encompasses an area of four thousand square meters, with three square towers instead of Jahili's round towers (Power and Sheehan 2011). This makes it architecturally unique compared to other forts in the region (figures 10.16 and 10.17). Like most of these forts, it has a mosque nearby, on the south side next to the main gate (figure 10.18).

From 1944 to 1966, the fort was occupied by Sheikh Zayid bin Sultan, the youngest of four sons of Sheikh Sultan bin Khalifa, and it became his palace and *diwan* (administrative offices; Power and Sheehan 2011). His eldest son, the late Sheikh Khalifa bin Zayed Al Nahyan, was president of the UAE until 2022. He was born at Muwaiji Fort, which added value to the significance of the site.

10.3.2.2 Rehabilitation Project

Between 2009 and 2015, a rehabilitation project was carried out at Muwaiji Fort with the goal of opening it to the public. A new building was envisioned that would house a permanent exhibition for HH Sheikh Khalifa bin Zayed, where visitors would learn about the archaeology and history of the place and experience the old life in the fort. Other cultural and social activities would also be hosted there.

In conceptualizing the design, project team members sought to introduce a new, modern venue in which to host the exhibition, integrating it with the fort's layout while respecting the building's architectural spirit and without impacting the underground archaeology. A major site enhancement and landscape design was inspired by the oasis theme. The northwest earthen tower was rehabilitated to allow public access to the new exhibition; it now has a climate control system with audiovisual elements and *majlis* (sitting areas for cultural and social gatherings) on the top floor.

Prior to the start of construction, an archaeological investigation was done in the courtyard and around the building to define the existing underground archaeological features that would help direct the overall design. In addition, a hypothetical archaeology line was established as a "red line" or boundary not to be crossed by the new building. Another hypothetical line, this one from the top, indicated the height limit of the walls with respect to the fort's architecture and visual integrity. These two lines were the main parameters that guided the design of the new building (figures 10.19 and 10.20). It was decided to make the walls of the new building transparent to maintain a connection with the open courtyard.

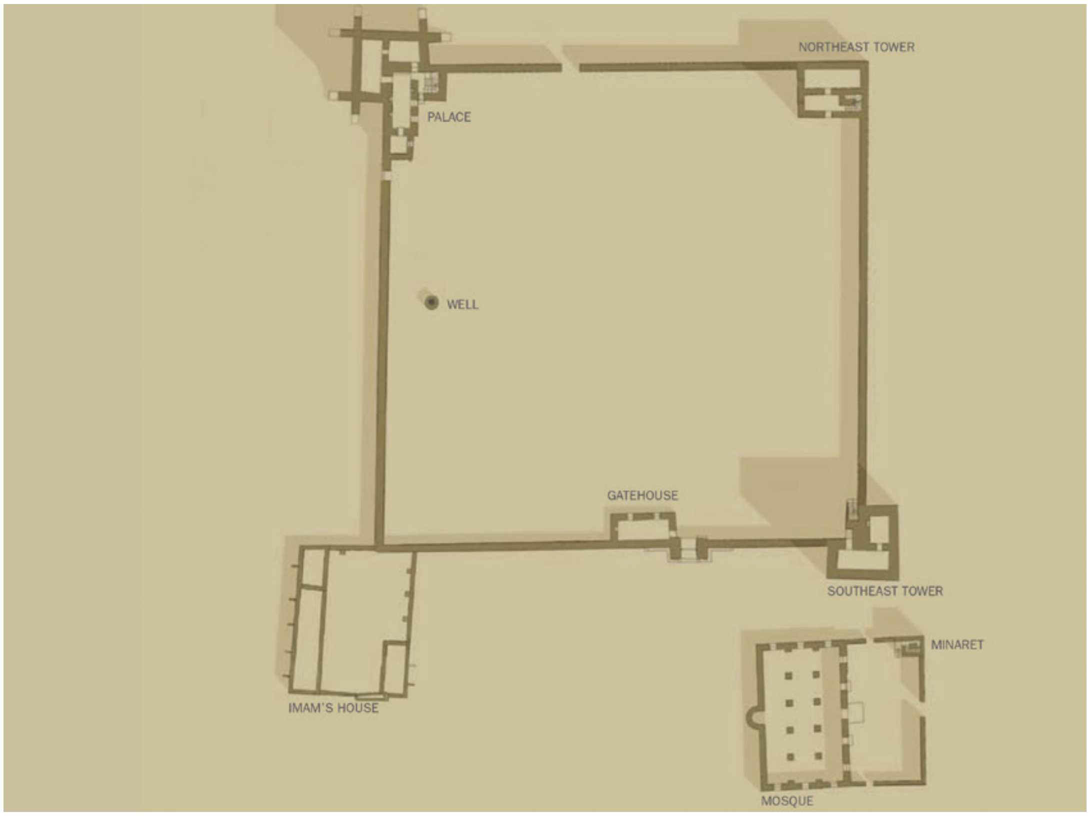


FIGURE 10.16. Site layout with the different components. *Source:* DCT Abu Dhabi.

FIGURE 10.17. Panoramic view of the fort from outside. *Source:* DCT Abu Dhabi.

FIGURE 10.18. The fort before the project. The two photos on the right show the mosque near the fort. *Source:* DCT Abu Dhabi.

10.3.2.3 Implementation Overview

Construction of the new venue was done in parallel with conserving the existing building (figure 10.21). Structural improvements were undertaken at the south main gate and the northwest tower. The stone layer at the bottom of the walls, which had been added in 2005, was dismantled and replaced with mud bricks. A careful conservation was also performed on the courtyard water channels as well as the southeast and northeast towers (figure 10.22).

The northwest tower was a hot spot of conservation activity during the project, since it was the only tower out of the three that was rehabilitated and integrated into the new exhibition venue. One of the challenges was to restore the old historic wooden lintels. These lintels, which spanned the doors and windows of the tower, were extensively deteriorated. After careful condition assessment and lab testing, conservation methods were carried out such as epoxy resin injection into the lintels to improve their condition and strength (figure 10.23a). Another challenge at this tower was the structural load-bearing capacity of the floors to receive visitors. The solution involved retaining the roofs, which were made from traditional palm beams, and installing new floors built from laminated wood beams. These beams were carefully inserted and integrated with the roof without compromising the building's integrity.

The main south gate presented another issue. After the top plaster was removed, it was discovered that the two columns of the gate were constructed in two different phases. Unfortunately, these two phases were not integrated using the best building techniques, which could lead to failure. The building fabric was historically significant and could not simply be reconstructed. Following a thorough structural assessment, the issue was resolved with an innovative solution that employed a geogrid consolidation system for both columns (figures 10.23b and 10.24).

In the fall of 2015, Muwaiji Fort and its new, permanent exhibition venue opened to the public in a national ceremony. Since then, the fort has maintained its status as an Al Ain destination for both the local community and tourism (figures 10.25 and 10.26).

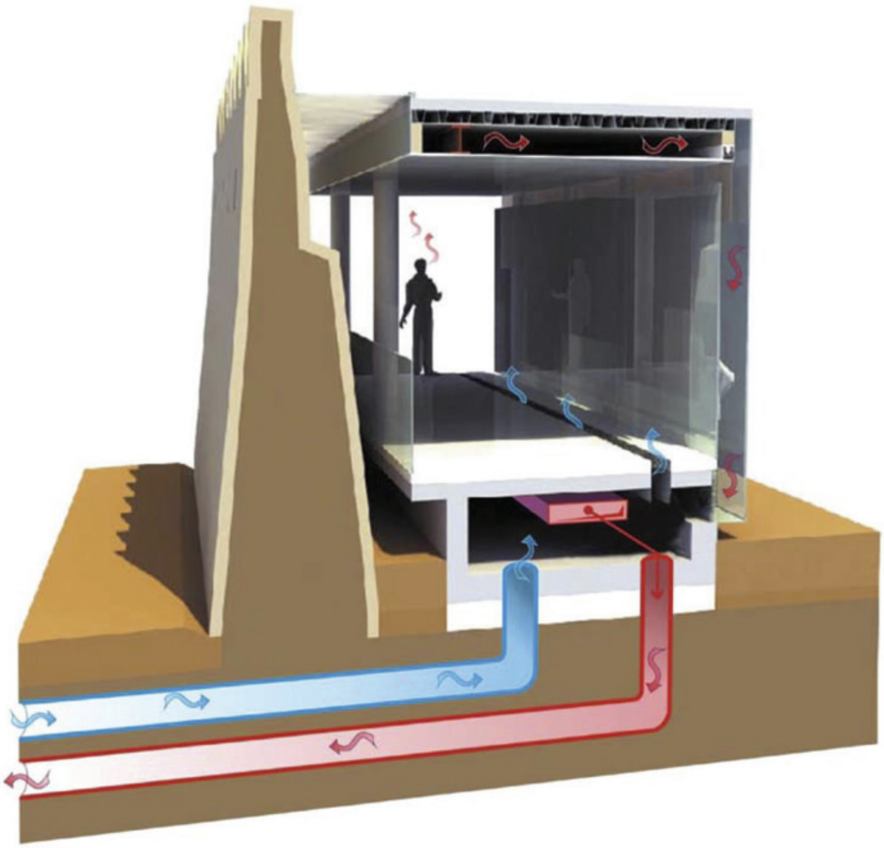


FIGURE 10.19. Schematic drawing showing plans for the installation of utilities. *Source:* DCT Abu Dhabi.

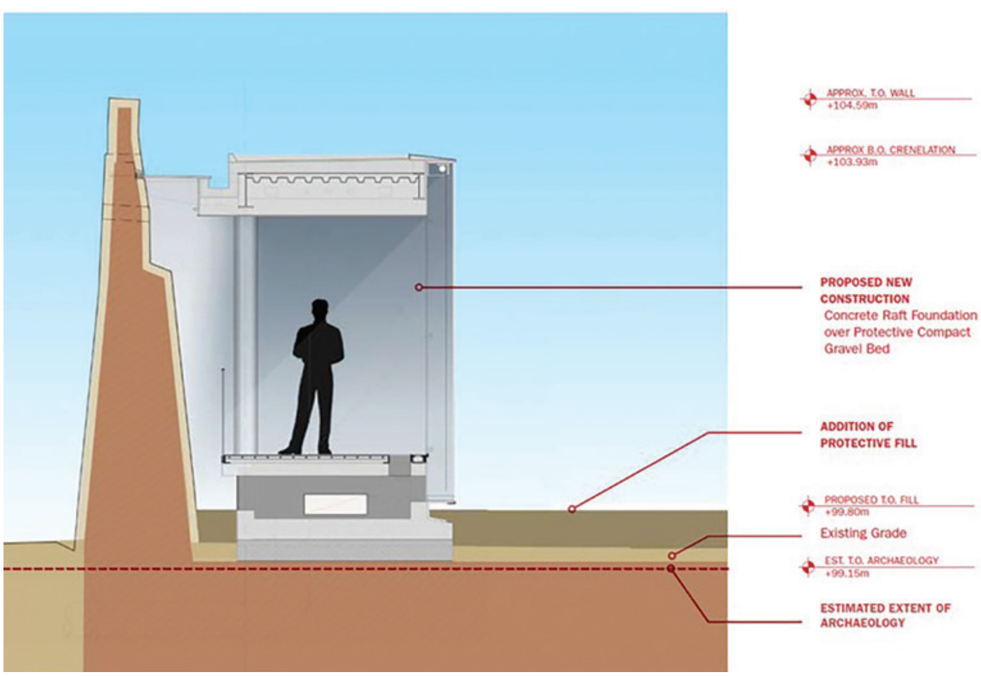


FIGURE 10.20. Schematic drawing showing the archaeology line and the top of the fort wall as design boundaries for the new construction. *Source:* DCT Abu Dhabi.

FIGURE 10.21. Photo in 2010 showing a general view of the courtyard of Muwaiji Fort during the rehabilitation project. Construction of the new building to house the permanent exhibition can be seen at the upper right. *Source:* DCT Abu Dhabi.

FIGURE 10.22. Reintegration of the mud bricks in the base of the walls. The adjacent traditional water channels are cleared and ready for consolidation. *Source:* DCT Abu Dhabi.

(A)

(B)

FIGURE 10.23. (a) A technician injects epoxy resin into a wooden lintel in the northwest tower of Muwaiji Fort to help improve its condition following conservation. (b) Detail of a column of the south gate at Muwaiji Fort. A geogrid compensates for poor connection between building phases and transfers the tensile forces to a larger area instead of a localized point. *Source:* DCT Abu Dhabi.

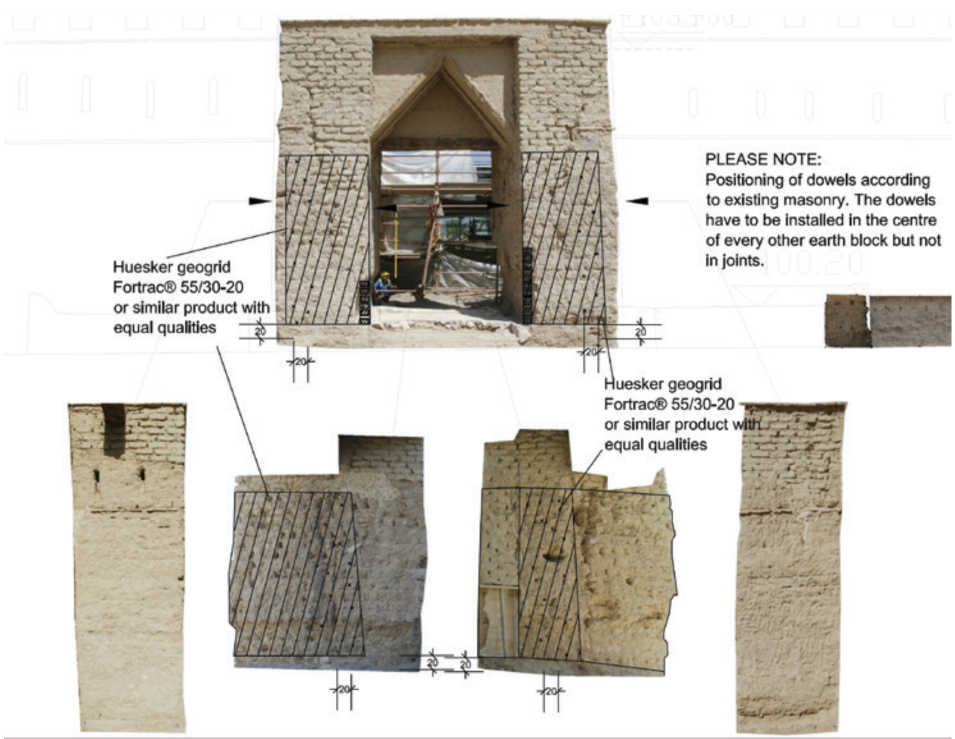


FIGURE 10.24. Breakdown of the geogrid consolidation system used to strengthen the columns of the south gate at Muwaiji Fort. *Source:* DCT Abu Dhabi.

FIGURE 10.25. View of the rehabilitated main south gate at Muwaiji Fort during the opening ceremony, 2015. *Source:* DCT Abu Dhabi.

FIGURE 10.26. General view of the fort during the opening ceremony. *Source:* DCT Abu Dhabi.

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MAINTENANCE AND MONITORING OF EARTHEN SITES

11

Overleaf: **Earthen mortar pointing repairs made during an Emergency Interventions field exercise at the EAC22 course, Al Ain, United Arab Emirates. Source: J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.**

11

MAINTENANCE AND MONITORING OF EARTHEN SITES

Aqeel Ahmed Aqeel

11.1 What Is Preventive Conservation?

Preventive conservation, periodic monitoring, and regular maintenance of sites are essential measures to limiting decay and increasing the life span of historic buildings. Even after successful conservation of a particular site, the causes of decay may still exist and, in some cases, may be impossible to eliminate completely. Causes differ from site to site, even those in close proximity, and may involve climatic, human, environmental, and usage factors. The best approach is to minimize the effects of decay by employing careful preventive conservation measures; these may be physical interventions and/or consistent monitoring of the issues present.

This chapter provides an introduction to preventive conservation and maintenance approaches, with applied examples to case studies at the World Heritage Site of Al Ain. The practice of preventive conservation includes those measures or actions applied to tangible cultural heritage for the prevention of possible future causes of damage or for mitigation of the further spread of existing deterioration (DCT 2018). These may include direct interventions or new actions aimed at improving the longevity of a structure (such as underpinning, installing buttresses or shelters, and upgrading roofs or drainage) and the use of monitoring tools (such as structural crack or deformation monitors, ground moisture sensors, and weather stations).

11.1.1 Preventive versus Curative Conservation

Preventive conservation differs from curative conservation. Curative conservation involves the measures or actions that are applied to cultural heritage to repair damage that has already occurred. These measures may include applying traditional techniques already explained in chapter 7 of this publication such as replacing beams, lintels, or roof matting materials with in-kind elements or more modern interventions such as geogrid consolidation, stitching cracks using fiberglass, and underpinning foundations, among others (Aqeel et al. 2012).

Table 11.1 summarizes the differences between the two approaches in the field of conservation.

Table 11.1. Differences between preventive conservation and curative conservation approaches

Preventive conservation	Curative conservation
• Cost-effective in the long term • Lower impact on historic building fabric • Greater reversibility • Slower visible results • Requires extensive knowledge regarding causes of decay • Requires full understanding of the site's context before intervening • Deals with a wider range of professionals beyond the field of heritage conservation (e.g., termite control, climate, and asbestos experts)	• Lower cost in the short term • Greater impact on historic building fabric to improve its condition • Faster visible results • Reacts to conditions directly without necessarily addressing the causes • Deals mostly with professionals in the field of heritage conservation

11.1.2 Advantages and Disadvantages of Preventive Conservation

When comparing curative conservation and preventive conservation, the latter successfully achieves conservation goals in terms of safeguarding the authenticity and integrity of cultural heritage. This approach is usually totally reversible and has low or minimal impact on the built fabric. In addition, a good preventive conservation system will provide better results in the long term at a lower cost.

Although preventive conservation appears to be the most suitable approach for dealing with cultural sites, it is not always easy to achieve. Most cultural sites using this method require successful, continuous monitoring and management. This can be difficult, as the number of workers and specialists in the field of conservation is limited, and often they do not have all the means and funding they need at their disposal. Preventive conservation requires many resources to help determine the causes of a particular problem, which in turn leads to the need for research, investigations, and laboratory testing, all of which come at a price. Because preventive conservation requires more time to see tangible results, an impatient public or local community may complain to authorities or post complaints on social media platforms. The negative feedback may prompt the conservation body to speed up the process by adopting a remedial approach at the expense of a preventive one. Furthermore, sites of greater significance or value may be prioritized over lesser sites that are then relegated to the back burner.

Finally, preventive conservation simply may not be possible in certain cases, as the causes of decay may be known and well studied but may not be possible to successfully address. In these situations, periodic curative maintenance may be the best approach.

11.2 Types of Preventive Conservation

For historic buildings and sites, preventive conservation can be organized into three categories—primary, secondary, and tertiary (Della Torre 2010, cited in Van Balen 2015):

1. Primary prevention, related to the means and measures that aim to avoid the causes of the unwanted effects (e.g., regular maintenance, application of moisture/vapor barriers)
2. Secondary prevention, related to the means and measures of monitoring that allow early detection of the symptoms of unwanted effects (e.g., environmental control devices)
3. Tertiary prevention, related to means and measures that help avoid the further spread of the unwanted effects or the generation of new unwanted effects (drainage, rainwater system, roofing, automatic air exchange)

Using a medical analogy, these definitions classify the preventive conservation actions based on the type of damage and its occurrence. Since primary prevention aims to prevent the root causes of any anticipated damage, this step will usually take place before the damage occurs, following a thorough assessment of the causes and effects. Since it is a known problem and the cure is known, then this type of intervention task is a planned ahead (proactive) task and is not a surprise. For example, in the case of the roof of a historic building in which the drainage opening has been blocked by birds nesting, when it rains, water will overflow, which will lead to damage to the roof. A primary preventive action would be cleaning the opening and installing some spikes, preventing birds from nesting in the first place. Secondary preventive action usually happens when we know that the cause is not fully eliminated. In this case, regular monitoring will be needed, and early-stage action will be required before it happens. Coming back to the same example of the roof, let us assume hypothetically that the conservator does not have birds' spikes to install in the opening. In this case, the secondary preventive action will be to keep an eye on the opening and monitor it from time to time. If bird nesting reoccurs, then the conservator removes it immediately, though the issue might again reoccur, since the root of the problem has not been resolved. This example shows that secondary prevention can sometimes be a planned task for a known problem. Another example of secondary prevention for unplanned tasks is monitoring structural cracks in the building. In this case, the action will be needed only if the crack is in progress; if it is stable, no response is required.

As for tertiary prevention, the causes cannot be eliminated, so the aim is to prevent the effects from escalating to the point that they require a curative conservation action. For example, let us imagine an archaeological earthen building that was recently discovered and exposed. It is known that weather such as rain or wind will directly impact the structure. Let us assume that no measures have been taken and it has rained heavily, causing early damage to the building fabric. The rain cannot be eliminated, and the effects have already occurred. A tertiary preventive action at this time will be either backfilling the earthen structure again or sheltering the site to prevent the spread of the damage. Using the same example, if rain is expected, then sheltering the site immediately after exposing it will be considered a primary prevention action.

These three categories of preventive conservation overlap depending on when the damaging effects have occurred or are expected to occur. Another example to illustrate these overlaps is a known issue for most historic buildings—namely, the rising damp on the walls. A high-water table and the salinity of the soil combined with water ingress are the main causes of rising dampness, which eventually leads to basal erosion. The main objective is to eliminate the factors that cause basal erosion, such as water and salts. The primary prevention action can be to cut through the wall base and install a waterproofing layer. This will eliminate the cause, and basal erosion will not happen. The secondary prevention action could be the periodic inspection of the wall base to verify if the problem has been eliminated. The tertiary preventive action would be required if any symptoms appear, such as efflorescence or humidity on the walls. This preventative measure would consist of applying a desalination product on the walls before it intensifies, followed by a conservative curative intervention.

Preventive conservation can also be categorized based on the location of the preventive actions. It can be further classified into direct and indirect actions. Direct preventive actions are executed on-site to protect or eliminate the causes of decay. Conversely, indirect preventive actions occur off-site, concentrating on the surrounding areas and aiming at protecting the site from the causes of decay or eliminating the causes (see table 11.2).

11.3 Applications of Preventive Conservation

Preventive conservation encompasses a wide range of actions to protect heritage sites from the micro level (e.g., building level, walls, rooms) to the macro level (e.g., sitewide level, neighborhoods, lands). To this end, it requires a deep understanding of the causes of these issues and the involvement of professionals with a wide range of expertise in decision-making and planning. These actions need to address all kinds of damages ranging from environmental threats such as floods, rain, and earthquakes to biological threats such as infestation from birds or invasive pests (e.g., termites, beetles).

Table 11.2. Examples of direct and indirect actions to heritage sites

Direct protection	Indirect protection
• Reburial • Shelter coating • Structural supports and wall buttresses	• Retaining walls • Drainage system • Termite control • Fencing • Shelters

Other reasons for implementing preventive conservation involve modern developments in or around the heritage site, including new construction, transportation in or around the area, and the rising pollution caused by both. Human behavioral activities, including the impact of visitors and large public events at heritage sites, are also considered threats that require preventive actions. Even the historic fabric itself can present a threat if poor construction materials or poor traditional techniques were used in building the site.

11.4 Case Studies

This section discusses the use of preventive conservation in five case studies in Abu Dhabi. Each case study is assigned one of the three categories of prevention (primary, secondary, or tertiary), notes when the action is typically carried out (before or after damages), and lists the type of protection (direct or indirect protection) and the type of threats or reasons prompting conservation.

11.4.1 Case Study 1: Bin Suroor House

Category: Tertiary prevention

Type: Before or after damages / direct protection

Threats: Rain / construction / poor building materials

The Bin Suroor House features the remains of a residential building, with one freestanding wall, and is situated on a farm on the edge of a cliff. The main threat is the state of conservation of the original building materials, which suffer from continuous deterioration induced by environmental factors. The structural stability of the site has become critical. In addition, a new concrete boundary wall was built very close to the site. The main preventive and emergency conservation response was to install structural supports around the wall to protect it from any imminent structural failure (figure 11.1). This is a temporary emergency action until long-term solutions are implemented.

11.4.2 Case Study 2: Bin Biduwa House

Category: Primary prevention

Type: Before damages / direct protection

Threats: Lack of structural stability

At the Bin Biduwa House, the focus was on a freestanding earthen wall. Concerns arose about its stability, particularly after the remains of another freestanding wall within the house collapsed. At the first stage, ring steel pipes were erected around the wall to allow for close monitoring for several years. After traces of remains of the walls of the surrounding rooms were discovered, it

FIGURE 11.1. Scaffolding structural supports around Bin Suroor Southern House in Al Ain. *Source:* DCT Abu Dhabi.

was decided to partially rebuild these around the freestanding wall. These new structures would serve as a buttress and as an indicator of the shape of the original room (figure 11.2).

11.4.3 Case Study 3: Daramkah Tower

Category:	Primary prevention
Type:	Before damages / indirect protection
Threats:	Floods/rain

At Daramkah Tower, the earthen tower was built over a small hill. Over time, the hill eroded from rain and local floods, which exposed part of the wall at the base of the tower (figure 11.3). There were concerns that if this continued, it would affect the structural stability of the wall base. In response, a wall buttress was built to reshape the cliff in this area and direct water away from the wall base (figure 11.4).

11.4.4 Case Study 4: Muwaiji Fort

Category:	Secondary prevention
Type:	Before damages / indirect protection

FIGURE 11.2. Freestanding wall at Bin Biduwa House, Al Ain, supported by the partially reconstructed walls. *Source:* DCT Abu Dhabi.

Threats: Termites

Muwaiji Fort was rehabilitated as an exhibition space for His Highness Sheikh Khalifa bin Zayed Al Nahyan, president of UAE. As an earthen fort with traditional wooden elements, Muwaiji was under imminent threat from termite infestation, which not only has an aesthetic impact on the fabric but also may compromise the structural stability of the wooden roofs. The main challenge posed by termites in earthen buildings is that the insects can burrow paths hidden behind the mud plaster from ground level to the roof without any visual indications on the surface. To prevent that from happening, a termite baiting system was implemented to detect any infestation before it impacts the building itself. Baiting stations were placed all around the fort and monitored monthly by termite specialists (figure 11.5).

11.4.5 Case Study 5: Muraijeb Fort

Category: Secondary prevention

Type: Before or after damages / direct protection

Threats: Lack of structural stability

Muraijeb Fort is a three-story earthen structure with high-value authentic fabric. It was restored in the 1980s by adding mud layers and bricks and rebuilding the roofs. After a partial collapse of

FIGURE 11.3. Daramkah Tower, Al Ain, before building the wall buttress. *Source:* DCT Abu Dhabi.

FIGURE 11.4. Daramkah Tower, Al Ain, after building the wall buttress. *Source:* DCT Abu Dhabi.

FIGURE 11.5. Termite baiting stations around Muwaiji Fort, Al Ain. *Source:* DCT Abu Dhabi.

these new layers, assessment and monitoring of the buildings' structural behavior was carried out. Monitoring was done by placing indicators over cracks in the walls (figure 11.6) to record the building's movement and better understand its behavior to predict any possible failures (Muhammad 2013).

11.5 Maintenance of the Site

Does the conservator's job end after implementing all the tasks involved in these methods? The simple answer is never. A heritage site will always require careful attention, even after completion of all conservation tasks. The next step is to understand the maintenance approach for the site.

Historic buildings are like any other structure: they combine several elements and spaces and, on many occasions, have a function that is managed by owners and/or operators. In many cases, threats to historic buildings cannot be eliminated, but they can be managed. This also requires continuous monitoring and control and, when necessary, intervention.

According to article 1 of the Burra Charter, maintenance is "the continuous protective care of a place, and its setting. Maintenance is to be distinguished from repair which involves restoration or reconstruction" (Australia ICOMOS 2013, 2). Article 16 states, "Maintenance is fundamental

FIGURE 11.6. Monitoring cracks at Muraijeb Fort, Al Ain. *Source:* DCT Abu Dhabi.

to conservation . . . [and] should be undertaken where fabric is of cultural significance and its maintenance is necessary to retain that cultural significance" (6).

Like conservation, there are also two main types of maintenance:

1. Preventive: monitoring and protection before damages (e.g., inspections, visitor controls, urban policies)
2. Corrective: repair of damages (e.g., roof repairs, replacement of damaged elements, replastering)

These also overlap with conservation if restoration or reconstruction is required, as mentioned above in the Burra Charter. In some cases, if the maintenance tasks are known and planned to be repeated in a periodic manner, then it is called cyclical maintenance, or periodic maintenance.

11.5.1 Developing a Maintenance Plan

As part of the outcomes of a conservation management plan (CMP), general policies and specific strategies for maintenance of the targeted cultural heritage site are laid out: "Maintenance is subject to a strategic plan. Planned preventative maintenance is the process of using a strategic plan to replace [or repair/stabilize] things before they have failed" (Menzies 2000, cited in Maxwell and Bridgwood 2021, 52). The maintenance strategy can be further developed when the site is active or conserved.

The British Standard Institution defines maintenance as "the continuous care of a historic building and is the most common and important activity in their conservation and preservation." It also mentions that "the most effective means of putting a maintenance strategy into practice is through a maintenance plan" (2013, 28).

A maintenance plan is a structured document outlining comprehensive guidelines for the management and upkeep of a system, structure, or asset. It typically includes the following:

- Schedule of activities: A predetermined timetable detailing both inspection and repair tasks to be carried out within specified time frames.
- Cost estimations: Anticipated expenses associated with maintenance activities, encompassing labor, materials, equipment, and other relevant resources.
- Resources estimation: Assessment of the necessary tools, materials, workforce, specialized personnel, and any other resources required to execute maintenance tasks effectively.
- Inspection forms: Predesigned documents to facilitate systematic evaluation of the condition of the asset during inspections.
- Inspections and monitoring logbook: A chronological record of inspection activities and ongoing monitoring efforts, documenting findings, observations, and any necessary actions taken.
- Maintenance repairs logbook: A comprehensive record of maintenance and repair activities performed, including details such as dates, tasks completed, materials used, and personnel involved.
- Drawings: Visual representations or schematics providing detailed insights into the structure or system under maintenance.
- Relevant reports: Documented analyses and findings pertinent to the maintenance plan, such as condition assessments, structural evaluations, termite inspections, and climate assessments.
- Visitation record: Documentation of visits made to the site for inspection, maintenance, or other purposes, including dates, purposes, and observations made.
- Climate report: Analysis of weather patterns and environmental conditions that may impact the maintenance requirements or performance of the asset.
- Planned events: Scheduled activities or events relevant to the heritage site, such as performances, maintenance activities, scheduled programs, and so on.

- List of stakeholders and their addresses and roles: Comprehensive roster identifying individuals or entities involved in or affected by the maintenance plan, along with their contact information and respective responsibilities.
- Diagnostic conservation reports and implementation reports: Detailed assessments and recommendations regarding conservation measures and implementation strategies to preserve the integrity and functionality of the asset over time.

Figure 11.7 summarizes the main types of maintenance under a CMP.

11.5.2 Coordination of Stakeholders

On many occasions, a heritage site will have many stakeholders involved in managing it. This becomes evident once the decision has been made to rehabilitate the site and make it accessible to the public. The stakeholders may include the site operator or owner, facility managers, members of the heritage team or authority, and the general public who will make use of the site. Although the roles and duties of each stakeholder are different, their work activities overlap. This calls for effective coordination and balanced assignment of tasks among the parties that will not negatively affect their respective interests or goals. Any coordination agreement should also be part of the CMP.

As an example, in Abu Dhabi, three main stakeholder groups are involved in any heritage site open to the public. The first is the Heritage Environment Department (HED), responsible for studying, documenting, and protecting a site's historic fabric. The second is facilities management (FM), whose main role is to ensure that the site is operating according to engineering design and safety protocols and that all electromechanical installations are being effectively managed. Finally, the site owner or operator, also called cultural site management, is responsible for the overall operation, including running the venue, receiving visitors, and organizing public events. Maintaining and conserving specific elements within the site is not a straightforward task and requires a clear, careful distribution of roles and responsibilities. This led the Department of Culture and Tourism (DCT) in Abu Dhabi to establish a policy document to clarify the responsibilities in each phase and for each case (DCT 2022). The four main phases for maintaining an activated site for the public are as follows:

1. Assessment phase
2. Planning phase
3. Response phase
4. Regular inspection and monitoring phase

In the assessment phase, the primary goal is to thoroughly understand the effects and causes of issues to develop effective plans for corrective and preventive actions. This phase involves documenting the assessment process through various means, such as graphic documentation,

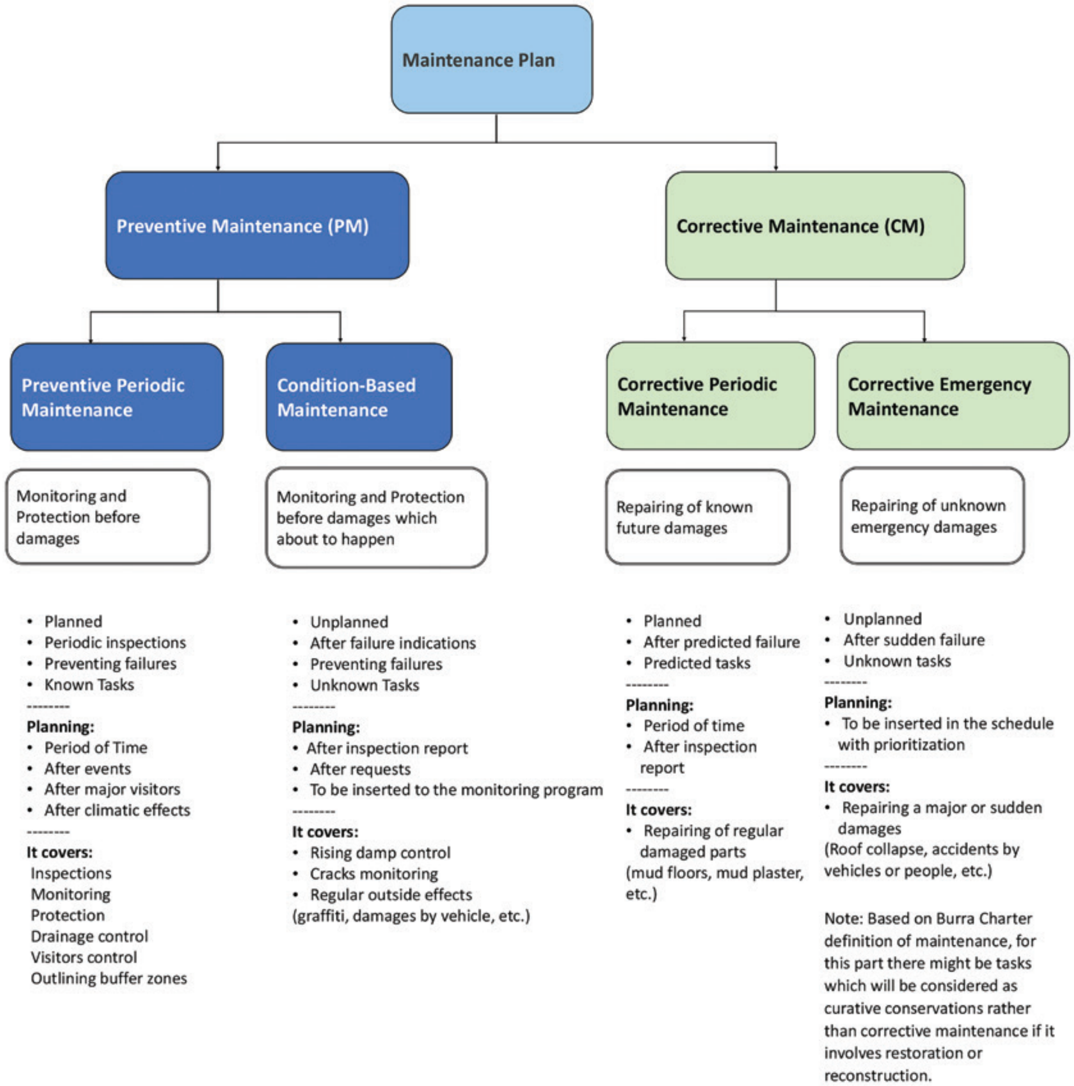


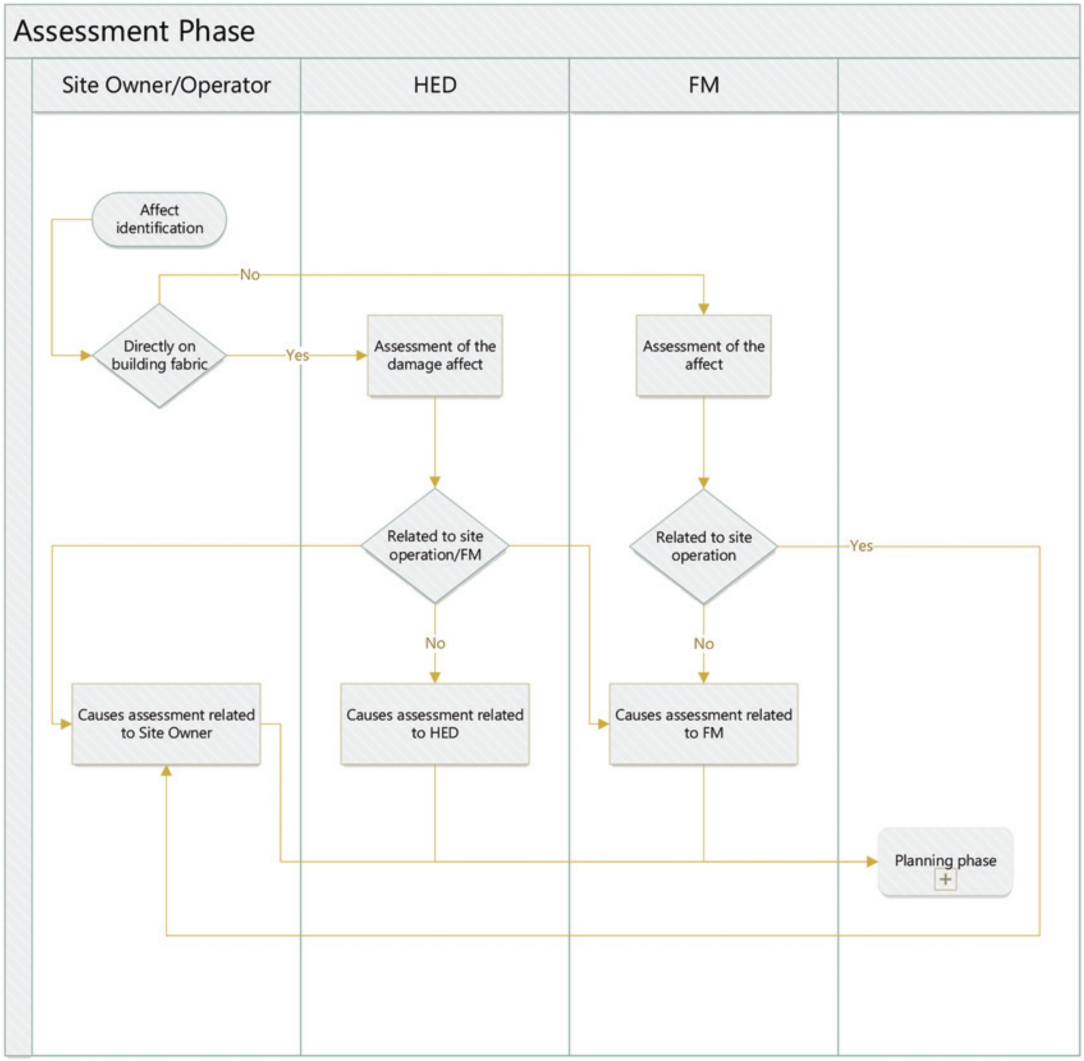
FIGURE 11.7. A summary workflow of the tasks involved in a maintenance plan for historic buildings, including the actions undertaken for preventive maintenance and corrective maintenance (DCT 2010). *Source:* DCT Abu Dhabi.

photographs, and written reports, enabling the monitoring of issue evolution and intervention effectiveness. Assessments may occur through periodic inspections or monitoring, with reports typically covering two key aspects: an Effects Assessment Report detailing observed effects in terms of location, severity, and impact type and a Causes Assessment Report aimed at diagnosing and identifying potential underlying causes. Technical expertise may be required from specialized teams corresponding to identified causes.

A flowchart of the assessment phase, part of a management plan created by the DCT for a cultural heritage site, is used to guide stakeholder coordination and is shown in figure 11.8 (DCT 2022).

The first step is to report damage. If it is directly to the building fabric, the damage should be first checked by HED. After this initial assessment, HED will go on to assess the causes, if this falls under their auspices. If it does not, FM will take over. For example, if moisture is observed on the

FIGURE 11.8. Flowchart detailing steps in the assessment phase for stakeholder coordination at a cultural heritage site operated by the DCT. *Source:* DCT Abu Dhabi.



mud plaster at Al Jahili Fort, the site operator reports it to HED, since it is directly on the building fabric. HED conducts an initial assessment and finds the cooling system is leaking. In this case, HED then directs the issue to FM to assess the cause, and FM's findings are incorporated into the next planning phase.

Successful stakeholder coordination allows buy-in from building owners, managers, operators, and even the public, where required. Maintenance planning, especially for earthen buildings that were designed to be continually renewed, is the only way to ensure the continued success of a rehabilitation or restoration project and its enjoyment by future generations.

The planning phase follows the issuance of Effects Assessment and Causes Assessment reports, providing a structured framework for rectifying identified issues. This phase entails the development of a comprehensive plan incorporating specific details such as required actions related to both causes and effects, a detailed schedule for implementation, potential impacts on site function, coordination with relevant teams, and arrangement of necessary resources.

Actions related to causes are prioritized over those related to effects, with scheduling dependent on factors such as the severity of effects, time of year, and urgency of implementation. Coordination among stakeholders, including the site operator and relevant departments, is crucial for minimizing impacts on site function, accessibility, day-to-day operations, and visitor experience. Additionally, coordination with teams involved and arrangement of requirements are essential aspects addressed during this phase to ensure effective implementation of planned actions.

The response phase is dedicated to executing the tasks outlined in the action plan developed during the planning phase, with coordination between HED and FM depending on task responsibility. This phase comprises five key stages: mobilization, on-site coordination, implementation, demobilization, and completion. Mobilization involves obtaining approval from the site operator and mobilizing necessary resources as per the action plan. During on-site coordination, stakeholders ensure enabling works are completed before task implementation, considering impacts on building fabric, MEP installations, and site operations. Implementation prioritizes addressing causes before effects, with periodic rectification for known, ineliminable causes. Once the primary implementation tasks are completed, the stakeholder responsible for enabling works should undertake the final touches. Demobilization involves cleaning and clearing the site, with postimplementation monitoring recommended. Completion requires the responsible stakeholder to produce a written report following departmental standards, reflecting the action plan's content, to be shared with primary stakeholders.

Regular inspection and monitoring involve systematically tracking defects, environmental conditions (e.g., rain, humidity, wind, temperature), and intervention performance over a defined period. Each stakeholder follows their established inspection protocols: the site operator reports changes to relevant departments (HED or FM), FM conducts regular inspections accessible to the HED team, and HED conducts visual inspections every three months, increasing frequency as needed based on effect severity. Documentation is vital for tracking effect progress, with the site operator coordinating a standardized logbook accessible to all stakeholders, necessitating collaboration with the Digital Transformations Department to establish the required platform.

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THE CONSERVATION OF EARTHEN SETTLEMENTS IN OMAN

12

Overleaf: The historic earthen settlement of Al Hamra, Oman. *Source:* J. Paul Getty Trust and Department of Culture and Tourism Abu Dhabi.

12

THE CONSERVATION OF EARTHEN SETTLEMENTS IN OMAN

Soumyen Bandyopadhyay

12.1 Introduction to the Conservation of Historic Earthen Settlements

Historic urban settlements made of earth serve as a testament to the evolution of urban development over time. We can find them in northern Africa, the Middle East, and Asia and in entire urban earthen ensembles in the Americas. These magnificent earthen sites have been recognized as culturally significant for their aesthetic, social, and cultural values and as physical evidence of the historical development of a region.

Unfortunately, these sites are under threat from obsolescence and abandonment, which results in their gradual deterioration and eventual collapse. This situation is due in part to changes in the economic and social structures that originally supported the sites. These issues are common across many regions with an earthen building tradition. Conserving and managing these settlements and sites demand a multidisciplinary approach that addresses economic, social, cultural, and technical challenges holistically.

This chapter focuses on Oman's earthen settlements to illustrate a comprehensive methodology for their documentation, conservation, and sustainable development. Central to this approach is the UNESCO Recommendation on the Historic Urban Landscape (HUL; UNESCO 2011), which emphasizes the importance of considering both tangible and intangible heritage elements, sociocultural practices, and the dynamic nature of urban areas in conservation efforts. On November 10, 2011, UNESCO's General Conference unanimously adopted the *Recommendation on the Historic Urban Landscape*, marking UNESCO's first issue on the historic environment in thirty-five years. This recommendation serves not to supplant existing doctrines or conservation approaches but to complement them, offering an additional tool to harmonize policies and practices for conserving the built environment within broader urban development objectives while respecting the inherited values and traditions of diverse cultural contexts.

The 2011 *Recommendation* is used by the World Heritage Committee to promote a holistic approach to managing historic urban areas (UNESCO 2011). It aims to integrate urban heritage conservation strategies more effectively into the broader framework of sustainable development goals. By doing so, it seeks to bolster efforts—both public and private—that aim to safeguard and enrich the human environment's quality. The approach it advocates involves adopting a landscape perspective for identifying, conserving, and managing historic areas within their larger urban contexts. This entails considering the interconnected physical forms, spatial organization, natural features, and settings as well as the social, cultural, and economic values inherent to these areas.

This approach tackles policy, governance, and management challenges by engaging diverse stakeholders—ranging from local to international and encompassing public and private sectors—in the urban development process.

The HUL approach follows the steps outlined in the value-based conservation method discussed in Chapter 4 of this publication. It represents an urban area, shaped by a rich historical accumulation of cultural and natural values, extending beyond the conventional concepts of a "historic center" or "ensemble." It embraces the wider urban context and its geographical surroundings.

12.2 Oman and Its Cultural Landscapes: Context

Oman is a country uniquely distinguished from the rest of the Arabian Peninsula by its geology, topography, climate, history, society, and culture. The practice of Ibadism, mainly in the ad-Dakhiliyah and ash-Sharqiyah regions, as well as the diversity of Islamic sects present along the coast, adds to this distinctiveness.

The main geographic characteristic that shapes the traditional built environment of northern Oman is the Oman mountain chain that stretches in an arc from the Strait of Hormuz in the north to Ra's al-Hadd in the southeast, following the curve of the coast of the Gulf of Oman. Rising to more than 3,000 m, this great central chain divides the northern part of the country into six regions (figure 12.1):

1. The northern coastal plain (al-Batinah region)
2. The northern outer foothill and *wadi* (dry water drainage courses activated by rainfall) region
3. The northern mountain region (Oman Mountains)
4. The northern inner foothill and *wadi* region
5. The northern *wadi* region and alluvial fan (*bajada*)
6. The combined sand masses and barren terrain, the Empty Quarter (ar-Rubʿ al-Khali), and ash-Sharqiyah Sands (ar-Rimal ash-Sharqiyah, previously Ramalt al-Wahiba; see figure 12.1, after Scholz 1978)

Lying south of the largely barren al-Wusta region and contiguous with Yemen, the ecology of the Zufar (Dhofar) region is unique in the Arabian Peninsula due to the relationship among the mountain core, the sea, and the annual southwest monsoon winds. Between mid-June and

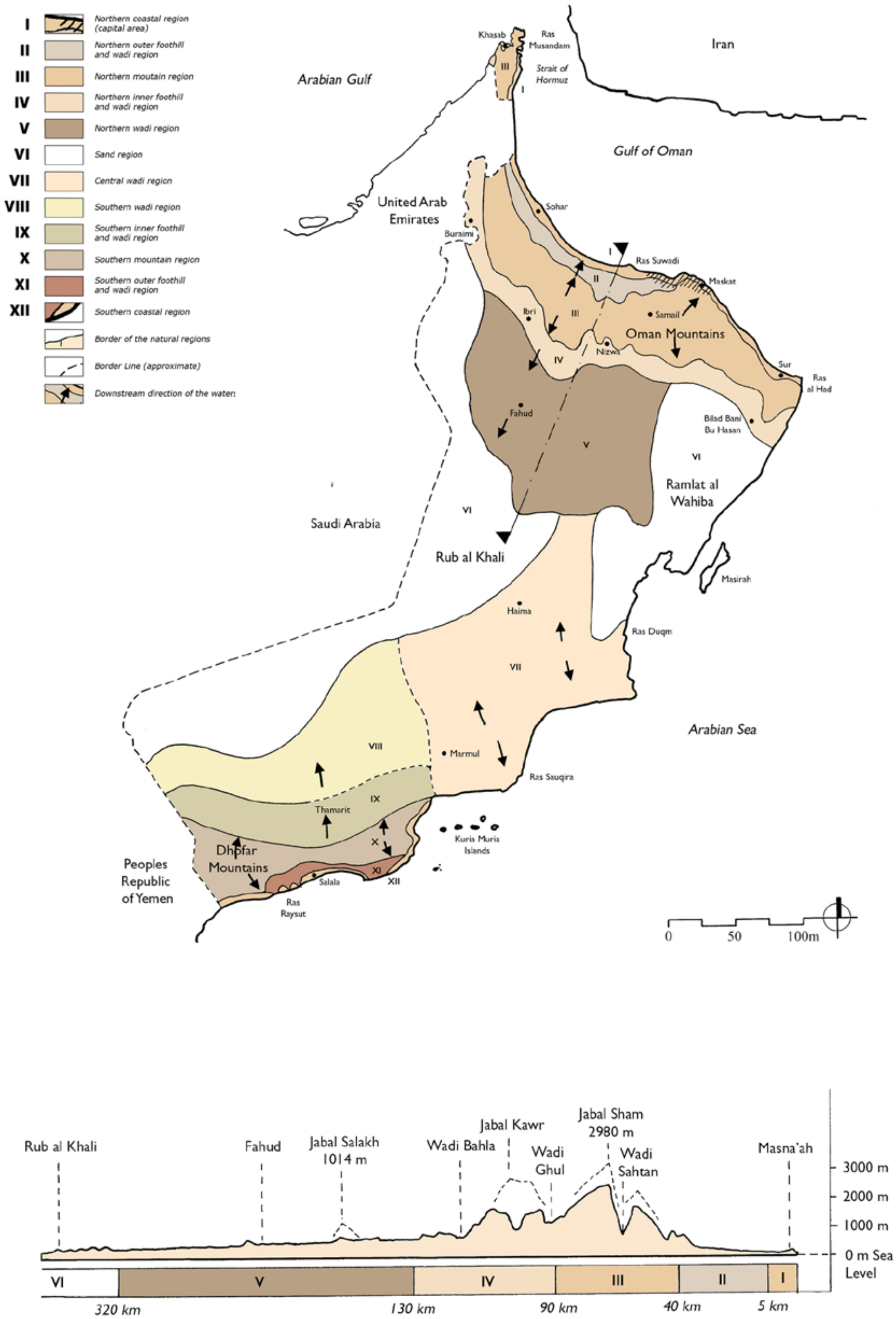

FIGURE 12.1. The six major geographical regions of northern Oman. *Source:* Bandyopadhyay (2011, 17), redrawn following Scholz (1978, 6).

mid-September, these Indian Ocean monsoon winds transform the Salalah plain and the neighboring mountains and significantly impact the traditional settlements.

The Oman Mountains divide the country into a landlocked interior and a long, narrow coastal strip. The flatness of the coastal land contrasts with the mountainous hinterland and the extended barren landscape that lies beyond the foothills. An expansive drainage network, consisting of several *wadi* systems, runs down the Oman Mountains and gives shape to the foothill regions and the desert foreland (Scholz 1978; Wilkinson 1977).

12.2.1 Settlement Diversity from the Coast to the Desert

Several factors—including geomorphology, climate, availability of water, the relationship between arable and nonarable land, livelihoods and social structures, and trade and exchange—determined the location and form of the traditional settlements. While the Omani coast developed as a seafaring, outward-looking, cosmopolitan entity, the interior, often considered the "real" Oman, evolved into a more introverted society and culture. Coastal settlements were reliant on fishing and their links with the world through seafaring and trade. Inland settlements were shaped by their social and land-bound connections with the rest of the Arabian Peninsula. This pattern played out in other areas. The al-Batinah coast in the northeast developed as a continuous strip of connected settlements, while the inland settlements were characterized by isolated oasis developments along *wadi* systems with disaggregated settlement quarters.

The narrow al-Batinah coastal plain (30 km at its widest) represents a near-continuous settlement strip stretching from Fujairah in the United Arab Emirates to as far south as Muscat (Masqat) that relies on agricultural and maritime resources. Set behind the settlements is an agricultural belt irrigated by a mixed well system (*tawi*; *zajrah*/*jazrah*; the latter are the large agricultural wells often employing domesticated animals for water extraction) and open channels. To capture the prevailing sea breeze, the houses in al-Batinah—from those in small fishing towns (e.g., as-Suwayq and al-Khaburah) to larger urban centers (e.g., Suhar and as-Sib)—have a courtyard design that is surrounded by a high wall, with rooms set against the perimeter and fronted by porticoes (*liwan*). The built-up area typically occupies about 60% of the enclosed space. Building materials range from baked bricks (in Suhar) and mud bricks to the use of palm fronds (*barasti*) in coastal huts. South of as-Sib, the coast is interrupted further by mountains, creating small, isolated settlements at the mouth of *wadis* (e.g., Qurayyat and Tiwi) and trading ports (e.g., Muscat, Matrah, Qalhat, and Sur), which have played important roles in Omani history (figure 12.2).

Oasis settlements have existed since time immemorial, taking advantage of geophysical and climatic conditions. Initially, they identified locations where water was naturally available and were later complemented by wells (*tawi*), springs (*ʿayn*), and eventually, water distribution and irrigation systems (*aflaj*; sing., *falaj*). Settlements evolved, shaped not only by topography but also by the ethnic and tribal diversity that was introduced through millennia of migration, trade,

FIGURE 12.2. View of the walled town of Muscat, looking north toward the naturally protected harbor created by the Oman Mountains plunging into the sea at this location. *Source:* ArCHIAM Collections (Centre for the Study of Architecture and Cultural Heritage of India, Arabia and the Maghreb), photograph by John Warr (1971).

and exchange. Major oasis centers took advantage of land-bound trading augmented by more remote maritime opportunities. Urban character and architecture—civic, defensive, and religious—varied widely, and building types showed influences from across the region, including external influences introduced by Arab merchants.

The large oasis settlements of the outer and inner foothill regions employ *aflaj*, consisting of a network of underground galleries and overground channels that distribute water for drinking as well as for irrigation and funerary purposes. *Aflaj* are fed either by aquifers located in the mountains (*dawudi falaj*), by springs (*ʿayni*, spring-fed), or by intercepting perennial flow on *wadi* beds (*ghayli*). In 2006, five Omani *aflaj* were inscribed on the UNESCO World Heritage List.

Major oasis settlements in the foothill regions (e.g., ar-Rustaq and Nakhal in the north; Nizwa, Manah, and Bahla in the south) control key *wadi* systems and cover large expanses with several settlement quarters (*harah*; pl., *harat*) spread across the agricultural land, taking advantage of the topography, *wadi* flow, and the course of the *falaj*. In the seventeenth century, new settlements such as those at al-Hamra' and Birkat al-Mawz were established at the base of the Oman Mountains by the ruling Yaʿaribah imamate in collaboration with key tribes (e.g., the ʿAbriyin and Bani Riyam) of the region to establish political control. The market towns on the edge of the desert, such as Sinaw, Manah, and Adam, were sites of trade between settled and nomadic populations; nomads would travel significant distances to trade in cattle, milk and honey, dried fish, and other goods. Since the 1970s, the built environment has undergone a drastic change (Wilkinson 1977; Costa and Wilkinson 1987).

12.2.2 Components of the Urban Settlement

Omani inland oases consisted of several *harat*—the larger ones often fortified and self-sufficient—separated by dense date-palm plantations (*zara'*). In Manah, for example, which lies 20 km southeast of the key oasis town of Nizwa, the principal *harah*, Harat al-Bilad, was located at the heart of the oasis. It contained a multitribal population, a characteristic shared by other core settlements such as Harat al-ʿAqr (or core settlement) in both Bahla and Nizwa. The other quarters, al-Fiqayn, Maʿmad, and al-Maʿarra, which lie on the northern, western, and southern edges of the oasis, respectively, had a largely monotribal character.

The interior foothill settlements use the available arable land to the fullest through sensitive irrigation techniques that exploit seasonal and perennial flows in the *wadi* and by employing the sophisticated *aflaj*. The ancient *aflaj* in Manah, Falaj al-Fiqayn, draws water from aquifers in the foothills of al-Jabal al-Akhdar. The core elements of the oasis—the market (Suq al-Bilad), the main settlement (al-Bilad), the fort (Hisn an-Najad), and the Friday Mosque (Masjid al-Jamiʿ)—stretch like beads along a north–south axis separated by open spaces. These spaces acted as buffers between the different tribal groups and were used for periodical ambulant trading as well as to station camels. Indigo dyeing (in Nizwa) and pottery making (in Bahla), as well as other traditional crafts, were also carried out in large open spaces outside the settlement. A peripheral location was earmarked for graveyards, generally located outside settlements and occasionally next to a funerary mosque.

In addition, Bahla, Ibra', ʿIbri, Izki, Nizwa, Manah, and other major oasis towns served as large market centers for exchanging goods with the regional nomadic populations and as a place where weaving, pottery making, metalworking, and tanning and dyeing were practiced. Livestock herding was a complementary economic activity primarily practiced by the seminomadic (*shawawi*) population. The coastal settlements, on the other hand, formed a more or less continuous strip along the shore focused on fishing and maritime trading.

Settled life on the edge of the vast sandy expanse of central Arabia was determined by the availability of water, again usually tapped through wells or the *aflaj* system. The raison d'être for these communities was trade with the nomads and camel herders as well as exchanges with people in the larger foothill oases. Communities such as Sinaw and Adam exhibit the dispersed type of urbanism characteristic of these settlements, with tribally distinct groups living in separate villages within the oasis. The mountain settlements of Oman, such as Bilad Sayt and Misfat al-ʿAbriyin, are located on the steep sides of valleys and require negotiating the most forbidding topographies via terraced fields and carefully located built clusters (Atkins 2005; Bandyopadhyay 2011; Bandyopadhyay et al. 2015; Bandyopadhyay, Quattrone, and Goffriller 2014; Bandyopadhyay, Quattrone, Goffriller, Reza, and al-ʿAbri 2014b).

12.2.3 Features of the Townscape

Harat al-Bilad, in Manah, is a *harah* that has the townscape features typical of most large oasis settlements in inland Oman (figure 12.3). Located near the center of the oasis, with the market (Suq al-Bilad) to the north and the fort (Hisn an-Najad) to the south, this settlement quarter is fortified by an exterior wall of stone and mud brick, with four gateways (*sabah*; gate: *bab*), each facing one of the cardinal directions. The north and south gates (Bab al-Burj and Bab an-Nasr),

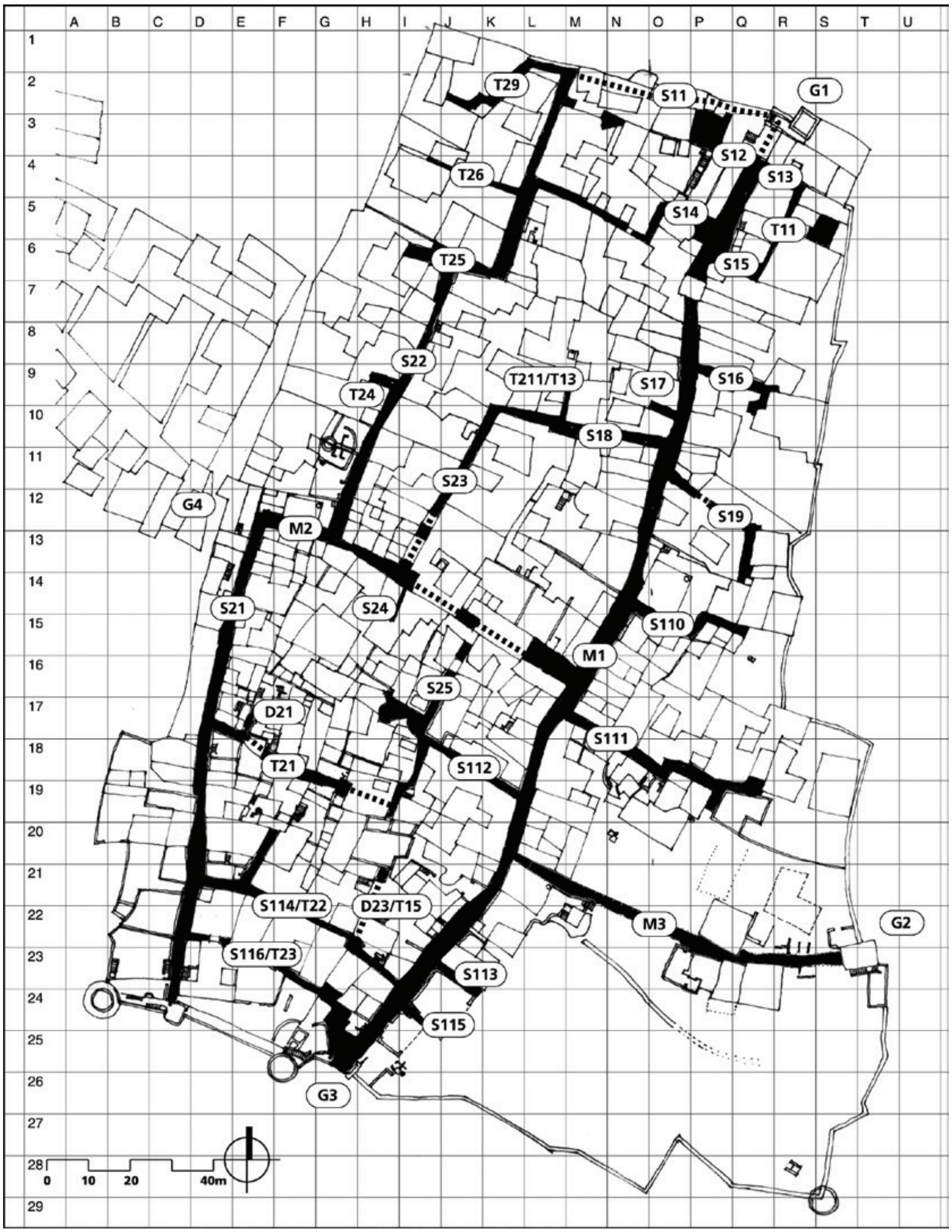

FIGURE 12.3. Harat al-Bilad settlement quarter, Manah oasis. Plan showing streets and lanes, gateways, and mosques. *Source:* Bandyopadhyay (2011, 69).

Main streets: M1. Kaʿb al-Bilad; M2. Sikkat al-ʿUqud; M3. Sikkat Harat al-ʿAyn.

Streets off M1: S11. Sikkat az-Zalam (Sikkat ar-Ruh); S12. Lane leading to Sablat al-Wali; S13/S15/T11. Sikkat al-ʿAli; S14. Sikkat al-Bayadir; S16. Sikkat Abu / Awlad Rawashid / Rashid; S17. Sikkat at-Tawi/ Sikkat Hawd ad-Darb; S18/S23. Sikkat bin Qasim; S19. Sikkat al-Karjah / Awlad Karjah; S110. Sikkat ash-Sharah / Sikkat Nus Sudus; S111. Sikkat al-Ghuwayr; S112/ S25. Sikkat ad-Dahmash.

Streets off M2: S21 & S114/T22. Sikkat al-Qasabah; S22. Sikkat al-Gharabah; S23/ S18. Sikkat bin Qasim; S24. Dead-end lane; T21 & S25/ S112. Sikkat ad-Dahmash.

Gates: G1. Bab al-Burj / Bab ar-Rawlah; G2. Bab Harat al-ʿAyn; G3. Bab an-Nasr; G4. Bab ad-Daʿnayn/Daʿnin.

Mosques: R1. Masjid al-ʿAli; R2. Masjid ash-Sharah; R3. Masjid al-ʿAyn; R4. Masjid ar-Rahbah.

which face the market and the fort, respectively, are guarded by two formidable watchtowers, one square (Burj al-Juss) and the other circular (Qalʿat an-Nasr). The east gate (Bab Harat al-ʿAyn) provides access to the agricultural area, incorporated in the eighteenth century. The deep-vaulted west gate (Bab ad-Daʿnayn/Daʿnin) faces an even later extension beyond the settlement boundaries.

The quarter has three main streets (street or passage: *sikkah*): Kaʿb al-Bilad (Main Street), Sikkat al-ʿUqud (Street of Arches), and Sikkat Harat al-ʿAyn (Street of the Spring Quarter). Civic and communal amenities—mosques, Qura'nic schools (*madrasah*), meeting halls, shops, and administrative buildings—are largely concentrated in the entrance square, Harat at-Tabil (figure 12.4). Kaʿb al-Bilad, the longest of the three streets, follows the main north–south axis of the

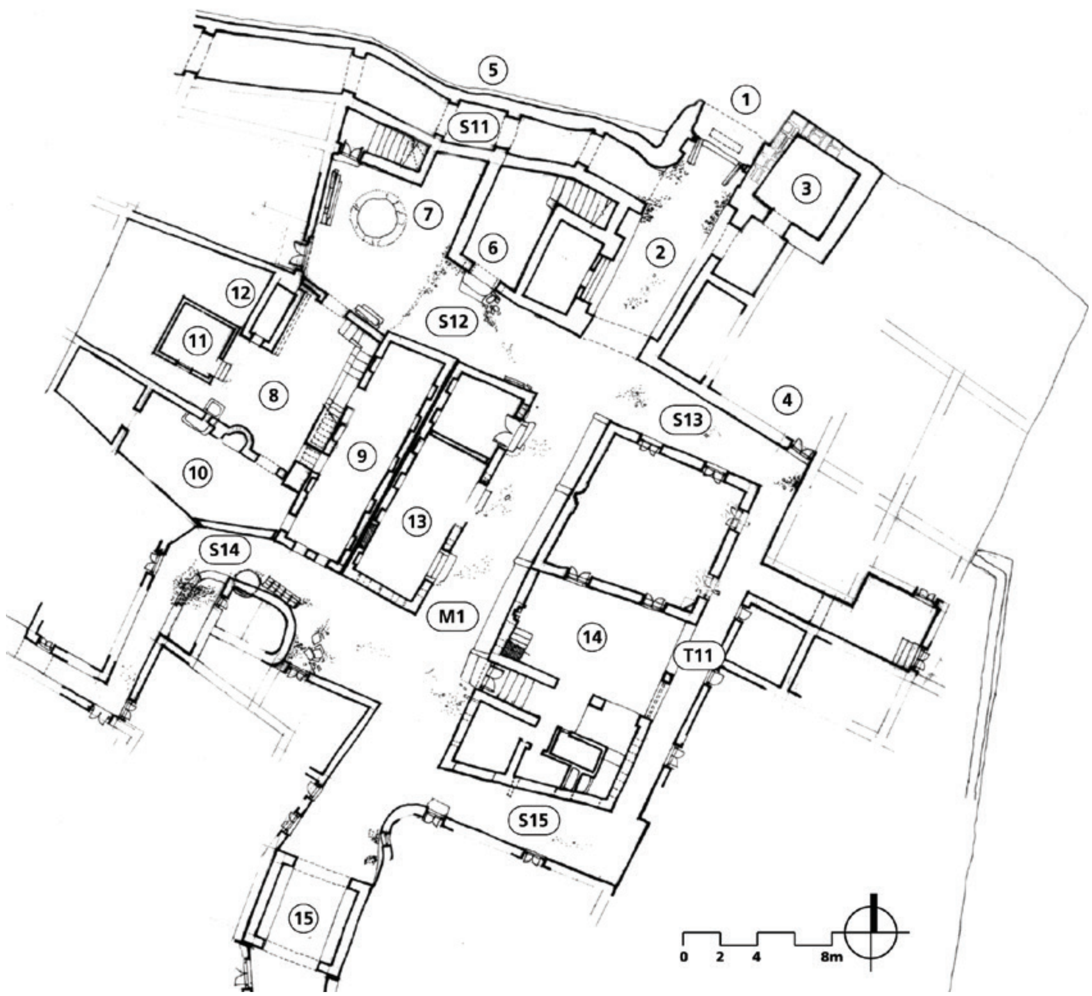

FIGURE 12.4. The entrance square, Harat at-Tabil, in Harat al-Bilad settlement quarter, Manah oasis; plan showing key civic facilities. *Source:* Bandyopadhyay (2011, 74).
1. Gate, Bab al-Burj / Bab ar-Rawlah; 2. Entranceway (*sabah*); 3. Tower, Burj al-Juss; 4. Shaykh's house; 5. Northern wall; 6. Access to first floor of gateway; 7. Roasting pit (*tannur*); 8. Courtyard; 9. Communal hall for administration (*sablah*), Sablat al-Wali; 10. Confinement cell; 11. Telegraph office; 12. Observation post; 13. Communal hall for water management and *madrasah*, Bayt (or Sablat) al-Falaj Fayqayn; 14. Mosque, Masjid al-ʿAli; 15. Archway, ʿUqud Yusuf; M1. Main street, Kaʿb al-Bilad; S11. Lane, Sikkat az-Zalam / Sikkat ar-Ruh; S12. Lane to Sablat al-Wali; S13/S15/T11. Lane, Sikkat al-ʿAli; S14. Lane, Sikkat al-Bayadir.

oasis. From the entrance square (Harat at-Tabil) inside the north gate, it extends south as a wide passage flanked by mainly residential buildings, punctuated by several narrow side lanes that intersect with it, with two of the mosques, Masjid ash-Sharah and Masjid al-ʿAyn, on its eastern edge (figure 12.5). Sikkat al-ʿUqud originates from the west gate and meets the main street; it passes under the elaborate arcade from which it derives its name. Sikkat Harat al-ʿAyn originates from the east gate and meets the main street by the northern edge of Masjid al-ʿAyn. Unlike the other two streets, Sikkat Harat al-ʿAyn does not exhibit a continuous built-up character, as this agricultural area never fully developed into a residential quarter. Such uneven urban development is evident in Nizwa and other large oasis settlements. Beyond these main streets, a maze of narrow lanes (*sikkah*) and dead-end passages (*darb*) provide access to the dense clusters of houses (Bandyopadhyay 2004, 2011).

12.2.4 Architectural Components and Features

The main architectural components of an Omani oasis quarter are civic buildings such as mosques (*masjid*; pl., *masajid*), communal meeting halls (*sablah*; pl., *sbal*), convenience stores (*dukkan*), and *madrasah*. These are usually located along the main streets and sit within a dense residential fabric. The *madrasah* normally used the mosques or meeting halls in the mornings, and the shops occupied externally accessible ground-floor rooms in residential buildings.

Masjid ash-Sharah is an example of the type of mosque prevalent in inland Oman. Positioned on the eastern side of the main street, this mosque has a prominent location within the settlement quarter. Entry is from the main street, although there are two additional points of access into the complex from the narrow lanes that separate the mosque from the neighboring residential buildings. The entrance passage leads onto a large terrace (*sahn*/*barrah*), which functions as an outdoor extension of the prayer hall during larger Friday congregations or ritual gatherings of significance. The terrace is held between the ablution block (*wudu'*) and the covered prayer hall (*masjid*) on the east and west, respectively. Access to the main prayer hall is from the terrace, with secondary access from the north through the entrance passage.

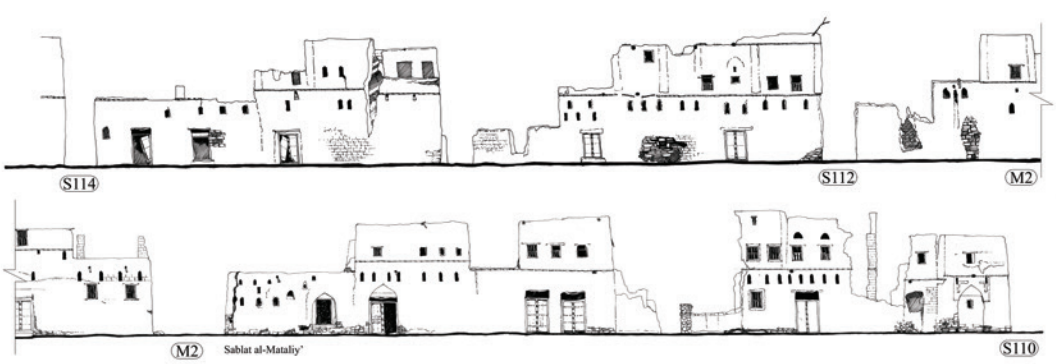

FIGURE 12.5. Part elevation along the eastern face of the main street, Kaʿb al-Bilad, in Harat al-Bilad settlement quarter, Manah oasis, showing the location of the mosques, ash-Sharah (with *madrasah*) and al-ʿAyn; a sweet shop; and several intersecting lanes. *Source:* After Bandyopadhyay (2011, 80).

The interior of the prayer hall is divided into two bays consisting of an arcade of pointed arches supported by two circular stub columns symmetrically disposed about the central axis. A small domical construction (*bumah*) on the rooftop, usually located at the northeast corner of the prayer hall, is a distinctive feature of mosques of the Ibāḍī sect in Oman and is accessed by a corner rung ladder that leads to a roof hatch. The focus of the whitewashed interior of the prayer hall is a finely decorated rectangular frame (2 m wide by 5 m high) of the prayer niche (*mihrab*; pl., *maharib*) in the center of the *qiblah* wall; the *qiblah* indicates the direction of Mecca. Not all prayer niches are decorated, though most usually contain a series of shallow arches receding into the wall. Masjid ash-Sharah's decorated *mihrab* employs carved gypsum with five blue-and-white Chinese porcelain bowl inserts. It was created in 1516–17 CE by the artisan ʿAbdullah al-Humaymi, a resident of Manah, who went on to create many other decorated prayer niches in the neighboring oases.

The *sablah*, or the traditional meeting hall, is entirely unique to Oman. The majority of these semipublic male-only reception halls (*majalis ʿamm*, distinguished from private reception rooms, or *majalis khass*) were intended for use by a specific tribe and their associated client groups. Some meeting halls played a more extended role, for example, by combining the governor's reception (*sablat al-wali*; governor: *wali*), or as a venue for the auctioning of *falaj* water rights on certain days, as well as a *madrasah* for young children during the mornings. A tribe's possession of a *sablah* reflected its demographic, political, economic, and social superiority or its evolving power and status within a settlement. When used as a general meeting place, tribe members would convene at times determined by the five daily prayers. *Sbal* were also used in times of celebration (e.g., during Eid festivities and weddings) and mourning and as accommodations for overnight guests. In wartime, the *sablah* would also act as the fortified position of a tribe; the spatial and formal peculiarities of some meeting halls were directly influenced by this defensive intent. Most meeting halls, however, were simple structures comprising a rectilinear room and ancillary spaces for the preparation of coffee and for general storage.

Courtyards were an important feature of vernacular coastal dwellings in Oman, but in houses in inland oasis towns, the courtyard was given a subtle articulation by deconstructing its essential functions. In these dense, compact towns, the ground-level courtyard was largely absent, making the first-floor terrace its direct equivalent. The ground floor consisted of storage cells (*makhzan*; pl., *makhazan*) and pens for domesticated animals. Water wells and bathing areas were also part of this organization unless the dwellings were sharing a communal well and washing facility. Larger dwellings made use of small courtyards (*shamsiyah*) to allow light into the deep-plan ground floor. The employment of larger courtyards (*hawsh*) was more frequent in communal spaces shared among dwellings. Such courtyards contained a communal well and washing arrangement and served as a gathering place for women and children of the households and surrounding neighborhoods. The front room in smaller dwellings was used as a multipurpose space where women carried out their daily chores, children played, and agricultural produce and fodder were stored. Most importantly, the women of the neighborhood assembled here during their morning and afternoon coffee meets (*duha* and *taʿasir*, respectively). It was also the room that provided access one level up to the first-floor living quarters.

Many dwellings in these inland oasis towns were double-storied. The location and alignment of the staircase (*daraj* or *darjah*) were such that the upper level was always hidden from direct view as one stood at the entrance door. Rooms on the first floor were organized around a terrace, normally situated above the ground-floor multipurpose room. The terrace was the central focus of the first floor and was sometimes surrounded by covered galleries or loggia (*dihriz*) providing access to the sleeping rooms (*hijrah* or *ghurfah*). The kitchen (*matbakh*), a latrine, and an occasional grain store (*khalil*) were also part of this first-floor arrangement. A pit underneath the latrine on the ground floor collected the night soil, which was periodically removed for use as manure in the fields. Dwellings mostly had a single entrance—only a few had a secondary entrance from another street. Their facades were solid in appearance, punctuated only by a door and small, high-level openings on the ground floor and larger windows on the first floor (Costa 2001; Bandyopadhyay 2000, 2004, 2005; Baldissera 1994).

12.3 Historic Urban Landscape Survey Methodology: A Fieldwork-Based Approach within the HUL Framework

The documentation and assessment of the Historic Urban Landscape are fundamental for the development of value-based conservation and management plans. As explained in the introduction, by adopting the *Recommendation on the Historic Urban Landscape* (UNESCO 2011), a holistic methodology can be established that integrates urban heritage conservation within the broader scope of sustainable development frameworks. The HUL approach emphasizes the notion of the "historic urban landscape," which was introduced for the first time in the UNESCO Vienna Memorandum in 2005. This concept recognizes the dynamic and evolving nature of urban areas, described as "the result of historic layering of cultural and natural values and attributes" (UNESCO 2011). Indeed, the HUL approach expands the notion of urban heritage conservation beyond historic centers, embracing the broader urban fabric and its geographical context. This holistic view integrates built environments, natural features, and infrastructure with land use patterns and visual dynamics. Crucially, it also considers sociocultural practices, economic processes, and intangible heritage elements that shape urban identity.

By addressing urgent contemporary challenges such as uncontrolled urbanization, climate change, mass tourism, and the market exploitation of heritage resources, the HUL framework aims to balance heritage conservation with sustainable urban development. This ensures that Historic Urban Landscapes can adapt to modern needs while preserving their values and significance.

The first step in implementing the HUL approach is mapping cultural, human, and natural resources to identify and document the city's tangible and intangible heritage assets. The preferred methodology for primary data collection is fieldwork-based documentation. This approach ensures that data is detailed and current, which is crucial given the rapid deterioration of earthen construction, especially when buildings are uninhabited and not regularly maintained. The level of and attention to documentation are dictated by the nature of the urban fabric—the complexity of the spatial configuration, its construction, and its materiality.

In line with the HUL approach, the documentation necessarily needs to capture the nature of the urban space and identify the characteristics and significance (e.g., urban, architectural, social, historical) and threats present there (e.g., state of preservation of structures and urban spaces). Furthermore, for urban conservation, a careful urban infrastructure survey is required to fully understand the site's infrastructural conditions and capacity, its strengths and weaknesses, any potential economic opportunities, and social as well as environmental threats. The data gathering should consider carefully the urban scale, from the wider town or oasis settlement to the character of the neighborhood space adjoining building clusters.

12.3.1 Collection of Base Material

Before conducting the fieldwork, it is essential to collect relevant existing data from local and international sources on the diverse aspects of the site, including the following:

- reports, guidelines, research publications, etc.
- contemporary and historical data relating to urban spaces, buildings, and infrastructure as well as topographic and geotechnical conditions of the sites

12.3.2 Physical Documentation: Terrestrial and Aerial

While documentation tools and techniques have been explained in chapter 5 of this publication, their applications vary in the specific application to the recording of urban settlements. The work begins with an initial reconnaissance fieldwork operation, or "walk around," to become familiar with the site (figure 12.6). This involves a preliminary desk-based exercise of site zoning into alphanumerically marked sectors for ease of operation and identification and use of this map drawing as a guide during reconnaissance. Letters are assigned to identifiable settlement clusters and groups and numbers to individual "spatial units," including all dwellings, communal structures, and open spaces. The zoning plan, which is generated and updated in computer-aided digital drawings (CAD) as fieldwork progresses ensures a cohesive and organized approach to the documentation effort.

The following key documentation approaches are adopted during fieldwork.

FIGURE 12.6. ArCHIAM reconnaissance fieldwork in the coastal village of Mirbat. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

12.3.2.1 Graphic Documentation

Sketch plans, sections, and elevations on the urban scale are produced on white or graph paper, the latter helpful in the representation of proportion for largely orthogonal structures. Tracing paper is also used to sketch over, should an upper-level plan be required. Sketches should record all infrastructural urban components as well as site plans and sections through open spaces and building clusters (figure 12.7).

12.3.2.2 Measuring, Geomatic Survey, and 3D Scanning

Comprehensive measurements of sketched features (open spaces, streets, and alleys) are taken according to conventional methods of trilateration, using tape and laser measuring tools at locations according to distance and state of preservation of the built fabric. Selected features are geolocated with a handheld GPS unit to aid CAD graphic representation and enhance the accuracy of the drawn documentation. Additionally, 3D scanning technology is used to trace and digitize urban and building elements. The output is then assembled in a geographic information system (GIS) format.

12.3.2.3 Photographic Documentation

Extensive photographic documentation of urban spaces is captured in sequence, ensuring comprehensiveness. Significant elements or objects are recorded in detail following established standardized guidelines. An aerial photographic record is also made using aerial photography

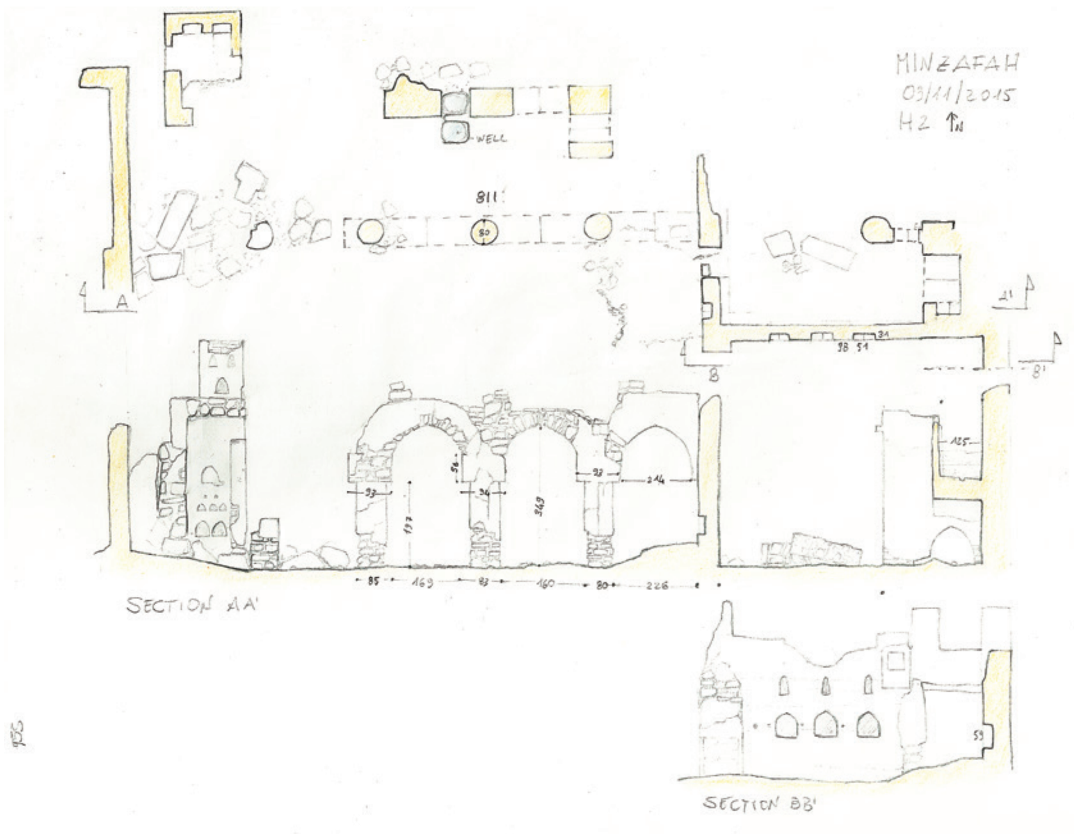

FIGURE 12.7. Fieldwork sketches produced during architectural documentation at Minzafah. *Source:* ArCHIAM Collections.

captured by a drone, orthorectified using Agisoft or similar photogrammetric software (figures 12.8 and 12.9).

12.3.2.4 Architectural Survey and Recording

Completion of individual documentation context sheets is carried out to record significant information about the built units and urban spaces. This includes the recording of typological characteristics, historical and social context, state of preservation, and modification, materials, and conservation concerns.

12.3.2.5 Archaeological Survey

Archaeologically relevant datable material, such as pottery and organic remains, is photographed and collected where necessary (see chapter 6.4 on the archaeology of earthen sites for more information).

12.3.3 Ethnographic Documentation

An important aspect of documentation is the recording of firsthand testimony on the settlement's social and material history from current and former inhabitants. This work is essential, as

FIGURE 12.8. Preparation for drone photography in Mudayrib. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

FIGURE 12.9. Aerial photograph of Harat Al Bu Rashid settlement quarter in Sinaw oasis. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

in many cultures and contexts—including those of Oman—local knowledge and memory are for the most part not preserved in any written form. The advanced age of many of the interviewees gives this stage of the process additional urgency, as memories of the past are quickly fading in the country's highly dynamic and rapidly expanding economy (figure 12.10). Recording testimonies of stakeholders is also necessary to capture their aspirations for the future. The interviews are conducted using audio and video recorders and transcribed as needed.

12.3.4 Site Vulnerabilities, Heritage Values, and Challenges

The development programs implemented in Oman since 1970 have triggered a rapid transition from traditional to modern living. Modernization and the simultaneous globalization of lifestyles, needs, and aspirations have induced many inhabitants to abandon the vernacular settlements, which in turn have inexorably decayed. Traditional sites and processes have been largely ignored in favor of new settlements that afford vehicular access and are constructed using contemporary materials. In areas where some inhabitants have remained, physical alterations, including demolition and new development of urban structures and buildings, have occurred, and open spaces and agricultural land have been reconfigured. Furthermore, changes in building practices have been brought on by the growing availability of modern materials and the simultaneous loss of traditional building skills.

Site and building vulnerabilities are identified, documented, and later analyzed under broad categories to devise conservation and rehabilitation strategies. Vulnerabilities are determined through the combined action of human-caused and environmental degradation factors. The former involves the physical transformation of the original built fabric—for example, the addition and juxtaposition of new construction made from modern materials to the original built fabric made from stone masonry, *sarooj* mortar, or palm tree wood floors. Environmental degradation includes the impact of rainwater, wind, water runoff and water stagnation, and change in

FIGURE 12.10. Ethnographic documentation conducted by ArCHIAM team member in Oman. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

moisture content, leading to erosion of buildings and the site topography, which in turn affects the townscape (Bandyopadhyay et al. 2015; Bandyopadhyay, Quattrone, Goffriller, Reza, and al-ʿAbri 2014b, 2014a, 2014c; Bandyopadhyay, Quattrone, Goffriller, and al-ʿAbri 2014b, 2016).

12.4 Development of a Conservation and Heritage Management Master Plan

12.4.1 A Holistic Approach

A conservation and heritage management plan for the revitalization of a traditional settlement should be both culturally and technically informed. It should be centered on the developmental requirements of the community, with a focus on education, training, and traditional knowledge-based skills development of the built environment and the society. For heritage conservation purposes, the intent should be to move away from an entirely tourism-focused approach (which would lead to cultural commodification) and toward a more sustainable alternative, in which traditional everyday activities can continue to play an important role in the local economy.

This approach takes a holistic view of development that goes beyond the notion of the settlement as an assemblage of built structures and artifacts and devotes specific attention to the present state of life and future aspirations of the inhabitants, ownership status of structures, and opportunity for public-private partnership. Conservation and development strategies are informed by internationally accorded ICOMOS charters and UNESCO Operational Guidelines, particularly the HUL recommendation, which set out how the significant values of a settlement, as well as its integrity, heritage, and material culture, are to be safeguarded within a context of sympathetic development.

A key theoretical concern is to keep in mind alternative definitions and models of development while questioning preconceptions regarding the close nexus between development and economic growth. Plan proposals should acknowledge the intertwined nature of development and heritage conservation and its management in seeking to unleash the site's opportunities to the fullest by reassessing heritage resources and sustainable lifestyle options.

At the core of the approach lies the restoration of local communities' appreciation for their own heritage, which uncritical impositions of "modernity" have often tended to erode. Actively integrating local stakeholders into the development process and empowering them in decision-making not only helps provide an economic incentive to become involved but also encourages the preservation of traditional skills in construction, crafts, and intangible heritage. At the settlement level, the goal is to avoid heritage "museumification" and instead focus on the settlement's revitalization and reintegration into the country's economy. In the long term, tourism, energy production, agriculture, and a host of associated creative industries based on traditional socioeconomic and cultural practices will ensure the survival of these ancient villages as well as their sustained growth and distinctive presence within a global economy.

12.4.2 HUL Tools

To develop an effective conservation and heritage management plan for the revitalization of traditional earthen settlements, it is essential to integrate the HUL tools, ensuring that the plan is both culturally and technically informed. The HUL toolkit offers a range of interdisciplinary tools that address the various facets of urban heritage management, and these should be adapted to fit the specific local context of the settlement in question. The key areas included in the toolkit are community engagement, knowledge and planning, regulatory systems, and financial tools. *Community engagement tools* are essential for fostering dialogue and resolving conflicts among diverse stakeholders, ensuring that conservation efforts align with the community's cultural values and priorities. *Knowledge and planning tools* are dedicated to the documentation and evaluation of urban heritage, ensuring its conservation and authenticity while guiding sustainable development. *Regulatory systems* establish the legal framework necessary for managing both physical and intangible aspects of heritage. Finally, *financial tools* are designed to support innovative development projects while preserving heritage values and significance, utilizing a mix of funding sources and partnerships to guarantee sustainable long-term outcomes.

The following complementary and interconnected precepts must guide any intervention to be carried out on the earthen-built fabric of an urban settlement for conservation and rehabilitation purposes:

- authenticity in both material and form in the conservation of urban clusters and open spaces
- compatibility, as conservation must not degrade the urban and building character

Once a site has been rehabilitated, the best way to preserve it from future deterioration is its continued utilization, even if for a new purpose, which in turn will encourage regular upkeep.

12.4.3 Analysis of Settlement Data

The fieldwork data collected are analyzed to get insights into the significance, strengths, and opportunities of the site; threats to its continued sustenance; and its future potential and offerings, all of which inform the heritage development brief. These findings fall into the following categories:

- *Architectural and urban mapping*. Data in this category contribute to the definition of urban and architectural significance, spatial ordering, hierarchy, connectivity, typological variations, and so on (figure 12.11).

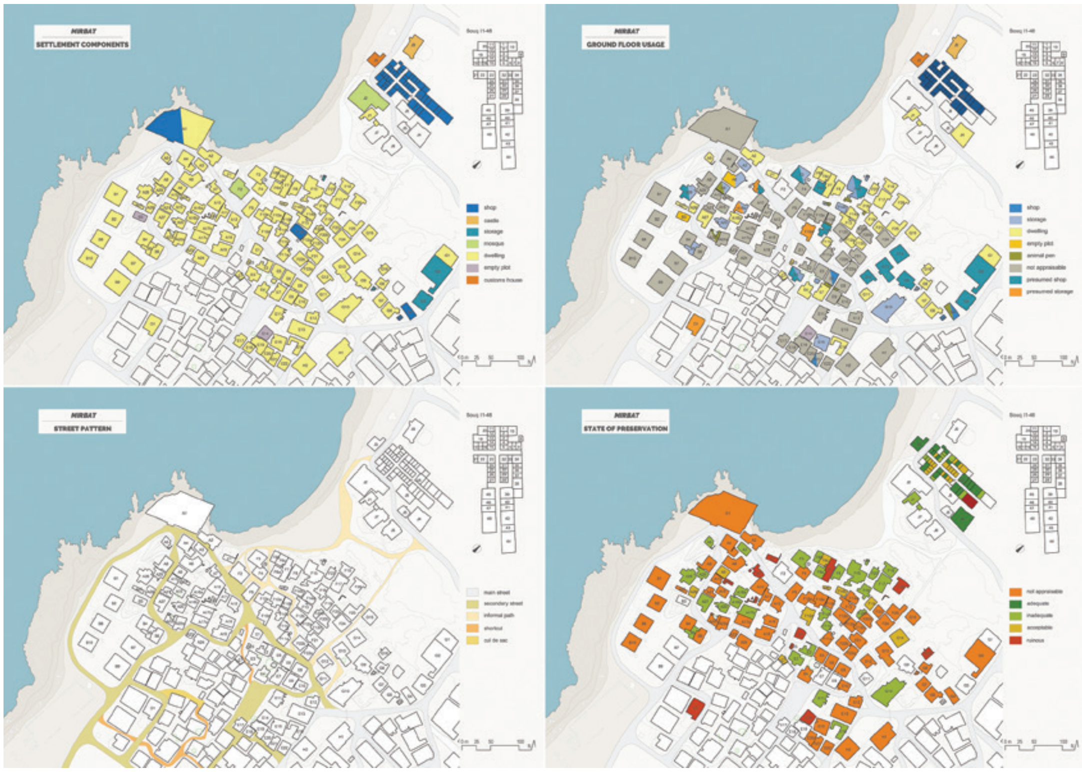

FIGURE 12.11. Architectural and urban mappings of the coastal village of Mirbat. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

- *Morphological and typological analysis.* The above quantitative and visual analyses and mappings of primary fieldwork data are further informed by qualitative information from secondary data sources. This enhances the understanding of urban and architectural characteristics that contribute to the character of the settlement (figures 12.12 and 12.13).
- *General historical and sociocultural background study.* Findings in this category support the establishment of key characteristics of the site and include understanding general planning approaches of the city (if the earthen settlement is within a wider urban environment) as well as analysis of the regulatory framework and existing economy.
- *Architectural, urban, sociocultural, and historical significance assessment.* The identification of key significance is critical for any heritage site in understanding the site's heritage value.

12.4.4 Ten Key Principles

Development approaches for a master plan for the site are determined using ten key principles or criteria based on ICOMOS International Charter for Conservation and Restoration (ICOMOS 2004) and recent conservation strategies such as HUL:

1. Minimum intervention.
2. Reversibility.

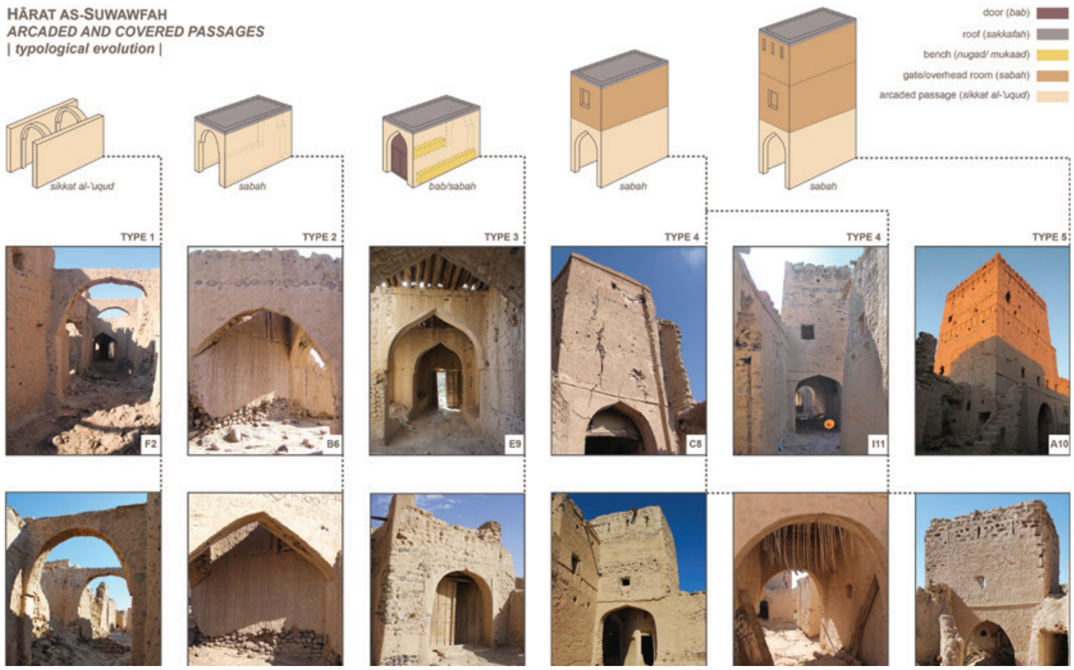

FIGURE 12.12. Analysis of typological evolution of arcades and passages from Harat as-Suwawfah quarter in Sinaw oasis. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

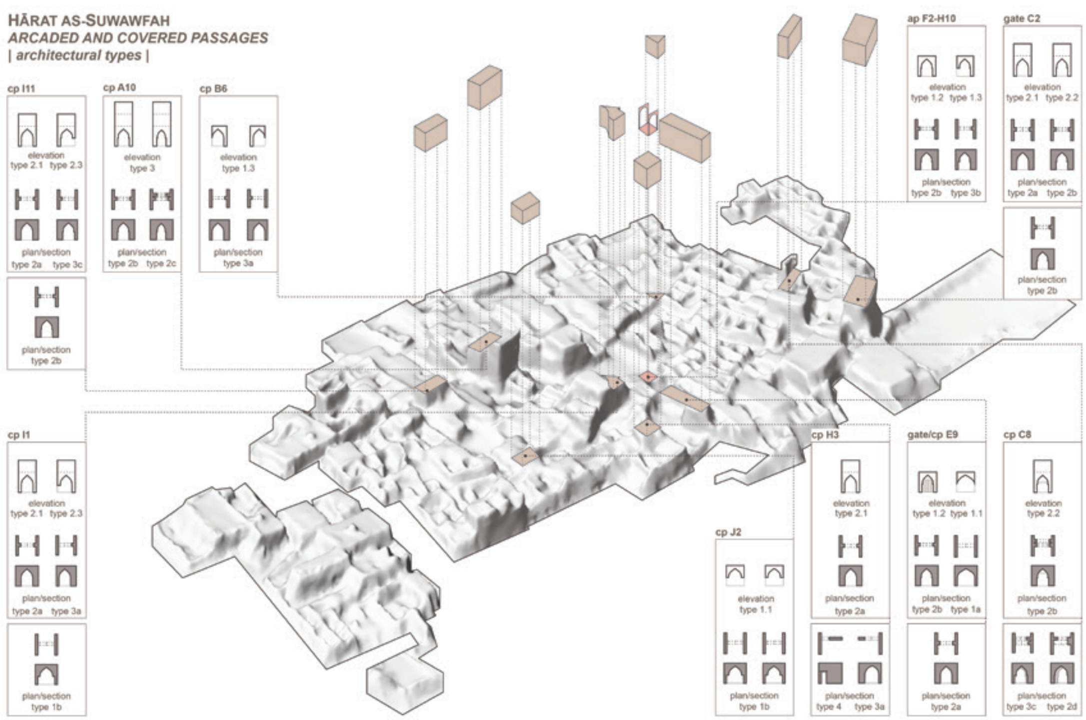

FIGURE 12.13. Analysis of arcades and passages from Harat as-Suwawfah in Sinaw oasis. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

3. Retention of buildings, settlements, and context: conserve vistas, views, spaces, and enclosures and sensitively interpret as necessary.
4. Anthropological approach to heritage management and reuse.
5. Integration of the younger generation through reuse and interpretation of the site.
6. Private- and public-sector engagement that fosters organizational and individual stakeholder cooperation.
7. Combined bottom-up and top-down approaches.
8. Introduction of functional diversity, including using innovative thinking and technologies to come up with possible compatible uses for existing buildings.
9. Sustainable management and conservation.
10. Concepts for new buildings that rely not on copies, replicas, or pastiches but on significance-based interpretation. This principle means that a variety of architectural languages may be appropriate, and the quality of the relationship between old and new is critical and dependent on the significance of the urban area. There may be instances where continuing past forms, materials, and styles that sustain traditional building practices may be necessary or other cases where new forms of architectural expression may be appropriate following principles of comparable scale, forms, setback, textures, etc. (Bandyopadhyay et al. 2015; Bandyopadhyay, Quattrone, Goffriller, and al-ʿAbri 2014a, 2014c, 2016; Bandyopadhyay, Quattrone, Goffriller, Reza, and al-ʿAbri 2014a, 2014b; Bandyopadhyay and Quattrone 2014)

12.5 Design of a Conservation and Heritage Management Master Plan

12.5.1 A Conservative Approach

A conservative approach to the master plan is adopted in accordance with the HUL recommendation (UNESCO 2011, 2013, 2016) and supported by the Valletta Principles for the Safeguarding and Management of Historic Cities, Towns and Urban Areas adopted by the ICOMOS International Committee on Historic Cities, Towns and Villages (CIVVIH) in 2011. This approach safeguards the values of the settlements, their integrity, and the heritage and material culture within a context of sympathetic development and effectively managed change. Following the establishment of a broad philosophy, a set of general policies for development and conservation is proposed, along with a set of detailed guidelines for restoration, consolidation, rebuilding, and redevelopment.

These guidelines should be followed by a set of more specific developmental/design strategies applicable to the site. Going forward, these guidelines should undergo regular review and refinement as the project proceeds.

Designing a Conservation and Heritage Management Master Plan in alignment with the HUL framework requires an approach that views conservation as the management of change (Historic England 2008). This perspective recognizes that urban landscapes are dynamic and constantly evolving while preserving their heritage values. Central to this is the integration of participatory methods, particularly involving local stakeholders, to ensure that heritage conservation remains relevant to the community.

The plan's primary objective is to safeguard the integrity of the settlement and its cultural heritage within a context that allows for sympathetic development. This involves establishing a broad conservation philosophy followed by general policies for development and detailed guidelines for restoration, consolidation, and redevelopment. These guidelines should not be static; they require regular review and refinement to adapt to the ongoing evolution of the urban landscape, ensuring that both heritage and development needs are met effectively as the project progresses.

12.5.2 Testing Strategies and a Phased Approach

Testing of the above principles and key conservation aspects in relation to the remaining built fabric is important and should be aimed at retaining the urban character of the settlement. The following strategies should be applied to all development and conservation measures:

- Maximum understanding of the architectural features and social values will be achieved prior to any intervention, which should be the minimum required to achieve those aims. Where analysis dictates that preservation in situ of a traditional building is unwarranted, it will be preserved by record.
- Morphology of the original phase of the fabric, or the phases deemed most significant, will be safeguarded and/or highlighted to preserve the identity, integrity, and authenticity of the site.
- All reasonable attempts will be made to ensure the appropriate and, if possible, authentic reuse of any redundant urban components and features.
- Retention of the scale and rhythm of the urban fabric, informed as much as possible by data collected through fieldwork or by reliable historical information, will be ensured.
- Traditional materials will be used wherever and whenever practicable during construction works within the settlement for the consolidation and/or rebuilding of existing components or the construction of new components.
- Where rebuilding is required to preserve a unit of the building cluster or define the urban character, all attempts will be made to clearly distinguish those reconstructed elements based on accurate documentation and those founded merely on conjecture.
- All measures will be taken to remove debris, hazardous construction, and organic and inorganic waste from the site and to prevent any such disposal in the future. All reusable building materials and architectural components should be salvaged, cataloged, and stored for reuse.

A phased approach to the master plan is proposed, designed to prioritize buildings and sites of significance that are under threat and to promote sustainable tourism development. This would also allow for supporting infrastructure (transport, energy resources, waste disposal) to be implemented in phases. Such infrastructure should carefully consider building up the site's carrying capacity in terms of the population and activity load that could be accommodated at any given time.

12.5.3 Visualization of the Master Plan

The proposal for the master plan is sketched out, suggesting zones of activity and introducing appropriate programs and supporting infrastructure while retaining the character of the settlement (figure 12.14). Other visualization techniques aid the testing and resolution of smaller-scale design interventions (figures 12.15 and 12.16). These context-specific proposals are informed by thorough precedent studies analysis (Bandyopadhyay et al. 2015; Bandyopadhyay, Quattrone, Goffriller, and al-ʿAbri 2016, 2014c; Bandyopadhyay, Quattrone, Goffriller, Reza, and al-ʿAbri 2014a, 2014b, 2014c).

12.6 Case Study: Misfat al-ʿAbriyin

The master plan proposal for the Old Village of Misfat al-ʿAbriyin in Oman was based on a strategy that involves integrating tourism with management of the settlement's significant heritage and the need for development that builds on key economic pillars of such mountain communities: agriculture, animal husbandry, and associated crafts. ArCHIAM (Centre for the Study of Architecture and Cultural Heritage of India, Arabia and the Maghreb) facilitated the establishment of the Misfat Community Cooperative (Misfat al-ʿAhliya), which played a significant role in

FIGURE 12.14. Master plan sketch drawing for Harat as-Suwawfah and Harat Al Bu Rashid quarters in Sinaw oasis. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

FIGURE 12.15. Proposal for the rehabilitation of the market (*souq*) in Misfat al-ʿAbriyin village. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

FIGURE 12.16. Visualization of the restoration proposal for the gateway, Sabah al-Nargila, at the Harat al-ʿAqr settlement quarter in the Bahla oasis World Heritage Site. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

community consultation and in organizing participatory design workshops during development of the master plan and in tourism leadership following implementation of the plan.

The intent of the master plan was to increase the potential of the communal areas of Misfat al-ʿAbriyin to sustain the daily life of the community, thus nurturing local identity values and enriching the tourism experience. Four focal activity/experiential areas were developed around a central hub housing the administrative facilities for the cooperative: by reviving the market (*souq*) in its original location, emphasizing culinary training, and developing agricultural and animal husbandry products (figure 12.17). The culinary experience was located in Harat ash-Shua' to the west of the settlement; the animal husbandry around the northeastern entrance, Sabah as-Sur; and the agricultural experience in Harat as-Safil, an area south of the market.

Improving tourism capacity by providing additional accommodations in the Old Village was a top priority. This was considered in relation to the settlement's existing spatial structure and the appropriate enhancement of its infrastructure and energy production. However, the master plan also sought to consolidate and expand the currently inhabited residential area by encouraging property owners to restore their vacant properties by either returning to the *harah* for living or converting their properties into second homes. The aim was to form a continuous and cohesive inhabited neighborhood along the northern edge of the settlement, creating a stronger sense of

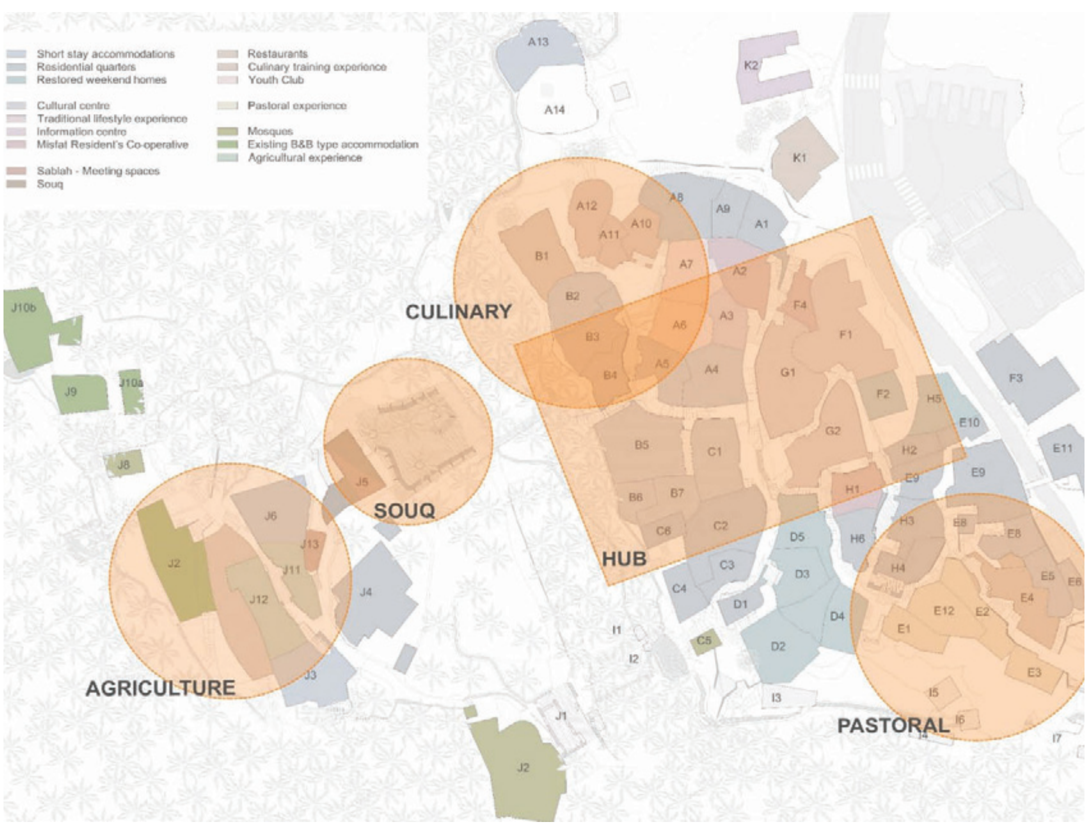

FIGURE 12.17. The four proposed activity areas around a central administrative hub in Misfat al-ʿAbriyin village. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

FIGURE 12.18. Restoration of the Harat ash-Shua' square in Misfat al-ʿAbriyin village. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

FIGURE 12.19. Adaptive reuse of a dilapidated dwelling as a café-restaurant in Misfat al-ʿAbriyin village; rear view from the oasis. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

FIGURE 12.20. Adaptive reuse of an old dwelling as a café-restaurant in Misfat al-ʿAbriyin village; internal view of the installed new staircase. *Source:* ArCHIAM Collections and Ministry of Heritage and Tourism, Oman.

community. Finally, acceptable accommodations were planned for expatriate agricultural workers who currently inhabit several dwellings dispersed across the settlement.

Part of this master plan has been realized through architectural and urban interventions that included the restoration, rebuilding, and adaptive reuse of three traditional stone buildings; the rehabilitation of interconnecting public spaces and pathways; and the development of a parking area (figures 12.18, 12.19, and 12.20; Bandyopadhyay et al. 2015).

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GLOSSARY

Adaptation. The modification of a place to suit the existing use or a proposed use where it has minimal impact on the cultural significance of the place (Australia ICOMOS 2013b).

Adobe. A mixture of wet earth and admixtures made into bricks and dried in the sun. In construction, adobe bricks are bonded together with mud- or lime-based mortar joints, and coats of earthen or lime-based plaster often cover adobe walls to prevent them from eroding. The word *adobe* evolved from the Middle Egyptian (ca. 2000 BCE) word *dj-b-t*, meaning "mud brick." As Middle Egyptian evolved into Late Egyptian, Demotic, and finally Coptic (ca. 600 BCE), *dj-b-t* became *tobe* ("mud brick"). This evolved into the Arabic *al-tub* (*al*, "the" + *tob*, "brick"), which was assimilated into Spanish as *adobe*. Used synonymously with the terms *mud brick* and *earth block* (Elborgy and Berkin 2018).

Aesthetic value. The sensory and perceptual experience of a place—that is, how we respond to visual and nonvisual aspects such as sounds, smells, and other factors having a strong impact on human thoughts, feelings, and attitudes. Aesthetic qualities may include the concept of beauty and formal aesthetic ideals. Expressions of aesthetics are culturally influenced (Australia ICOMOS 2013b).

Architectural conservation. The process through which the material, historical, and design integrity of built heritage are prolonged through carefully planned interventions. The architectural conservator uses scientific methodologies outlined by the conservation field and other specialties and applies them for the study, analysis, conservation, and/or restoration practices on the fabric of historic buildings (Berdecía-Hernández 2020).

Arish. Arabic term for traditional buildings made from the leaves of date palms, which have provided shelter from the extreme climate of the Arabian Peninsula for generations. Often associated with earthen buildings, in an arish structure, palm stems and leaves are used in ingenious ways to create habitable structures that provide both shade and ventilation (Piesik 2012).

Attributes. Features of a place that convey or express cultural significance and may include its physical location, external and internal form, fabric and use, layout, planning, design (including color schemes), fittings, artworks, objects, construction systems, technical equipment, gardens, landscapes or other settings, and aesthetic qualities.

Authenticity. Characteristics that most truthfully reflect and embody the cultural heritage values of a place (English Heritage 2008). A culturally contingent quality associated with a heritage place, practice, or object that conveys cultural value is recognized as a meaningful expression of an evolving cultural tradition and/or evokes among individuals the social and emotional resonance of group identity (Nara + 20 2014).

Backfilling. The refilling of an excavated area with some sort of fill material such as sand or gravel. This technique, sometimes also referred to as reburial, is often used in combination with a porous barrier such as geomesh or geotextile to protect archaeological sites from further decay.

Basal erosion (coving). A product of the combination of rising moisture, soluble salts from the ground that destabilize the building material, and wind erosion. The outcome is deep erosion at the wall base, often on either side. Can ultimately lead to complete or partial collapse of a wall.

Binder. Material that acts as a bonding agent that, when mixed with aggregates and water to form grouts or mortar, is used to bond various masonry units together to play a structural and decorative role in a building. Binders define the physical and chemical properties of the mortar, including its strength, how quickly it hardens or sets, and how it reacts with surrounding materials (Christiansen 2021).

Capillarity. A phenomenon associated with surface tension whereby liquids can travel horizontally or vertically (against the force of gravity) in small spaces within materials. For example, rising dampness in masonry is the result of *capillary action*.

Clay. A type of fine-grained natural soil material containing clay minerals. Clays develop plasticity when wet due to a molecular film of water surrounding the clay particles but become hard, brittle, and nonplastic upon drying or firing. Clays are fine-grained minerals with particle diameters of <2 μm (0.002 mm). Common types of clays include (1) *kaolinite*, a clay mineral that is the weathering product of feldspars and has a white, powdery appearance; (2) *illite*, which resembles muscovite in mineral composition, only finer-grained, and is the weathering product of feldspars and felsic silicates; (3) *smectite*, a clay mineral that is the weathering product of mafic silicates; is stable in arid, semiarid, or temperate climates; and has the ability to absorb large amounts of water, forming a watertight barrier; and (4) *montmorillonites*, a very soft phyllosilicate group of minerals that form when they precipitate from water solution as microscopic crystals.

Cob (cobb). A building material that comprises soil, straw (or another fibrous organic material), water, and occasionally lime. Cob construction relies on the builder's hands and feet to form lumps of earth mixed with sand and straw. Because there are no forms, ramming, cement, or rectilinear bricks, cob lends itself to organic shapes, including curved walls, arches, and niches (Houben and Guillaud 1994).

Communal value. Value deriving from the meanings of a place for the people who relate to it or for whom it figures in their collective experience or memory (English Heritage 2008).

Compatible use / compatibility. A use that respects the cultural significance of a place. Such a use involves no or minimal impact on cultural significance (Australia ICOMOS 2013a).

Conservation management plan. A document that sets out what is significant about a place and consequently what policies are appropriate to enable that significance to be retained in its future use and development. For most places, it deals with the management of change (Kerr 1996, 1).

Consolidation. The act of stabilizing degraded or weakened areas by introducing or attaching materials capable of holding them together; a treatment used to strengthen deteriorated materials to ensure their structural integrity (AAT Online, n.d.).

Cultural landscape. The term *cultural landscape* represents the interactions between man and nature. They are illustrative of the evolution of human society and settlement over time, under the influence of the physical constraints and/or opportunities presented by their natural environment and of successive social, economic, and cultural forces, both external and internal (UNESCO 2003).

Cultural significance. Aesthetic, historic, scientific, social, or spiritual value for past, present, or future generations. Cultural significance is embodied in the place itself, its fabric, setting, use, associations, meanings, records, related places, and related objects. Places may have a range of values for different individuals or groups (Australia ICOMOS 2013).

Earthen architecture. All that is built with raw earth, comprising different ways of building and various techniques such as rammed earth, adobe, wattle and daub, cob, and so on. Earthen architecture includes vernacular and monumental heritage, archaeological sites, contemporary architecture, self-built construction, and so on (Houben and Guillaud 1994).

***Falaj* (pl., *aflāj*).** Arabic term for the network of underground galleries (*qanat*) and overground channels that distribute water for drinking as well as for irrigation. The *falaj* is fed either by aquifers located in the mountains, by springs, or by intercepting perennial flow on *wādī* beds (seasonal water drainage courses).

Flocculation. The process by which fine particulates are caused to clump together into a floc. The floc may then float to the top of the liquid, settle to the bottom of the liquid (sedimentation), or be readily filtered from the liquid.

Grout. In conservation of architectural surfaces, a bulked fluid material that can be injected behind stuccos, wall paintings, or mosaics to fill cracks and voids and reestablish adhesion between delaminated layers upon setting. Injection grouts are composed of one or more binders, aggregates, and admixtures, plus a fluid, typically water (Biçer-Şimşir and Rainer 2013).

***Haram* (short vowel).** Arabic term for a protected place that includes a significant site, its associations, its intangible aspects, and its buffer zone (ICCROM Athar 2008).

Heritage value. The aesthetic, historic, scientific, cultural, social, or spiritual importance or significance for past, present, or future generations. The heritage value of a historic place is embodied in its character-defining materials, forms, location, spatial configurations, uses, and cultural associations or meanings (Canada's Historic Places, n.d.).

Historic Urban Landscape (HUL). The urban area understood as the result of a historic layering of cultural and natural values and attributes, extending beyond the notion of "historic center" or "ensemble" to include the broader urban context and its geographic setting (UNESCO 2011).

Integrity. Refers to the *wholeness and intactness* of the cultural or natural heritage and its attributes. For a site to meet the condition of integrity, it must include all elements necessary to express its Outstanding Universal Value (OUV), be of adequate size, and not suffer from adverse effects of development or neglect (UNESCO 2021).

Interpretation. Refers to the full range of potential activities intended to heighten public awareness and enhance understanding of cultural heritage sites. These can include print and electronic publications, public lectures, on-site and directly related off-site installations, educational programs, community activities, and ongoing research, training, and evaluation of the interpretation process itself.

Intervention. Any action, other than demolition or destruction, that results in a physical change to an element of a historic place (Parks Canada 2017).

Inventory. Ongoing records for identifying as well as describing heritage places for a range of purposes, including heritage management and protection and public appreciation. Inventories are typically produced at a variety of geographic scales, including international, national, regional, local (e.g., city), and site levels. In some cases, topical or thematic inventories are produced, such as those of shipwrecks, rock art, or industrial heritage, whether through legal mandate or by professional or voluntary organizations with topical concerns (Myers 2016).

Maintenance. The continuous protective care of the fabric and setting of a heritage place or site and is to be distinguished from repair (ICOMOS 2017).

Majālis. Arabic term for semipublic reception hall.

***Medina* (*madinah*).** Arabic word meaning "city," often referring to the historic center.

Minimal intervention. Using only as much new material as necessary to repair damage and prevent further deterioration while making the new material clearly distinguishable from the original. This is closely linked to the idea of preserving authenticity. The changes should not distort the physical fabric or be based on conjecture (Ureche-Trifu 2013).

Monitoring. The systematic and regular inspection or measurement of the condition of the materials and elements of a historic place to determine their behavior, performance, and rate of deterioration over time (Canada's Historic Places, n.d.).

Mortar. A heterogeneous mixture of binder, aggregate, and water that is used to bond masonry units such as brick, adobe, and stone (NPS 2022).

Outstanding Universal Value (OUV). Having cultural and/or natural significance that is so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity. As such, the permanent protection of this heritage is of the highest importance to the international community as a whole. The World Heritage Committee defines the criteria for OUV required for inscription of a property on the World Heritage List (UNESCO 2021).

Photogrammetry. The art, science, and technology of obtaining reliable information about physical objects and the environment through the processes of recording, measuring, and interpreting photographic images (Wolf, Dewitt, and Wilkinson 2014).

Porosity. Water absorption by capillarity. Building materials, both natural (stones) and artificial (bricks, lime, and cement mortar), contain a certain volume of empty space. This is distributed within the solid mass in the form of pores, cavities, and cracks of various shapes and sizes. The total sum of these empty spaces is called porosity, a fundamental characteristic of building material that affects its physical properties (durability, mechanical strength, etc.; Borelli 1999).

Preservation. The process of maintaining the fabric of a place in its existing state and retarding deterioration (Australia ICOMOS 2013b).

Preventive care (preventive conservation). Preventive conservation involves all measures and actions aimed at avoiding and minimizing future deterioration or loss. They are carried out within the context or on the surroundings of an item but more often on a group of items, whatever their age and condition. These measures and actions are indirect—they do not interfere with the materials and structures of the items. They do not modify their appearance (ICOM-CC 2008).

Qiblah. Arabic term indicating the direction toward the Ka'ba (ICCROM Athar 2008).

Rammed earth (*pisé, pisé de terre*). A mixture of sand, soil, clay, and other ingredients compressed through ramming within forms to create building elements. Rammed-earth construction is a structural building method of compressing a soil-based mixture into a hard material (Houben and Guillaud 1994).

Reconstruction. The process of returning a place to a known earlier state. Reconstruction is distinguished from restoration by the introduction of new material into the fabric (Australia ICOMOS 2013a).

Rehabilitation. The act or process of returning a property to a state of utility/compatible use through repair or alteration that makes possible an efficient contemporary use while preserving those portions or features of the property that are significant to its historical, architectural, and cultural values (Grimmer 2017).

Restoration. Intervention made with the deliberate intention of revealing or recovering a known element of heritage value that has been eroded, obscured, or previously removed rather than simply maintaining the status quo. It may also achieve other conservation benefits; for example, restoring a roof on a roofless building may make it both physically and economically sustainable in the long term (English Heritage 2008).

Retrofitting. Involves the upgrading of an existing building to meet code or safety requirements (fire, structural/seismic, emergency and disabled access, etc.).

Revitalization. A process of economic, social, and cultural redevelopment of a civic area or neighborhood. Heritage area revitalization concentrates on historic buildings and other heritage resources to achieve economic, social, and cultural objectives (Heritage BC 2022).

Sarooj. Arabic term for a traditional water-resistant render used in the construction of irrigation channels, wells, and other applications. There are several mixtures of *sarooj* common to the Middle East region that are based on fired and ground clay with admixtures such as limestone, animal dung, and straw. It is mixed with water to form a stiff paste and typically kneaded or beaten to reach optimum working consistency (Meddah et al. 2020).

Scientific value (technical value). The information content of a place and its ability to reveal more about an aspect of the past through examination or investigation of the place, including the use of archaeological techniques. The relative scientific value of a place is likely to depend on the importance of the information or data involved; on its rarity, quality, or representativeness; and on its potential to contribute further important information about the place itself or a type or class of place or to address important research questions (Australia ICOMOS 2013b).

Shoring. A form of prop or support, usually temporary, used during the repair or original construction of buildings and in excavations. Temporary support may be required, for example, to relieve the load on a masonry wall while it is repaired or reinforced.

Significance. The value of a heritage asset to this and future generations because of its heritage interest. That interest may be archaeological, architectural, artistic, or historic. Significance derives not only from a heritage asset's physical presence but also from its setting. The sum of the cultural and natural heritage values of a place is often set out in a statement of significance (English Heritage 2008).

Social value. The associations that a place has for a particular community or cultural group and the social or cultural meanings that it holds for them (Australia ICOMOS 2013b).

Spiritual value. The intangible values and meanings embodied in or evoked by a place that give it importance in the spiritual identity or the traditional knowledge, art, and practices of a cultural group. Spiritual value may also be reflected in the intensity of aesthetic and emotional responses or community associations and may be expressed through cultural practices and related places (Australia ICOMOS 2013b).

Stabilization. Treatment procedures intended to maintain the integrity of cultural property and to minimize deterioration (AIC 2022).

Stakeholders. The people and organizations who are involved in or affected by an action or policy and can be directly or indirectly included in the decision-making process (NCEP 2022).

Statement of significance. A summary of the cultural and natural heritage values currently attached to a place and how they interrelate, which distills the particular character of the place. The statement of significance should identify the relative importance of the heritage values of the place (where appropriate, by reference to criteria for statutory designation), how they relate to its physical fabric, the extent of any uncertainty about its values (particularly in relation to potential for hidden or buried elements), and any tensions between potentially conflicting values (English Heritage 2008).

Treatment. The deliberate alteration of the chemical and/or physical aspects of cultural property, aimed primarily at prolonging its existence. Treatment may consist of stabilization and/or restoration (AIC 2022).

Vernacular. Indigenous, made locally by inhabitants using local materials and traditional methods of construction and ornament; specific to a region or location.

Waqf. Arabic term for a system of endowment that was developed in Islamic communities to secure the sustainable management and conservation of public institutions, including mosques, water sources, and so on (ICCROM Athar 2008).

Wattle and daub. A composite building method used for making walls and buildings in which a woven lattice of wooden strips (wattle) is covered (daubed) with a wet earthen material that is usually some combination of wet soil, clay, sand, and straw (Houben and Guillaud 1994).

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Hossam Mahdy is an independent consultant and researcher on the conservation of built heritage based in Oxford, UK. He earned his PhD from Glasgow University; MSc from Raymond Lemaire International Centre for Conservation, Leuven; and BSc from Ain Shams University, Cairo. He is a member of ICOMOS-UK and the president of the ICOMOS International Scientific Committee on Vernacular Architecture (CIAV). He is an advisor to the World Heritage Unit at ICOMOS International Secretariat, Paris, and a consultant to the Heritage Commission in Riyadh, Saudi Arabia. Hossam has more than thirty years of experience as an architect, researcher, consultant, and lecturer on built heritage conservation. His previous roles included the founder and head of the Conservation Section at the Department of Culture and Tourism, Abu Dhabi, UAE; the head of the Heritage Section at the Alexandria Mediterranean Research Centre at the Bibliotheca Alexandrina; a consultant to the Getty Conservation Institute for the management plan for Queens Valley in Luxor; a consultant to the Ministry of Culture in Egypt on urban conservation in Historic Cairo; and a lecturer on conservation at South Valley University and various Egyptian universities. His academic research focuses on culture-specific approaches, philosophy, and practices of conservation in the Arab region. He was also a Getty conservation scholar for the period 2016–17. Hossam is the author of *Glossary of Arabic Terms for the Conservation of Cultural Heritage* and *Approaches to the Conservation of Islamic Cities: The Case of Cairo*. Both were published by ICCROM.

Benjamin Marcus is a conservator and project specialist at the Getty Conservation Institute's Department of Buildings and Sites. He holds a master's degree in historic preservation from Columbia University and joined the GCI in 2012, initially as manager of the GCI-ICCROM International Course on Stone Conservation in Rome. Currently, he manages the International Course on the Conservation of Earthen Architecture in Abu Dhabi and Oman. He also works on the Seismic Retrofitting Project (SRP) in Peru and is engaged in the design of a ten-year strategy for the GCI's Earthen Architecture Initiative (EAI). At the GCI, he has developed various capacity-building activities, including seismic retrofitting workshops in Peru; training in conservation principles for the archaeological site of Bagan, Myanmar; and courses on earthen materials analysis and grouting for the Terra 2022 conference in Santa Fe, New Mexico. He also managed the development and implementation of the rehabilitation plan for Kasbah Taourirt in Ouarzazate, Morocco. Before joining the GCI, he was a building conservator with the Abu Dhabi Authority for Culture and Heritage, where he managed conservation for earthen buildings and archaeological sites. He was also a conservator with Page & Turnbull in San Francisco and held internships with the GCI and Global Heritage Fund, working internationally on projects ranging from the rehabilitation of an Ottoman historic district in Kars, Turkey, to the conservation of Roman mosaics in Tunisia. He is an expert member of the ICOMOS Scientific Committee on Earthen Architectural Heritage (ISCEAH).

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Peter Sheehan is an archaeologist who has been working in the Middle East for more than twenty-five years. He holds a BA in ancient history and archaeology from the University of Birmingham and an MA in conservation from the University of York. He has worked on numerous archaeological and historic building conservation projects throughout the region since 1989, particularly in Egypt and the United Arab Emirates. He has a particular interest in urban site formation processes and has published extensively on his work in and around the Roman fortress of Babylon in Old Cairo and on the development of the historic oasis landscape of the World Heritage Site of Al Ain. Since 2007, he has been working for the Department of Culture and Tourism–Abu Dhabi, first as historic buildings manager and now as head of historic buildings and landscapes, where he has been involved in the site management, conservation, and interpretation of historic buildings throughout the Emirate.

Alessandra Sprega is a conservation architect and associate project specialist at the Getty Conservation Institute. She holds a BA and an MA in architecture from the University of Roma Tre as well as a second MA and a PhD in conservation studies from the University of York. Her doctoral research involved a comparative analysis of two historic centers—York (UK) and Amatrice (Italy)—both of which have experienced significant impacts from natural disasters. Using participatory GIS methods, she investigated how community knowledge and memory contribute to heritage resilience in these settings. Throughout her PhD, she worked with several UK conservation practices. Her roles primarily involved designing conservation solutions for listed buildings in the North of England. In addition, she worked as a teaching assistant for the Applied Building Survey MA module at the University of York. There, she organized and led a teaching session within the Heritage Documentation Workshops—Using Photogrammetry with GIS for Cultural Heritage, a joint initiative by the University of York and CEPT University in Ahmedabad, India. Currently, she is working at the GCI on three key components of the Earthen Architecture Initiative (EAI): the Seismic Retrofitting Project in Peru, the Earthen Architecture Course in the UAE and Oman, and EAI's broader research and strategic goals. Additionally, she is a member of ICOMOS–ISCEAH and was recently awarded an honorary research associate position at the University of York.

Henri Van Damme has devoted most of his career to the study of geomaterials like clays, glass, cement, soils, muds, rocks, and concrete, with applications in the fields of construction, energy, or environment. He is also interested in architecture, conservation, urban sciences, and teaching methods. Now an independent consultant, he has spent three years (2014–16) as an invited visiting professor in the Civil and Environmental Engineering Department at MIT, on leave from the Ecole de Physique et Chimie Industrielles (ESPCI) de Paris, where he has been a professor of thermodynamics and materials science since 1999. Born in Belgium, Van Damme received his graduate degree (1969) in bio- and chemical engineering and his PhD degree (1974) in materials science, both from the Catholic University of Louvain (UCL), before moving to the National Center for Scientific Research (CNRS), Orléans, France, from 1974 to 1999. His interest in earthen architecture led him to spend a sabbatical as a scholar at the Getty Conservation Institute in 2006 and 2021. He has been collaborating extensively with CRAterre and with Amaco, the French national project on innovative education methods in construction materials science and architecture. In the same vein, he participated as an instructor in the first and second International Course on the Conservation of Earthen Architecture (EAC) organized by the GCI and the Abu Dhabi Tourism and Culture Authority, UAE, in 2018 and 2022. He is the author of approximately two hundred peer-reviewed papers and book chapters, with more than two-thirds of this on clays, soils, and construction materials.

Clemencia Vernaza is a Colombian sociologist and conservator with over 40 years of experience in mural painting. She has trained in mural painting and stone conservation at ICCROM, conservation of earthen architecture in Grenoble, and mid-career training in modern and contemporary art conservation at the Guggenheim Museum. She also holds a Master's degree in World Heritage at Work from the International Labor Organization (ILO) in Turin and another in heritage virtualization from Alicante, Spain. Clemencia was a scholar at the Getty Conservation Institute, where she conducted research on the training of mural painting conservators in Latin

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Christof Ziegert is managing and scientific director of ZRS Ingenieure GmbH, a part of ZRS Architekten Ingenieure, Berlin, Germany. The company is specialized in conservation design for earthen buildings and has been working worldwide and in the UAE since 2007. His project portfolio includes world-famous archaeological sites such as Uruk and Babylon, as well as the conservation of historical palaces and castles in the Middle East, including the Old Palace in Doha, Qasr Al Hosn in Abu Dhabi, and Jahili Fort in Al Ain. As a trained mason, he works on construction sites and trains local specialists in conservation techniques. Christof is Honorary Professor of 'Building and Conservation with Earth' at the University of Potsdam, Germany, and Scientific Director of the Certificate Course in Earth Building at the Bauhaus University in Weimar, Germany. He is Chairman of the standardization committee Earth Building Materials NA 005-06-08 AA at the German Institute for Standardization and for 20 years has been a board member of the German Earth Building Organization "Dachverband Lehm e.V.". Christof Ziegert is ICOMOS Member and Expert Member of the International Scientific Committee for Earthen Architecture Heritage (ISCEAH).