Peripheral earth retaining solutions for building basements at the intersection of Fontes Pereira de Melo Av. and António Augusto Aguiar Av., in Lisbon

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Abstract: The excavation for the construction of basements has some inherent concerns to the safety of the work and the surrounding structures. In urban areas these concerns are higher due to the ground high density of occupation. The objective, here, is to study solutions of peripheral earth retaining structures and the respective behavior. For this purpose, the initially designed solution for the peripheral earth retaining structures of the case study were analysed and alternative solutions were created in order to minimize displacements and costs. The alternative solutions are focused on the earth retaining structures solution. The behavior of the earth retaining structures was analysed, as were the grounds and the surrounding structures, Using different earth retaining structures and with different bracing elements. Through modelling with the software Plaxis 2D the ground behavior was analyzed, identifying the most sensitive areas, and enabling the study of the earth retaining structure behavior for all the construction phases.It was possible to conclude that the alternative solutions were viable. Through safety and displacements verification this conclusion was reinforced.

Keywords: Urban Excavation, Earth retaining, Piles, Modelling, Deformations, Safety

1. Introduction

Urban construction implies a lot more precautions than usual, due to surrounding infrastructures and services. In the construction of basements, the concerns are accumulated, since the good behavior of the foundations of the neighbour buildings.That being said, there are regulations that have to be complied with, so that safety is not compromised, (CML, 2013). The main constraints in this type of work are those related to geological and geotechnical aspects and, as previously mentioned, the affected neighbourhood conditions and services.

Flexible earth retaining structures

Flexible support structures can be referred to as earth retaining structures or walls, and encompass all structures where deformations, due to the ground pressures, produce a significant effect on the distribution of pressures and efforts for which they are dimensioned, bending moments and transverse stresses, (Peck, 1972). They are elements of reduced thickness constituted by reinforced concrete, steel or wood, supported by struts, anchors and/or embedments of passive type, (NP - EN 1997-1, 2010). There are different types of flexible structures, the mono supported, that correspond to a single structural support at the top of the earth retaining structures, the self-supporting ones, which are embedded in the ground, mobilizing the passive horizontal earth pressures present at the front of the earth retaining structures to balance the active horizontal earth pressures , and the multi supported, which have two or more supports. Multi-supported earth retaining structures are widely used for the construction of basements with significant excavation depth. In multi-shored earth retaining structures passive elements are used (struts). The high stiffness of the struts restraints the earth retaining structures displacements, which are designed to balance almost all the horizontal earth pressures. The displacements are reduced at the top because the struts are placed in the beginning of the excavation work. However, they tend to increase in depth since there are mobilizing horizontal earth pressures from the ground behind the earth retaining structures. The movement created by the earth retaining structures can be considered as a rotation around the top in the direction of the excavation pit, (Fernandes, 1983). On the other hand, multi-anchored earth retaining structures use active elements (ground anchors). These do not work, neither for their rigidity, nor for imposing displacements, but mainly for the change in the states of stresses that are caused in the supported ground. The stresses σ_1, vertical stresses, constant, and σ_3, horizontal stresses, variable, are analyzed as major stresses and are thus maintained during excavation and pre-stresses phases.

In the graph represented in Figure 1, 3 different phases are indicated. Phase 1 corresponds to the excavation and since σ3 decreases, there will be an increase in the deviation stresses, q, difference between σ_1 and σ_3. Phase 2 is the anchoring stage, where, increasing the stresses σ_3 and consequently decreasing the deviation stresses leads to partially recover the deformations. In phase 3, the excavation is carried out again and the displacements correspond to the curve on the graph, where the final deformation is at the point 3A, corresponding to a higher value of deformation, which should be controlled within the design of the earth retaining structures itself, (Guerra, 2007).

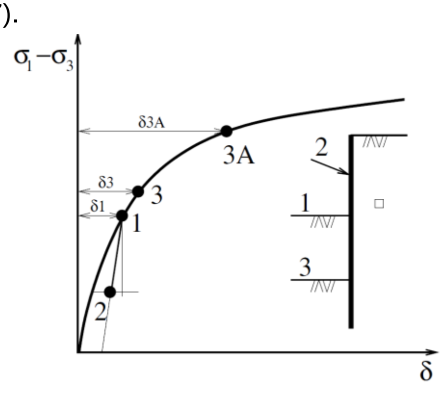

Figure 1 - Schematic representation of the evolution of the stresses state in ground elements supported by anchored earth retaining structures,(Guerra, 2007)

Flexible Earth retaining structures Technology

The peripheral earth retaining structures through definitive Berlin walls, also known as Munich-type walls, are composed of concrete panels, which are executed in a phased manner and in each of them there is a central ground anchor or shoring (Brito, 2001). The earth retaining structures of shaped piles (Brito, 2002) are constituted by a set of molded piles that are next to each other or even intersected, forming a discontinuous wall where the piles are connected by a crowning beam at the top and by several distribution beams in depth.

The main difference between these two methods in terms of use is that the piled earth retaining structures wall is a technique that will allow the surrounding grounds to not undergo such significant displacements and make it easier to prop up the earth retaining structures with an alternative to the use of ground anchored. It is a technique that presents many advantages in particular with regard to the execution time, but it entails higher costs compared to the definitive Berlin walls. In this second technique the material is more basic and the required equipment is less specialized.

Excavation Support Structures

The solutions adopted for the peripheral earth retaining structures, mentioned above, need the existence of elements that support and balance the horizontal earth pressures during the excavation. For that, shoring, anchors and slab bands are used.

The shorings are elements that can be of steel, concrete or wood. They have provisional character and their main function is to support and control deformations. They are inexpensive, fast-running and do not require a skilled technician to place them, although it has the disadvantage of taking up space within the excavation area.

The ground anchors have temporary or definitive character and are constituted by the head, shaft and sealing bulb. The advantages of ground anchors rely mostly on the fact that it is a safe method, it’s easy to locate in the ground and allows a better control of the horizontal displacements. The disadvantages are related to the need for specialized stuff.

Slab bands are a solution that, from a technical and economic point of view, can be considered interesting. Their objective is to support the earth retaining structures walls and are often used together with steel trusses. It allows the reduction of the time of execution of the work, since, in general, they have a definitive character, which allows the central zone of the excavation zone to be released for the circulation of machines and equipment. In areas where the neighbour structures are sensitive, they minimize the disturbance of the surrounding grounds and are also elements with by stiffness. However, it is a methodology that requires greater compatibility with the architectural and structural solutions and needs to use vertical elements for temporary support.

2. Case study

The work under study, is at the urban center of Lisbon, in an area that has several restraints inherent to its surroundings. Figure 2 shows the aerial view of the site, where it is possible to identify Av. Fontes Pereira de Melo, Av. António Augusto Aguiar, Rua São Sebastião da Pedreira and Fénix Urban Hotel as limits of the intervention área.

Figure 2 - Aerial view of the place of intervention (GOOGLE, 2017)

The project of the work under study is related to excavation and peripheral earth retaining structures, for the construction of 6 basements. Two different techniques were used for the earth retaining structures, definitive Berlin walls and earth retaining structures of shaped piles, fastened with slab bands and ground anchors.

Main restraints

The geological-geotechnical scenario is characterized by recent materials, landfill and alluvial deposit, miocene sedimentary layer, clays and limestones, and volcanic facies layer dating from Neocretacions, volcano-sedimentary complex of Lisbon.

Table 1 shows the estimated values for the characteristics of the different types of grounds.

Table 1 - Estimated values of the adopted geotechnical parameters

	N_{SPT}	γ_t (KN/m^2)	ϕ'	c' (KPa)	E (MPa)
At	9 - 60	18	27	-	8
a	60	18	3	-	10
M^I_1	>60	20	32	25	60
	53 – 60	20	30	20	50 – 60
	>60	21	36	25	60
CVL	W_5 (N_{SPT}>60)	21	34	20 – 25	60

The main concerns of the location focus on the existence of the ML tunnel and the Tunnel Marquês of. These are structures that require great care and are quite sensitive. The adopted solutions take these aspects into account, preserving their integrity, before and after the work.

Design solutions

Figure 3 and figure 4 show the design plans of the solutions initially design for the different basements, 0, -1 and -2, and for basements -3 and -4, respectively.

In the upper part of the building, coinciding with São Sebastião da Pedreira street, a permanent Berlin-type wall solution was used, top-down construction of reinforced concrete wall pannels supported by vertical micropiles with a tubular section. The BD, CD and DE elevations, coinciding with the Fontes Pereira de Melo Av. and António Augusto Aguiar Av., are the ones that have the tunnel conditionings, therefore it was necessary to adopt a technique that would allow a greater rigidity of the wall to avoid that the resulting displacements of the excavation affected the neighbour structures, using earth retaining structures with piles. There are also elements, such as buttresses, which play an important role in balancing the earth retaining structures wall. These allow the support of the slab band and the decrease of the length of their span so that the displacement, at half span, is reduced, and there for allowing the verification of the service limit state.

Figure 3 - Plant of the design solution for basements 0, -1 and -2 (A Pinto & Pita, 2016)

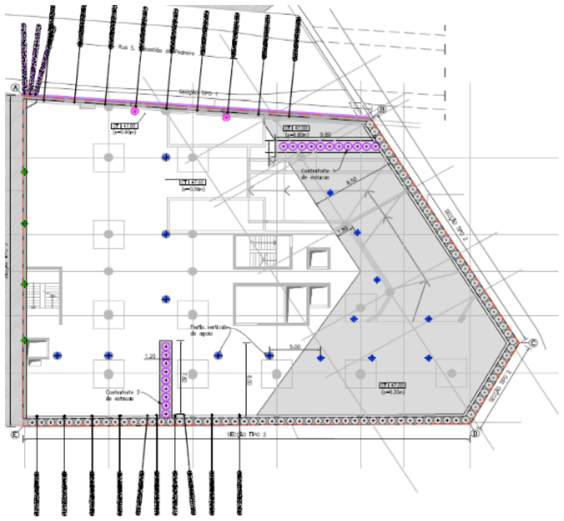

Figure 4 - Project solution plan for basements -3 and -5 (A Pinto & Pita, 2016)

Monitoring and survey plan

The monitoring and survey plans are fundamental tools to guarantee the safety of the excavation and earth retaining structures works, as well as of the neighbour infrastructures, being of great importance for the control of their behavior. Given the characteristics of this work, the existence of the Marquês and of the Lisbon metro (ML) tunnels near the excavation area, this task becomes crucial.

3. Modelling the earth retaining structures solutions

The modelling was done with the software Plaxis 2D, in order to simulate the ground behavior. According to the initially designed solutions in the case study, 3 cross sections were studied. These are in the BC elevation, where the ML tunnel (1) is located, and in the DE elevation, where the Tunnel Marquês is still partially at the surface (2) and when it is completely underground (3), as indicated in figure 5.

Figure 5 - Plan of the intervention area with the cross sections, that will be studied, marked

For the modelling in Plaxis it was necessary to characterize several elements, such as, the geometry, the material, the mesh and the construction phasing used. As presented in figures 6,7 and 8.

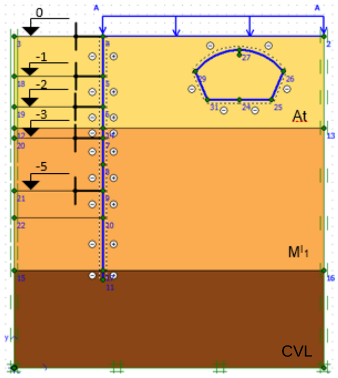

Figure 6 - Cross section in the BC elevation, transverse to ML tunnel

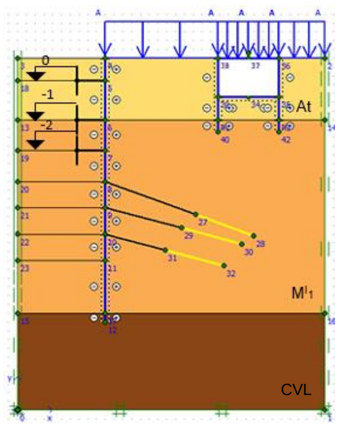

Figure 7 - Cross sections in the DE elevation, transverse to the tunnel of the Marquês located on the surface

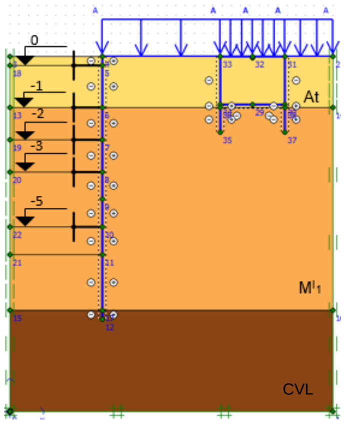

Figure 8 - Cross sections in the DE elevation, transverse to the tunnel of the Marquês, underground

In order to determine the stiffness value of the slab bands, it was necessary to transform them, with two-dimensional behavior, in struts with uniaxial behavior, using equation (1) and the model presented on figure 9 and figure 10, using the SAP2000 software.

$$K = \frac{F}{\delta} \tag{1}$$

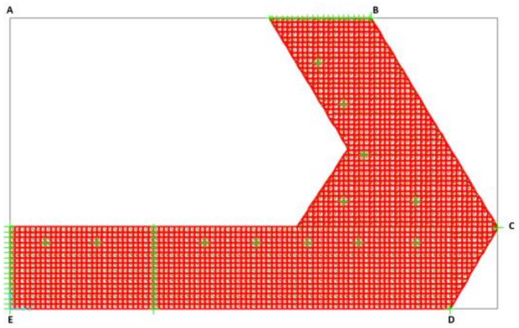

Figure 9 - Slab band model in SAP2000, basements 0, -1 and -2

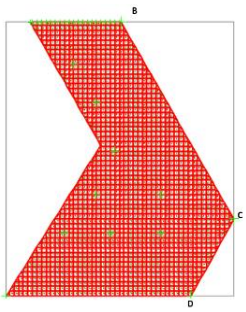

Figure 10 - Slab band model in SAP2000, for basements -3 and -5

The results of the modelling, using the software Plaxis, were compared with the alert values and the alarm values, verifying that they were inferior to the security limits.

The cross section in the BC elevation, transverse to the ML tunnel, is shown in figure 11, where the total displacements are presented.

Emphasis is placed on the final level of excavation, where was observed exists, during the excavation process. In the piled earth retaining structures it is possible to identify higher value displacements at the 4th level of excavation, where the maximum value was verified. At the base of the earth retaining structures a wedge is created that causes displacements to the interior of the excavation. The control of this zone is indispensable for the evaluation of the displacements at the ML tunnel. At the top of the piled earth retaining structures, a rotation is created around this point. This factor tends to be contradicted by the existence of the bracing elements, because when performing the 1st level of excavation the slab band restricts the displacements in this zone. The same thing happens along the piled earth retaining structures, with the difference that at the other levels the earth retaining structures already has displacements when the slab bands are installed, they only begin to perform their functions in the next levels.

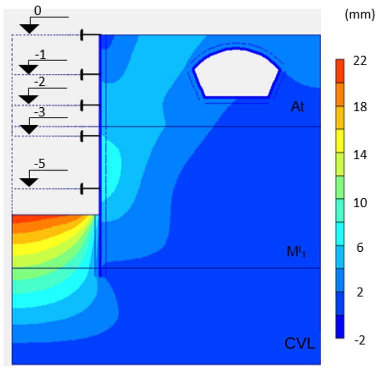

Figure 11 - Total displacements associated with the solution initially designed for the cross section in the BC elevation, transversal to the ML tunnel

Figure 12 corresponds to the cross section in the DE elevation, transversal to the tunnel of the Marquês located on the surface, section in trench. Through the figure it is possible to verify that the earth retaining structures has bigger displacements where the ground anchors are located. It is also apparent that the sealing bulb is located in an area where the displacements are smaller, thus indicating their proper functioning. Regarding tunnel discharges, they are higher in the area where the connection is made between the surface and the ground, resulting from the fact that the tunnel does not have its upper part, thus operating as a trench.

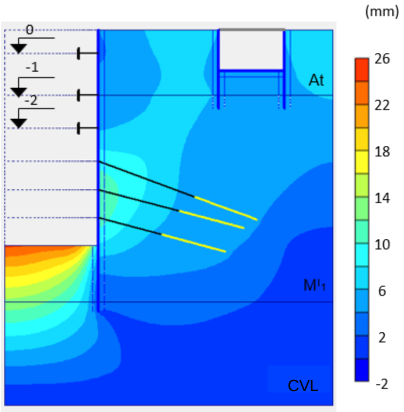

Figure 102 - Total displacements associated to the initially design solution of the cross section in the DE elevation, transversal to the tunnel of the Marquês located on the surface

Similar to what was mentioned for the cross section in the BC elevation, transverse to the ML tunnel, in the section referring to the elevation DE, transverse to the Tunnel Marquês, when it is buried, the behavior of both the earth retaining structures and of the ground are similar, as can be verified in figure 13. There are no displacements at ground the surface geotechnical, fact that results from the ground characteristics, because in the first cross section, the landfill, ground with less resistant characteristics, has bigger thickness than in the present cross section.

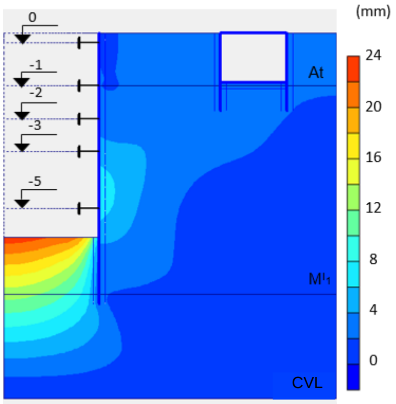

Figure 113 - Total displacements associated to the initially design solution of the cross section in the DE elevation, transverse to the tunnel of the Marquês, buried

4. Modelling of alternative solutions

Several alternatives were created, besides the initially design solution of peripheral earth retaining structures, in order to compare the behavior of the ground, the earth retaining structures structure and neighbour structures, as well as the associated cost. Table 2 summarizes the studied alternatives. In addition to the indicated alternatives, the characteristics of the piled earth retaining structures were also changed.

Table 2 - Summary of the alternatives studied

	Cross-sectional location	Description of the changes from the initially designed solution
A	BC – ML	- Replace the 2 bands of slabs by 3 levels of ground anchors with different lengths
A	DE - Marquês (inside)	- Replace the 2 bands of variable length slab by 3 levels of ground anchors with different lengths
A	DE - Marquês (inside)	- Replace the 2 bands of slab with variable length by 2 levels of ground anchors of the same length
B	BC - ML DE - Marquês (inside)	- Replace the 2 slab bands with 1 on the floor -4 with greater length
C	DE - Marquês (surface)	- Change the inclination of the ground anchors to match the entire wall
C	DE - Marquês (surface)	- Remove ground anchors from the middle and increase the length of the last level having all the same inclination
D	BC - ML and DE - Marquês	- Decrease the length of the slabs of the first 3 basements

Alternative A

The alternative A corresponds to the study of the behavior of the earth retaining structures when the type of bracing (slab bands) in basements -3 and -5 is changed to ground anchors, in the cross sections located in the elevations BC and DE, when the tunnel of the Marquês still underground. In the DE cross section two alternatives were studied, A1 and A2. Through the analysis of the displacements resulting from the Plaxis modelling, it was concluded that these values are close to the modelling values of the solution initially designed.

This alternative has constructive advantages in that the intersection of the earth retaining structures walls, BC and DE, have the same characteristics, specifically, spacing between ground anchors, angle of inclination and length of the cables in the same floor and the prestressed load.

The choice of alternative A1 shows benefits at this level too. These measures also make the construction of the workplace more safe because, the more variations between the elements, the greater the probability of errors due to an inadequate reading of the design elements. The fact that ground anchors are placed as an alternative to the slab bands has the advantage of allowing the space inside the workplace to be more freed up for the circulation and execution of other works. The disadvantage is economic. Because the slab bands are definitive elements, this will lend that the monetary amount spent for the peripheral earth retaining structures to be used for the design of structures. Regarding the time of execution, assuming that each level of ground anchors takes about a week to put in place, due to the wait to be able to prestress the ground anchors, it is considered that its execution is faster than the slab bands, because, in the slab bands, the time of casting the reinforced concrete is higher.

Alternative B

Alternative B consists of evaluating the possibility of replacing the two originally proposed slab bands at basements -3 and -5 by one at floor -4, with changes in their length and the characteristics of the piled earth retaining structures. This alternative results from the fact that the largest displacements of the earth retaining structures in the solution initially designed are located at the depth of the floor -4 and, in this place, the excavation depth is high compared to the other levels.

This alternative offers several advantages: the fact that if only one slab band is executed, at the depth of the floor -4, instead of two located at the levels of basements -3 and -5, the work is reduced. This factor allows a reduction of the execution time and also of the associated cost. Safety is maintained and the displacements obtained are close to those obtained in the solution initially designed. Another important aspect is that it allows a greater workability because, on basements, the depth between slabs will be higher, and in large excavations it will be difficult to remove the excavated materials, since the grounds begin to be stiffer. This way, the work is made easier, increasing productivity.

Alternative C

Considering the compatibility of the alternatives, with the objective of adopting the same solution along the earth retaining structures wall, the behavior of grounds and structures (piled earth retaining structures and tunnel) was evaluated with the same alternatives adopted in alternative A. That is, placing ground anchors with the same inclination and altering the piled earth retaining structures. As in alternative A, which was separated in A1 and A2, in alternative C the same method was followed. The alternative C1 consists of 3 levels of slab bands and 3 of variable length ground anchors, and alternative C2 is composed of 3 levels of slab bands and of 2 levels of anchors.

The main advantage of alternative C is the compatibility of the constructive solutions along the earth retaining structures. The C1 solution conjugated with A1, and the C2 solution with A2 are viable solutions, as they allow the same bracing solution to be adopted along the piled earth retaining structures wall.

Alternative D

Alternative D studies the change in size of the slab band corresponding to the first 3 levels of bracing.

In this alternative, the fact that the slab bands have a shorter length allows for the release of space in the excavation area, which is a favorable factor. The difference in length is not significative (1m), however, the volume of land to be excavated, conditioned by the existence of slab bands located on the upper floor, decreases. These features allow a higher productivity and, which means, shorter execution time and smaller costs, as the costs associated with work and equipment decrease. A smaller amount of concrete and reinforcement is also used, however this difference is less significant.

5. Comparative analysis of solutions

Analyzing figure 14 corresponding to the BC elevation, transverse to the ML tunnel, it is concluded that the displacements at the beginning and at the end of the earth retaining structures converge to the same location and, with the exception of alternative B, the maximum displacement occurs approximately at the same location. These displacements resulting from the modeling are somewhat higher than the modeling of the solution initially designed, although this value does not exceed 2mm. The alternative solutions result in different deformation of the piled earth retaining structures, the effect of the different bracing elements and their location, recalling that ground anchors and slab bands were used for these elements.

Since the results are less than half the alert value, and even if none of the alternative solutions have had lower displacements than the initially design solution, these solutions are valid. The values of the displacements are very close to the initially designed solution, so they were not considered a disadvantage, and from an economic and run-time perspectives, they will present as advantages.

In the elevation of the Tunnel Marquês, when it is located at the surface, figure 15, the deformation shape resulting from the excavation and earth retaining structures processes are closer to the initially design solution than in the previous cross section.

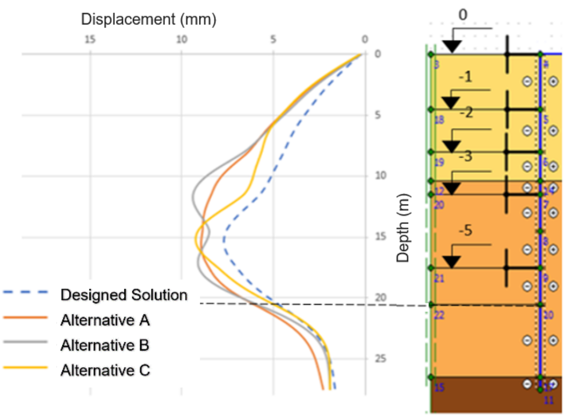

Figure 14 - Comparison of displacements in the piled earth retaining structures in the BC elevation, transversal to the ML tunnel

The results are once again far from the alert and alarm values, indicating the safety of the construction processes. In certain points, the deformation shape presents smaller displacements relative to those of the initially designed solution, being, its maximum difference approximately 1mm when compared to the initial solution.

In the previous elevation, in the deformation shape of the different alternatives, it is visible that different bracing elements were considered due to their variation. In this case, since the same solution is used, earth retaining structures of piles with slab bands in the first 3 basements and ground anchors in the remaining basements, changing its characteristics, the earth retaining structures adopts a similar format.

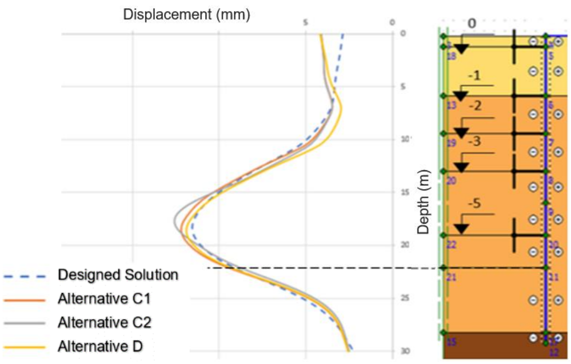

Figure 15 - Comparison of the displacements in the piled earth retaining structures in the elevation DE, transversal to the Tunnel Marquês located at the surface

Similarly to the results in the BC elevation, transverse to the ML tunnel, in the DE elevation, when the Tunnel Marquês is located on the surface, figure 16, the deformation shape of the different alternatives present the same behavior. Since there was the concern of making the constructive method of the two consecutive elevations compatible, these results were expected. The difference between these and the alert values are distinct without compromising security. The alternative A2 is the one that requires more attention, and if it does not have great advantages in execution time and from an economic point of view, it will be the least viable solution to be solution

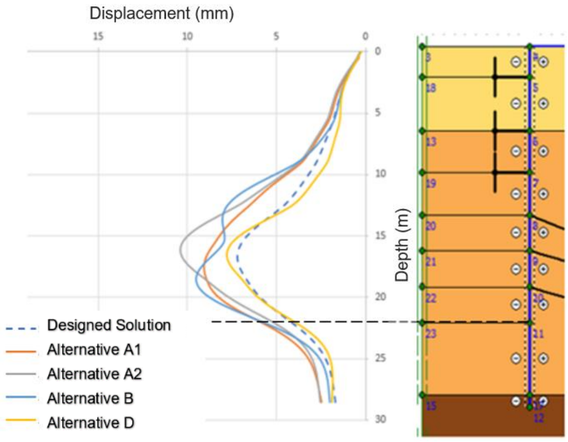

Figure 16 - Comparison of the displacements in the earth retaining structures of piles in the DE elevation, transversal to the tunnel of the Marquês, buried

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For the creation of alternative solutions, there was, from the beginning, the concern of compatibilization of the elevations so that the adopted solution presented characteristics as close as possible to the initial solution. It is in this sequence of ideas that combinations of alternative solutions were created and were presented in table 3.

Table 3 - Peripheral earth retaining structures solutions

Combination	BC (ML)	DE (Marquês – surface)	DE (Marquês – buried)
1	A	C1	A1
2	A	C2	A2
3	B	C1	B
4	D	D	D

Global comparative analysis

Table 4 shows the results obtained for each solution, referring to the maximum horizontal displacements of the earth retaining structures for cross a cross section in each elevation and the cost resulting from the economic analysis. Regarding the safety, all alternatives are within the parameters.

Table 4 - Global comparative analysis of solutions

Solutions / Combinations	Horizontal displacements of the earth retaining structures (mm)			Cost (€/m²)
	Elevated BC (ML)	Elevated DE (Marquês – surface)	Elevated DE (Marquês – buried)	
Initially designed	7,8	11,6	7,3	413
1	9,1	12,2	9,1	358
2	9,1	12,6	10,4	339
3	9,7	12,2	9,5	283
4	9,3	11,9	7,8	283

Taking into account the data in the previous table, it is possible to verify that the alternative solutions are economically more advantageous than the originally designed solution. However, there are slightly higher displacements than this solution. As mentioned previously, the results of the displacements, obtained for the piled earth retaining structures are much lower than the alert and alarm values, and therefore do not cause any additional concerns.

Regarding combination 2, it is the one that presents the greatest economic advantages. In terms of displacements, in terms of displacements it's the solution where larger displacements are located on the DE elevation. The combination with the fewest advantages is combination 3 because the benefits gained from building the earth retaining structures solution with higher costs are not compensated by lower displacements. In contrast, combination 4 is the one with the highest costs, but there is the benefit of displacements being lower. In the DE elevation, combination 4 is the one that reduces the displacements more. In the BC elevation, although the displacements are not the smallest, are also quite satisfactory. The difference between combination 1 and combination 2 is the omission of one anchorage level in the DE elevation, so, the resulting displacements were expected.

Comparing combination 1 with combination 3, it can be concluded that the second is more advantageous in that it has a lower cost per square meter of earth retaining structures wall, and the variation of the displacements between them is less than 1 mm. These two combinations have different levels of bracing, the combination 1 consists of ground anchors and the combination 3 of slab bands. The slab bands have greater stiffness, providing inferior displacements when compared with ground anchors.

Given the above, combinations 1 and 4 are the ones with the most advantages, comparing the two, the second one is chosen because it is considered that in economic terms the difference between them is around 74 €/m^2, in favor of combination 1, and in in terms of displacements in the piled earth retaining structures, the difference between them is less than 1.5mm.

6. Main conclusions

By analyzing the displacements on the piled earth retaining structures in the different constructive stages, the behavior of the earth retaining structures was verified when it is supported by different bracing elements, slab bands and anchors. Slab bands are structures that have high stiffness, however, because they work only in a plane, they mainly control the horizontal displacements. As far as the control of the displacements through the slab bands is concerned, they are controlled after they are layer, that is, at the following levels of excavation. In the case of ground anchors, what is verified is: the reduction of the displacements when the ground anchors are stressed and also their action at the following levels of piled.

Comparing the deformation shapes of the earth retaining structures of piles, when slab bands or ground anchors are used, it's concluded that they are similar. When placed at the same level they have the same type of behavior, however, due to the fact that the slab bands generally present greater rigidity, the resulting displacements are lower on them than on the ground anchors.

The modelling of alternative solutions was done based on the values obtained for the initially designed solution. Comparing the values obtained with the values of alert and alarm presented in the project, it is verified that these are much lower (half the alert value).

The fact that the workplace is located in the city center always raises additional concerns, and adding that the ML and the tunnel Marquês are located right next to it, it is necessary to take greater caution at the structure, design leading to an attempt to reduce as much as possible damage risk.

7. Future developments

Given that the project is in the licensing phase, after this stage, the topics that will be listed below would be of interest for progression of the study carried out.

- Follow-up of the work being done;
- Comparison of the proposed solutions with the results of the monitoring devices;
- Through the results of instrumentation devices, perform back-analysis, in order to obtain similar modelling results. This retro analysis will upgrade the characteristics of the ground, with the goal of bringing them closer to reality, that is, to approximate the behavior of the ground resulting from the modelling to what was verified in the workplace. This work will allow a calibration of the models used.

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