Excavation and Retaining Wall Solutions near Gare do Arco do Cego, in Lisbon

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Abstract: The present work consists on the analysis of flexible earth retaining structures. Excavation and peripheral retaining structures work under *Defensores de Chaves Avenue*, *Lisbon* is used as case study. The retaining wall, in this construction site, consists of a curtain of bored piles wall with two support levels materialized by ground anchors and corner shoring. A three-dimensional model of the peripheral earth retaining structures earth retaining structures structure was modeled in the finite element software SAP2000. In the three-dimensional model, two types of analyses were performed, one considering only the final phase of the excavation, and the other considering the construction phase. A comparative analysis was carried out between the two types of analysis to understand the influence that successive of excavation phases have on the final behavior of this type of solution.

An alternative support solution, for the retaining wall, using two level of struts was also studied. This solution is materialized by slab bands around the periphery of the earth retaining wall, forming a closed frame and complemented by seven shoring beams.

After analyzing the two solutions, the main structural elements were checked for safety, followed by a comparative analysis of the structure behavior as well as the associated costs.

Keywords: Excavations; urban areas; retaining walls; bored pile walls; modeling; displacements.

1. Introduction

The increase of population and the high densification of urban center constructions has good to the necessity of using the subsoil for the construction of underground infrastructures. This work focuses on the construction of underground works in urban areas.

One of the reasons that led to the increase of underground constructions and, consequently, to excavations of greater depths was the need to increase the number of city parking lots.

These works have a construction area limited by the neighboring constructions. For this reason, the type of structures most used for the accomplishment of an excavation, in urban environment, are flexible support structures which allow for a vertical excavations, which increases the profitability of the construction area.

The carried out work will focus on the analysis of a case study concerning the excavation and earth retaining wall for the construction of a 4-basement car park next to the *Arco do Cego* Gare, in Lisbon. The solution was analyzed through its three-dimensional modeling using the finite element software SAP2000.

An alternative solution for the support of the retaining wall was designed and analyzed in order to check the influence of this type of support system on the retaining wall's behavior, through a comparative analysis of the deformations, efforts and costs of the two solutions.

Each solution was submitted to two types of analysis, the first considering only the final phase of the excavation and the second considering the several excavation phases. A comparison of the results was made in order to confirm if the consideration of the construction phases has an important influence on the final horizontal displacements.

2. Flexible Retaining Walls

The flexible earth retaining structures are usually slender structures whose operation depends essentially on their bending strength, meaning its weight contribution is insignificant. Since they are flexible structures, and, as such, are subject to deformations imposed by the earth pressures that will influence the size and distribution of these pressures as well as the stresses to which they are dimensioned. There are several types of flexible support structures, which differ by its components, as the materials and the constructive process. (Matos Fernandes, 1983).

The stability of the curtain can be assured by one or more levels of support realized through ground anchors or props, with temporary or definitive character. The props operate by compression, usually supported by two opposing walls of the earth retaining structures or at the corners. While the anchors work, essentially, due to the change of pressure in the soil, although the rigidity and displacements imposed by the prestress contribute to improve the behavior of this type of structures (Guerra, 2008b).

When constraints exist that prevent the use of anchors or props, it is possible to use the slab bands as a support system of the earth retaining structures. The slab bands will act as high stiffness beams in the horizontal plane, perpendicular to the earth retaining structures structure and are applied, where possible, to the entire perimeter of the excavation pit, forming a rigid frame that will work as a support system of the earth retaining structures structure.

The analysis of the earth retaining pressures in flexible support structures is a very complex question because as it is a problem of soil-structure interaction, so the pressure in the contact between the soil and the structure can not be explained by any classic theory of earth retaining pressures, since it is the results of the interaction process (Guerra, 2008c).

Terzaghi and Peck proposed the equivalent earth pressure diagrams (Figure 1) which definition is based on the observation and measurement of the compressive stresses in the struts of earth retaining structures performed to date.

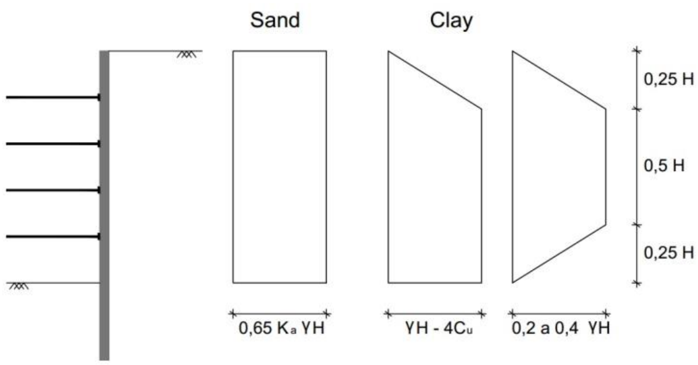

Figure 1 – Equivalent earth pressure diagrams proposed by Terzaghi and Peck

Where, k_a is the active earth pressure coefficient, γ is the bulk unit weight, c_u is the undrained shear strength and H is the excavation overall height.

These diagrams allow to estimate the forces at the props. In the case of anchored curtains, the problem of determining the pressures developed beneath the structure does not arise. The question here rests in the values for which scales the prestressing load is applied to the anchors so that the behavior of the system is the desired one.

Terzaghi and Peck diagrams can also be used for a preliminary design of the pre-stress, since the anchors are pre-stressed to balance the correspondent apparent earth pressure resultant with the admissible behavior of the excavation (Guerra, 2008b).

In the present work, the curtains of bored piles were studied. This solution is constituted by a set of reinforced concrete piles, connected to each other through a capping beam at the top. Depending on the excavation height, soil type and allowable displacements there may also be one or more depth distribution beams.

3. Case Study – Parking Lot in Arco do Cego, Lisbon

The subject of this Master thesis is the excavation works and the peripheral earth retaining structures required to build four basements and one half-basements at the 'Parque de Estacionamento Público' of Arco do Cego. This construction will be built between the intersections of João Crisóstomo Avenue and Defensores de Chaves Avenue, in Lisbon (Figure 2).

Figure 2 - Aerial view of the construction site (adapted from JETsj, 2015a)

In this study, the types of structure adopted for the excavation works were curtains of bored piles spread along the perimeter and King Post retaining walls structures, supported by temporary ground anchors and props.

4. Modeling

The model comprised the use of curtains of bored piles, each placed 1,2 meters apart along the excavation perimeter, with two levels of support in depth made with temporary ground anchors and corner shoring. The geometry of the excavation area is represented in the Figure 3, marked in red.

The peripheral earth retaining structure was modulated using the finite element software SAP2000 with 3D modeling (Figure 4). In order to simplify the model, it was assumed a rectangular area for the excavation measuring 88,8x16,8 m^2 (marked in black in Figure 3). The excavation height was defined as constant and measuring 12,9 meters (height from point A to B in Figure 3).

Figure 3 - Real and adapted excavation site representation (plan)

The Φ600mm spaced 1,20m bored piles curtains were composed by one capping beam at the top with a section of 0,80x0,70m2 (to level 0,0 m) and five distribution beams with a section of 0,6x0,4m^2 (to level -2,0, -7,8, -10,7, -12,9 m). There are also two sets of struts placed at levels -2,0 m and -7,8 m.

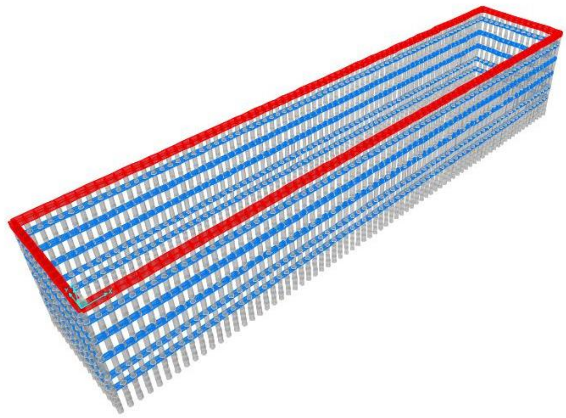

Figure 4 – 3D model (SAP2000)

The ground pressures the curtains back side were simulated using distributed loads applied along the length of the bored piles. The value of each distributed load was determined using the apparent earth pressure diagrams proposed by Terzaghi and Peck.

5. Solution 1 – Anchors as system support

For this solution, the support levels were made using corner shoring and provisional anchors, each placed 3,6 meters apart along the perimeter. The two sets of struts are placed at levels -2,0m and -7,8m. The side elevation from AB and CD are composed by 20 anchors and 4 corner shoring for each level of support.

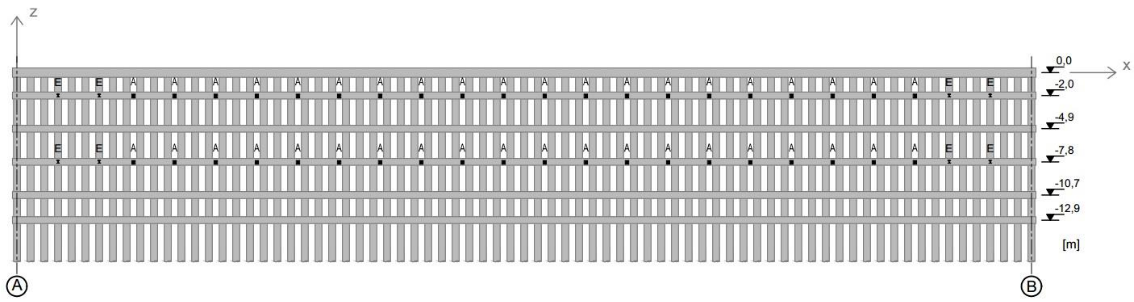

Figure 5 – Levels of Struts for Solution 1 (view)

This structure was studied in two different analysis, the first analyis, only contemplated the final excavation phase, while the second analysis considered successive phases of excavation. The maximum values for horizontal displacement at the final phase of the excavation works are shown in Table 1.

Figure 6 shows the horizontal displacements of the curtains for each analysis. As one can see, the results obtained for the second analysis reveals more constraints compared to the previous one.

Table 1 – Horizontal displacements of the curtains for each analysis (Solution 1)

Depth [m]	0,0	-2,0	-4,9	-7,8	-10,7	-12,9	-16,9
δ_H (Analysis 1) [mm]	0,5	1,2	2,3	1,1	0,6	0	0
δ_H (Analysis 2) [mm]	4,5	4,6	4,9	2,7	1,1	0	0

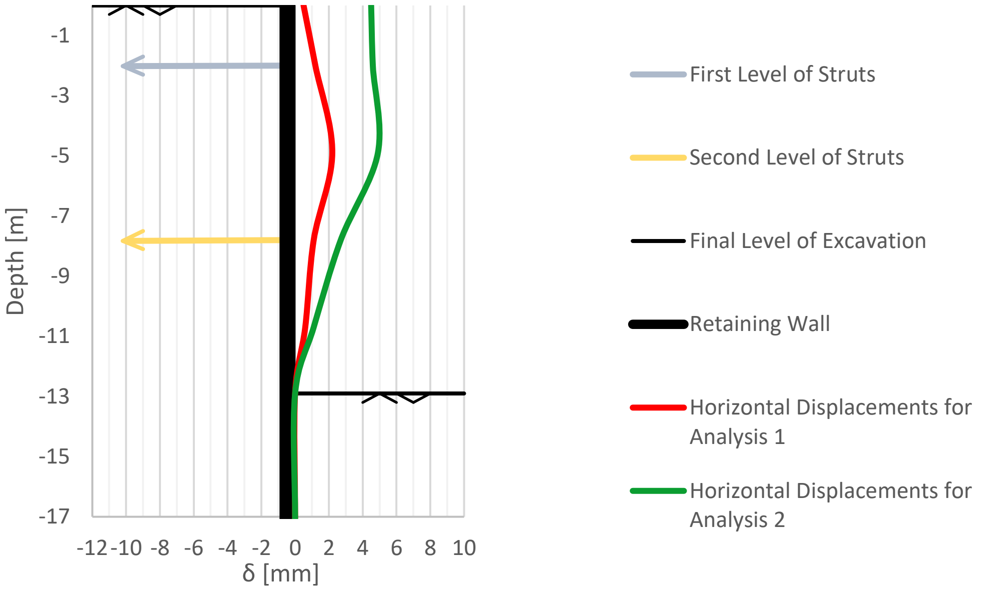

Figure 6 – Comparison of horizontal displacements for both analysis (Solution 1)

6. Solution 2 – Slab Bands as Support System

In this research, it was performed also an alternative study, in which the levels of struts were materialized by slab bands, each with 3 m wide and 0,68m of thickness, placed along the earth the earth retaining curtain, forming a closed frame. The slab bands were shored by seven beams in each level of struts (Figure 7 and Figure 8).

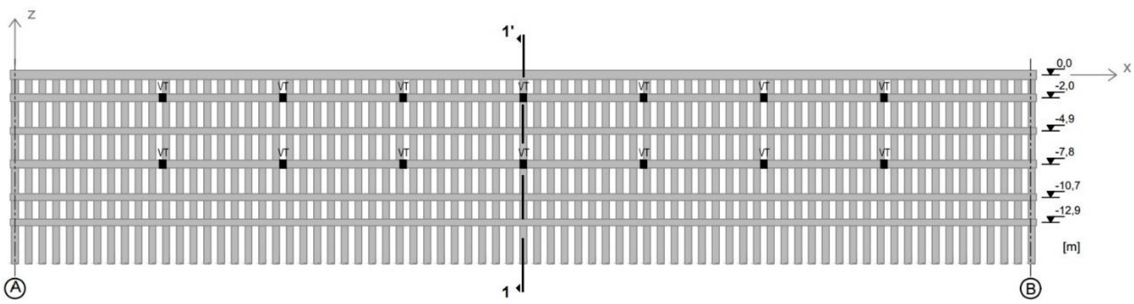

Figure 7 – Levels of Struts for Solution 2 (view)

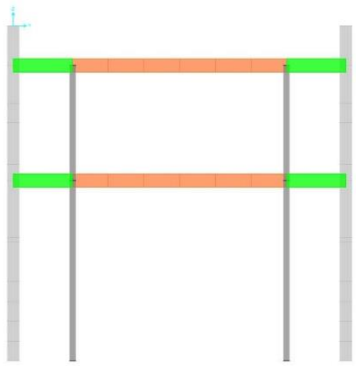

Figure 8 – Section 1-1' of 3D model for Solution 2

The second solution was studied using the same assessment as before. It was divided in two cases, in which the first case only considers the end of excavation and the second one includes the successive excavation phases.

The results obtained for the horizontal displacement of the curtains in both analysis are shown in Table 2 and Figure 9. The results show larger displacements for the second analysis.

Table 2 – Horizontal displacements of the curtains for each analysis (Solution 2)

Depth [m]	0,0	-2,0	-4,9	-7,8	-10,7	-12,9	-16,9
δ_H (Analysis 1) [mm]	2,3	1,9	3,2	1,6	0,9	0	0
δ_H (Analysis 2) [mm]	6,4	5,4	5,7	3,2	1,4	0	0

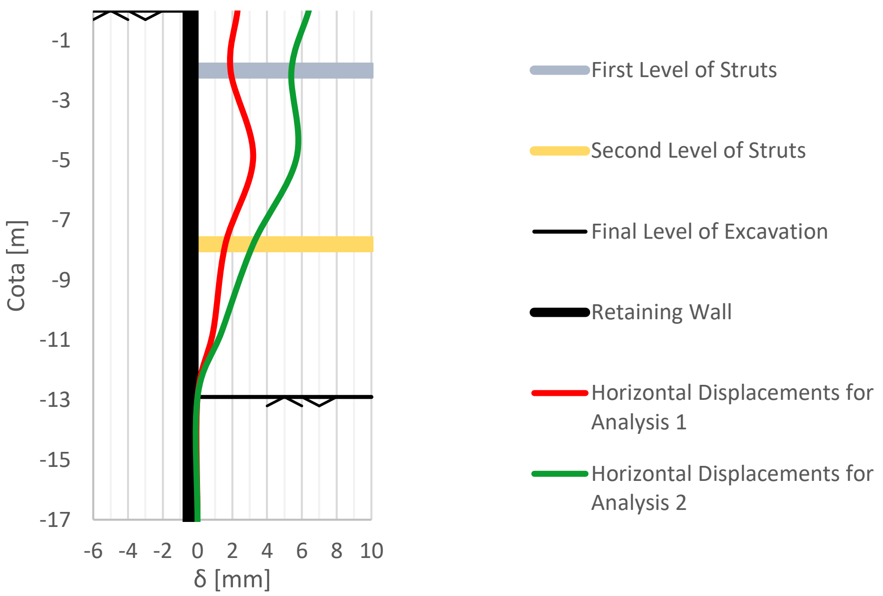

Figure 9 – Comparison of horizontal displacements for both analysis (Solution 2)

7. Comparison between Solution 1 and 2

This study was complemented with a comparison between the two solutions presented. Figure 10 shows the displacements of the wall for analysis 2 in both solutions. One can see that the displacements are greater for the solution 1.

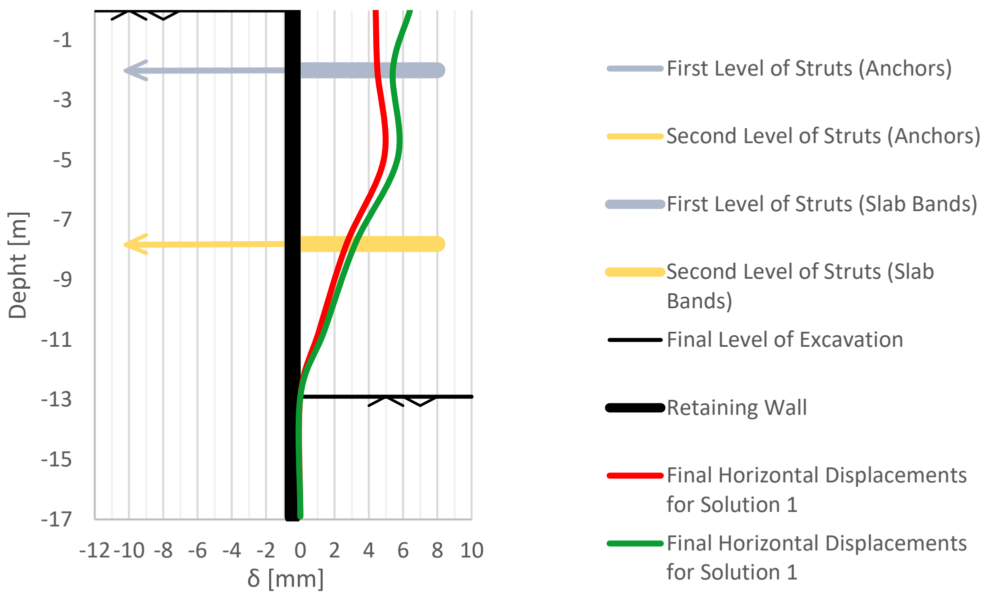

Figure 10 – Comparison of horizontal displacements for the final phase of both Solutions (Analysis 2)

Furthermore, Figure 11 shows the comparison between both solution for the curtain behavior and after the introduction of the struts. The continuous lines (phases 1, 3 and 5) marks the displacements after the excavation phase and the dashed line represents the displacement after the installation struts. When the ground anchors are installed, they produce an opposing displacement to the one caused by the earth pressures acting at the curtain back side (Figure 11 a)). This effect decreases the displacements verified before.

In the second solution, the support for the retaining wall structure was made with slab bands, as they have higher stiffness. The introduction of this type of support doesn't lead to displacements of the wall, only prevents further displacements during next excavation phases (Figure 11 b)).

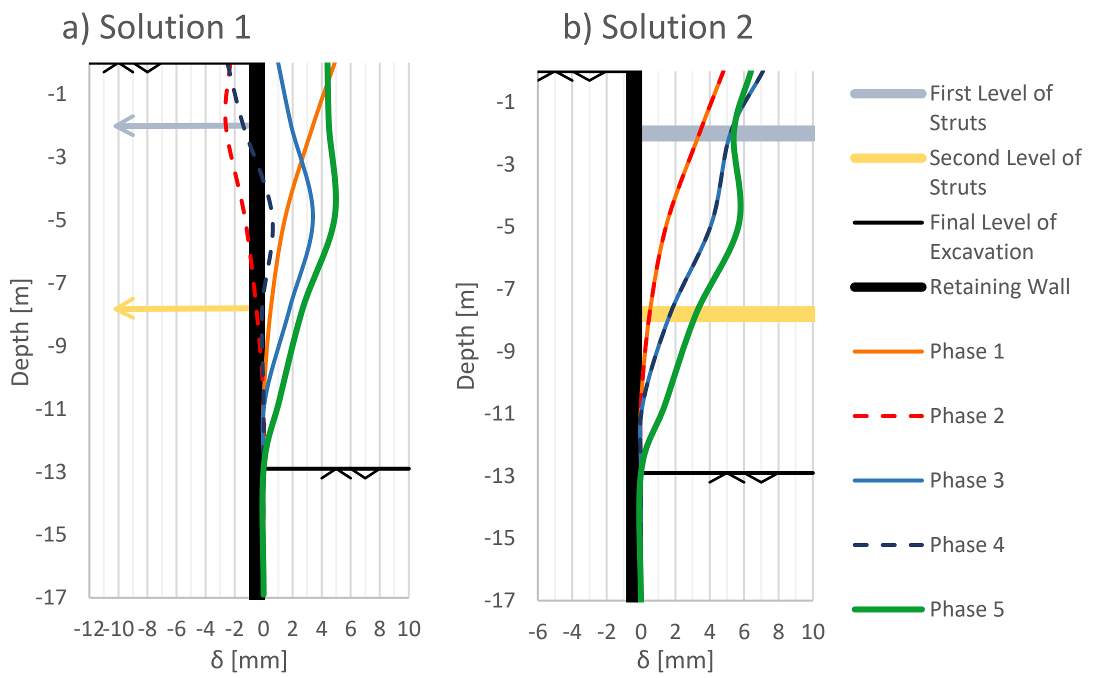

Figure 11 – Behavioral comparison after the introduction of support systems for each solution

A comparative economic analysis was made for each solution. The costs were only estimated for the elements that were different between the solutions. These are the structural elements used in both support systems. In solution 1, it was considered only the anchors and props, while solution 2 contemplated the slab bands and shoring beams.

The costs calculated were 38,1 €/m^2 and 30,5€/m^2 for Solution 1 and 2, respectively.

8. Final Remarks

The objective of this study was to analyze the behavior of anchored bored piles curtain using the 3D modeling finite element software SAP2000, in the construction site, near to Gare do Arco do Cego in Lisbon.

In order to reproduce the pressures of the soil acting at the curtain, distributed loads applied along the length of the bored piles, more adopted. The value of each distributed load was determined using the apparent earth pressure diagrams proposed by Terzaghi and Peck.

Two types of analysis were made for each solution. The analysis 1 contemplates only the end of excavation and analysis 2 considers the successive of excavation phases.

The results obtained for each analysis showed that the use of successive phases of excavation affects stresses and displacements of the final phase of excavation. Furthermore, it demonstrates also that the final phase may not be the more critical one.

Since this study comprises two types of support solutions for the retaining wall, it was possible to perform a comparative analysis in order to understand the effects of each solution in the behavior of flexible support structures.

The final displacements for each solution were compared in Figure 10, in which one can conclude that solution 2 creates more horizontal displacements than solution 1.

In Figure 11, one can see that horizontal displacements in the first phase of excavation were 4,9 mm for the top and 3,4 mm for the first level of struts.

The introduction of ground anchors, in solution 1, decreases the displacements originated in the first phase of excavation, whereas, the placement of slab bands in solution 2, only prevents further displacements during next excavation phases. These behavioral differences can justify the discrepancies observed at the end of excavation phase of the two solutions.

Nonetheless, solution 2 can be considered a good alternative if, for some reason, it's not possible the use of an anchored solution.

Regarding the economic analysis made for both solutions, one can verify that the differences are not significant. However, solution 2 is slightly cheaper and some of their structural elements, like slab bands and beams, can be integrated at the final solution.

Because Solution 2 consists of a definitive structure there is no need of removal and deconstruction. As a result, the system will have higher stiffness and smaller displacements than it would have if the temporary support system were removed.

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