Structural Analysis of Historic Construction – D'Ayala & Fodde (eds)

Application of non-destructive techniques at the Katholikon of Dafni Monastery for mapping the mosaics substrata and grouting monitoring

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ABSTRACT: The Katholikon of Dafni Monastery, one of the most important monuments of the middle-byzantine period situated near Athens, has suffered severe damages due to the 1999 earthquake. Several studies have been engaged, in order to collect all relevant data of the internal masonry structure and that of the mosaics substrata by applying non-destructive techniques, such as Ground Penetrating Radar (GPR) and Seismic techniques including tomographies. In some areas these techniques have been used both before and after grouting.

1 INTRODUCTION

The Katholikon of Dafni Monastery, situated near Athens, is an 11th century world Heritage Monument, famous for its excellent mosaics (Delinikolas et al. 2003). Due to the 1999 Athens earthquake both the masonry structure and the mosaics have suffered severe damages (Miltiadou-Fezans et al. 2004). On the basis of the results of a series of research programs, investigations and detailed studies undertaken by the competent authorities of the Hellenic Ministry of Culture, the application of adequate hydraulic grouts injections was decided for the repair and strengthening of its load bearing structure and for the in situ conservation of the detached mural mosaics (Miltiadou-Fezans et al. 2003). The masonry grouting was initiated in June of 2006 and completed in April 2007, while that of the mural mosaics is still in progress.

In this framework, several studies have been engaged, in order to collect all relevant data for the internal masonry structure and that of the mosaics substrata by non-destructive techniques, such as GPR (Côte et al. 2004, Vintzeleou et al. 2004) and seismic techniques. In some areas these techniques have been already used both before and after grouting. These techniques have been selected as they are fully complementary, by virtue of their ability to provide different information in the structural diagnostic process (MacCann et al. 1988).

On the basis of a preliminary study (Côte et al. 2004), high frequency ground-penetrating radar mapping of more than 50 mosaics, related to their very near bearing-structure, has been realized, in order to locate doubtful zones including delaminations, changes of substrata mortar (i.e. recent repairs) or buried heterogeneities. The results of this work, in conjunction with the manual sonic classification realized by the competent Conservators, can be very useful for a more detailed and less subjective evaluation of mosaics substrata pathology.

Furthermore, the possibility of using non destructive procedures to monitor the movement of the grout, in real time, during injection was also investigated. The main objective was to develop a methodology for detecting, during the injection process, the location of any change behind the mosaic's first or second substrata, which could be assimilated to void filling, so that to be able to take corrective measures if necessary (complementary supporting of areas with extended delaminations etc). The first results of this approach realized on a model were very promising (Côte et al. 2004). In this paper the results of similar

measurements, conducted first on a test wall and afterwards on the Katholikon itself, are presented and commented upon.

Investigations have been also realized to control the grouting effect into the masonry walls, using two seismic techniques. The objective herein was to propose a simple survey methodology which gives information for the mechanical characterization of the materials inside the structure. This approach includes some sonic 2D travel time tomographies that present the advantage to describe a section of the structure, and may illustrate the nature and the geometry of its interior (stone blocks, fillings, . . .). A first campaign using this technique has been undertaken in non injected and semi-injected areas, as well as in injected ones. A second campaign is still in progress comprising the repetition of the tomographies after the completion of the injections. Furthermore, these few tomographies permit the understanding and calibration of the behaviour of exhaustive Vp transmission measurements that can be practiced over the major part of the structure.

2 RADAR TECHNIQUES

2.1 *Mosaics mapping*

In 2005, an exhaustive radar survey has been realized on the fifty main mosaics of the Katholikon of Dafni Monastery. The principle of the radar technique, which is particularly adapted to masonry structures (Maierhofer & Leipold 2001, Valle et al. 1999), is based on the transmission of an electromagnetic pulse, at very high frequencies, through the examined structure. Successive echoes caused by reflections at the inner layered structures are recorded through time signals and eventually the juxtaposition of these signals enables the construction of a time–section (GPR profile), which can be related to the internal geometry of the investigated structure.

For this specific application a 1.5GHz central-frequency antenna has been used. The applied procedure has already been tested by Côte et al. (2004). For reasons of comparison the selected parameters remained constant during the execution of the radar survey. Thanks to specific parallel radar profiles, maps can be constructed from chosen trenches of the structure. The gray-color scale of these maps is related to the amplitude of the echoes in that trench. In this specific case, maps were constructed, representing the energy of the first part of the radar surface wave.

As the wavelengths of the radar technique are about 7 cm in the mosaics, echoes from the substrata are mixed with the surface echo, therefore the resolution is not enough to distinguish one from the other. As consequence, the radar parameter was fixed ($\Delta t \sim 1$ ns) in order to map the first few centimeters including the mosaic itself and its substrata.

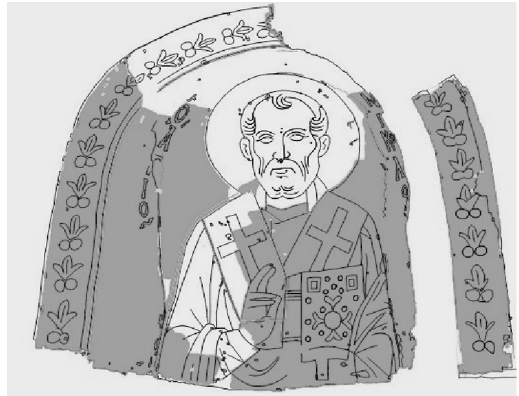

Figure 1. Manual-sonic map of "Saint-Nicolas, constructed by the mosaic's conservators". Damaged zones are in gray.

The objective of the current study is to correlate this radar gray-scale maps to a level of detachment or heterogeneity by comparing them to the manual-sonic maps and the pathology ones, constructed by the Conservators of the mosaics. Although, it has to be noted that this comparison has certain limitations, due mainly to the fact that GPR maps are constructed based on a multi-valued gray-scale, while the manual-sonic maps consist of two values (bad or good), deriving from subjective human-expert senses.

Apart from the aforementioned maps, all the information selected by the Conservators concerning the nature of the substrata mortar has been taken into account in order to investigate any possible existence of GPR data-similarities among the mosaics exhibiting the same substrata. Four main types of mortars were identified: (i) the original lime based mortar (Byzantine period), preserved only in very few mosaics, (ii) the Novo-type mortar (late 19th century interventions), having as binder natural hydraulic lime, used in the vast majority of the mosaics, (iii) the cement-based mortars (1950's interventions), used in a small percentage of the mosaics and (iv) the cement-lime based mortars (1960's interventions), found as well in a small percentage of the mosaics (Chryssopoulos et al. 2003). The coexistence of all types of mortars is possible in cases of great size mosaics, due to previous interventions.

The two following examples show the significance of such non-destructive technique, which can be automated in order to obtain comparable information. For the mosaic "Saint-Nicolas" (Figs 1–2), radar results indicate that the head and the left shoulder and arm correspond to a sound area, confirmed also by the manual-sonic map. The rest of the mosaic is either completely detached or/and the nature of mortar used for the substrata is utterly different from the one of the sound area. This result is also confirmed by the fact

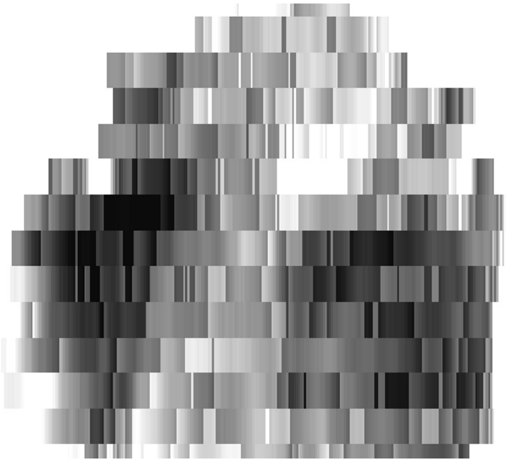

Figure 2. Sub-surface radar map of "Saint-Nicolas". The damaged zones are in dark.

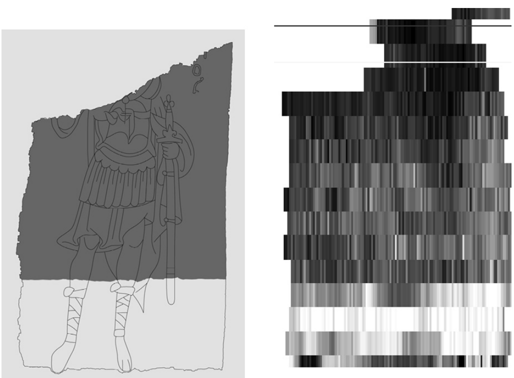

Figure 3. Manual-sonic and sub-surface radar maps of "Saint-Orestes". Damaged zones are in dark.

that, the substrata mortar of the sound part is a cement-based one, whereas the rest of the mosaic conserves the initial lime based mortar.

Similar results were observed in the case of the mosaic "Saint-Orestes", located on a masonry arch, (Fig. 3), where once again radar information shows clearly the existence of two areas: a sound basis and an upper part which is either completely unstuck from the masonry or/and the mortar is of completely different nature. The results are again completely coherent to the mortar composition of the mosaic substrata. The lower sound part is a cement based mortar. The upper part conserves the initial lime mortar used by the Byzantine artists.

In the case of mosaics having great size, (over few squared meters) and mainly one type of substrata mortar, correlation can be more complex, as for the example of the "Birth of Virgin" (Figs 4–5). The

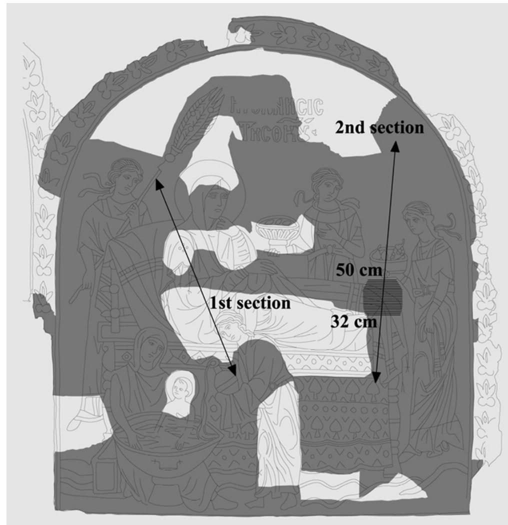

Figure 4. Manual-sonic map of the "Birth of Virgin". The more light the color is, the more sound the mosaic is. The black arrows correspond to the sections of radar monitoring during the masonry grouting.

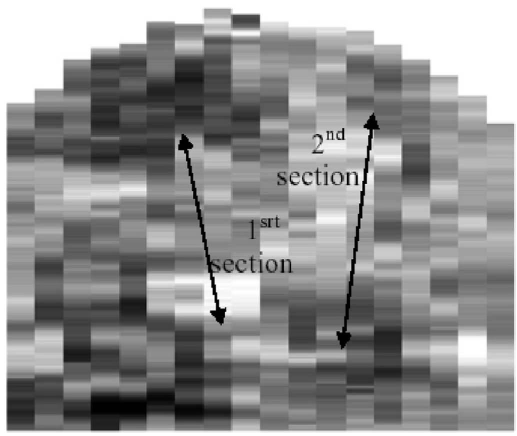

Figure 5. Near-surface radar map of the "Birth of Virgin" mosaic (done in 2005).

manual-sonic map constructed by the mosaic's conservators indicates a quite extended problematic area, while the radar maps present a more complicated situation including different levels of detachment or heterogeneity. The Novo mortar (based on hydraulic lime) has been mainly used for the substrata of the mosaic.

From the above presented results it seems that when the mortars used are quite different in nature, as in case of lime and cement mortars, the radar profiles can reveal this difference in a quite obvious way and this is in accordance with the manual sonic maps. On the contrary when the Novo mortar, based on hydraulic

lime, is used in the most of the surface the results are more complicated, than the ones presented by the manual sonic maps.

2.2 *Grouting monitoring applied on a wall model*

A test wall, enclosing purposely voids and cavities at specific locations has been constructed by the Directorate for Conservation of Ancient and Modern Monuments. Furthermore two square mortar structures (60 × 60 × 5 cm) have been attached to this wall, simulating mortar used for wall mosaics substrata. In both cases empty spaces have been left in between the mortar structure and the wall. The scope of the whole experiment was to make a test of grouting procedure, using three different hydraulic grouts compositions designed in purpose, and to examine the long term behavior of grouts hardening in site conditions. The wall has been injected in collaboration with the Directorate for Technical Research on Restoration in two phases. In the first phase a lower and medium zone was injected using two different grout compositions. In the 2nd phase the upper zone has been injected. During this injection application (2nd Phase of grouting) a radar system (1.5 GHz antenna and survey wheel) has been also used, in order to record the progress of grouting behind the one of the mortar structures (Fig. 6a).

In Figure 6b a schematic presentation of all the sides of the wall and the injection entrances and exits is given. In Figure 6c the two selected 44-cm vertical GPR paths are noted. The grouting procedure was realized at six stages, in order to allow the gradual collection of GPR data after the completion of each grouting stage. The selected setting parameters of the radar system remained constant and same with those applied on reference GPR profiles, conducted prior the initiation of grouting. For each injection, the location of entrances and exits and the quantity of grout consumed per entrance were noted.

The first four injections were performed at locations far away from the tested area, whereas the last two injections were performed in the vicinity of the two vertical GPR profiles (Fig. 6d).

As the injection was just applied, the grout containing 80% of water has been too conductive for radar. Thus, we have studied the amplitude of the surface wave itself. Figure 7 shows the evolution of the amplitude of the surface echo at the GPR path A after the completion of each grout injection.

During the first three injections the signals remained stable, possibly due to the fact that grouting had been applied far away from the tested area. After the completion of the fourth injection the appearance of a void (A1) at about [16–27 cm], possibly filled, is observed. A second void (A2) at about [35–44 cm] is also detected after the completion of the fifth injection, which is conducted directly at the tested area and corresponds to the highest amount of the consumed grout. During this injection, moisture was detected on the wall surface itself. The presence of this second void and perhaps its filling is confirmed after the sixth injection.

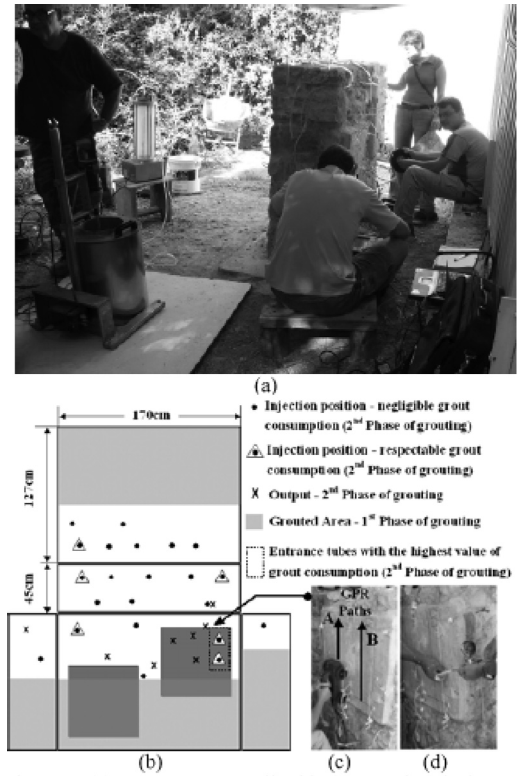

Figure 6. (a) Test masonry wall with the grouting devices on the left and the radar team on the right, (b) Schematic representation of the test wall – 1st and 2nd Phase of grouting, (c) Mortar structure attached to the test wall, simulating the mosaics substrata – GPR Profiles, (d) Application of the 5th injection of the 2nd phase, situated close to the tested area.

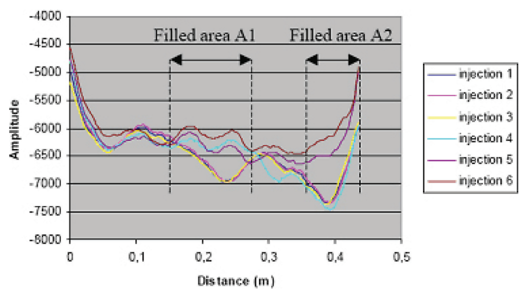

Figure 7. Amplitudes of the surface echoes, obtained from successive radar profiles at GPR path A, after each elementary injection.

Similar results are obtained regarding the GPR Path B (Fig. 8). One void at about [28–35 cm]

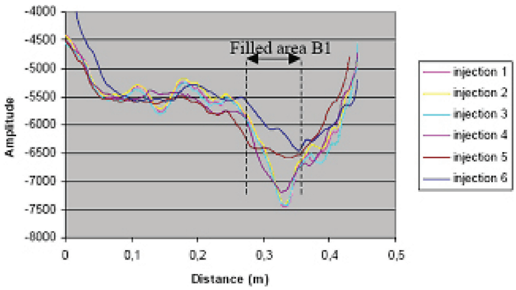

Figure 8. Amplitudes of the surface echoes, obtained from successive radar profiles at GPR path B, after each elementary injection.

is also detected after the completion of the fifth injection.

2.3 *Grouting monitoring applied on mosaics*

In March 2007, based on the experience acquired from the wall model, two mosaics of the Katholikon of Dafni Monastery, Juda's Betrayal and Birth of Virgin, have been monitored during grouting by means of GPR measurements, in order to detect the progress of grouting in real conditions. Several GPR profiles were performed on two selected linear sections located on each one of the two examined mosaics after the completion of a series of sequential grout injections (Figs 9–11). The setting parameters for all profiles were remained constant and same with those selected for the reference profile conducted for both mosaics prior the initiation of grouting.

In order to detect and localize any change caused by the grouting effect, the reference profile of each mosaic was subtracted from all the corresponding GPR profiles. In order to ensure accuracy regarding the location and start position of the successive profiles, a survey wheel was used.

The main information obtained from these two grouting monitoring are the followings.

Figure 9 reveals that a void has been filled after the 4th injection, which is located inside the masonry behind the "Juda's Betrayal" mosaic, at the beginning of one of the profile. This is the only important change detected on this section.

Regarding the "Birth of Virgin" mosaic (Fig. 10), after the 2nd injection, a void filling, just behind the mosaic, between 32 to 50 cm of the right section, has been detected, as presented in Figure 11. This area corresponds to a detached zone according to the manual sonic map of the conservators (see Fig. 4). Along this linear section no other notable change has been detected. Concerning the left section, no significant change was detected. This result was expected, as the examined area was located in a sound area according to the manual sonic map.

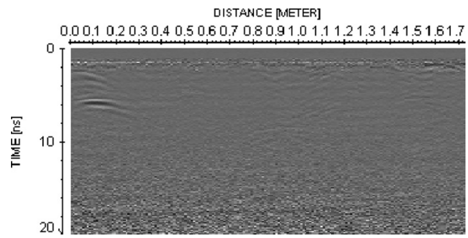

Figure 9. Subtraction of profiles on the "Juda's Betrayal" mosaic after the 4th injection.

Figure 10. Localization of the tested sections (between scotch papers) of the mosaic "Birth of Virgin".

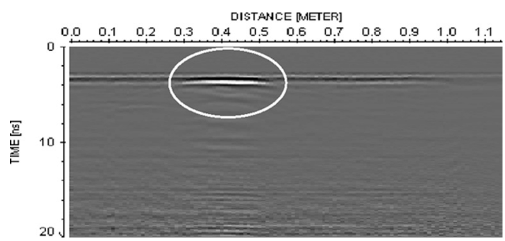

Figure 11. Subtraction of profiles on the "Birth of Virgin" mosaic after the 2nd injection.

Through these two examples of radar monitoring during injection, we can consider that the radar technique could be a useful tool for surveying the injection in real time. However, the application of such a technique in practice revealed two main limitations.

First of all, it must be noted that the resolution of the radar detection depends on the wavelength (of the order of few centimeters), whereas the size and moreover the thickness of the probable defects, can be millimetric. Secondly, another important aspect is the selection of the appropriate linear section for the performance of the survey, as it is practically difficult to monitor the whole mosaic (inability to ensure an untrammeled movement of the survey wheel on the mosaic, due to the presence of a great number of plastic tubes used for the performance of the grout injection).

Thus it is not evident that the grout will really pass behind the area that is monitored.

3 SONIC TECHNIQUES

3.1 *Sonic tomography*

Aim of the complementary seismic tomography campaign was the construction, with a non-invasive fashion, of a map revealing the internal mechanical properties of the masonry walls. By means of measuring travel times of the compression wave between source and receiver points located on opposite sides of the walls, it is possible to derive a compression wave velocity map. In the case of an a priori homogeneous material, the appearance of a lower-velocity zone indicates that the material has been weathered locally. Seismic transmission tomography based on travel times is more sensitive to zones of micro-cracking, than it is to isolated cracks, especially if the micro-cracks are not closed and if the material has been damaged. In the case of a homogeneous medium, the difference in travel times, both with and without an isolated crack, might very well be of the same order of magnitude as the level of accuracy in the selected times. Seismic amplitudes or rising times are more sensitive to cracking than travel times, but remain substantially more difficult to implement within real investigation processes (Spathis et al. 1983).

At the Katholikon of Dafni Monastery some tomographies were performed at different zones, suitably selected for further investigation regarding the grouting process.

During an initial series of experiments, an optimum distance between the source and receiver points was determined, so that the information contained on the tomography maps would be sufficient enough to perform the same diagnostic evaluation to the one of a denser map. It was shown that a distance of about 10 cm, which leads to a total number of about 400 rays, could be a good compromise.

A multi-channel acquisition system (10 bits, 1 MHz/channel) was used to collect and store the seismic signals (Fig. 12). Since the shortest source-receiver travel times amount to some ms, the sampling frequency was set at 1 MHz, in order to ensure acquiring a sufficient number of points for picking the arrival times. The source consisted of a hammer coupled with an accelerometer, while the receivers were accelerometers attached to the wall. Both the receiver and source signals were recorded for all possible source-receiver combinations. The time pickings were subsequently carried out in the laboratory. These arrival times and coordinates were then fed into the inversion process.

The tomography algorithm employed in this paper is known as "RAI-2D"; it has already led to numerous applications in both soil surveying (Abraham et al. 1998) and structural NDT (Côte & Abraham 1995). RAI-2D has been inspired by the Simultaneous Iterative Reconstruction Technique (SIRT - Gilbert 1972). The field of investigation is discretized into a mesh of points, on which the seismic velocity gets defined. One of the key features of RAI-2D pertains to its influence zones, which as opposed to a fixed block-discretization grid are used when selecting rays to calculate slowness at a given grid point. The size of these influence zones constitutes one of the adjustment parameters that allow RAI-2D to adapt its convergence process to the type of actual data. This algorithm is also characterized by its use of circular analytical rays. The level of accuracy for civil engineering purposes inherent in this simple and rapid inversion technique, which has been widely tested, using both synthetic and field data, is similar to that provided by other more complex methods based on matrix inversions and sophisticated ray path computations.

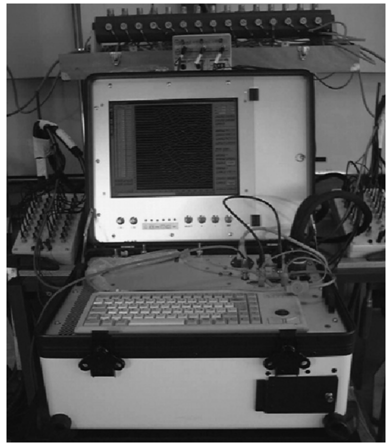

Figure 12. Seismic acquisition system.

It is recommended to include certain complementary information with the final velocity map in order to guarantee the quality of the survey and facilitate its interpretation.

First of all, algorithm convergence should be tracked from a statistical point of view (mean residual, standard deviation). Furthermore, the residual statistics of each source and receiver should be checked, so as to eliminate those sources and/or receivers displaying out-of-scale statistical values. Secondly, since both the precision and resolution of the velocity map are linked to the ray coverage, the plot of rays should at least be studied. For instance, in zones with few rays, the velocity value is less precise than in zones with well-distributed and large numbers of rays.

A horizontal tomography over a length of about 3 m for a 0.8 m thick wall is presented in Figure 13. The convergence of the algorithm is reached after 50 iterations. Not any a priori model is implemented in this

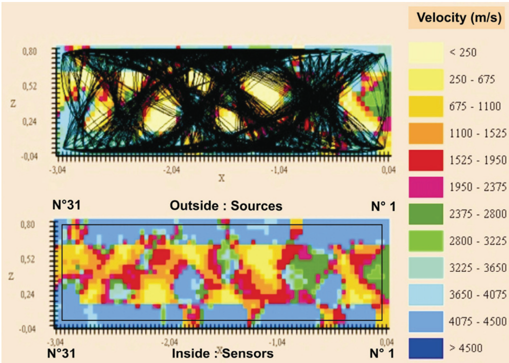

Figure 13. Tomographical reconstruction in a grouted area.

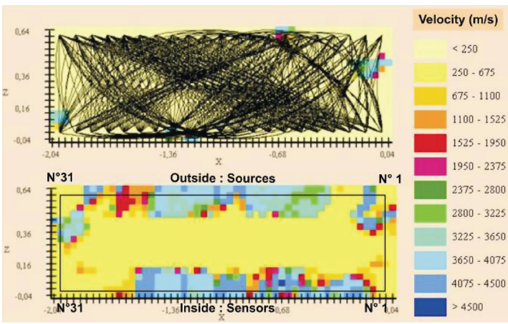

Figure 14. Tomographical reconstruction in a non grouted area.

process. The real edges of the wall are figured by the black lines.

This image illustrates quite clearly the inner building-up of this wall. Three leaves are observed. On both external parts of the wall the high velocities are associated to stone masonry, while the lower velocities at inner part are associated to the infill material. It is quite interesting to notice that the geometry of the stone facings is well presented. The thickness of the stones can be estimated. The linear arrangement of the inner face of these facing stones is obtained without any geometrical control of the solution, neither with any a priori model. The mean velocity of the stones is about 4200 m/s while the mean velocity of the filling materials is about 1500 m/s. This part of the wall has already been grouted.

The tomography illustrated in Figure 14 has been realized in a non grouted part of the structure. The process is identical to the one of the previous case. Here the investigated length of the wall is about 2 m for a thickness of 0.6 m. This time, the pickings of first arrivals for each signal are much more difficult.

The attenuation of the signals is very strong. The early beginning of each signal is quite soft and then the accuracy of the picking decreases. Nevertheless, the reconstruction algorithm converges to a three-leaf medium (again without a priori information). This time, the inner filling materials are associated with very low velocities (500 m/s).

The comparison of these two cases permits to conclude that the grouting survey of such masonry structures may be achieved by the observation of the velocities of their inner part. Adapted tomographical algorithms are able to reconstruct the inner geometry of such structures.

These tomographies can be realized over some particular areas, while a simple punctual time transmission set can consider the whole structure by a convenient scanning.

3.2 *Sonic transmission testing*

Some simple sonic transmission tests have been realized at Dafni Monastery. The acquisition devices are quite simpler than the ones applied to tomographical measurements. A couple of accelerometers are linked to an acquisition card or to a simple oscilloscope. A hammer equipped with a shock accelerometer constitutes the source, whereas a second accelerometer is the receiver. The measurement principle is based on positioning the accelerometers face to face on both sides of the wall and knocking the wall in the vicinity of one of the accelerometers, which is used as a trigger. The first arrival time can be then picked on the signal from the other sensor. The whole set is then displaced and a scan of wall or of a part of wall can be performed.

The example illustrated in Figure 15 corresponds to a set of measurements conducted over a vertical line along a wall which has been grouted up to the limit indicated by the dotted line. Beyond this line, the behavior of the sonic measurements changes radically.

Two other measurement sets (over horizontal lines) are plotted in Figure 16. They have been obtained at two levels of the same wall. The upper level has not yet been grouted. The difference in the behavior of the mean transmission velocities is quite obvious.

Such measurements are relatively easy to be performed and interpreted. Large parts of structures can be then observed. Some indicators can be deduced for the qualification of the homogeneity of the structure before any treatment. In case of complex behavior, a complementary tomographical arrangement can be performed. After grouting, the same measurements can be repeated in order to evaluate the efficiency of the intervention.

4 CONCLUSIONS

High frequency Ground Penetrating Radar (GPR) mapping of more than 50 mosaics, related to their very near bearing-structure, has been realized, in order to locate doubtful zones including delaminations, changes of structures (i.e. recent repairs) or

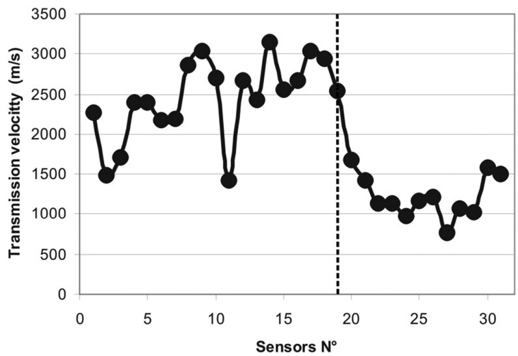

Figure 15. Sonic transmission velocities across a wall partially grouted.

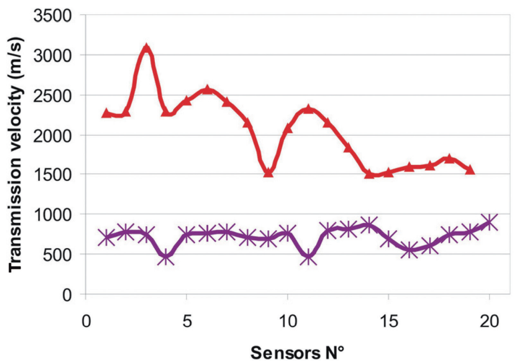

Figure 16. Sonic transmission velocities across a similar wall grouted (red) or not yet grouted (purple).

buried heterogeneities. The results of this work in conjunction with the manual sonic classification realized by the competent conservators were very useful for a detailed evaluation of mosaic substrata.

Sonic tomographies permit the understanding and calibration of the behavior of exhaustive Vp transmission measurements that can be practiced over some areas of the structure. These investigations are complementary to simple transmission investigations that need simply to locate corresponding measurement grids on both sides of the wall. At each node, the transmission time is measured. The map of these mean velocities for an entire wall may be constructed before and after a grouting process. Their comparison leads to a verification of the homogeneity of the wall after the grouting process.

The co-evaluation of NDT results can be a useful tool for the assessment of the efficiency of the grouting intervention.

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