Excavations in Urban Areas – Ampliation of Santander Totta Business Center

Luís Miguel Guerra de Sousa Machado

Department of Civil Engineering, Instituto Superior Técnico, Universidade Técnica de Lisboa – PORTUGAL

February 2016

ABSTRACT

Nowadays the main problem for the construction sector in urban spaces is the lack of space, new construction techniques are needed to maximize the surface living area. As such, excavations and retaining walls have great relevance, and this kind of retaining have a lot of geotechnical knowledge and it's important to know the soil properties, so we can know which kind of soil we are going to work and its implications on a flexible structure such as retaining walls. This dissertation has a goal of studying the flexible structure behavior of a retaining wall, for that study it was necessary a monitoring a site at *Calouste Gulbenkian Avenue,* related to the expansion of Centro *Santader-Totta*, in which the solution was a Concrete Soldier Pile Wall. From the observation and instrumentation plan of the site it was possible to get the horizontal displacements over the several phases. Also it was done a theoretical analysis of the same displacements by using the finite element modelling program "Plaxis 2D" and by using the data from the construction project it was possible to create a model similar to reality and obtain the displacements. Comparing these theoretical displacements with the displacements obtained by instrumentation, it was possible to make a back analysis of the soil properties from back analysis new models were created and new displacements obtained with purpose of bringing closer the maximum horizontal displacements from instrumentation at the final excavation. At the end two alternatives solutions were analyzed, one consists in a optimization of the performed solution and other in a new type of retaining solution. They were analyzed using "Plaxis" to obtain the displacements on the retaining wall and make comparison between all solutions to determine which could be the better possible solution. Also a brief economic analysis was made of the alternative solutions and performed solution.

Keywords: Excavation; earth retaining structures; Concrete Soldier Pile Walls; instrumentation; modelling; back analysis.

1. Introduction

The evolution of new construction techniques it's connected with the appearing of challenges such as costs reductions, shorter deadlines, increase of productivity, better quality, etc… One of the problems it's the decrease of new spaces for construction in urban areas.

In urban spaces the demand for the increase of ground floors it's high so the need for the introduction of excavation and retaining techniques it's higher, especially in the extension of office or company buildings.

The principal solutions are the flexible retaining wall structures, these structures allowed to make vertical excavations and the peripheral earth retaining solutions of the soils at the excavation perimeter. There are many flexible retaining wall techniques such as bored pile walls; *Berlin walls*; *Concrete Soldier Pile walls*; *Sheet Pile wall*…

The choice of the technique will depend on many factors such as the soils on site, the presence of a high phreatic level, the presence of rocks, vicinity constrains, etc… In some geological scenarios it's needed a ground improvement technique like *Deep Soil Mixing*; *Jet Grouting Columns* and *Stone Columns* to develop the soil properties before the application of a flexible retaining wall structure.

This dissertation it's about the study of those flexible retaining walls techniques during an excavation, to help the study it was visited an excavation and peripheral earth retaining structures of site related to the expansion of the *Santader-Totta* center, located near *Calouste Gulbenkian Avenue*, in Lisbon.

1.1 Flexible Retaining Walls

The difference between design flexible retaining walls and rigid walls it's the fact that it's not possible to develop a theory to calculate the earth pressures on a flexible wall, because they depend of factors like the allowed deformations of the support system and the stiffness of the wall. It's a problem of soil-structure interaction, so the earth pressure cannot be explained by an earth theory. However, Terzaghi and Peck realized numerous studies and force measurements on shored retaining walls and determined the earth pressures diagrams.

The results show that the shape of the diagrams of pressures and its values can change, even on the excavation, related with construction process factors. The diagrams only determine the forces on the shores and not the pressure on the wall. In the structural design this forces on the shores must be multiplied by factors of 1,2 in case of sandy soils and 2,0 in case of clays.

The performance of this type of structures has been very positive, as they have been highly competent as support and earth retaining structures of deep excavations, especially in urban areas, without causing damage to buildings and structures nearby. It is only for this reason that this support solution becomes economically competitive but also due to its incorporation into the final structure. Besides this structure also does foundation support, sealing and coating without subsequent processing.

1.2 Multi-anchored Retaining Walls

The flexible retaining wall can be anchored, shored or embedded. The advantage of the anchored solution to shored is that a free space is created inside the excavation pit that allows a better circulation of workers and machines.

On a shored retaining wall the Terzaghi and Peck diagrams allowed to predict the forces on the shores but in an anchored retaining wall the problem its different, because it's not important the force that will exist but the force that must be applied by the pre-stress on the anchor. The pre-stress used in each anchor must be designed so the behavior of the flexible structure would be the desired. This behavior is determined by the displacements that occur on the structure step by step during the excavations phases until the final excavation level.

On a multi-anchored retaining wall the stiffness it's not the principal limitation for the displacements but the pre-stresses can be, but aren't the only issue. Nuno Guerra (2007) in *Estruturas de Contenção Flexíveis- Cortinas Multi-Ancoradas* showed that an anchored retaining wall works specially by the alteration of the stress state of the soil caused by the anchors and also proved that the introduction of the pre-stress on an anchor makes the deformations of the system be lower in the next excavation phases than if it isn't introduced the pre-stress. So it's very important to determine the correct value of pre-stress to apply on anchors, if the value its lower that it should be, the force on anchors will increase. If it is higher, the forces on anchors will decrease over the construction phase.

1.3 Munich Walls

Munich retaining walls it's a technique used on soils that have some cohesion and compacity and it's very important that the phreatic level its lower than the level of the excavation, since this solution don't have a good behavior. It consists on reinforced concrete panels that are supported by steel beams or micropiles to increase the stiffness of the solution. In the case of this dissertation it was used micropiles that have been executed before the execution of the reinforced concrete panels. After the micropiles are executed, it's needed a top beam to join all micropiles to avoid displacements between them. The process continues with the excavation of the primary panels, only after the execution of the primary panels, can the secondary panels (which are located between the primary) start to be excavated. This process is repeated level after level until the desired depth is achieved. It's important on the excavation of the primary panels that exists two adjacent benches of soil on each side of the excavation that will stand the tensions released by the soil decompression – arch effect. The ground anchors are drilled after the panel it's done, then they are sealed and after 4 to 5 days it's possible to apply the pre-stress using hydraulic jacks.

1.4 Bored Pile Walls

Bored piles curtains are another solution of peripheral retaining walls, it's a good solution to achieve great depths but it's not the best solution for soft soils and the presence of water percolation can cause problems on the concrete before setting. This solution consists on reinforced concrete piles connected by a caping beam at the top and several distribution beams in depth, depending on the levels of ground anchors considered. This beams prevent displacements between the piles, the piles are spaced and between them is applied a shotcrete lining.

2. Case Study: Project of Excavation & Retaining of the *Santader-Totta* Center Expansion

The site it's located between *Calouste Gulbenkian Avenue* on North and West, the bike path of Campolide on South and on the East with the building of *Banco Santander-Totta*, with a deployment area near of 4.000m^2 (Figure 1). Since great part of the new building its located below ground, it will be needed to make excavations on a great depth and since the site is in the middle of Lisbon it's not possible to choose a solution of slopes, so the peripheral retaining solution consists on "*Munich Wall*" solution by an *Up-Down* system. The retaining wall will extend over 300m and will have variable heights between 4,0m and 26,0m and also variable thickness between 0,30m and 0,40m.

Figure 1 Plan view of the future excavation

2.1 Geologic and Geotechnical Nature

To determine the geological and geotechnical nature of the site it was necessary to analyze three geological and geotechnical investigation campaigns on different times.

The first campaign was realized between October of 1973 and February of 1974 by the company *"Tecnasol FGE, Fundações e Geotecnia, S.A"*. Seven boring tests were made in several points of the perimeter of the "*Banco Santader-Totta*" building, but only the bores S1, S2 e S3 adjacent to the building on the South area will be important for this project.

The second campaign was realized on March of 2001 for the same company, and three bores were made but only the bore S2 that it's near the principal building is in the perimeter of excavation.

The third campaign was realized on October of 2012 for the company *"JetSJ Geotecnia LDA/Tecnasol FGE, Fundações e Geotecnia, SA"* and were realized three bores (ST1, ST2 and ST3) and one bore with a piezometer (ST4/PZ) on South area near the bike path.

From the campaigns it was found landfills allover (sand-silt-clay) and the Lisbon Volcanic Complex (LVC) of NeoCretaceous period, corresponding to a set of basaltic lava flows, where 3 geotechnical zones (ZG) were defined: ZG3 (landfills deposits, desegregated tuffs, and basalts (W5). In this zone the SPT tests shows 12 to 60 blows); ZG2 with thickness between 0,5m (ST1) and 3,4m (ST4) it's a layer of compacted tuffs and volcanic breccias, also very fractured basalts (W4 and W4-3) and ZG1 witch is the best layer corresponding to basalts (W2-3, F3-4).

2.2 Instrumentation and Monitoring Plan

The *Instrumentation and Observation Plan* allows managing the risk associated to the excavation works, making an important contribution for the execution of the excavation and the construction of the retaining structure on safety and economic conditions. A complete plan should include the description of the instruments, the frequency of the readings, the criteria of warning and the reinforcement measures to be adopted in the cases of warning.

The measures that instrumentation gives are horizontal and vertical displacements of the wall, horizontal displacements at the retaining walls, the force at the anchors, the interstitial pressure and the phreatic level.

The location of the instruments included Topographic Targets to measure horizontal and vertical displacements of the wall, Piezometers to measure the interstitial pressure and phreatic level, Inclinometers to measure the horizontal displacements behind the retaining walls and load cells to measure the force on the anchors.

The frequency of the readings was weekly, and the maximum displacements accepted are 20mm to Section 1 (horizontal and vertical) 35mm/40mm to Section 2 (horizontal/vertical).

2.3 Solution Modeling

For modeling it was used the finite element software "*Plaxis 2D*", the results that this program obtain are a good approximation of the reality but only if the soil parameters and the properties of the materials are a good representation of the reality.

Due to the peripheral retaining wall lenght, in the thesis two sections were studied: Section 1 it's a good representation of the majority of the concrete soldier pile walls on the site with nearly 20,0m of height and it's located on project's elevation AB. The Section 2 was also studied because it was the most concern case since it's the highest Munich Wall of the site, has 31,00m of height and it's located on elevation HI of the project.

This modelling gave the values for displacements and forces of the soil and structure and it was compared to the values obtained by instrumentation, one of the goals of this dissertation.

2.4 Executed Solution

In the modelling process was adopted the *Hardening Soil* for the soil parameters because it's the model that better represents the reality. In Table 1 are the soil parameters for each ZG of the model, these values were taken from the initial project of the construction.

Table 1 Hardening Soil parameters of the ZG's

Parameters	**Soils**		
Hardening Soil	***ZG1***	***ZG2***	***ZG3***
Υ_{unsat} $[kN$	20	20	22
E_{50}^{ref} $[kN/m^2]$	30000	40000	100000
E_{oed}^{ref} $[kN/m^2]$	30000	40000	100000
E_{ur}^{ref} $[kN/m^2]$	90000	120000	300000
c' $[kN/m^2]$	30	40	80
φ' $[°]$	35	40	40
m $[-]$	1	1	1
Ψ $[°]$	0	0	0
Material	Draine	Drained	Drained
Interface Reduction Fact	Rigid		

In Figure 2 and Figure 3 it's represented the geometry of the two sections, the soil layers; the inclination of the slope on Section 2, the design of the retaining wall and the anchors was given by the project of the construction.

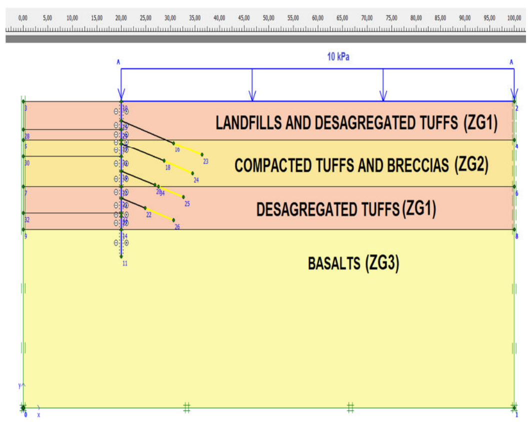

Figure 2 Model Geometry of Section 1 in Plaxis

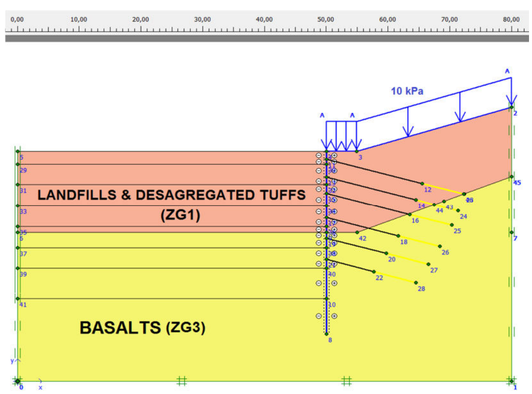

Figure 3 Model Geometry of Section 2 in Plaxis

After the geometry is defined and all properties are in the "*Input*" the next step was the "*Calculate*" and the "*Output*" of results. The major difference between the calculation of the two sections is that Section 2 has a slope and so it was needed to create a new phase called "*Gravity Loading*" (before any phase of construction) that generate the initial stresses in the soil before any construction work because "*Plaxis*" don't generate automatically initial stresses by considering the K_0 procedure, like it happens in the case of an horizontal surface.

After the displacements are calculated, the Figure 4 it shows the horizontal displacements on Section 1 for the last step of excavation, with a maximum value of 9,9mm at 12,00m depth in the excavation direction, and in Figure 5 the vertical displacements with a maximum value of 2,1mm of uplifting at the excavation soil surface.

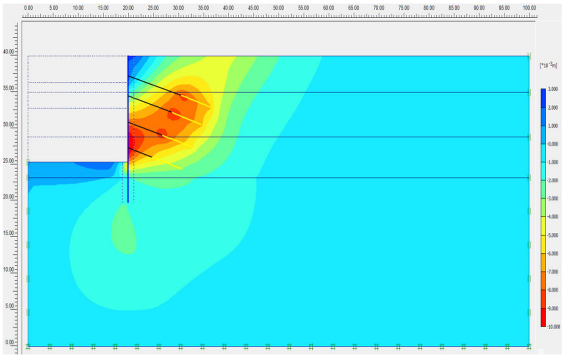

Figure 4 Horizontal Displacements for Section 1 (maximum=9,91mm)

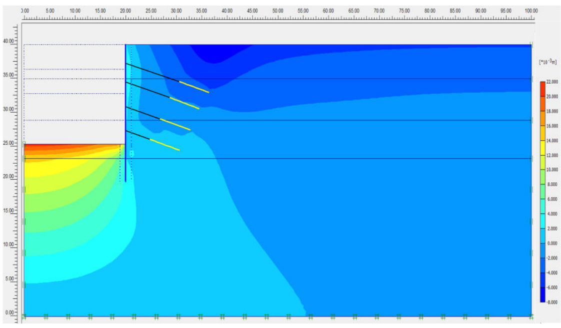

Figure 5 Vertical Displacements for Section 2 (maximum=2,1mm)

The horizontal displacements on Section 2 for the last step of excavation are in the Figure 6, with a maximum value of 15,98mm at 12,00m depth in the excavation direction, and in the vertical displacements with a maximum value of 30,46mm of uplifting at the excavation soil surface.

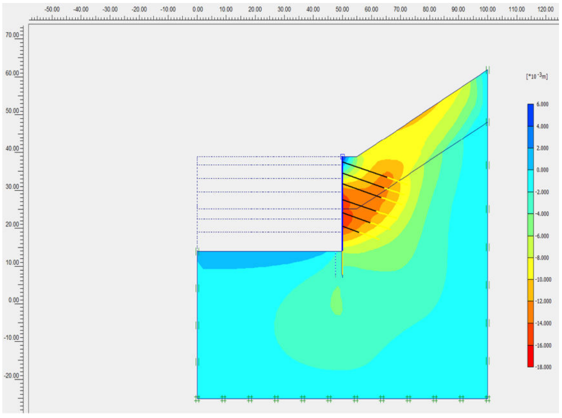

Figure 6 Horizontal Displacements for Section 2 (maximum=15,98mm)

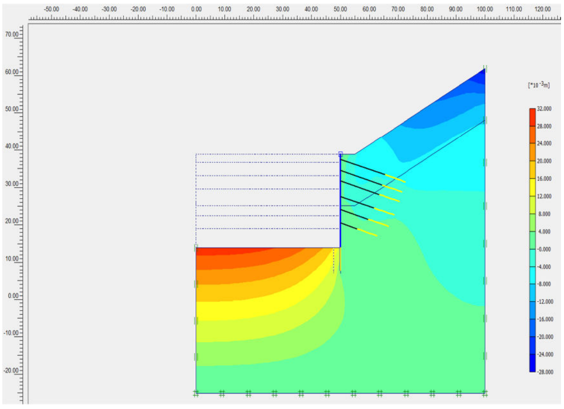

Figure 7 Vertical Displacements for Section 2 (maximum=30,46mm)

The deformations of the retaining wall were also analyzed, and aren't similar to the results of instrumentation displacements. So it was needed a back analysis to approach the values to the instrumentation results.

2.5 Back Analysis

Having the instrumentation results on horizontal displacements on both sections, only the soil properties were changed during the modelling in order to calculate new displacements. After many iterations the soil properties on Section 1 and Section 2 (Table 2 and Table 3) were reached, that gave me the displacements of both sections (Figure 9 and Figure 8). On Section 2, there's a gap on the top of the wall between the optimization and the values of instrumentation, but the values of displacements in the inclinometers don't gave much confidence since the values of the topographic targets for the same depth (0,5m) gave different displacements. About Section 1 there is a closer approximation of the optimization to the displacements of the instrumentation, this happens because the Section 2 it's the highest retaining wall and it's normal that the differences between the modelling and reality shows a higher gap when the height of the solution increases.

Table 2 Optimizaton of soil parameters for Section 1

Hardening Soil Parameters	Soils			
	ZG1	**ZG2**	**ZG1**	ZG3
$\Upsilon_{unsat}\ [kN/m^3]$	20	**20**	**20**	22
$E_{50}^{ref}\ [kN/m^2]$	30000	**60000**	**90000**	100000
$E_{oed}^{ref}\ [kN/m^2]$	30000	**60000**	**90000**	100000
$E_{ur}^{ref}\ [kN/m^2]$	90000	**180000**	**270000**	300000
$c'\ [kN/m^2]$	30	**50**	**60**	80
$\varphi'\ [°]$	35	**40**	**40**	40
$m\ [-]$	1	**1**	**1**	1
$\Psi\ [°]$	0	**0**	**0**	0
Type of Material	Drained	**Drained**	**Drained**	Drained
Redution Factor of the Interface	Rigid			

Table 3 Optimization of soil parameters for Section 2

Hardening Soil Parameters	Soils	
	ZG1	ZG3
$\Upsilon_{unsat}\ [kN/m^3]$	**20**	22
$E_{50}^{ref}\ [kN/m^2]$	**90000**	100000
$E_{oed}^{ref}\ [kN/m^2]$	**90000**	100000
$E_{ur}^{ref}\ [kN/m^2]$	**270000**	300000
$c'\ [kN/m^2]$	**60**	80
$\varphi'\ [°]$	**40**	40
$m\ [-]$	**1**	1
$\Psi\ [°]$	**0**	0
Type of Material	**Drained**	Drained
Redution Factor of the Interface	Rigid	

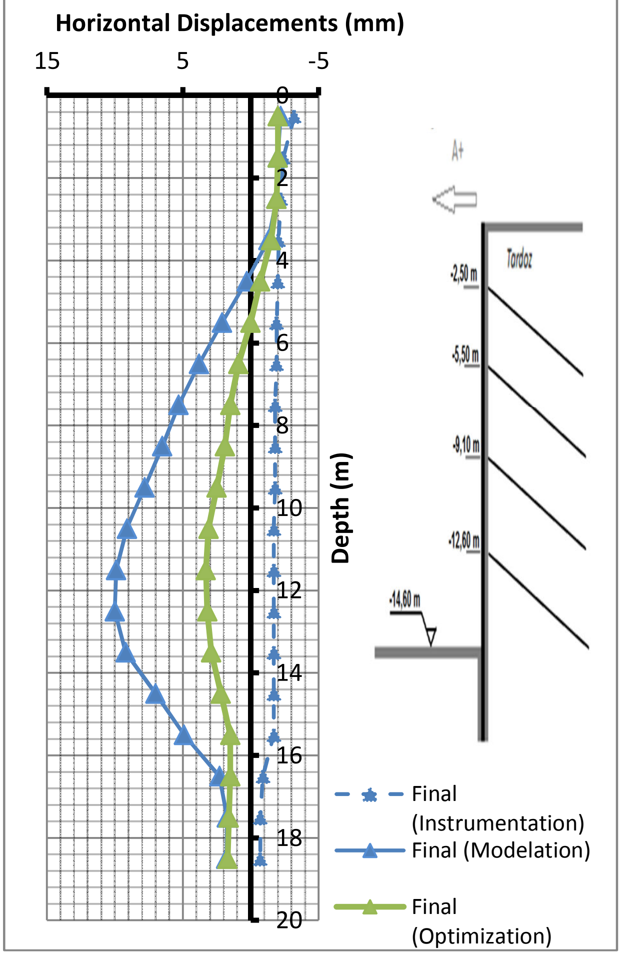

Figure 8 Horizontal Displacements of Instrumentation, Modelling and Optimization of Section 1

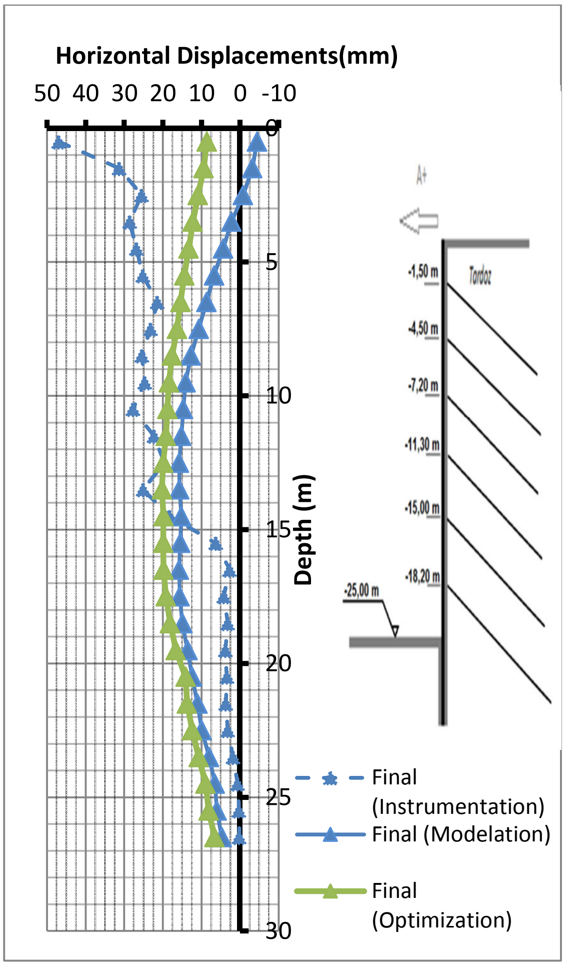

Figure 9 Horizontal Displacements of Instrumentation, Modelling and Optimization of Section 2

3. Alternative Solutions

Two alternative solutions were studied to realise if it was possible to reach an optimization of the purposed solution The first alternative solution was an optimization of the purposed solution on the site, not executing the last level of ground anchors on both sections in study, was definied "Solution 1" as the purposed Munich wall solution and "Solution 2" as the optimization of the Munich wall. The soil properties were the same after the back analysis and the properties such as EA; EI and w for the materials were exactly the same as "Solution 1", also the surcharge at the back surface of the excavation (20 kPa).

The second alternative retaining solution or "Solution 3" was a bored pile wall, in this case the modelling process was different: first the "plate" that describes the wall it's a uniform material, not activated section by section as the Munich wall modelling process; second the properties of the "plate" material (reinforced concrete piles spaced 1,50m between them) have different values of EI, EA and w by comparison of a Munich wall with micropiles. The properties and geometry of the ground anchors are the same when compared to the "Solution 1". On Figure 10 we can see the horizontal displacements at the wall on section 1 and in Figure 11 for section 2, of the two alternative solutions (Solution 2 & 3) the purposed solution (Solution 1) and the instrumentation values for the displacements.

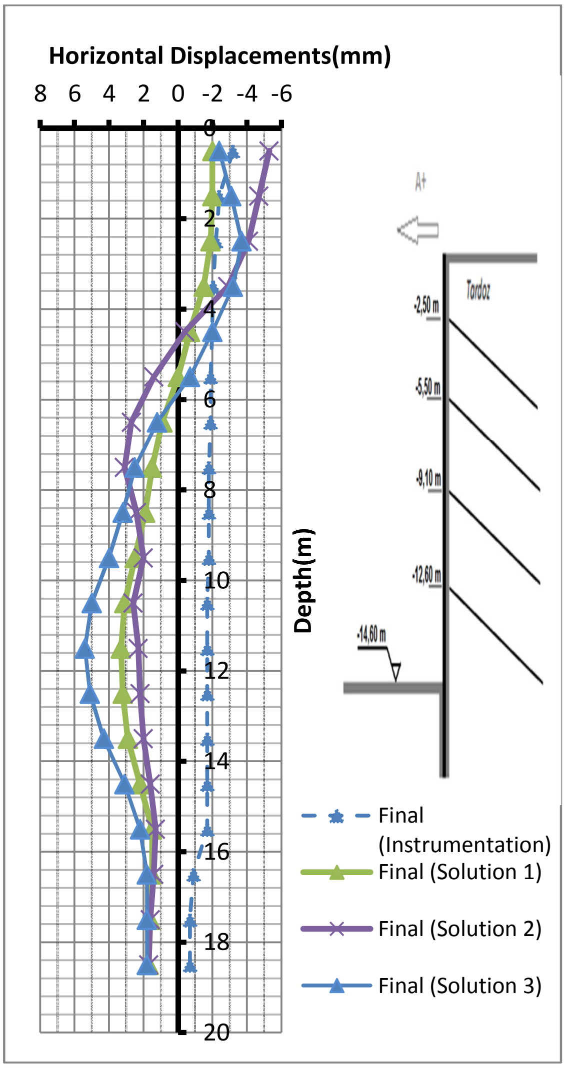

Figure 10 Horizontal Displacements of the 3 solutions on the wall (Section 1)

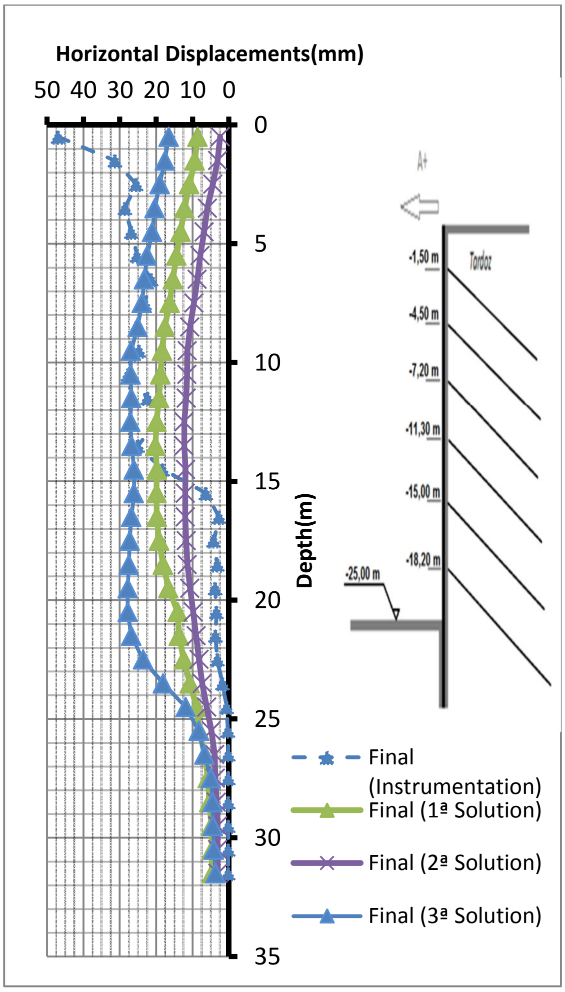

Figure 11 Horizontal Displacements of the 3 solutions on the wall (Section 2)

Observing the figures, we can see the difference between horizontal displacements of the solutions, especially on Section 2, its possibly to conclude that the Solution 3 has the higher displacements due to its lower values for axial and bending stiffness (EA and EI), the Solution 2 have lower displacements by comparing with Solution 1, the justification of this results it's only theoretical and not proved and it will be presented on the next chapter.

4. Economic and General Analysis

After analyzing the displacements, it's important to make a brief economic analysis of the three solutions: the purposed solution of the concrete soldier pile wall and the two alternative solutions, and try to reach on a general conclusion by including displacements and the costs of each solution.

Table 4 Costs and Horizontal Displacements on the wall for the 3 solutions

Solução	Section 1		Section 2	
	Max. Horizontal Displaces (mm)	Cost (€)	Max. Horizontal Displaces (mm)	Cost (€)
1	3,50	56.200,40	19,90	98.225,65
2	3,11	54.064,40	12,51	95.435,65
3	5,41	34.846,30	27,85	50.719,77

The Table 4 shows that the most expensive solution it would be the Solution 1, it's normal that the Solution 2 it's cheaper since is an optimization of Solution 1 by removing the last level of anchors on both studied sections.

The best solution in terms of costs it was the Solution 3, it's also normal since a bored pile solution has less costs that a concrete soldier pile retaining wall and also has a higher productivity.

In terms of displacements on the wall we can see that it's hard to get a conclusion between Solution 1 and Solution 2 since the maximum horizontal displacements in Section 1 for Solution 1 are established at 12,00m depth and in Solution 2 are on 7,50m depth. So we assume the Section 2 as the best section to compare the maximum displacements and it shows that the displacements are higher on Solution 1, on a theoretical point of view it doesn't make much sense that if you take a ground anchor the displacements became lower, so this shows the limitations or the errors that this kind of modelling can have. Or in a theoretical response since the last anchor was embedded on a very stiff and hard soil such basalt the pre-stress applied on the anchor should pull the retaining wall in direction of the ground so this can show that probably the properties of this soil were not totally correct on the input of the modelling.

In the case of the Solution 3 the maximum horizontal displacement it's higher in both sections by comparison to the other two solutions; its normal since this solution allows a better deformation control, so in general terms, shows an higher EI and EA values that the concrete soldier pile wall solution.

In general case, this dissertation shows that the Solution 2 would be the best solution in terms of a balance between displacements and costs.

5. Conclusions and Future Developments

One of the main objectives was to analyze the results of a flexible earth retaining structure. To obtain the results it was necessary the finite element modelling program "*Plaxis 2D*", wich enable to obtain several information such as vertical and horizontal displacements of the soil, bending moments, axial and shear forces at the retaining wall. After getting the theoretical displacements it was possible to compare with the values of instrumentation at the site, by comparing both values in several phases of the excavation, was reached the conclusion that the soil parameters of the first model were not a good approximation of the reality, so a back analysis was needed to minimize the difference between the estimated and observed the maximum values of horizontal displacements at the final stage of excavation.

After getting a better approximation of the model to the reality, it was time to analyze two other retaining solutions by modelling using the properties that were reached at the back analysis, one of those solutions was an optimization of the concrete soldier pile wall and the values calculated for horizontal displacements on the wall were 5,64mm for Section 1 and 12,51mm for Section 2 by comparison with the values of the 1st solution on Section 2 the displacements were lower and for the Section 1 were higher, but it didn't show a great difference of horizontal displacements which means that was possible to do an optimization of the retaining solution. The other solution was a bored pile retaining wall; the modelling of this solution gave horizontal displacements on the wall higher than the 1st solution in both sections studied (5,41mm for Section 1 and 27,85mm for Section 2).

At the end a brief economic analysis was made to conclude that the bored pile solution is 40% less expensive than the Munich retaining wall, proving that probably the solution used was not the best in terms of costs and displacements.

In a future development it's really important to have a better and more extensive soil investigation of the site to increase the possibility to modelling with values similar to the soil properties in situ, especially in a complex geotechnical scenario such is the Lisbon Vulcanic Complex.

6. Bibliography References

Brito, J. d. (2002). *Cortinas de Estacas Moldadas.* Lisboa.

Cravinho, A., Brito, J., Branco, F., Vaz Paulo, P., & Correia, J. (n.d.). *Muros de Berlim e Muros de Munique - slides da disciplina de tencologias de construção de edificios.*

Guerra, N. M. (2007). *Estruturas de Contenção Flexíveis- Cortinas Multi-Ancoradas.* Lisboa