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The role of crosshole seismic tomography for site characterization and grout injection evaluation on Carmo convent foundations

M.J. Coelho, F.M. Salgado & L. Fialho Rodrigues
LNEC - Laboratório Nacional de Engenharia Civil, Lisboa, Portugal

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ABSTRACT: The Carmo convent (XIV century) is founded on a silty-sand formation subjected to several negative impacts that have weakened the stiffness and strength characteristics of the local soils. A previous finite element analysis was carried out to assess the stability conditions for constructing a new underground railroad passing 20 meters below the convent foundations. The results indicated that upper soils might be, in some areas, highly uncompressed and very close to failure or in a plastic state. To confirm these and to try mapping the higher uncompressed zones, various instrumental measurements and in situ tests were carried out, including an extensive crosshole seismic tomography survey on 26 crosshole sections to obtain their P-wave velocity field. In general, the seismic tomographies obtained validated the finite element results.
A jet grout treatment test was carried out at a zone under the convent foundations where the seismic tomography had revealed very low P-wave velocity. Afterwards, the crosshole seismic test was repeated and the corresponding tomography showed that upper soil velocities had increased to values near the velocities for deeper (and less disturbed) soils. Additionally, three crosshole seismic tomographies were performed at a control site with a geological setting similar to the convent foundations, but not subjected to the same negative impacts. The P-wave velocities obtained for these undisturbed soils are about the same as the velocities for the convent foundations after the grout treatment, which confirms the test injection efficiency in improving soil characteristics below the Carmo convent foundations.

1 INTRODUCTION

The Carmo convent is a historical building from the XIV century located on the Carmo hill in Lisbon downtown. It is founded on miocenic terrains basically consisting of silty-sand soils, above the water table. These soils belong to “Areolas da Estefânia” formation (Almeida, 1986). In this formation, mainly at the surface and at deposit top, there are highly uncompressed soils (loose and very loose sands), which have already posed stability problems during the construction of several public works, like the Rossio railway tunnel (Almeida, 1991) and the Carmo convent itself (Fr. de St^{a} Anna, 1745) . Furthermore, at the convent site, this formation has been subjected to several negative impacts, like the 1755 Lisbon earthquake (M>8), which caused severe damages to the convent, due to the structure dynamic movements and due to the partial slope failure of Carmo hill. More recently, in the last decades, some shops on Carmo street, at the hill foot, have expanded their storage area by digging galleries inside this formation below the convent foundations. Since these galleries were excavated by artesian methods, the surrounding soils were significantly uncompressed. The impact from the earthquake and from diggings weakened considerably the stiffness and strength characteristics of local soils.

In 1996, due to the planned construction of a new underground railroad line, passing 20 meters below the convent foundations, it was necessary to study the site stability conditions. A finite element tension-deformational analysis for the convent foundation soils was carried out by Consórcio (1996a), based on available geological and geotechnical data (Consórcio, 1993). The results indicated that the soils between the galleries roof and the convent foundations might be in some areas highly uncompressed and very close to failure or in a plastic state (Consórcio, 1996a, Salgado, 1996 and Salgado & Coelho, 1996).

In view of these results, micro-piles were designed to reinforce the convent foundations. The micro-piles were to be founded on the “Areolas da Estefânia” underlying formation, named “Argilas dos Prazeres”, in order to transfer the structure load to this deeper and stronger formation. However, this solution could pose other problems related with the uncompressed soils under the convent foundations. Micro-pile construction could dense the deeper sands and therefore cause additional movements on upper uncompressed soils. Another problem would be the possible negative friction on micro-piles caused by the creep or erosion of upper soils. To overcome these problems, the grout injection of these upper soils was proposed (Consórcio, 1996a, Salgado, 1996 and Salgado & Coelho, 1996).

To confirm the finite elements analysis and to map the higher uncompressed zones, an extensive crosshole seismic tomography testing was carried out by LNEC (*Laboratório Nacional de Engenharia Civil*) on 26 crosshole sections (see Fig. 1), using some of the micro-pile boreholes before their construction. The seismic tomographies obtained showed that soils above the galleries had much lower P-wave velocities than soils (of the same type) below the galleries, therefore validating the finite element results (Salgado & Coelho, 1996). Another objective of crosshole seismic tomography was the grout injection evaluation. The main-chapel zone, with an underground gallery below its foundations, in particular the F77-F92 crosshole section (gray zone in Fig. 1), was a critical zone from the stability point of view, where finite element analysis indicated a possible plastic state and the crosshole seismic tomography revealed very low velocities in the upper soils. Consequently, a jet grout treatment test was carried out in this zone to evaluate if injection could improve the soil characteristics (Consórcio, 1996b,c). After grout injection, the crosshole seismic test was repeated and the corresponding tomography showed that soil velocities had increased to values closer to the velocities for deeper and less disturbed soils.

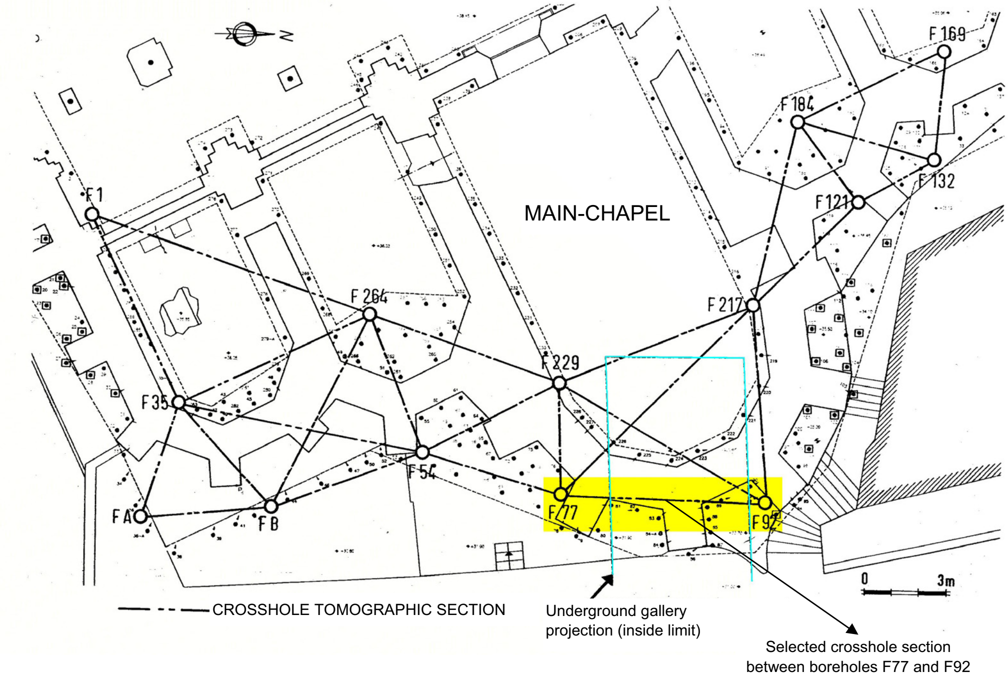

Figure 1. Carmo convent site: plane view of investigation area and tomographcic sections arrangement. The gray zone indicates the selected crosshole section (between boreholes F77 and F92), where grout injection was evaluated (adapted from Coelho, 2000).

To evaluate if this seismic velocity increment due the soils grout injection is acceptable, i.e., to evaluate if this grout injection type was sufficient to increase the soils strength and stiffness to adequate values, LNEC carried out a seismic tomographic test at a control site where the same geological formation ("Areolas da Estefânia") occurs, but where the upper soils are not or are less uncompressed. So, their P-wave velocities were expected to be representative values for soils with adequate stiffness and strength from a stability point of view.

This paper presents the seismic tomographies obtained at the crosshole section selected for the grout injection test, before and after injection, as well as the seismic tomographies at the control site, where the existence of no uncompressed soils was considered.

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2 GEOLOGICAL SETTING

2.1 *Carmo convent site*

At the Carmo convent site, there is a sedimentary formation from miocenic age, named "Areolas da Estefânia". According to the previous geological-geotechnical study performed on this site (Consórcio, 1993), this formation consists mainly of fine silty-sand ("areolas"), medium sand, sandy-clay and interbedded calcarenite. Locally, this deposit is about 15 to 22 m thick with crossed stratification and frequent lateral *facies* variations. Under this formation, there is another miocenic sedimentary formation named "Argilas dos Prazeres" consisting basically of gray or green silty-clay. In general, there is a sandy-fill with variable thickness (0.5 to 10 m) above the convent foundations.

Fill soils are classified as loose, "Areolas da Estefânia" soils as loose to medium dense, and "Argilas dos Prazeres" soils as stiff to hard. The water table occurs near the interface between the two miocenic formations and therefore the upper formation ("Areolas da Estefânia") is unsaturated.

The sub-vertical boreholes F77 and F92 that were 32 and 34 m long define the crosshole section considered in this paper (see Figs. 1 and 3). They intercepted, from the top, 0.5 to 2 m of random sandy fill, 5.5 m of convent foundation material (probably consisting of a blend of rockfill and mortar), 15 to 15.5 m of silty-sand with interbedded calcarenite ("Areolas da Estefânia" formation) and under this, they intercepted silty-clay soils from "Argilas dos Prazeres" formation. This crosshole section also intercepts an underground gallery nearly transversal to it with about 11 m length and a vertical section of about 3.5 m height to 5 m width. This gallery was excavated from a shop on Carmo street, at Carmo hill foot, about 8.5 m below the foundations of the main-chapel of Carmo convent (Figs. 1 and 3). As Fig. 3 shows, this gallery was excavated inside "Areolas da Estefânia" formation and has a concrete lining of about 0.30 m.

2.2 *Control site*

A control site was chosen with a geological setting similar to the convent site but assumed to be an undisturbed site. This site is located on the crossroads of Anchieta and Capelo streets (in Lisbon) about 300m SW from Carmo hill crest (Carmo convent site), so the impacts from the 1755 earthquake are less severe (no slope failure occurred here). Additionally, no underground excavations or galleries exist at this site. Therefore, it was considered that, here, the original soils from "Areolas da Estefânia" formation would not be uncompressed and would have adequate stiffness and strength for site stability.

At this site, three sub-vertical boreholes F1 to F3 arranged in triangle were drilled to about 28 to 30 m depth (Fig. 4) and three crosshole seismic tomographies were performed at F1-F2, F2-F3 and F3-F1 sections. These boreholes intercepted from the surface, 1.5 to 2 m of sandy fill and 22.8 to 23.5 m of "Areolas da Estefânia" materials, where the upper 5 to 8 m was silty-sand with interbedded calcarenite or calacarenite with interbedded sand and the next 15.5 to 17.5 m was silty-sand. Under this formation they intercepted the "Argilas dos Prazeres" formation consisting here basically of silty-clay with interbedded marlstone.

3 SEISMIC TOMOGRAPHIES

3.1 *Method guidelines*

Over the last two decades, crosshole seismic tomography has been widely used to study the elastic properties of materials for a wide range of applications, from large engineering sites to ancient building surfaces (Pessoa, 1990 and Coelho, 2000).

For this particular crosshole seismc tomography, the objective is to reconstruct the P-wave velocity distribution in the crosshole section based on a multitude of seismic ray paths corresponding to crosshole seismic measures (Fig. 2). These measures can be the attenuation and velocity of both compressional and shear waves, but the most widely used is the P-wave velocity due to significant facility and quickness in data acquisition and unambiguity in time picking, in relation to S-wave velocity and attenuation measures.

For P-wave velocity tomography, the P-wave measured travel times are inverted into a velocity matrix, which comprises the area with seismic ray coverage. The most often used velocity inversion or reconstruction techniques are well described in the literature (Nolet, 1987, Pessoa, 1990 and Lo & Inderwiesen, 1994) and start with an initial velocity model for which the modeled travel times of seismic rays are calculated. The differences between modeled and measured travel times for seismic rays, called residuals, are then used for improving the initial model for the velocity distribution.

3.2 *Selected section at Carmo convent site*

At the main-chapel zone, below which there is an underground gallery about 8.5 m from its foundation (see Figs. 1 and 3), the seismic tomography of crosshole section F77-F92 (before the injection) showed very low P-wave velocities in the upper soils, between the foundation and the gallery, according to the finite elements analysis. This zone was selected to test a jet grout treatment to evaluate if injections would improve the elastic properties of these soils. After the grout injection, the crosshole seismic test was repeated and the corresponding

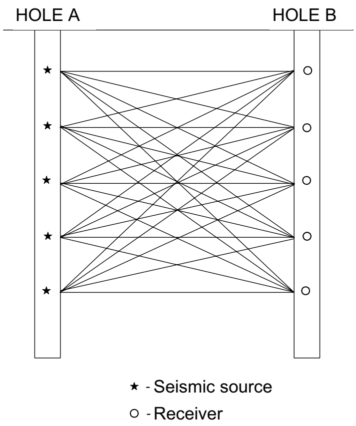

Figure 2. Field set-up for crosshole seismic tomography.

seismic tomography revealed velocity increments showing that upper soils velocity had increased to values closer to deeper soils velocity, namely to the ones below the underground galleries at the convent site.

At F77-F92 crosshole section, detonation caps were used as seismic source at borehole F92 and Oyo geophones were used as receivers at F77 borehole. The boreholes were steel cased. A twelve-channel digital data acquisition system (ABEM Terraloc MKIII) was used. Distance between boreholes is about 7.5 m. Both source and receiver intervals were, in general, 2 m, before and after injection. Seismic sources were located between 4 and 28 m along F92 borehole (additional shot at 29 m was performed after injection). Receivers were located along F77 borehole between 4 and 30 m before injection and between 2 and 28 m after injection (injection reduced the available length of F77 borehole). Therefore, the seismic ray coverage was not exactly equal before and after injection. Totals of 173 and 183 seismic rays (travel times) were used for tomographies, respectively before and after injection. Original seismic records were re-analysed and reprocessed for this paper but giving slightly differences in seismic tomographies comparatively with the ones presented in Salgado & Coelho (1996) and Coelho (2000).

The crosshole section was discretised by a grid of rectangular cells with 1m horizontal to 1.5m vertical and the same grid was used before and after injection tomographies. The center points of these cells (only those crossed by straight rays) are shown at seismic tomographies in Fig. 3. In the tomographic inversion processing the approximation of straight ray paths was used and a constant P-wave velocity for each cell was assumed. A SIRT (simultaneous iterative reconstruction technique) type algorithm implemented by Pessoa (1990) was used with minimum and maximum P-wave velocity constraints of 300 and 4000 m/s. The initial models were uniform velocity models equal to straight ray mean velocity (1024 m/s before injection and 1289 m/s after injection).

Fig. 3 shows the seismic tomographies corresponding, in both cases (after and before injection), to the fourth iteration. Even without numerical convergence, these models (with small number of iterations) were chosen to avoid the increment of velocity artefacts. The mean residual error (percentage value corresponding to the quotient between mean of absolute values of residuals and mean of measured times) is about 13% before injection and 15% after injection.

As Fig. 3 shows, the seismic tomography before injection revealed very low velocity in the upper soils, above the gallery, immediately below the convent foundations, where a zone with velocity less than 500 m/s occurs. Seismic tomography after injection shows a clear velocity increment in this zone evidencing a stiffness increment by means of soil grout injection. Apart from this and the two high velocity artefacts on bottom left corner and top right corner, seismic tomography after injection has a velocity distribution similar to the tomography before injection. Despite the complexity of the geological setting (with high velocity contrast structures) and the straight ray assumption, the seismic tomography revealed a reasonable concordance with it, except for the gallery location.

The relative maximum velocity centered about the gallery position can be explained by the existence of the gallery concrete lining, where certainly seismic rays suffer high bending because P-wave velocity is much higher in concrete than in sandy soils and in air surrounding the lining.

P-wave velocity difference obtained by subtracting cell velocity, before injection, from cell velocity, after injection, is mapped in Fig. 3(c). The most significant velocity increment (apart from the artefacts of bottom left corner and top right corner) occurs on upper soils between the convent foundations and the gallery evidencing good injection results.

3.3 *Sections at control site*

At this site, boreholes F1 to F3 were also steel cased and the distance between boreholes was about 8-9 m. Both source and receiver intervals were 2 m for all three sections. Seismic sources were located between 3 and 29 m along F1 and F2 boreholes. Receivers were located along F3 borehole between 2 and 26 m and along F2 borehole (for F1-F2 section) between 1 and 29 m. Totals of 205, 177 and 182 seismic rays (travel times) were used for F1-F2, F2-F3 and F3-F1 tomographies. The same acquisition equipment and tomographic processing as those

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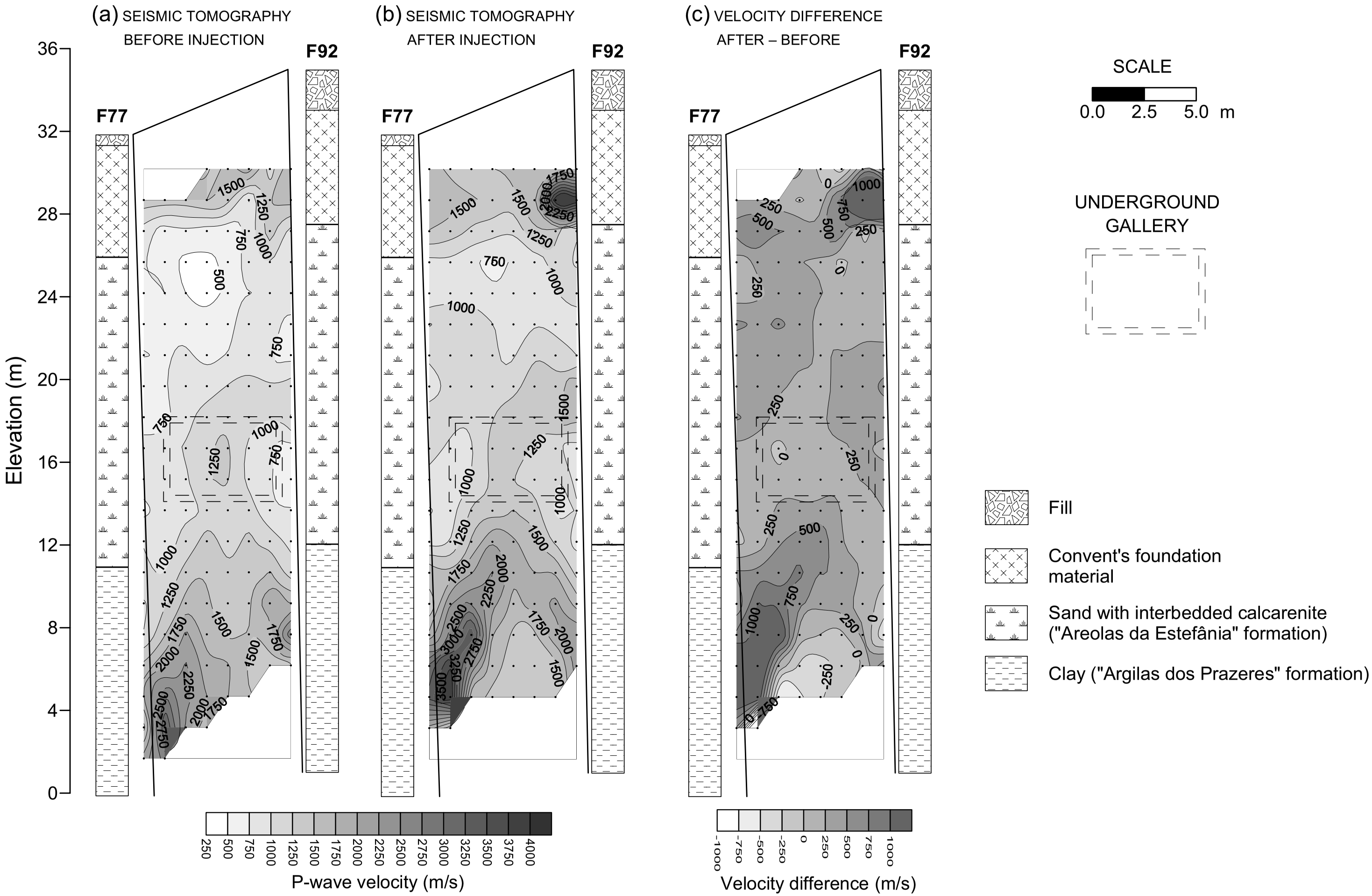

Figure 3. (a) and (b): Selected section seismic tomographies before (a) and after (b) grout injection. (c): Velocity difference map (after grout injection – before grout injection).

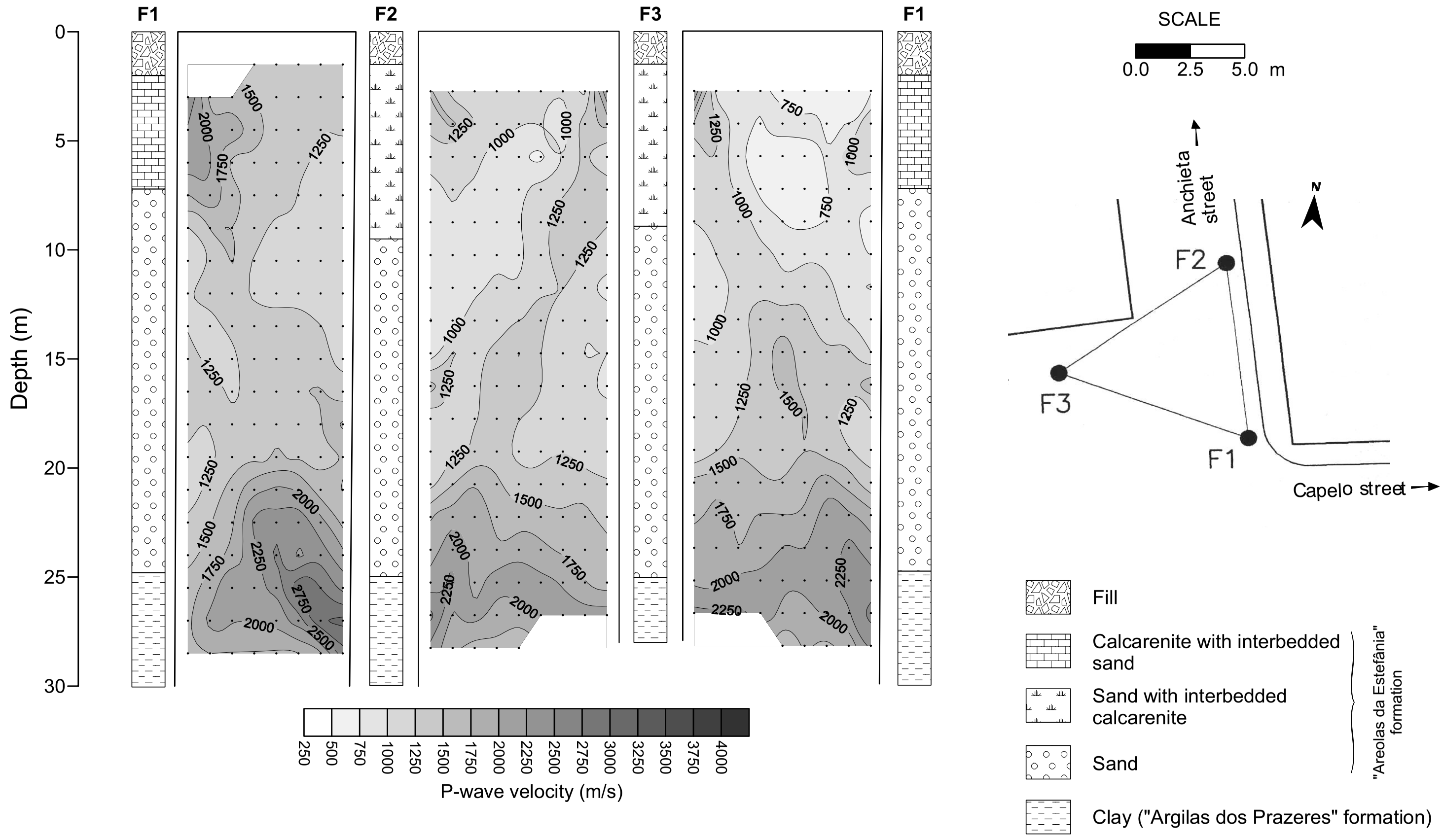

Figure 4. F1-F2, F2-F3 and F3-F1 seismic tomographies at control site.

used in convent site tomographies was also used here, including cell dimensions, velocity constraints and uniform velocity initial models.

The seismic tomographies in Fig. 4 were obtained at fourth iteration for all cases and have residual errors of about 6-10%. There can be observed that P-wave velocities at "Areolas da Estefânia" formation are higher than F77-F92 section velocities, before injection, but are about the same values as the ones attained at F77-F92 section after injection. This confirms that jet grout treatment performed at the selected zone of the convent foundations was sufficient to increment soils strength and stiffness to adequate values for site stability and for micro-pile construction with minimal adverse effects.

4 CONCLUSIONS

The Carmo convent is founded on a sedimentary formation where the soils are locally disturbed by past events that have weakened their stiffness and strength characteristics. This could endanger the stability of the convent during the construction of a planned underground railroad below the convent foundations.

Included in the studies for site stability conditions, a crosshole seismic tomography survey was carried out, which characterized the convent foundation soils, by means of P-wave velocity, evidencing some very low velocity zones.

After a jet grout injection test performed at a very low velocity zone, the corresponding crosshole seismic tomography was repeated revealing a P-wave velocity increment to values closer to the ones of deeper and less disturbed soils. To confirm if these higher velocities were characteristic of the same type of soils but with suitable strength and stiffness, an additional crosshole seismic tomography test was carried out at a control site where the same geological formation exists but where soils are undisturbed. The P-wave velocities obtained at the control site had about the same values as those obtained in the convent foundations after grout injection. Therefore, it was confirmed the grout injection test efficiency in improving the characteristics of soils under the Carmo convent foundations to acceptable values. Both set of results also showed that grout injection should be done, and how it should be done, in the remaining weak zones of the convent foundations.

In summary, crosshole seismic tomography significantly contributed to the characterization of the convent foundation soils and, in this case, it has also proved to be an indirect method to evaluate the grout injection efficiency.

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