Excavation and Earth Retaining Solutions in urban centers conditioned by the surroundings: Execution of the Access Tunnel to FPM41´s Building

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Abstract: The shortage of parking is one of the biggest problems in today's cities. Thus, more and more, buildings have to meet this need. However, the use of the subsoil for the construction of structures requires a careful study, due to the conditioning factors for its development.

The theme of this Dissertation arises in the context of the exposed problem, presenting the solutions of earth retaining structures that allowed the execution of the access tunnel to FPM41´s building. The soil characteristics and the constraints of the work, namely the neighboring buildings, required the application of three containment solutions: Bored Pile Walls, King Post Walls and Retaining Walls.

In the development of the work, emphasis will be placed on changes made to the project. These were of extreme importance, since they demonstrated that there are difficulties which are only possible to verify in the work environment, also demonstrating at the geotechnical level, the importance of an increased and rigorous study as a standard.

The monitoring of the construction highlighted the importance of the Instrumentation and Observation Plan as a means of ensuring the integrity of the structures that could be affected by the building process, measuring their displacements through appropriate devices.

Resorting to Plaxis computer program, a model of the most critical solution in the case study (King Post Walls) was elaborated. Hence, a comparative analysis between the values of the displacements obtained in the modeling and those of the instrumentation is presented, trying to clarify the reasons for their differences.

Keywords: Earth Retaining Structures, Access tunnel, Bored Pile Walls, King Post Walls, Instrumentation and Observation Plan, Modeling.

Introduction

In recent years, the construction industry in Portugal has shown tremendous growth, more specifically in central Lisbon. Nevertheless, this area of the city is already overcrowded as a consequence of growing real estate and tourism markets, which appeal to an increasing number of people seeking housing, commercial and service spaces. In order for these needs to be satisfied, it is necessary to oftentimes create unique and extremely complex solutions, without compromising the building's structural safety.

A scarcity of ample spaces for new constructions and the insufficient number of parking areas which ensure the population's need for mobility and comfort prompt a greater subsoil exploitation, namely for the construction of underground parking facilities and respective access points, often ensured through tunnels. Thus, it is indispensable to acquire a deep knowledge regarding the characteristics of soils and of the groundwater level, among others.

On the other hand, constructions in areas with a high density of structures requires these constructions to be confined to their lot area. It is, hence, indispensable that adjacent constructions of high heritage and social value be taken into consideration, as these cannot sustain any changes to their conservation status.

The above-mentioned problem is aligned with the topic of this Dissertation, which aims to study the retaining solutions used in the development of a tunnel (case study) and the significance of the geological and geotechnical studies indispensable for that development. Special attention is also given to the Instrumentation and Observation Plan, as a means to ensure the preservation of the surrounding heritage. In order to complete the study of the selected solutions, the numerical modeling program *Plaxis* was employed, and a model of the solution presenting the most unfavorable results in Monitoring was created.

The case study in this Dissertation consisted in the construction of an access tunnel to a car park, at 5 de Outubro Avenue and Pinheiro Chagas Street. Considering the constraints associated with this construction, namely Dr. Anastácio Gonçalves House Museum and Dr. Alfredo da Costa Maternity Hospital, it was necessary to resort to three distinctive retaining solutions.

According to [1], retaining structures can be classified as rigid, flexible and mixed. In the construction at hand, two flexible retaining structures were implemented, Bored Pile Wall and King Post Walls, and one rigid retaining structure, Retaining Walls.

Next, some theoretical underpinnings related to rigid and flexible retaining structures shall be presented, in accordance with the underlying assumptions of the case study, the access tunnel to the car park of FPM41’s building.

Rigid Retaining Structures

Rigid retaining structures use their own weight to ensure its capacity and its resistance. This allows for the balance of exerted thrusts in the backside of the retaining wall by using the gravitational force induced by its own element, avoiding thus possible occurrences of sliding and wall collapse. Rigid retaining structures are able to move when subjected to thrusts from retained soil [2].

The relationship between earth thrusts and the movement of the retaining wall is classified into at rest, active or passive states. This classification is performed according to Coulomb's theories which allow the thrusts exerted on the retaining wall to be estimated, taking in the existence of movement at the wall base.

Flexible Retaining Structures

Flexible retaining structures, on the other hand, do not use their respective weight to support retained soil. In turn, these structures use their flexural strength, and their structural stability relies on the introduction of horizontal support, namely struts, and their own foundations.

Flexible retaining walls are characterized by reduced slenderness and thickness. As a consequence, they are more susceptible to earth pressures and present larger displacements. This, in turn, means a higher capacity of stress distribution due to its deformability, leading to smaller bending moments than those associated with a rigid retaining wall [2].

Due to the introduction of horizontal support, the distribution of earth pressures and thrusts must be redefined over the course of the construction. It is, hence, necessary to assess the stress exerted at each strut level, so that its sizing can be developed in accordance with the pressures to be balanced by the retaining wall. Terzaghi and Peck introduced apparent lateral earth pressure diagrams which allow for the calculation of these stresses [3].

When using these diagrams, special attention must be given to the proposed retaining solution and to the influence area of each strut (the portion of soil for which each strut is responsible). The spacing between each strut (or strut level) tends to be constant, whereby the strains installed in each strut (or strut level) eventually become rather similar.

As flexible structures resort to horizontal elements, it is necessary to take into consideration vertical stresses resulting from their installation when sizing these structures.

King Post Walls

King Post Walls present several advantages, among which the following can be highlighted: the cost-effectiveness related to the construction process, the low level of expertise required from workers and that of the used technology, and the need for a smaller building site. The latter is particularly relevant nowadays, as construction works are increasingly limited by their surroundings and their development is restricted to their lot area, as the case study in hand verified [4].

Nonetheless, the application of these walls also entails some disadvantages concerning its execution in an urban area since it prompts soil decompression in adjacent land even though it does not require that land in order to be implemented. The decompression of adjacent ground may lead to the occurrence of settlements at the foundation level of adjoining structures. These settlements are, in turn, susceptible to result in serious damage. An answer to this problem is oftentimes to resort to reinforcement systems in adjacent grounds

[4]. In this case study, cement grout was used to reinforce the soil.

King Post Walls are built from the top down to the base of the wall, through the reinforced concrete panels which are horizontally supported (in this case through struts). The panels are founded by introducing micro-piles or metal beams [2].

The construction process is phased and carried out by levels. It is indispensable to respect the intervals between each concreting from one level to the next. Each of these levels is composed by primary and secondary panels, which must be built alternately, starting with the primary panels. This rule, in the construction of King Post Walls, stems from the fact that advantage is taken from the arching effect throughout the excavation stage by using soil berm (these support adjacent grounds when executing the panels). Hence, throughout the excavation, there is a significant reduction in the strains in the excavation area and an increase of those strains in the lateral adjacent ground [2].

Bored Pile Wall

The peripheral retaining solution named Bored Pile Wall is defined as "a discontinuous wall of piles with little distance between them, possibly intersecting each other" [5]. These piles, which are an integral part of the wall, are done inside the ground, before the excavation stage, and can be done through diverse methods. Nonetheless, taking the construction site location in an urban area into account, spaced bored piles were chosen. In this kind of retaining walls, the stabilization of the soil between the piles is also achieved through the arching effect.

A disadvantage of this solution consists of not ensuring the watertightness of the retaining wall, which in most cases leads to the mandatory use of drains, as verified in the case study.

So as to ensure the peripheral retaining wall stability, other elements are introduced besides piles, such as the capping beam, distribution beams and support struts.

Case Study: Access tunnel to FPM41's Building

The construction at hand was the car access tunnel to the car park of FPM41's Building (an office building which was also under construction), falling within the scope of Project of Excavation and Peripheral Retaining Wall. Taking its location into account, in central Lisbon, which lacks in available parking facilities, it became indispensable to ensure underground parking. The access to the underground car park was done precisely through the above-mentioned tunnel.

Figure 1 (taken from [6]): Aerial view of the tunnel's implementation area

Figure 1 shows the site location (in Lisbon's city center) and its sheer dimension, as well as the several constraints associated to its development.

Constraints associated with neighboring conditions

According to Figure 1, the main constraints regarding neighboring constructions were Dr. Alfredo da Costa Maternity Hospital, Dr. Anastácio Gonçalves House Museum and “Saldanha" car park. The tunnel construction led, in turn, to the diversion of several existing grid systems, namely water, electricity, telecommunications and sewage.

Geological-Geotechnical Characterization

The “prevailing geological environment in the site's subsoil involves the occurrence of sedimentary facies substratum dated back to the Miocene, representing the lithoestratigraphic unit of *Argilas dos Prazeres* (clay of the Prazeres formation, MPr), coated in modern materials of anthropic origin, named *Depósito dos Aterros* (At)” [7].
As previously mentioned, the access tunnel to the car park of FPM41’s building was developed simultaneously to the building itself. Thus, in order to build the tunnel, the values used had been gathered during the site investigation campaign for the construction of the building, composed by a foundations inspection pit (PF1) and five vertical drilling surveying systems (S1, S2, S3, S4, and S5). Given the fact that S3 was the closest surveying system to the tunnel's location, this was chosen to carry out the soil characterization to be inserted in the modeling program *Plaxis*, presented in the next sections.

Instrumentation and Observation Plan

To ensure the safeguarding of the heritage surrounding the tunnel, 17 topographic targets were installed in the façades of the buildings which could undergo deformations. Thus, the following measurable properties were ascertained: vertical and horizontal displacements in nearby buildings.

In the Project Description, it was established that the readings of the above-mentioned topographic targets would be carried out weekly. Nevertheless, in the wall belonging to Dr. Anastácio Gonçalves House Museum, the need was assessed to measure the displacements twice a week, in order to ensure that this building would not suffer excessive deformations.

Consequently, the following safety criteria were defined:

- “Alert Criterion: maximum horizontal displacements of around 20 mm, and vertical displacements of approximately 15 mm;
- Alarm Criterion: maximum horizontal displacements of around 40 mm and vertical displacements of approximately 30 mm” [6].

According to [8], all the structures respected both the Alert and the Alarm Criteria with considerable leeway. As would be expected from the established periodicity of the readings, the House Museum wall presented bigger displacements, having reached -7 mm at topographic target MCM2 and -5 mm in the yy and zz axis. In Figure 2, the location of the previously mentioned topographic target can be observed.

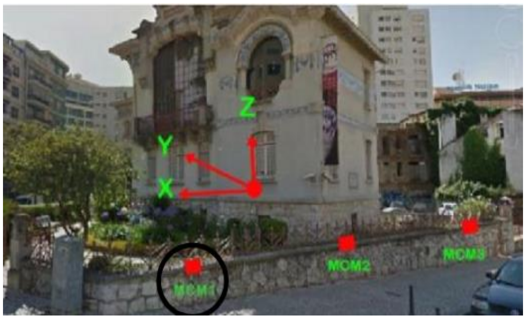

Figure 2 (taken from [8]): Location of the three topographic targets in the House Museum wall

In the area of the tunnel closest to the House Museum, the implemented retaining solution was King Post Walls. As this was the solution with the most unfavorable results in the monitoring, the respective modeling was carried out, using the numerical modeling program *Plaxis*.

Modeling

The modeling program *Plaxis* serves the purpose of assessing the stability of the retaining structures and respective deformations, considering the different stages involved.

With the modeling of the King Post Walls solution, a comparative analysis was established between the displacement values obtained in the *Plaxis* program and those obtained in the Instrumentation. This analysis allowed for a deeper knowledge regarding the behavior of these retaining structures.

Firstly, the geometry of the model was defined, setting a model of 10 m width (in which 4 m correspond to the length in which the tunnel excavation was executed) by 20 m height, "adopting 15-nod triangular elements for the finite element mesh" [4]. Furthermore, the structural elements for the retaining wall were determined: reinforced concrete panels, strut, micro-pile and heel.

Secondly, the characteristics of the different soil layers were ascertained, taking into account the soil characteristics assessed in the site investigation campaigns. At this stage, it was necessary to establish the Material Model as Hardening soil model, as this would best simulate the soil's behavior,

In Table 1, the soil parameters inserted in the program are shown.

Table 1: Characteristics of the geotechnical layers introduced in *Plaxis*

		Zonas Geotécnicas			
		ZG1	ZG2	ZG3	ZG5
Cotas		80 – 76,5	76,5 – 71,5	71,5 – 70	70 - 60
Modelo		*Hardening- soil*	*Hardening- soil*	*Hardening- soil*	*Hardening- soil*
Parâmetros	γ_{unsat} [kN/m³]	19	19	20	20
	γ_{sat} [kN/m³]	19	19	20	20
	E^{50}_{ref} [kN/m²]	5 000	10 000	20 000	60 000
	E^{50}_{oed} [kN/m²]	5 000	10 000	20 000	60 000
	E^{50}_{ur} [kN/m²]	15 000	30 000	60 000	180 000
	c_{ref} [kN/m²]	1	5	10	20
	v^{nu}_{ur}	0,3	0,2	0,2	0,2
	e_{init}	0,5	0,5	0,5	0,5
	Φ [º]	25	28	32	38
	Ψ [º]	0	0	0	0
	R_{inter}	1	1	1	1
	p_{ref} [kN/m²]	100	100	100	100
	m	0,5	0,5	0,5	0,5

In Figure 3, it is possible to visualize the numerical model defined in *Plaxis*.

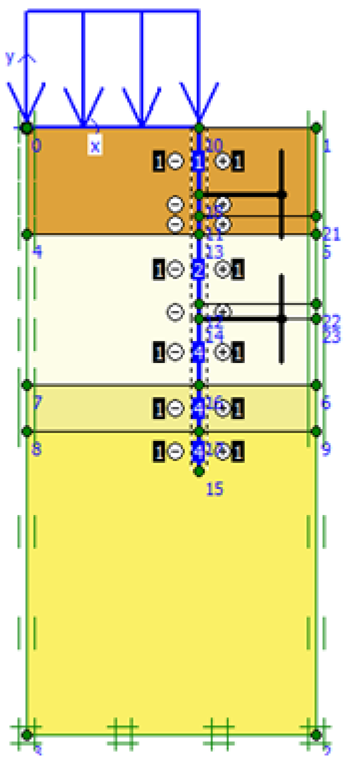

Figure 3: Numerical modeling of the proposed solution

Having completed the definition of the model, of the material characteristics and of the structural elements, the corresponding stages of the construction phases of the King Post walls were established, and calculations were carried out concerning the stresses and the deformations on the retaining wall, as well as on the soil.

In Figures 4 and 5, the horizontal and vertical deformations of the retaining structure in the final stage of its construction are depicted.

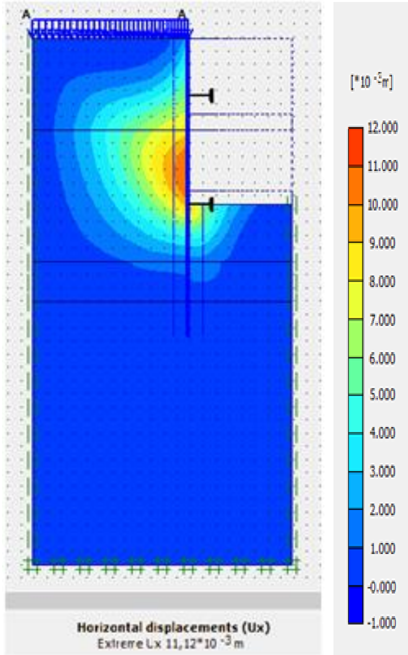

Figure 4: Horizontal deformations of the King Post Walls in the final phase

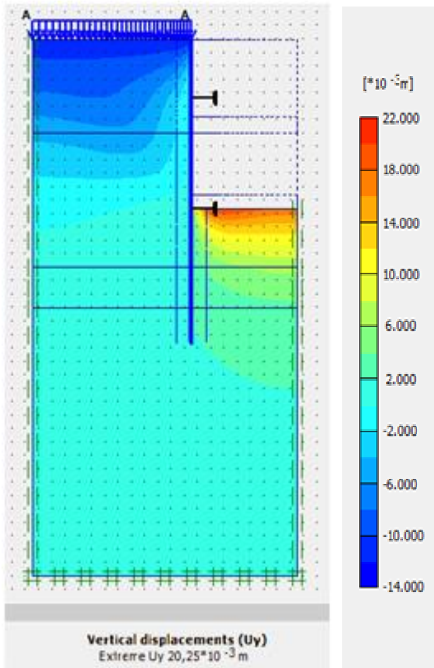

Figure 5: Vertical deformations of the King Post Walls in the final phase

According to the data presented in Figure 4, the highest horizontal deformations were found in the backside of the retaining wall. The highest horizontal deformation assessed was 11.12 mm and took place in the backside of the retaining wall, at the second level of the reinforced concrete panels which comprise the King Post Walls.

By analyzing Figure 5, it is possible to assert that vertical deformations were quite noticeable in two distinct locations: on the base of the excavation and on the surface soil, in the backside of the retaining wall. However, even though the highest deformation occurred on the base of the excavation (whereby ground heave occurred as the displacement values are positive), this did not present significant consequences in the behavior of neighboring buildings, namely regarding displacements and/or settlements. Thus, this deformation was not considered in the comparative analysis of the results. In the surface soil, in the backside of the retaining wall, the highest vertical displacements were 14 mm negative, which means settlement occurred.

Although the displacements undergone by the retaining wall did not surpass any of the defined safety criteria, the 14 mm settlement (vertical displacement) was extremely close to the limit defined under the Alert Criterion.

As mentioned, *Plaxis* also allows for the calculation of the stresses on the structural elements. In this Dissertation the stresses to be analyzed were the axial stresses on the strut and on the heel. The axial stress installed on the strut was -109.12 kN/m, whereas on the heel it was -30.98 kN/m. This difference emerges from the fact that the resistance and cohesion values of the soil in which the heel was introduced were much higher than those ascertained in the layer where the strut was built.

Analysis of the Findings: Comparison with the Monitoring Results

Among the several limitations of the program, it is necessary to emphasize that it is impossible to establish a direct comparison between the results obtained in the monitoring stage and those calculated in *Plaxis*. In the monitoring campaigns, the topographic targets were installed in the façades of neighboring buildings, outside the excavation area. In the program *Plaxis*, the modeling of the proposed retaining solution was developed, and the displacements of both the King Post Walls and the adjacent ground were evaluated. However, the displacements of the buildings surrounding the tunnel were not ascertained. This means that there is no place in which both the results from the monitoring and the results from the modeling were obtained.

Despite the limitation exposed in the previous paragraph, the analysis of the obtained displacements was not hindered, as the topographic targets installed in the wall of Dr. Anastácio Gonçalves House Museum were located very close to the location of the King Post Walls. Hence, attempts were made to provide reasons for the discrepancies between the results obtained in the *Plaxis* and the results collected in the construction site, during the monitoring campaigns.

Next, the reasons which contributed most significantly for the worsening of the displacements calculated by the program:

-Besides the conservative criterion when choosing the values to be inserted in the program, the previous treatment to the soil, carried out through cement grout columns, was not taken into consideration. Otherwise, this condition would lead to smaller displacements as the soil would present better characteristics than those simulated in *Plaxis*;

-King Post Walls present a particular feature: these take advantage of the arching effect, which leads to soil berms supporting the adjacent grounds throughout the excavation. This phenomenon occurs three dimensionally; nevertheless, in *Plaxis* this solution was modeled in 2D, which means that this effect was not properly considered, leading to bigger deformations than those ascertained in the monitoring campaigns;

-In *Plaxis* it is not possible to correctly simulate the construction process of King Post Walls, more specifically the alternate execution of the primary and secondary panels and the waiting times for the concreting of the different levels of reinforced concrete panels.

Main Conclusions

Continuously monitoring the construction was indispensable for learning and subsequent exposition of the stages associated with the above-mentioned building processes. This was due to not only the dimensions of the construction, but also the need for articulating the three very different retaining solutions in a small ground area.

Naturally, the reiterating presence in the construction site contributed, decisively, to acquiring knowledge in several fields of Civil Engineering which complete, in practical terms, the theoretical learning acquired in an academic context over the course of six years in Instituto Superior Técnico.

The *in situ* monitoring of the several stages of the proposed solutions revealed itself to be absolutely essential to perceive the difficulties regarding the respective execution. In fact, although the safety criteria for each phase have been dully followed, it was necessary to review the project.

Finally, even though the modeling program *Plaxis* present some limitations, its application when modeling peripheral retaining solutions is crucial, as it allows for a deeper knowledge into the deformations and strains of any given solution in each construction stage. Thus, the most sensitive areas and the areas requiring more attention can be ascertained. These advantages present virtually no cost, either in financial terms or in terms of time spent.

This Dissertation aimed at contributing for a better understanding of the functioning of retaining structures in urban areas; of the importance of the Instrumentation and Observation Plan for correctly monitoring the constraints to the construction; and of the need for a deeper knowledge of the soil characteristics, so as to ensure the viability of the proposed solutions and the correct development of models in modeling programs, such as *Plaxis*.

By completing this Dissertation, it can be concluded that the main initially proposed objectives have been accomplished.

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