Excavation and Peripheral Earth Retaining Solutions at *K-Tower*, in Lisbon

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Abstract

In a scene of rapid growing population, together with its migration towards the urban areas, the geotechnical project importance is emerging as a way to optimize the sparse space still available in the urban core. Facing a fast squared meter price rise, and under the light of sustainability and resilience, the geotechnical project complexity was substantially increased by the high number of conditioning factors and the rising demand for underground space.

In this context, the present work squires the geotechnical project for the K-Tower, office building to be, located in Lisbon, which faces the Lisbon Metro tunnel. For this contract, a spaced pile wall solution was carried out with temporary ground anchors and corner struts as bracing elements.

Therefore, the critical section was modelled by means of a finite element software, *Plaxis 2D* in order to analyze the performance of the chosen solution. Hence, by comparing values collected at the site through instrumentation with the numerical model output ones, a back-analysis was carried out in order to reduce the gap between the numerical and the monitoring values.

Finally, after ensuring serviceability and ultimate limit states, a similar but more economical solution was studied and proposed. This solution promotes a wider spaced pile wall optimizing the steel rebars per pile when compared to the original designed solution. This solution attempts to maintain the structural performance while optimising costs, deadlines, material and environmental impact.

Keywords: Peripheral earth retaining structures, pile walls, modelling, tunnel, monitoring

1. Introduction

The rapid increase in population has led to an exponential demand for space in urban areas. In a way to contour this problematic, people are seeking more underground space. Hence, the excavation and retaining project has become a major player among the remaining projects. Using the city of Lisbon as an example, its erratic topography represents a challenge to the geotechnical engineers. In this context, the sustainability together with the urban complexity, requires stability assurances, both global and local. Logically, this implies a well-suited instrumentation and monitoring plan in order to control deformations of both ground and neighbouring structures based on alert and alarm criteria.

The present case study explores an excavation and peripheral earth retaining structure in a densely constructed place in Lisbon. It is situated in Avenida Recíproca, in Lisbon, and regards the construction of an office tower with basements next to the Lisbon Metro.

Therefore, this work focuses on: an analysis of the adopted solutions, its performance, which was then compared to the numerical solutions attained for the designed project and an alternative and more efficient solution to the project.

2. Spaced Bored Pile Walls

Spaced bored pile walls are an economic and fast solution for retaining cohesive soils. This solution takes advantage of the arch effect to stabilize the soil between piles and is commonly anchored or braced with struts in order to assure its horizontal stability. It is a flexible solution that is executed with an auger and a *Kelly* bar and is concreted *in situ*.

3. Case Study: K-Tower, Lisbon

The current case study is located on a slope bordered by Rua Conselheiro Lopo Vaz to the North, by Avenida Recíproca to the North, by the Moxy Hotel to the West and by the Lisbon underground subway tunnel to the East. The plot has a total area of 7711m2 [1] and is presented in Figure 1.

Figure 1 – Schematic, in 3D and plan, of the lot and neighbouring conditions. Moxy Hotel plot in blue and K-Tower plot in red. Adpated from Reunia and KREST (2019-2020) [1] [2]

3.1 Main Restraints

Regarding the neighbouring structures, the main restraints identified for the project were the Moxy Hotel and the Lisbon Metro tunnel. The existence of the Lisbon Metro structure close to the site implies extreme care and a rigorous instrumentation and monitoring plan, which restrains the retaining solution adopted for the specified project.

Along with the latter, according to the Geological Map of Portugal (Sheet 34-B and D), the geological charts present a sequence of Miocene layers composed of sands, limestones, and some shallows on the South limit of the site. The geotechnical zones identified on the geological and geotechnical study are presented in Table 1 [3].

Table 1 – Geotechnical zones and geomechanical parameters for the case study [3]

Zone	Materials	N_{SPT}	γ [kN/m^3]	Φ' [°]	E' [MPa]
ZG1	Landfills and severely decompressed Miocene	< 20	18	25	4
ZG2A	Severely decompressed Miocene – silty sands and biocalcarenites	21 – 33	18	30	8
ZG2B	Decompressed Miocene – silty sands, clays and biocalcarenites	32 – 48	19	33	11
ZG2C	Decompressed Miocene – silty sands and biocalcarenites	48 – 57	20	36	20
ZG3	Slightly decompressed Miocene – silty sands, clays and biocalcarenites	≥ 60	21	37	60

3.2 Adopted Solution

For this purpose, taking into account the restraints mentioned above, it was designed an anchored spaced pile wall with corner struts and a traditional cantilever wall. However, more emphasis was given to the spaced pile wall since it is the most complex solution. The retaining adopted solution is show in Figure 2.

Figure 2 – Anchored spaced pile wall and traditional cantilever wall solution on the South border

3.3 Instrumentation and Monitoring Plan

In order to manage the associated geotechnical risk regarding the behaviour of the retaining and adjacent structures and infrastructures, an Instrumentation and Monitoring Plan was created, thus, confirming the wall behaviour, reducing costs, and controlling the construction sequence. Therefore, alert and alarm criteria were set as boundaries for the allowed displacements/loss of prestress of the wall. Accordingly, this tool which is imposed by Regulamento Municipal da Urbanização e Edificação de Lisboa (RMUEL) [4] is and should be seen as an investment. The alert and the alarm criteria for each structure/anchor are shown in Table 2 [5].

Table 2 – Alert and alarm criteria for both structures and ground anchors [5]

Location	Instruments	Measurement	Direction	Alert Criteria	Alarm Criteria
Retaining Structures	Topographic Targets	Maximum Displacements	Horizontal	30mm	40mm
			Vertical	20mm	30mm
	Load cells in Ground Anchors	Load Change	-	15%	25%
Neighbouring Structures	Topographic Targets	Maximum Displacements	Horizontal	20mm	40mm
			Vertical	15mm	30mm
Lisbon Metro Tunnel Structure	Topographic Targets	Maximum Displacements	Horizontal	7mm	10mm
			Vertical	7mm	10mm
Lisbon Metro Rails	Topographic References	Maximum Displacements	Horizontal	±3mm	±5mm
			Vertical	±3mm	±5mm

*** Alert and alarm criteria established by the Lisbon Metro, ML**

Evolution of horizontal displacements measured by an inclinometer and evolution of a ground anchor load measured by a load cell on the studied section are presented in Figure 3 [6].

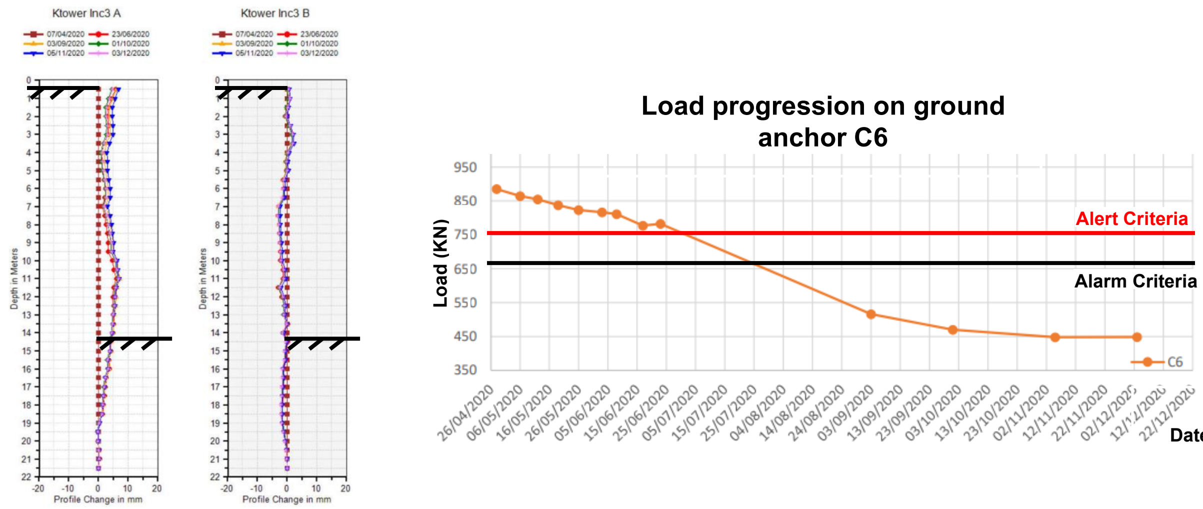

Figure 3 – Evolution of horizontal displacements measured in inclinometers (left) and load measured in load cell on ground anchor C6 on the studied section. Adapted from DrillGo (2020) [6]

3.4 Modelling of the Executed Solution

In order to study the mechanical behaviour of the retaining structure and Lisbon Metro Tunnel, a finite element method software was used (Plaxis 2D) [7] to model the critical section of the retaining design. On that account, the choice of the critical section was defined by the most rigorous criteria on deformation. Therefore, according to Table 2, the critical section is the closest section to the Lisbon underground subway tunnel. The critical section and the model geometry are present in Figure 4.

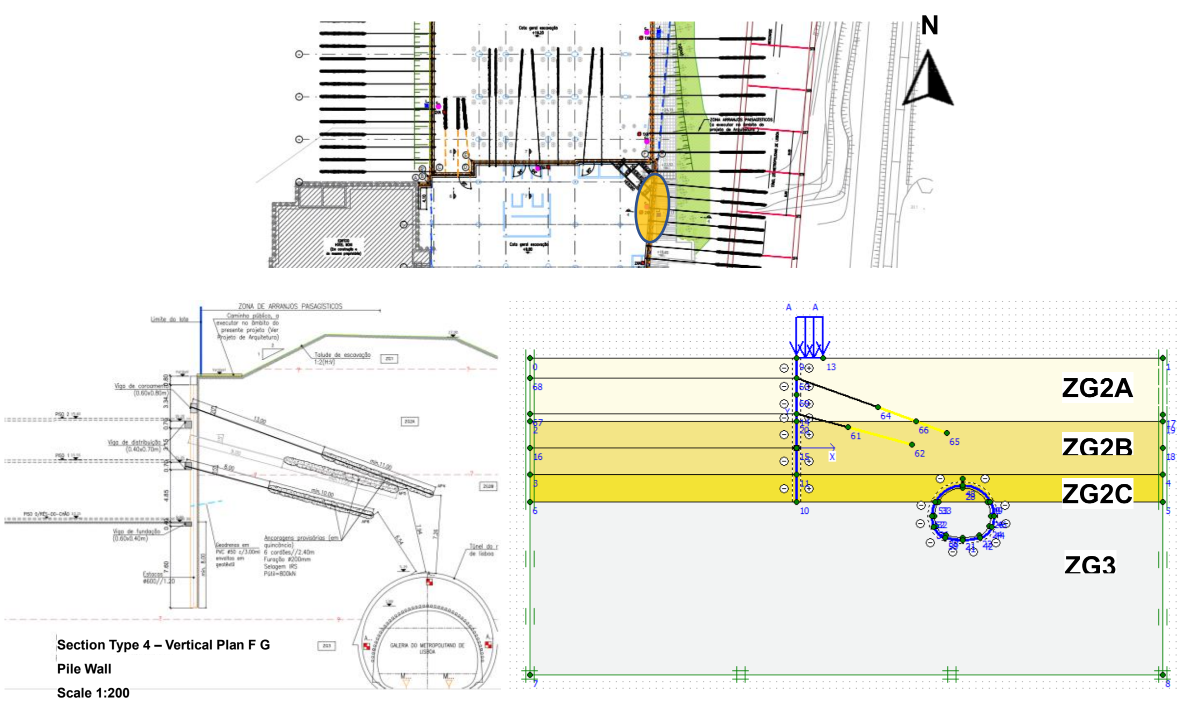

Figure 4 – Critical section in plan, section and model geometry

Note that for all models, a drained analysis was carried out using the Hardening-Soil model, an isotropic hardening model. Furthermore, a correct soil parameterization is of utter importance on this type of modelling. For the critical section model, most parameters used were based on the geological and geotechnical study information. Note that all Young's Moduli were increased in 20% in comparison to the geological and geotechnical study. Also, the stiffness modulus for unloading-reloading was considered between 5 and 6 times the stiffness moduli for the Miocene deposit layers of Lisbon. The following geotechnical parameters were used for the soil layers:

Table 3 – Geotechnical parameters for the different modelled layers

Zone	c' [kPa]	γ_{unsat} [kN/m^3]	γ_{sat} [kN/m^3]	Φ' [°]	φ [°]	E^{ref}_{50} [kN/m^2]	E^{ref}_{oed} [kN/m^2]	E^{ref}_{ur} [kN/m^2]	*m*	R_{inter}
ZG2A	4	18	21	30	0	9,60E+03	9,60E+03	5,76E+04	0,50	0,90
ZG2B	10	19	22	33		1,32E+04	1,32E+04	7,92E+04	0,50	0,90
ZG2C	20	20	23	36		2,40E+04	2,40E+04	1,20E+05	0,50	0,90
ZG3	40	21	23	37		7,20E+04	7,20E+04	3,60E+05	0,50	0,90

Since the soil heave is not considered critical due to the high unloading-reloading Young's moduli, the work focuses on the horizontal deformation of the wall as well as on the total deformation of the Lisbon Metro tunnel section. The global displacements, the wall horizontal displacements and the total displacements of the Lisbon Metro tunnel are presented in Figure 5.

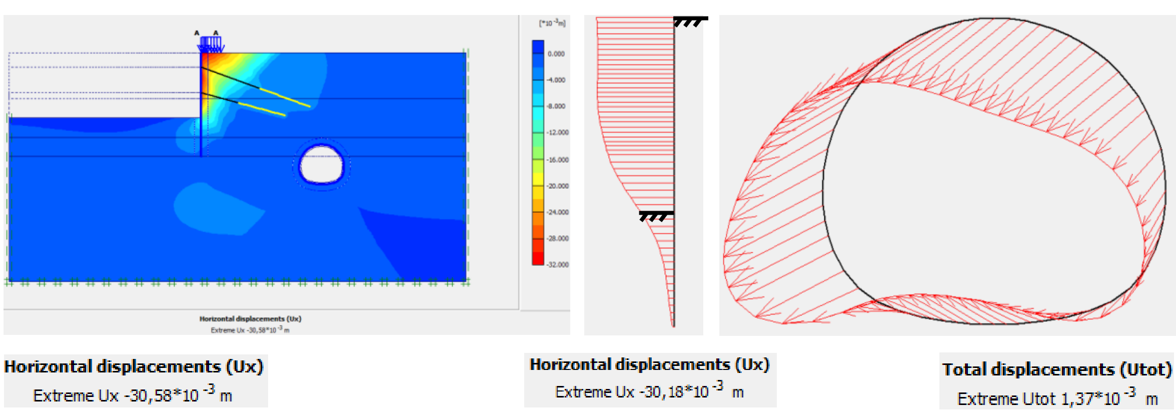

Figure 5 – Horizontal displacements (global and wall) and total displacements for Lisbon underground subway tunnel section – original model

The stresses and the deformations obtained on the wall in the last modelling stage were also verified against the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) according to the Eurocode 7 (AC1-C2) [8]. For the SLS, it was considered a H/500 limit, in which the wall deformation does not comply with. The stresses estimated on the retaining wall are presented in Figure 6.

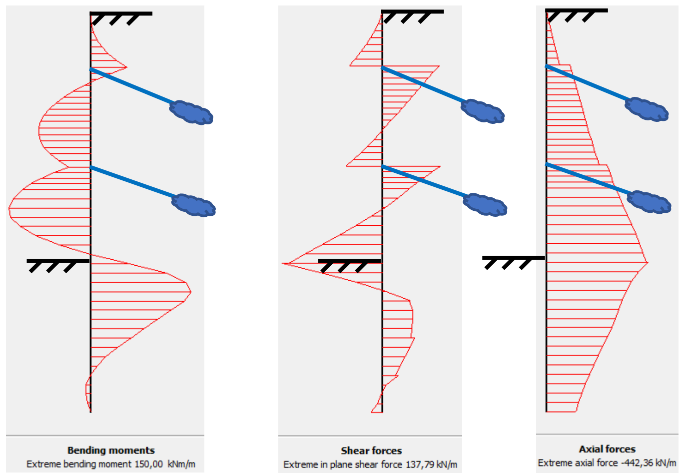

Figure 6 – Bending moments, shear forces and axial forces applied on the modelled wall

3.5 Results Comparison

Comparing the results obtained through the model with the site instrumentation ones, it is possible to observe a clear gap between both sets of results. The 6,7mm horizontal displacement obtained in the inclinometer in Figure 3 is 5 times lower then the 30,18mm horizontal displacement obtained in the last stage of the model. Regarding the tunnel section, the 1,37mm obtained through modelling are around 750 times higher than the ones obtained in the *in situ* topographic campaign, 0,004mm.

3.6 Back Analysis

Due to the large discrepancy between the two sets of results, a back analysis was performed in order to close the gap between them. Since, the soil parameters suggested by the geological and geotechnical study don't refer to the shear strength of the Miocene layers (c'), the back analysis looks for c' values that lead to similar deformations to the ones obtained by the *in situ* monitoring. The values of c' chosen for the back analysis take into account the increase in shear strength with an increase of the ground vertical stresses (deep layers have higher c' than superficial ones for the same materials) and are presented in Table 4.

Table 4 – Optimized shear strength values

Parameter / Geotechnical Zone	ZG2A	ZG2B	ZG2C	ZG3
c' [kPa]	4	10	20	40
c' revised [kPa]	**25**	**60**	**80**	**90**

The global displacements, the wall horizontal displacements and the total displacements of the Lisbon Metro tunnel obtained from the back analysis are presented in Figure 7.

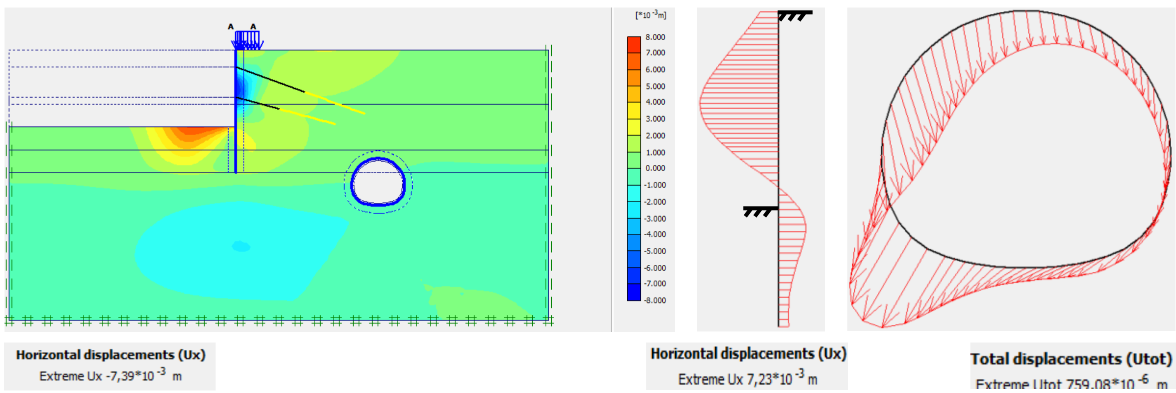

Figure 7 - Horizontal displacements (global and wall) and total displacements for the Lisbon Metro tunnel section - back analysis model

4. Alternative Solution

In the sequence of the geotechnical parameters obtained in the previous chapter, an alternative solution was analysed taking advantage of the optimised shear resistances. This solution intends to reduce costs, construction time and reduce the environmental footprint.

After many considerations, it was proposed a spaced pile wall solution similar to the original one with a wider spacing of 1,30m between piles (1,20m from design) and a wider solution of anchors, spaced by 3,9m (2,4m from design). Moreover, due to the high resistance stresses, it is proposed an optimised steel percentage for the piles, with only 7Ø25mm and Ø12//0,25mm stirrups for each branch (2 branches). This optimised solution saves up 12 piles and 15 anchors among the 193 piles and 122 anchors considered in the original design.

4.1 Modelling of the Alternative Solution

In order to test the solution, a new model was developed taking into account the new structural geometry but with a similar conceptual solution as in the original solution (Figure 4). The global displacements, the wall horizontal displacements and the total displacements of the Lisbon Metro tunnel retrieved in the alternative solution model are presented in Figure 8.

Furthermore, it is convenient to state that both solutions with less inclined anchors and with smaller anchors with a larger grout drilling diameter were tested and were excluded since they provided a way too conservative approach.

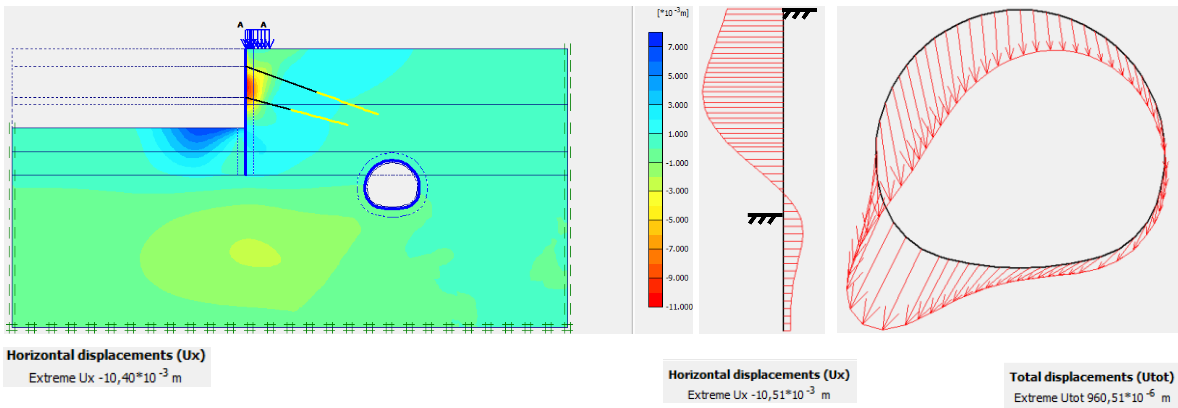

Figure 8 - Horizontal displacements (global and wall) and total displacements for the Lisbon Metro tunnel section – alternative solution model

It is possible to observe that even considering a less conservative solution, the behaviour of the soil and structures is still within limits, especially the tunnel section that still presents submillimeter results.

4.2 Economic Analysis

Since an alternative solution is presented, an economic analysis of both the original and alternative solutions brings additional value to the work, mainly to the contractors. For this analysis, the quotes were supplied by the original project designer company, JETsj. Accordingly, the final quotes provided for each design solution are displayed in Table 5. It is possible to see that the proposed alternative solution faces a 13,41% reduction when compared to the original design one.

Table 5 – Final quotes for both the original and alternative retaining wall solution

Solution	N.º of piles	N.º of anchors	Total Price [€]	∆P [€]	∆P [%]
Original	193	122	619 219,48	83 020,22	13,41%
Alternative	181	107	536 199,26		

5. Final Remarks

Even though a 3D analysis would present itself worthy, in a way that the arch effect between piles could be observed and verified and the behaviour of both the Lisbon Metro tunnel and the remaining adjacent structures could be more complete, the results obtained via 2D analysis were satisfactory.

Concerning the models develope using Plaxis 2D software, these verified the designed original solution, allowing a comparison between the numerical results and the results provided by the *in situ* monitoring. Therefore, a back analysis was possible and the shear resistance values for each layer were revised. This allowed to study and propose an alternative solution based on the original one: a wider 1,30m spaced pile wall versus the 1,20m and a wider 3,9m spaced anchor solution versus the 2,4m designed and a reduction of the steel reinforcement in each pile. The pile reinforcement reduction was considered after checking the Ultimate Limit States for the piles using the AC1-C2 in Eurocode 7. The Serviceability Limit States using a H/500 as a deformation limit for the horizontal displacements of the wall was also observed. It was concluded that the alternative solution didn't have a great impact on expected displacements through a 2D analysis. This solution also proved to be 13,41% cheaper for the contractor company.

It is suggested an evaluation of the possible prestress reduction on ground anchors, a 3D analysis of the model and a study of the impact of temporary anchors being active since the Summer of 2020 since the superstructure construction hasn't started yet.

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