Extended Abstract: Excavation and retaining walls in urban centers
Case study – Hotel at Andrade Corvo street and Sousa Martins street, Lisbon

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1. Introduction

With the generalized growth of the economy in Portugal, there has been a great promotion in the construction sector, especially in the urban centers, due to its great valorization. This valorization generates the need to build underground floors, and therefore, soil retaining walls.

This thesis is based in a construction work, Hotel Avedon, taking place in Lisbon, at the intersection between Rua Sousa Martins and Rua Andrade Corvo. For this construction work, a bored pile wall was projected. In this document it is explained all the its properties and the options to provide it auxiliary support.

A bored pile wall model was developed in Plaxis 2D, simulating the real conditions, and its results were compared with the results obtained in the Monitoring and Observation Plan. These Plan was developed, with the objective to ensure safety during the excavation work, where horizontal and vertical displacements, in the pile wall and in the neighboring buildings, were continuously measured.

With all the data about the pile wall´s behavior, it was possible to optimize the amount of rebars in the piles.

Alternative solutions were also modeled in Plaxis 2D and compared with the adopted solution.

Finally, based on the analysis conducted throughout the document, a solution is proposed to this case study.

2. Excavations and retaining walls

When performing an excavation, it is required to guarantee the safety of the neighborhood. In order to meet this, soil retaining walls are built. They allow the excavation to occur safely, not harming the neighboring buildings nor the workers themselves. These structures also allow all the work to be carried out inside the intervention area, as they withstand the earth pressures throughout the excavation.

These structures can be of many types, such as Berlin type walls, Munich type walls, diaphragm walls or bored pile walls [1].

Supporting these structures, there can be different types of auxiliary support structures.

3. Bored Pile walls

When chosen this earth retaining solution, piling equipment is used to build all the piles along the excavation perimeter. The piles, ø=600 spaced 1,20 meters at axis, make the wall that support the pressures caused by the soil.

In this type of retaining structure, ground anchors and the shoring are commonly used.

4. Auxiliary support structures

The earth retaining walls generally are not able to hold out by themselves the earth pressures. So, it is necessary to have auxiliary support structures, to guarantee safety and stability. Even when the retaining wall is able to hold out the earth pressures, shoring or ground anchors are used to control displacements, as they may affect neighboring conditions.

The most common type of these structures are [2]:

- Shoring, that can be used in opposing faces of the excavation or at corners;
- Ground anchors, that are usable if the ground and the neighborhood allow it. They have the big advantage of not occupying any space inside the excavation pit;
- Slab bands, that have the advantage of being a definitive element;
- Others, such as buttresses.

5. Excavations´ influence on neighboring constructions

During excavations, the neighboring ground can experience compressions and decompressions, that can result in displacements and settlements in other constructions [3]. These constructions in the urban centers are usually old ones, and so, very sensitive to suffer with minor movements.

Eurocode 7 requires some designs, to guarantee the safety of these neighboring constructions, such as a continuous monitoring of their behavior. Usually, targets are placed in them, and read periodically, looking for any kind of movements.

6. Case study

This thesis´ case study is located at the intersection between streets Andrade Corvo and Sousa Martins, in Lisbon. It is surrounded by two buildings, in the North and in the East, as shown in Figure 1 and in the scheme presented in Figure 2.

This new construction will be a Hotel with six floors, with four basements. At the northeast corner of the excavation, there will be a patio at the level of the -1 basement. It means that, at this corner, the excavation will only be performed until that level.

The intervention area is about 1709 m².

Figure 1 – Case study location

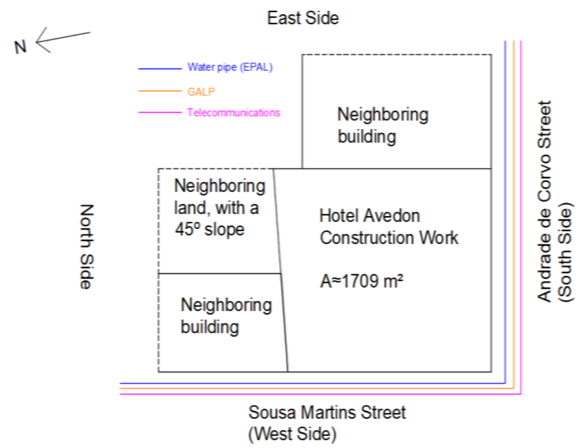

Figure 2 - Neighborhood scheme

In order to start the construction work, it was necessary to access all the conditionings that could endanger the neighborhood.

6.1. Main conditionings

6.1.1. Geological / geotechnical conditionings

For the ground study, continuous rotation sampling probes were carried out and dynamic penetration tests were performed, generally called standard penetration test (SPT). The results revealed the existence of four distinct geotechnical zones, which can be seen in the scheme presented in Figure 3.

This excavation takes place in Picoas, where it belongs to the geological formation of Argilas e Calcários dos Prazeres (MPr), from the Miocene era. Above this formation, composed of silty clays, there is a layer of human originated landfill deposits. The silty clays get harder as the depth increases [4].

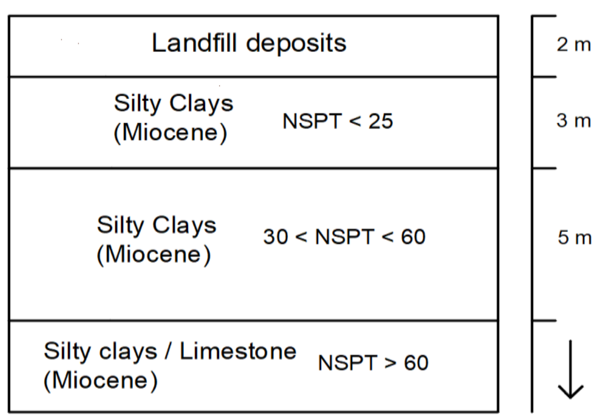

Figure 3 – Soil layers scheme

6.1.2. Neighborhood Conditionings

As it can be seen in Figure 2, there were some conditionings regarding neighboring buildings and underground infrastructures, that were taken into account when excavating.

6.2. SOLUTION ADOPTED TO SUPPORT THE EXCAVATION

The solution adopted to withstand the earth pressures was a bored pile wall, in all perimeter of the excavation. These piles have a diameter of 600 mm, and 1,20 meters spacing between axis. However, there were different types of auxiliary support elements in the four sides of the wall.

On the South side of the excavation, facing Andrade Corvo street, the pile wall was supported by temporary ground anchors, and steel profiles shoring at the corners.

On the West side, facing Sousa Martins street, the auxiliary support was identical to the one in the South side: ground anchors, and steel shoring at the corners, as shown in Figure 4.

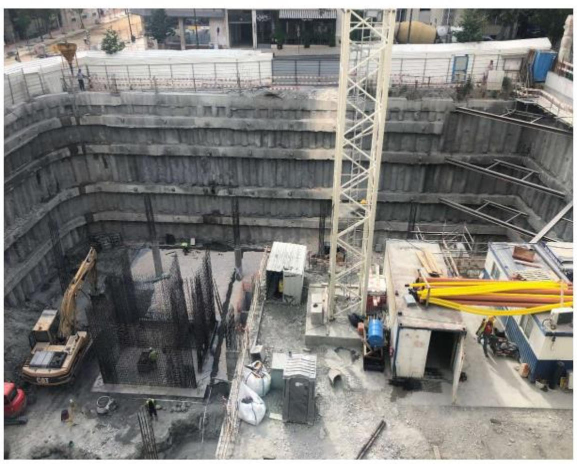

FIGURE 4 - WEST SIDE OF THE EXCAVATION

On the North side, the elements used to support the wall were different in the two halves. In the first half, temporary ground anchors and corner steel profiles shoring were used. In the second half, characterized by the presence of the patio at the level -1, it was built a concrete wall to support the earth pressures. To support this wall, five concrete buttresses with 12,80 meters of height were built. These buttresses were founded over a big footing, with an “L” shape, and with 2,10 meters of thickness. In Figure 5 is shown a part of the reinforcement for this footing.

FIGURE 5 - FOOTING´S REINFORCEMENT

On the East side, the support was similar to the one in the North Side. In its first half, there was the concrete wall with 12,80 meters of height, and the five buttresses supporting it, in the patio area. In the second half, only shoring at the corners was used. In Figure 6 is shown the patio zone.

FIGURE 6 - PATIO AREA

6.3. MONITORING AND OBSERVATION PLAN

Given the nature and location of this construction work, the Monitoring and Observation Plan was especially important, to control displacements in both the earth retaining structures and the neighboring constructions.

In this Plan, alert and alarm values were defined, shown in Table 1, so that action can be taken if those values were reached. If the structure´s behavior reveals displacements close to those values, additional auxiliary support elements would be placed.

Following this plan, were installed:

- Topographic targets are placed, allowing the device to be read. The measurements reading is carried out using a total station;
- one inclinometer, in the West side, to measure horizontal displacements at the ground;
- load cells, in the South and West side, to control the load at ground anchors;
- one piezometer, to investigate the water levels during the excavation.

TABLE 1 – ALERT AND ALARM VALUES

Alert and Alarm Values		
Displacements	**Alert Values (mm)**	**Alarm Values (mm)**
Horizontal	15,0	25,0
Vertical	10,0	15,0

6.4. MODELING THE PILE WALL IN PLAXIS 2D

The software Plaxis 2D was adopted to model the executed pile wall, trying to simulate all the real conditions. The software uses finite elements for a nonlinear analysis of deformations and soil stability, allowing the back analysis with the real deformations registered in site.

6.4.1. Hardening Soil Model

Contrary to the Mohr-Coulomb model, the hardening soil model considers the hardened state of the soil, with the increase of stress, and it is based on a non-linear behavior [5].

In this model, it is possible to simulate the behavior of different types and ground layers. This model was used in all the modeling performed in this document.

6.4.2. Model Characterization

It was defined that the model would represent the West side of the excavation, facing Sousa Martins street. To draw this section, a window of sixty meters wide and twenty-five meters high was defined, so that later it was possible to visualize the soil behavior in the neighboring area of the wall. The mesh was generated considering triangular elements of fifteen nodes, in order to present results with an increased level of detail. The model is shown in Figure 7.

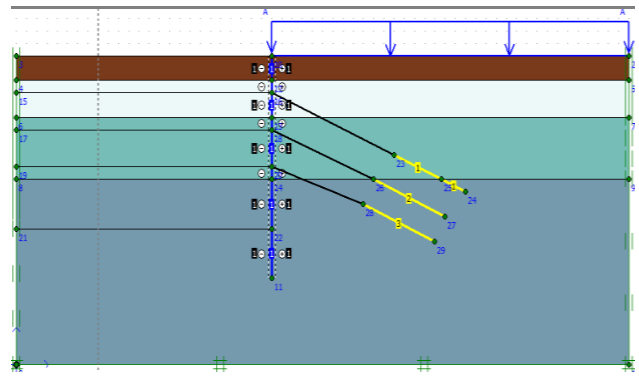

FIGURE 7 – PLAXIS MODEL

6.4.3. Ground Characterization

At the developed model, four geotechnical zones were considered. These four different ground layers are the same as shown in Figure 3. Their characteristics are displayed in Table 2. These properties were defined based on the data obtained from the geological site investigation.

TABLE 2 – GROUND GEOTECHNICAL PROPERTIES

Parameters *Hardening-Soil*	**Landfill deposits**	**Silty Clays NSPT<25**	**Silty Clays 30<NSPT<60**	**Silty Clays NSPT>60**
γ [kN/m^3]	17	19	19	20
c' [kPa]	0	5	10	20
ϕ' [˚]	25	27	31	33
Ψ [˚]	0	0	0	0
E50ref [kPa]	5000	15000	40000	50000
Eoedref [kPa]	5000	15000	40000	50000
m [-]	0,5	0,5	0,5	0,5
Eurref [kPa]	15000	45000	120000	150000
Vur [-]	0,2	0,2	0,2	0,2
Pref [kPa]	100	100	100	100
K0 [-]	0,58	0,55	0,49	0,46
Rf [-]	0,9	0,9	0,9	0,9

6.4.4. Bored Pile Wall Characterization

To characterize the concrete pile wall, it was necessary to edit the properties of the element "Plate" in the software. As the concrete was a C30/37, a Young´s modulus of 30GPa was considered. The piles have a diameter of 600 mm, spaced 1,20 meters, and with this property, the axial stiffness (EA) and flexural stiffness (EI) were calculated.

At last, the values of the own weight of the pile wall as well as the Poisson coefficient were introduced.

6.4.5. Ground Anchors

There were represented three anchorages levels, as shown in Figure 4. These elements have a spacing length of 3,60 meters and should embrace a pre-stress force of 650 kN. It means that a pre-stress force/m of 180 kN/m was considered.

6.4.6. Construction Phases

All the main construction phases were considered in the developed model.

6.4.7. Results

The initial stresses were generated using the K0 procedure, with the values presented at Table 2. The deformed finite element mesh is represented in Figure 8.

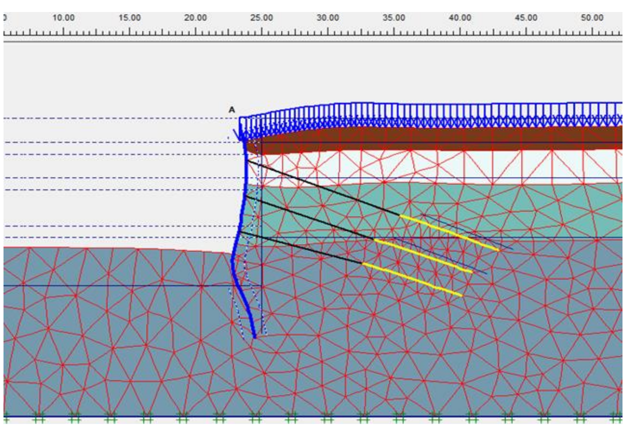

FIGURE 8 – DEFORMED MODEL

The maximum deformation value lies beneath the third ground anchors level, with a value of 11 mm. The horizontal and vertical displacements are represented in Figures 9 and 10, respectively.

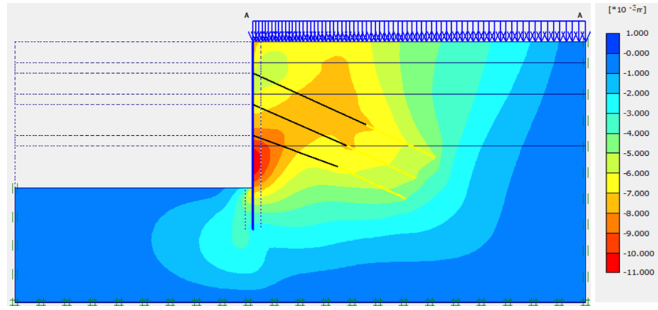

FIGURE 9 – HORIZONTAL DISPLACEMENTS

The horizontal displacements start increasing from the second ground anchors level down. The maximum value (11mm) is acceptable, as it is lower than the alert and alarm values shown in Table 1.

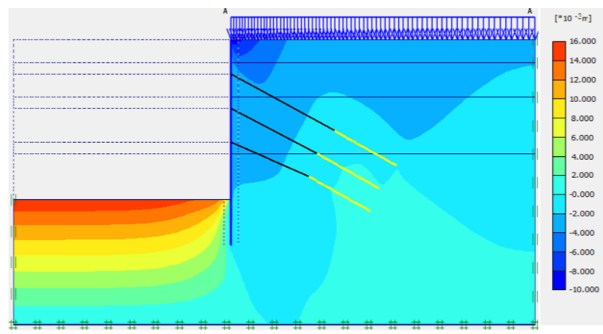

FIGURE 10 - VERTICAL DISPLACEMENTS

The maximum vertical displacement registered had a value of 16 mm. It isn´t concerning, because it represents a ground upward movement at the excavation base.

6.5. COMPARISON BETWEEN MODELING RESULTS AND REAL MONITORING RESULTS

The modeling results (on the left) and the inclinometer results (on the right) for the same West side of the excavation, show similar results. The maximum value is equal for both cases (11), although at different depths. In Figure 11 and Table 3 is shown a displacement comparison between the two.

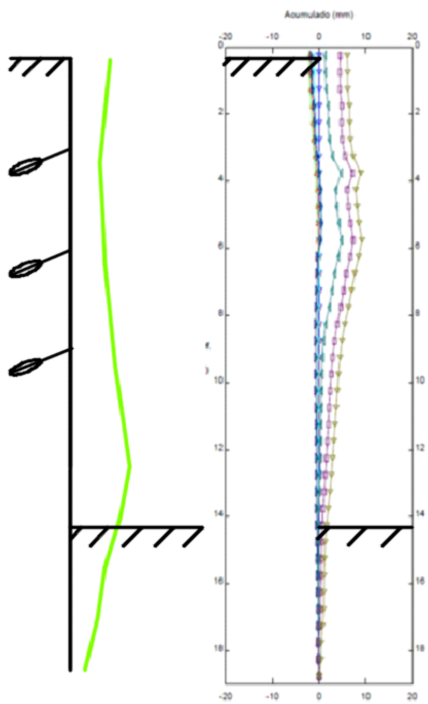

FIGURE 11 – HORIZONTAL MOVEMENTS

TABLE 3 - DISPLACEMENT COMPARISON

Depth	**Real horizontal displacement (mm)**	**Modeling horizontal displacement (mm)**	**Difference (mm)**
0 m	7	8	+ 1
Level 1 – 3 m	8	6	- 2
Level 2 – 6 m	11	7	- 4
Level 3 – 9 m	5	9	+ 4
12,5 m	3	11	+ 8
15 m	2	8	+ 6

7. ALTERNATIVE SOLUTION – ONLY TWO GROUND ANCHORS LEVELS

In this chapter, a model was created to investigate the wall and ground response to a reduction in the number of ground anchors levels. The deformed finite element mesh is represented in Figure 12.

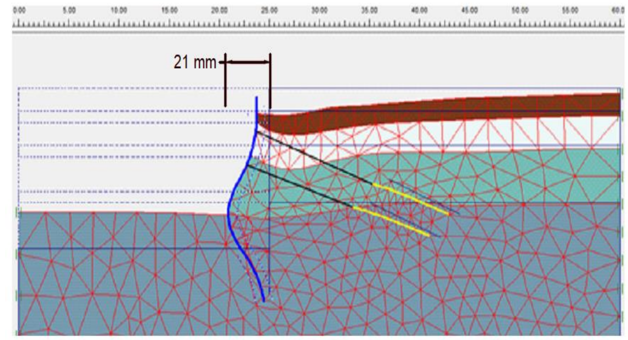

FIGURE 12 - DEFORMED MESH OF THE ALTERNATIVE SOLUTION

As it can be seen, the deformation beneath the second anchorages level increased, with its maximum value of 21 mm occurring to a 9 meters' depth, where the third anchorages level originally was. In Figure 13 is shown this solution´s horizontal displacements, and in Table 4 a displacement comparison is presented, between the modeled solutions, with two and three ground anchors levels.

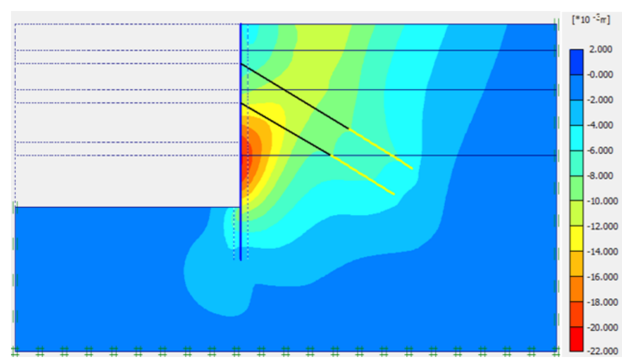

FIGURE 13 - HORIZONTAL DISPLACEMENTS FOR THE ALTERNATIVE SOLUTION

TABLE 4 - DISPLACEMENT COMPARISON, BETWEEN THE TWO SOLUTIONS

Depth	**3 anchorages levels (mm)**	**2 anchorages levels (mm)**	**Difference (mm)**
0 m	8	6	- 2
Level 1 – 3 m	6	8	+ 2
Level 2 – 6 m	7	12	+ 5
Level 3 – 9 m	9	21	+ 12
12,5 m	11	20	+ 9

As expected, the displacements got higher than in the solution with the three ground anchors levels. In the alternative solution, the maximum horizontal displacement has a value of 21 mm, which lies between the alert and alarm criteria values. Of course, this last values were established for the original solution, and they would probably differ for this alternative solution.

The efforts in the wall also increased, as shown in Table 5.

TABLE 5 - EFFORTS COMPARISON

Solution	**Maximum stresses**		
	Axial Forces (kN/m)	**Shear Forces (kN/m)**	**Bending Moments (kNm/m)**
3 anchors levels	453	151	129
2 anchors levels	540	173	172

8. PROPOSED SOLUTION

In this chapter, a solution is proposed to all the project regarding the retaining structures and the auxiliary support structures.

8.1. Bored Pile Wall

For the pile wall, the following characteristics are proposed (Figure 14):

- Ø=600 spaced 1,2m at axis;
- Longitudinal reinforcement: 7Ø25;
- Shear reinforcement: Ø12//0,20;
- Cover: 7 cm.

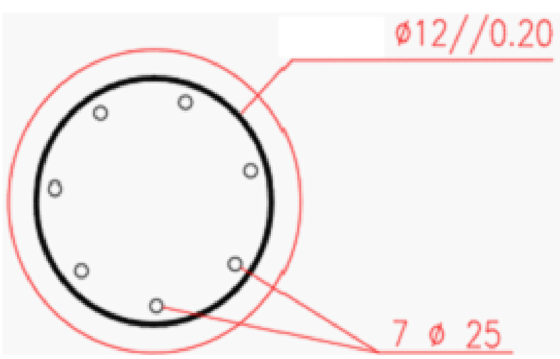

FIGURE 14 - PROPOSAL FOR THE PILES´ REINFORCEMENT

8.2. Auxiliary support structures

8.2.1. South side and West side (Andrade Corvo and Sousa Martins streets):

In these two sides, the proposal lies on increasing the space between ground anchors, to the double of its original value. The total elimination of the third anchors level showed displacements close the alarm value. In Figure 15 is represented a view of the solution.

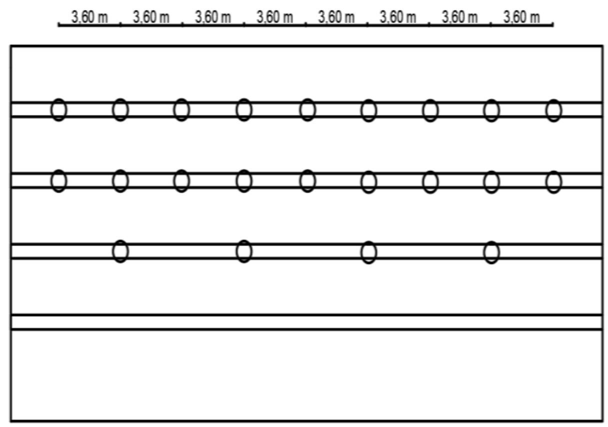

FIGURE 15 - VIEW OF THE GROUND ANCHORS LAYOUT AT THE SOUTH AND WEST SIDE

8.2.2. North side and East side:

In these sides, what differs on both solutions is the support structures in the patio area. In the original project, concrete buttresses were designed to support the concrete wall 12,80 meters high. In this proposal, slab bands supported by micro piles would replace the buttresses. It would have economic advantages, as well as an easier execution. Figure 16 shows an illustration of the proposed. Four slab bands levels, being the last one at ground level.

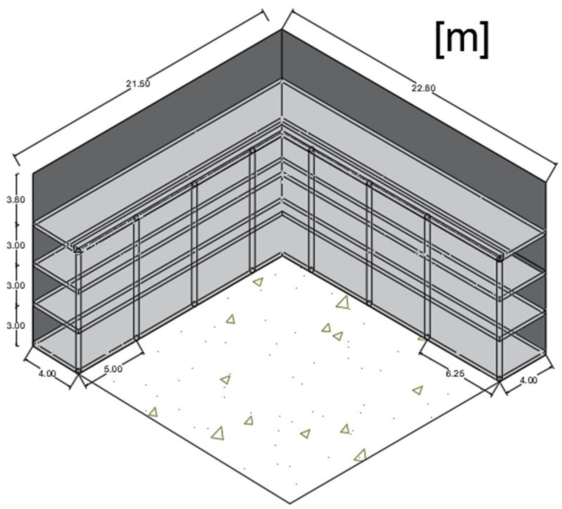

FIGURE 16 – SLAB BANDS SUPPORTING THE CONCRETE WALL

<u>Modeling of the Slab Bands Solution</u>

Once again, using Plaxis 2D, the previous solution for the patio area was modeled, to make sure the slab bands could withstand the earth pressures on the wall. In Figure 17 is represented the model introduced in the software.

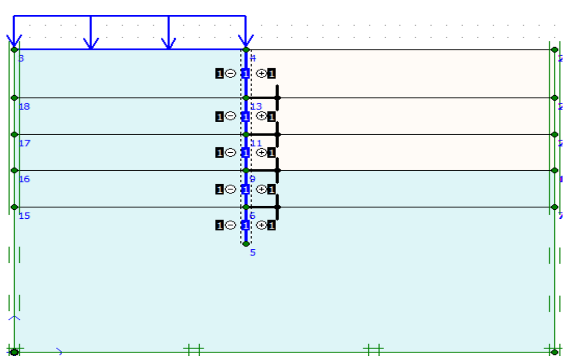

FIGURE 17 – SLAB BANDS MODEL INTRODUCED IN PLAXIS 2D

After the definition of all the ground, slab bands and wall properties, the construction phases were introduced. Then, after generating the initial stresses, it was possible to run the model. The deformed finite element is shown in Figure 18, and its horizontal displacements displayed in Figure 19.

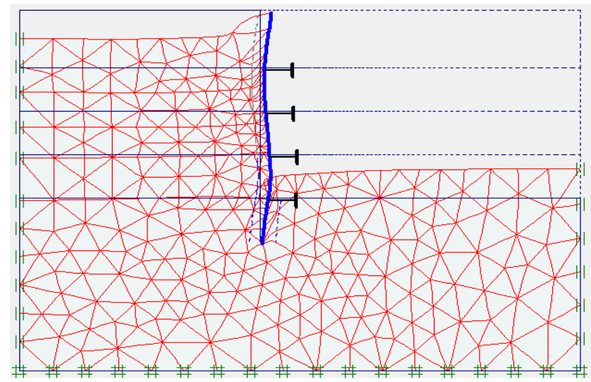

FIGURE 18 - DEFORMED MESH OF THE CONCRETE WALL

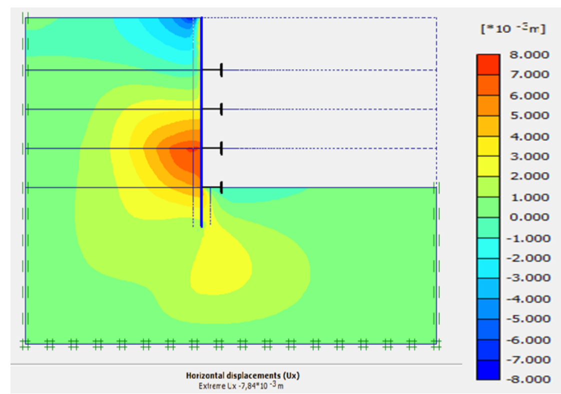

FIGURE 19 – CONCRETE WALL HORIZONTAL DISPLACEMENTS

From Figures 18 and 19, it´s understandable that the concrete wall supported by the slab bands exhibited a good behavior. Its maximum horizontal displacement took place near the third slab band, and had a value of 8 mm, which is an excellent result in terms of stability.

It would be a valid alternative to the designed buttresses solution, with the economic benefits presented ahead.

9. PROPOSED SOLUTION

After analyzing the behavior of the different structures studied in this thesis, it is now important to analyze the estimated costs of the different solutions: the adopted one and the proposed. To estimate these costs, the quantities were measured, and the prices given by CYPE software [6]. This analysis does not consider the works common to both solutions, like, for example, the excavation work.

The proposed solution, as described above, has three main differences when compared with the adopted one:

- Reinforcement reduction in Piles;
- Ground anchors optimization;
- Slab bands instead of the buttresses.

The costs for the original solution and the proposed one are shown, respectively, in Table 6 and Table 7.

TABLE 6 - COSTS FOR THE ORIGINAL SOLUTION

Element	Unit Cost	Dimensions	Units	Total Cost
Bored piles (m)	134,60 €/m	18 m	189	457.909,20 €
Ground anchors (un)	70 €/m	20 m	44	61.600,00 €
Buttresses (m³)	400 €/m³	7,85 m³	11	34.540,00 €
Footing (m³)	197,51 €/m³	404,20 m³	1	79.833,54 €
Piles under footing (m)	134,60 €/m	9 m	21	25.439,40 €
Total				659.322,14 €

As it can be seen from Table 6, the buttresses and the footing represent a relevant percentage of this solution´s total cost.

TABLE 7 - COSTS FOR THE PROPOSED SOLUTION

Element	Unit Cost	Dimensions	Units	Total cost
Bored piles (m)	114,72 €/m	18 m	189	390.277,44 €
Ground anchors (un)	70 €/m	20 m	38	53.200,00 €
Slab bands (m²)	90,60 €/m²	708,80 m²	1	64.217,28 €
Micro-piles (m)	67,12 €/m	15 m	8	8.054,40 €
Micro-piles´ coating (m³)	440,37 €/m³	0,98 m³	8	3.452,51 €
Border beam (m³)	328,11 €/m³	7,98 m³	3	7.851,68 €
Total				527.056,57 €

The proposed solution in this chapter shows a cost reduction in about 130.000,00 €, proving its potential.

Analyzing some elements separately, the following differences were registered:

- The reinforcement reduction meant a cost safe of 67.000,00 €;
- Ground anchors optimization meant a cost safe of 8.400,00 €;
- The slab bands, instead of the buttresses, meant a cost safe of 56.000,00.

10. Conclusions

At first, it´s important to mention that the objectives initially proposed were achieved. The elaboration of this document allowed the increase of knowledge about flexible earth retaining structures in urban centers, especially in the clay soils from the Miocene. It was noted that these soils have a high stiffness, with an increasing difficulty to excavate as depth increases.

In excavation works in urban centers, the Monitoring and Observation Plan is extremely important, as it allows the builder to manage the structures' behavior, once it is difficult to know the geological parameters accurately.

The modeling of the real scenario in Plaxis 2D, allowed the comparison of displacements with the ones obtained with the inclinometer installed in Rua Sousa Martins. The displacements were similar, and showed a good behavior of the pile wall. The results given by the inclinometer registered the maximum displacement (11mm) at a depth of 6 meters, while the modeling showed its maximum displacement (11mm too) at a depth of 12,5 meters, near the excavation bottom.

After this first modeling, alternative solutions were modeled too. The first alternative tried to suppress the third ground anchors level. Naturally, the efforts and deformations in the pile wall increased. The maximum displacement was, at that point, 21 mm. As this value was very close to the alarm value, the third ground anchors level reveals itself as necessary, at least partially.

The last objective of this thesis was to propose a solution for all the work regarding the earth retaining wall and its auxiliary support elements. This proposal was based on a continuous monitoring of the construction work, allowing a numerical back analysis. As expected, was reached the conclusion that there was some overdesign in the original project. The safety in this kind of constructions must be unquestionable, so the overdesign is common.

The proposed solution showed a good structural behavior of the pile wall and the concrete wall, as well as lower costs and probably lower work times.

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