Non-Destructive Techniques Applied to Monumental Stone Conservation

Beatriz Menéndez

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/62408

Abstract

Non-destructive techniques have always been used in the study of built cultural heritage because of the high cultural value of the concerned objects and the need to preserve them as intact as possible. In this chapter, different non-destructive techniques applied to the conservation of historical building are presented. The selected techniques concern the measurement of some physical properties of the building materials measured at the surface: water absorption, permeability, water content, cohesion, hardness and so on; the actual conditions of the building: stress state, deformation, crack growth and so on; and in-depth physical properties: mechanical properties, inner structure of walls, damp location and salt content. Some of these techniques are used for inspection of the building at a given time, whereas others can be applied for long periods of time to investigate the evolution of the building or of one of its parts (e.g., crack propagation) with time.

After presenting the physical background of each method, the main objective of this review is to focus on the applications, especially to discuss which information can be supplied and to present published results in each case. Some techniques are very simple and require very inexpensive equipment but others, which are mainly adaptations of field geophysical techniques, use more sophisticated technology and require post-acquisition treatments based on more complex physical principles.

Finally, some examples of combinations of different techniques are presented because a unique method cannot provide all the information needed to understand the weathering processes taking place in a building. The final goal of the studies is to contribute to the preservation of the cultural heritage. The choice of the conservation strategies and methods should be based on a deep knowledge of the building, and non-destructive testing is usually the only way to get it.

Keywords: Non-destructive techniques, Stone conservation, Built cultural heritage, "in situ" studies, Monumental stone

1. Introduction

Conservation of built cultural heritage requires a deep knowledge of the building itself, its construction and restoration history, its structure, the nature and properties of the employed construction materials, their degradation degree, etc. but also of the external/internal conditions affecting the building: stress state, damp localization and humidity degree, climatic conditions, traffic, etc. Only a very superficial part of the building can be directly reached and studied. Due to their cultural value, sampling in order to determine the composition and properties of building materials is not always possible or desirable: this implies that non-destructive "in situ" inspection becomes the only way to study the building. In some cases, samples can be taken and studied in the laboratory but there are other features that can only be determined on site in the monument: cracks opening, stress and strain evolution or even the inner structure of walls. Some properties are measured not because their variation constitutes a risk for the integrity of the monument but because its change will affect the aesthetics of the building, as colour changes due to the application of some restoration products or procedures (consolidation, hydrofugation and cleaning).

According to Fitzner a study of a cultural heritage building in order to conserve and preserve it will follow three steps: anamnesis, diagnosis and therapeutical steps [1, 2]. The anamnesis includes the monument identification, location, history, environment and so on. The diagnosis step determines the building materials, their properties and state of deterioration to decide the need (or not) of preservation measures. When necessary, the final step consists of the conception, tests, application of therapeutical measures and of a long-term survey and maintenance of the building. For each of these phases, non-destructive techniques are nowadays necessary.

"In situ" non-destructive testing (NDT) have been employed during long time on conservation studies of monuments. For example, Karsten tube has been used since the middle of 19th century to measure water absorption of building materials [3]. This method, consisting in a continuous water supply on the surface of the materials, can be considered as an example of techniques that can be non-destructive in some cases, that is, when done on stone or brick surface, and destructive when applied on water-sensitive surfaces as plaster renders or frescoes. At the same period, geophysical techniques started to be used for archaeological campaigns. More recently, some geophysical techniques started to be applied for laboratory characterization of porous materials and then to "in situ" study of buildings and particularly to historic building conservation. Most of the NDT applied to cultural heritage have been implemented and tested in laboratory or field geology before being applied "in situ" on historical buildings. Cosentino et al. [4] use the term "micro-geophysics" to discuss about these techniques because the equipment has to be "miniaturized" to be used on buildings. An important difference between cultural heritage studies compared to geological ones is the fact that more than one face could be inspected and then better results than in classical geophysical investigations can be obtained. One major technical problem is the size of the probes.

NDT techniques can be applied "in situ", do not require to retrieve destructively samples and are nowadays an indispensable tool in cultural heritage for the characterization of materials, their degradation and weathering degree but also to assess the effectiveness of conservation interventions and to evaluate the compatibility of materials [5]. “In situ” NDT techniques on conservation studies are used to

i. estimate physical and chemical properties of building materials and their conservation state,

ii. characterize the “environmental” conditions of buildings, including water content (spatial distribution, salt content and so on) and stress field.

iii. monitor the evolution of the building, materials properties, crack opening and strain.

NDT techniques can be associated to destructive tests providing information that NDT cannot provide [6]. Literature concerning non-destructive techniques applied to built heritage conservation is very large. The goal of this chapter is to present, in a synthetic way, the different available techniques and show some examples of their applications on built cultural heritage. Many different techniques are presented from very simple ones using cheap technologies to more complex ones needing expensive high-technology equipment. Some NDT techniques deal with the superficial part of stones or other building materials, and others explore the inner parts of the building. The examination depth can go from millimetric to metric scale. We present studies realised on masonry, mainly stone, and also on bricks, as well as some studies concerning plaster renders, frescoes, statues and so on. We focus on methods to evaluate physical properties of materials, but chemical or mineralogical analytical methods are not discussed. This chapter is not a technical description about the different techniques but rather an introduction to the different possibilities of application. For each technique, a brief description of the physical basis is done, and the emphasis is put on the information they can provide and their interests in cultural heritage. Examples of applications are shown.

The first and maybe the most important NDT always applied is “expert” visual observation [7]. This observation allows to planning the study campaign and the choice of the suitable techniques to be used. Visual inspection is important but it is not enough for a deep characterization of the materials and present pathologies. One of the most important aspects conditioning the success of any NDT study is the observer’s experience. Under good conditions, we can consider that non-invasive techniques are the most appropriate tool for the evaluation of the internal structure and materials quality of cultural heritage [8]. It is important to keep in mind that every studied case should be considered as unique. No strict general rules can be applied in cultural heritage studies.

2. Geometrical information and mapping

2.1. Observation and mapping

As mentioned in the introduction, the first and oldest non-contact technique applied to cultural heritage is observation. This observation can be done with naked eye or by means of optical devices and contribute to generate maps in which all relevant information are synthesised. Traditionally, naked eye observations are complemented by magnifying glass observation but without the possibility of taking pictures. Photography is the traditional way of reporting observations on site. Fibre optics microscope (FOM) can be used "in situ" to acquire magnified images of surfaces. High resolution (up to 600×) and contrasted images can be obtained and stored without any surface preparation. This kind of images can be employed in many different ways, including the identification of textures and composition of surfaces, the study of decay phenomena, the investigation of surface morphology and the evaluation of cleaning and consolidation inventions. Several examples of images taken by FOM on surfaces of monuments are shown in the work of Moropoulou et al. [5].

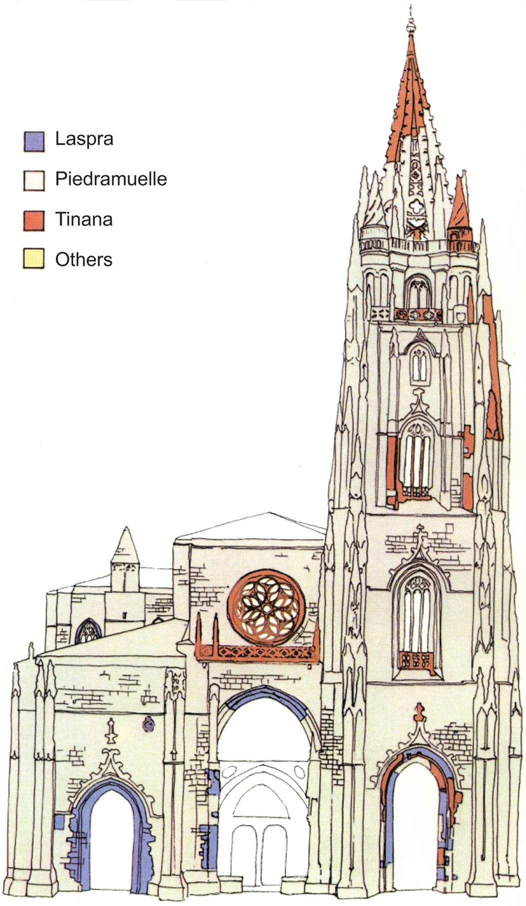


Figure 1. Lithological cartography of the main façade of the Cathedral of Oviedo (Spain) [9].

Esbert and Marcos [9] have mapped the different stones employed in the construction of the Cathedral of Oviedo (Spain). The cartography of one façade is shown in **Figure 1**. An example of weathering cartography of different parameters (weathering forms, rate and damage categories) of the Tomb no 778 of Petra site (Jordan) is shown in the work of Fitzner [10]. The classification of weathering forms used by these authors consists of four levels: Level I with four groups of weathering forms (loss of stone material, discoloration/deposits, detachment and fissures /deformation); Level II, each group is subdivided into main weathering forms (25); Level III with 75 individual weathering forms and Level IV with the differentiation of individual weathering forms according to intensities. More details are provided in the study of Fitzner and Heinrichs [11]. In **Figure 2**, we observe a map of the degradation forms presented in one façade of the Saint Nicolas Church of Maisons Laffitte (France). The chosen nomenclature and colours are the ones proposed in the ICOMOS-ISCS [12]

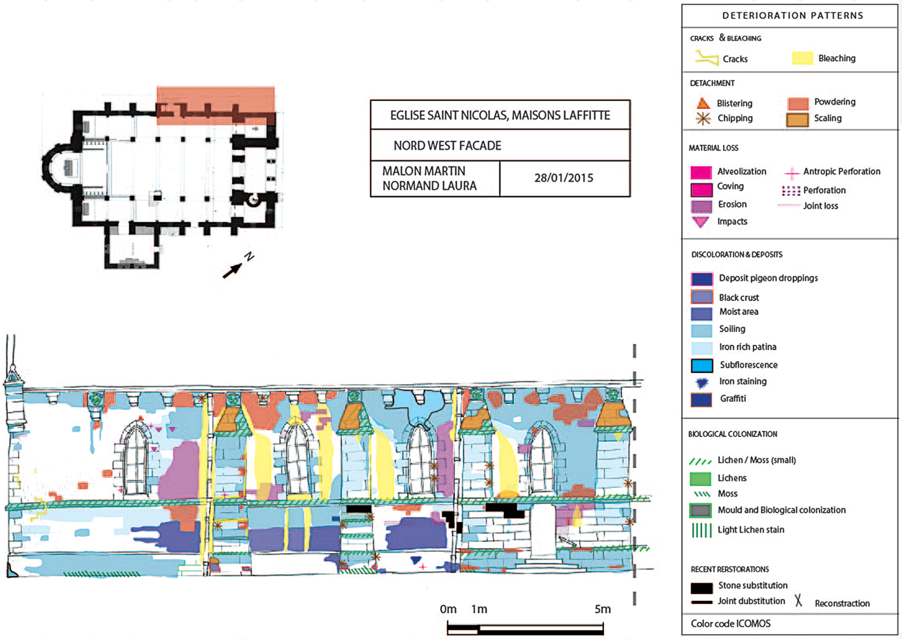


Figure 2. Mapping of weathering types of the Saint Nicolas church at Maisons-Laffitte (France).

2.2. Three-dimensional models

Photogrammetry is the science of making measurements from photographs. Usually, several pictures of the same object taken from different places are combined to obtain three-dimensional (3D) information of the object. Classically, we have the aerial photogrammetry, with pictures taken from an aircraft and usually pointed vertically towards the ground, and close-range photogrammetry, where the camera is close to the object. There is an established procedure about how to configure the position and orientation of the camera to obtain the most useful information. A video illustration of this technique can be seen in [13]. Digital cameras have facilitated the automatic treatment of such images, allowing also quantitative measurements [14]. For example, Solla et al. [15] applied photogrammetry to build the 3D structure of a bridge. To obtain a final 3D model with enough high resolution, they realised several small 3D models, each model was defined using three or four photographs, with consecutive models overlap of 40%. In the study of Arias et al. [16], photogrammetry is used for monitoring the evolution of a crack in the masonry of the Basilica da Ascensión in Galicia (Spain). A wall presenting a long vertical crack has been modelled by photogrammetry in 2001 and 2003, during this period an increase in crack size of 12% has been measured.

Terrestrial laser scanning allows a faster collection of the 3D coordinates of objects and can be applied at different scales for large surface on site of for smaller object with high resolution on site or in the laboratory. There exist different ways of processing the signal to obtain the 3D model; more detail about this technique can be found in the study of Yastikli [14]. Several authors have used this technique on cultural heritage with different objectives. In the work of Heinrichs and Azzam [17], high resolution 3D terrestrial laser scanning is used to study five rock-cut monuments in Petra. The obtained data were used to assess their original architecture, weathering damage, calculate the rock mass removed for monument creation, water run-off on the monument, etc. They installed an environmental survey network measuring temperature, humidity and electrical resistance. These measures have been done at surface and at different depths on the stone until 18 cm. Localisation of environmental data on a 3D model (orientation, slope and so on) allows a good interpretation of weathering processes.

2.3. Digital image analysis

Vazquez et al. [18] proposed to use digital image analysis of wall pictures to distinguish between unweathered limestone, weathered limestone and areas with more or less thick efflorescence. They applied this technique to the conservation study of the Chapel of Falla located in the Crypt of the Cadiz Cathedral (Spain). They distinguish six "classes" based on the grey level range, from 0 to 109: unweathered limestone; from 110 to 129: weathered limestone; from 130 to 159: efflorescence type 1; from 160 to 179: efflorescence type 2; from 180 to 190: efflorescence type 3 and from 191 to 255: efflorescence type 4. Efflorescence thickness increases from type 1 to 4. In this way, they can quantify the percentage of surface belonging to each type.

A similar study has been performed by Crespo et al. [19] in the ruins of Santo Domingo (Pontevedra, Spain) combining colour optical images with images obtained by a terrestrial laser scanning. They used not only the geometrical information given by laser scanning but also the intensity of the reflected signal. They combined the red channel signal of the colour image with backscattered laser intensity (sum, ratio) and they applied statistical clustering procedures to the pixel level of the resulting image. They obtained a good automatic classification of granite ashlar with remaining lime/mortar and granite ashlars affected by high moisture content. Meroño et al. [20] applied a combination of 3D model from a terrestrial laser scanner with multispectral images to the study of Santa Marina de Aguas church (Cordoba, Spain). They arrive to separate different areas with stone, plaster, wood and different kinds of degradations. As they use a 3D model, they can calculate not only 2D projections but also real surface distribution.

http://dx.doi.org/10.5772/62408

Cartography of lithology and pathologies needs as much as possible detailed support of the façade, wall or object to be studied. Even if traditional methods are still used as a first approach, more sophisticated and accurate results can be obtained by the use 3D acquisition techniques and by architectural lasergrammetry and photogrammetry associated with devoted software. There is also the possibility of using GIS software to integrate other information such as numerical data and detail pictures.

2.4. Measurements of stress and strain

Structural problems are very common on cultural heritage. Their origin can be very different and many times they are released or accelerated by external causes, natural as earthquake, dryness or flood or anthropic like works done in the building or in the surroundings. The first control devices were just glass or plaster plates placed on cracks to survey if the cracks continue to grow or not. Nowadays, there are many different ways to control and measure stress supported by building, the propagation and evolution of cracks or the deformation of the structure. A brief description of some of these methods will be presented here.

2.4.1. Stress measurement

The flat-jack test (**Figure 3**) is a slightly destructive test to measure the "in situ" stress conditions. Mortar joint is cut out to introduce a flat jack (deformable steel capsule made out of two cold-formed steel halves welded together where a fluid can be injected under pressure to open them). The flat jack is then inserted into the cut and the pressure is gradually increased until the original distance between both sides is reached. This pressure is equal to the original stress state on the masonry [21]. By using two parallel flat jacks, applying an increasing pressure and registering the induced deformation, stress–strain curves can be done and Young's modulus can be measured [22]. After data acquisition, the cuts are refilled with mortar. Several examples can be seen in the study of Simoes et al. [23]. Bartoli et al. [24] used single and double flat-jack tests in the characterization of the mechanical properties of the Torre Grosa in San Gimihna (Siena, Italy). The masonry of the tower was composed of an internal layer in bricks and mortar joints and an external side composed of calcareous ashlars and a filling between then with a heterogeneous material. They measured stress values and Young's modulus in both internal and external walls. These data were used in a 3D finite element model of the tower.

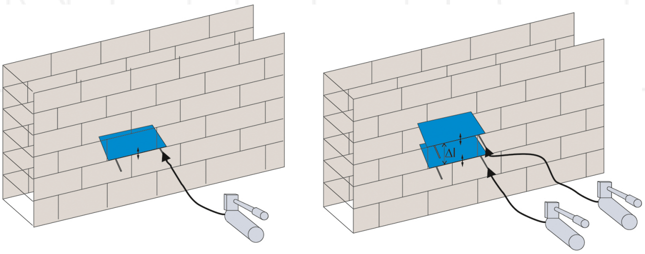


Figure 3. Simple and double flat jack techniques.

2.4.2. Strain measurement

Several systems can be used to measure strain, most of them are based on measuring distances and displacements: extensometers, inclinometers, callipers, linear variable differential transducers and so on. Monitoring can be done manually or automatically. Structural control can be static or dynamic [25]. Static monitoring consists in measuring displacement and inclination, without any external excitation source. The sources of deformation could be soil settlements, excessive load and temperature changes. Dynamic methods control the behaviour of the structure in response to an external vibration. These vibrations can be due to environmental vibrations, passive sources (traffic, wind and bell ring) or forced vibrations and active sources (hammering system or vibrodines). The response of the material is recorded by a network of accelerometers installed in chosen parts of the building. The vibration response is characteristic of the local and global behaviour of the building. Dynamic tests are used in the conception of the physical model of the structure.

Monitoring systems can be installed permanently or periodically and should be installed over a long period of time, more than 1.5 years to avoid seasonal variation errors. Sometimes instruments measuring deformation are installed in hardly accessible places, because of crack location and also to avoid vandalism. Nowadays, the information registered by strain gages or other instruments is tele-transmitted but, for example, in Castillo de San Marcos (St Agustine, Florida, USA) in 1987, the gage results were read using a tripod-mounted telescope [26]. Different movements can be monitored: relative movements of vertical structures, absolute horizontal movements, differential settlements and tilting.

For monitoring crack evolution, a detailed crack pattern survey should be carried out. The most frequently measured parameters to characterise crack relative movements are opening and sliding. In several Coptic monuments, more than 95 crack gauges and 10 temperature gauges have been installed in order to control the deformation behaviour of the monuments during restoration works [27].

In [28] a study is presented where the evolution of several cracks located in the Madara Horsemen, a rock bas-relief carved on the NW scap of the Madara Plateau (Bulgaria) included in the UNESCO World Heritage List have been followed during 10 years. Seven cracks cut the rock face that bears the bas-relief and three of them have been considered as dangerous. In 1990, a survey campaign started and three extensometers and five bench marks for calliper measure have been installed in different strategic locations. The obtained information allows one to model the dynamics of the rock blocks. For each extensometer, deformation has been measured in three directions: X, compression of crack; Y, moving of the rock slice/prims inside the massif and Z, uprising of the rock slice/prims. The authors concluded that movements along the rock face depend on seasonal and daily temperature fluctuations but movements in the periphery of the plateau, with higher velocities, are very sensitive to earthquakes.

Several applications of long-gauge sensors to monitor structural stability of different heritage building in Switzerland, Italy, Russia and Korea can be seen in the work of Glisic et al. [29]. They used SOFO (“Surveillance d’Ouvrages par Fibres Optiques” or structural monitoring by optical fibres) interferometric sensors. A description of the SOFO system can be found in the study of Inaudi et al. [30] and Inaudi [31].

3. Physical properties

We describe how to measure selected physical properties that are relevant for characterizing building materials and the different techniques that can be used.

3.1. Water absorption

Water is the most important weathering agent in buildings, and special attention needs to be paid to water transfer. Water contribute to stone degradation, among others, (i) by dissolving minerals, allowing the reaction of atmospheric pollutants with mineral grains and (ii) by the transport of soluble salt that will crystallize and become one of the most active ageing processes. The moisture distribution in buildings depends on the porosity of the materials, the pore size distribution and the environmental conditions. Two mechanisms are responsible for the introduction of salt in monuments, capillary rise of groundwater and infiltration of rainwater [32]. To know the kinetics of water absorption, several laboratory experiments are used: capillarity absorption, total immersion and so on. In monuments, different techniques have been employed to quantify the capacity of building materials to absorb water. Maybe the most common is the Karsten or RILEM tube. It consists of a cylindrical open reservoir in contact with the surface of the wall and connected to a graduated pipe. The opening of the cylinder can be vertical or horizontal to do measures in vertical or horizontal surfaces. The reservoir is filled through the pipe until a fixed level. Water starts to move to the porous material, and water height in the pipe is monitored as a function of time. Similarly to laboratory absorption tests, a coefficient is obtained as the ratio between the absorbed water in a time interval. The obtained results are very sensitive to the characteristics of the surface, roughness and weather conditions (temperature and relative humidity) [33]. This test is commonly used to measure the hydrophobic quality of restoration products, and it can be used also on joints to test the quality of the contact. A deep study about this test can be found in the study of Hendrickx [34] with a description of the experimental details, analytical models and examples of validation of these models. Mirowski pipe is similar to Karsten tube, but the pipe is closed and the reservoir is filled with a sponge [35]. The Italian pipette is another similar method. Common diameter of cylindrical reservoirs varies between 2 and 3 cm.

The contact sponge method [36] consists of a sponge enclosed in a contact plate. The sponge is higher than the vertical border of the plate. The sponge is filled with water, and the whole (sponge and plate) is weighed. The sponge is pressed manually against the stone surface until the vertical borders of the base touch the stone surface. After a selected time, the sponge is weighed again [35]. The amount of water added to the sponge, the applied pressure and the contact time depend on the material to be tested are fixed [3]. The permeability box consists of a rectangular box of 16 cm×34 cm filled with water and with an open surface in contact with the wall. The level of water in the box is maintained constant, and the amount of water that has penetrated into the wall is recorded. Another simple method, the water drop test, consists in placing a drop of water (or a non-polar liquid) on the surface of the material and observing the evolution of the water with time [37]. Depending on the behaviour of the water drop, we can determine whether the surface is water repellent or not, if the surface is not water repellent but underneath there is an impermeable layer, etc. This method cannot be applied on vertical surface. Schematic drawings of these different setups are shown in **Figure 4**.

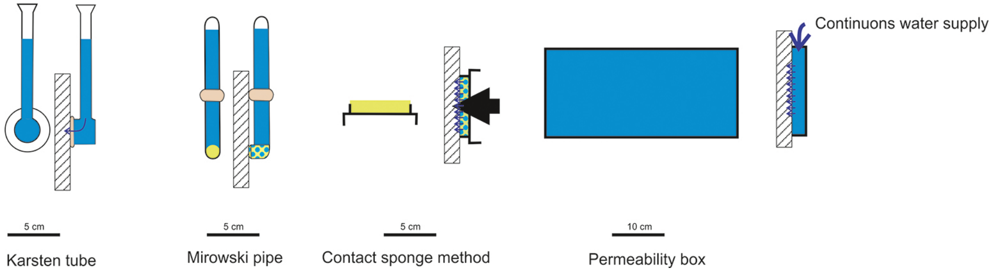


Figure 4. Different systems to measure water absorption “in situ”.

In the work of Vandevoorde et al. [36], we can see a comparative study of the contact sponge methods, Karsten tube and Mirowski pipe in seven different stones with porosities between 10 and 30%. They compare these “in situ” measurements to laboratory capillarity rise method results. They found that contact sponge is capable of measuring initial water uptake in low porosity stones with high precision but it is not convenient for long time measurements or in high porosity stones due to the small amount of water supply. Karsten pipe is more convenient for longer time measurements and in high porosity materials. The results obtained by the Mirowski pipe were not convincing.

Another method has been proposed in the study of Drdácký et al. [38]. This method has the possibility of continuous measurement of water intrusion into the surface, allowing long-term measurements and recording. According to the designer, this method reduces the number of operators, it is more precise, effective and faster [39]. This pistol-like device measures the time necessary for the absorption of predefined volume of water and it can be used on inclined surfaces.

3.2. Permeability

Permeability is defined as the capacity for fluids (gas or liquid) to flow through a porous material. The term permeability is commonly employed for single fluid transport produced by a difference in the hydraulic head between two points in a completely saturated medium. Water absorption takes place in a unsaturated medium, and the driving forces are capillarity and gravity. There are two ways of measuring permeability (i) steady-state method, where a flow is imposed to the porous medium under constant hydraulic gradient and flow is measured and (ii) transient or pulse method where hydraulic head is instantaneously raised (or lowered) at one end of the sample and variation of pressure with time is recorded. The steady-state method corresponds to the permeability box test. The most common method employed for “in situ” measures uses the second experimental conditions (pulse method).

Brown and Smith [40] do a review of the different gas permeameters used in laboratory and field applications. They have developed a portable syringe air permeameter to be used on rock outcrops and cores. This permeameter induces a vacuum on the surface of the stone by suddenly increasing the volume of a chamber in contact with the stone surface. Air flows from the stone to the chamber gradually increasing the pressure on the chamber. Air pressure is registered as a function of time and from this pressure variation air permeability is estimated. This device was originally thought to measure rock permeability inhomogeneity in outcrops but it is actually used for “in situ” permeability measurements on buildings. This device is actually commercialized as TinyPerm by New England Research, Inc. (**Figure 5**). “In situ” air permeability measures have been done with this permeameter in two buildings of Paris (France) restored with lime mortars in order to check the compatibility of repair mortars with the original stone, the Euville limestone [41]. Similar measurements have been performed on laboratory samples of the same materials. It was found that the stone permeability is higher than the permeability of mortars by a factor between 1.5 and 15, despite the high scatter in the data. This method is a very convenient way of having ‘in situ” estimation of materials permeability and its inhomogeneity.

Figure 5. Tiny Perm (New England Research Inc.) taken with the permission from Brown and Smith [40].

Filomena et al. [42] compared air permeability measurements on 51 cylindrical and bedding parallel sandstone cores (∅ 2.54 cm, L 5cm) obtained with three different laboratory permeameters and the Tiny perm. They found that the permeability derived from Tiny perm measures in laboratory is about 37% lower than the ones obtained in confined samples. They concluded that probe permeameters have the advantage of providing closely spaced, non-destructive permeability data, which are mostly suitable to get 3D permeability value, to estimate the anisotropy effects and heterogeneity. Another system based on the same principal is the "Torrent permeability tester method" (Permea-TORR), but in this case vacuum is produced by a pump. Sena da Fonseca et al. [43] measured the permeability in 15 limestones and marbles from Portugal with a Permea-TORR and found very good relationships with the open porosity and the water absorption.

3.3. Humidity/water content

As "in situ" amount of water contained in a building material cannot be measured directly without sampling, different properties, which values change as a function of water content, can be used to estimate it. In order to validate the procedures, values of the measured properties in materials with well-known water content are used as standard for comparison. There are several kinds of moisture meters originally designed to estimate the humidity of wood that are now used on other built cultural heritage materials. Usually, they are not calibrated for stone but they can be used to estimate humidity variability in a site. The obtained results are affected by several factors such as the weather (especially humidity), the degradation of the surface, the presence of biological colonisation and so on [44]. There are two basic families of devices, one based on the measurement of the electrical resistivity of the materials, called "pin meters"; and a second group based on the measurement of the impedance, also called "pinless meters" or electromagnetic wave meters (**Figure 6**). In pin meter, a small electrical current is passed between two pin tips, therefore, the measurement provides information only on a very thin line between both pins. Pinless moisture meters use a larger sensor pad that emits electromagnetic signals; therefore, the measures correspond to a larger area of the surface than in pin meters. The pin moisture meters need less access area that the pin-less one. In the same study, on Paris buildings previously described, we found better correlation between the nature of the studied material (mortar or stone) and water content with a pinless meter than with a pinless meter.

Figure 6. Left: Pin moisture meter (Protimeter), right: pinless moisture meter (Tramex).

3.4. Surface cohesion

Another very important property when quantifying the superficial weathering degree of buildings material is the cohesion of their surface. Several very simple slightly destructive tests are traditionally used.One consists in selecting a part of the surface on which a squared frame with an open surface of 10×10 cm is placed, then brushing this surface 10 times in the vertical and 10 times in the horizontal direction, and collecting the detached material. The collected material is dried and weighted. The results are expressed in grams per square centimetre [37]. Dividing the result of the test by the density of the obtained material, we can estimate the thickness of the removed layer [33]. The size of the collected grains can also be measured in the laboratory.

Another way to quantify the cohesion of surfaces is the peel-off resistance measured by the Power Strip test [45]. A Power Strip tape (20 mm x 50 mm) is applied and evenly pressed to the stone surface. A spring balance is attached to one end of the tape with a clamp. Afterwards, the strip is peeled off and the employed force recorded by the balance. The material stuck on the tape can be observed and weighted at the laboratory. If necessary the test can be repeated several times. The peel-off resistance is calculated from the force and the surface of the strip. The weather conditions have a great incidence on the obtained results [37]. Drdacky et al. [46] proposed a standardization of this method, also called Scotch Tape test, for assessing the cohesion and consolidation characteristics of historic stone surfaces.

Some authors used the roughness as a measurement of the surface quality. There are several ways of measuring it but most of them are not relevant for “in situ” measurements because the height range of the technique is too small to be applied on granular materials. In the study of Alvarez de Buergo et al. [47], a portable optical surface roughness meter has been used to select the best cleaning condition of the stone masonry at several areas of the Cathedral of Segovia (Spain). Hand profilometer can measure micro-relief amplitude from 0.5 to 6 mm [48]. Laser 3D scanners have also been used to characterise the 3D profile of stone walls and art object surfaces. Gomez-Heras et al. [49] used 3D laser scanner for monitoring the evolution of sample surface during salt crystallization test. This kind of technology can also be applied for “in situ” observations.

3.5. Surface hardness

Hardness of the surface is another property usually considered to determine the conservation degree of building materials. It is measured mainly by the Schmidt Hammer or sclerometer. The Schmidt Hammer was originally devised for carrying out “in situ”, non-destructive tests on concrete [50]. It gives an immediate indication of the compressive strength of the material using the linear calibration curve supplied with each instrument [51]. It measures the height of rebound of a plunger impacting the surface at a defined pressure. There are different kinds of Schmidt hammer. The most employed in rock outcrops and building stones is the ‘N’ type with an impact energy of 2.207 Nm. Another type used in weak stones is the ‘L’ type with an impact energy of 0.735 Nm. More details about the use of Schmidt hammer and its correlation to uniaxial compressive strength can be found in the study of Aydin and Basu [52]. This test is very common on built cultural heritage studies. The Duroscope has a similar mechanism of operation but with a smaller and pointed plunger and a smaller spring-loaded mass. It can be used for surfaces with low strength. With Duroscope, the precision of the measure depends on the smoothness of the surface [53].

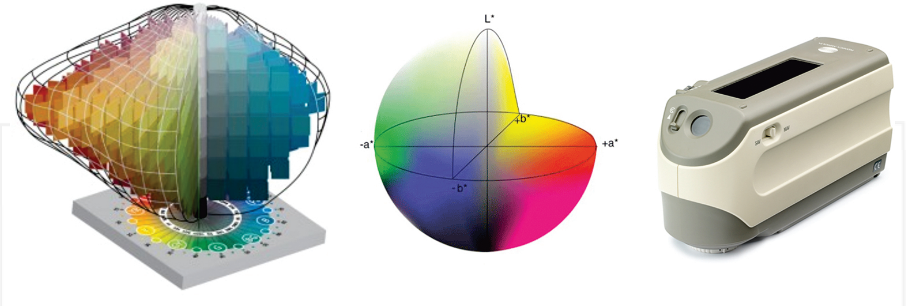
The Equotip is another device to test the mechanical properties of stone surfaces. In this case, a ball hits the surface with a fixed energy, and the velocity of the ball as it rebounds is recorded. There are different kinds of Equotip devices depending on the nature of the ball (tungsten carbide, ceramic and polished diamond), its size (2.8, 3 and 5 mm) and the impact energy (3, 11 and 90 Nm). The Equotip type D has been used to measure surface hardness changes of common Portland limestone, Cornish granite and a standard marine concrete exposed to coastal environment in the work of Coombes et al. [54]. They found that the durometer can detect changes on the surface hardness after short exposition period (months). This information indicates that it should also be useful in studying weathering in buildings environments. **Figure 7** shows pictures of a Schmidt Hammer, Duroscope and Equotip.


Schmidt hammer Duroscope Equotip

Figure 7. Different systems to measure surface hardness. Schmidt hammer (Proceq), Duroscope (Hitec Enterprises Inc) and Equotip (Proceq).

3.6. Color

Color is one of the most common properties measured in monumental stone, mainly when some preventive or restoration treatment will be applied or when stone ashlars should be replaced, as they can change the aesthetics of the building. Colour changes can be due to darkening by air pollution [55], to fire damage of stones [56],and so on. There are different systems to quantitatively express the colour. Traditionally, the Munsell color system has been used. The first edition of the Munsell Book Color has been edited in 1929. The Munsell system has three dimensions: HUE, which is the common name of the colour (red, green and yellow); VALUE, which represents the light strength and goes from 10 (white) to 0 (black) and CHROMA, which measures the degree of colour strength (intensity) and goes from neutral (grey) to maximum (there is not arbitrary end of the scale). So, colour is expressed as HUE/VALUE/CHROMA. Munsel colour chart served to determine the colour value of material by visual comparison between the objet and different sheets with colour samples. Nowadays, colorimeters and spectrocolorimeters measure the colour and can register the light spectrum in an automatic way. There are others systems to express colour as the CIELAB, values L*a*b*, where L* is lightness and goes from 0 (black) to 100 (white), a* axis is the red/green colour, with green at negative a* values and red at positive a* values; b* axis is the yellow/blue colour, with blue at negative b* values and yellow at positive b* values. All these systems are represented on "color solids". For example, **Figure 8** shows the Munsel and CIEL color solids and a spectrocolorimeter.



Munsell color solid CIELAB color solid Spectrocolorimeter

Figure 8. Color measurement systems and spectrocolorimeter (Konica Minolta).

4. Methods adapted from field geophysics

In this group, we use a classification depending on the employed techniques rather than on the measured property as before. We do a brief description of the physical principle of each technique, the different operating modes and we show some applications from bibliography.

4.1. Infrared thermography

Infrared thermography (IRT) is one of the non-destructive techniques, which is most frequently employed in civil and architectural inspections, especially on cultural heritage. It is used in the different phases of the studies: diagnosis, preventive maintenance and to verify the result of restorations. In cultural heritage, it has been applied for the study of very different aspects: detection of holes on masonry, plaster detachment from a wall [57], moisture location, material weathering, delamination between corroding reinforcement bars and surrounding materials [58], presence of cracks, biological colonization [33], evaluation of restoration materials [5] and the use of different kinds of mortars [59]. It is a non-contact method, which can be applied to wide surfaces of walls. Therefore, it can be used in hardly accessible spots or on irregular surface and/or with non-planar shapes [7]. Some IRT cameras have high spatial and thermal resolution. This technique presents a particular interest in the study of frescoes where it is not possible to use contact techniques [25]. One limitation is the limited penetration depth (some centimetres).

The camera receives infrared radiation emitted and reflected by the surface. The electromagnetic signal is transformed in an electrical signal and finally in a false colour image. Infrared waves have wavelengths ranging from 0.78 to 1000 μm but those between 7 and 14 μm are typically captured by thermographic camera sensors [60]. Thermal resolution can go from 0.08 to 2°C depending on the camera. The wavelength shifts with the temperature of the surface, decreasing as temperature increases. The signal arriving to the camera depends on the emissivity of the material (capacity of the material to emit energy), the surface colour, reflections on metal or glazed surfaces, meteorological conditions and the distance between the camera and the surface. Apparent different temperatures may be caused by variation in thermal diffusivity of materials that depends on thermal conductivity, specific heat and density of materials [15]. Technical aspects are also important as the characteristics of the camera and the calibration process needs to avoid biased measurements [57].

In cultural heritage, two kinds of thermography methods are employed: passive thermography and active thermography. Both need a temperature change during the test. Passive thermography used natural heating or cooling, the energy source is the sun. Thermography registers differences in temperature due to differences in heat transfer. Active thermography uses an external known source of heating or cooling to register the heat flux. In passive thermography, a single snapshot is used, whereas in active thermography a series of images (or a movie) is required. In "pulse thermography," the surface is heated briefly and then the temperature is recorded during cooling. In "lock-in thermal," a sine-modulated lamp heating is used, and the time dependence between reference and temperature signals is recorded [5]. Passive thermography is used for large areas and active thermography for the study of small areas of special interest. Generally, passive thermography is qualitative, whereas in active thermography some parameters as thermal conductivity can be calculated. APT methodology consisting of a combination of instrumentation and work flow providing fast, high resolution, low cost approach that automatically acquires, corrects and processes geo-located, temporally anchored, building scale thermal surveys has been used in the study of Hess et al. [60]. This method based on image mosaic permits the survey of whole buildings with high resolution.

The equipment consists of an infrared thermocamera with a specific wavelength range, different kinds of lenses and data treatment facilities. Active thermography also needs a heating source.

4.1.1. Application to detachments detection

Detachments create an air layer between the stone/bricks and the plaster. This air layer represents a thermal resistance to heat flow, preventing the heat flowing from the wall to the plaster during the cooling periods or from the plaster to the wall during heating. When the surface is in equilibrium with the environment (no heating or cooling), detachments cannot be observed. In passive thermography, during the day, detached areas are hotter than the areas without detachment; during the evening (cooling), they are cooler than the rest.

Thermography can detect not only plaster or other render detachments but also external bricks or stone detachment. de Freitas et al. [57] compared numerical simulation, physical model and "in situ" measurements of render detachments. They created a laboratory wall model with air bubbles between a concrete masonry and a polymeric render and heated the surface using an infrared heat source simulating solar radiation. They did also some measures on residential buildings façades in Porto (Portugal) on several areas where detachments were suspected and selected by the percussion method (which will be explained later). The results obtained by numerical simulations agree with the experimental data.

Jo and Lee [61] used active thermography for blistering detection on five-story pagoda located in the Magoksa Temple, Gongju (Korea). They tested different heating systems, and they concluded that lamps are unsuitable for large stone monuments and decided to use an infrared heater with a halogen lamp. **Figure 9** shows the obtained result on the four faces of the pagoda.

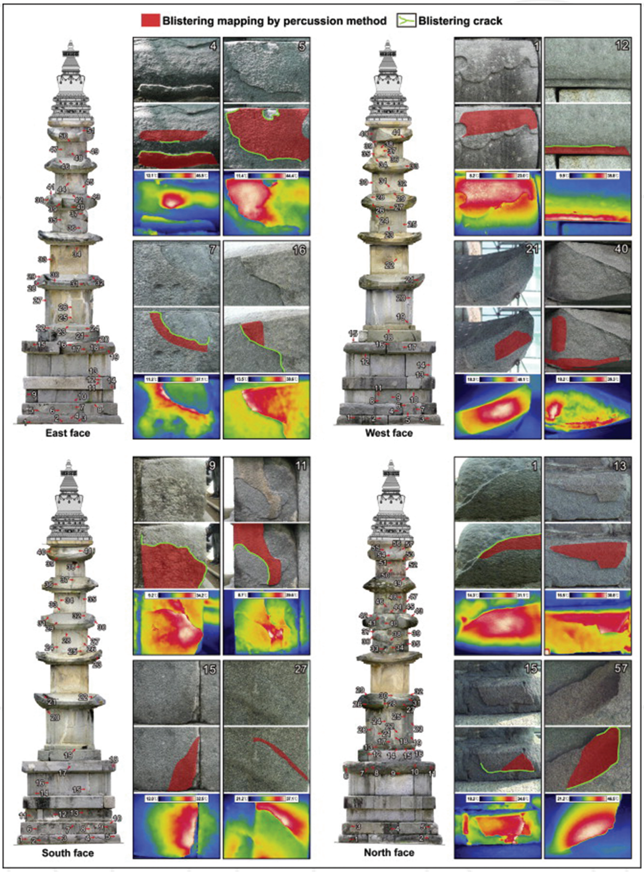


Figure 9. Active thermography applied to a pagoda from the Magoksa Temple (Korea) [61].

4.1.2. Application to the detection of voids or cracks

As for detachments, air in voids, pores or cracks produce lacks on thermal conductivity and are observed as detachments by thermal anomalies. Two thermographic campaigns on the Santa Maria ad Cryptas (Fossa, Italy) have been performed [59], one in 2007 and a second after the 6 April 2009 earthquake. During the first campaign, they found an incipient formation of cracks not visible with naked eye. After the earthquake, the analysis showed that some damage induced by the earthquake corresponds to thermal anomalies previously detected (**Figure 10**).

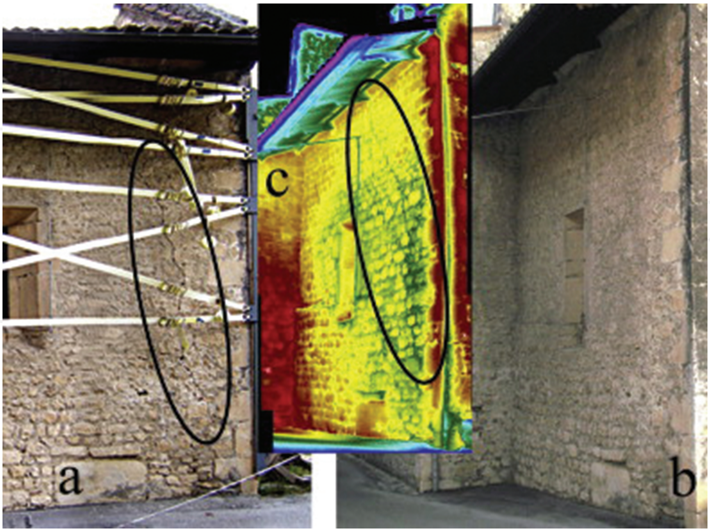


Figure 10. Passive thermography applied to the detection of cracks. (a) Lateral wall of the Church of Santa Maria ad Cryptas (Italy) after the 2009 earthquake; (b) aspect in 2007; (c) thermography image taken in 2007 showing traces of incipient splitting of the masonry. [59].

4.1.3. Application to the detection of materials contrast

Different types of stones, bricks and mortars have different thermal properties that result in different temperature response during cooling or heating phases.

Three different kinds of thermal tests have been applied in the Monastery of the Assumption of the Virgin (Ioannina, Greece) [62]: (i) “graduated heating thermography,” where the increase of the surface temperature was registered during heating; (ii) lock-in thermography, with a sine-modulated lamps heating and (iii) the pulse phase infrared thermography, where the surface is heated briefly and the temperature decrease is recorded. The three techniques were applied to the donor’s inscription and different characteristics have been evidenced: detection of delamination and detached areas, the presence of different depth and material type, different substances used in the paint mural and pre-existing murals.

4.2. Acoustic, sonic and ultrasonic methods

This group of techniques is largely the most employed in the study of cultural heritage. It goes from very simple and inexpensive ones to more sophisticated with a large number of sensors and advanced computation for data analysis.

4.2.1. Simple acoustic tests

A very old and common technique used to detect detachments on render, known as acoustic tracing, is to knock the surface with a finger phalange to check if it "sounds empty." In such a way, it is possible to locate the areas with likely rendering defects. The sound can be analyzed directly by the operator listening or it can be recorded and analyzed with electronic devices. Another technique consists in dragging a chain along the surface and listening to the emitted sound, or in the "natural percussion" method to analyze the sound generated by the rebound of a sphere dragged along the surface [63]. A semiautomatic variation is called AAT [64]. The material is excited by a hard rubber sphere hitting the surface, the location and the sound are recorded by a video camera. A special software allows the production of maps of detached areas. All these methods could substitute infrared thermography on polish surface. In order to do automatic discrimination of sounds, some acoustic analyses on the audible spectrum have been presented in the work of Sklodowski et al. [63]. They tested different tapping instruments, such as finger, rubber sphere a wire in a hard plastic coating. This last one has been considered as providing the best results. Bläuer et al. [37] used a 50 cm rod with a steel ball of 2 cm in diameter at one end but they also proposed to use a metal wire or a small Allen key.

Another technique consists in using a loudspeaker placed at the end of a duct in contact with frescoes surface at the other end [65]. Loudspeaker excites plane waves normal to the duct axis and the response of the portion of fresco in contact with the duct is measured with microphones. Collini and Garziera [66] use a contactless method based on a loudspeaker and a microphone but in this case they used acoustic absorbency and not frequency response. The loudspeaker and the microphone are placed, respectively, 1 m and 1 cm away from the fresco. They find a good correlation between the measured absorbency and the detachment thickness on artificial reproduction of frescoes with defects. Using also loudspeakers as acoustic excitation, the surface vibration can be measured by a scanning laser Doppler vibrometer [67].

4.2.2. Wave velocities measurement

It is the most simple acoustic measurement that can be used in cultural heritage material characterization. In consists in generating an elastic wave at a source point and registering its arrival at another point: if we know the distance between the two points, measuring the travel time of the wave which propagates from the source point to the receiver allows one to calculate the wave velocity (**Figure 11**). The wave can be generated by a percussion (sonic, frequency around 5 kHz) or by a piezoelectric transmitter (ultrasonic, frequency higher than 20 kHz). The receiver is usually a piezoelectric accelerometer converting vibration into electric signal. The simplest experimental procedure consists in measuring just the arrival time of the wave but the entire signal can be recorded and processed to calculate attenuation, energy or other wave parameters that can provide information about the elastic and mechanical properties of material along the wave path. There are three experimental setups to measure wave velocity "in situ" depending on the accessibility: (i) the direct method, where the wave source and the receiver are on opposite faces of the object (e.g., in columns), (ii) the semi-direct method, where emitter and receiver are located at a given angle (e.g., in building corners) and (iii) the indirect method, where the source and the receiver are placed on the same surface.

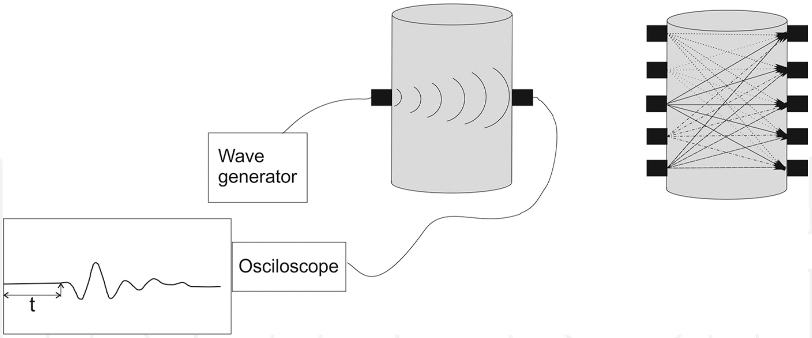


Figure 11. System for measuring wave velocity (left), to do acoustic tomography (right).

Two kinds of body waves are used on acoustic studies, primary (P) or compression waves and secondary (S) or shear waves. P waves can move through solid rock and fluids and the vibration direction is parallel to the direction of wave propagation. S waves are slower than P waves and can only propagate through solid rock, not through any fluid medium. S waves move particles perpendicular to the direction of wave propagation. In a homogeneous isotropic solid, the elastic properties of the material can be estimated from P and S wave velocities and density. Higher frequencies provide higher resolution but attenuation increases with frequencies. It is important to find the appropriate frequency as a function of the material and the wave travel distance. As a general rule, ultrasonic technique is suitable for small objects [68] and sonic for buildings.

These methods are used to estimate the density and elastic properties of materials (e.g. Young's modulus and Poisson ratio), it can indicate the presence of voids and cracks and effectiveness of repair by injection. In the case of inhomogeneous materials, the interpretation of the results is not simple [25]. Fort et al [69] in situ P wave velocities and Schmidt hammer surface strength and they found a direct relationship between them and an inverse correlation between P wave velocity and the decay of several granites of the Guadarrama mountains in Spain. In the study of Bromblet et al. [70], the P wave velocities of 62 marble columns of the cloister of the church Saint Trophime of Arles (France) have been compared with the values taken 16 years before (1993–2009) to estimate the evolution of their degradation over this time. They found a significant variation, sometimes the P wave velocity decreases but sometimes it increases. This increase could be due to the reduction of water content within the masonry because of the 2003/2004 restoration campaign. In the study of Pamplona and Simon [71], a similar work has been done on six marble sculptures but including acoustic tomography for some of them. They could study the weathering evolution and the effect of applied consolidation treatments.

Sklodowski [72] presented a method based on the propagation of superficial Rayleigh waves using edge probes rather than volume waves like with the previous techniques. Piezoelectric transducers are glued to the surface of steel edges providing only linear contact with the surface. Measurements are made using one transmitting and one or two receiving transducers at a distance of several centimetres without any contact interphase. The method provides wave velocities in a very superficial part of materials (few mm). In the work of Sklodowski [72] two studies in bricks and marble are presented, and differences in velocities between degraded and not degraded materials are observed.

4.2.3. Impact-echo technique

This method is based on impact-generated sound waves (about 2–50 kHz) that propagate through masonry and are reflected by internal discontinuities (cracks, detachments, reinforced structures and so on) [73]. It has been developed for the investigation of concrete structures, and it can determine the size and depth of these discontinuities. Waves are recorded, and the frequency spectrum is calculated. For each geometrical discontinuity, different waveforms and spectra are generated and dominant patterns (number and distribution of peaks in the spectra) can be recognized. Its main advance is that it does not need to couple the transducer with the surface but, on the other side, it is tedious in the sense that it requires many measurements without the possibility to determine the dimensions of defects filled with water. A robot to automatise the measurements is in development [74]. **Figure 12** shows the principle and the equipment required for the impact-echo technique.

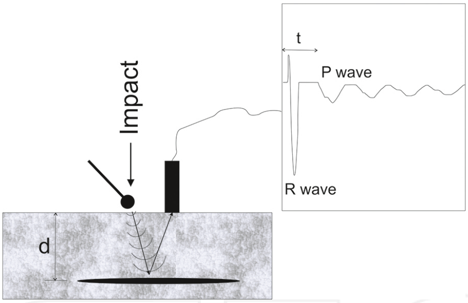


Figure 12. Impact-echo system.

Even if the impact-echo technique was originally designed for concrete, it has also been applied for the study of stone masonry [75] with good results. The required equipment includes a hammer or steel sphere, a wave receiver, amplifier and signal analysis facilities. If several measurements are done with increasing distances between impact and receiver [76], a mini-seismic method is developed, which can be interpreted as a classical seismic test.

4.2.4. Sonic or ultrasonic tomography

It consists in obtaining a 3D distribution of wave velocities in the interior of the studied object. In this case, a large number of measurements needs to be done with many different wave paths between emitter and receiver covering as much as possible the volume to be investigated

(Figure 11). Several transducers can be used but the number of points can also be increased by repeating the measurements at different locations. Both sonic and ultrasonic waves can be used. Signals are recorded, and time flight and amplitude are generally used in calculations. The tomographic technique can be used in 2D or 3D mode. To obtain good results, a precise knowledge of the geometrical and structural model is necessary. In a single block object, only the geometrical model is needed, but in multiple element objects, the inner structure and composition should be known. We can assimilate this tomography to the one applied in seismology because it uses the same inversion methods. The equipment consists of survey tools to precisely determine the position of the measure points, sonic or ultrasonic equipment and tomography software for inversion calculations.

One example of acoustic tomography in the sculpture of Leonora d'Aragone (Francesco Laurana) is presented in the study of Capizzi et al. [68]. This sculpture (22 cm x 40 cm x 43 cm) is carved from a unique block of microcrystalline marble and presents possible crack problems. High-resolution ultrasonic tomography was the most appropriate technique to monitor the structural continuity of a possible fracture and to investigate the internal marble conditions. A 3D ultrasonic tomography was obtained from 157 measurement points spaced from 2 to 5 cm (1832 raypaths). Extensive signal processing has been done before inversion. **Figure 13** shows some of the results obtained.

Figure 13. 3D ultrasonic travel time tomography on the Eleonora d'Aragona statue. Adapted from Cosentino et al. [4].

This technique gave also good results in a granitic megalithic of Axeitos (La Coruna, Spain) [77] where the heterogeneous structure in terms of conservation could be determined (**Figure 14**). Another example of a map of ultrasonic velocities as indicator of stone degradation level is found in the study of Fitzner [10] where the results for the Lion horoscope of the Nemrut Dag in Turkey are shown. Velocities go from 300 to 4500 m/s clearly showing the most degraded areas.

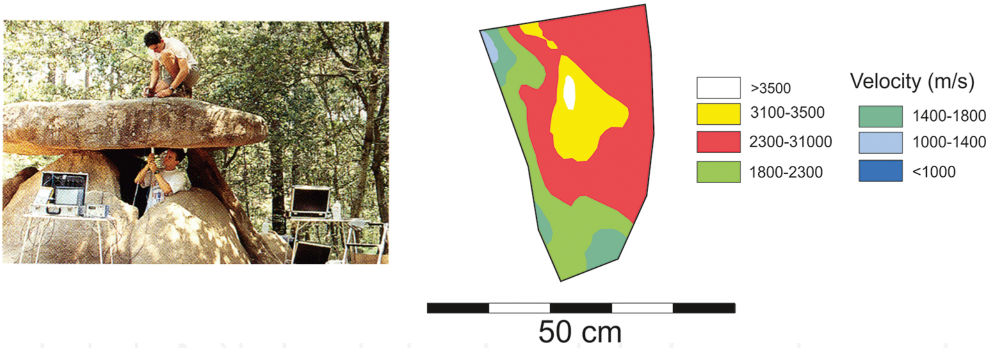


Figure 14. 3D ultrasonic tomography of the megalith d'Axeitos (Spain). Reproduced with the permission from Ebert et al. [77].

4.2.5. Monitoring using acoustic emission techniques

Acoustic emission (AE) is not an inspection technique but a monitoring one. When a crack is created or propagates, elastic energy is released through elastic wave propagation (similar to earthquakes). Recording signals generated by these waves is an indicator that cracking processes are active. The acoustic emission technique records continuously the elastic energy released during micro-crack generation, crack propagation or crystallization events. This elastic energy propagates in the sample as elastic waves, which can be detected and converted into electrical signal by piezoelectric acoustic emissions transducers. Several parameters are of interest like the number of recorded events (number of wave trends), and for each event the number of counts (number of times amplitude crosses a predefined threshold), the duration of each event, etc. In a continuous homogenous material, the recording of acoustic emissions by several transducers located at different positions can lead to the localization of the source of the acoustic emission, similarly to the localization of earthquakes. In buildings, it is quite difficult to localize the source of the events. High-frequency events propagate in masonry with greater attenuation. Based on experimental results, some authors [78] found that for a distance of 10 m in a tower of complex masonry structure, acoustic emission only with frequency components lower than 100 kHz are detectable.

This technique is currently used in rock mechanics but only few examples can be found of its application to cultural heritage. Two examples in the study of salt crystallization in the laboratory are presented in the works of Grossi et al. [79] and Menéndez and David [80] Grossi et al. [79] registered acoustic emissions during classical crystallization tests with sodium sulphate; and Menéndez and David [80] registered AE during non-classical crystallization tests with gypsum. An example of the use of acoustic emission techniques to monitor the crack growth in three medieval towers in Alba (Italy) can be found in the study of Anzani et al. [81]. They used the number of counts as an indicator of the energy released. They monitored two towers during around 1500 hours and another during 3500 hours. During this time, several seismic events took place and they were reflected in a peak of acoustic emission signal. A continuous background of acoustic emissions has also been registered indicating a permanent crack growth. A masonry building (Casa Capello, Rivoli, Italy) has been monitored to evaluate the status of cracks that spread out after the collapse of a breast wall [82]. An 800-hour campaign showed that acoustic emission activity corresponds to highest velocity of crack advancement. The crack growth and the associated acoustic emission are shown in **Figure 15**, based on the study of Carpinteri and Lacidogna [82].

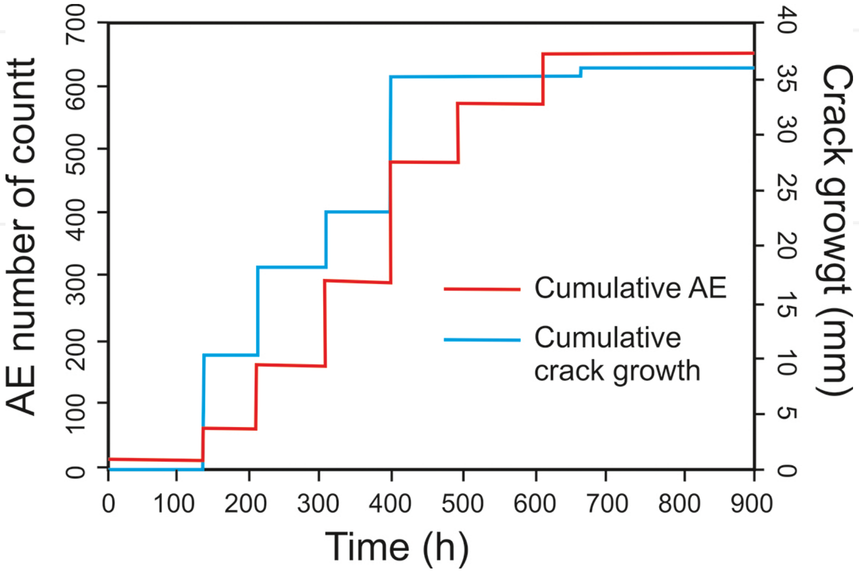


Figure 15. Cumulative crack growth and associated acoustic emission activity in Casa Capello (Rivoli, Italy). Adapted from Carpinteri and Lacidogna [82].

Another example can be found in the study of Suarez del Rio et al [83], where the acoustic emission close to several cracks of the Cathedral of Palma de Mallorca (Spain) has been monitored. They also measured displacements in those cracks. They conclude that the origin of cracks in this building is mainly due to thermal expansion more than mechanical problems because AE activity was much higher during day time than at night, was more important in the external part than in the internal one of the cathedral and also because displacements measured in the South façade were more important than in the Nord one.

4.3. Electromagnetic techniques

4.3.1. Electrical methods

This method consists in injecting an electrical current between two electrodes on the material and measuring the resulting voltage difference on another couple of electrodes (**Figure 16**). By changing the distance between electrodes, electric profiles are obtained. The electrical current can be direct or alternating. The goal is to obtain the resistivity distribution of the interior of the material. The resistivity of materials depends on the mineralogy, fluid content, porosity and water saturation degree [8].

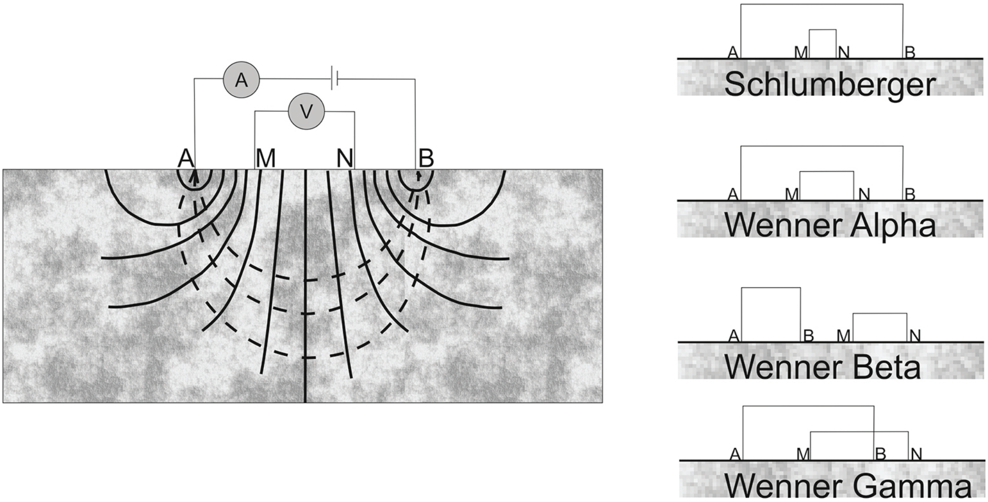


Figure 16. Principle of the electrical method (left) and different electrode arrays (right).

4.3.1.1. *Methods using injected current*

The electrodes can be spatially distributed in different ways. There are different types of spatial electrodes array: if all the electrodes are aligned, several arrays are possible such as Schlumberger, Wenner (alpha, beta or gamma), Lee and dipole; if they are not aligned, square or rectangular arrays can be used [84]. A 2D and 3D resistivity distribution can be obtained by changing the distance between electrodes. Two-dimensional parallel profiles in one or two direction can allow obtaining 3D representation of the material [8]. In the electrical resistivity tomography, the potential field distribution within an irregular shaped object is difficult to model [68].

Numerous 2D and 3D electrical tomographic surveys carried out on walls, columns and floors using direct electric current are shown in the study of Cosentino et al. [85]. The data were interpreted by back-projection inversion software or by 2D and 3D complete inversion procedure. They used a 256-channel instrument but there are instruments with larger number of channels. A problem was the choice of the electrodes; small electrodes with similar contact resistance are required. They used disposable electrocardiogram electrodes with external adhesive strip. An example of their results is shown in **Figure 17** for an ancient wall (~1.5 m thick) covered by a mosaic in the Fountain Room of Zisa Palace in Palermo. This mosaic presented some moisture problems. The 3D inversion in a 2 m×3 m area permitted to locate a water leakage area at 70–80 cm inside the wall, which was related to an unknown pipe collecting water from the roof.

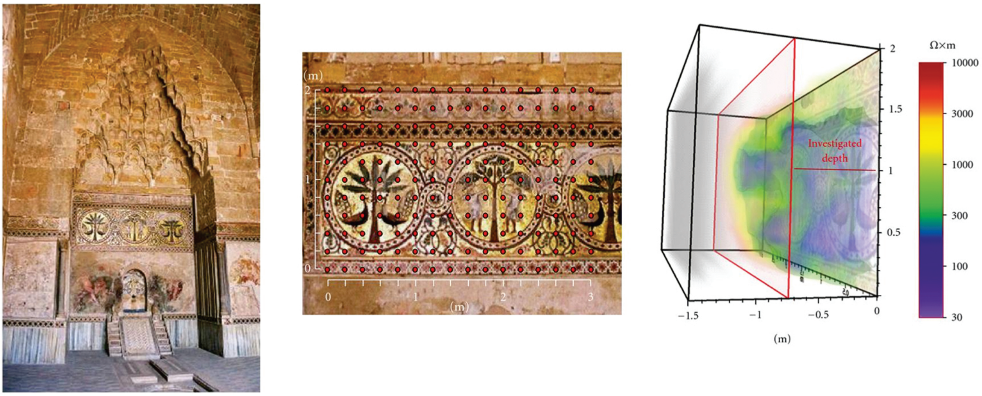


Figure 17. Frontal wall of the Fountain Room of the Arabian Zisa Palace in Palermo (left); position of the 176 potential electrodes (centre) and 3D inversion model of the acquired data (right). Adapted from Cosentino et al. [4].

Martinho et al. [86] combined resistivity tomography data with soluble salt analysis in three stone bas-reliefs located in the ground floor of the cloister of the Santa Cruz Monastery in Coimbra (Portugal). The results indicate that lower resistivity values are located in the areas of lower salt concentration. Moisture and salt distribution pointed to more than one source of moisture. The lower resistivity values correspond to severe decay areas. Electric resistivity tomography made possible to estimate the thickness of the panels.

Alternating current has been used in the study of Biernat et al. [87] to identify damp distribution in a wall. They used several current and voltage electrodes and independent power sources to find conductivity distribution by inversion of the data (electric impedance tomography). They concluded that this method can be of great importance in controlling the quality of damp proofing solutions.

4.3.1.2. Self-potential method

In this method, no current is injected, only the natural potential difference is measured. Differences in electrical potential can be due to electrofiltration, thermoelectrical, electrochemical or mineralization potentials [8]. Self-potential signals in cultural heritage material can be related to redox reactions and interstitial humidity within stones and mortars [88]. This method can be used, mainly, for determination of moisture content. Self-potential tomography is useful for practical application on flat surfaces [88]. Martinho et al. [89] combined this technique with classical studies (macroscopic stone description, qualitative visual assessment of stone deterioration, quantification of salts, etc), seismic refraction method and infrared thermography on a Gothic tomb located in the Igreja da Graca church (Santarem, Portugal). They found a direct linear relationship between self-potential and temperature.

4.3.2. Ground penetrating radar

This technique is similar to the acoustic technique but with another kind of waves. This technique is also an adaptation of a geophysical on site technique. In this case, electromagnetic pulses (frequency 500–2500 MHz) are injected into the material by an antenna (**Figure 18**). The most common experimental setup is the reflection mode with the antenna moving in one direction on the surface and the receiving antenna moving at the same time as the transmitter. Both antennas are usually placed on the same device. In transmission mode, the receiver is placed on an opposite surface of the objet. This method is less common and generally is only used to measure the signal velocity for calibration of the test.

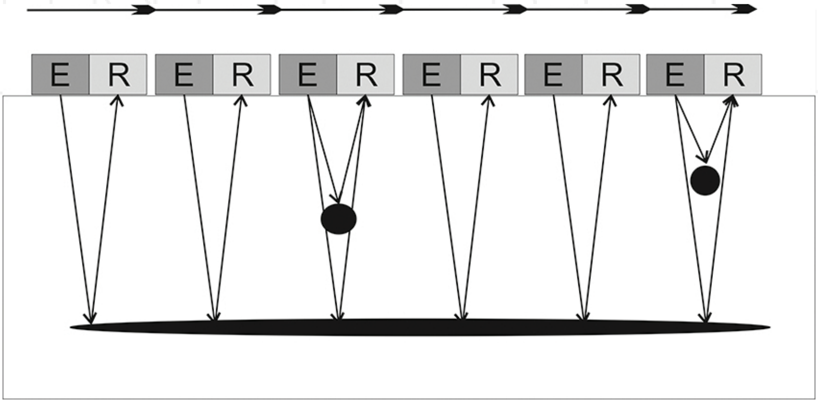


Figure 18. Principle of ground penetrating radar (GPR).

The propagation of the radar signal depends on the conditions and dielectric properties of the materials. For example, for geologic profiling at depths between 0 and 30 m, the antenna can have a frequency of about 100 MHz; in archaeology, with depths between 0 and 10 m, antennas of frequency 200–300 MHz can be used and for shallower objects to be detected, frequencies of 1000–2500 MHz can be employed. Penetration depth decreases with the frequency of the signal but the spatial resolution of the method increases with frequency.

The measured parameters are the signal velocity and the attenuation. The signal is reflected by an interface separating two media with different dielectric constants and the travel time corresponds to a distance twice the depth of the interface. As in acoustic methods, the choice of the antenna depends on the material and on the size and location of the defects.

This technique gives good results in detecting and locating fractures and discontinuities into the materials but does not allow estimating the mechanical parameters. Furthermore, it is difficult to apply in small objects or irregular sculpted surfaces [68]. In **Figure 19**, we can observe the reconstruction of the layers along the cross section of Monte di Pieta (Naples, Italy) façade [90].

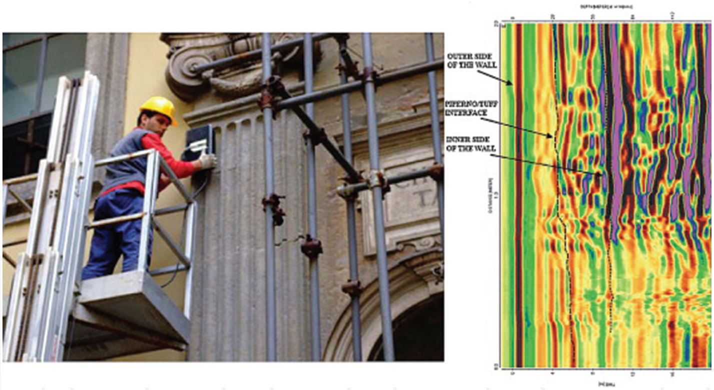


Figure 19. GPR applied to Monte de Pieta (Naples, Italy): pilasters and radar section with the construction layers[90].

Ground penetrating radar (GPR) has been used for a structural evaluation of several ancient stone masonry arch bridges in the NW of Spain still in use [91]. They realized two parallel profiles through the bridges at 1 m distance between them. The final goal was to elaborate finite difference time domain models of the bridges. They could detect ancient restorations, reconstruction of arches or all along the pathway; differences in building materials in the same stonework; presence of possible hidden arches or different historical shape of the structure; identification of reinforcement solid piers; thickness of the stone ring and nature of foundations.

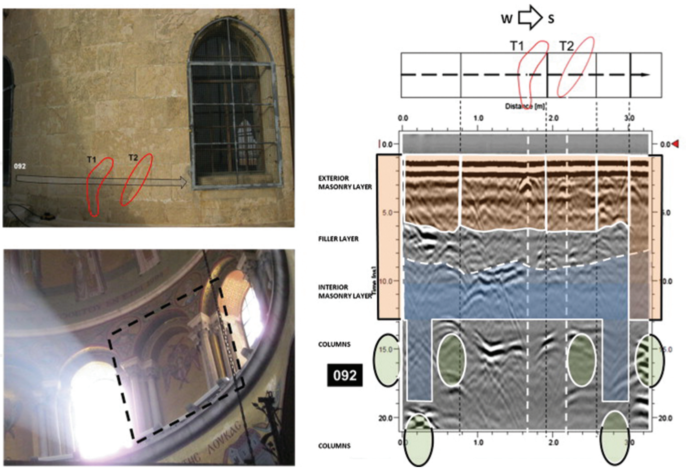


Figure 20. Upper left: External view of the southwest masonry of the Dome of the Catholic, Church of the Holy Sepulchre: position of the GPR scan and cracks T1 and T2. Lower left: Interior view of the back side of the examined area. Right: GPR scan with the interpretation of the interior structure [5].

In **Figure 20**, we can observe a typical result obtained by processing data for a GPR survey [5]. The profile corresponds to the exterior masonry of the Dome of the Catholic part in the Church of the Holy Sepulchre. Two cracks were observed in the exterior and in the GPR data and we can observe how they penetrate the complete thickness of the ashlars. The position of the filler layer between the external and internal ashlars can be determined.

4.3.2.1. Application: GPR 3D reconstruction

It consists in obtaining a 3D volume of the radar data by acquiring a dense subset of parallel 2D radar profiles [92]. The position of traces and distance between them should be accurately obtained in order to produce good 3D reconstructions. The shorter the distance between traces the more precise the 3D reconstruction. The volume rendering can be done by special softwares. Orlando and Slob [93] applied this technique to monitor cracks in a building with structural problems probably induced by movements of terrain. They used a GPR with 2 GHz bipolar antennas, with dipoles placed in a rectangular arrangement and doing four profiles at the same time: between parallel x-direction antennas, between parallel y-direction antennas, perpendicular with x direct source and y receiver and with y antenna as direct and x as receiver. Several 10 m profiles were done with spacing 0.1 m, four times a year to follow the crack evolution on a floor. They did not find any significant difference between the different periods of observation and conclude that this method is partially suitable for direct crack detection.

4.3.2.2. Application: Radar tomography

As in acoustic tomography, GPR tomography is generally used to map the interior of objects that can be accessed from at least two sides [92]. Tomography uses the direct transmission method. Transmitter and receiver antennas are separated and located successively in various positions to entirely cover the area under investigation. For every measurement, the velocity is calculated, and an inversion method applied to reconstruct the internal structure. An application of this technique to the study of piers in the cathedral of Noto (Portugal) can be seen in the study of Binda et al. [94]. Antennas were placed at different heights of the pier, one every 10 cm (46 acquisitions, 4.6 m) at each height a single signal was recorded, holding the transmitter and moving the receiver in all the positions at the opposite sides of the pier. Examples of application of radar tomography to study of internal structure of lapideous balcony corbels and the juxtaposition of patinas on urban environments are shown in the work of Cosentino et al. [85].

5. Combination of several NDT

A unique NDT technique cannot give all the necessary information to understand the conservation problem of the building. Information is needed about the nature of the materials, their properties, the 3D structure of the building and the evolution of all these characteristics with time. A combination of several techniques is always employed, sometimes only “simple” techniques are enough to cover the goals of the study but sometimes these simple techniques should be combined with one or more complex techniques. For example, before doing acoustic tomography, GPR will be very helpful to have a first approach of the internal structure and allows the construction of the geometrical model to carry out the numerical inversion. Acquisition methods should be referred to the same geometric system to correlate the information provided by the different methods [15].

Many examples can be found in the literature showing the interest of combining information coming from different non-destructive techniques. Solla et al. [15] used photogrammetry, thermography and GPR to study the Lubian bridge (Galicia Spain). This bridge has a very complicated history from the XV century with different reconstructions, rebuilt and restoration campaigns using different materials: original masonry (granite ashlar), granite masonry with clay mortars, cement, pavement of granite flagstones and cement. Photogrammetry allows one to do a detailed 3D reconstruction of the bridge; thermographic contributes to the identification of different materials and GPR is used to establish the internal structure of the bridge with the different areas of original and restoration/reconstruction parts.

A combination of GPR and acoustic techniques has been used to study the structure and the conservation degree of a column proceeding from the Hospital of Saint Pau I la Santa Creu in Barcelona (Spain) [95]. The column has been moved to the laboratory for investigation. They performed series of GPR vertical and horizontal profiles with spacing 5 and 3 cm, respectively, vertical profiles height was 110 cm. Acoustic tomography has been performed using 13 sensors placed around the column and with a hammer as vibration source. After these non-destructive tests, mechanical compression test has been done and the interior of the column could be observed after breakage. GPR vertical and radial profiles give different and complementary information about the internal array of bricks, presence or not of reinforcement elements but differentiating between voids or cracks and changes in material is difficult just with GPR data. Seismic data inform about the presence of damaged areas. In this example, NDT techniques show the presence of a metallic pipe in the interior of the column, the pipe was corroded in some areas, which could be related to the most damaged zones.

Kilic [58] applied a combination of GPR and thermal survey to the study of Urla primary school (Turkey), an Ottoman structure of XVI century. The results show how an integrated approach using a combination of NDT methods can detect defects affecting the structural condition, both visible and hidden, of historical buildings. This is especially interesting in cases of lack of written documentation on the original construction (position of pipes, internal structure and so on).

In the Non-Destructive Testing in Civil Engineering (NDTCE'09) conference, a very large set of different examples of application of NDT and minor destructive techniques in different sites in Italy has been presented by Binda and Saisi [7]. These examples concern the survey of structural damage associated with cracks, the detection of multiple leaf walls or detachments, presence of voids or inclusions, determination of the masonry "quality" and moisture detection. Each example presented has different problems and the employed techniques vary to solve them. In each example, a combination of two or more techniques is employed: cartography of materials and cracks, georadar, sonic or ultrasonic tests, thermography, single or double flat jacks and power drilling method (partially destructive). As a general conclusion, the authors stated that the use of NDT in the diagnostic of historic buildings is not an easy task, the problem to be solved and the appropriate techniques should be well known.

Bergamo et al. [96] presents an application of several NDT and minor destructive techniques to the study of arch bridged in use in Italy. They concluded that georadar is useful to investigate this type of structures; vibrational analysis, flat-jack and penetration tests are useful to investigate the causes of damage and to calibrate the finite element models of the bridges. They found that thermography is the most reliable technique to detect moisture, discontinuities and the presence of different building materials.

The choice of the techniques will depend on the historical interest of the object, the actual danger and the financial possibilities. A table with the different NDT techniques used in cultural heritage is presented in the study of McCann and Forde [97], with for each technique the measured parameter(s), the advantage and disadvantage and the relative cost. This table can be a useful tool for a first approach to select the methods that can be applied for a particular building.

In the study of Meneely et al. [98], a toolkit to monitor historical buildings in order to know their evolution with time and with the change of environmental condition (climatic change and atmospheric pollution) is presented. This kit is based on an initial 3D laser approach to spatially map data collected from other techniques. They proposed to use/measure (i) high quality digital photography (ii) colorimeter, (c) permeability, (iv) ground penetrating radar, (v) thermography, (vi) X-ray fluorescence to analyse the surface chemistry and others. All this information can be stored in a Geographical Information System to obtain spatial distribution of different parameters and the relationships between them. The frequency of the survey depends not only on financial and logistical constraints but also on the rate of change of the site.

6. Conclusions

Many different "in situ" non-destructive techniques are available for the study of built cultural heritage. Some of them are very old techniques of almost a century ago, whereas others are based on the most recent technology and are still in development. As an example of a technique under development, we can cite a system using microwaves to measure water and salt contents on frescoes and mural paintings based on the relationships between these parameters and the dielectric properties of the materials [99].

NDT techniques are of especial interest to construct analytical or numerical models of buildings. Carino [73] constructed a finite element model of the main façade of the Mote di Pieta de Naples (Italy) that could simulate the construction and its historical phases in order to justify the existing major damages and to estimate the current state of stress. In the construction of the model, they used data from 3D laser scanning, GPR and flat-jack techniques.

As a general conclusion, we can say that every study on built cultural heritage used a combination of NDT. The number and the complexity of this technique depend on the interest of the building, its conservation degree, the goal of the study and the available budget. Different NDT techniques are complementary, and the combination of data provided by each technique is crucial to understand the past behaviour or the building and to predict the future one as a function of new conditions affecting the building (mechanical, climatic and so on). Most of the time, NDT are the only way to have "access" to the inner part of the building. Great progress has been done in this field in the last decades, and the research is still very active.

Acknowledgements

I like to thank Christian David for his thorough reading and clever suggestions about the organization and the writing of this chapter.

Author details

Beatriz Menéndez

Address all correspondence to: beatriz.menendez@u-cergy.fr

Geosciences and Environment Cergy (GEC), University of Cergy-Pontoise, Cergy-Pontoise, France

References

[1] Fitzner B. Damage diagnosis on stone monuments – in situ investigation and laboratory studies. In: Proceeding of International Symposium of the Conservation of the Bangudae Petroglyph, Ulsan City/Korea, 15 July 2002. Ulsan City Korea: Stone Conservation Laboratory, Seoul National University, 29–71.

[2] Fitzner B. Documentation and evaluation of stone damage on monuments. In: Proceedings of the 10th International Congress on Deterioration and Conservation of Stone, 27 June–2 July 2004. Stockholm, Sweden, 667–690.

[3] Svahn H. Non-Destructive Field Tests in Stone Conservation: Final Report for the Research and Development Project: Literature Study. 2006. Riksantikvarieämbetet. Stockholm, 63 p.

[4] Cosentino OL, Capizzi P, Martorana R, Messina P, Schiavone S. From geophysics to microgeophysics for engineering and cultural heritage. International Journal of Geophysics. 2011; 2011: 8, ID: 428412. DOI: 10.1155/2011/428412

[5] Moropoulou A, Labropoulos KC, Delegou ET, Karoglou M, Bakolas A. Non-destructive techniques as a tool for the protection of built cultural heritage. Construction and Building Materials. 2013; 48: 1222-1239. DOI: 10.1016/j.conbuildmat.2013.03.044

[6] Bosiljkov V, Uranjek M, Zarnic R, Bokan-Dosihkov V. An integrated diagnostic approach for the assessment of historic masonry structures. Journal of Cultural Heritage. 2010; 11: 239-240. DOI: 10.1016/j.culher.2009.11.007

[7] Binda L, Saisi A. Application of NDT to the diagnosis of historic structures. In: Proceedings of the Non-Destructive Testing in Civil Engineering NDTCE'09, Non-Destructive Testing in civil Engineering Conference, June 30–July 3 2009. Nantes, 27 p.

[8] Martinho E, Dionisio A. Main geophysical techniques used for non-destructive evaluation in cultural built heritage: a review. Journal of Geophysics and Engineering. 2014; 11: 1-15. DOI: 10.1088/1742-2132/11/5/053001

[9] Esbert RM, Marcos RM. Las piedras de la Catedral de Oviedo y su deterioración. Colegio Oficial de Aparejadores y Arquitectos Técnicos del Principado de Asturias, 1983. Oviedo, 147 p.

[10] Fitzner B. Diagnosis of weathering damage on stone monuments. Macla.2014; 18: 21:28. 18: 21-28.

[11] Fitzner B, Heinrichs K. Damage diagnosis on stone monuments – weathering forms, damage categories and damage index. In: Prikryl R, Viles HA Ed., Abstracts of the International Conference "Stone Weathering and Atmospheric Pollution Network (SWAPNET)", 7–11 May 2001. Prachov Rocks (Czech Republic).

[12] ICOMOS-ISCS. Vergès-Belmin Ed. Illustrated glossary on stone deterioration patterns. 2008. ISBN: 978-2-918086-00-0. Champigny sur Marne, France

[13] Photogrammetry. http://culturalheritageimaging.org/Technologies/Photogrammetry/

[14] Yastikli N. Documentation of cultural heritage using digital photogrammetry and laser scanning. Journal of Cultural Heritage. 2007; 8: 423-427. DOI: 10.1016/j.culher.2007.06.003

[15] Solla M, Asorey-Cacheda R, Nuñez-Nieto X, Conde-Carnero B. Evaluation of historical bridges through recreation of GPR models with the FDTD algorithm. NDT&E international. 2016; 77: 19-27. DOI: 10.1016/j.ndteint.2015.09.003

[16] Arias P, Armesto J, Ordonez C, Lorenzo H, Caparrini H. Damage quantification and monitoring in masonry monuments through digital photogrammetry. Key Engineering Materials. 2007; 347: 291-296. DOI: 10.4028/www.scientific.net/KEM.347.291

[17] Heinrichs K, Azzam R. Investigation of salt weathering on stone monuments – the 'petraSalt'research project. Proceedings of the 19th Conference on Engineering Geology and of the Forum for young Engineering Geologists, 13–15 March 2013, Munich: Kurosch Thuro.

[18] Vazquez MA, Galan E, Guerrero MA, Ortiz P. Digital image processing of weathered Stone caused by efflorescences: a tool for mapping and evaluation of stone decay. Construction and Building Materials. 2011; 25: 1603-1611. DOI: 10.1016/j.conbuildmat.2010.10.003

[19] Crespo C, Aemesto J, Gonzalez-Aguilera D, Arias P. Damage detection on historical buildings using unsupervised classification techniques. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. 2010; 38(5): 184-188.

[20] Meroño JE, Perea AJ, Aguilera MJ, Laguna AM. Recognition of materials and damage on historical buildings using digital image classification. South African Journal of Science. 2015; 111(1/2): 68-76. DOI: 10.17159/sajs.2015/20140001

[21] RILEM. Recommendation MDT. D. 4: In-situ stress tests based on the flat jack. Materials and Structures. 2004; 37: 491-496. DOI: 10.1617/14119

[22] RILEM. Test method recommendations of RILEM TC 177-MDT 'Masonry durability and on-site testing' - D.5: In-situ stress - strain behaviour tests based on the flat jack. Materials and Structures. 2004; 37: 497-501. DOI: 10.1617/14120

[23] Simoes A, Gago A, Lopes M, Bento R. Characterization of old masonry wall: flat-jack method. Proceedings of the 15th World Conference on Earthquake Engineering, 24–28 September, 2012. Lisbon, Portugal, 10 p.

[24] Bartoli G, Betti M, Giordano S. In situ and dynamic investigations of the "Torre Grossa" masonry tower. Engineering Structures 2013; 52: 718-733. DOI: 10.1016/j.engstruct.2013.01.030

[25] Binda L, Saisi A, Tiraboschi C. Investigation procedures for the diagnostic of historic masonries. Construction and Building Materials. 2000; 14: 199-233. DOI: 10.1016/S0950-0618(00)00018-0

[26] Fenn DB, Rutenbeck T, Knab LI, Clifton JR, Nistal-Moret BBG. Structural monitoring of Castillo de San Marcos national monument. Program report of Old Cultures in New Worlds, 8th ICOMOS General Assembly and International Symposium, 1987. Washington, 400-407.

[27] Rossi PP, Rossi C. Surveillance and monitoring of ancient structures: recent developments. In: Structural Analysis of Historical Constructions II. Possibilities of Numerical and Experimental Techniques - Proceedings of the IVth International Seminar on Structural Analysis of Historical Constructions, 10–13 November 2004. Padova, Italy: Taylor & Francis, Technology & Engineering, 1466.

[28] Dovrev N, Avramova-Tacheva E, Kostack B. Monitoring of the cracks affecting the "Madara Horseman" rock bas-relief, North-East Bulgaria. In: St Ivan Rilski, Kostov RI, Gaydarska B, Gurova M Eds., Geoarcheology and Archeomineralogy. Proceedings of the International Conference, 29–30 October 2008. Sofia: Publishing House, 385-390.

[29] Glisic B, Posenato D, Casanova N, Inaudi D, Figini A. Monitoring of heritage structures and historical monuments using long-gage fiber optic interferometric sensor – an overview. In: Baidar Bakht and Aftab Mufi Ed. Proceeding of the 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure, 1–16 November 2007. Vancouver.

[30] Inaudi D, Casanova N, Glisic B. Long-term deformation monitoring of historical constructions with fiber optic sensors. In: Lorenço PB, Roca P, Eds., Historical Constructions 2001. Guimaraes.

[31] Inaudi D. SOFO sensors for static and dynamic measurements. Proceedings of the 1st FIG International Symposium of Engineering Survey for Constructions and Structural Engineering. 28 June–1 July 2004, Nottingham, United Kingdom. 10 p.

[32] Charola AE. Salts in the deterioration of porous materials: an overview. Journal of the American Institute for Conservation. 2000; 39: 327-343. DOI: 10.1179/019713600806113176

[33] Menezes A, Gloria Gomes M, Flores-Colen I. In-situ assessment of physical performance and degradation analysis of rendering walls. Construction and Building Materials. 2015; 75: 283-292. DOI:10.1016/j.conbuildmat.2014.11.039

[34] Hendrickx R. Using the Karsten tube to estimate water transport parameters of porous buildings materials. Materials and Structures. 2013; 46: 1309-1320. DOI: 10.1617/s11527-012-9975-2

[35] Vandevoorde D, Cnudde V, Dewanckele J, Boone M. Comparison of non-destructive techniques for analysis of water absorbing behavior of stone. In: Proceeding of the 12th International Congress on the Deterioration and Conservation of Stone; 22–26 October 2012; New York. 10 p.

[36] Vandevoorde D, Cnudde V, Dewanchele J, Brabant L, de Bouw M, Meynen V, Verhaeven E. Validation of in situ applicable measuring techniques for analysis of the water absorption by stone. Procedia Chemistry. 2013; 8: 317-327. DOI: 10.1016/j.proche.2013.03.039

[37] Bläuer C, Frazen C, Vergès-Belmin V. Simple tests in stone conservation. In: 12th International Congress on the Deterioration and Conservation of Stone, 22–26 October 2012. 8 p.

[38] Drdácký M, Černý M, Slížková Z, Zíma P. Microtube device for innovative water uptake measurements. In: Krüger M, Ed., Proceedings of the European Workshop on Cultural Heritage Preservation, Berlin 26–28 September 2011. Fraunhofer IRB Verlag: Stuttgart, 126-130. ISBN: 978-3-8167-8560-6

[39] Drdácký M, Hasníková H, Lesák J, Zíma P. Innovated water uptake measurements on historic stone surfaces. In: Proceeding of the 12th International Congress on the Deterioration and Conservation of Stone, 22–26 October 2012. New York, 10 p.

[40] Brown S, Smith L. A transient-flow syringe air permeameter. Geophysics. 2013; 78 (5): D307-D313. DOI: 10.1190/geo2012-0534.1

[41] Menéndez B, Lopez-Arce P, Mertz JD, Tagnit-Hamou M, Aggoun S, Kaci A, Guiavarch M, Cousture A. Stone-mortar interaction of similar weathered stone repair mortars used in historic building. Accepted In: Proceedings 13th International Congress on the Deterioration and Conservation of Stone, 6–10 September 2016. Glasgow.

[42] Filomena CM, Hornung J, Stollhofen H. Assessing accuracy of gas-driven permeability measurements: a comparative study of diverse Hassler-cell and probe permeameter devices. Solid Earth. 2014; 5 (1): 1–11. DOI: 10.5194/se-5-1-2014

[43] Sena da Fonseca B, Castela AS, Duarte RG, Neves R, Montemor MF. Non-destructive and on site method to assess the air-permeability in dimension stones and its relationship with other transport-related properties. Materials and Structures. 2015; 48: 3795-3809. DOI: 10.1617/s11527-014-0440-2

[44] Duarte R, Flores-Colen I, de Brito J. In situ testing techniques for evaluation of water penetration in rendered facades - the portable moisture meter and Karsten tube. In: Proceedings of the XII International Conference on Durability of Building Material and Components, 12–15 April 2011. Porto, 8 p.

[45] Meinhardt J, Snethlage R, Auras M. Natural stone monitoring – Investigation methods for a reliable evaluation of the effectiveness of conservation measures. In: 12th International Congress on the Deterioration and Conservation of Stone, 22–26 October 2012. 14 p.

[46] Drdacky L, Lesak J, Rescic S, Slızkova Z, Tiano P, Valach J. Standardization of peeling tests for assessing the cohesion and consolidation characteristics of historic stone surfaces. Materials and Structures. 2012; 45:505–520. DOI: 10.1617/s11527-011-9778-x

[47] Alvarez de Buergo M, Vazquez-Calvo C, Fort R. The measurement of surface roughness to determine the suitability of different methods for stone cleaning. Geophysical Research Abstracts Vol. 13, EGU2011-6443 EGU General Assembly, 2011.

[48] Dabski M. Rock surface micro-roughness, Schmidt hammer rebound and weathering rind thickness within LIA Skálafellsjökull foreland, SE Iceland. Polish Polar Research. 2014; 35(1): 99–114, 2014 DOI: 10.2478/popore−2014−0008

[49] Gomez-Heras M, Smith BJ, Viles HA, Meneely J, McCabe S. HD Laser scanning for the evaluation of salt decay laboratory simulations of building limestone. In: Proceedings of the Salt Weathering on Buildings and Stone Sculptures Conference, 22–24 October 2008. Copenhagen, 149-158.

[50] Viles J, Goudi A, Grab S, Lalley J. The use of the Schmidt Hammer and Equotip for rock hardness assessment in geomorphology and heritage science: a comparative analysis. Earth Surface Processes and Landforms. 2011; 36: 320-333. DOI: 10.1002/esp.2040

[51] Christaras B. Non destructive methods for investigation of some mechanical properties of natural stones in the protection of monuments. Bulletin of the International Association of Engineering Geology. 1996; 54: 59-63.

[52] Aydin A, Basu A. The Schmidt hammer in rock material characterization. Engineering Geology. 2005; 81: 1–14. DOI: 10.1016/j.enggeo.2005.06.006

[53] Torok A. Surface strength and mineralogy of weathering rusts on limestone buildings in Budapest. Building and Environment. 2003; 38: 1185-1192. DOI: 10.1016/S03360-1323(03)00072-6

[54] Coombes MA, Feal-Perez A, Naylor LA, Wilhem K. A non-destructive tool for detecting changes in the hardness of engineering materials: application of the Equotip durometer in the coastal zone. Engineering Geology. 2013; 167: 14-19. DOI: 10.16/j.enggeo.2013.10.003

[55] Grossi C, Esbert RM, Diaz-Pache F, Alonso FJ. Soiling of building stone in urban environment. Building and Environment. 2003; 38: 147-159.

[56] Torok A. In situ methods of testing stone monuments and the application of nondestructive physical properties testing in masonry diagnosis. In Materials, Technologies and Practice in Historic Heritage Structures, 2010. Netherlands: Springer. DOI: 10.1007/978-90-481-2684-2_10

[57] de Freitas S, de Freitas VP, Barreira E. Detection of façade plater detachments using infrared thermography – A nondestructive technique. Construction and Building Materials. 2014; 70: 80-87. DOI:10.1016/j.conbuildmat.2014.07.094

[58] Kilic G. Using advanced NDT for historic buildings: Towards an integrated multidisciplinary health assessment strategy. Journal of Cultural Heritage. 2015; 16: 526-535. DOI: 10.1016/j.culher.2014.09.010

[59] Paoletti D, Ambrosini D, Sfarra S, Bisegna F. Preventive thermographic diagnosis of buildings for consolidation. Journal of Cultural Heritage. 2013; 14: 116-121. DOI: 10.1016/j.culher.2012.05.005

[60] Hess M, Vanoni D, Petrovic V, Kuester F. High-resolution thermal images methodology for non-destructive evaluation of historic structures. Infrared Physics & Technology. 2015; 73: 219-225. DOI: 10.1016/j.infrared.2015.09.020

[61] Jo YH, Lee CH. Quantitative modeling and mapping of blistering zone of the Magoksa Temple stone pagoda (13th century, Republic of Korea) by graduated heating thermography. Infrared Physics & Technology. 2014; 65: 43-50. DOI: 10.1016/j.infrared.2014.02.011

[62] Kordatos EZ, Exarchos DA, Stavrakos C, Moropoulou A, Matikas TE. Infrared thermographic inspection of murals and characterization of degradation in historic monuments. Construction and Building Materials. 2013; 48: 1261-1254. DOI: 10.1016/j.conbuildmat.2012.06.062

[63] Sklodowski R, Drdacky M, Sklodowski M. Identifying subsurface detachment defects by acoustic tracing. NDT&E International. 2013; 56: 56-64. DOI: 10.1016/j.ndteint.2013.02.002

[64] Drdacky M, Lesac J. Non-invasive survey of detachment of historic rendering. In: FortR, Alvarez de BuergoM, Gomez-HerasM, Vazquez-CalvoC, Eds. Heritage, Weathering and Conservation, 2006. London: Taylor & Francis Group, 591-597.

[65] Del Vescovo D, Fregolent A. Assessment of fresco detachments through a non-invasive acoustic method. Journal of Sound and Vibration. 2005; 284: 1015-1031.

[66] Collini L, Garziera R. A contact-less diagnosis system for frescoes. Part 2: acoustic excitation-acoustic response. NDT&E International. 2013; 56: 76-81. DOI: 10.1016/j.ndteint.2013.02.006

[67] Castellini P, Esposito E, Legoux V, Paone N, Stefanaggi M, Tomasini EP. On field validation of non-invasive laser scanning vibrometer measurement of damaged frescoes: experiments on large walls artificially aged. Journal of Cultural Heritage. 2000; 1 (Supplement 1): S349-S356. DOI: 10.1016/S1296-2074(00)00145-X

[68] Capizzi P, Cosentino PL, Schiavone S. Some tests of 3D ultrasonic travel time tomography on the Eleonora d'Aragona statue (F. Laurana, 1468). Journal of Applied Geophysics. 2013; 91: 14-20. DOI: 10.1016/j.jappgeo.2013.01.012

[69] Fort R, Alvarezde Buergo M, Perez-Monserrat EM. Non-destructive testing for the assessment of granite decay heritage structures compared to quarry stone. International Journal of Rock Mechanics & Mining Sciences. 2013; 61: 296–305. DOI: 10.1016/j.ijrmms.2012.12.048

[70] Bromblet P, Vergès-Belmin V, Simon S. Ultrasonic velocity measurements for the long-term monitoring of the degradation of marble columns in the cloister of the church Sait-Trophine in Arles (France). In: 12th International Congress on the Deterioration and Conservation of Stone, 22–26 October 2012, 11 p.

[71] Pamplona M, Simon S. Long-term condition survey by ultrasonic velocity testing of outdoor marble sculptures. In: 12th International Congress on the Deterioration and Conservation of Stone; 22–26 October 2012, 11 p.

[72] Sklodowski M. Application of ultrasonic edge probes to on-site testing of mechanical properties of historical materials. In Tiano P, Pardini C, Eds., Proceedings of the International Workshop – SMW08 In situ Monitoring of Monumental Surfaces, 27–29 October 2008. Florence, Italy: Edifir, 177-186. ISBN: 978-88-7970-390-1

[73] Carino NJ. The impact-echo method; an overview. In Chang PC, Ed. Proceedings of the 2001 Structures Congress & Exposition, Washington, D.C., 21–23 May 2001, 2001. Reston: American Society of Civil Engineers, 18 p.

[74] Hola J, Schabowicz K. State-of-the-art non-destructive methods for diagnosis testing of building structures – anticipated development trends. Archives of Civil and Mechanical Engineering. 2010; 10(3): 5-18. DOI: 10.1016/S1644-9665(12)60133-2

[75] Sadri A. Application of impact-echo technique in diagnoses and repair of stone masonry structures. NDT&E International. 2003; 36: 195–202. DOI: 10.1016/S0963-8695(02)00064-6

[76] Miranda LF, Rio J; Miranda Guedes J, Costa A. Sonic impact method – a new technique for characterization of stone masonry walls. Construction and Building Materials. 2012; 36: 27–35. DOI: 10.1016/j.conbuildmat.2012.04.018

[77] Ebert RM, Ordaz J, Alonso FJ, Montoto M. Manual de diagnostico y tratamiento de materiales pétreos y cerámicos, 1997. Col legi d'aparelladors i Arquitectes Tècnics de Barcelona: Barcelona.

[78] Carpinteri A, Lacidogna G. Damage evaluation of three masonry towers by acoustic emission. Engineering Structures. 2007; 29: 1569-1579. DOI: 10.1016/j.engstruc.2006.08.008

[79] Grossi CM, Esbert RM, Suarez del Rio LM, Montoto M, Larenzi-Tabasso M. Acoustic emission monitoring to study sodium sulphate crystallization in monumental porous carbonate stones. Studies in Conservation. 1997; 42: 115-125.

[80] Menéndez B, David C. The influence of environmental conditions on weathering of porous rocks by gypsum; a non-destructive study using acoustic emissions. Environmental Earth Sciences. 2013; 68: 1691-1706. DOI: 10.1007/s12665-012-1861-2

[81] Anzani A, Binda L, Carpinteri A, Invernizzi S, Lacidogna G. A Multilevel approach for the damage assessment of historic masonry tower. Journal of Cultural Heritage. 2010; 11: 459-470.

[82] Carpinteri A, Lacidogna G. Monitoring a masonry building of the 18th century by acoustic emission technique. WIT Transactions on the Built Environment. 2001; 55: 327–337. DOI: 10.2495/STR010321

[83] Suarez del Rio LM, Gomez Ruiz de Argandona V, Calleja L, Rodriguez Rey A, Grossi-Sampedro CM, Montoto M. Acoustic emission monitoring of the Cathedral of Palma de Mallorca (Spain). In Materials, Technologies and Practice in Historic Heritage Structures, 2010 Netherlands: Springer, 351-365. DOI: 10.1007/978-90-481-2684-2_18

[84] Chapellier D. Prospect ion électrique de surface. Geophysics on line course 2002. Université de Lausanne, Institut Français du Pétrole.

[85] Cosentino PL, Capizzi P, Fiandaca G, Martorana R, Messina P. Advances in Microgeophysics for engineering and cultural heritage. Journal of Earth Science. 2009; 20(3): 626-630. DOI 10.1007/s12583-009-0052-x

[86] Martinho E, Alegria F, Dionisio A, Grangeia C, Almeida F. 3D-resistivity imaging and distribution of water soluble salts in Portuguese Renaissance Stone bas-reliefs. Engineering Geology. 2012; 141-142: 33-44. DOI: 10.1016/j.enggeo.2012.04.010

[87] Biernat K, Idziaszek-Gonzalez A, Nita K, Sikora J, Wojtowicz S. Nondesructive impedance method of brickwork damp identification. Proceedings of the 42 International Conference and NDT Exhibition, NDE for Safety/DEFEKTOSKOPIE 2012, October 30–November 1 2012. Sec u Chrudimi (Czech Republic), 7-12.

[88] Cammarano F, Di Fiore B, Mauriellon P, Patella D. Examples of application of electrical tomographies and radar profiling to cultural heritage. Annali di Geofisica. 2000; 43(2): 309-324. DOI: 10.4401/ag-3631

[89] Martinho E, Dionisio A, Almeida F, Mendes M, Grangeia C. Integrated geophysical approach for Stone decay diagnosis in cultural heritage. Construction and Building Materials. 2014; 52: 345-352. DOI: 10.1016/j.conbuildmat.2013.11.047

[90] Lignola GP, Manfredi G. A combination of NDT methods for the restoration of monumental façades: The case study of Monte di Pieta (Naples, Italy). Journal of Cultural Heritage. 2010; 11: 360-364. DOI: 10.1016/j.culher.2009.11.010

[91] Solla M, Lorenzo H, Rial FI, Novo A. Ground-penetrating radar for the structural evaluation of masonry bridges: Results and interpretation tools. Construction and Building Materials. 2012; 29: 458-465. DOI: 10.1016/j.conbuildmat.2011.10.001

[92] Topczewski L, Fernandes FM, Cruz PJS, Lourenço PB. Practical implications of GRP investigation using 3D data reconstruction and transmission tomography. Journal of Building Appraisal. 2007; 3: 59-76. DOI: 10.1057/palgrave.jba.2950060

[93] Orlando L, Slob E. Using multicomponent GPR to monitor cracks in historical buildings. Journal of Applied Geophysics. 2009; 67:327-334.

[94] Binda L, Saisia A, Tiraboschia C, Vallea S, Collab C, Fordec M. Application of sonic and radar tests on the piers and walls of the Cathedral of Noto. Construction and Building Materials. 2003; 17: 613–627. DOI: 10.1016/S0950-0618(03)00056-4

[95] Santos-Assunçao S, Perez-Garcia V, Caselles O, Clapes J. Assessment of complex structures with GPR compared to other non-destructive testing studies. Remote Sensing. 2014; 6: 8220-8237. DOI: 10.3390/rs6098220

[96] Bergamo O, Campione G, Donadello S, Russo G. In-situ testing procedure as an integral part of failure analysis of historical masonry arch bridges. Engineering Failure Analysis. 2015; 57: 31–55. DOI: 10.1016/j.engfailanal.2015.07.019

[97] McCann DM, Forde MC. Review of NDT methods in the assessment of concrete and masonry structures. NDT&E International. 2001; 34: 71-84. DOI: 10.1016/S0963-8695(00)00032-3

[98] Meneely JD, Smith BJ, Curran J, Ruffell A. Developing a 'non-destructive scientific toolkit' to monitor monuments and sites. Proceedings of the ICOMOS Scientific

Symposium Changing World, Changing Views of Heritage, 7 October 2009. Valletta, Malta. 9 p.

[99] Olmi R, Bini M, Ignest A, Priori S, Riminesi C, Felici A. Diagnoses and monitoring of frescoes using evanescent-field dielectrometry. Measurement Science and Technology. 2006; 17: 2281-2288