Excavation and Peripheral Earth Retaining Solutions

Case Study: Hotel Meliá Lisbon

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ABSTRACT

The growing occupation of the urban area made the construction of new structures and the demolition of pre-existing ones more difficult, as well as boosting the need of exploring the underground, making it pertinent to study excavation and peripheral retaining solutions for these areas, which pose some challenges, particularly due to the existence of sensitive neighboring structures, such as tunnels and historic buildings.

As a result, the solutions become scarcer and their reliability and safety became more fundamental than ever, tending to be designed conservatively, as we will see throughout this thesis, namely while interpreting and analyzing the results of the Monitoring and Survey Plan.

We will begin by introducing the earth retaining structure solutions used, detailing their construction techniques, fields of application, advantages and disadvantages as well as the bracing systems used in them.

The main objective of this dissertation was to monitor and analyze the construction of the 6 underground floors of the future Hotel Meliá, located in the center of Lisbon, from the beginning of the works until the excavation of its ground floor.

It should be noted that at the peripheral earth retaining walls the Bored Pile solutions was used, as well as the King Post Wall with cast in situ reinforced concrete panels, in one of the alignments.

Throughout this work, both the adopted solutions and alternatives for the peripheral earth retaining wall are explained, justified, and compared. It is important to point out that this structure is located at the intersection of two streets with high pedestrian and road traffic. Changes to the initial project and its reasons are also addressed.

Finally, it will be concluded that, despite the extraordinary design of this underground structure, a more exhaustive soil characterization would have allowed for an eventually more optimized solution and, consequently, a more economically viable one.

KEYWORDS: Monitoring, Excavation, Earth Retaining Walls, Ground anchors, Struts, Slab Band.

1. INTRODUCTION

The need to explore and occupy the underground (namely using underground floors for parking) increases due to high demand and lack of space available for new buildings.

To create safe infrastructures, it is essential to define the soil characteristics of the area where those will be placed. To do so, it is crucial to observe the behavior of the earth retaining structure as well as of the neighboring structures. Keeping in mind that the results obtained through geotechnical surveys (isolated bore holes) may be numerically and interpretively extrapolated but there is a high degree of uncertainty associated with this process,

Taking that into consideration, there is a set of interesting difficulties and challenges, from the Civil Engineering point, which make this dissertation worth writing.

Therefore, for a case study located at the intersection of Avenida António Augusto de Aguiar and Avenida Fontes Pereira de Melo, the following goals were defined:

- Obtain a real experience of project and construction, identifying the different participants – recognizing their role –, the resources involved and the difficulties of execution.
- Identify, understand, and clarify all earth retaining structure structures relevant for this case study – detailing the processes involved, their limitations, benefits, and risks.
- Create records for the different construction phases of this case study, regarding the foundation and earth retaining structure.
- Analyze the results of the instrumentation placed and based on these results, make a critical comment on the implemented solutions.
- Assess possible alternative design solutions, particularly the eventual reduction of the earth retaining structure rigidity.

2. EXCAVATION AND PERIPHERAL EARTH RETAINING WALLS

The main purpose of earth retaining structure structures is to support the soils and the structure itself, preventing the land from sliding. They are "part of the structure of buildings whose function is to contain the land on the periphery of the construction" [1].

Specific characteristics of the construction, like depth of excavation, neighborhood conditions and soil characteristics, associated costs or execution times, among others, define which solution is more appropriated for each intervention.

2.1 KING POST WALLS

The king post walls, with reinforced concrete cast in situ panels, is permanent earth retaining solution commonly used in Lisbon. The solution integrates steel profiles, previously installed on the ground, which will support the reinforced concrete panels, designed to resist the bending moment and shear efforts caused by the earth pressures. They are ideal when the implantation area is small or when there are limitations in accessing the construction area.

This technique is not suitable in situations where the groundwater level is near the surface and requires soils with some level of compacity and cohesion [1]. It's not common for it to generate landslides or land instability as it allows for small levels of excavation and interspersed panels.

2.2 BORED PILES WALLS

The bored piles wall structure is an earth retaining solution that consists of bored piles, in general braced by ground anchors, slab bands or struts. The space between the piles defines the type of wall used – spaced, tangent or secant [2] – and complies with the instructed in project. The maximum distance between them is the value of its own diameter.

As main advantages could be pointed out: i) can reach high depths (up to 45 meters); ii) wide variety of diameters for its execution; iii) does not imply excessive vibrations during the execution; iv) in case of secant piles, an impermeable wall can be achieved. As main disadvantages are possible to emphasize: i) difficulty to ensure the perfect verticality of the piles; ii) not a watertight structure (except for secant piles); iii); requires specialized equipment and labor.

2.3 EARTH RETAINING STRUCTURES

The stated structures require, in general, bracing solutions using ground anchors, struts or slab bands.

- <u>Ground anchors</u> are bracing elements that work in tension [3], due to the "change in the state of tension that they cause in the soil" [4]. They are formed by a foundation area, a fastening area to the structure to be anchored and a linear connecting structure between the first and the second.
- <u>Struts</u> are bracing elements that work in compression. They are placed on the retaining walls to (based on [5]) absorb existing loads and limit deformations. When used temporarily, they support the final structure until it acquires enough strength to support itself. They tend to be very simple, usually just a linear structure working in compression. Were originally made of wood, evolving to other materials such as concrete and steel (most common ones).
- <u>Slab bands</u> result from the phased construction of the slabs and aim to restraint the deformation of retaining walls at the expense of parts of those final slabs (slab bands), executed in a 1st phase. They work in the horizontal plane, in one direction like struts and in the perpendicular direction like bending beams. This is generally made across the entire periphery of the building's basements, forming a highly rigid frame and a free and unobstructed central space that allows work to continue (based on [6]). The frame is built by levels (top to bottom) following the evolution of the excavation. Once the bottom floor is reached, the slabs are finished, in a 2nd phase concreting (bottom to top).

3. CASE STUDY

This dissertation focuses on the peripheral earth retaining structure solutions used in the hotel unit (Hotel Meliá) to be carried out at the intersection of the Fontes Pereira de Melo Avenue with the António Augusto de Aguiar Avenue, in Lisbon. It should be noted that the lot is also surrounded by significant structures and infrastructures like the Hotel Fénix Urban, the Lisbon Subway and the Marquês roadway Tunnel (as showed in Figure 1).

Figure 1– Site location [7]

The existing buildings and constructions on the site were previously demolished, except for the wall facing the São Sebastião da Pedreira Road and the foundation walls of the pre-existing buildings. These demolitions were carried out in a phased and controlled manner as the excavation was carried out.

The peripheral earth retaining structure solutions used in the construction of the cellars were pilling curtains and a king post wall, both resorting to ground anchors, steel struts and concrete slab bands. The use of these solutions was greatly limited by the surroundings of the site.

The building has an area of about 1430 m^2 per floor. It has 13 upper floors, 3 half underground floors and another 3 underground floors for parking. This paper will focus on the last 6.

3.1 Geological and Geotechnical Conditions

The geological and geotechnical framework of the site was made from a characterization of a geological and hydrogeological investigation plan – which included the execution of 3 geotechnical surveys with dynamic penetration tests (SPT) – and laboratory tests from the collected samples.

The Geological-Geotechnical Report, stated ath Peripheral Earth retaining structure Project [8], indicated, based on Portugal's geological map, that following scenario, from bottom to top:

- The Volcanic-Sedimentary Complex of Lisbon, predominating at the site subsoil, which dates to the Neocretaceous.
- The Lisbon Miocene layer, known as Clays and Limestones of *Prazeres* (MPr), with heterogeneous granulometry.
- The ground surface is covered by modern materials of anthropic nature, called Alluvial Deposits (a) and Landfill Deposits (At).

Piezometers were also installed to monitor the presence of water and where its levels were throughout the entire excavation phase. It was possible to identify the water table about 20 meters below the ground floor level, close to the bottom of the excavation.

3.2 Adopted Solutions

In general, for the earth retaining solutions used in this case study, the choice of ground anchors at the upper levels was avoided so that they would not interfere with the surrounding infrastructures. The bored piles wall was, overall, braced by slab bands to ensure the stability of the earth retaining structure in the temporary phase of the excavation.

At the lower levels (floors -4 and -5), where the neighboring structures – Lisbon Metro tunnel and Marquês tunnel – were already at a higher level, temporary ground anchors were used, as they no longer interfered with those infrastructures. On the D-E alignment, close to the Hotel Fénix, as the structure of the roadway tunnel was already an open pit solution, it was possible to make anchors at all levels.

3.2.1 Bored piles wall

At the alignments where the bored piles wall solution was used, the main characteristics were the following:

- Alignment A-A' – Ø 500mm piles, 0.75m apart, with an average length of 15m.
- Alignments B-C/C-D/D-E – Ø 800mm piles, 1.20m apart, with an average length of 27m.

It was necessary to build a reinforced concrete lining wall (shotcrete) at the piles face, increasing the main wall rigidity and continuity. This lining wall was progressively executed as the excavation evolved ("top-down" sequence).

The ground anchors were placed between piles, with different distances between them to fit the earth retaining structure needs. The stability and final rigidity of each wall was reinforced by the structure itself in the final phase (Figure 2).

Figure 2 – Alignment D-E (northen area) – Pile curtain with a reinforced concrete wall and anchors

3.2.2 Slab Bands

The slab bands were only used on floors 0, -1, -2 and -3 since, as mentioned, it was not possible to use ground anchors on these levels.

The geometry of the slab bands was conceived to minimize interference with the execution of the cellars bellow and to allow the movement of machines and people. Their vertical support, during the excavation phase, was guaranteed by the earth retaining structure walls and HEB260 steel profiles (temporary pillars) (Figure 3).

Figure 3 – Alignment B-C – Slab bands with HEB260 metal profiles working as temporary pillars

3.2.3 Reaction Frame

Given the geometry of the excavation site, and the difference between the ground levels at Rua São Sebastião da Pedreira and Avenida António Augusto de Aguiar – about 10 to 12 meters – the slab strips above floor -3, inclusive, were supported through a reaction frame (Figure 4).

This frame is formed with elements of the permanent structure, composed by by columns and wall in reinforced concrete, supported by micropiles, and braced by steel struts" [8]. It functions as a buttress and will integrate the permanent structure. Its purpose is to transfer the horizontal loads from the slab bands to the foundation of the structure.

Figure 4 – Alignment A-B – Reaction frame

3.2.4 King Post Wall

The excavation of king post wall was protected by a curtain of grout columns (Ø 250 mm, 0.25m apart), alternately reinforced with HEB 120 steel profiles, built behind and along the wall the wall (allowing greater excavation panels) (Figure 5).

Figure 5 – Alignment A-B – King Post Wal with protection of grout columns

3.3 Main Challenges

The main challenges of both project and construction of the earth retaining structures were due to:

- Extremely ambitious deadline given the following constraints:
    - actual execution conditions.
    - limited space by the construction area itself.
    - impossibility of implementing lifting means covering the entire site.
    - difficulty in removing the excavation products.

- pandemic situation (COVID-19), which forced confinement and reduced availability of human and material resources.
- the site being in a dense urbanized area.
- existence of the centenary masonry wall at Rua São Sebastião da Pedreira (unknown characteristics and uncertain demolition).

3.4 Monitoring and Survey Plan

The Monitoring and Survey Plan was a proactive tool in the implementation of measures that ensured a safe and economic progress of the excavation works. The analysis of the values obtained from it (placed and observed during the construction phase) allowed to conclude that all parameters were far below the alarm levels and that the alert values were rarely reached or slightly exceeded.

Monitoring devices were placed with the following purposes:

1. Assessment of groundwater levels – A piezometer was placed in the A-B alignment, which indicated that the water was at 12/13 m deep.
2. Monitor the behavior of the neighboring structures
    - 2.1. Facades of the neighboring buildings – 97 topographic targets were installed. They recorded maximum displacements of about 8 mm in the horizontal plane and 5 mm in the vertical plane (far from their respective alert values – 20 mm and 15 mm). An oscilloscope was also installed which recorded values far bellow the 1,5 mm/s acceptable limit.
    - 2.2. Subway tunnel – 21 topographic targets were installed inside the tunnel which recorded a maximum displacement of 5 mm for an alert value of 7 mm.
    - 2.3. Roadway tunnel (*Túnel do Marquês*) – 24 topographic targets were installed inside the tunnel. No displacements above 5 mm were registered for an alert value of 7 mm.
    - 2.4. Viaduct over Rua São Sebastião da Pedreira – A fissurometer was installed to control any movements that might increase the previously existing fracture in the viaduct, which did not occur during the entire execution work.
3. Assessment of the behavior of the earth retaining structure structures
    - 3.1. Geometry of the earth retaining structure walls – The following equipment was installed to monitor any movements of the earth retaining structure structures:

      3.1.1. Inclinometers – 7 inclinometers were installed along the earth retaining structure perimeter to measure horizontal displacements. The measured values were always far from the 25 mm alert level.

      3.1.2. Topographic targets – throughout the work 57 topographic targets were installed on the periphery and inside the excavation, which did not register displacements above 15 mm for alert values of 25 mm.
    - 3.2. Change of load levels on anchors:

      3.2.1. Load cells – 7 load cells were installed to measure the ground anchors prestress. In general, those values did not vary above 10%, which is the alert criteria.

4. POSSIBLE ALTERNATIVE SOLUTIONS

The analysis of the values observed by the monitoring devices shown that there was an excellent suitability of the projected solution and its consequent construction, revealing that perhaps a too conservative attitude was taken in the characterization of the crossed soils.

These excellent values made it possible not to execute the lower levels of ground anchors, an attitude that could possibly have been extended to more situations, namely the reduction of: i) number of piles; ii) diameter of the piles; iii) number of ground anchors; iv) number of slab bands.

Simplifying that the relationship between the deformations of the structural elements varies linearly with the inertia/strength of those sections (which is not true, since the earth retaining structure is highly hyperstatic), leads to lower resistance values than those that would be obtained if the entire structure and ground were modelled, so this simplification remains on the safety side. A sensitivity analysis based on that found that, given the displacements recorded on the inclinometers, it would be possible to admit an increase in these displacements of around 60% to reach the alert values.

For illustrative purposes only, and to have some sensitivity of values, a 30% reduction of piles was assumed, which led to a saving of approximately 111 000 € while a 30% reduction in ground anchors resulted in a price decrease of approximately 40 000 €.

It is concluded that a reduction in the diameter of the piles would have few advantages, since reducing the diameter strongly reduces the inertia of the pile. Altering a Ø800 mm pile to a Ø500 mm pile would implicate a 37.5% reduction in diameter, but a drastic reduction of approximately 87% in the inertia.

A reduction in the number of slab strips could also be considered, which would need several calculation simulations – whose cost might not offset the eventual savings. However, the amount of final material applied in the work is practically the same (except for vertical supports) since these structures are used as reinforcement of the retaining walls in a provisional phase, but they are part of the final structure.

A more detailed study of the soil and its characteristics could have been carried out, as it would probably be an asset not only in terms of costs but also in the duration of the work, however, as the final price of the work is approximately €3 500 000, the price reduction associated with the reduction in the rigidity of the earth retaining structure would have some impact but would not be very significant. Given the associated risk, it seems reasonable that such preventive and cautious decisions were taken.

5. FINAL REMARKS

The aim of this work was to better understand the behavior of peripheral earth retaining structures in dense urban areas, their influence on adjacent infrastructures and to gain a new perception of the complexity involved in the execution of a work of this magnitude. The presence in the site was essential to better understand the difficulties related to the design and execution of a structure of this type.

It was possible to testify that the ground heterogeneity as, in fact, a determining condition, proving that the ground must be carefully and competently studied, before and during the excavation work.

The Monitoring and Survey Plan proved to be totally efficient, as it mitigated the consequences associated with the degree of uncertainty involving the geotechnical parameters. In any situation the alarm limits were approached. During the excavation works, with the information gathered from the monitoring and campaigns, it was possible to analyze the real performance of the earth retaining solutions.

The biggest challenge was to find a balance between the maximum economic optimization of the solution without compromising the safety, respecting deadlines and, today more than ever, minimizing the environment impact (Figure 6).

Figure 6 – View of the excavation at the final level

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