URBAN EXCAVATIONS AND RETAINING STRUCTURES IN THE VICINITY OF SENSITIVE INFRASTRUCTURES

Hotel in Av. Fontes Pereira de Melo

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Abstract

The growing demand and increase in value of the urban space seen in the last decades, combined with a relatively recent, but significant initiative to free the space at the surface, has led to an expansion in use of the subsoil.

Consequently, the number of deep excavation works, characterized by the nearby presence of pre-existing structures and infrastructures sensitive to the impacts resulting from the excavation, as increased.

The present work addresses one of these new projects, particularly the excavation works necessary for the construction of the new hotel unit, Hotel Meliã, to be implanted at Av. Fontes Pereira de Melo, in Lisbon, close to the Marquês de Pombal urban road tunnel and yellow line of Lisbon's metropolitan tunnel.

A collection of information regarding excavations executed in the vicinity of the area of interest is presented, followed by a retro analysis based on the monitoring of the excavation works associated to the construction of the building adjacent to the area to be intervened.

The proposed solutions are evaluated by means of two-dimensional finite element analysis, particularly the impact of the excavation in the pre-existing adjacent tunnels.

One solution considering buttress piled walls, analysed by means of three-dimensional finite element analysis, is proposed as a viable alternative for the same project.

Key words: *Deep excavation, retaining structures, urban space, numerical modeling, adjacent tunnels.*

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1. INTRODUCTION

The growing demand and increase in value of the urban space seen in the last decades, combined with a relatively recent, but significant initiative to free the space at the surface, has led to an expanding use of the subsoil. Consequently, there has been an increase in deep excavation works.

These excavations inevitably cause changes in ground stresses, that are accompanied by deformation and displacement of the surrounding soil. When excavations are carried out in the vicinity of pre-existing structures and infrastructures, risk regarding potential damage to these elements is generated. Consequently, the current urban excavation projects are generally characterized by a high and growing complexity.

The present work addresses one of these new projects, particularly the excavation works necessary for the construction of the new hotel unit, Hotel Meliã, to be implanted at Av. Fontes Pereira de Melo in Lisbon, close to the Marquês de Pombal urban road tunnel and yellow line of Lisbon's metropolitan tunnel.

In this context, information regarding excavations executed in the vicinity of the area of interest is presented, followed by a retro analysis based on the monitoring of the excavation works associated to the construction of the building adjacent to the area to be intervened.

The proposed project solutions are evaluated by means of two-dimensional finite element plane strain analysis, particularly the impact of the excavation in the pre-existing adjacent tunnels.

One alternative solution considering buttress piled walls, analysed by means of three-dimensional finite element analysis, is proposed as a viable alternative for the same project.

2. CASE STUDY: HOTEL IN AV. FONTES PEREIRA DE MELO

The studied project pertains to the development of a new hotel unit, Hotel Meliã, to be implanted at Av. Fontes Pereira de Melo, in Lisbon, Portugal (Figure 1).

This development encompasses the construction of a 15 story above ground level structure, 3 floors located partially below ground surface and 3 levels of basements completely underground, which demand an excavation of approximately 1321m^2 in plan view extending to a maximum depth around 21m to 23m.

2.1 SITE DESCRIPTION

The excavation site, located in Lisbon's urban center, is enclosed by several structures and infrastructures. Namely, the Av. António Augusto Aguiar, where the Marquês de Pombal urban road tunnel exists, to the southwest; the Av. Fontes Pereira de Melo, where the yellow line of Lisbon's metropolitan tunnel, is located, to the southeast; the São Sebastião da Pedreira street, to the northeast and the 11 story above ground level structure and 6 levels of basements of Fenix Urban hotel to the northwest.

Additionally, the presence of several utilities, both above and underground, is anticipated around the construction site.

Moreover, in the interior of the excavation site, remain the foundations of the structures that previously existed, as well as the approximately 10m in height masonry retaining wall that faces the São Sebastião da Pedreira street.

With the presence of these adjacent structures and infrastructures, this project had to consider the execution of the excavation with minimal impact to these elements. Therefore, the preservation of the structural integrity of the existing adjacent tunnels, structures and utilities during the excavation was of utmost importance.

Figure 1: Aerial view of the construction site (Source: Google Earth)

2.2 LOCAL HYDROLOGICAL AND GEOLOGICAL CONDITIONS

Aiming to characterize the various geological formations present in the area of interest, site investigations, comprised of three vertical boreholes, piezometric readings and identification laboratory tests were carried out. The location of the boreholes is identified in Figure 2.

According to the geotechnical investigations report [1], the following geological formations are identified within the construction site: landfills (At - holocene), alluvial deposits (a - holocene), Clays and Limestones of Prazeres (M^{I}_{1} - miocene) and Lisbon's Volcanic Complex (β - eocene).

Landfills, the result of the earthworks carried out inside the construction site associated to the earth modeling necessary to the construction of the previously existing

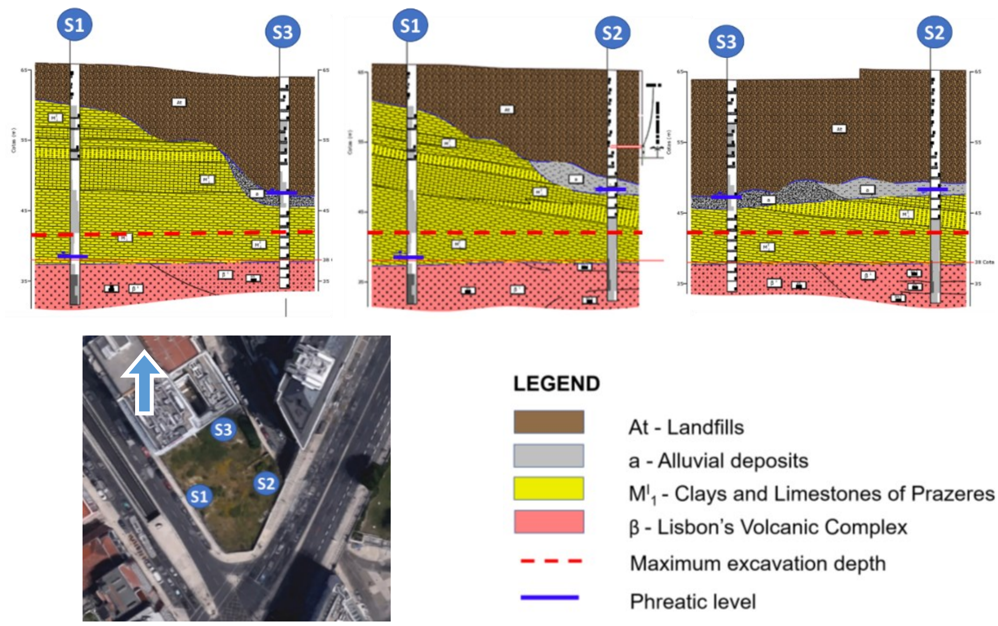


Figure 2: Geological interpretive profiles (adapted from [1])

buildings, with a thickness varying from 6,0m to 16,50m, composed of a mixture of sands, silts and clays, with pebbles and remnants of ceramic pieces, make up the superficial layer identified in the construction lot.

The alluvial deposits, associated to a water line, that previously run along the São Sebastião da Pedreira street, were intercepted below the landfills in S2 and S3, as a mixture of silty sand and round gravel.

The Miocene formations are a very heterogeneous mixture of marls, clays and silty clays with carbonate nodules.

The materials of the "Lisbon Volcanic Complex" are predominantly basalts (S1 and S2) and residual silty soils (S3).

The interpreted geological profiles are presented in Figure 2.

The groundwater level was detected, during the site investigations, between 16,20m (S3) and 27,0m (S1) depth.

Simultaneously examining the position of the water level recorded in the piezometers and the permeability characteristics of the local subsoil, it is possible to admit as probable the existence of a 'suspended' water table.

2.3 PROJECT SOLUTIONS

According to [2] and [3], the underground part of the building is to be constructed within peripheral retaining structures materialized by contiguous bored pile walls and a king post wall with underground slabs and temporary prestressed ground anchors serving as support.

Associated to the king post wall solution, it is planned to execute cement columns, reinforced with HEB120 metal profiles, up to the final excavation level, behind the concrete wall, aiming to minimize the decompression associated with the opening of king post panels, during the construction process.

A schematic plan view of the proposed retaining solutions is presented in Figure 3 and Figure 4.

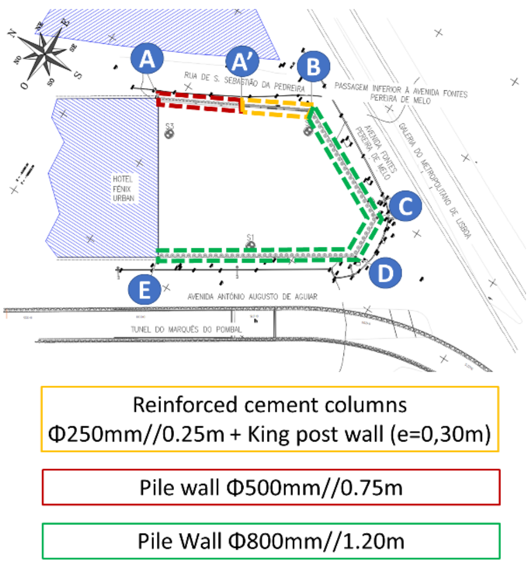


Figure 3: schematic plan view of the project retaining solutions

3. NUMERICAL ANALYSIS OF THE PROJECT RETAINGING SOLUTIONS

3.1 GEOTECHNICAL PARAMETRIZATION

Given the local geological scenario, the numerical analyzes were carried out considering three distinct geotechnical zones: ZG1, corresponding to alluvial and landfill deposits; ZG2, covering the soils belonging to the geological unit "Clays and Limestones of Prazeres"; and ZG3, representative of the basalts belonging to the "Lisbon Volcanic Complex".

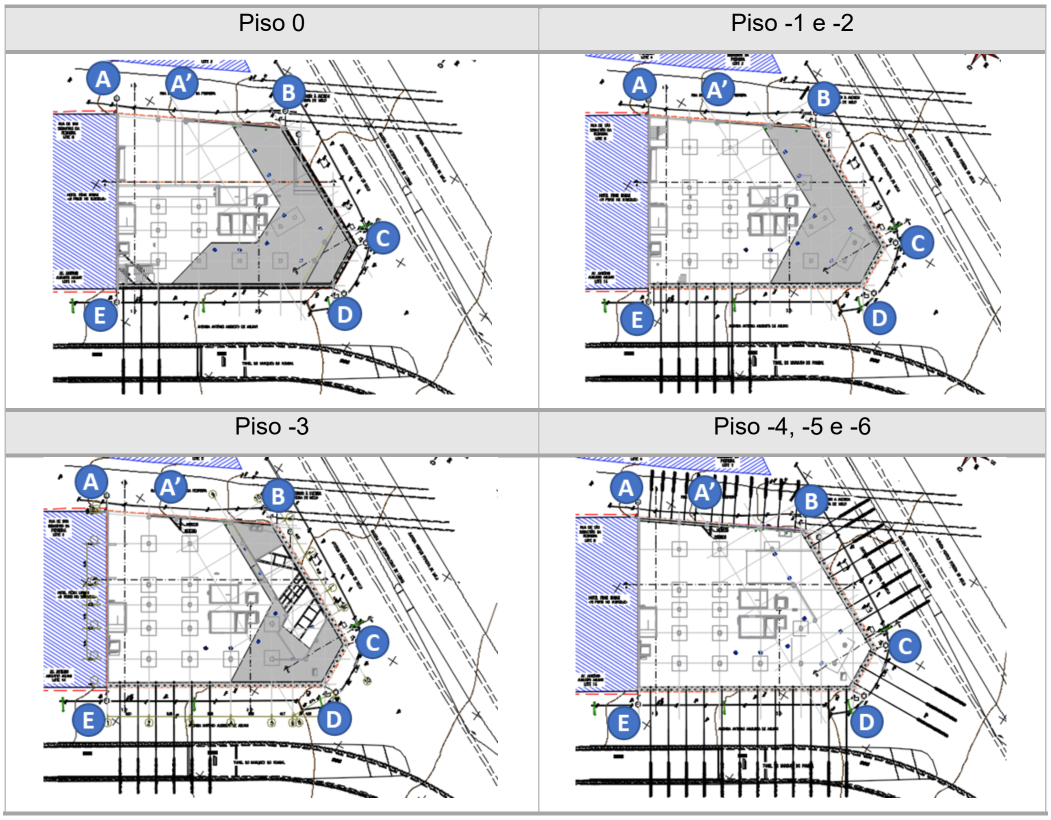


Figure 4: Schematic plan view of the project retaining solutions

Given the deformability characteristics of the various geotechnical units, it was decided to simulate their behaviour considering the perfectly plastic linear elastic constitutive model (Mohr-Coulomb model), the Hardening soil small strain model (HSsmall) and Hardening Soil model (HS) for ZG3, ZG2 and ZG1 respectively.

To assess the values of the geomechanical parameters, empirical correlations based on the results of the standard penetration tests, information from tests and experience of excavations close to the area of interest [4], as well as the geotechnical parameterization studies of Lisbon's miocene clays [5] and the "Lisbon Volcanic Complex" [6], were used.

The estimated mechanical parameters of the three geotechnical zones are listed in Table 1.

3.2 LOCAL EXPERIENCE

To validate the results of the numerical analysis, information on excavation works carried out in the vicinity of the area to be intervened was collected.

It is intended to obtain a first estimate of the displacements of the retaining structure based on the performance of the various technologies used in the same geological formations, in order to frame the results obtained by the finite element analyses, thus allowing a critical evaluation.

The information collected is summarized in Figure 5, where the maximum horizontal displacements ($\delta_{h,max}$) registered during the execution of the works and respective excavation depths (H) are presented. These results are organized according to the different types of retaining structure employed.

Table 1: Geotechnical parametrization

	ZG1	ZG2E	ZG2C	ZG3
Constitutive model	HS	HSsmall	HSsmall	Mohr-Coulomb
Behaviour	Drained	Drained /Undrained	Drained /Undrained	Drained
c' [kPa]	0,1	0,1 a 15	20	186
φ [°]	30 a 34	36,4	33	68
Ψ [°]	0	0	0	0
γ_{unsat} [kN/m^3]	18	20	20	26,6
γ_{sat} [kN/m^3]	19	21	21	26,6
K_0	0,44 a 0,50	1,0	1,0	0,351
E' [MPa]	-	-	-	3303
E_{50}^{ref} [MPa]	10 a 20	50 a 70	50 a 70	-
E_{oed}^{ref} [MPa]	10 a 20	50 a 70	50 a 70	-
E_{ur}^{ref} [MPa]	40 a 80	150 a 210	150 a 210	-
E_{ur}^{ref}/ E_{50}^{ref}	4	3	3	-
m	0,65	0,8	0,8	-
υ_{ur}	0,2	0,2	0,2	0,265
p^{ref} [kPa]	20	265	265	-
R_f	0,9	0,9	0,9	-
R_{inter}	0,8	0,8	0,8	1,0
G_0^{ref} [MPa]	-	314	314	-
$\gamma_{0,7}$	-	9,66x10^{-4}	9,66x10^{-4}	-
K_x [m/s]	1,00x10^{-4}	1,00x10^{-9}	1,00x10^{-9}	1,00x10^{-9}
K_y [m/s]	1,00x10^{-4}	1,00x10^{-9}	1,00x10^{-9}	1,00x10^{-9}

The analysis of Figure 5, suggest that the monitoring results collected are entirely below the envelope defined by the ratio δh,max/H=0.20% proposed by Ou *et al* (1993) for excavations in clay [7]. It is demonstrated, in reality, that most results present δh,max/H ratios below 0.10%.

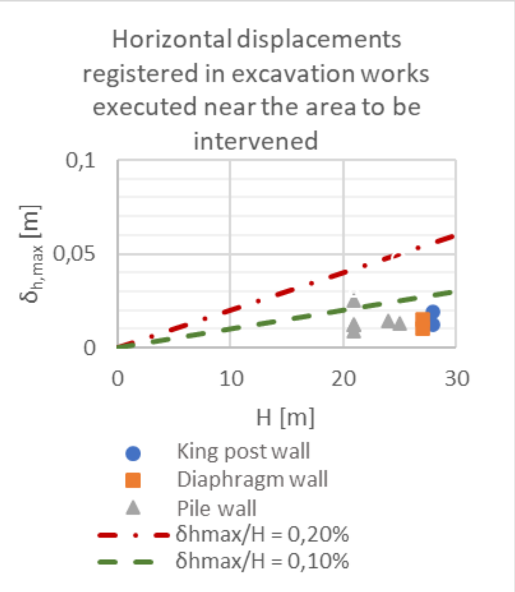


Figure 5: Horizontal displacements and respective excavation depths of excavation works executed near the area to be intervened

3.3 BACK ANALYSIS

To validate the proposed geomechanical parameterization, a retro analysis, based on the results of the monitoring of the excavation works carried out for the construction of the underground floors of the building adjacent to the intervention area, the Fenix Urban hotel, was also carried out.

The description of the works and monitoring results were consulted in [8].

According to the author, the excavation works for the Fenix Urban hotel were carried out employing a 0,30m thick king post wall and nine levels of temporary prestressed ground anchors, reaching a maximum depth of approximately 28m.

Using the geotechnical parametrization, presented in Table 1, the horizontal displacements of the Fenix Hotel, were estimated by means of a two-dimensional finite element plane strain analysis, using

PLAXIS 2D software. The finite element mesh of the model is illustrated in Figure 6.

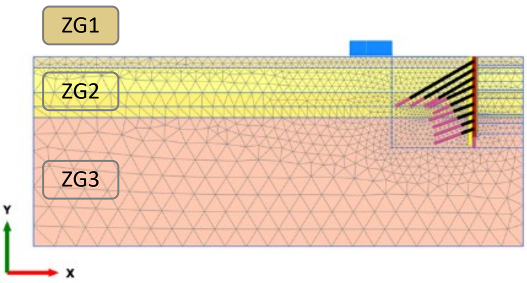


Figure 6: Finite element model, developed in PLAXIS 2D, for the estimate of the horizontal displacements of hotel Fenix's retaining wall

All the structural elements that integrate the performed analyses were modeled as linear elastic, with the characteristics of the materials and dimensions mentioned in [8].

The estimated horizontal displacements were then compared to the displacements measured in the inclinometers installed during the excavation works.

In order take into account the tridimensionality aspect of the excavation, capable of influencing the displacements developed during the excavation, the plane strain ratio proposed by Ou *et al.* (1996) [7] was used.

This way it was possible to estimate the displacements resulting from a plane strain scenario, based on the values measured on the inclinometers and compare them directedly to the numerical estimate.

The displacements estimated in the numerical model and measured in the inclinometers are presented in Figure 7.

Based on results in Figure 7, it was concluded that the initial estimated geomechanical parameterization, presented in Table 1, appears to be adequate. However, it was not possible to accurately determine part of the parameters. Thus, the study developed to analyse the excavation solutions for the Meliã hotel include sensitivity analysis in order to assess the influence of these parameters on the results.

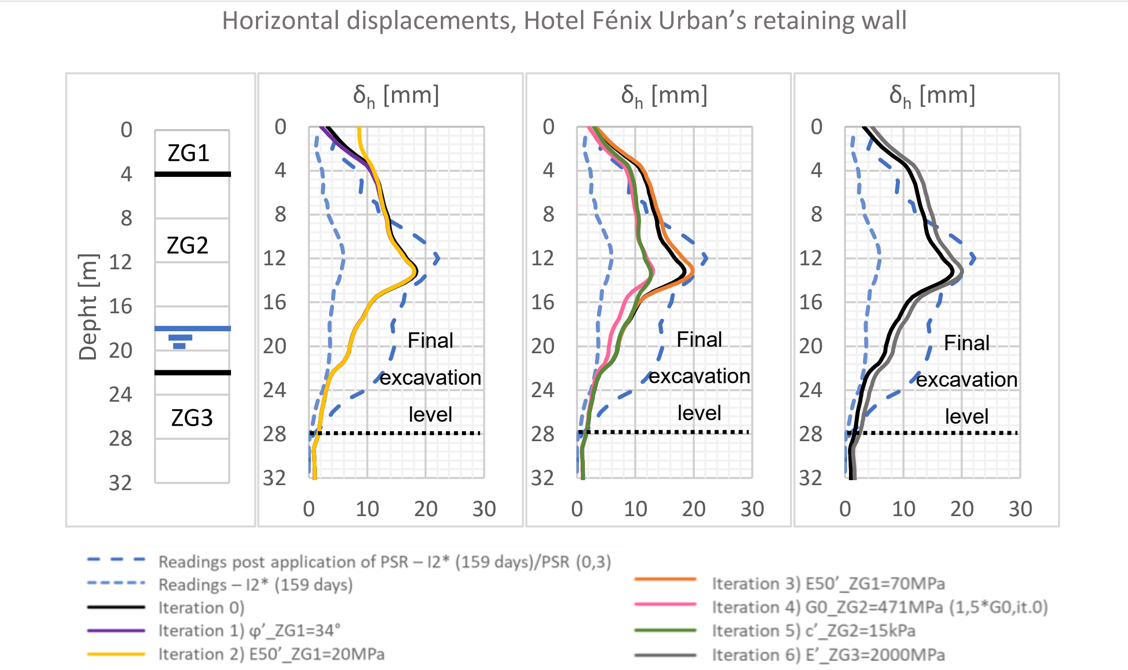


Figure 7: Horizontal displacements of Hotel Fenix Urban's retaining wall

3.4 MODELS

The retaining solutions proposed for the elevations that face Av. Fontes Pereira de Melo and Av. António Augusto Aguiar, in which the yellow line gallery of the Lisbon's metropolitan tunnel (TML) and the Marquês de Pombal urban road tunnel (TRM) develop respectively, are evaluated by means of two-dimensional finite element plane strain analysis, particularly the displacements of the retaining wall and the impact of the excavation in the pre-existing adjacent tunnels.

The three numerical models developed in PLAXIS 2D are presented in Figure 8, Figure 9 and Figure 10.

All the structural elements that integrate the performed analyses were modeled as linear elastic, with the characteristics of the materials and dimensions mentioned in [17] and [18].

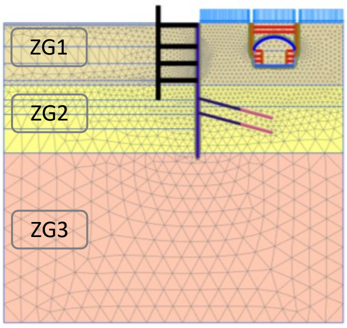


Figure 8: Finite element model, developed in PLAXIS 2D, for the analysis of the projected retaining solution to the elevation that faces the Av. Fontes Pereira de Melo

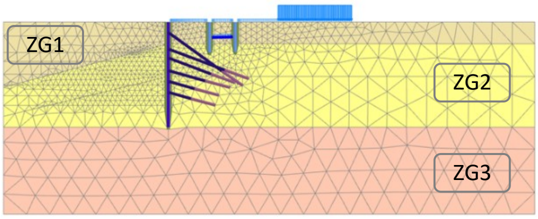


Figure 9: Finite element model, developed in PLAXIS 2D, for the analysis of the projected retaining solution to the elevation that faces the Av. António Aguiar – Model 1

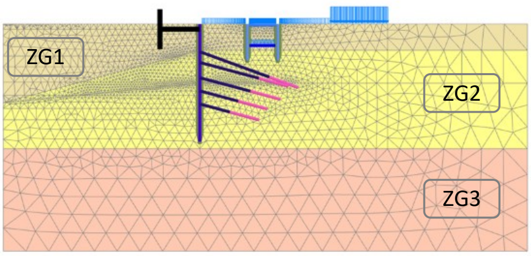


Figure 10: Finite element model, developed in PLAXIS 2D, for the analysis of the projected retaining solution to the elevation that faces the Av. António Aguiar – Model 2

The retaining walls and structures of the pre-existing tunnels were modeled as plate elements. The prestressed ground anchors were modeled as a combination of "node to node anchors" and "embedded beam rows".

The slab bands were modeled as "fixed-end anchors", with an axial stiffness estimated through finite element analysis carried out using SAP2000 (v20).

Seeking to estimate in the best possible way the initial stress state of the soil adjacent to the area to be intervened, the calculation sequence adopted started by simulating the construction of the existing tunnels. Only after, was simulated the pile wall installation, followed by the sequential excavation and execution of the support elements (prestressed ground anchors and slab bands) necessary for the construction of the underground floors of the Hotel Meliã.

3.5 RESULTS

The horizontal displacements estimated for the retaining walls, alongside the corresponding horizontal values measured in the inclinometers (dashed black lines) installed near the sections of analysis are presented in Figure 11.

The maximum displacement values estimated in the retaining structures and in the existing tunnels are summarized in Table 2.

3.6 DISCUSSION

3.6.1 RETAINING WALL

Regarding the horizontal and vertical displacements of the retaining structures, all calculations produced maximum displacements, lower than the values of 25mm and 15mm corresponding to the warning criteria for horizontal and vertical displacements, respectively.

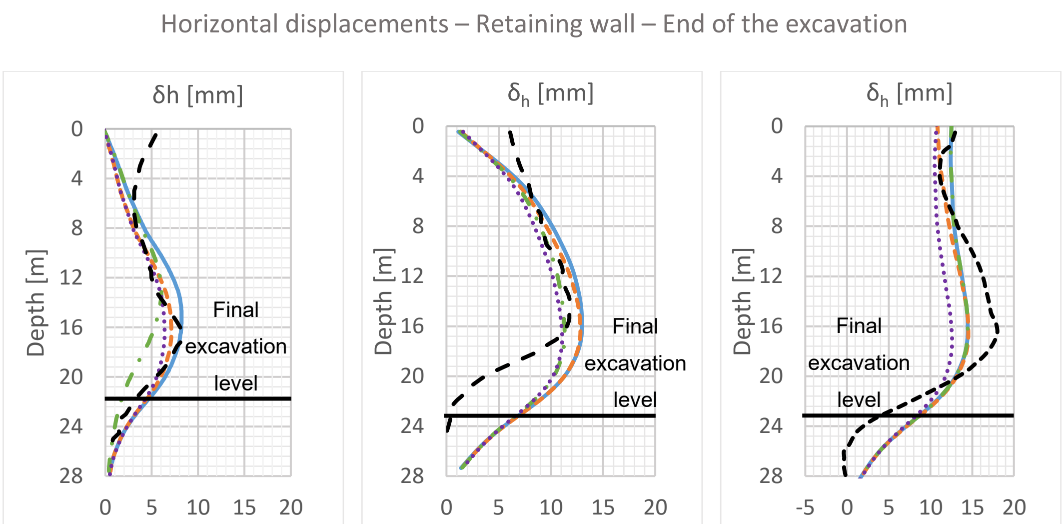
The comparison of the estimated horizontal displacements with the values recorded on the inclinometers, after completion of the excavation works, reveals, in most situations, a good agreement.

It should also be noted that the ratios between the estimated maximum horizontal displacement and excavation depth were less than 0.1%, thus agreeing with the values previously recorded in similar works.

3.6.1 ADJACENT TUNNELS

The horizontal and vertical displacements of approximately 2mm, estimated for the metropolitan tunnel agree with the readings of the displacements made, in said infrastructure, within the scope of the instrumentation and monitoring plan defined in the project.

Regarding the Marquês de Pombal urban road tunnel, the estimated values resulted in



a) Av. FPM *b) Av. AAA – Model 1* *c) Av. AAA – Model 2*

Figure 11: Horizontal displacements estimated and registered in the inclinometers at the final excavation phase

Table 2: Maximum diplacements estimated for the retainning wall, the metropolitan tunnel (TML) and thr Marquês de Pombal urban road tunnel (TRM)

Model	Retaining wall			TML / TRM		
	$\delta_{v,max}$ [mm]	$\delta_{h,max}$ [mm]	δ_{hmax}/H	δ_{max} [mm]	$\delta_{v,max}$ [mm]	$\delta_{h,max}$ [mm]
Av. FPM	0,84	8,22	0,038%	3,16	2,291	2,225
Av. AAA - Model 1	2,12	12,98	0,059%	7,792	1,664	7,613
Av. AAA - Model 2	2,98	14,45	0,063%	9,639	1,817	9,636

an overestimation of the horizontal displacements and an underestimation of the vertical displacements of the tunnel, when compared with the readings of the displacements made in said infrastructure.

4. ALTERNATIVE SOLUTION

As an alternative solution for the elevations that face Av. Fontes Pereira de Melo and Av. António Augusto Aguiar, a retaining solution is proposed, using slab bands of the future underground floors , which, acting as a set of horizontal beams, resist the impulses and direct them to buttresses materialized by 800mm in diameter, spaced apart by 0.60m bored piled walls, arranged perpendicularly to the alignment of the peripheral retaining wall, inside the excavation site, spaced along the periphery, on average, 6m between them.

The piles that materialized the buttresses will reach maximum depths of approximately 33m, in order to guarantee a minimum embedment of 4m of the basaltic stratum. As for the extension of the buttresses in plan, it is predicted that they will present a development of 6m.

The described alternative solution was, analyzed by means of three-dimensional finite element analysis.

The estimated displacements, indicate that the proposed solution is a viable alternative for the same project.

5. CONCLUSIONS

Information regarding excavations carried out in the vicinity of the intervention site, was presented which allowed to conclude that the maximum horizontal displacements obtained are, in most cases, below 0.10% of the excavation depth.

Aiming at validating the geomechanical characterization of the materials interested, a back analysis was carried out, through two-dimensional finite element analyses, based on the results of the monitoring of the excavation works of the building adjacent to the lot in question.

Two-dimensional numerical analyzes were carried, only for the solutions corresponding to the elevations that face Av. Fontes Pereira de Melo and Av. António Augusto Aguiar, in which Lisbon’s metropolitan tunnel and the Marquês de Pombal Road tunnel respectively develop.

The results obtained revealed a good agreement regarding the displacements of the retaining structures measured in the scope of the instrumentation and monitoring plan, but an overestimation of the displacements of the existing tunnels.

An alternative solution for the elevations that face Av. Fontes Pereira de Melo and Av. António Augusto Aguiar was proposed, including buttresses, materialized by secant bored pile walls, arranged perpendicularly to the alignment of the peripheral retaining wall, inside of the excavation site.

This alternative solution was analyzed through three-dimensional finite element analyses, and it was found that it can guarantee the service limit states of deformation of the adjacent tunnels, as well as deformation of the retaining structures.

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