

RESEARCH ARTICLE

Geophysical surveying of the ancient walls of the town of Cagliari, Italy, by means of refraction and up-hole seismic tomography techniques

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Abstract

The ancient walls of Santa Croce in the town of Cagliari (Sardinia, Italy), date back to the Middle Age and have had, until the nineteenth century, several interventions with superpositions and modifications. Beyond the historical and archaeological interest, the study of the structure of the ancient walls became necessary in view of building an underground car parking just at the base of the walls itself. With this purpose, in addition to classical archaeological surveys a geophysical non-destructive survey with seismic techniques has been carried out, namely two refraction tomographies aimed at characterizing the rocks at the base of the walls, and four up-hole tomographies across the walls itself. These geophysical surveys provide good geotechnical information on the foundation condition, the problematic feasibility of the underground parking and, along with the archaeological procedures, on the heterogeneous structure of the walls.

KEYWORDS

archaeology, Cagliari, military architecture, refraction seismic tomography, up-hole seismic tomography

1 | INTRODUCTION

At the beginning of the thirteenth century the Republic of Pisa began to build the upper part of the city of Cagliari with a defence line within which the district called 'Castello' (the Castle) would arise (Cadinu, 2015). A century later, the Aragonese expanded the perimeter of the defence line with vertical walls and cylindrical towers still detectable in the west side of Castello. Major changes took place in the sixteenth century through a construction system consisting of ramparts interconnected by walls inclined at the base. The constructive system of the walls included, between the main body of the walls and the outside, an embankment of earth and dry wood bundles, supported by a masonry structure well described in the military treaties of that time. In order to lighten the structure, this system also implied the construction of a series of short walls (septa) orthogonal to the main body and laterally interconnected by means of arched roofs; the bastion was subsequently integrated externally by a masonry shirt – generally but not everywhere of remarkable

thickness – not connected to the main body or to the sects. This system, widely adopted for building fortresses in Sardinia, was particularly in line with the military treatise '*Della Fortificazione delle città*' (*Fortification of the Cities*), published in Venice in 1564 by two specialists of the sixteenth century, Girolamo Maggi and Jacopo Fusto Castriotto (Maggi & Castriotto, 1564). In fact, the earlier treatise has been the reference book for the brothers Giorgio and Jacopo Paleari, military engineers at the service of the Crown of Spain from 1558 to 1589. Figure 1 shows the constructive technique explained earlier.

In the west area of 'Castello', some of the most significant works by Paleari were aimed at modifying and completing the works designed by Rocco Capellino from Cremona (northern Italy), active in Sardinia from 1552 to 1572 (Spano, 1861).

The most relevant of these additional works has been the bastion of Santa Croce (Figure 2) built between 1568 and 1578, later affected by several collapses with subsequent reconstruction and completion works (Viganò, 2004).

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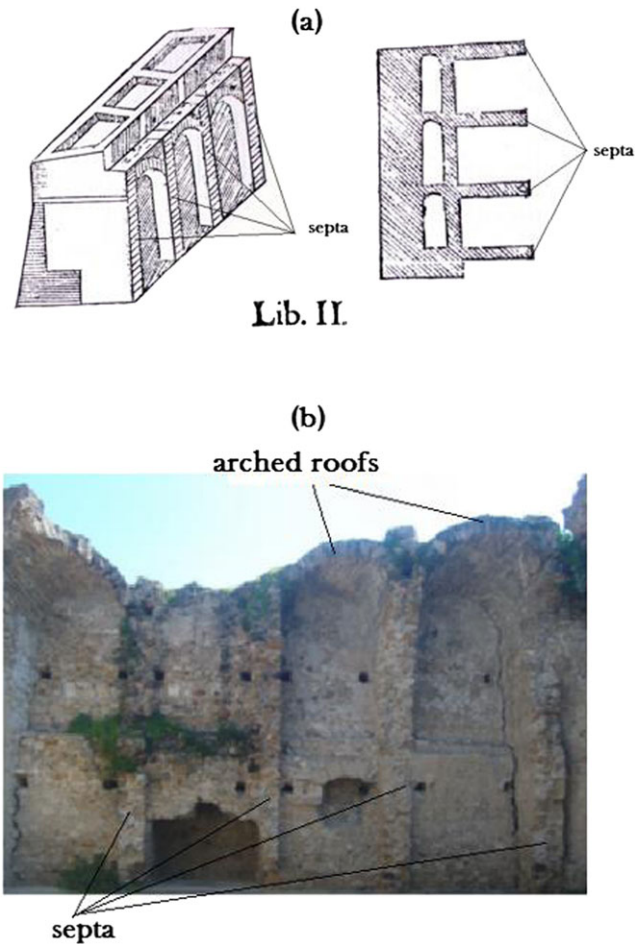


FIGURE 1 Constructive technique with septa connected by arched roofs: (a) axonometric view of the septa system (after Maggi & Castriotto, 1564, modified), and (b) remains of an example of the constructive technique realized by Giorgio Paleari in Alghero, northern Sardinia (Pirinu, 2013) [Colour figure can be viewed at wileyonlinelibrary.com]



FIGURE 2 The bastion of Santa Croce today [Colour figure can be viewed at wileyonlinelibrary.com]

The transformations of the defence line in the area of Santa Croce are represented in the historical cartography and in the drawings realized by the military engineers, which have so far allowed the reconstruction of some fundamental steps of the entire works (Pirinu, 2013). In this area is currently being planned the construction of an underground parking at the foot of the bastion. These future works could interfere with the static conditions of the current structure of the monumental complex and then require special attention in the designing phase and detailed knowledge of the complex itself and the boundary conditions. For this last reason, but also – maybe above all – with the aim of satisfying the large interest of acquiring more details on the structural features and evolution of the historical complex, a geophysical study has been planned and executed.

2 | GEOPHYSICAL DATA ACQUISITION AND PROCESSING

Geophysical prospecting is often used in the study of historical structures and important archaeological sites, both in order to obtain archaeological information and to verify their conditions, especially in view of interventions that may in some way interfere with them: ground penetrating radar (GPR), seismic refraction tomography, electrical resistivity tomography, time-domain electromagnetic soundings, are among the most often used geophysical methods in archaeological prospecting (e.g. Orlando, Cardarelli, Cercato, & De Donno, 2015; Ovenden, 1994; Polymenakos, Papamarinopoulos, Miltiadou, & Charkiolakis, 2005).

The geophysical techniques here employed are the seismic refraction tomography and the up-hole seismic tomography (Balìa, 2013; Bregman, Bailey, & Chapman, 1989), the latter rarely employed in archaeological research. The first stage consisted of two seismic P-wave refraction tomographies placed just in the area where the underground parking should be realized, that is at the base of the ancient walls, as shown in Figure 3. Data acquisition was carried out by means of a 48-channel digital seismic recorder with a 24-bit A/D converter, record length of 300 ms and 0.125 ms sampling interval. The acquisition was as follows: spread length 160 m, 12 Hz natural frequency geophones at intervals of 3 m, shot interval 6 m, plus two external shots; energy source: hand hammer 8 kg. Data processing was performed by means of a software based on a non-linear optimization technique (ASA, Adaptive Simulated Annealing; e.g. see Ingber, 1996) that works in terms of modelling, starting from the set of the first-arrival times and the spread geometry.

The second stage of geophysical data acquisition consisted of four up-hole P-wave seismic tomographies across the ancient walls. Figure 4 shows a qualitative scheme of the up-hole tomographies. Data acquisition was carried out with the same apparatus used for the refraction tomographies, with 12 Hz horizontal geophones fixed to the surface of the walls by adhesive strips, at 1 m interval from each other along vertical lines, 12 geophones for each tomography; the shots were realized inside vertical boreholes drilled on the top of the upper courtyard, at 1 m interval from each other, by means of a new down-hole energy source (Balìa & Uda, 2015); data processing was done with the same software employed for refraction tomographies. Figure 5 shows the position of the four up-hole tomographies used in the study.

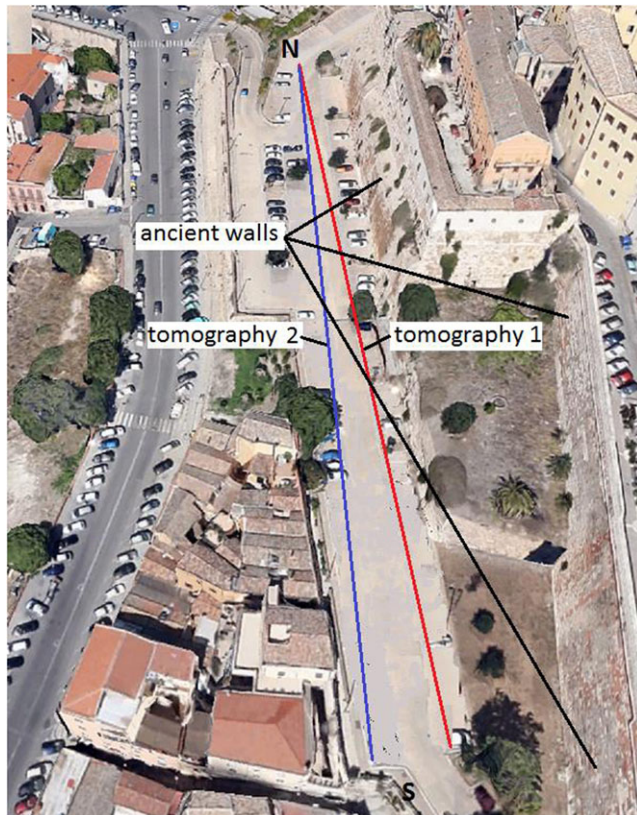


FIGURE 3 Position of the two seismic refraction profiles – To which correspond tomography 1 and tomography 2 – In the area of the future underground parking [Colour figure can be viewed at wileyonlinelibrary.com]

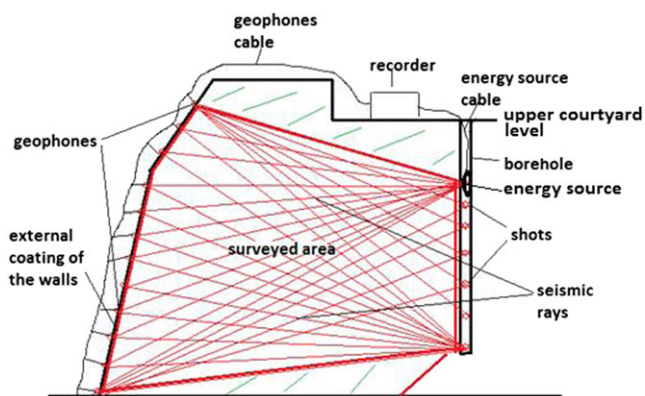


FIGURE 4 Data acquisition scheme of the up-hole tomographies [Colour figure can be viewed at wileyonlinelibrary.com]

3 | INTERPRETATION OF THE GEOPHYSICAL RESULTS IN TERMS OF GEOTECHNICAL, ARCHAEOLOGICAL, AND HISTORICAL MEANINGS

3.1 | Refraction tomographies

Figures 6 and 7 show the two seismic refraction tomographies: black and grey small triangles on the top indicate the position of geophones and shots, respectively. The P-wave velocity is represented in the colour scale at the bottom of Figure 7. Surface

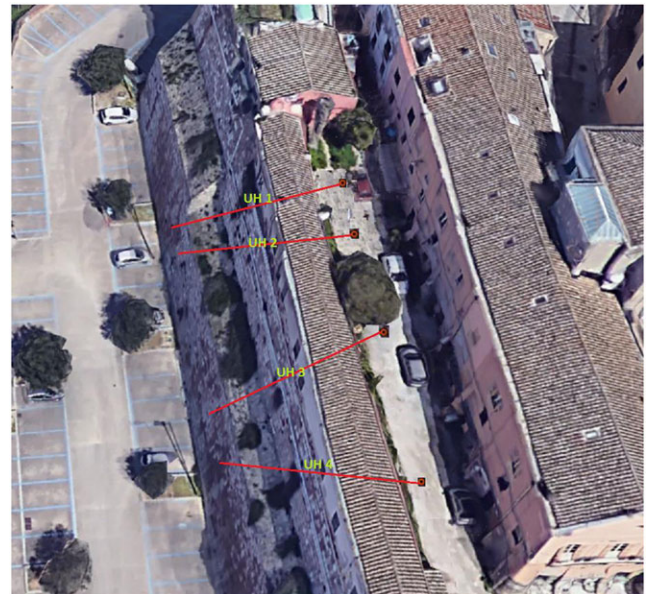


FIGURE 5 Position of the four up-hole tomographies across the walls [Colour figure can be viewed at wileyonlinelibrary.com]

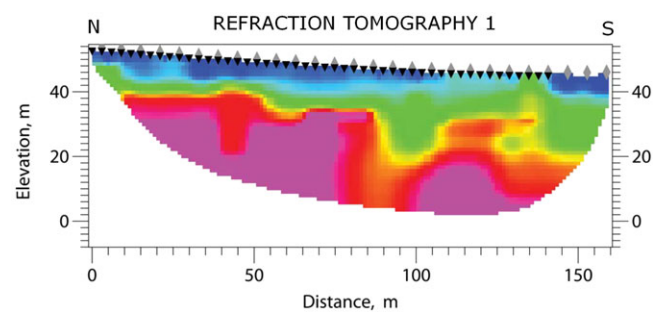


FIGURE 6 Refraction tomography 1, the closest to the base of the ancient walls [Colour figure can be viewed at wileyonlinelibrary.com]

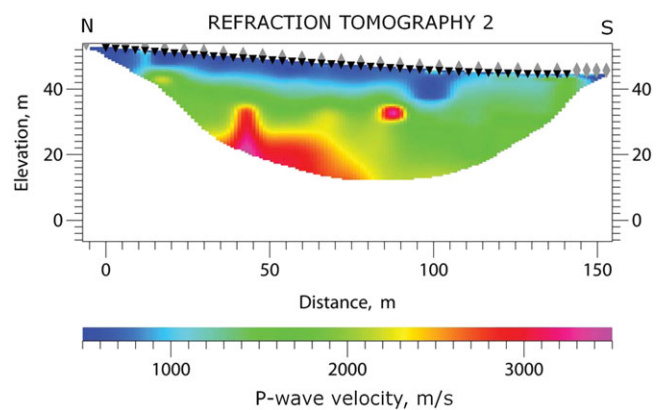


FIGURE 7 Refraction tomography 2, the farthest from the base of the ancient walls [Colour figure can be viewed at wileyonlinelibrary.com]

materials have P-wave velocity of the order of 500–1000 m/s (blue), relatively weathered Miocene limestone has a velocity of 1700 m/s (green) and the bedrock, made up of less weathered or integer Miocene limestone, has a velocity in the range 2800–3500 m/s (red–purple). According to the tomographies – integrated with four shallow probing holes × the thickness of surface

materials, loose and made up of soil composed with the remains of bricks and pebbles, is of the order of 0.5–6 m, and that of weathered limestone is in the range 3–20 m.

The thickness of surface materials is almost the same in the two tomographies while that of weathered materials is smaller in tomography 1 – that is close to the walls – and increases rapidly westwards, as clarified by the comparison of the two tomographies. In fact, as shown in Figure 8, the ancient walls are founded on limestone that deepens the more you move away from the walls. Especially in tomography 1 several discontinuities appear, such as the one at the progressive 75–110 m, where the limestone is clearly weathered and/or fractured. In the refraction tomography 2, the isolated rocky boulder immersed in weathered rock at the progressive of 85 to 90 m and depth of about 12 m from the surface is clearly depicted. After all, it could be said that the foundations of the ancient walls are presently good but, as argued later, this condition is not sufficient for the safe construction of the underground parking.

3.2 | Up-hole tomographies across the walls

While the earlier commented refraction tomographies provide information mainly useful for geotechnical purposes, the up-hole tomographies provide information with high historical and archaeological meaning. From the geophysical point of view, the four tomographies, shown in Figures 9–12 with the archaeological interpretation, exhibit similar characteristics. The numbers in Figures 9–12 are associated as follows:

- 1: compact Miocene limestone with P-wave velocity of 3500 to 4700 m/s;
- 2: weathered Miocene limestone with P-wave velocity of 2000 to 2500 m/s;
- 3: highly weathered Miocene limestone with P-wave velocity of about 1500 m/s;
- 4: man-made structures with variable P-wave velocity;
- 5: filling materials with low P-wave velocity (less than 1000 m/s).

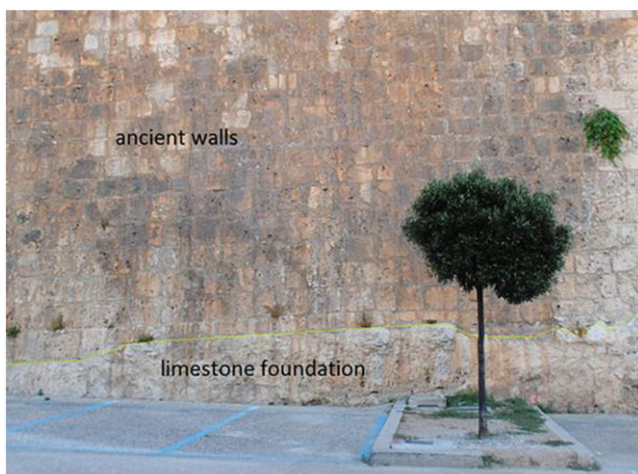


FIGURE 8 The Miocene limestone basement of the walls [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

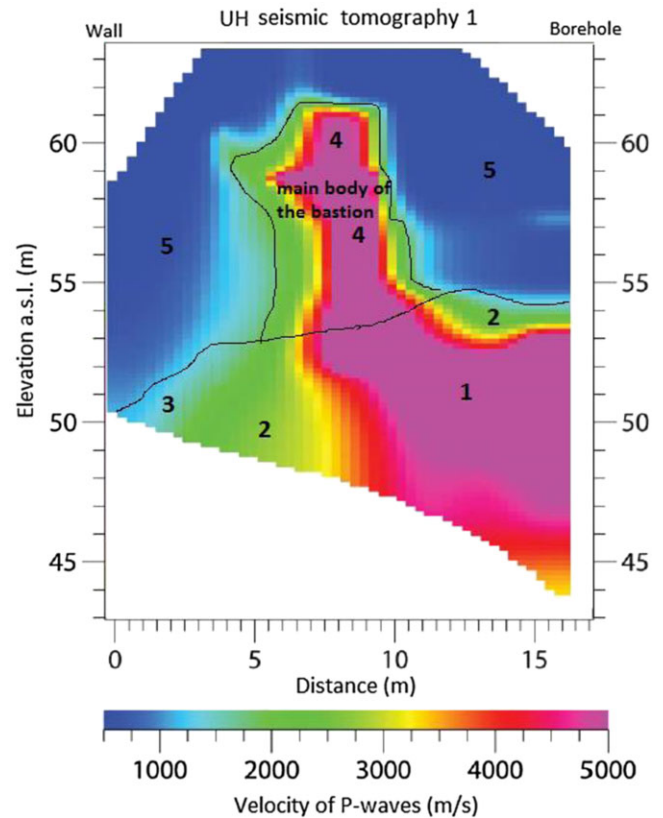


FIGURE 9 The main body of the bastion, apparently in good conditions [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

Generally, as also confirmed by borehole stratigraphies, the depth to limestone bedrock is of the order of 8 to 10 m with respect to the ground level of the court where the drillings were placed, that is shown on the right-side of the figures (Figures 9–12).

The up-hole tomography 1 in Figure 9 shows the core of the ancient walls almost integer, and the abundant filling on both sides; the high P-wave velocity, which reaches the order of 5000 m/s, showing that the masonry in this area is still of good quality.

The up-hole tomography 2 in Figure 10 shows different conditions since only the base portion of the wall seems integer while the upper part is disconnected: in Figure 10, this upper part is marked as ‘relict of the main body’ but an alternative interpretation, supported also by the position of the earlier said relict, might make you think it is a septum. On the top-right side of the same up-hole tomography 2, appears a buried wall immersed into the filling. As confirmed by a shallow excavation, this narrow wall is the foundation for the houses built in the nineteenth century on top of the ancient walls and still existing.

The interpreted up-hole tomography 3 in Figure 11 demonstrates that the construction or reconstruction criteria have not always been the same along the development of the ancient walls. In fact, a typical structure with big steps is well depicted: most probably, owing to the collapses occurred in this area, as mentioned in the literature (Viganò, 2004), and reconstruction having been made with structures that are massive or, more simply, have been reinforced on both sides of the original wall: this type of intervention is mentioned in the manuals of military buildings of the time (e.g. Maggi & Castriotto, 1564)

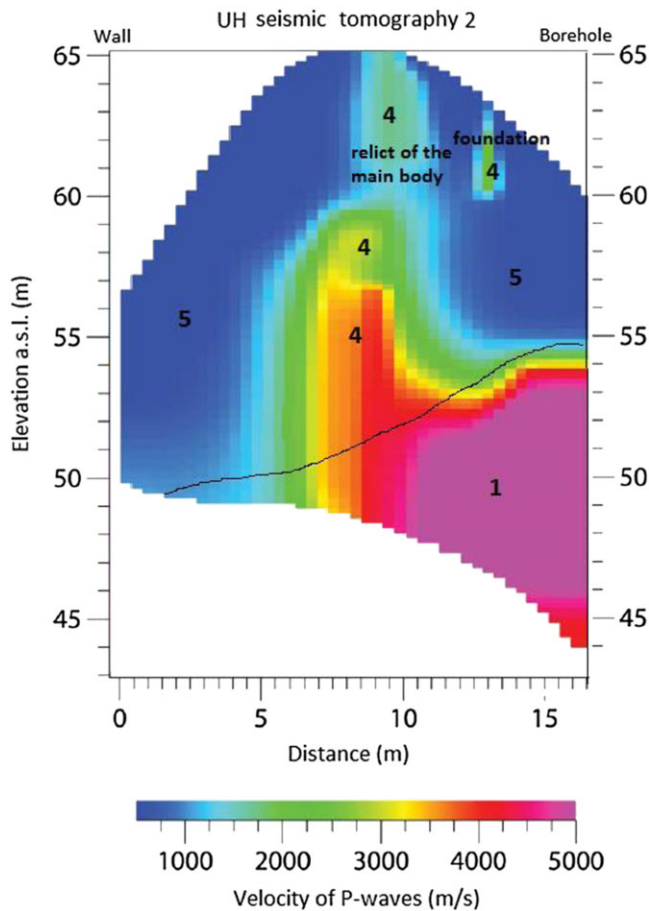


FIGURE 10 In spite of what can be seen from the outside, the tomography shows that in this area the bastion has been damaged [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

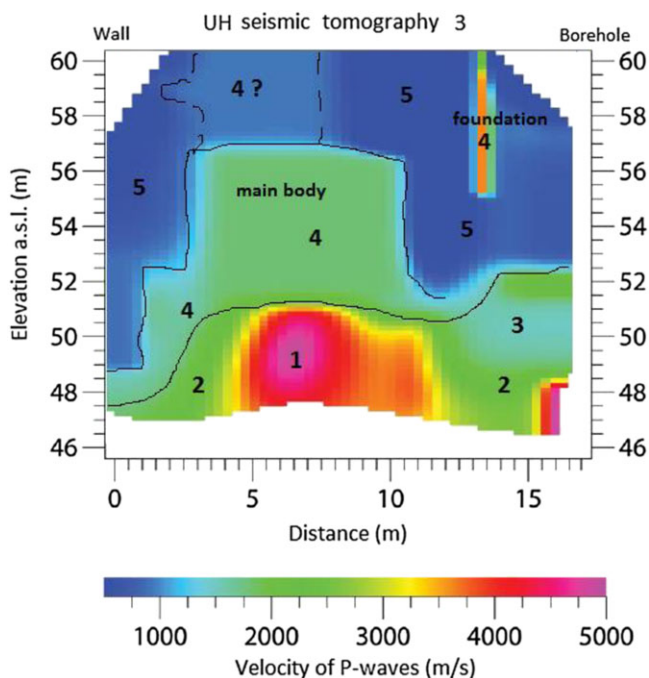


FIGURE 11 Up-hole tomography 3: The construction technique seems different with respect to what is seen in Figures 9 and 10 [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

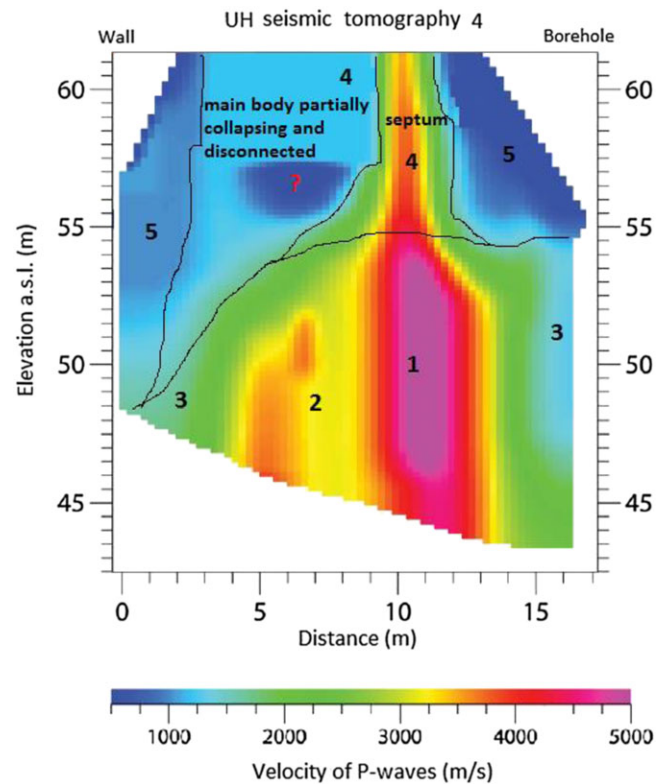


FIGURE 12 Up-hole tomography 4: The structural components of the ancient walls seem to have been revealed [Colour figure can be viewed at [wileyonlinelibrary.com](#)]

among the possible ones to reinforce the structures. On the top of the main body, there is a kind of low-velocity shadow whose shape recalls the top of the main body as appears in Figure 9: the shape is very similar but we cannot be sure of the said correspondence without additional investigations. Again appears, on the top-right, of the buried foundation wall.

Figure 12 shows a possible and suggestive interpretation of the up-hole tomography 4. Apart from the limestone base, in the top half of the tomography, from right to left, we see: filling > integer septum > main body in poor conditions > filling. The reason for why the septum is integer while the main body is not, could be attributed to the substantially different conditions at the foundation. In fact, while the septum – which is a relatively light structure – is founded on an almost horizontal rock surface, the main body lies on a bedrock inclined of about 45°: bad static condition that facilitates sliding and consequent disconnection of the blocks. Incidentally, it should be emphasized that prior to current geophysical surveys there was no certainty about the architectural solution with septa interconnected with arched roofs in the area of the present research. The low-velocity hole inside the wall (question mark) could be a kind of tunnel or chamber.

3.3 | Synthesis of the geotechnical evidences

Further to what has already been mentioned, it is noticeable that in the up-hole tomographies nothing appears about the outer rock-coating of the ancient walls clearly shown in Figure 8. This means that what we see is nothing but a simple coating with modest thickness,

whose functions are purely aesthetic and of containment of the loose filling materials purposely disposed to dampen the destructive effects of artillery shots and protect the true structure of the walls; the small dimensions of the blocks support this interpretation. Therefore, although at present there are no signs of subsidence, the body of the ancient walls does not appear to be massive, continuous or homogeneous, being mainly constituted by fillings and structures in poor static conditions. In fact, a geotechnical modelling of the complex of the foundations and walls, substantially based on overall geophysical results (both refraction tomographies and up-hole tomographies) concluded that:

... The opening of the excavation could result in an instability condition, both in the new rock wall produced by the excavation itself and in the overhanging historical wall and in the materials it contains. The present situation, although characterized by an evident condition of stability, includes some critical zones – located at the base of the bastion – from which, in the absence of a proper containment, breakage surfaces would develop following the excavation. In order to maintain the whole stability it is necessary to intervene, before and at the same time of the development of the excavation, to prevent the stress redistribution as calculated in the numerical simulations carried out. (University of Cagliari–Italy, Internal Technical Report, unpublished)

Summing up, it must be emphasized that the refraction tomography technique revealed to be useful only for geotechnical purposes, while the up-hole tomographies provided high detail information for both geotechnical and historical/archaeological purposes.

4 | CONCLUSIONS

As mentioned in the introduction, the original target of the geophysical surveys was to acquire useful data for verifying the feasibility of underground parking in the area in front of the ancient walls. However, the geotechnical modelling of the historical complex, consisting of the foundation soils and the body of the walls, suggested to suspend – at least temporarily – the construction of the underground parking.

Beyond the geotechnical information provided mainly by the geophysical work, the results of the up-hole survey clarify the inner structure of the ancient walls and confirms the presence of constructive systems widely used in the fortresses of the Spanish Mediterranean, consisting of an embankment supported by masonry structures that combine massive elements with slender ones (masonry septa), the latter in the origin connected each other by masonry vaults and not rigidly connected to the outer finishing of the walls.

In at least three of the four up-hole tomographies, apart from collapses and consequent reinforcements and reconstructions attributable to the Paleari brothers – who intervened to expand and partially rebuild the walls in the years 1576–1578 – are visible

constructive profiles recalling the original architectural solutions of Rocco Capellino which often used step profiles – such as that identifiable in tomography 3 – in other construction sites in Sardinia, for example the walls of Alghero, north-western Sardinia (Pirinu, 2013). Another factor, which is important to expand the catalogue of designing and creating solutions of fortifications such as those here treated, is that while generally the outer shirt of the walls is thick (in Alghero both Capellino and the Paleari brothers adopted thicknesses in the order of 3 m at the base), in the case of the bastion of Santa Croce, as revealed by the up-hole tomographies, the thickness is smaller, no more than 1 m.

Finally, although originally the seismic surveys were not specifically designed for historical-archaeological purposes, they have proved to be a powerful tool for analysing the hidden conditions in sites where direct excavations are not always allowed and where other geophysical techniques, for example the electrical and electromagnetic ones, including the widely used ground penetrating radar (GPR), suffer from high noise levels and cannot guarantee the required resolution and depth of investigation; this can be said especially for the up-hole seismic tomography technique, for which no previous application examples in archaeology have been found in the literature.

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