Solutions for Excavation, Earth and Facade Retaining Structures

Case Study – Building Liberdade 203

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ABSTRACT: The construction market in Portugal has been adapting according to the reality and context in which it is inserted. It's in the great demographic centres, especially in noble areas of significant cultural value, where there have been higher levels of demand for construction and rehabilitation zones. There is, therefore, the need to maximize the space given the current value it holds.
It's in this context that the topic of the present study arises, which addresses the use of peripheral retaining techniques that support the execution of excavation works and the realization of buried structures, based in a project – *Building Liberdade 203* – that will serve as a case study. The objective will essentially be to describe and characterize these technologies by assessing the respective construction processes and by comparing the production phase to the respective execution project. Of all the processes involved, special attention will be given to the execution of King Post wall retaining structures and to the (realization of) anchors used as supporting structures. These are the preponderant elements defined for the solution, not only of the present case study, but also in most works of similar nature.
The techniques used to support the facades of the existing building will be addressed, for it is a mandatory condition in the remodelling and/or rebuilding of properties classified as cultural heritage (as is the case). This obligation, although conditioning, is a reality that construction companies must deal with.
The Instrumentation and Observation Plan will also be highlighted, as well as the importance of its correct implementation, for it is an essential tool in maintaining safety conditions in works of this nature.

Key Words: Construction, Excavation, Retaining, King Post Walls, Anchors, Facades, Instrumentation.

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1. Earth Retaining Structures

There has been in Portugal a significant increase in the value of land and space, mainly in the large demographic centres, which is a consequence of the increase in demand in these areas, especially in the real estate and tourism markets. Therefore, there is a need to carry out large-scale construction projects both in height as in depth.

For the execution of basements or underground structures it's necessary to construct retaining structures, which, as the name implies, have as their function the support of the lands behind the excavation areas, thus allowing the existence of work platforms at various levels. Peripheral retaining structures allow the execution of vertical or near-vertical excavation, and are fundamental to constructions in which the lack of space is the greatest constraint verified.

There are several techniques for the execution of earth retaining structures, and rigorous selection criteria should be used to define the most viable solutions for each project (table 1).

Table 1 - Technical and economic criteria for the determination of earth retaining structures

Technical Criteria	Economic Criteria
• Geological and geotechnical conditions of the site; • Neighbourhoods conditions; • Accesses and construction site areas; • Groundwater level; • Required resistant criteria; • Excavation depth.	• Technical expertise required; • Cost of specialized equipment; • Labour and materials; • Execution deadlines; • Available budgets.

1.1. Rigid and Flexible Structures

The EC7 (Eurocode 7 - Geotechnical Design, 2010) [1] foresees the existence of several types of peripheral retaining structures, according to their mode of operation and interaction with the terrain they must sustain. These can be rigid, flexible or mixed retaining structures [3]. The latter, as the name implies, encompass a mixture between the two techniques previously mentioned. The rigid retaining structures are support elements whose strength and capacity derive essentially from their own weight. From this assumption, they are dimensioned so that the gravitational force exerted by themselves allows the retaining of the impulses of the land and the control of possible excessive displacements or landslides. They generally show considerable thicknesses and foundations with or without protruding elements.

In flexible, non-rigid retaining structures, it's not the self-weight that guarantees the structural stability and the impulse-resistant capacity of the land to be contained. These types of structures function essentially by bending, in which the stability is ensured by horizontal support elements and their foundations. Consequently, they are characterized by reduced thicknesses, allowing a better exploitation of the excavation areas, which makes them the preferred peripheral solution in zones where space is a scarce resource. Flexible retaining structures can be distinguished by their supporting conditions [2]:

• Self-supporting, where stability is guaranteed through the buried area of the curtain;

• Mono-supported, where the horizontal supports (struts or anchors) have only 1 level / horizontal alignment;

• Multi-supported, where the horizontal supports have several levels / horizontal alignments.

1.2. King Post Walls

King post walls consist of in a flexible peripheral retaining solution, falling into the category of multi-supported walls, and were the most suited solution for the case study of the present dissertation. Used as a frequent solution in Portugal since the 1970s, it shares several similarities with the temporary Berlin walls, namely regarding the staged execution by levels and the introduction of vertical support elements along its perimeter. These structures are characterized for their high deformability during the excavation and construction phases, being also highly influenced by the soil-structure interaction. The control of the supported ground displacements is a very important factor, especially when the excavation is in the surroundings of a building or any type of construction.

It's difficult to create a direct relationship between the excavation/wall movements and the building displacements. Therefore, the frequent practice consists in limiting the wall's displacement, as an indirect control method to prevent any damage to structures adjacent to the excavations. That displacement limiting criteria, named alert and alarm limits, should be applied in an early phase, and even contributing to the choice of the peripheral contention method. The displacement limits must be adequate for each situation and monitored during the construction works.

This solution is not appropriate to all types of soils. To use it, soils with undrained behaviour are required, allowing the execution of vertical cuts. In addition, this technique is not suitable in situations in which the groundwater level is near the surface.

King Post Walls are dug and implemented alternately, remaining between panels portions of land that support stress fields. In this technique, the critical phase for excessive displacements is the panel's excavation phase, and the time that goes between the concreting phase and propping or anchor stressing. Movements are caused by changes in the stress field in the surrounding soil, mainly due to the horizontal and vertical stress relief.

2. Earth Retaining Support Structures

The flexible peripheral retaining structures must be, in most cases, complemented by horizontal support elements which provide, to the overall solution, greater resistances to the impulses transmitted by the adjacent grounds. Exceptions are, for example, situations where the execution of retaining walls only take advantage of the stability conferred by the buried part of the curtain and the consequent passive impulse that's generated by the terrain [3].

The use of horizontal support elements is, therefore, recurrent, among which are the shoring, concrete slab bands and ground anchors. The main difference between these elements is their materialization in the solution: the concrete slab bands and the shoring are inside the excavation perimeter, while the stressed anchors occupy the soil adjacent to the excavation ground. These elements guarantee an increase of stability to the structure, pressing it against the soil and restricting its movements. The pressures exerted depend on aspects such as the soil-structure interaction, the characteristics of the terrain or the external loads in question [4].

The choice between a peripheral earth retaining solution supported by struts and/or concrete slab bands, or a solution using stressed anchors depends on several factors, such as the specific characteristics of the construction (depth of excavation, neighbourhood conditions and soil characteristics), associated costs or execution times, among others.

3. Case Study – Building Liberdade 203

The case study presented in this thesis is about a construction work in Lisbon's downtown, located in Rua Rosa Araújo and Avenida da Liberdade. The new building will be mainly composed by luxury apartments in the upper floors and commercial stores in the ground floor. The buried levels will mostly serve as a parking lot space. The existing buildings could be considered divided into three structurally distinct zones, designated blocks A, B and C (figure 1), generally consisting of six raised floors and a buried floor. Between blocks A and B there was a connecting building, apparently of more recent construction, with only two raised floors.

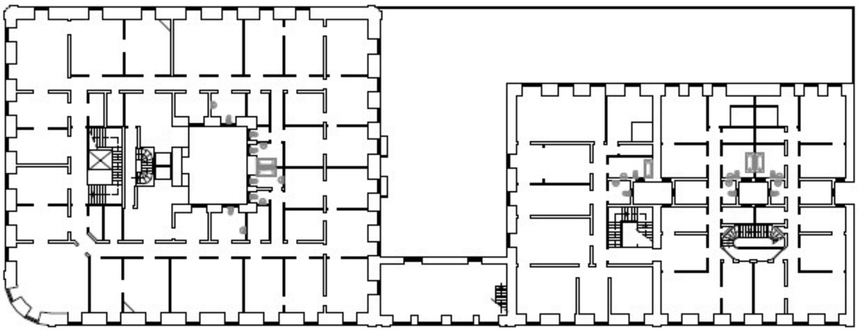

Figure 1 - Plant of the existing buildings (Block A at the left, connecting building at the centre, Block B at the left)

The architectural project predicted the complete demolition of block C, the complete interior demolition of block B and connecting building, preserving only the front and back facades, next to Rua Rosa Araújo. It would be in the space affected to these zones that the new building, with six raised floors and three cellars, would be constructed. In the Block A area, the project predicted the rehabilitation of the building's interior, and no additional floors, both elevated and buried, would be built. The construction area had a value of about 12500m^2, with an implantation area of about 1700m^2.

3.1. Geological and Geotechnical Conditions

To determine the geological and geotechnical conditions of the surroundings, two exploration campaigns were carried out. The first, executed by OPWAY in July 2008, consisted of the following works:

• Six mechanical probes with rotating drilling, diameter Ø86mm and continuous sampling, designated S1, S2, S5 to S8;

• Dynamic penetration tests of the SPT (Standard Penetration Test) type, spaced 1.5 m apart;

• Installation of four piezometers in rigid PVC pipes, diameter Ø50mm, involved in drainage layer with protective cap, in the S1, S2, S5 and S8 probes;

• Two DPSH tests (heavy penetrometers) replacing the S3 and S4 probes;

• Laboratory tests on the samples collected in the surveys.

Subsequently, in June of 2015, the second campaign of exploration carried out by the company Tecnasol was carried out, in which the following works were recorded:

• Two mechanical probes with rotary drilling, diameter Ø86mm and continuous sampling, designated by S9 and S10;

• Dynamic penetration tests of SPT type, spaced 1.5 m apart;

According to [5], and based on the analysis and interpretation of the results obtained in the survey campaign the following geotechnical zones were defined, observable in table 2.

Table 2 - Adopted geotechnical parameters for each zone

Geotechnical Zone	Description	N_{SPT}	Internal friction angle ϕ′ (º)	Cohesion C′ (kPa)	ϒ (kN/m³)	E′ (MPa)
C1	Landfill deposits	3-30	25	-	16	2
C2A	Silt clay and limestone fragments irregularly consolidated	29-60	30	40	21	70
C2B	Limestone fragments irregularly consolidated, loams and decomposed basalts	24-60	30	20	21	50
C3	Basalt, limestone breccia and crystalline limestone	>60	40	25	22	150

3.2. Solutions and Construction

One of the initial works carried out in practically the entire perimeter of excavation, to improve the resistance of the adjacent ground and limit its decompression, was the execution of vertical and sub-vertical cement columns, in the layer corresponding to the landfill materials.

According to current practice in this type of work and based on the analysis of the main existing constraints, king post walls were adopted as the main solution for the peripheral earth retaining of the excavation area. The fact that the presence of groundwater levels was not detected until the final excavation depth, which could render this solution unfeasible given the poor watertight capacity it presents, is another argument that supports its adoption. The use of shorings were considered, in all four corners of the excavation zone, to complement the king post walls.

Figure 2 - Execution of the formwork (left) and steel framework (right) of king post walls

For the support of the main facade, near Rua Rosa Araújo, it was foreseen the realization of two support beams founded by vertical micropiles. The connection system between these three elements (interior and exterior beam, plus facade) would be achieved by the application of a sewing mechanism composed of stressed bars of the Gewi-Dywidag type. It was also predicted the execution of three temporary metallic structures, fixed to the existing wall through connections in previously defined places and with recourse to bolts embedded in the facade. These structures would be supported by reinforced concrete elements, also based on vertical micropiles.

Figure 3 - Interior support beam (left) and metallic support structures of the main facade (right)

The solution for the support of the back facade was based on the same principles used in the front facade, through the realization of two support beams founded by micropiles, sewed together by the steel stressed bars characterized in the last paragraph. The main difference between the two systems is based by the fact that the back facade is completely inside the excavation zone. Therefore, unlike the main facade, where the internal micropiles are already locked horizontally due to their connection to the Munich wall panels, this doesn't occur in this situation. As a solution to the horizontal locking and to guarantee the security to buckling effects in these micropiles, it was recommended the realization of slab bands in reinforced concrete, at various heights, located inside the excavation area, and connected to the nearest concrete wall. It was also predicted the execution of three temporary metallic structures, similarly to the ones executed in the front facade.

Figure 4 - Exterior (left) and interior (right) support beams of the back facade

To ensure the locking of these micropiles to the horizontal forces due to the wind and the earthquake, UNP metallic profiles were also placed, in a diagonal arrangement in two directions, and connected to each other as well as to the slab bands through steel plates.

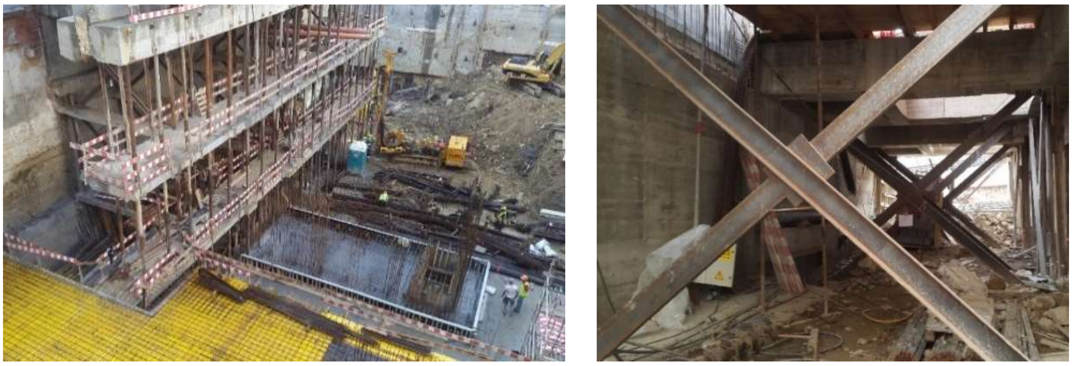

Figure 5 - Concrete slab bands (left) and diagonal UNP metallic profiles (right)

3.3. Instrumentation and Observation Plan

The main objective of the Instrumentation and Observation Plan is to monitor the evolution of the work and the behaviour of certain critical areas, namely the facades supported and the king post walls, contemplating additional measures of reinforcement if necessary. The monitoring of the behaviour of neighbouring structures and infrastructures during the construction phase is equally fundamental and obligatory. This plan consisted in measuring the following aspects:

• Horizontal and vertical displacements of the support structures and facades;
• Vertical and horizontal displacements of neighbouring constructions;
• Horizontal displacements of the soils behind the earth retaining structure;
• Measurement of the load installed in the anchors.

A measuring campaign was carried out, during the beginning of the demolition works, and a horizontal displacement tending towards the interior of the excavation room in the order of 40mm was verified in the target ED1A1 (upper level of the first alignment in the main facade). Consequently, it was decided to add one more level to the metallic structures that were containing the main facade, which was completed approximately mid-September and was verified the stabilization of the movements.

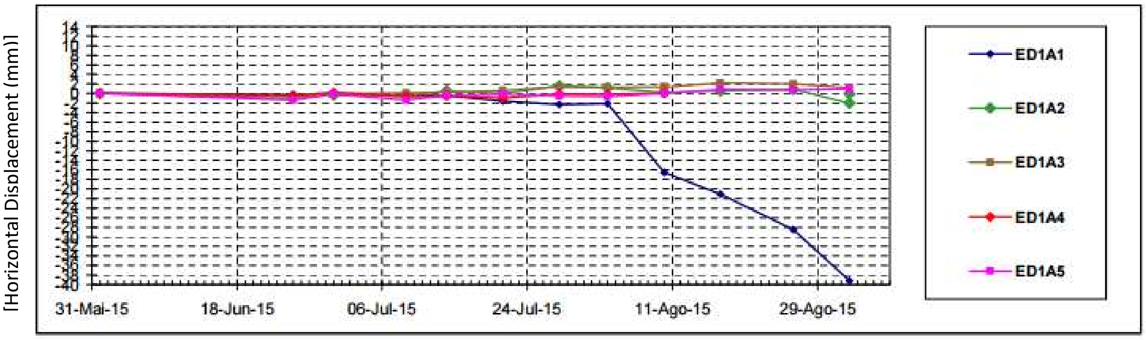

Figure 6 – Horizontal displacements in the upper target in the main facade that implied the execution of an addition level of the tower structures (removed from [6])

In the following campaigns, values began to be obtained in both facades that showed horizontal displacements into the excavation area with special incidence in the targets on the upper levels. This behavior coincided with the drilling in the foundation of the main facade for the realization of the micropiles. The trend in the interior movements continued in the readings that followed, and it was decided to implement a horizontal shoring system located in the upper third of the facades. This structure was completed in mid-November, when excavation and execution of king post walls were under way.

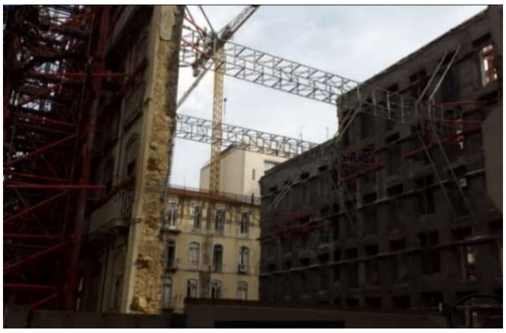

Figure 7 - Horizontal shoring system at the top of the facades

4. Main Conclusions

It is considered that the general approach and the design of the technologies integrating the general solution for the excavation and peripheral and facade retaining structures is the most appropriate in works that have the characteristics that are verified in this case study. The choice of king post walls is the most adequate technique, mainly because it allows better rates of work and use of existing space, which was scarce and limited. It's also a technique that entails reduced costs compared to other types of solutions (diaphragm walls, for example), and does not require very high technical expertise or large needs in terms of construction area. Also, the fact that it allows the excavation work to be carried out at the same time is a great advantage. However, it's important to note that not all the necessary conditions for the feasibility of this technique were guaranteed from the outset, since although there were no groundwater levels that could affect the performance of the panels, it was necessary to carry out previous soil consolidation treatments through the execution of cement columns, to control the decompression generated during the excavation procedure. The completion of these consolidation works required equipment and specialized staff, which makes the overall solution more expensive, but it's an adequate choice because it allows greater flexibility in the excavation work, ensuring a greater general cohesion of the land.

It can also be considered that the realization of ground anchors, as support elements to the retaining walls, is the best solution for this type of works, since it guarantees, once again, the best use of the existing space. This factor is so significant that there is a widespread use of ground anchors in current works of similar characteristics. Only when there are impediments to its execution - existing buildings with basements on the periphery of the excavation, presence of infrastructure networks in the vicinity or even prohibitions or legal inhibitions - the necessity to resort to different techniques arises. As an example, for alternative techniques, one could consider the exclusive use of shores, or the execution of the methodology "Top-Down". The first is a solution that does not have characteristics that allow it to be a competitive solution in these situations, since it implies great consumption of space and, consequently, obvious limitations in the work carried at the excavation area. A solution like this depends greatly on the dimensions of the excavation area, making it impractical when it presents considerable values. However, it turns out to be the expected solution for the corners of the excavation area, since the space consumption is smaller and ends up being a better alternative than the ground anchors, because it is more economical and has a faster execution rate.

Regarding the "Top-Down" method, which consists of the execution of the buried structure from top to bottom - where the building slabs serve themselves as support elements for the peripheral earth retaining structures – it's not an adequate solution for this construction since it's a technique only used in situations where traditional support methods are not feasible. This technology has considerable disadvantages because it is more complex, costly and entails great constraints on excavation work (as these are performed under the slabs already made).

As for the system used for the support of the main and back facades, there are no great considerations to be made in terms of the solution adopted, since it is always necessary to guarantee the transmission of loads to the competent grounds, and the horizontal support in height. Possible differences could exist, mainly in the characteristics of the facade support towers themselves (location, height or fastening systems, for example) and in the foundation elements of the reinforced concrete structures supporting them, as well as to the facade beams. It should be noted that the fact that the foundation of the main facade has been partly maintained, contributing as a resisting element to the earth pressures of the soils beneath, allowed an important increase of flexibility for the excavation procedures on this front.

Comparing the staging of the construction processes defined in the project with their application in the construction phase, it was verified that there were no significant or unforeseen variations that have jeopardized the expected work performance. Only a few changes were observed in the execution of the earth retaining panels at the front of the main facade, where ground anchors were executed by advance, as well as the execution of panels of the second level without the application of the stress to the anchors of the upper level.

As mentioned, this option was taken based on the need to increase production on this front, with the assumption that the previous treatment with cement columns, and the existence of the foundation wall of the main facade, would guarantee the capacity to support the earth pressures that occurred. It should be noted that this detour to the procedure could in no way be taken solely by the contractor, and was supported by the other responsible entities. On the other hand, it was indispensable to use the instrumentation and observation plan, to ensure the appropriate monitorization of the behavior of the affected land and structures, as well as the displacement of the facades maintained. Another aspect that was not contemplated initially was the realization of the shoring, through a horizontal steel structure, at the top of the facades, to control the respective horizontal displacements that occurred during the excavation work. However, it was already a predicted hypothesis as a reinforcement measure and its implementation was timely, serving unequivocally the objectives it proposed. It's considered, nonetheless, that it would be beneficial to have made this horizontal shoring at an earlier stage, after the demolition of the top floor of the existing building. Although the option of not initially realizing this structure is obvious, since it's a solution that entails costs to the owner, if it had been carried out in a previous phase, it would have implied a greater ease of execution and, consequently, gains in terms of time invested in it’s application. It would also be an addition of redundancy to the general solution of facade support, which is always positive in terms of the safety of the work and the personnel that is affectionate to it.

Lastly, it should be noted that, even though there have been no major deviations from the implementation of the solutions defined in the project, the execution of works of this size and characteristics, in an area of such strong constraints as Lisbon downtown, has constant challenge during all stages of construction. It’s an extremely complex process in terms of logistics in which, if there’s an absence of proper planning and preparation, unforeseen events of lesser order of magnitude can occur. These events, when added together, can make the difference between a successful or unsuccessful work. Mention should be made, for example, of the difficulty encountered in accessing the work site for the largest transport means and equipment and the day-to-day impact on the inhabitants and neighboring services, among others. However, it is considered that in this case study there was the capacity for resolution and adaptation needed, in the face of the requirements and obstacles that arose during its own development.

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