

# Decomposed rock mass characterization with crosshole seismic tomography at the Heroísmo station site (Porto)

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**ABSTRACT:** At the Heroísmo station site (of Porto underground) there is a granitic rock mass formation named “Granito do Porto”, where the rock mass presents significant heterogeneity, with highly weathered and fractured rock zones and with frequent and large intercalations of residual (saprolitic) soil from granite. At the request of Transmetro-ACE, LNEC carried out crosshole seismic tomographies on several crosshole sections with about 30m depth in order to zone and to characterize these heterogeneities.

The tomographies obtained showed heterogeneous P-wave velocity distributions with frequent velocity inversions in depth according to highly weathered and fractured rock zones detected at the boreholes and even with the core recovery rates, especially for the case of residual soil. The lowest velocity zones occur typically on the surface region, above the water level, where the decomposition, weathering and fracture density are more accentuated and where the rock mass is more uncompressed.

## 1 INTRODUCTION

The Heroísmo station of the Light Rail Metro System, for the Metropolitan Area of Porto, is located at the intersection of Rua do Heroísmo and Rua António Carneiro, in the centre of Porto. This station belongs to Line C, which links the interface centres of Campanhã and Trindade. This line is a tunnel about 2.3km long excavated by a TBM-EPB tunneling machine. The Heroísmo station was designed as an underground cavern structure with excavation from an access shaft.

Due to the heterogeneity of the granitic rock (“Granito do Porto”), in the area of the access shaft of the station, with various decomposed and fractured zones being found, seismic tests were carried out between boreholes in order to characterise the site in terms of P-wave velocity variations. These crosshole tests sought to obtain a broader coverage of the zone, as large volumes of rock were included in the seismic ray coverage between boreholes. The crosshole tests were based on a group of eleven boreholes (BH01 to BH11 on Fig. 1) until about 30m depth. For each of the tested crosshole sections (CRH01 to CRH10 on Fig. 1), the field set-up for P-wave crosshole seismic tomography was applied to obtain P-wave travel times along ray paths disposed in fans in the section. These multiple travel times measured along several directions allowed the bidi-

dimensional tomographic inversion of the times into the P-wave velocity field of the areas crossed by seismic ray paths (Coelho & Oliveira, 2001).

This paper summarises the local geological conditions, supported by the drilling investigation, as well as the method used for the seismic test and for the data processing, and the main results obtained.

## 2 GEOLOGICAL SETTING AND DRILLING INVESTIGATION

The rock mass found at the site, shown in Fig. 1, belongs to the formation known as “Granito do Porto”, which is from the Hercynian age. In general, it is a very heterogeneous, medium-grained, two mica, granite. According to the International Society for Rock Mechanics classification (ISRM, 1981), the granite found ranges from moderately weathered (W3) to highly weathered (W4) and, sometimes, completely weathered, corresponding to a residual soil (W5, W6), even at considerable depths. Blocks of several dimensions of slightly weathered rock (corestones) can also exist, surrounded by granite that is almost decomposed and disintegrated into soil. The rock mass fracturing (discontinuity spacing) varies from moderately/lightly fractured (F3/2) to very fractured (F5).

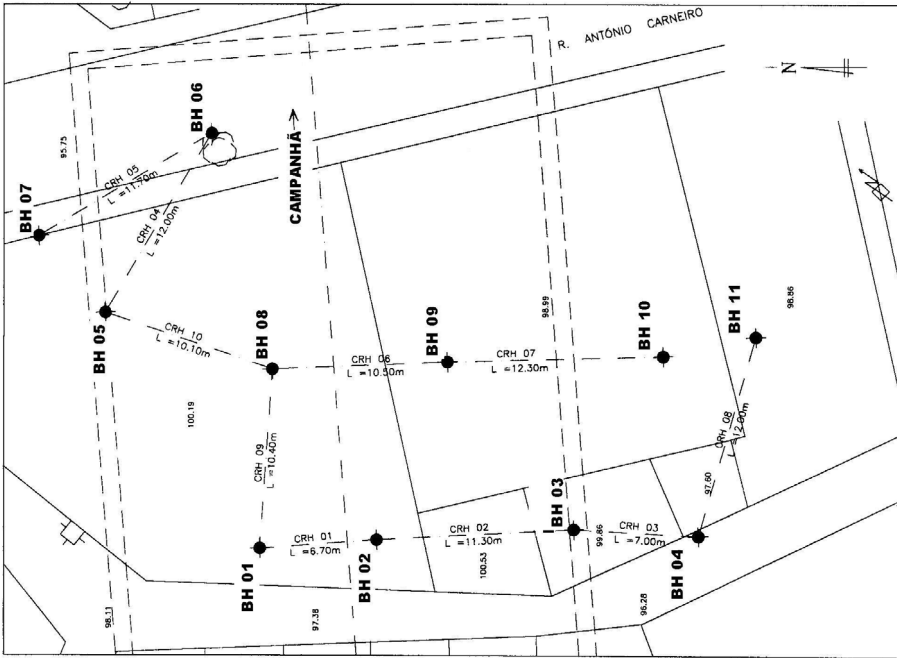


Figure 1. Plane view of the investigation site with the boreholes used (BH01 to BH11) and with the seismic crosshole sections carried out (CRH01 to CRH10).

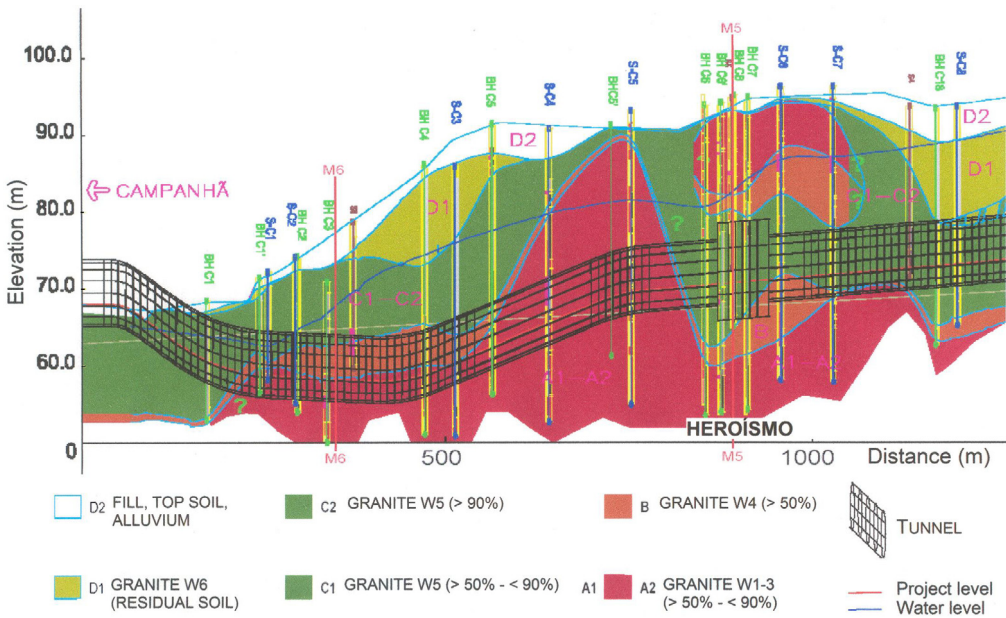


Figure 2. Geotechnical zoning for Line C profile, between Campanhã and Heroísmo station (adapted from Carminé, 2000 and Fruguglietti et al., 2000).

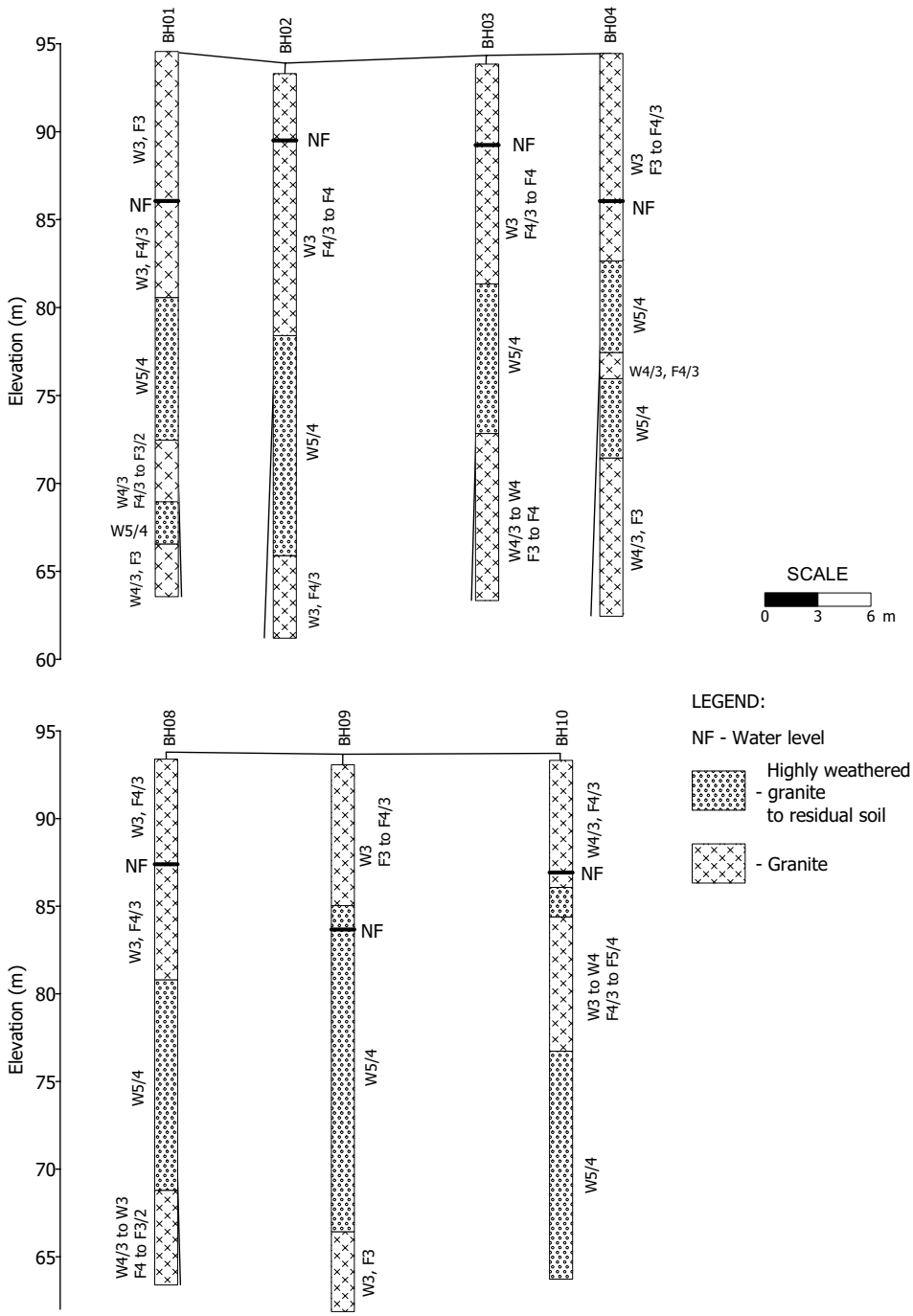


Figure 3. Borehole logs for BH01-BH02-BH03-BH04 and BH08-BH09-BH10 profiles (adapted from Transmetro-ACE).

The geological and geotechnical investigations carried out between 1995 and 1999, with a large number of mechanical tests and drilling being done, mainly along the underground sections, showed a very heterogeneous rock mass, both horizontally and in depth. Fig. 2 presents part of the geotechnical zoning along Line C (Carminé, 2000 and Fruguglietti et al., 2000), between Campanhã and the Heroísmo zone.

It should be stressed that all the eleven boreholes (BH01 to BH11) drilled in the access shaft zone show high variation of granite weathering with depth. The boreholes show zones ranging from moderately to very weathered granite, with fracture density between F3/2 and F5, to a decomposed granite, and vice versa, as Fig. 3 shows for the two longest profiles (BH01-BH02-BH03-BH04 and BH08-BH09-BH10). At the zones described as completely to highly weathered granite (W5/4), the core recovery rates were, in general, very low. It should be pointed out that this "residual soil" exists at several depths and sometimes has significant extensions in depth (more than 15m height on BH09 borehole). In the area nearest to the surface, the granite is moderately to highly weathered (W3, W4/3) with fracture spacing varying from moderately spaced to closely spaced, with some intermediate sections (F3, F4/3, F4).

The water level at BH01 to BH11 boreholes was about 4.5 to 10m deep.

### 3 CROSSHOLE SEISMIC TOMOGRAPHIES

Crosshole seismic tomography tests were carried out by LNEC at CRH01 to CRH10 sections (Fig. 1) to obtain the P-wave velocity field (Coelho & Oliveira, 2001).

The seismic tomographies for the BH01–BH02–BH03–BH04 profile (formed by CRH01, CRH02 and CRH03 adjacent sections) and for the BH08–BH09–BH10 profile (formed by CRH06 and CRH07 adjacent sections) are here presented as the most significant examples of this site characterization.

#### 3.1 Data acquisition

The field set-up for pure crosshole seismic tomography used at the Heroísmo station site consisted on placing the seismic source at successive depths in one borehole and recording the source-generated seismic waves at several receivers located along the adjacent borehole. This multiplicity of crosshole seismic measures corresponds to different ray paths along the crosshole section, such as those illustrated in Fig. 4 assuming straight ray paths. From these seismic records it is possible, at least theoretically, to pick the travel time (hence the velocity) or/and amplitude (hence the attenuation) for both P and S-waves. Nevertheless, in practice, due to the difficul-

ties arising from data acquisition and from ambiguity in S-wave and amplitudes picking, the P-wave travel times are the most often used measurements.

For the crosshole tests at the Heroísmo station site, spacing along boreholes between successive receivers and seismic sources was about 1.5m. Borehole distances varied between 6.7m (CRH01 section) and 12.7m (CRH07 section). Electrical detonation caps were used for seismic sources and Oyo geophones were used for receivers. An ABEM Terraloc seismograph was used for data acquisition and recording. Seismic records had in general a high signal/noise ratio, making it possible to pick first break travel times without pre-processing. Higher noise records and records of which the first break travel times were beyond the expected velocity range were disregarded.

The steel cased boreholes used were sub-vertical and their (small) deviations to vertical were measured with an inclinometer. The mean values of these deviations were used for seismic data processing and for definition of the tomographic planes (Coelho & Oliveira, 2001 and Oliveira & Coelho, 2003). As BH01 to BH04 boreholes are almost coplanar, the CRH01, CRH02 and CRH03 sections were considered on a single tomographic plane (BH01-BH02-BH03-BH04 profile). A single tomographic plane (BH08-BH09-BH10 profile) was also considered for CRH06 and CRH07 adjacent sections.

Totals of 926 and 741 seismic rays (travel times) were used for BH01-BH02-BH03-BH04 and BH08-BH09-BH10 profiles. Fig. 4 shows these rays where straight ray paths were assumed.

#### 3.2 Tomographic inversion

The crosshole seismic tomography here applied reconstructs the P-wave velocity field for a profile, from the P-wave travel times measured along a multitude of seismic ray paths at the crosshole sections considered for the profile. The measured travel times are inverted into a velocity matrix (grid of cells), which comprises the area with seismic ray coverage, by a tomographic inversion technique implemented and described by Pessoa (1990). This is a SIRT (Simultaneous Iterative Reconstruction Technique) type that uses the approximation of straight ray paths and assumes constant velocity for each cell of the grid. The process starts with an initial velocity model (matrix) for which the modeled travel times of (straight) seismic rays are calculated. Differences between modeled and measured travel times for seismic rays, called residuals, are then used for improving the initial model for the velocity distribution.

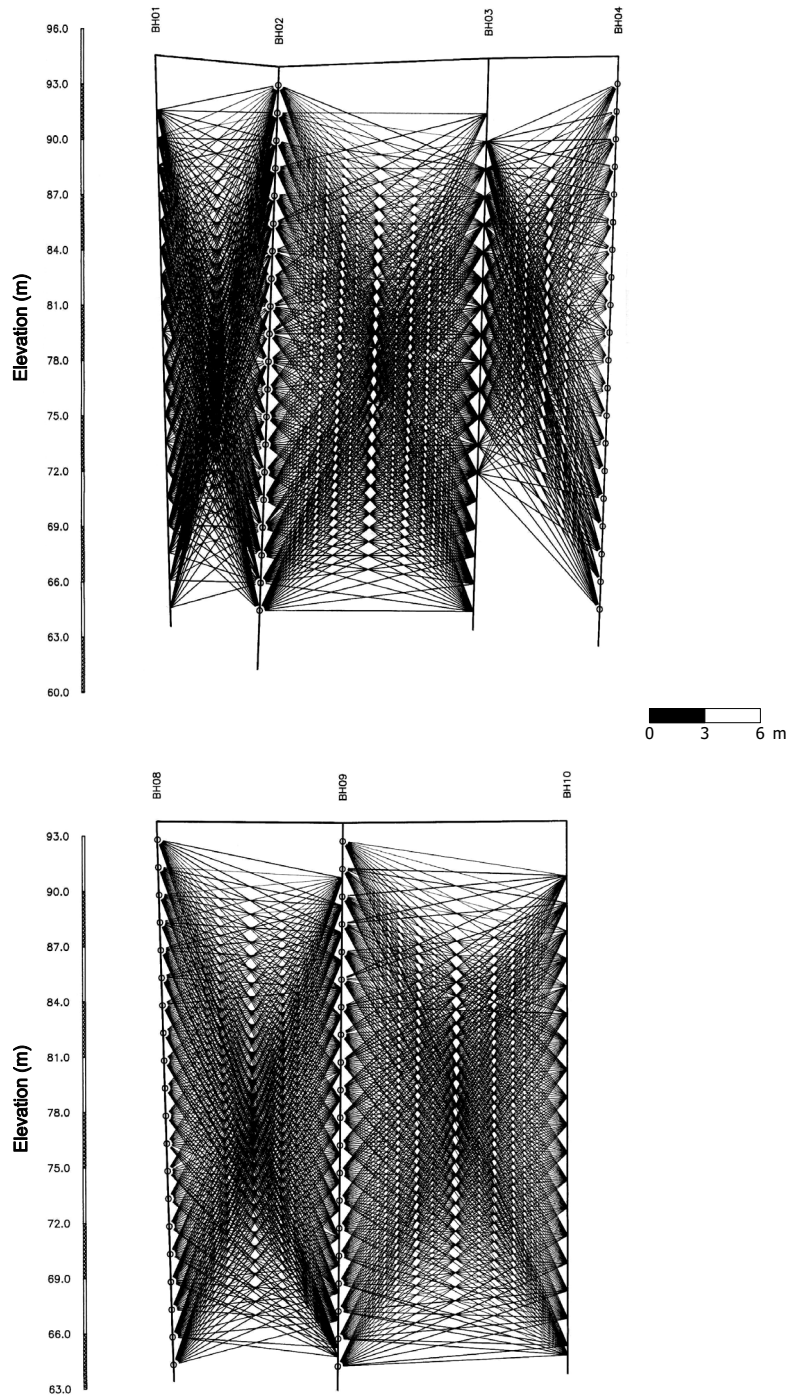


Figure 4. Seismic ray coverage for BH01-BH02-BH03-BH04 and BH08-BH09-BH10 profiles.



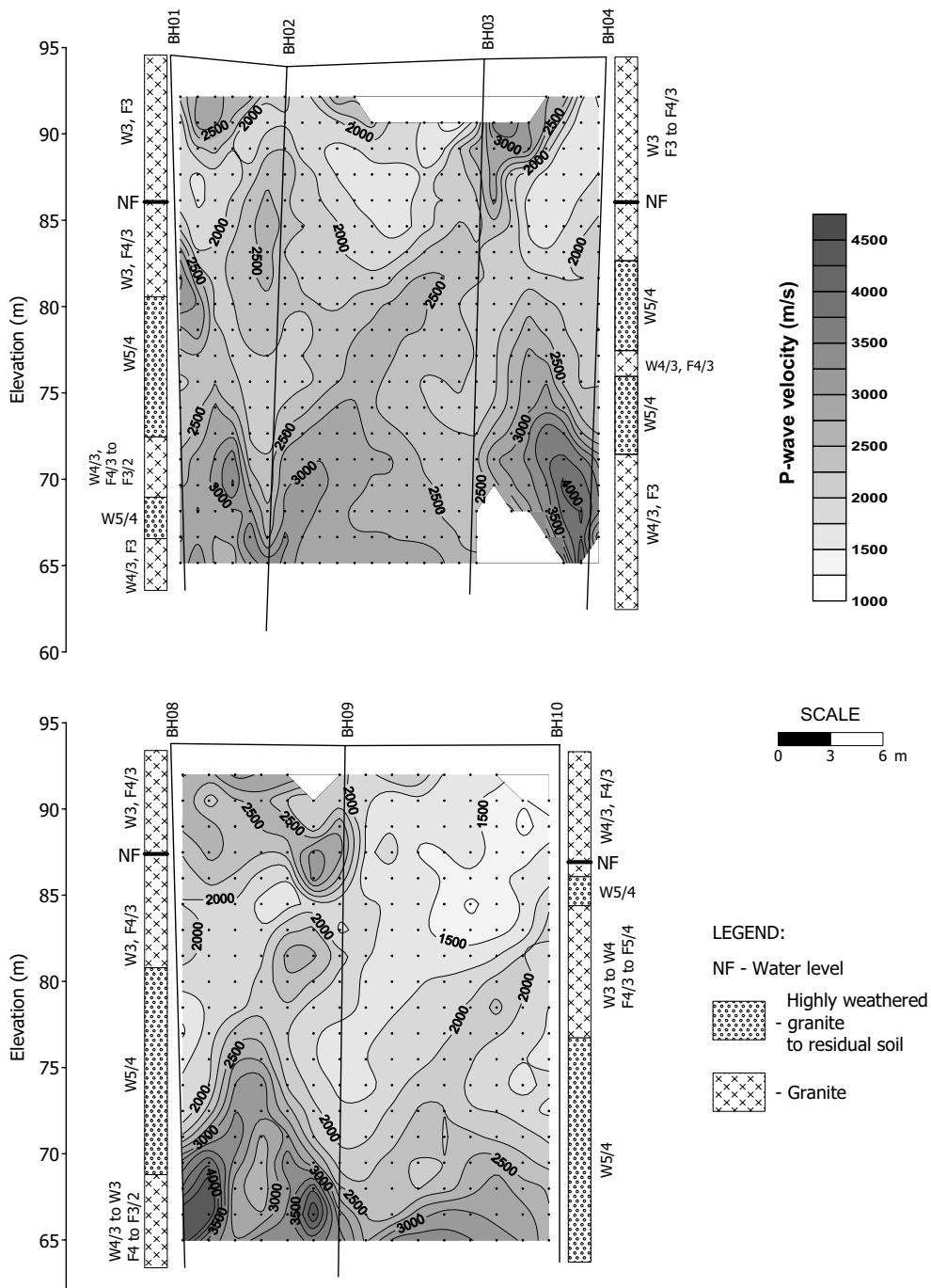


Figure 5. Seismic tomographies for BH01-BH02-BH03-BH04 and BH08-BH09-BH10 profiles.

The algorithm uses minimum and maximum velocity constraints for limiting the artefacts increment.

The BH01-BH02-BH03-BH04 profile was discretized by a grid of rectangular cells with 1m horizontal to 1.5m vertical. For the BH08-BH09-BH10 profile, 1.5m width square cells were used. The seismic tomographies of Fig. 5 show the center points of the cells crossed by straight rays. Initial models with uniform velocity (equal to mean of straight ray velocities) were used for both profiles, being 2406m/s for the BH01-BH02-BH03-BH04 profile and 2122m/s for the BH08-BH09-BH10 profile. Constraints of 340 and 4500m/s were used respectively for minimum and maximum P-wave velocity.

The seismic tomographies presented in Fig. 5, obtained by the tomographic inversion process described above, were chosen as the best estimations of the P-wave velocity field on the profiles. Even though without numerical convergence of the residuals, second iteration tomography, for the BH01-BH02-BH03-BH04 profile, and fourth iteration tomography, for the BH08-BH09-BH10 profile, were selected, to avoid the increment in velocity artefacts.

The mean residual error (percentage value corresponding to the quotient between the mean of the absolute values of the residuals and the mean of the measured times) for these tomographies is about 10% for the BH01-BH02-BH03-BH04 profile and 7% for the BH08-BH09-BH10 profile. These small values of residual error, together with the fact that the mean velocity of cells is very close to the mean velocity of straight rays for each profile, evidence high agreement (correlation) between the geophysical models and the measured travel times for seismic rays.

#### 4 SEISMIC CHARACTERIZATION OF THE ROCK MASS

The seismic tomographies obtained at the site defined the main heterogeneities of the rock mass and characterized, by P-wave velocity, their different structures with high resolution. The tomographies showed significant variations and frequent velocity

inversions, both laterally and in depth, evidencing a heterogeneous rock mass with irregular allocation of weathering and fracturing zones.

The highest velocity inversions and gradients are in general well correlated with the changes in the rock weathering and in the fracture density detected at the boreholes. This correlation makes it possible to deduce about the mechanical quality of the rock mass between boreholes.

In general, deeper zones have relatively higher velocities than shallower zones. This trend, despite being likely to reflect an increment in the mechanical quality of the rock mass, for some zones, is mainly related to the rock mass saturation in depth (in opposition to the unsaturated upper region), and can also be influenced by the rock mass compression increment with depth. The lowest velocity zones (less than 1500m/s) typically occur above the water level, on the uncompressed region, where the rock mass is certainly more weathered (or even decomposed) and more fractured. Simultaneously, some high velocity zones (above 2500m/s) occur on surface and unsaturated region, like the ones observed close to BH01, BH03 and BH09 boreholes in BH01-BH02-BH03-BH04 and in BH08-BH09-BH10 profiles. In these zones, the rock mass has locally a higher mechanical quality.

From the set of tomographies obtained at the site, it was possible to characterize quantitatively the rock mass, by means of the P-wave velocity range, as Table 1 shows. From the borehole logs, two kinds of materials were considered: granite and “residual soil” (highly weathered granite to residual soil, W5/4). This “residual soil” occurs below water level, for almost all of the boreholes used. Because saturation has a high influence on the P-wave velocity of rock mass, granite above and below the water level were considered separately.

Table 1. Characterization of rock mass at the Heroísmo station site, by means of P-wave velocity obtained from crosshole tomographies.

Material	Weathering grade	Fracture density	P-wave velocity	P-wave velocity characteristic range
			m/s	m/s
Granite, above water level	W3	F3	2000 – 2750	1250 – 2750
		F4/3 to F4	1500 – 2500	
	W4/3 to W4	F4/3 a F5/4	1250 – 1750	
Granite, below water level	W3	F3	2000 – >3000	1750 – >3000
		F4/3 to F4	1750 – >3000	
	W4/3 to W4	F3/2 to F4	2000 – >3000	
“Residual soil” (highly weathered to decomposed granite), below water level	W5/4	—	1750 – 2500	1750 – 2500

## 5 CONCLUSIONS

The crosshole seismic tomographies carried out at the site of the access shaft to Heroísmo station provided, by means of P-wave velocities, a high resolution zoning of the rock mass. Furthermore, by correlation with borehole logs, the mechanical quality of the rock mass, namely between boreholes, can be inferred from those seismic tomographies.

The tomographies obtained are characteristic of a heterogeneous rock mass with highly variable mechanical quality, either in depth or laterally, and with irregular weathering (and fracture density) distribution.

This geophysical method produced useful additional information about the rock mass, in complement to the data from drilling and other mechanical investigations.

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## REFERENCES

- Carminé, P. 2000. Geological-geotechnical conditions along underground sections of “Metro do Porto” project. (in Portuguese). *Proceedings 7º Congresso Nacional de Geotecnia. Porto, Portugal, April 10-13, 2000, Vol III: 1377-1388.*
- Coelho, M.J. & Oliveira, M. 2001. *Crosshole seismic tomographies at “Heroísmo” station site.* (in Portuguese). Relatório (Report) 137/01-NP, LNEC, Lisboa.
- Fruguglietti, A., Gasparini, M. & Centis, S. 2000. Influence of geotechnical conditions on the excavation method of “Metro do Porto” project. *Proceedings 7º Congresso Nacional de Geotecnia. Porto, Portugal, April 10-13, 2000, Vol III: 1391-1400.*
- ISRM. 1981. *Rock characterization, testing and monitoring – ISRM Suggested Methods.* Editor: E. T. Brown. England: Pergamon Press Ltd.
- Oliveira, M. & Coelho, M.J. 2003. Heroísmo station site. Crosshole seismic tomographies. (in Portuguese). *Proceedings Jornadas Hispano-Lusas sobre Obras Subterráneas. Madrid, Spain, September 15-16, 2003: 477-486.*
- Pessoa, J.M.N.C. 1990. *Application of tomographic techniques to crosshole seismic exploration.* (in Portuguese). Trabalho de síntese (Monography), Provas de aptidão pedagógica e capacidade científica (Public examination for Assistant), Universidade de Aveiro, Portugal.