OTHER TOOLS FOR INVESTIGATION AND MONITORING

Overview of Diagnostic Indirect Tools for Conservation

John A. Fidler

Tools and techniques for the surveying, recording, and documentation of historic places are part of a diverse and complicated field. When applied in the service of conservation rather than for academic research purposes or as part of an archaeological investigation, the application of the equipment and methods to achieve specific conservation-related outputs becomes particular and essential, driven by the needs of the architects, engineers, and conservators involved in the conservation process.

Too often the dialogue between surveyors and conservators becomes mired in the technical language of their respective professions—language that neither party fully understands—often leading to differing expectations. When conservation professionals do not have the option of delegating surveying, recording, and documentation to others, or wish to deliver these components themselves, the integration of actions is often more successful. The problem comes with larger, more complicated projects in which specialist equipment, software and data manipulation, and other complexities are required for cost-effective delivery. This section attempts to define and explain the types of tools available and place them in a conservation context, prior to describing their function and use in more detail.

In conservation, there are two distinct areas of survey and recording, with a degree of overlap between them:

1. **Metric surveying and recording.** This area is used to establish the quantifiable physical disposition of form and space. Base documentation can be employed in subsequent complementary phases of a conservation project to map historical, technical, and other data for assessment, analysis, and synthesis of information to create a plan, then inform, guide, and instruct others in taking conservation action.
2. **Diagnostic surveying and recording.** This area is used to locate, isolate, assess, or monitor physical phenomena affecting the heritage asset. Additional documentation can overlay base documentation and further inform the conservation project's development in relation to buried or concealed features, deforming or moving components and providing indications about their condition and performance in time.

Some tools, such as tape measures, levels, and total station theodolites, involve direct handheld or hand-eye relationships with the operator that are generally simpler to understand and use and are cheaper to operate than indirect tools. Indirect technology such as radiography or thermography—often from the medical, aviation, or military arena—requires specialized operators and software as well as expensive equipment whose documentation needs to be interpreted for the conservation team to benefit from the data. Although many pieces of equipment and their associated software are being simplified by their manufacturers to the "point-and-shoot" kind of format of, say, a digital camera, they remain expensive items usually contracted temporarily or deployed as part of a subcontractor's hardware. The following is an overview of the diagnostic indirect tools available for conservation.

Water Optical and Digital Endoscopy

The simplest way to describe endoscopy is to use the analogy of a periscope: it enables operators to look through a long, rigid, or flexible tube inside the fabric of a building through holes as small as 4–5 millimeters in diameter. Until the recent development of tiny digital cameras with motorized focusing, endoscopy used light-guide bundles of fiber-optic cables to transmit light into cavities, collect received light, and pass images back to the eye. With range-finding optics, the equipment can be used to determine the location or dimensions of cavities or objects, assess the condition of concealed pipes or fixings, or aid the routing of wiring within composite construction.

Water, Plumb, and Laser Leveling

To assess the trueness, level and relative levels, and plumb or vertical nature of an element of construction–for example, subsiding floors, leaning walls, or sagging beams–a variety of levels can be employed for repeatable measurements. The simplest and one of the oldest construction tools is the plumb bob. A heavy weight is suspended on the end of a long string or wire, which is hung vertically from the top of a structure. The base of this pendulum is then suspended in water or oil to minimize movement. The vertical line can be measured at fixed points against the structure to determine the lean of the wall. Laser plumb bobs are used in the same way.

The term *laser* is an acronym for light amplification by stimulated emission of radiation. Lasers emit light in a narrow, well-defined beam within a coherent set of wavelengths, and over short distances are extremely straight. Used horizontally, lasers can be used to align features, determine disposition or deflection, and measure angles. A simpler, cheaper tool is the water line level, which consists of a flexible, small-diameter plastic or rubber hose pipe with open ends to which plastic or glass ends are added. The hose is filled with water and the two ends moved up or down, even around corners, and the horizontal level is determined by equalization of atmospheric pressure.

Oblique Angle and Color Filter Photography

A simple method of finding concealed doorways or window reveals under plastered or stuccoed walls is to use oblique angle or color filter photography. Oblique angle photography captures subtle shadow lines of inconsistencies and changes of plane in plaster surfaces. Color filter, or colored light, photography captures partial and different reflectances in surfaces and helps to reveal patches and changes in surface under coatings.

Infrared Photography and Thermography

Infrared film photography is being superseded by thermography or thermal imaging, a type of infrared imaging used to discern concealed openings and other anomalies under the surfaces of historic facades and internal paneled walls. Thermographic cameras detect radiation in the infrared range of the electromagnetic spectrum (roughly 900–14,000 nanometers, or 0.9–14 µm) and produce images of that radiation. Because infrared radiation is emitted by all objects based on their surface temperatures, thermography makes it possible to "see" variations in temperature caused by different materials, voids, and other changes of construction.

Radiography

Shorter energy wavelengths are necessary to deploy radiographic imaging to "see" concealed objects within the historic fabric and record it on film. X-ray radiography in the range of 15–33 kilovolts can be used to find and assess the condition of timber framing under plasterwork, or of floor construction without lifting carpets. Linear accelerator (LINAC) radiography and gamma radiography have also been employed in the megavoltage range to locate and quantify steel reinforcement in bridge decks or corroding buried wrought iron in the stonework of lighthouses and country houses.

Magnetometry

Magnetometer surveys are a type of geophysical mapping technique that relies on the stability of the world's relatively static magnetic field. These surveys can detect anomalies caused by cultural objects interfering with that magnetic field. They can be used to locate long-forgotten conduit systems, as well as pipes, cables, or remains buried in the ground.

Metal detectors are employed for pachymetry (e.g., thickness) measurement in masonry structures by utilizing electromagnetic induction to detect underlying metalwork. They are used especially in the construction industry to detect and size steel reinforcing bars buried in concrete, as well as pipes and wires buried in walls and floors. In its simplest form, a metal detector consists of an oscillator, which generates a current that passes through a coil, producing an alternating magnetic field. If a piece of metal, which is electrically conductive, is close to the coil, eddy currents will be induced in the metal; this in turn produces an alternating magnetic field of its own. If another coil is used to measure the magnetic field (acting as a magnetometer), the change in the magnetic field due to the metallic object can then be detected.

Ultrasound Pulse Transmission

Ultrasound surveys and testing, or sonography, constitute a diagnostic imaging technique used to measure the thickness from one side of solid, dense, homogeneous materials and to detect flaws and anomalies in their interiors. The technique has been used, for example, on the Houses of Parliament, in Britain, to measure the thickness of corrosion layers on the underside of the cast-iron roof without lifting the panels. It is a nondestructive testing process utilizing sound frequencies in the 2–10 megahertz range, though for special purposes other frequencies are used; for instance, lower-frequency ultrasound (50–500 kilohertz) to inspect lower-density materials such as wood. In France, the technique is used to assure the quality of quarry stone before processing by searching for concealed cementation lines and fossil anomalies that may break or cause misalignment of saws during cutting.

Pulse Radar

Radar is an acronym for radio detection and ranging. When fired at the ground or at a thick masonry structure, long-wave radiation is partly reflected at the surface, partly absorbed, and partly transmitted through the construction. Reflections and echoes from this energy are transmitted back to the receiving antennae, and the time delays in transmission and losses in signal strength are compared to those in the original signal to reveal changes in the data. When interpreted, radar information can locate and measure the distance between and size of inconsistencies and anomalies within a structure. The geometry of such concealed or buried objects–for example, wrought-iron cramps in stone masonry, reinforcing bars in concrete, or ceramic pot fillers in concrete floor construction–can reveal the nature and sometimes the condition of these materials.

Radio Emission or Electrolocation Cable/ Pipe Detection

All live electrical cables, and all electrically conducting materials through which an electrical current can be induced, will emit an electromagnetic field in the range of 50 hertz to 400 kilohertz (from low- to high-frequency power) that can be detected by a radio detector. As the energy travels a given distance, and if the detection devices have two radio antennae set at a precise distance apart, the depth within the ground, wall, or floor of the cables or metalwork can be calculated. This electromagnetic time domain reflectometry is used to locate modern electrical systems that are in need of replacement in historic buildings. Once identified, removal of the system can be carried out without excessive damage to the original fabric.

Stress-wave Transmission (impact-echo)

Using transducer technology, surface and subsurface vibrations in structures can be detected and used to determine anomalies, voids, and other construction problems in otherwise homogeneous construction. First, the heads of the transducer are placed on either side of a masonry column, for example, or along the side of a historic railway's viaduct. The structure is then hit or impacted with a known measured force or drop hammer so that the superstructure vibrates and measurements can be taken of the signals. If there are asymmetrical patterns in the signals, estimations can be made of construction voids and their location and depth within the fabric.

Transducer Movement Sensing

Linear variable differential transducers and accelerometers are devices that translate physical structural movements (displacement and shear) and vibrations into electrical signals that can be collected and analyzed. The pistonlike transducers are fixed across cracks on a building. Wires are then attached that lead to a data logger or convenient interrogation point. The "piston" arm is made of ferrous magnetic material and moves freely backward and forward within an electrical coil as the crack on the building moves. This alters the electrical voltage of the system and the resultant changes are registered on the data logger. Automated systems with telemetric connections monitor historic bridge movements in many cities today. The Tower of Pisa, in Italy, was monitored in Watford, England, in real time using these devices, which measured rate and degree of the tower's tilt, subsidence, and crack and arch deformation.

Many of the aforementioned devices use nondestructive or keyhole surgery techniques to aid conservation of valuable historic fabric. Some devices are expensive to purchase and use, others more economical to buy or lease when needed. But none is a substitute for a keen eye, patient assessment, and human logic, all of which will always be needed to conserve the best of the past for the future.

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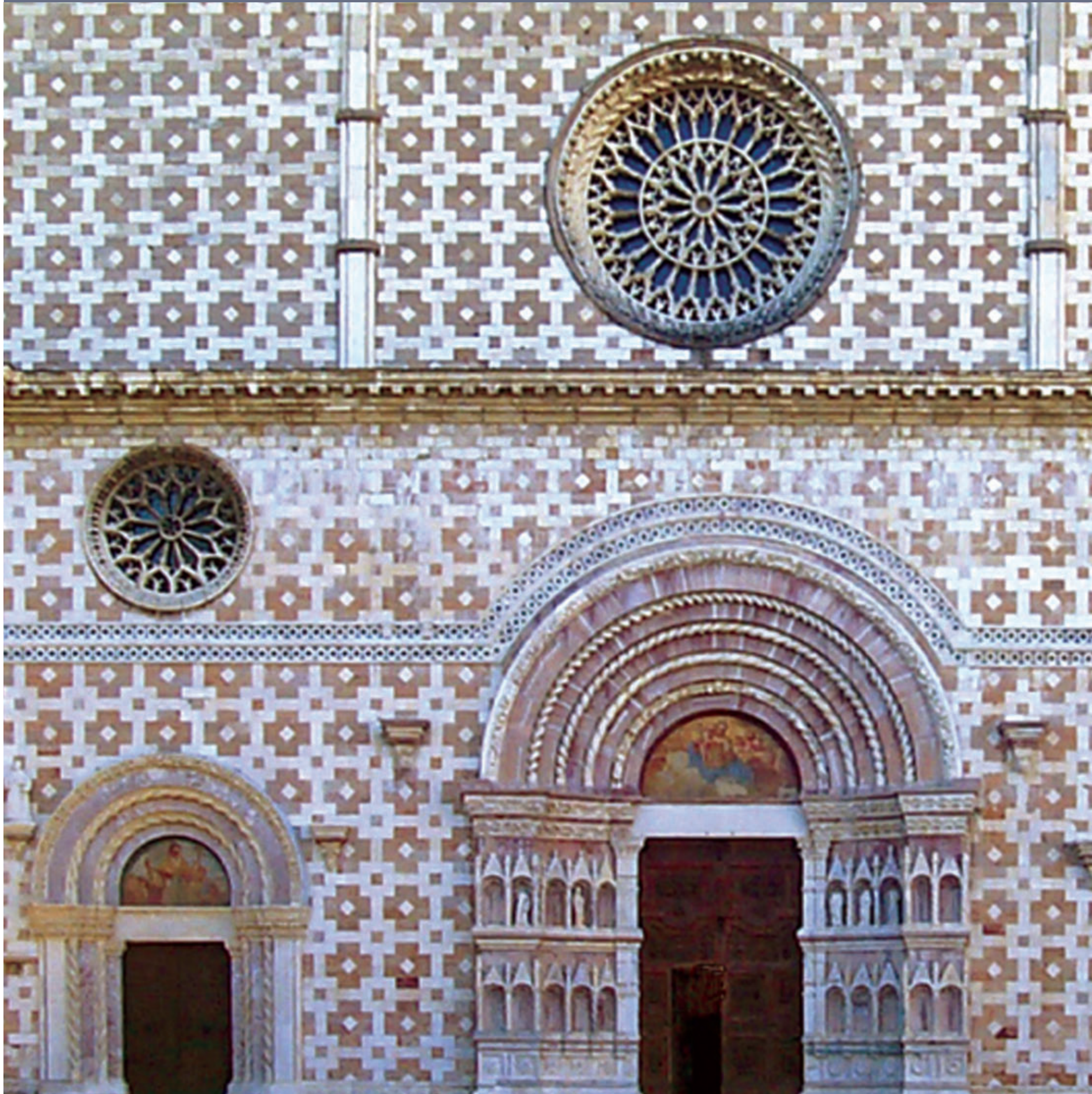
Subsurface Conditions

Marco Tallini

The Basilica of Santa Maria di Collemaggio, in L'Aquila, is the most celebrated medieval church in the region of Abruzzo, in central Italy. The pink and white limestone ashlars that form its stunning facade have cracked and deteriorated, leaving the building vulnerable.

How can the subsurface conditions of the basilica's masonry facade be assessed to indicate where treatments should be carried out?



Facade of the Basilica of Santa Maria di Collemaggio, showing its magnificent arrangement of pink and white limestone. Photo: © Marco Tallini.

Collemaggio, Italy

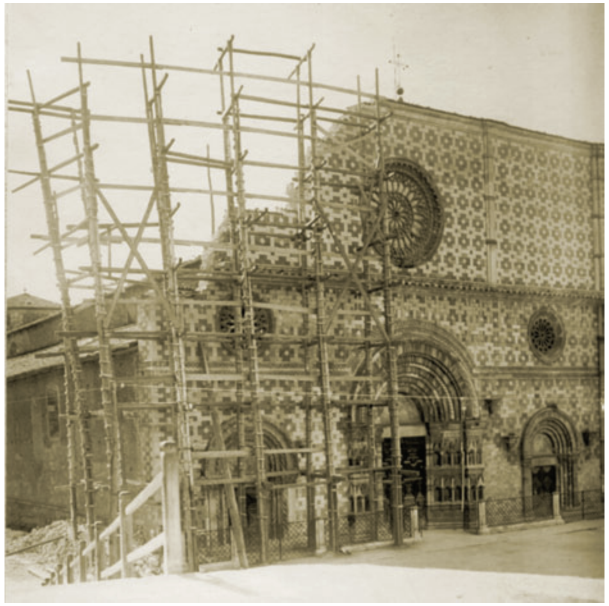
The Basilica of Santa Maria di Collemaggio stands on the site where a traveling hermit named Peter of Morrone, founder of the Celestine order, spent the night after meeting with the pope. The Virgin Mary appeared to the hermit in a dream and asked him to build a church in her honor. Construction of the basilica began in 1287 on land that was purchased by the Celestines. Inside this edifice, Peter of Morrone was crowned Pope Celestino V in 1294 and later buried there. As part of his coronation, he instituted the original Papal Jubilee, designating the basilica a pilgrimage site.

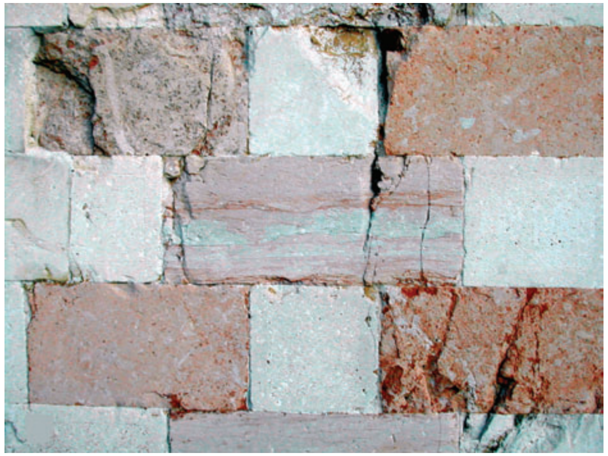
A stunning example of Abruzzese Romanesque and Gothic architecture, the building owes its originality to the magnificent geometric arrangement of ashlars on its facade. The blocks of pink and white local limestone form an intricate woven pattern, giving the church a jewel-box appearance. The facade wall consists of a rubble core faced with dressed stone, and it is these inner and outer ashlars that have cracked and deteriorated.

Over the centuries, the church was the subject of several building campaigns involving aesthetic improvements and structural repairs to damage caused by recurring earthquakes. After the 1915 earthquake, the upper left side of the facade was rebuilt with an accurate replica of the original ashlar coursework. During the 1970–72 restructuring phase, the roof was elevated and the interior baroque decorations removed to restore the building to the style of its medieval period. The raising of the roof increased the seismic vulnerability of the building. Furthermore, the facade presented several deterioration conditions such as surface soiling, cracking, and detachment through exfoliation, splintering, and flaking.

A conservation project was initiated in 2005 to stabilize and clean the facade of Santa Maria di Collemaggio. Detailed knowledge of the church's internal masonry structure was key in this restoration project. Recognizing the detachments and cracks and investigating the extent of subsurface deterioration were crucial in verifying the stability of the facade. The documentation process served to inform conservators about the condition of the masonry so that they could plan the conservation intervention and mitigate any seismic vulnerability caused by detachment zones between the ashlar facing and the internal masonry.

Santa Maria di Collemaggio, following the 1915 earthquake. Photo: © Ministero per i BAP per l'Abruzzo.





Detail showing the masonry deterioration of the facade caused by seismic stress. Photo: © Marco Tallini.

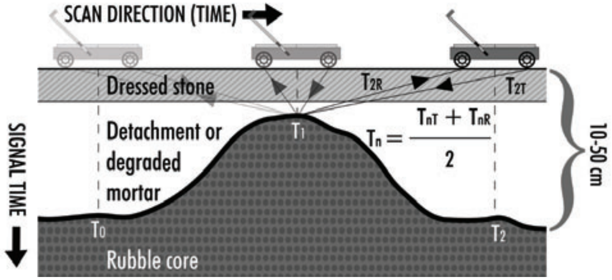
Ground-penetrating Radar

Several techniques exist to investigate subsurface conditions of structures. In the field of cultural heritage, ground-penetrating radar (GPR) uses electromagnetic waves to investigate the underground or internal structures of natural and human-made objects. Although traditionally used in archaeological surveys to initiate or plan excavations, GPR has been successfully employed in investigating the characteristics of and damage to walls and masonry structures, such as voids, detachment, cracks, leaks, and deteriorated mortar joints, to inform conservation projects.

An alternative to GPR is infrared thermography, which detects temperature radiation in the infrared range of the electromagnetic spectrum and produces images of that radiation. Infrared thermography offers fast data acquisition and output, requires no contact with the medium, and can record a large area; however, it has a shallow depth of inspection, is easily affected by thermal perturbations during acquisition of data, and interferes with the emissivity of the object it is measuring. Ultrasonic testing and micro-video-camera inspection can provide useful information but were not considered because they require invasive contact–hammering and micro drilling, respectively–and are time consuming.

GPR was more appropriate for this study because it is a nondestructive technique that requires little contact with the medium. In addition, this tool has a good level of accuracy and is easy to handle and transport. GPR testing was therefore used in order to understand the internal masonry structure of the facade by determining the thickness of the wall, to locate cracks and areas of detachment, and to identify where consolidation treatment was needed.

Technicians using GPR for data acquisition near the basilica's rose window. The GPR system was applied directly to the building's surface. Photo: © Marco Tallini.



During GPR acquisition of data, a point-shaped target generates a hyperbole-shaped radar anomaly. Drawing: Steve Rampton.

The GPR basic system consists of a data acquisition unit and two transmitting and receiving antennae. The transmitting antenna sends pulses of high-frequency radio waves. When a wave hits the boundary of an object that has different electrical properties, the receiving antenna records these variations, known as anomalies, that are reflected in the return signal. The output of the GPR survey is a radar section of the investigated medium showing the direction of the wave trajectory as a function of depth. A surface-shaped target generates a surface anomaly similar in shape to the measured surface, whereas a point-shaped target produces a hyperbolic radar anomaly in which the waves become more spherical as the distance increases between the antenna and the target.

The conductivity of the ground or medium through which the signal travels affects the range of the scan, and the frequency of the signal affects the resolution of the scan. Higher-frequency waves are used for shallower depths and improve spatial resolution of the reflected signal. Two frequencies were chosen for this study. A 600-megahertz (medium frequency) antenna reached about 4–5 meters with a resolution of about 2–5 centimeters. A 1600-megahertz (high frequency) antenna reached about 1 meter with a resolution of about 1 centimeter.

A team of two trained users methodically collected the data. First, the equipment was calibrated by scanning a part of the investigated area where the construction technique and masonry characteristics were already known. Then, based on a grid of radar sections of the facade for both frequencies with a scan spacing of 40 centimeters, the entire facade was scanned. The regular geometric arrangement of the ashlars facilitated scanning of the facade without a complex coordinate system.

The mesh and location of the grid sections corresponded to the vertical and horizontal alignment of the ashlar courses, with a mesh of three-by-three courses. The radar scanning lines were placed in the middle of each course. About three hundred radar sections for each antenna were acquired. The GPR scanned the entire facade below the middle cornice and was extended to two areas located to the right and left of the central rose window, above the middle cornice.

The collected data were visualized and processed by two experienced specialists using GPR software (Ingegneria dei Sistemi, 2000). Two filters were applied to all the radar sections. The first filter (soil sample) removed the effect of distortion due to the air-masonry interface between the GPR antennae and the outer facade. The second filter (pass band) removed background noise in both vertical and horizontal directions. Different types of anomalies visible in the calibration radar section were identified with known voids, cracks, and other building conditions. These conclusions helped interpret the other radar sections, as known voids and cracks could be assigned a specific anomaly type. A team of engineers, archaeologists, and architects participated in interpretation of the data.

Thickness of the facade wall was measured with the 600-megahertz antenna. The right side of the facade wall proved to be 20 centimeters thinner than the left side except in the lower band, which was about 10 centimeters thinner. The radar anomaly marking the boundary between the wall and the air on the opposite side (interior of the basilica) was usually well outlined; however, the radar signals were less clear in areas where the inner face of the wall had architectural or decorative elements.

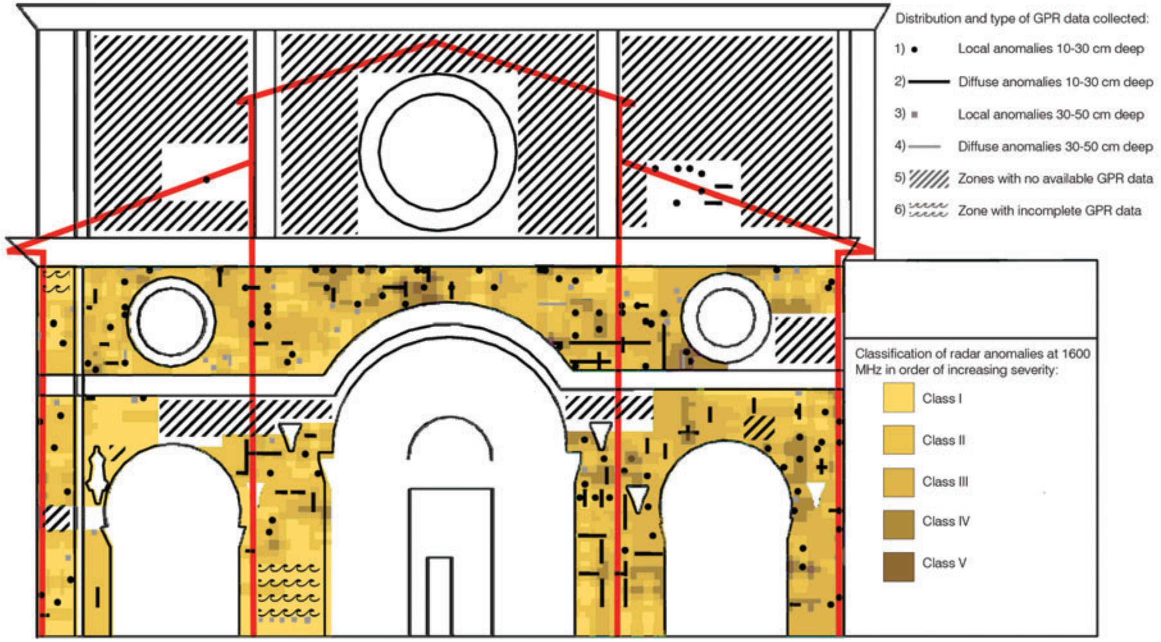
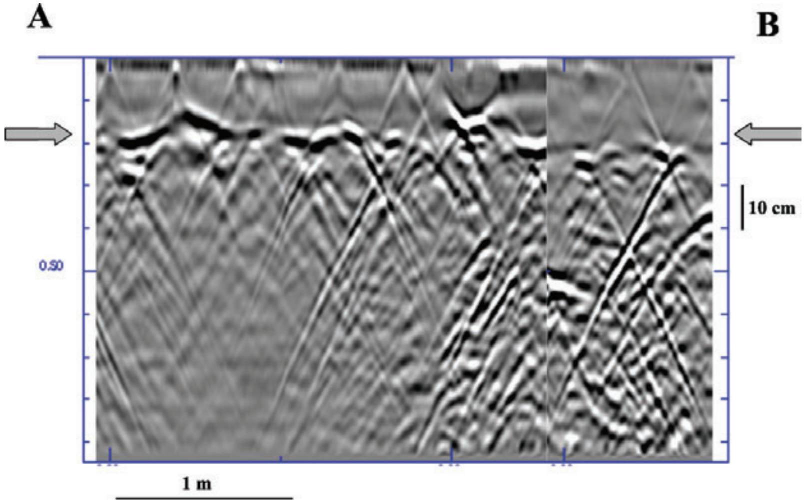


Diagram of the basilica, showing radar anomalies (1600 MHz) after filtering and rasterizing. Colors show anomalies classified according to increasing gravity (classes I–V). Diagram: © Marco Tallini.

A 1600-MHz radar section. The arrows highlight strong anomalies probably related to the widespread detachment of the ashlar facing from the rubble core or to zones of degraded mortar. Image: © Marco Tallini.



Treatment plan for the facade, implemented in spring 2005 based on conditions mapped in previous diagrams. Colored areas are related to the increasing density of the grout. In some cases, injections were combined with the insertion of 12-mm-thick stainless steel. Diagram: © Marco Tallini.

The 1600-megahertz GPR survey identified structural features of the masonry and the middle cornice that supported elements of the facade, and also identified areas of deterioration. The varying densities of materials were reflected in the radar anomalies, but the heterogeneous composition of the wall made the radar sections difficult to read. Many radar echoes interfered or hid the anomaly signals corresponding to detachments, voids, and degraded mortar joints. Nevertheless, detachments of the ashlar facing from its rubble core were generally visible as surface anomalies at the interface, while detachments at the middle cornice were shown as strong hyperbolic anomalies located at regular steps. In some cases, anomalies were observed inside the ashlar facing, probably corresponding to cracks or voids. Furthermore, the radar sections exhibited evenly shaped anomalies every 2 meters. These matched the through-stones placed between the inner and outer ashlar facings to support the middle cornice.

An Answer

GPR was effective in investigating the internal structure of the basilica's facade in depth and at high resolution. This technique requires little contact with the inspected medium; however, data analysis can be a lengthy process depending on the area of investigation. At the basilica, data were acquired in a week and processed and interpreted over a one-month period. The results were quite accurate, enhanced by the signal calibration. The participation of specialists from various disciplines was helpful in comparing different possible interpretations of the deterioration phenomena reflected in the radar sections.

Using the high-frequency radar results, voids and cracks in the degraded ashlars and mortar joints were located and areas requiring injection grouting, as well as density of the grout, were determined. The medium-frequency testing allowed characterization of the internal structure of the facade and measurement of the thickness of the wall. A mathematical model was generated and used in calculating the depths of the voids as well as in planning the retrofitting work to mitigate the seismic vulnerability of the basilica.

The objectives of the 2005 restoration campaign were to improve and reestablish internal cohesion of the facade wall against seismic stress and to reduce water infiltration. The activities included injection grouting with a hydraulic lime-based grout and insertion of 12- millimeter-by 100-centimeter-thick stainless-steel bars. To help prevent leaks of the injection mixture, voids and surface cracks on the outer facade were first plastered. Grouting was then carried out on the back inner-face facade, starting at the bottom and moving perpendicularly toward the top. The mortar mixture was injected, and the stainless-steel bars were placed so as to reach the rubble core and the inner zone of the ashlars. Grouting was combined with steel reinforcement predominantly around the rose window and in the upper right corner of the facade.

Marco Tallini is associate professor of applied hydrogeology at L'Aquila University, Italy. His fields of interest focus on GPR application in environmental geology, civil engineering, and geoarchaeology. He has authored numerous papers on GPR application, hydrogeology, and regional geology.

Monitoring Movement

Giorgio Croci

The Tower of Pisa, in Italy, has been moving and tilting since its construction began. The heavy masonry load on the unstable clay subsoil and previous unsuccessful attempts to save the tower have contributed to its tilt. In the late 1980s, its lean approached a critical point and the tower was near collapse.

If the famous tower is to be saved for future generations, how can its stability be monitored before, during, and after necessary interventions?

The studies and designs in this illustrated example were carried out by a committee composed of Professors M. Jamiolikowski (chairman), John B. Burland, R. Calzona, M. Cordaro, G. Creazza, Giorgio Croci, M. D'Elia, R. Di Stefano, J. de Barthelemy, S. Settis, L. Sanpaolesi, F. Veniale, and C. Viggiani. Soil engineering was devised by John Burland, professor of soil mechanics at Imperial College, London, and monitoring was carried out by BRE, Watford, England.

View from the fourth balcony of the Tower of Pisa, following the structural stabilization campaign. Photo: © Gary Feuerstein, 2002.

Pisa, Italy

The Tower of Pisa, the construction of which began under the direction of Bonanno Pisano in 1173, started leaning shortly after the tower's foundations were laid. This, combined with Pisa's war against Florence, halted construction. Work resumed a hundred years later, only to stop again in 1278 for the same reasons. A final effort to complete the tower began in 1360, but the uneven settlement continued and the lean increased as more weight was added. In each period of construction, attempts were made to remedy the problems but were always unsuccessful. The upper portion was built vertically even as the tower leaned, resulting in a slight bend to the north.

Finished in 1370, the cylindrical tower consists of two faces of limestone ashlar blocks assembled without mortar around a conglomerate core of lime mortar and stone rubble. An interior staircase spirals upward toward the belfry and allows access to colonnaded balconies on each of six floors. At less than 20 meters in diameter and 60 meters high, the tower serves as the campanile to the adjoining duomo, or cathedral. The tower is an interesting example of Byzantine influence between the medieval and Renaissance periods and is famed for its extreme lean.

The stratigraphy of the subsoil is at fault. It is composed of sand and clay silts for the first 8 meters, followed by medium-gray sand for 2 meters on top of 11 meters of Pancone clay. The settling of up to 2.5 meters vertically is concentrated in this layer of Pancone clay. A seasonal fluctuation in the water table and an increased pumping of groundwater has exacerbated the problem. As the water table rises, the inclination of the tower increases, mainly between the months of September and December.

In the early twentieth century, the first detailed measurements of the displacement were scientifically recorded using survey equipment. Then, in 1934, a pendulum was hung inside the tower to measure the displacement of the top with respect to the base and therefore any change in inclination. The pendulum consists of a cable suspended from the sixth floor that descends to the first floor with the help of a small weight. This plumb line traces the horizontal displacement as the tower continues to move. Various interventions were attempted throughout the centuries, including diverting groundwater, injecting concrete into the subsoil, and prohibiting automobile traffic near the tower. Even the bells were silenced, yet the tower continued to move. By 1987, when the tower and its surrounding buildings were inscribed on the UNESCO World Heritage List, the lean had increased to more than 5 degrees, or more than 5 meters from vertical. An intervention was urgently needed.

In 1989, after the collapse of a masonry tower in nearby Pavia, the prime minister of Italy and the city of Pisa formed an international research committee of engineers, architects, conservators, and scientists to study the tower's situation and propose a solution. Because of the tower's significance and economic contribution to the city, there were few constraints except time and politics. The structure's current rate of movement and severe lean made the committee determined to act before the end of the millennium. World-famous experts in structural and soil engineering were invited to propose solutions to the committee, while the most modern and sophisticated equipment was made available. The first step, though, was to study any movement and accurately monitor the tower.

The Tower of Pisa in 1993, with its belfry under conservation during the preliminary stabilization phase. Photo: © Gary Feuerstein, 1993.

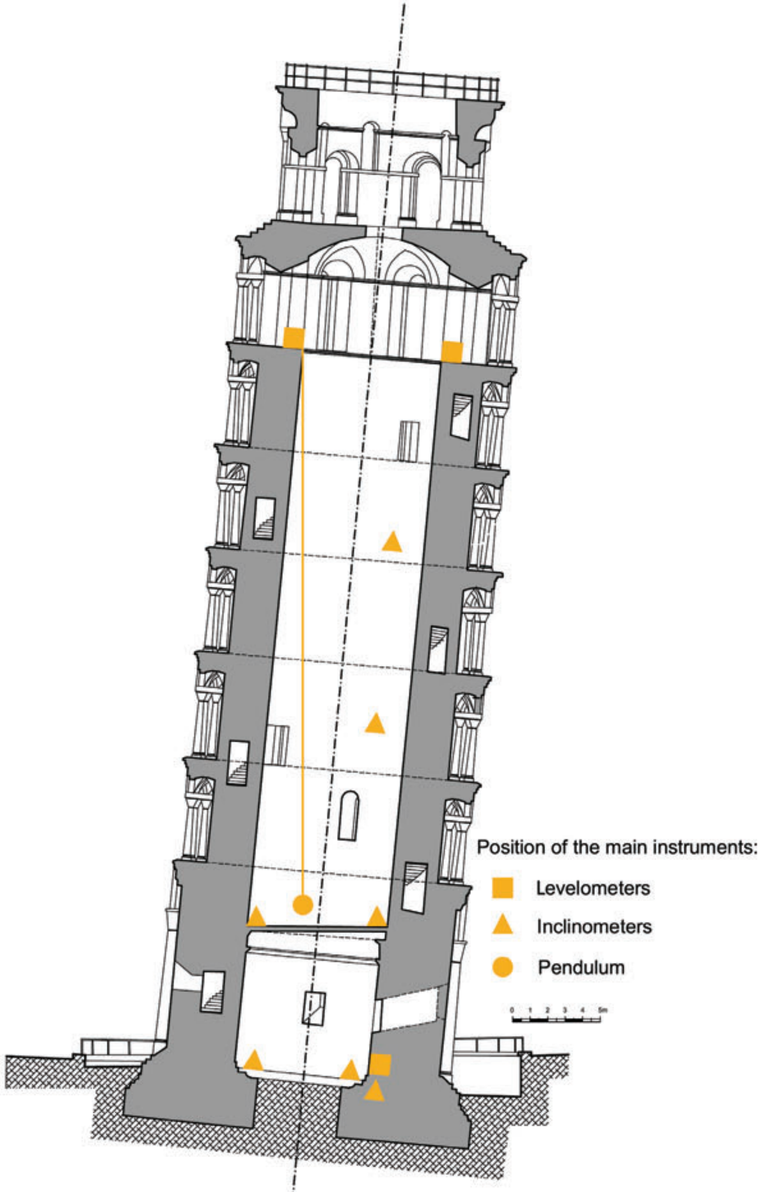
Automated Monitoring System

A variety of tools were required. The committee installed modern computerized measuring and monitoring systems to examine the tower and its surrounding soil. The system included special devices to measure the amount of lean, vertical settlement, cracks, and any other movement.

The first obvious measurement needed was degree of inclination. This was accomplished with the use of several inclinometers, which are sensitive, extremely accurate electronic levels that measure degree of tilt or angle using a sensor set against an artificially generated horizon. These instruments were mounted in various configurations throughout the tower along different axes to capture degree of tilt and rotation. The inclinometers and their placement informed the engineers of the present degree of tilt and, more important, informed them in real time of any changes in the tower as they carried out their interventions.

The tower is not only leaning but also sinking vertically; therefore, another device–a levelometer system–was needed to measure the amount of differential settlement. This system is a series of small containers filled with a special liquid and interconnected by a hydraulic network. As the liquid reaches the same horizontal level in each of the containers, the change in distance between this common level and the bottom of each container provides a measure of the vertical relative settlements.

The tower also moves daily by small amounts. Movement due to temperature differences and wind forces in masonry buildings is typical, but in situations when the structure is at risk, it is important to establish a base measurement. This measurement informs engineers whether any



The placement of devices throughout the tower provides a picture of the structure's overall condition. Drawing: © Giorgio Croci.

Clockwise from top left: weather station; biaxial inclinometer, which measures tilt in both north–south and east–west directions; accelerometers, which measure three-axis seismic acceleration; transductors, which measure strain on cracks. Photos: © Giorgio Croci.

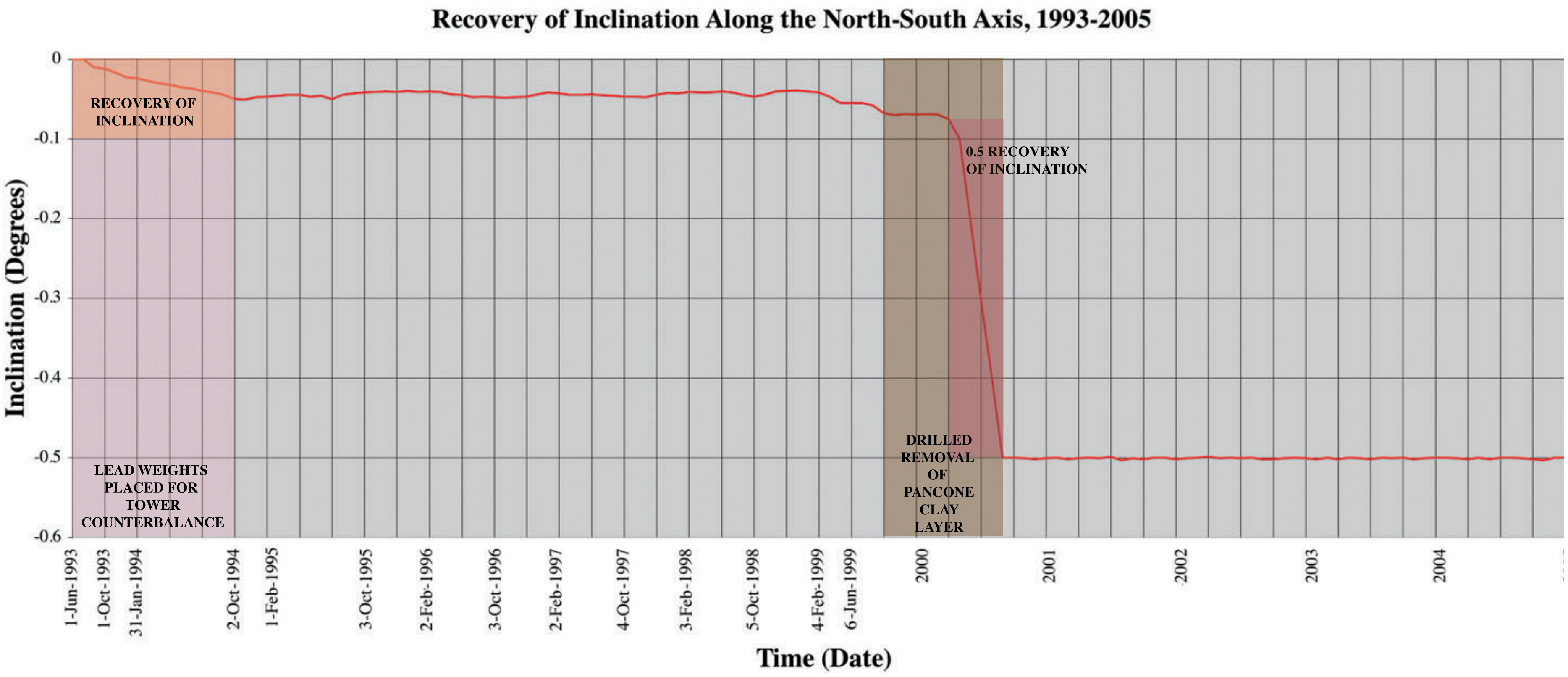
movement is due to a strong wind, a sunny day, or, more important, their intervention or an impending failure. A weather station was positioned on top of the tower to record wind direction and speed, ambient temperature, and radiation from the sun. Thermometers were placed inside the masonry on different floors to correlate deformations of the structure with temperature. These measurements record how the structure reacts to environmental forces and were useful before and during work on the tower.

Cracks are also typical in masonry buildings, especially in towers eight hundred years old. They can be beneficial by relieving stress but also can be a warning sign of more serious issues. Strain gauges were installed to measure crack propagation or reduction in twenty-five different locations. These highly sensitive instruments were affixed to the cracks and essentially converted mechanical motion into an electronic signal. The gauges were calibrated to take into account temperature changes and other material properties. As with environmental measurements, the crack monitors served to inform the engineers as they conducted their studies and made changes to the tower.

Less complicated, nonelectronic, and inexpensive inclinometers, soil sample techniques, and simple crack-measuring devices are available. However, in the case of such an important tower in risk of collapse, the engineers required the most sensitive monitoring and measuring tools. These devices were connected to data loggers, or small computers that recorded all the measurements continuously, providing the engineers with time-sensitive information. From the data, changes were plotted to give an accurate picture of deformations, vertical settlement, movement, and temperature. The results were therefore immediately available for use by the committee to formulate theories and propose appropriate action. As action was taken, the same devices recorded the intervention.

The measurements and studies showed that the inclination of the tower progressively increased to a critical point. The force corresponding to the weight of the tower had compressed the soil twice as much on the southern side than on the northern side. The tower was in imminent risk of collapse due to a sudden subsidence of the soil.

Chart showing recovery of inclination. Lead weights reduced tower lean by 52 seconds. With the removal of the clay layer, the lean was further reduced by a half degree (nearly 10%) and stabilized. Chart: © Giorgio Croci.



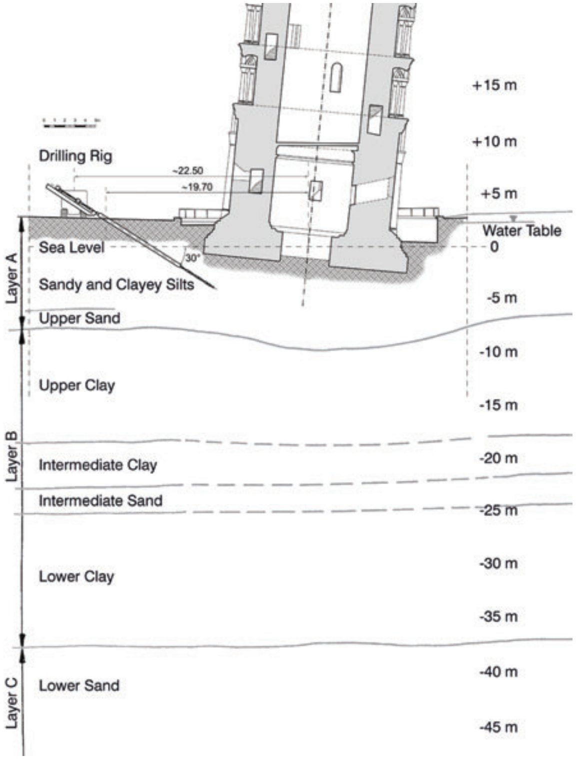
An Answer

In 1993, the committee set urgent provisional measures to prevent further movement by applying 600-ton blocks to the north side of the tower's foundation. This was later increased to 900 tons. The sophisticated monitoring system already in place reflected a reduction in the inclination of around 52 arc/seconds, or about 0.014 degrees. More important, the tilt of the tower was halted. In 1998, cables were provisionally applied around the tower and anchored to massive weights hidden behind other buildings. This was done as a precautionary measure before starting further interventions.

The definitive stabilization of the tower began in 1999. Thirty-five cubic meters of soil were removed from the subsoil under the north border of the foundation through a series of twelve casings drilled diagonally into the ground. The result of this excavation was the formation of small cavities that were progressively closed, producing small artificial differential settlements to counteract the south tilt of the tower. This operation progressed slowly and carefully. Soil continued to be removed in small quantities. Data were collected from the monitoring system and analyzed to evaluate the impact of each extraction on the movement and tilt of the tower.

When the operation was completed in 2001, nearly 10 percent of the tilt had been recovered. The committee and the Italian Ministry of Culture agreed that this value retained the important lean while guaranteeing stability. At present, the monitoring system continues to operate, showing that the tower is stable and its inclination is the same as it was in the middle of the eighteenth century.

Giorgio Croci is a professor of structural engineering at the University of Rome "La Sapienza." He has participated in many studies and projects dealing with structural design and restoration, investigating structural damage and material decay on sites in Italy and worldwide. He received a gold medal from the mayor of Pisa for his work as a member of the research committee in charge of the restoration of the tower.



Drilling allowed the strategic removal of clay from the subsoil under the tower's foundation. Drawing: © Giorgio Croci.

Lead weights were used to reduce the tower's lean. Photo: © Giorgio Croci.

Traditional Techniques

Caterina Borelli

For centuries in the Hadhramaut Valley, in southern Yemen, the sole means of construction was mud brick. In response to the changing needs of the local communities and the development of the paved road network, new materials and technology have been introduced that threaten to transform the built environment and erase a timeless tradition of local building techniques.

How can these building techniques and traditional skills be recorded? How can this record help conserve this unique built environment?

This illustrated example was part of a project done in collaboration with architectural conservator Pamela Jerome. A technical paper on the subject was also published.

View of Wadi Do'an, at Al Gorha. The village's traditional earthen construction allows the structures to blend in to the surrounding cliffs and contrasts with the green valley floor. Photo: © Pamela Jerome.

Modern concrete and block constructions in Wadi Hadhramaut. Photo: © Pamela Jerome.

Abandoned historic building in Wadi Hadhramaut, in disrepair. Photo: © Pamela Jerome.

Hadhramaut, Yemen

Wadi Hadhramaut is an inland valley in a desert region that consists of a network of smaller, subsidiary valleys. Villages are built along the edges of the lush, cultivated valleys, and houses blend into the surrounding landscape .

Centuries of building with local mud, straw, and lime have created a landscape of incredible multi-storied buildings that reflect a refined construction technology. In 1982, UNESCO recognized the unique natural and cultural environment of the wadi and included it in its nomination of the walled city of Shibam as a World Heritage Site.

The lack of resources and the remoteness of the region restricted economic development, and the built environment remained unchanged until the early 1990s. Following the unification with North Yemen, more attention was given to the area. Roads were paved to facilitate access to the Indian Ocean and inner valleys. Water, electricity, and cement became more easily available. To provide for the resulting building boom, new building techniques were introduced, reflecting the changing needs of the population.

The practice of traditional building and maintenance techniques began to fade away. Where skill and time were once essential to building with mud bricks, less experienced masons can now build with concrete in a matter of days. Historic buildings have been neglected, abandoned, and left in disrepair. Every step of the traditional building process known by the local masons, and their oral histories and impressions, needed to be documented to produce a durable and informative record.

Video Technology

Documentary video was the tool chosen to thoroughly record the buildings, construction technique, and living heritage of Wadi Hadhramaut. Structure and production were conceived based on preparatory research and on the interaction between the filmmaker and the architectural conservator Pamela Jerome. The filmmaker served as director, producer, camera operator, and sound person. The architectural conservator conducted the interviews, wrote an academic paper describing in detail the building technique, and advised on the content of the video. The filmmaker visually translated the issues and points of relevance that surfaced from this interaction with the architectural conservator, making informed decisions that gave the film greater value. As part of the preproduction phase, a scouting trip was conducted to establish contacts and determine if it was possible for a woman to travel freely in the area and carry out this project. Finally, fund-raising to cover the

Field equipment used to make the documentary video, including a mini–digital video camera (DV cam pictured), tripod, extra rechargeable batteries, microphones, and various tools for work in the field. To protect the equipment from dust and sand, the camera and tapes were stored in resealable plastic bags. Photo: © Caterina Borelli.

Recording the video documentary on site in Wadi Hadhramaut, Yemen. Photo: © Caterina Borelli.

Series of stills from the documentary, showing workers in Seyoun creating mud bricks for new construction. Soil is gathered and mixed with straw and water. The mixture is spread out evenly in a mold, which is lifted immediately. The mud bricks are then left to dry in the sun for a week. Photos: © Caterina Borelli.

it is superior and saturated with water.

Series of stills from the documentary, showing workers erecting a new building. After the stone foundation is laid, the mud bricks are stacked to build a wall. Photos: © Caterina Borelli.

The last layer of mud has to be smoothed and sloped so that the water runs off.

Series of stills from the documentary, showing the completion of a building. Workers are finishing off the new roof with mud. Photos: © Caterina Borelli.

Now, people want to build houses faster. It's not like as it was in the past.

Series of stills from the documentary, showing the process involved in maintaining traditional buildings in Hadhramaut. First, limestone rocks are fired in kilns. The resulting product, quicklime, is then slaked and used to waterproof, decorate, and whitewash earthen buildings. This practice is carried out regularly as part of the ongoing maintenance. Photos: © Caterina Borelli.

project's cost was an important and challenging endeavor that was partially met through a grant from the American Institute for Yemeni Studies.

Small-format video was used because it produces a broadcast-quality product, is small and portable, and is relatively inexpensive. Filming the documentary took two months and was conducted with a Sony Handycam VX1000 on a sturdy, fluid-head tripod. Often no electricity was available, so it was essential to have on hand a number of extra rechargeable batteries to power the camera. Various lenses were used, the most valuable being a wide-angle. Strong natural light was abundant, eliminating the need for supplemental lights; however, under certain circumstances a silver reflector was used to harness the natural light. In addition, a polarizing lens filter was used to enhance the natural light.

Sound was extremely important, and three different types of microphones were used to cover all situations. Two wireless radio microphones including a lapel microphone were used for interviews. A Sennheiser shotgun microphone captured more precise areas of sound. Headphones were used to check the sound recording in the field. The recording medium was Sony high-grade mini–digital videotapes. These tapes and the camera were placed into resealable plastic bags to protect them from sand and dust. Each tape was carefully labeled and protected from erasure by using the switch on the videotape. At the end of each day of filming, a diary entry was made of where and when the video was captured. Canned air was used to clean the camera every night.

Ongoing maintenance efforts in Hadhramaut also involve plastering the exterior of buildings with mud to conserve the mud-brick construction. Photo: © Caterina Borelli.

An Answer

More than thirty-five hours of video were shot. With the help of an assistant, the footage was extensively logged and the time code noted for every scene, interview, and sound. A backup of the tapes was made. The footage was then assembled into a rough-cut version that was reviewed by the filmmaker over a two-month period. After decisions were made regarding content and storyline, the footage was input into an Apple Macintosh computer and edited by a professional editor using Media 100, a computer software program. Excerpts from historic travelogues were later inserted to underline changes in the local environment. Technical content, language, and texts were verified during postproduction. Editing took approximately four months.

The final product is a one-hour documentary, *The Architecture of Mud*, in which every step of construction, from laying the foundation to the final quicklime waterproofing, is described in images and in the words of local masons and workers. It offers a thorough record of the built environment: villages, housing interiors and exteriors, and local traditions. The documentary was premiered at the Museum of Modern Art, in New York City, and has received accolades from professional conservators and filmmakers.

Video technology proved to be a very effective tool in many ways. First and foremost, it provides the necessary visual documentation should the need arise to recall a particular technique, consistency of material, work order, or style. Upon completion of the documentary, an Arabic version was screened in Yemen. During the screenings in the villages, the master builders who were present expressed their approval by spontaneously commenting for the audience. This communicated to the workers the importance of their craft and emphasized its significance worldwide. Positive reaction to the film created a climate of dialogue, trust, and respect, and has paved the way for implementation of new collaborative projects in the region.

Furthermore, because it addresses a general audience, the documentary reached far more people than expected and has been used as a didactic tool in academia and in museums around the world. The film provides a general foreign audience the opportunity to rethink some of their preconceptions of the regions and cultures of the world. At the same time, an informed foreign audience can find in the work many opportunities to reflect on issues related to architecture, preservation, ethnography, visual anthropology, Indian Ocean trade, and Middle Eastern studies.

Caterina Borelli is an independent director and producer based in New York and Rome. Her latest documentaries focus on the relation between architecture, tradition, and conservation. She has recently completed a documentary on the architecture of Asmara, the capital of Eritrea, focusing on the recognition of heritage in places with a colonial past.

Reading Interventions

Soon-Kwan Kim

The conservation of historic Buddhist temples in Korea derives from a long tradition of dismantlement and reconstruction. As these temples were rebuilt, hidden inscriptions describing details of the reconstructions were left on their structural timbers by generations of craftspersons. Many original decorations were painted over, obscuring important historic evidence. Over time, both these writings and decorative paintings have faded.

How can such faded or obscured clues to the history of these temple buildings be viewed and documented?

Detail of the multibracket system used in the construction of the Hall of Paradise (Geukrakjeon), in Bongjeong Temple, South Korea. Photo: Jong Hyun Lim.

Bongjeong Temple, South Korea

At the foot of Mount Cheondeung, in northern Gyeongsang Province, stand two of the oldest wooden Buddhist structures in South Korea. The Hall of Paradise (Geukrakjeon) and the Main Sanctuary (Daeungjeon) house images of the Buddha of Boundless Light and statues of his disciples. They are part of the Bongjeongsa temple complex begun in 672 by King Munmu's preceptor, Uisang.

Built primarily of interlocking wood beams and columns on stone foundations, the two temples represent the pinnacle of architectural and decorative painting styles from the Goryeo period (918–1392). During this period, most roof structures were built using simple, single wood-bracket systems (*jusimpo*). However, the Hall of Paradise is one of only three examples in Korea of a multi-bracket system (*dapo*). The brackets, interior beams, columns, and walls of the Hall of Paradise are decorated with paintings of colorful figures, geometric patterns, and floral designs. These decorations and paintings, which depict the Buddha teaching, are regarded as unique historical references that reflect the strong Buddhist artistic and religious influences at the time of construction.

Over time, these paintings and wood members deteriorated, damaged by humidity, insect infestation, and discoloration from oxidation and carbon deposits. Consequently, the temples underwent many restorations throughout the centuries. Conservation of temples in Korea follows a long tradition of completely dismantling the structure and rebuilding it. Each individual member is evaluated, deteriorated members are replaced if needed, and old pieces are reused in different ways and in new locations.

In the restorations of 1972 and 1996, workers noticed Chinese "graffiti" hidden among the older wooden members. These writings provided valuable clues about previous restorations and building processes. Unfortunately, the markings were extremely faded. The inscriptions were examined with a magnifying glass and an optical microscope, then recorded using sketches and conventional photography. In some cases, the characters were visible and simply documented, whereas in others they had been repainted by restorers based on their best judgment and past experience.

Despite these recent dismantlings and restorations, the Hall of Paradise and the Main Sanctuary still suffered from active structural problems. In 2002, the management of Bongjeongsa requested that the National Research Institute of Cultural Heritage (NRICH) in South Korea carry out a new dismantlement and rebuilding campaign that would include a detailed study of the writings on the wood elements and the faded decorative drawings. It was hoped that information gathered from the writings would inform and guide the restoration project.

The objectives of the study were to locate, identify, and interpret previously unknown writings and reinterpret the writings that had been overpainted. Other painted designs and finishes were also to be analyzed to provide a record for posterity and a chronology of previous interventions. After a preliminary meeting of the architects, conservators, and surveyors, it was determined that an advanced imaging method was required to find and examine these hidden works.

The Hall of Paradise, during restoration. Dismantlement of the temple allowed each building component to be documented individually. Photo: © Soon-Kwan Kim.

A Buddhist wall painting on the back side of the Main Sanctuary (Daeungjeon), during restoration. Photo: © Soon-Kwan Kim.

Infrared Reflectography

Paintings that have faded or been overpainted often contain traces of original pigment. This remnant material still reflects and absorbs light, but outside the visible spectrum. The surveyors decided to record the writings by capturing this invisible light through infrared reflectography (IRR).

IRR is a nondestructive digital or photographic imaging technique that uses a specialized digital detector or heat-sensitive film to capture absorption and emission characteristics of reflected infrared radiation between 750 and 2000 nanometers. The technique is simple, quick, and effective in investigating surface conditions by detecting original faded or hidden drawings, and in penetrating through upper layers of overpainted surfaces.

A Hamamatsu Super Eye C2847 IRR instrument was used in the study at Bongjeongsa. The instrument consists of three main components: an infrared emitter or lamp, a detector, and a computer. The lamp is positioned at an angle approximately 2 meters from the object being studied and emits a precise frequency of infrared light. The detector is aimed at a 90-degree angle 2 meters from the object and captures the reflected light. The computer displays and stores the resulting images. The team for this study included a professional operator who controlled the exposure of the detector, a specialized assistant who monitored and operated the computer, and a trained assistant who assembled the system.

IRR was carefully carried out on every dismantled wooden column, eave, and purlin from the Hall of Paradise and Main Sanctuary to locate and record any Chinese inscriptions. It was also used to examine faded decorative drawings and successive restoration paint layers. In order to compare the IRR image with the visible spectrum, each wooden member was also photographed with a conventional digital camera.

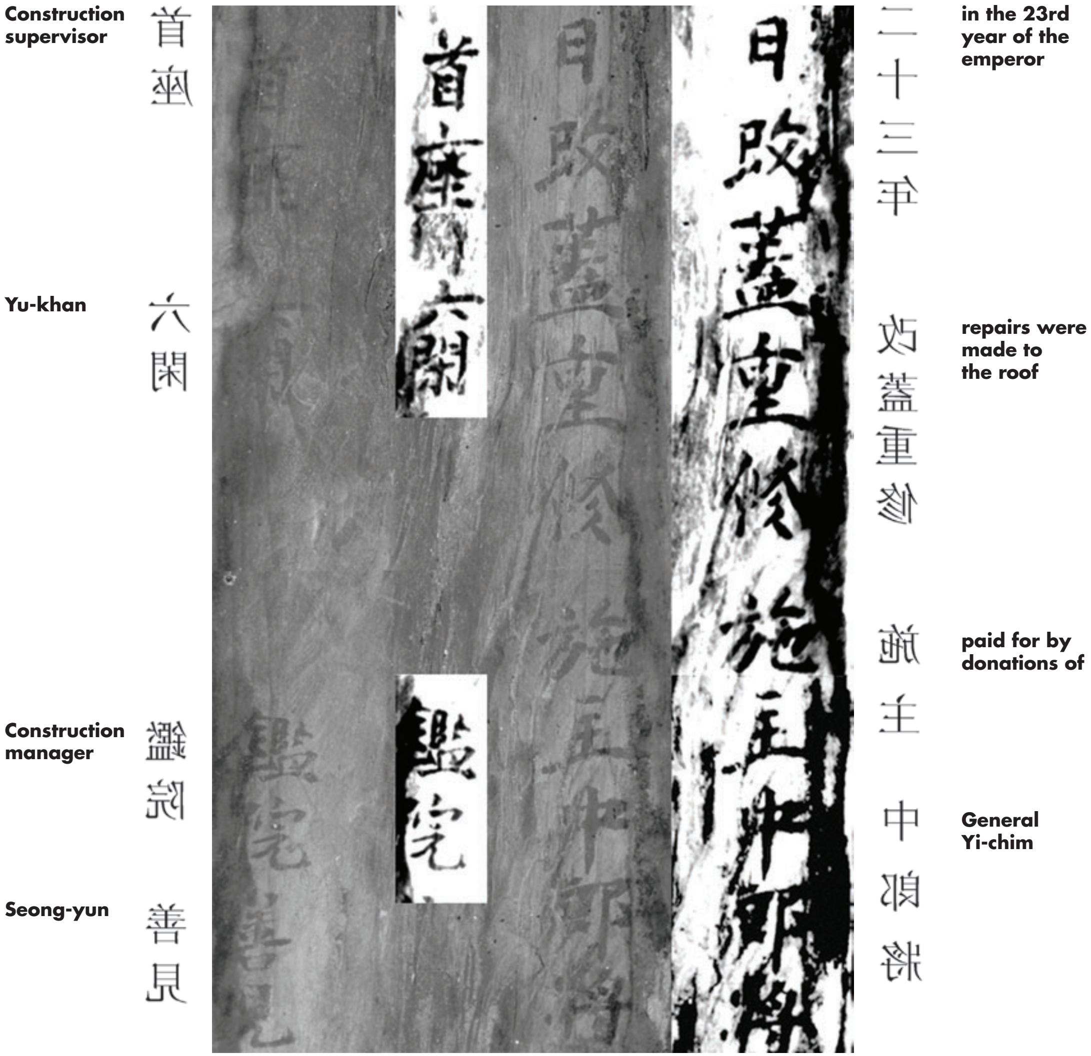
IRR instrumentation is affected by environmental conditions such as ambient temperature and humidity and is very sensitive to light and motion. Therefore, members of the study team carefully controlled their surroundings by positioning the instrument on a flat, stable work surface and maintaining uniform lighting. They also bracketed exposures, taking multiple images of the same subject using slightly different settings. This method produced more images than needed but greatly improved consistency and quality. In addition, the team had to be aware of the limitations of IRR. Infrared wavelengths can easily detect black, white, brown, and red pigments but are limited in detecting pigments that do not transmit or block infrared, such as azurite and malachite. Fortunately, the ancient pigments used at Bongjeongsa did not include these minerals, so this was not an issue.

IRR acquisition of the images was conducted both on the individual components and in situ for the composite building. Photo: © Soon-Kwan Kim.

Over the course of five days, more than six hundred IRR and conventional images were captured and processed. Processing consisted of quality control with the Zeiss KS 300 Image Analyzer program and editing for contrast and brightness using Adobe Photoshop. Photoshop was also used to assemble multiple images of large objects, as the IRR instrument used for this survey had a low-resolution (4800 dpi) detector, which limited the size of each image.

Once the data were processed, experts in ancient Chinese calligraphy were consulted to interpret the characters. The images and interpretations were discussed among art historians, painting conservators, architects, and project managers. The data were saved on CDs, and copies, along with a project report, were distributed to the Bongjeongsa management team and the Korean NRICH Digital Information Center.

The application of IRR at Bongjeongsa was successful in uncovering many important clues regarding the history of these buildings. Except for a few entirely missing or heavily soiled characters, most of the writings on the wooden members were successfully interpreted. Chronology of the numerous restorations, significant structural changes, original positions of the wooden members, and names of those involved in the ancient restorations were identified and documented. Archival records were corrected based on this study, making it possible to piece together entire periods in the history of the buildings. This information supported the 2002 reconstruction by assisting team members in dating and identifying important pieces that should receive special attention. Pieces that could be reused were also identified and carefully “reinserted” during reconstruction. Pieces that had deteriorated were conserved and eventually may be placed on display.



IRR was used to reevaluate visible-light photography of the top purlin in the Hall of Paradise. During restoration work in 1972, surveyors studying the Chinese characters by eye had misinterpreted the writing, resulting in inaccuracies in the archival record. Through the use of IRR in the 2002 survey, a character misidentified as “owner” was corrected to mean “caution.” Photo: © Soon-Kwan Kim.

An Answer

At the Hall of Paradise, the IRR team was able to correct previously misinterpreted Chinese characters from prior studies and interventions. In the Main Sanctuary, IRR was helpful in detecting original decorative patterns and overlapping paint layers on the Buddhist wall murals. The study of these original patterns was crucial in identifying the changing themes and stylistic characteristics of Goryeo Buddhist painting. As a result, the principal mural in the Main Sanctuary was identified as the oldest known of its type in Korea.

Due to their advanced state of paint deterioration, the murals of the Main Sanctuary had been traditionally repainted based on their original color scheme, as identified by the IRR study. However, no repainting had been done in the Hall of Paradise. Instead, conservation was carried out, and NRICH is researching ways to display a virtual restoration of the writings and decorative drawings.

Following the study, an image database was compiled, which included the raw and edited IRR images as well as postrestoration photographs. This central database system is managed by NRICH and is accessible to conservators and researchers interested in ancient Goryeo art history, architecture, and conservation science.

Soon-Kwan Kim is a project manager specializing in wall-painting research at the National Research Institute of Cultural Heritage, South Korea, and has investigated ten significant Buddhist temples using IRR. He received a master's degree in cultural heritage management at Myongji University, Korea, and has carried out several wall-painting conservation treatments, including the ancient tomb of Gobyep-ri and the Hall of Paradise of Moowui Temple. He has researched synthetic resins, the influence of acid rain on masonry, and traditional color paints of Korea. Currently he is involved in a project in North Korea on conservation of wall paintings in ancient tombs.

A monk (*right*) officiating at a ceremony to replace the construction records in the ridge beam. These records, transcribed with additional information after each period of construction, maintain the Korean tradition of passing documentation on to future generations. Photo: © Soon-Kwan Kim.

The Hall of Paradise, after completion of the 2002 conservation. Photo: © Soon-Kwan Kim.