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Foreword

This special issue of *Near Surface Geophysics* on GPR in Archaeology contains nine papers selected from among the best works presented at the session "Near Surface Geophysics for the Study and the Management of Historical Resources: Past, Present and Future", which was held at the European Geosciences Union General Assembly 2009 (19–24 April 2009, Vienna, Austria). In particular, the papers were selected so as to cover different and crucial aspects (from theoretical to methodological and practical) concerning with the use of ground-penetrating radar (GPR) for archaeological purposes and for the monitoring and diagnostics of historical buildings and artefacts.

The use of GPR in the above fields is well assessed but challenges still remain to be tackled in several directions such as: performing high-resolution and detailed diagnostics even in complex scenarios, with the aim of achieving a clear and useful visualization of the investigated scene by the archaeologists and the cultural heritage stakeholders. These aims demand advancements in the field of instrumentation to be able to achieve non-conventional measurement configurations and in data processing approaches by exploiting more accurate and advanced models of the electromagnetic scattering. These advances are even more necessary to comply with the most challenging future aim of achieving the 'quantitative' reconstruction of the scene in terms of electromagnetic properties, to provide not only information about the morphology (position, extent and geometry) of the targets but also their nature. On the other hand, the other main challenge for the future, not strictly limited to the application field of archaeology and cultural heritage, is concerned with the integration of GPR with other sensing technologies and methodologies, to obtain more complete, accurate and reliable information about the buried/embedded targets.

In this framework, the nine papers in this special issue represent some good research efforts to tackle the above-described challenges.

The first paper by Capineri *et al.* is concerned with the exploitation of a relatively novel concept of holographic radar for non-destructive testing, applied to cultural heritage items. The holographic radar operates at high frequencies in continuous wave mode and produces images with high in-plane resolution (about 1 cm). Its simplicity of construction and low cost makes this instrumentation very suitable in the case of the diagnostics of the surface and much shallower subsurface and examples of realistic applications are given in the paper for marble and stones investigation and wood structures inspection.

The following batch of three papers is concerned with novel data processing approaches able to accurately model the electromagnetic scattering phenomenon and push toward the future challenge of the quantitative reconstruction of targets.

Meschino, Pajewski and Schettini describe a theoretical study concerning a hybrid electromagnetic-statistic approach for the detection and localization of a perfectly-conducting circular cylinder, buried in a lossless half-space. A cylindrical wave approach was used as forward solver to provide input data for the proposed detection and localization procedure. The reconstruction procedure is based on a sub-array processing structure and several algorithms for the direction of arrival estimation have been implemented and exploited to solve the inversion problem. Numerical analysis is presented for different cylinders (in radius, location and distance from the array) for the cases of both free-space and dielectric half-space.

The paper by Bavusi *et al.* is concerned with the problem of the characterization of masonry and floor areas affected by fractures. In particular, for several realistic cases of interest in cultural heritage monitoring, a comparison is presented between the classical data processing approach based on migration, and a microwave tomography approach exploiting a simplified model of the electromagnetic scattering.

Catapano, Crocco and Isernia describe a new strategy for the quantitative reconstruction of the scenario under investigation, based on a two-step procedure. The first step is concerned with the morphological characterization of the targets, after this information is exploited to ensure the accuracy and the reliability of the second step, where the aim is the evaluation of the dielectric permittivity of the targets through the solution of a non-linear inverse problem. A feasibility assessment of the proposed strategy is given against synthetic data concerning wall inspection.

The paper by Kadioglu presents a new 3D visualization procedure able to identify the main features of the investigated scene in terms of archaeological remains. The 3D visualization procedure was applied to image buried archaeological remains in the Temple of Augustus in the Ulus district of Ankara, Turkey. Very complex and deep wall structures were visualized at any depth range inside (cella) of the Temple of Augustus and a few very narrow cubic anomalies exceeding 4 m deep were determined at the east side of the temple.

Barone *et al.* describe an interesting example of how GPR investigation is able to provide useful information for the restorers (e.g., location, dimensions and geometry of the structural lesions) in order to develop the best possible protection plan. Two cases in Rome have been presented; the first case is the GPR detection of fractures and internal lesions in the architrave of the Porticus Octaviae, a partially restored Roman building. The second case regards GPR survey in the important Zuccari Palace, to determine the internal structure above vaulted ceilings that host a series of 16th century frescos.

Utsi describes an interesting test case at a long-term training excavation site near the Roman fort at Gloucester, where the GPR survey addressed the need to extend information on adjacent areas where it was not possible to carry out further intrusive archaeological investigations. The results of the survey demonstrated the accuracy with which GPR data can be matched to excavation data and the improvement in target definition possible by means of the reduction of transect spacing.

The last two papers are good examples of the effectiveness of the integration of GPR with other sensing techniques.

The integration of GPR and ultrasonic tests carried by Masini *et al.* allowed one to analyse the state of conservation of marble columns in the Romanesque church of san Giovanni al Sepolcro in Brindisi, southern Italy, thus providing useful information for its structural restoration. The GPR data have been processed, thus allowing to identify cracks, reinforcement rebars and the medieval internal metallic hinges joining the stone trunks. The ultrasonic data allowed one to monitor the state of compactness and to assess the effectiveness of reinforcement interventions of the columns.

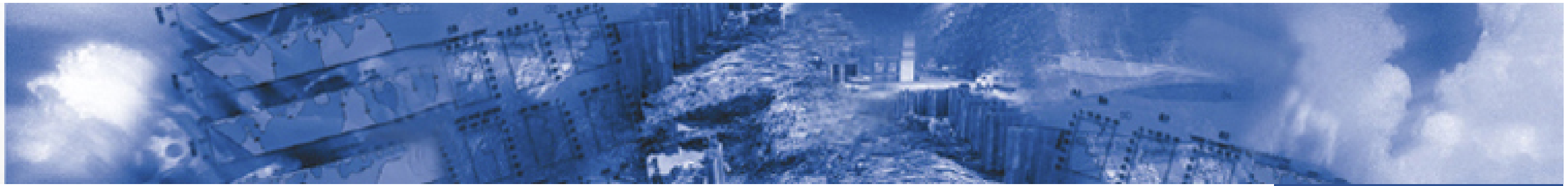
On the huge Nasca ceremonial centre of Cahuachi, southern Peru, the subtle geophysical contrast between earthen buried remains and their surroundings makes the detection of archaeological features very difficult. Such a challenge has been faced by Rizzo *et al.* by means of an integrated approach based on the use of GPR and geomagnetic methods, thus allowing the archaeologists to discover a rich ceremonial offering and to provide fundamental information on the last historical phase of Cahuachi as well.

We are grateful to all the authors for their contributions to this Special Issue on GPR in Archaeology.
We would also like to thank the reviewers for their time and efforts in the evaluation of the papers and for providing constructive comments, namely: Ibrahim Akduman, Monica Álvarez de Buergo Ballester, Massimo Bavusi, Adriana Brancaccio, Nigel Cassidy, Ilaria Catapano, Nectaria Diamanti, Fabrizio Frezza, Dean Goodman, Vincenzo Lapenna, Giovanni Leone, Giovanni Leucci, Neil Linford, Sergio Negri, Luigia Nuzzo, Raffaele Persico, Elena Pettinelli, Dave Redman and Erica Utsi.

We hope you enjoy this special issue!

Nicola Masini and Francesco Soldovieri
Guest Editors

Near Surface Geophysics



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Aims and scope

Near Surface Geophysics is an international journal for the publication of research and development in geophysics applied to near surface. It places emphasis on geological, hydrogeological, geotechnical, environmental, engineering, mining, archaeological, agricultural and other applications of geophysics as well as physical soil and rock properties. Geophysical and geoscientific case histories with innovative use of geophysical techniques are welcome, which may include improvements on instrumentation, measurements, data acquisition and processing, modelling, inversion, interpretation, project management and multidisciplinary use. The papers should also be understandable to those who use geophysical data but are not necessarily geophysicists.

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GPR in archaeology feature in *Near Surface Geophysics* special issue

The October 2010 issue of *Near Sur-face Geophysics* (Vol. 8, No. 5) features a special issue on ground penetrating radar (GPR) in archaeology, guest edited by Francesco Soldovieri and Nicola Masini. It contains nine papers selected from among the best papers presented at 'Near surface geophysics for the study and the management of historical resources: past, present and future', which was held at the European Geosciences Union General Assembly 2009 in Vienna. Papers for this issue of NSGwere selected to cover different and crucial aspects (from theoretical to methodological and practical) concerning the use of GPR for archaeological purposes and for the monitoring and diagnostics of historical buildings and artefacts.

The use of GPR in this context is well understood, but challenges still remain to be resolved in several directions, such as performing high-resolution and detailed diagnostics even in complex scenarios, with the aim of achieving a clear and useful visualization of the investigated scene by archaeologists and the cultural heritage stakeholders. Such objectives require advancements in instrumen-tation to achieve non-conventional measurement configurations and in data processing approaches to create more accurate and advanced models of the electromagnetic scattering. These advances are even more necessary to meet the biggest future challenge, that of providing a 'quantitative' reconstruction of the scene in terms of electromagnetic properties, so that information about the morphology (position, extent, and geometry) of the targets but also their nature can be obtained.

The other main challenge for the future, not strictly limited to applica-tions in the field of archaeology and cultural heritage, involves the integra-tion of GPR with other sensing tech-nologies and methodologies in order to obtain more complete, accurate, and reliable information about buried/embedded targets.

The nine papers in this special issue of NSG provide a good represen-tation of the efforts being undertaken to research these issues.

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Fabrizio Frezza, Cristina Ponti

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Article: Gravity anomaly modelling of multiple geological sources having differing strike lengths with arbitrary density contrast variations

Chakravarthi Vishnubhotla, B. Ramamma

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Joana Gafeira, D. Long, D. Diaz-Doce

[show abstract]

Near surface geophysics 08/2012; 10(4):303 - 314.

Article: Integrated analysis dispersed GPR pulses using deterministic and Bayesian inversion methods

J. Bikowski, J. A. Huisman, J. A. Vrugt, H. Vereecken, J. van der Kruk

[show abstract]

Near surface geophysics 01/2012; 10:641-652.

Article: A multidisciplinary analysis of the Crypt of the Holy Spirit in Monopoli (southern Italy),

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Integrated techniques for analysis and monitoring of historical monuments: the case of San Giovanni al Sepolcro in Brindisi, southern Italy

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ABSTRACT

In this paper, an integrated prospecting performed in the atypical Romanesque church of San Giovanni al Sepolcro in Brindisi, southern Italy is presented. Ground-penetrating radar (GPR) and ultrasonic data have been gathered on the circular load-bearing colonnade of the monument. Here the results achieved on two of the columns are shown. The GPR data have been processed and have allowed to identify and focus the medieval internal metallic hinges joining the stone trunks in one of the columns and some reinforcement rebars in the other (and probably also the residual track of a restored fracture). The ultrasonic data have allowed to monitor the state of compactness and to assess the effectiveness of reinforcement interventions on the columns.

INTRODUCTION

Non-destructive testing has gained great interest in the field of diagnostics applied to cultural heritage. The particular nature of the investigated structures, most of the time, discourages invasive investigation techniques and in certain cases even compels to contact-less measurements (Persico 2006). In particular, non-destructive testing can be exploited for the detection of fractures or for the investigation of pillars and columns within churches of particular historical and/or architectural relevance. This has been recently done in the Romanesque cathedral of Matera (Masini *et al.* 2008) and previously in the crypt of the Romanesque cathedral of Otranto (Leucci *et al.* 2007). In both cases, an integrated prospecting was performed, with ground-penetrating radar (GPR) and acoustic sounding or GPR prospecting and resistivity measurements, with the addition of a microclimatic investigation. Integrated prospecting is not only helpful to perform the diagnosis of monumental structures but can also represent a valuable tool for proper restoration and continuous preservation of them. In particular, the current campaign conditions can make some techniques better than others and different techniques can confirm the evidences or identify complementary aspects. This often makes integrated non-invasive prospecting a suitable strategy for monument monitoring even if, to the best of our knowledge, there is no current precise protocol to follow.

In this contribution, we propose a case history where an integrated prospecting has been performed in order to analyse the preservation state of some architectural elements of the church of San Giovanni al Sepolcro in Brindisi, southern Italy. This church is a Romanesque artefact that recently underwent restoration works. The Institute for Archaeological and Monumental Heritage (IBAM-CNR) has been put in charge of the task to analyse the constitutive materials, the superficial finishing (paintings, patinas, plasters etc.) as well as the main causes and products of the decay. In a previous investigation of the same structure, some information gained from the analysis of the materials has been fruitfully integrated with non-destructive testing (Calia *et al.* 2006). In this contribution, the results of an integrated prospecting, made up of GPR and ultrasonic measurements, are shown. The purpose is a post-restoration investigation of the structure. The GPR data have been elaborated with home-made codes, as described in the section 'GPR prospecting and processing', whereas the ultrasonic data have been averaged as described in the section 'Ultrasonic investigations'. This paper is completed by some historical and archaeological details about the monument, provided in the section 'The Church of San Giovanni al Sepolcro', some geological and petrographical details on the columns, provided in the sec-

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FIGURE 1
Photograph of the Church of S. Giovanni al Sepolcro.

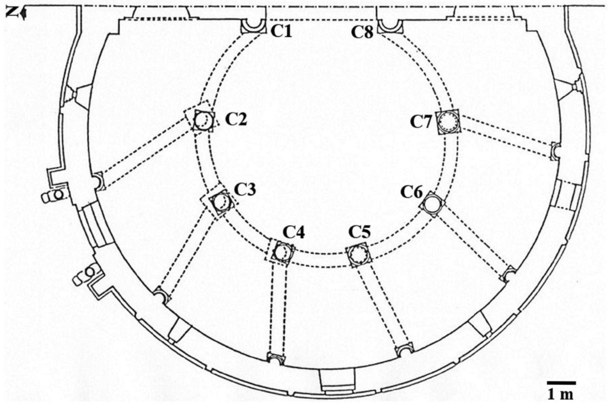

FIGURE 2
Plant of the Church of S. Giovanni al Sepolcro.

tion ‘Constituent materials of the architectural elements investigated’ and some conclusions.

The Church of San Giovanni al Sepolcro

San Giovanni al Sepolcro is a church whose first edification dates to the 11th century. However, it has been founded on the remains of a Roman *domus* and the site has been exploited also during the previous medieval age both as a burial place and for the production of lime. It is supposed that the church was founded by the Templars and, in historical documents of the 12th and 14th centuries, it is reported that the church was assigned to the Order of St John. It has been abandoned and restored several times, the last of which during the 1990s (Calia *et al.* 2006). Nowadays, it is property of the municipality of Brindisi, open to the public and also exploited for temporary exhibitions. In the church, the floor level of the 11th century has been replaced with a wooden floor, from which it is possible to see the underlying floor of the Roman *domus* with its floor mosaic. An image of the church is provided in Fig. 1, whereas a plan of the church (at the ground floor) is shown in Fig. 2. An interesting feature of the church is that virtually all its internal columns are visibly leaning with respect to the vertical direction (this is also clearly visible in Figs 3 and 6). This is possibly due to some original architectural error. During the last restoration, internal metallic reinforcement bars have been inserted in the columns and the previous externally visible fractures have been filled with suitable stuccos. We performed prospecting on all the internal eight columns of the church. From now on, these columns will be labelled C1...C8, according to the labels adopted in Fig. 2. The results achieved from columns C3 and C4 are exposed here.

CONSTITUENT MATERIALS OF THE ARCHITECTURAL ELEMENTS INVESTIGATED

A mineralogical-petrographic study of the constituting materials of columns C3 and C4 has been performed on thin sections by means of an optical microscope (Zeiss mod. Axioplan) in transmitted light.

Column C3 is composed of two sections, about of the same size, both made up of grey granite showing a fine and homogeneous grain size. From a microscopic point of view, this rock shows a granular and holocrystaline (from idiomorphic to allotriomorphic) structure made up of crystals with average size between 300–800 μm. The stone is mainly composed of sialic minerals, like feldspars (alkaline feldspars and plagioclases), quartz and a low amount of femic minerals, represented by amphibole (horneblende) and biotite. The feldspars, often twinned, have been affected by the chemical deterioration process (caolinitization and sericitization). The mineralogical composition of this rock allows to classify it as a granodiorite, according to the Streckeisen diagram.

Among the stone materials used in antiquity, it could be ‘Misio granite’ (Galetti *et al*. 1992). The provenance of this stone is from Kozak, near Pergamon in Turkey. This identification is based on the large amount of biotite (recognized by naked eye) in the crystalline matrix, as well as the fine granulometry.

The monolithic shaft of C4 column is made of Cipollino marble. It is a metamorphic rock showing a characteristic structure arising from the alternation of carbonatic and phyllosilicate layers, which give to the stone a typical exfoliated appearance, like an onion. This kind of rock, in antiquity was called ‘Marmor Caristium’ and was extracted in the Greek island of Eubea. This rock can be classified as an impure marble. Petrographical observations show a crystalline heteroblastic structure, mainly made of calcite crystals showing more or less stressed polysynthetic twinnings. Their size varies from a few microns to 1.5 mm. Quartz is very subordinate in abundance and it occurs as small grains with undulated extinction. Only some K-mica and chlorite crystals have been observed on the sampled area. The rock fabric is characterized by the elongation of the calcite crystals. Due to the petrographical characteristics previously described, both the granite and the Cipollino marble, on a centimetre scale, can be considered homogeneous materials with regard to their bulk. A substantial difference between them consists in the fact that the granite has an isotropic structure whereas the Cipollino marble, due to the oriented nature of its crystalline structure, is rigorously an anisotropic material. In the GPR and ultrasonic prospecting described in the following, however, this anisotropic nature has been neglected. In particular, with regard to the GPR prospecting, the results seemed clear enough and so the long and complicated work associated to the implementation of an inversion model for anisotropic media did not seem promising. Instead, with regard to the ultrasonic measurements, they have been performed to retrieve some average characteristics of the materials. In particular, in this case the processing was quite simple and this made the effort of accounting for the anisotropy not worth doing.

GPR PROSPECTING AND PROCESSING

The GPR measurements were performed on all the internal columns by the Subsurface Interface Radar (SIR) 3000 manufactured by GSSI. SIR 3000 consists of a digital control unit with keypad, VGA video screen and connector panel powered by a 12-V DC battery. The system was equipped with a 1500 MHz monostatic antenna connected by fibre-optic cables. The acquisition was in continuous mode but a reference metre rule was located along each profile and marked with a step of 0.1 m and this allowed us to adopt a distance normalization in order to mitigate the uncertainty about the antenna position (Rizzo *et al.* 2005; Masini *et al.* 2007). Moreover, suitable acquisition filters were selected in order to reduce low- and high-frequency noise while preserving a sufficient bandwidth to guarantee good resolution.

For each of the internal columns, both a scan along the column and a scan all around the column at a fixed altitude of 1.3 m were performed. All the vertical scans started from a height of 2.3 m (from the basement) downward.

With regard to the scans at a fixed height, we have preformed a theoretically simple but very effective processing. It consisted, after the zero timing and the muting of the interfaces, in a circular disposition of the data. More precisely, this reshaping has been based on the assumption (not rigorous, of course) that each GPR trace substantially provides the image of the inner columns along a diameter. Therefore, while turning around the circumference of the column, one retrieves the image of its inner twice. There are two possible ways to separate the two images: the first is to deal with the entire temporal length of the traces image, up to the reflection from the opposite side of the column with respect to the antennas (the point corresponding to this reflection is quite evident from the raw data and has been tested also by means of a moving target progressively brought near the column). In this way, each of the two consecutive stretches of π radians (covered by the antenna around the column) provides an image of the whole cross-section of the column. In this way one achieves two images of the cross-section, somehow joined side by side. Alternatively, one can ‘cut’ the data at one half of the time corresponding to the reflection from the opposite interface and can associate this time to a ray of the column rather than to a diameter. In this way one obtains two images of the column, somehow piled one on the other. We followed the second way and have retained the shallower image, more reliable than the second one, as it can easily be heuristically clued. While turning around the column, the raw data are ‘naturally’ displaced in a polar (θ,ρ) plane, where the abscissa can be associated to the angular position and the ordinate to the radial position that is proportional to the round trip time of the GPR signal. By means of a homemade Matlab code, we reported the polar image on a Cartesian (x,y) plane. The code has been tested by simulating some cases where the result of this reshaping is known. In particular, we tested that rectangles in the (θ,ρ) corresponded to truncated angular sectors in the (x,y) plane. As a future development, a more refined inversion processing (similar to those

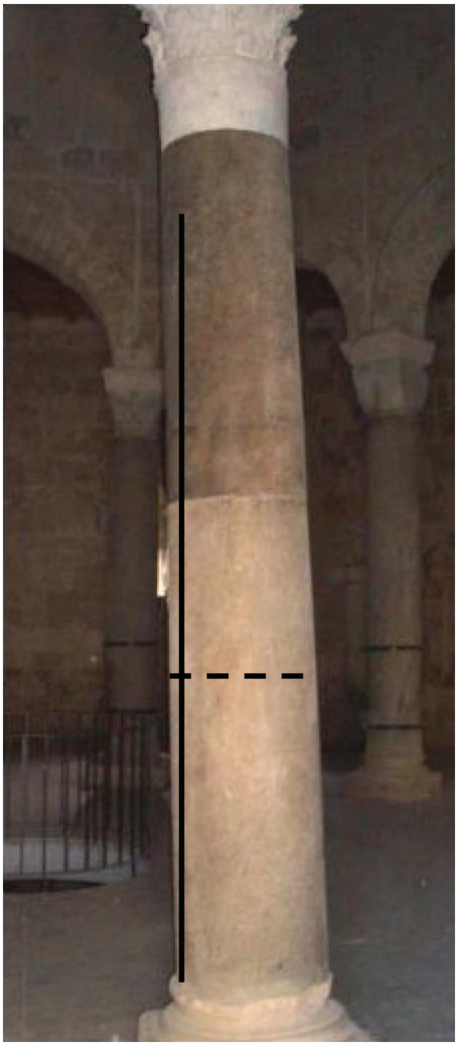

FIGURE 3
Photograph of column C3. The vertical line indicates the location of the GPR profile. The dashed line shows the location of the circular scan.

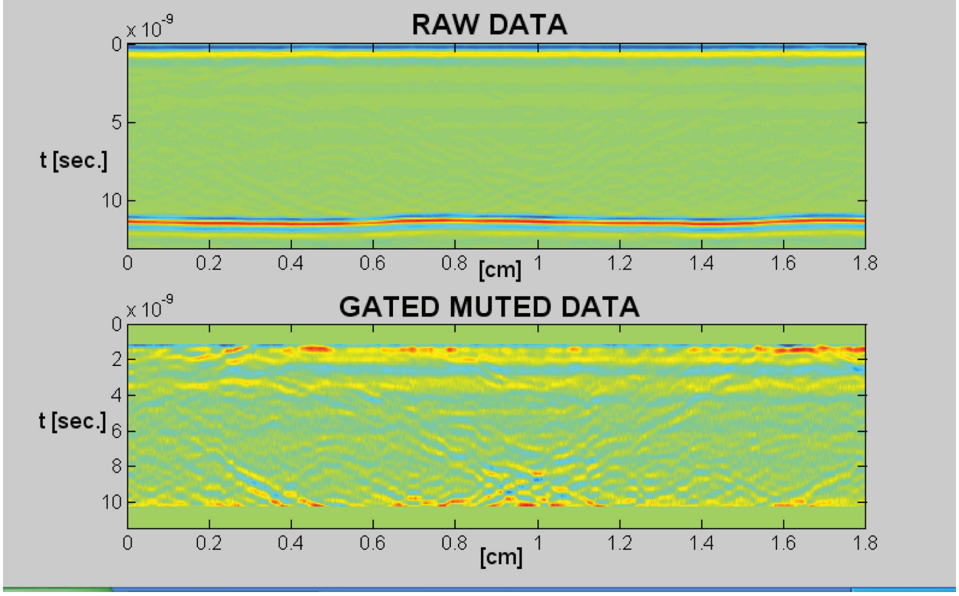

FIGURE 4
Raw data and gated and muted data for a circular prospecting around column C3 at a height of 1.3 m.

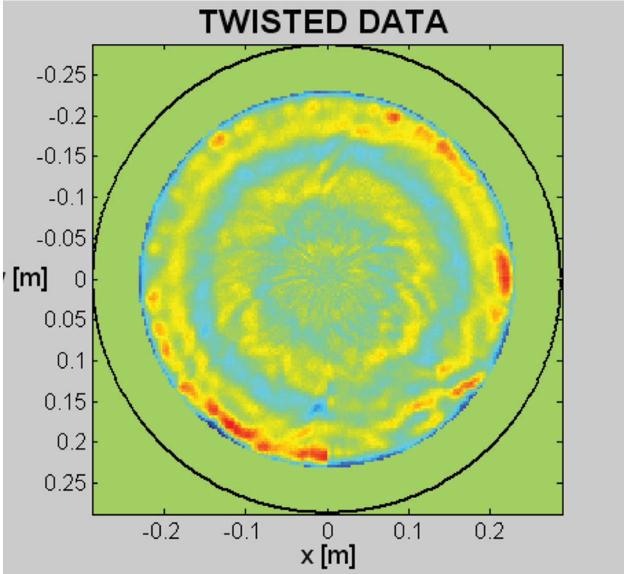

FIGURE 5
Twisted data for column C3 at a height of 1.3 m.

exploited for the vertical scans but making use of a different Green's function (Harington 1961)) is encouraged.

In Fig. 3 a photograph of column C3 is shown. On the image, the heights of the circular observation line and the vertical observation line have been put into evidence. In Fig. 4 the raw data and the data achieved after zero timing and muting of the two interfaces air-column are shown. These data refer to a complete turn around the column at the height of 1.30 m from its basement. The circumference of column C3 (average value, because the columns tends to slightly restrict in the upward direction) was 1.8 m, whereas the average circumference of column C4 was 1.9 m.

In Fig. 5 the 'twisted' data are shown. The interface air-column corresponds to the external circumference (black solid line). In particular, the muting of the first part of the signal is necessarily paid with the erasing of the shallower part of the column. As a matter of fact, column C3 seems quite well preserved and does not show any particular internal anomaly. The material that composes it (granite) is quite homogeneous in its nature and the apparent stratified structure visible in Fig. 4 (lower panel) and above all in Fig. 5 has not been fully understood by us at the moment. At any rate, we know that it is an artefact, both because of the *a priori* knowledge of the homogeneity of the constituent materials and because, if the layered structure were physical, it should appear also in Figs 9 and 10, in the form of vertical bars.

In Fig. 6 a photograph of column C4 is shown. Likewise with column C3, the levels of the circular observation line and the vertical observation line have been put into evidence. In Fig. 7 the raw data and the gated-muted data are shown, analogously to Fig. 4. In Fig. 8 the twisted data are shown, homologous to Fig. 5. As can be seen, this time the internal of the column is less homogeneous. This is the reason why the column is reinforced with the two metallic belts visible in Fig. 6.

From Fig. 8, we clearly appreciate the presence of two internal anomalies. We interpret them as two reinforcement bars and maybe the 'tail' of the lower hyperbola is due to some residual (after restoration) fracture profile. This interpretation is due to the fact that, on some other columns, the top of some reinforcement rebar is visible by eye, even if partially hidden in the stucco that the restorers have put on the columns. The image is much clearer than that provided by the gated and muted data of Fig. 7 (lower panel) and this shows the effectiveness of this reshaping. At this point, let us show the results of two vertical scans performed on the same two columns. In particular, in both cases the scan started from a height of 2.3 m from the basement, however, with regard to column C3 the scan has been performed down to the basement, whereas in the case of column C4 the scan has been arrested immediately before the lower circular belt that hindered continuing. Thus, the scan on column C4 is 2.1 m long instead of 2.3 m long.

The results obtained for column C3 are shown in Fig. 9, whereas the results obtained for column C4 are shown in Fig. 10. In both cases the figure shows, from the left to the right-hand side, the raw data, the gated and muted data and the result of a linear inverse scattering algorithm, respectively. The time-space conversion has been obtained measuring the propagation velocity in the column. This has been accomplished by means of the measure of the diameter, deduced by the circumference (as said, we have identified the reflection from the far interface of the column by means of a mobile external (metallic) target). In this way, we have estimated a relative dielectric permittivity equal to 8 for column C3 and equal to 7.5 for column C4. Even within the unavoidable uncertainty of this kind of the measure, we have verified that these values correspond quite well to the average values reported in literature for these kind of materials.

Moreover, the Cipollino marble results optically less dense than the granite, which is coherent with its averagely less compact structure. Let us also stress that a more precise non-invasive measure of the materials was virtually impossible. The raw data account for some propagation in air beyond the opposite interface of the column too. Moreover, from Fig. 10 (left hand and central panel), it is clearly distinguishable the passage of the GPR antenna on the upper circular belt, about at the ordinate $z = 1.2$. In particular, the belt erases the corresponding subsequent echoes, so that the hyperbolas appear as if they had been cut. The gated and muted data show some clear internal anomalies.

In the case of column C3, these are likely to be ascribable to internal metallic hinges between different trunks of column, because it was customary to link in this way different trunks of columns, as well as a column with its basement or its capital. In the case of column C4, instead, the anomalies are probably due to reinforcement bars inserted during the last restoration, performed in the 1990s. In fact, as said, some of the tops of these rebars are visible by eye and, moreover, the anomalies appear quite ‘punctually localized’.

Finally, on the right-hand side of both Figs 9 and 10, a focalization achieved by means of an inverse scattering algorithm is shown. The exploited model is based on the Born approximation and the relevant linear operator is discretized by means of MoM and point matching. The inversion is performed and regularized by means of a truncated singular value decomposition, numerically implemented by means of a homemade Matlab code. Details about this algorithm would be quite long and therefore interested readers are referred to, e.g., Persico (2006) and references therein.

Here, let us just specify some aspects related to the added value that can be provided by this inversion technique. First, with respect to a more classical migration algorithm, the approach of a linear inversion allows to account correctly for losses and is not related to stationary-phase-like approximations that can fail in near-field. Furthermore, the inversion by means of a singular value decomposition allows to choose the regularization level to apply to the reconstruction and above all allows to change it in real time if needed.

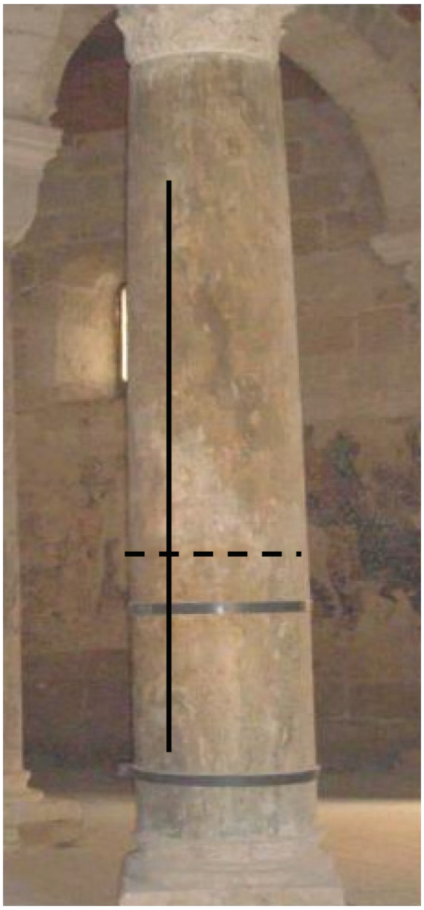

FIGURE 6
Photograph of column C4. The vertical line indicates the location of the GPR profile. The dashed line shows the location of the circular scan.

This is an important possibility, because the *a priori* choice of some optimal regularization level in practical situations is not an easy task and so this kind of flexibility of the inversion algorithm allows one to retain the result heuristically better versus the regularization level. From the inversion result, it can be seen that the presumed hinges seem vertically directed, whereas the presumed reinforcement bars seem to be directed along the radial direction, coherently to what is expected. The focalization effect is noticeable. In particular, with regard to column C3 (Fig. 9), the diffraction hyperbola a1 is virtually certainly referable to the metallic hinge between the two trunks of the column, the little pieces of hyperbolas a2 and a3 are probably referable to metallic connections between the upper trunk and the capital and between the lower trunk and the plinth, respectively. Instead, with regard

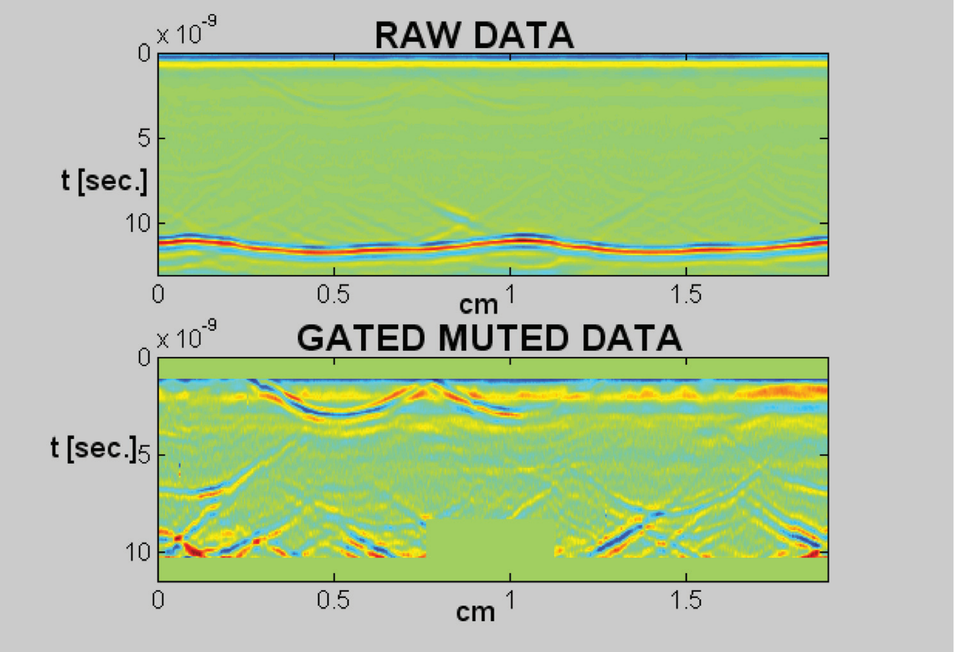

FIGURE 7

Raw data and gated and muted data for a circular prospecting around column C4 at a height of 1.3 m

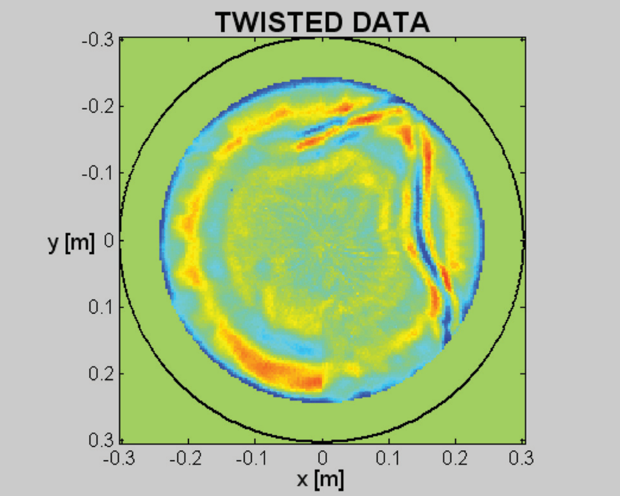

FIGURE 8

Twisted data for column C4 at a height of 1.3 m

to column C4 (Fig. 10), the diffraction hyperbolas b1, b2, b3 and b4 reveal the presence of reinforcement inserted in the column, whereas the apparent anomaly c is due to the external steel ring of reinforcement.

For comparison purposes, in Fig. 11 the inversion results are shown side by side with the results of a classical *f-k* migration algorithm, available within the post-processing software of the SIR 3000 system. The migration algorithm made use of permittivities automatically evaluated from the shape of the hyperbolas. In the case at hand, this automatic evaluation provided the values of 8.01 for column C3 and 7.57 for column C4. These values are noticeably close to those measured by us, based on the reflection from the opposite site of the column. From Fig. 11, we can see that the results of the two kinds of processing are not much different. Beyond some difference due to the choice of the basis function or some little difference of zero-timing, the main difference is that the migration algorithm still preserves some (even if attenuated) track of the hyperbolized pattern of the raw data, while the inversion does not.

ULTRASONIC INVESTIGATIONS

Ultrasonic investigations have been carried out on columns C3 and C4 to evaluate their state of conservation as well as the effectiveness of reinforcement interventions (bars) detected by GPR. This technique consists in the measure and observation of acoustic waves reflected/transmitted inside the investigated medium. Typical frequencies are 10^4–10^6 Hz . There are a number of applied methods. The most common are probably the reflection method and the direct transmission method. The first is based on the same principle of GPR (although it exploits waves of different nature) and makes use of a piezoelectric transducer at frequencies higher than 20 kHz in order to generate high-frequency ultrasonic pulses and investigate the presence of subsurface discontinuities (e.g., cracks), that back-reflect part of the energy. Signal traveltime can be directly related to the distance between the reflector and the observation point. Ultrasonic inspection in reflection mode is widely exploited for flaw detection/evaluation, dimensional measurements and material characterization. Its main limitations in the investigation of masonry structures are the high attenuation/scattering due to the heterogeneity of the materials (which limits the penetration depth) and the difficult implementation of a good coupling on rough surfaces, which can drive to a poor signal-to-noise ratio. The direct transmission method involves the crossing of a pressure wave through the structure from a source (piezoelectric transmitter) to a receiving sensor (accelerometer or piezoelectric receiver) located on the opposite side of the structure directly in front of the source point. The resulting wave velocity is an average value of the local velocity along the path. It can be plotted in a contour map and allows a simple evaluation of the relative internal condition of the structure and a semi-quantitative assessment of its mechanical properties.

On the marble columns ultrasonic tests in direct transmission mode have been performed by using a 2-channels, 24 bit MAE digital instrument (model A5000U) equipped with 55 KHz PUNDIT contact probes. The diameter of the transducers is 46 mm. For each position of the source, five measurements on the column have been taken, according to the scheme shown in the Fig. 12.

In order to obtain a good transmission of the acoustic energy and a good quality of the received signal, the ultrasonic probe has been matched to the marble by means of soft plasticine sticking to the transducer.

Let us clarify that, due to the less refined processing with respect to that applied to the GPR data and above all due to the intrinsic slightly smaller amount of information contained in the data (there are much less source and observation points and for each point the available datum was only the propagation time and not the entire received wave), with the ultrasonic prospecting we cannot look for a confirmation of the anomalies identified by means of the GPR prospecting. However, previous tests have shown that the presence of meaningful fractures is customarily associated to a substantial decrease of the propagation velocity

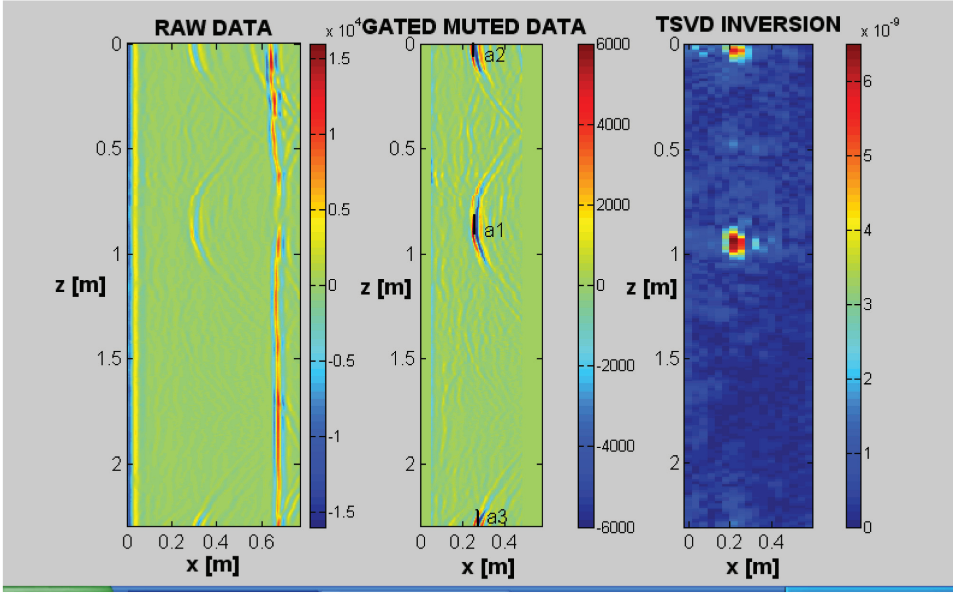

FIGURE 9
Vertical scan along column C3. The diffraction hyperbolas a1, a2 and a3 are referable to iron connections between the two trunks of the column, the upper trunk and the capital and the lower trunk and the plinth, respectively.

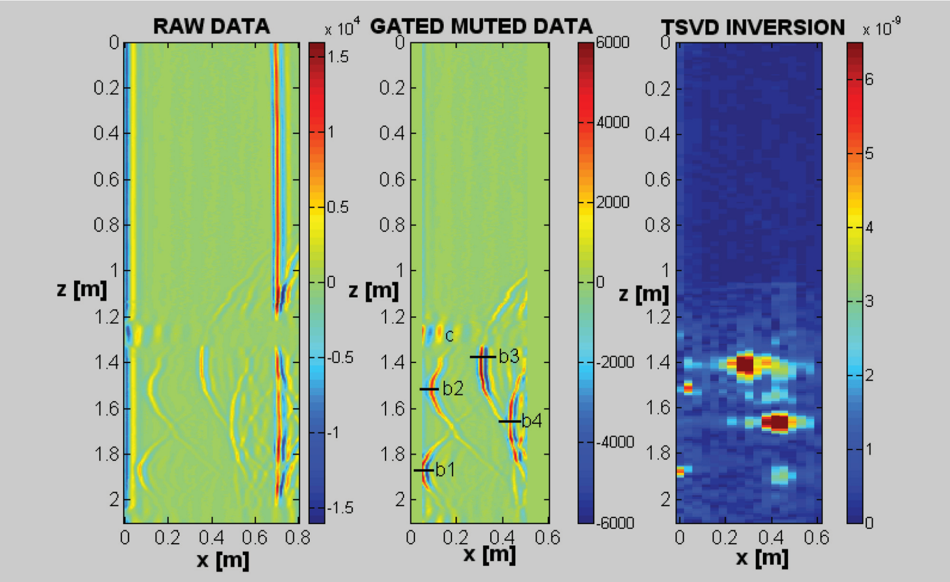

FIGURE 10
Vertical scan along column C4. The diffraction hyperbolas b1, b2, b3 and b4 reveal the presence of reinforcement inserted in the column, whereas the apparent anomaly c is due to the external steel ring of reinforcement.

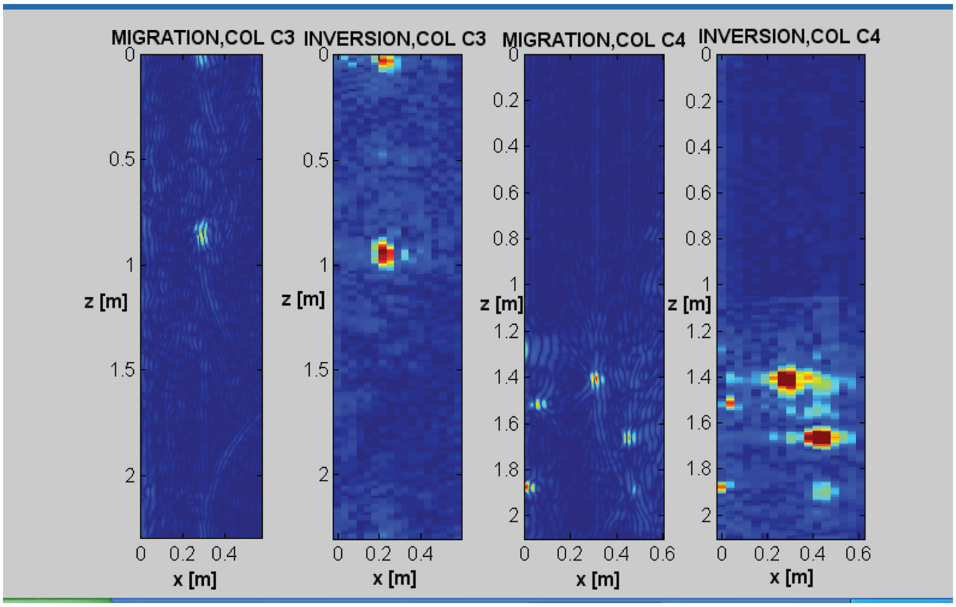

FIGURE 11
Comparison between the result of migration and inversion for columns C3 and C4.

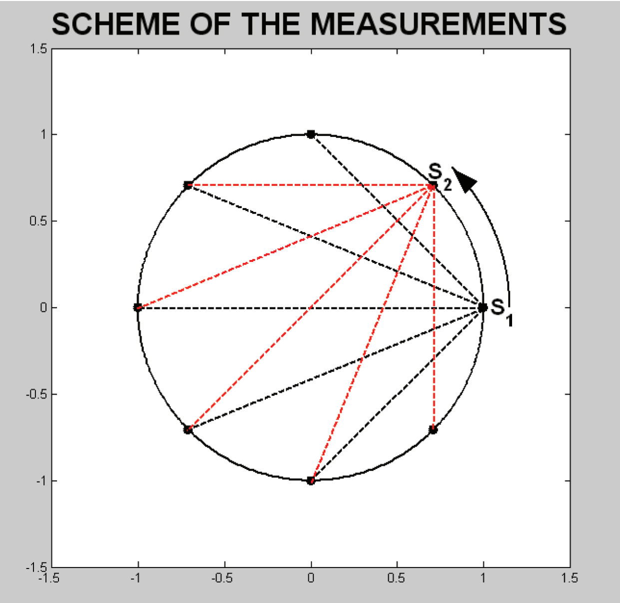

FIGURE 12
The data are taken according to the represented scheme. The source point is moved with an angular step of 45 degrees and for each source point five data are taken, starting from 90 degrees from the source point and with a step of 45 degrees.

(an analogous phenomenon is not recorded with the electromagnetic waves radiated by a GPR system). In particular, in the cases of the marble columns of some medieval churches in Apulia, affected by heavy cracks, ultrasonic tests measured minimum velocity values of 2200–2800 m/s in the damaged part and a velocity of 5000–5500 m/s in the well preserved part, with a standard deviation of the velocity of the order of 800–1000 m/s (Capriuoli *et al.* 2006; Nuzzo *et al.* 2008). So, the ultrasound prospecting is essentially aimed to measure the average propagation conditions of the ultrasonic waves inside the column. On column C3 the ultrasonic tests have been performed at heights (H) of 1.30m and 1.70 m: the latter is quite close to the discontinuity between the two piled trunks that compose the column. Column C4 has been investigated at heights of 1.40 m and 1.80 m. The lower height is relatively close to the upper steel reinforcement ring (see Fig. 6).

The tests showed high average velocities (from 4887–5007 m/s, see Table 1) in each of the four investigated sections and low values of standard deviation (from 74–135 m/s, see Table 1 and Fig. 13). Consequently the data provided by ultrasonic tests (velocities and standard deviations) on the two columns of the Church of San Giovanni in Brindisi are indicative of a fairly good state of preservation and homogeneity, also for the Cipollino marble of column C4. The tomographic pattern does not put in evidence any particular internal anomalies.

This confirms the effectiveness of reinforcement interventions carried out on column C4 and the choice to not strengthen column C3.

CONCLUSIONS

In this paper an integrated non-invasive measurement campaign on two columns of the church of San Giovanni al Sepolcro in Brindisi have been shown. Non-invasive techniques are often the only ones safely applicable to historical monuments and of course also in the described case history it would have been quite critical to make an investigation of the internal status of the columns by means of some invasive technique. It has been shown that the internal status of the monument does not appear to be critical. This result is not so obvious because, as said, virtually all the internal columns are visibly leaning and the trace of several (restored) fractures are still visible on several columns. GPR prospecting has been able to retrieve some archaeological information (in particular, about the insertion of conjunction metallic hinges in column C3) and some information about the performed restoring.

To these advantages, let us outline that there is no precise report about the exact position of the rebars inserted in column C4 and that many of them are not visible to the outer surface of the column, even if some of them are visible. So, the capability of a GPR to find them is a valuable resource if in the future some restorers should act again on the columns. Moreover, the inversion approach can focus meaningfully the inner anomalies. Let us also outline the fact that the linear inversion method has its intrinsic limits, as any focusing method (including of course the classical migration algorithm, nowadays commercially available within the post-processing software of any GPR system) and their correct application and interpretation requires some experience and often some multidisciplinary interaction. In particular, the interpretation of the data that have been provided in this paper do not rely on the mere results of the inversions but also on the *a priori* (petrographic, architectural and archaeological) available information. The ultrasonic prospecting allowed to check the good state of the inner parts of both columns C3 and C4. The average values of the propagation velocity of the acoustical waves are satisfying (values of the order of 50% of those measured would have been worrying) and the variations between the columns and between the velocity values at different heights within each column are not meaningful from a civil engineering point of view.

Post intervention monitoring is an important aspect in the proper preservation of cultural heritage and this paper shows an example, performed about fifteen years after the last restoration. Post interventions monitoring should be periodical and the data should be compared both with the expected results in a normal situation and with the previous data gathered in that specific monument. Within our possibilities, we will try to repeat the measurements in Saint John twenty years from now.

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TABLE 1

Minimum, maximum, average values and standard deviations of ultrasonic velocities measured on the two columns C3 and C4

	Column C3 **Z = 1.3 m; D = 0.56 m**	**Column C3** **Z =1.7 m; D = 0.54 m**	**Column C4** **Z = 1.4 m; D = 0.59 m**	**Column C4** **Z = 1.8 m; D = 0.59 m**
Min.	4630 m/s	4630 m/s	4687 m/s	4926 m/s
Max.	5072 m/s	5065 m/s	5043 m/s	5049 m/s
Average value	4971 m/s	4914 m/s	4887 m/s	5007 m/s
Standard deviation	135 m/s	149 m/s	101 m/s	74 m/s

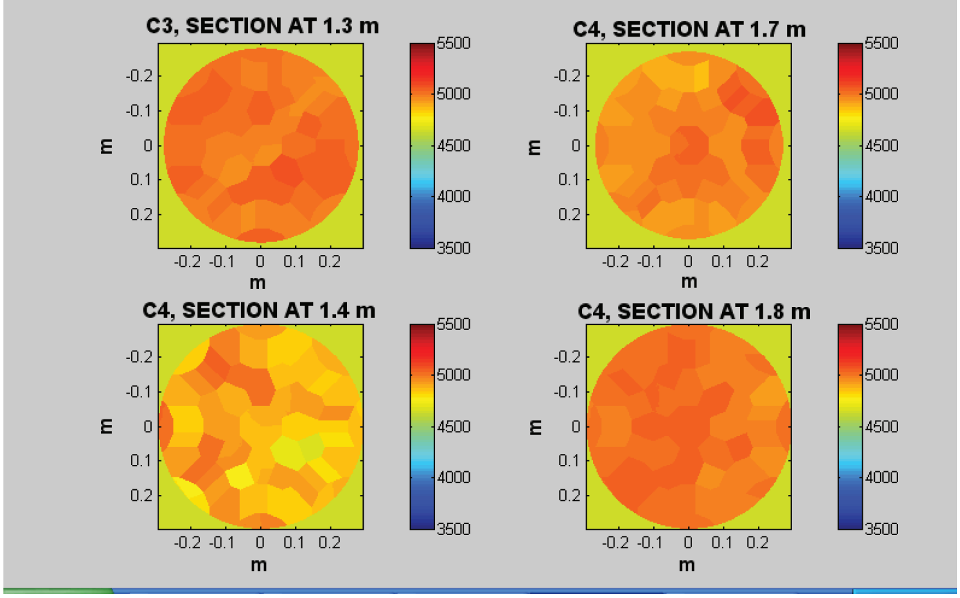

FIGURE 13

Ultrasonic tomography of columns C3 (sections at heights of 1.3 m and 1.7 m) and C4 (sections at heights of 1.4 m and 1.8 m)

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