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Deep excavation solutions in an urban environment - Distrikt residential project, Lisbon

Solutions d´excavation profonde en milieu urbain – Projet résidentiel Distrikt, Lisbonne

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ABSTRACT: This paper describes the main design and execution criteria adopted for the peripheral earth retaining solutions, required for the construction of three underground floors for the Distrikt Residential Buildings, located in the south of Parque das Nações, in Lisbon. The excavation, with 11 m of maximum depth, mainly intersected landfill layers and Lisbon Miocene soils (Areolas do Cabo Ruivo e Areolas do Braço de Prata). The excavation site is confined by several underground infrastructures, which are mostly inside a technical gallery, close to the excavation pit boundaries. It is also noteworthy the proximity to two buildings with several basements, as well as the possibility that the excavation can coexist with the construction of an underground car park, under Rua Mário Botas. To minimize the ground disturbance, as well as the deformations of the mentioned structures, a reinforced concrete bored pile wall with 600mm diameter was defined, braced in general by steel props and temporary ground anchors. In the elevations where the neighbourhood conditions didn't allow the execution of ground anchors, the retaining wall was braced by concrete slab's strips, which were connected to pile buttresses and supported by HEB200 micropiles. The main results of the monitoring plan are drawn and presented, including the analyses and comparison with the estimated values from the design phase.

RÉSUMÉ: Cet article décrit les principaux critères de conception et d'exécution adoptés pour les solutions de retenue périphérique du sol nécessaires à la construction de trois étages souterrains pour les bâtiments résidentiels Distrikt, situés au sud du Parque das Nações, à Lisbonne. L'excavation, d'une profondeur maximale de 11 mètres, a principalement traversé des couches de remblai et des sols miocènes de Lisbonne (Areolas do Cabo Ruivo et Areolas do Braço de Prata). Le site d'excavation est confiné par plusieurs infrastructures souterraines, principalement à l'intérieur d'une galerie technique, à proximité des limites de la fosse d'excavation. Il est également à noter la proximité de deux bâtiments avec plusieurs sous-sols, ainsi que la possibilité que l'excavation puisse coexister avec la construction d'un parking souterrain, sous la rue Mário Botas. Pour minimiser la perturbation du sol, ainsi que les déformations des structures mentionnées, un mur de palplanches en béton armé de 600 mm de diamètre a été défini, renforcé en général par des étais en acier et des ancrages temporaires. Aux endroits où les conditions du quartier ne permettaient pas l'exécution d'ancrages au sol, le mur de soutènement était renforcé par des bandes de dalle en béton, reliées à des contreforts de pieux et supportées par des micropieux HEB200. Les principaux résultats du plan de surveillance sont présentés, y compris les analyses et la comparaison avec les valeurs estimées de la phase de conception.

Keywords: Earth retaining walls; pile walls; slab bands; buttress; temporary ground anchors.

1 INTRODUCTION

The present article describes the solutions adopted for the excavation and peripheral soil containment, necessary for the construction of 3 underground floors of the Distrikt enterprise. The enterprise is located in the southern area of Parque das Nações.

The project envisages the construction of 4 towers with 13 elevated floors and 3 common underground floors, which occupy the total area of the plot and are expected to be used for car parking and technical areas. Figure 1 displays an aerial perspective of the intervention site.

Figure 1. Virtual view of the future residential building´s.

Previous research, such as Carvalho & Pinto, 2019; Tomásio & Pinto, 2019 and Pinto et al., 2017, have developed similar earth-retaining solutions for deep excavations in urban environments, as it will be presented in the following chapters.

2 MAIN CONSTRAINTS

2.1 Geological and geotechnical conditions

To characterize the geotechnical behaviour, associated with the soils present at site, a prospecting campaign was conducted involving the execution of 16 mechanical boreholes accompanied by Standard Penetration Tests (SPT) and the collection of samples for macroscopic classification. Additionally, 5 hydraulic piezometers were installed in some of the boreholes. According to the results obtained, the geological structure of the site is characterized by the presence of Miocene substrates corresponding to Areolas do Cabo Ruivo (M_{CR}) and Areolas do Braço de Prata (M_{BP}), overlaid by modern anthropogenic materials, Landfill Deposits (At), with a thickness ranging from 1.5 m to 7.9 m. The Miocene formations are mainly composed of fine silty sands with carbonate nodules or fossil remains. This units have a considerable thickness, reaching the end of the boreholes. Bio-calcarenite levels (pebble beds) with variable thicknesses ranging from 0.1 m to 2.0 m were also identified.

In the sample collection, it was identified the contamination of the uppermost layers of fossiliferous limestone (pebble beds), revealing the presence of hydrocarbons in 6 of the boreholes conducted, all located on the north of the plot.

In terms of hydrogeology, the Miocene layers function as a multilayer system, consisting of alternating permeable layers (sands, sandstones, and some limestones) with other semi-permeable layers, such as clays and siltstones. Therefore, the higher the percentage of fines (silt and clay), the lower the permeability. On the other hand, bio-calcarenite layers are often highly permeable due to their high porosity and can constitute more productive layers.

2.2 Neighbourhood conditions

The excavation site, bordered by roads, infrastructures, and buried networks, is notably close to the Parque das Nações technical gallery, where diverse service infrastructures are established. The integrity and operability of these infrastructures must be maintained during construction work, thus influenced the design of peripheral earth retainment solutions.

During the project´s development, excavation works could potentially occur simultaneously with the construction of the underground levels of the parking lot to be developed immediately adjacent to the plot. In this context, and for this elevation, it had to be defined interior bracing solutions that did not require occupying neighbouring plots. In the following figure it is possible to observe the main boundaries of the excavation site.

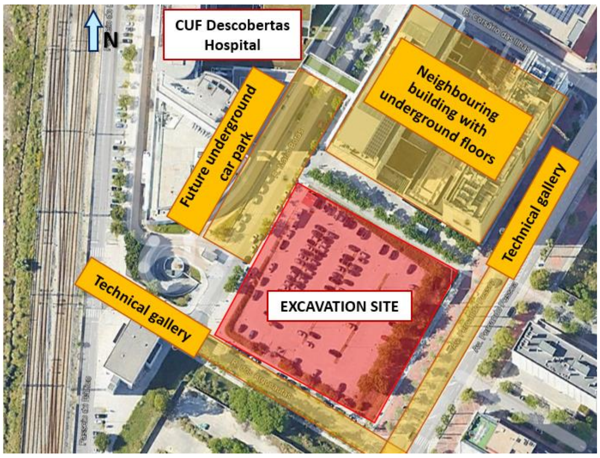


Figure 2. Main boundaries of the excavation site.

3 EXCAVATION AND PERIPHRAL EARTH RETAINING SOLUTIONS

In the design of the adopted peripheral earth retaining solutions, the following fundamental principles were sought to be respected, beyond the necessary horizontal retainment of the excavated grounds:

- Control soil deformations and surrounding structures and infrastructures to the excavation, allowing the adaptation to possible geological and geotechnical singularities;
- Ensure minimal interference with all adjacent structures and infrastructures.

Considering the existence of several conditioning factors, a reinforced concrete bored pile wall with 600 mm diameter piles and spaced 1.20 m, was defined. The bored pile walls were constructed using a telescopic Kelly bar technology, with temporary casing employed only at the top of the terrain to penetrate through the fill layers, when necessary.

During the excavation phase, the exposed soil between bored pile walls was generally protected with sprayed concrete with a minimum thickness of 8 cm, reinforced with metallic fibers, applied in two layers and properly drained through drainage pipes. These devices were served to collect and conduct water to the building's drainage system through vertical drainage pipes installed at the back of the wall and between the bored piles. In the regions where there was a higher probability of increasing locally the permeability and/or contamination of the soil, it was constructed a permanent reinforced concrete wall with 25 cm thickness, properly integrated to the bored pile walls.

The reinforced concrete bored pile wall was braced, in general, by multiple levels of steel props and pre-stressed ground anchors, to ensure the horizontal balance of the provisional earth retaining structures.

To ensure a better distribution of the forces along the curtain wall, as well as to prevent the excessive concentration of loads, the temporary ground anchors and steel props were connected to distribution concrete beams and crown beams. In the definitive phase, the stability of the curtain wall is provided by concrete slab strips, which will integrate the definitive concrete slabs of the underground floors, and the temporary ground anchors and steel props are deactivated after the completion of the definitive structure.

In elevations where the presence of neighbouring infrastructures or structures constrained the execution of ground anchors, a bracing system was defined, consisting in reinforced concrete slab bands, which function has horizontal beams (with the section of the future underground floors). The slab bands offer high stiffness to the earth retaining wall, resisting and transmitting the impulses acting on the curtain wall directly to the buttresses, which were also formed by bored piles. Considering the excavation depth, bracings were implemented at levels -1 and -2, with the initial excavation section carried out under a curtain wall that will be functioning as a cantilever. The design of the structural elements considered not only the necessary strength and stiffness to ensure safety and proper functionality but also the construction process associated with both the excavation and the execution of the underground floors. Figure 3 and 4 shows 2 plan views of the peripheral earth retaining structures and the respective shoring elements at each underground floor level.

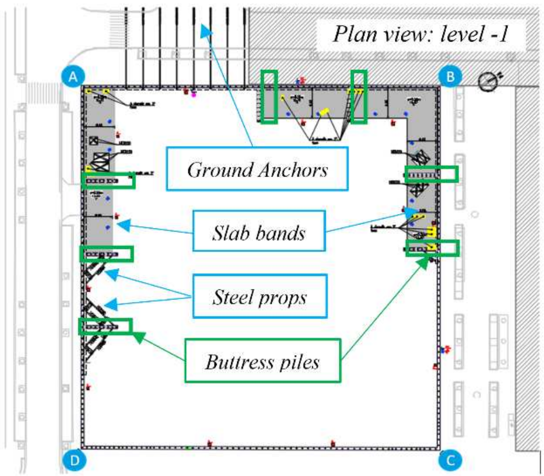


Figure 3. Design plan view of the peripheral earth retaining solution at level -1.

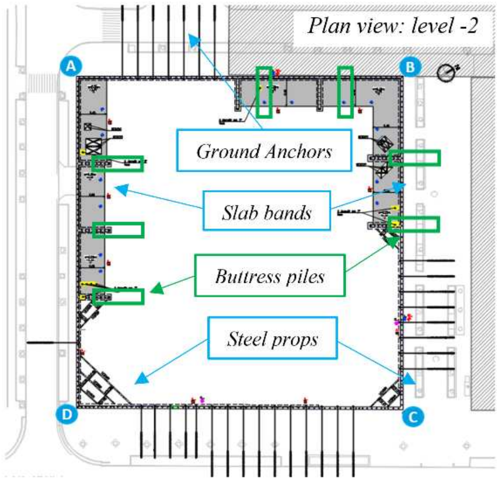


Figure 4. Design plan view of the peripheral earth retaining solution at level -2.

The ground anchors comprised 6 and 7 strands, each with a diameter of 0.6 inches, spaced at intervals of 3.60 m. A tensile load ranging from 600 kN to 800 kN was applied to these anchors, which varied in both length and inclination. The anchors inclination was specifically determined to prevent potential intersections with existing infrastructures and structures. Additionally, these inclinations facilitated the execution of the primary grout in geologically stable soil concerning the excavation´s geometry (Figure 5). The bond lengths were accomplished using the IRS system, incorporating double obturators and non-return valves, with a minimum hole diameter of 200 mm.

Figure 5. Bored pile wall shored by temporary ground anchors.

The configuration of the slab sections was defined with the aim of minimizing interference with the construction of the pillars and other structural elements within the ground floors. The slab bands exhibited an average width and thickness of 6.50 m and 25 cm, respectively. During the excavation phase, the slab bands were supported on the retaining walls and on HEB200 profiles, spaced approximately 6.50 m apart (Figure 6). These profiles were bonded for a length of 2.0 m within sections of Ø600 mm piles, reaching a depth of 4.0 m below the excavation´s bottom. The execution of the slab strips took place during the excavation phase, involving concreting against the ground over a layer of levelling concrete and plastic film.

Figure 6. Concrete slab strips supported by HEB200 micropiles and buttresses.

To ensure the bored pile wall essential´s drainage conditions, sub-horizontal drainage pipes were installed between the curtain´s piles, measuring 4 m in length and 50 mm in diameter. These pipes were made from high density polyethylene (HDPE), covered in a geotextile with a density of 150 g/m^2. It´s primary function was to facilitate internal drainage within the massif, thereby averting potential hydrostatic impulses resulting from rainwater infiltration. To guarantee the gravitational flow of collected water, these drainage elements were positioned with an upward slope of 10º from the horizontal and with a horizontal spacing of 3.60 m.

The water collected by drainage pipes was directed into the peripheral rain gutter, which ran parallel to the retaining wall. Below the excavation bottom level, there was no interference with the hydrogeological system, as the piles, being discrete and spaced elements, did not form a barrier to the water flow.

4 GEOTECHNICAL AND STRUCTURAL DESIGN

The assessment of the presented peripheral earth retaining solutions in terms of forces and deformations was conducted for all major construction phases using finite element programs such as PLAXIS 2D and 3D, specifically designed for this purpose. A constitutive model was developed to simulate the soil behaviour characteristics of a "Hardening Soil", considering a nonlinear constitutive relationship and variations in the soil's stiffness under applied stress states. The parameters outlined in Table 1 were applied in PLAXIS to model the soils.

Table 1. Geotechnical soil parameters.

Soil Type	ZG_{1A}	ZG_{1B}	ZG_{2A}	ZG_{2B}	ZG_{2C}
N_{SPT}	<10	10-30	10-30	30-60	60
Υ [kN/m^3]	18	19	19	20	21
Φ' [º]	27	31	32	33	36
E_{50}^{ref} [MPa]	8	20	40	50	200
E_{ur}^{ref} [MPa]	24	60	120	150	600
m [-]	0,5	0,5	1	1	1
R_f [-]	0,9	0,9	0,9	0,9	0,9

Soil Type: ZG_{1A} – Loosely compact sandy-clay fill; ZG_{1B} – moderately compact sandy-clay fill; ZG_{2A}– moderately compact sandy-silt soil; ZG_{2B} – compact sandy-silt soil; ZG_{2C} – very compact sandy-silt soil.

Soil Parameters: Υ – Volumetric weight; Φ' – effective friction angle; E_{50}^{ref} – elastic modulus corresponding to 50% of the ultimate tensile stress defined for a reference pressure (p_{ref} = 100kPa); E_{ur}^{ref} - elastic modulus for unloading/reloading at a stress level equal to the reference pressure (p_{ref} = 100kPa); m – power that controls the stress dependency of the elastic modulus; R_f – failure ratio.

The study of the reinforced concrete bored pile wall sections braced by slab bands, steel struts or temporary ground anchors was conducted through the development of a Plaxis 2D model. In contrast, due to the distance of the buttresses and the interaction of the slab bands with these elements, an analysis of this solution was performed using a Plaxis 3D model.

In the developed models, the curtain wall´s, slab bands and buttresses were represented using "plate" elements with elastic behaviour, while the ground anchors were modelled as "node-to-node anchor" elements, with the respective bond lengths modelled using "embedded beam row" elements.

The behaviour of the peripheral retainment structure was analysed for the main excavation phases, assessing crucial design parameters such as forces of the containment structures, deformations, stress states and stability of the soils to be contained. Figures 7 and 8 present the deformed mesh of the developed models.

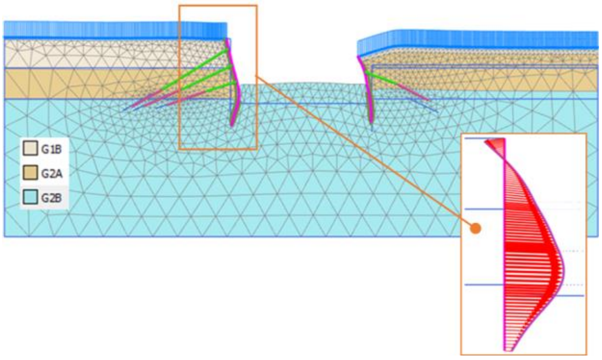


Figure 7. Deformed mesh of the excavation´s base level phase - Curtain wall braced by temporary pre-stressed ground anchors model.

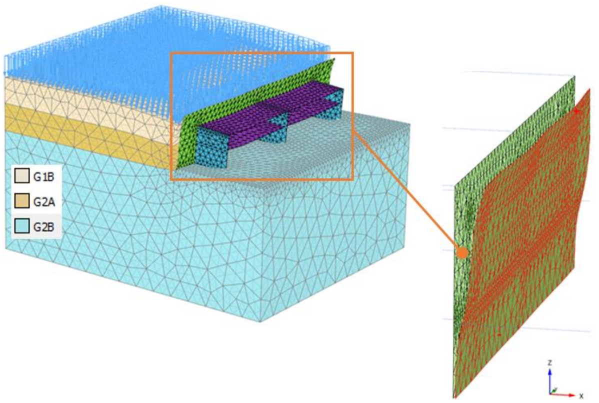


Figure 8. Deformed mesh of the excavation´s base level phase - Curtain wall braced by slab bands and buttresses model.

The maximum horizontal displacement estimated for the curtain wall supported by temporary ground anchors was 9 mm, and with slab bands and buttresses, it measured 56 mm. The results obtained were as expected, considering that the model composed of passive elements (slab bands and buttresses) exhibits greater flexibility and can accomodate larger deformations in the surrounding ground and curtain wall compared to the model incorporating active elements (temporary pre-stressed ground anchors).

Throughout the construction phase, deformations were observed to be less pronounced than those projected during the design phase, as it will be presented in the following section.

5 MONITORING AND SURVEY PLAN

Based on the complex framework of the site, a Monitoring and Survey Plan (MSP) was established with the aim of ensuring safety conditions and optimal functionality during the excavation and the execution of the geotechnical structures, as well as neighbouring structures and infrastructures. In this context, the following instruments were installed:

- 27 topographic targets distributed along the bored pile walls and edges of the slab bands to measure horizontal and vertical displacements;
- 4 load cells to measure the load of the temporary ground anchors;
- 2 inclinometers positioned behind the peripheral containment walls, to measure ground horizontal displacements;
- 2 piezometers to measure underground water pressure;
- 1 seismograph for vibration control during the excavation of areas with higher resistance.

Based on the conducted modelling, alert and alarm criteria was established for all instruments and monitored structures. Overall, readings consistently remained below the alert and alarm criteria defined in the project. In Figure 9, the schematic location of the instrumentation devices and some of the most notable results are presented.

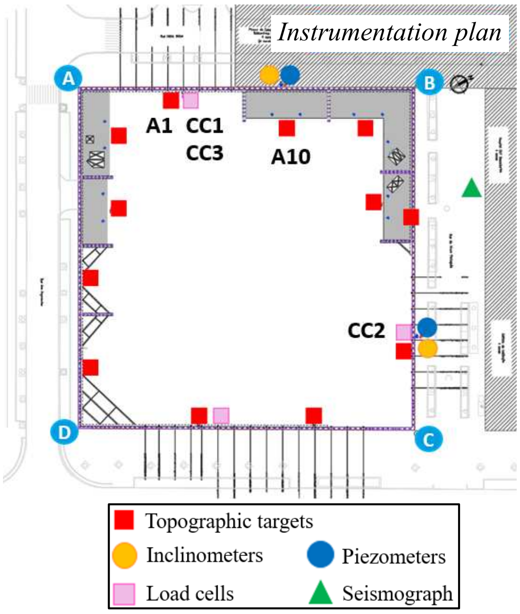
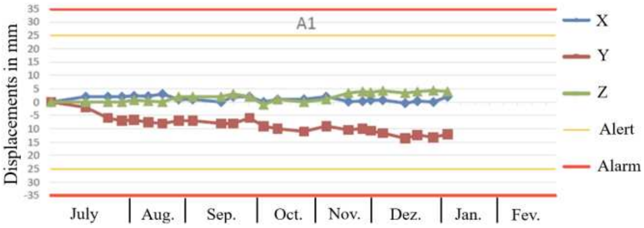


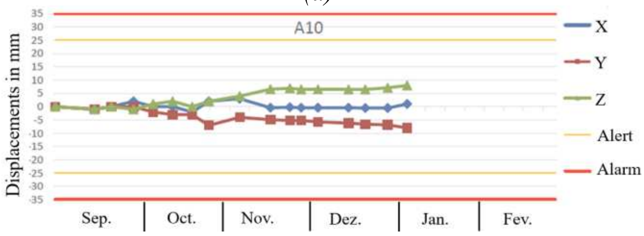
Figure 9. Instrumentation and monitoring plan.

As observed in the examples below, deformation values consistently remained below the alert criteria outlined in the project (yellow line in the graph), as shown in Figure 10. Regarding the monitoring of load cells, a minor adjustment to the initial load applied to the anchor tendons was noted, facilitated by a hydraulic jack. Subsequently, the load values remained nearly constant throughout the construction process (between June 2022 and January 2023), confirming the satisfactory performance of the project (Figure 11).

These conclusions are applicable to the remaining data instruments. However, in December 2022, a notable increase in water levels was observed due to heavy rainfall. In response, additional drainage pipes and temporary water collection zones were established to address this issue.



(a)



(b)

Figure 10. Displacement results on station A1(a) and A10(b).

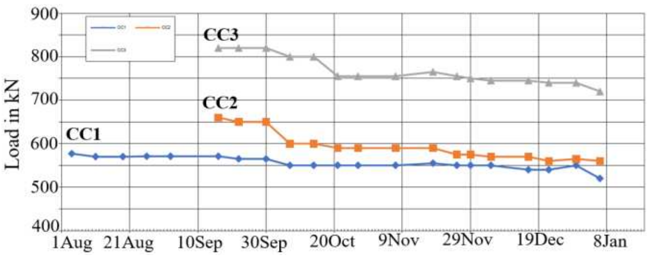


Figure 11. Load cell evolution of the ground anchors CC1, CC2 and CC3.

Considering the above, as of the present date with the conclusion of excavation and peripheral containment works, the instrumentation results serve to validate the suitability of the implemented solutions and the geomechanical parameters meticulously considered in the modelling. This paves the way for prospective optimization of similar geological and geotechnical solutions in the future.

6 CONCLUSIONS

In the scope of this article, it was possible to demonstrate the technical efficiency of reinforced concrete bored piles braced by various structural elements such as struts, temporary ground anchors and slab bands. The peripheral earth retaining solution presented displacements lower than those estimated in project and displayed a highly stable behaviour during the excavation works. Additionally, the use of slab bands not only overcame the encountered limitations due to the excavation´s site proximity to the technical gallery and the future underground parking lot, but also incorporated elements of the final structure, enhancing the economic efficiency of the solutions.

However, there were some on-site challenges that led to adjustments to the initial project solutions. The main challenge arose from an increased water flow into the excavation, given the intense rainfall experienced in December 2022 towards the end of the excavation works. To address this unforeseen circumstance and to ensure the integrity of the sprayed concrete between the piles, in response to the rising water flow into the excavation area, the number of drainage pipes was increased, and temporary water collection zones were established. In the definitive phase, the water collected by the pipes will be directed to the building's general drainage system.

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