Excavation and Retaining Wall Solutions used in the enlargement of the CUF Descobertas hospital in Lisbon

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Abstract:

In the last few years, the construction field has been facing several challenges, in order to make the best possible use of the available space. It can be noted an increasing superficial space occupation and valorization. Consequently new construction techniques were developed, exploring the usage of the underground space, maximizing the area of implementation available. This kind of projects requires an in-depth knowledge of the geologic/geotechnical conditions, as well as the neighborhood conditions and possible implications in nearby structures.

In this dissertation, the behavior of flexible retaining walls was studied, in urban area excavations, in particular the diaphragm walls technology, using as reference the CUF Descobertas Hospital case study, in Lisbon. Field data was gathered, through instruments installed in the retaining wall that allowed to analyze the horizontal displacements through the different stages of the construction process, studying how the excavation evolution reflects of the displacement observed in the wall.

A numerical modulation of the construction solution for this case study was made in the finite elements program Plaxis 2D. The displacements obtained in the program and through instrumentation were compared and a back-analysis was made that allowed to calibrate the model, obtaining more realistic displacements, also refining the values initially considered to the geotechnical parameters.

Finally, alternative and optimized solutions have been proposed and studied. A behavior analysis was made of these solutions namely in terms of horizontal displacements as well as a comparative analysis of all the proposed solutions throughout this dissertation, from a behavioral and economical perspective.

Keywords: Excavation; retaining walls; diaphragm walls; modelling; instrumentation; back analysis

1. Introduction

Nowadays, the construction sector face numerous challenges due to the lack of space in urban areas, as a consequence of the significant growing of the population in the cities. To overcome these challenges numerous new techniques were developed in order to promote the use of underground space to maximize the usable area of the building. In many cases this underground floors can be used for parking or utility areas.

This limitation of space requires that in the construction of underground floors, the excavation must be performed using vertical walls. In this kind of construction works, the stability of the excavation is achieved using flexible retaining structures such as, for example, diaphragm walls, bored pile wall or king post walls. In some cases ground treatment methods like *Jet Grounting* curtains and *Cutter Soil Mixing* walls can also be applied. The selection criteria to use a specific kind of method depends of several factors like the geological conditions of the site, presence of phreatic level and constraints due to the presence of neighborhood conditions.

To promote a better understanding of this subject, the excavation of 5 underground floors and construction of the retaining walls for the expansion of the CUF Descobertas hospital was followed during several visits on the construction site where the sequence of works were observed. Also, a monitoring plan was installed and the results will be analyzed during this work.

2.1. Flexible Retaining Walls

In the design of solutions that use flexible retaining walls to sustain the soil-structure interaction is important to understand that this is a problem because that is the deformation of the structure that changes the earth pressures diagram that act in that wall along with the internal forces (Guerra, 2012).

Several kinds of flexible retaining walls can be identified, made of different materials, such as reinforced concrete, steel or cement slurry, and with using different construction processes and sequences. The stability of these structures can be achieved using or not one or several levels of support. Usually at least one level of support is used: made by props or pre -stressed ground anchors. There are advantages in using anchors instead of props, mainly because they promote free space inside the excavation site that leads to a greater speed in the works. (Matos Fernandes, 1983).

2.2. Multi-propped Retaining walls

The behavior of this kind of structure is mostly because of the stiffness of the props that prevent movements of the wall. Designing this kind of structures is different than designing rigid walls, mainly because the theory of Rankine and Coulomb to describe the earth pressures acting in the wall cannot be applied here, because this is a problem of interaction between the soil and the structure. Therefore, it’s important to find a theory that can be used to calculate earth pressures acting in flexible retaining walls (Guerra, 2012).

To calculate the earth pressures distribution that act in a flexible retaining wall.the model developed by Tezaghi and Peck in 1976 can be used. The model suggests that the distribution of pressures can be calculated using the diagrams in Figure 1.

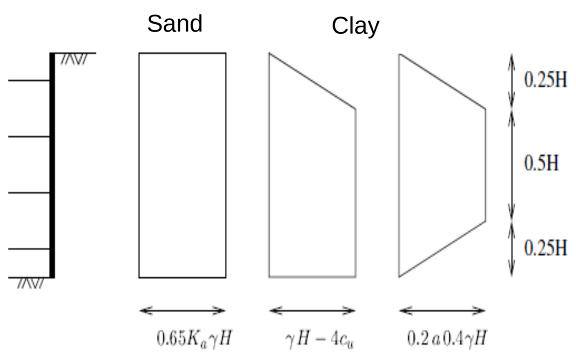

Figure 1 – Earth pressures diagram acting in flexible retaining wall

2.3. Multi-anchored Retaining walls

In the case of a multi-anchored retaining wall, a great percentage of load is applied in the anchors and the question is which value of load should be applied in each anchor. The behavior of this kind of structures is not the result of the stiffness of the anchors, but instead the efficiency of a multi-anchored retaining wall is the result of the changing of stress state of the soil during the successive phases of excavation, reducing the horizontal displacements.

2.4. Diaphragm Walls

Diaphragm walls consists in the execution of a retaining structure made of reinforced concrete that is built in several phases using a narrow trench excavated in the ground and supported by an engineered fluid, usually a clay bentonite mud or bentonite. Usually pre-stressed ground anchors are used to promote the stability of this solution. (Matos Fernandes, 1990).

This solution is well suited to excavations performed in congested areas and closed to sensible structures that can suffer damages due to the horizontal displacements induced by the excavation, also can work as a barrier in cases where the phreatic level intersect the excavation (Brito, 2001). The main disadvantages of this solution is the cost and the space in the construction site that is required mainly because of the equipment to reuse the bentonite clay. Is most commonly used for deep basements, but can also be applied in other situations like subways and pumping stations.

2.5. Bored Pile Walls

This technology that uses bored pile walls as a resistant element in a flexible retaining wall is very common because it's easy and fast to execute, and can be applied to almost any kind of geological material. Consists in the execution of a wall made of several piles with some distance between them. The soil between the piles is stabilized by the arch effect and usually some pre-stressed ground anchors are used in order to maintain the horizontal stability of the wall during the excavation. (Meireles & Martins, 2006). The major disadvantages of this solution: is the difficulty to guarantee that the wall is waterproof and aesthetically cannot be integrated in the final solution, it's necessary to build a wall made of concrete inside the building (Brito, 2002).

2.6. Ground Anchors

In almost any flexible retaining structure, its stability is achieved using pre-stressed ground anchors, which help to balance earth pressures acting in the wall, reducing horizontal displacements. The main reason to use ground anchors is because of the versatility associated to a low cost and easy execution.

In the other hand, the main disadvantages of using ground anchors is the need for specialized team and possible interference with the stability of buildings nearby (Brito, 2001).

3. Case Study: Enlargement of the CUF Descobertas hospital

The case-study presented in this paper is the excavation and the construction of the temporary retaining structure for the enlargement of the CUF Descobertas hospital, in the Parque das Nações area in Lisbon. The location for the construction site and the neighborhood conditions are represented in Figure 2.

Figure 2 – Plan view of the construction site area and the neighborhood conditions

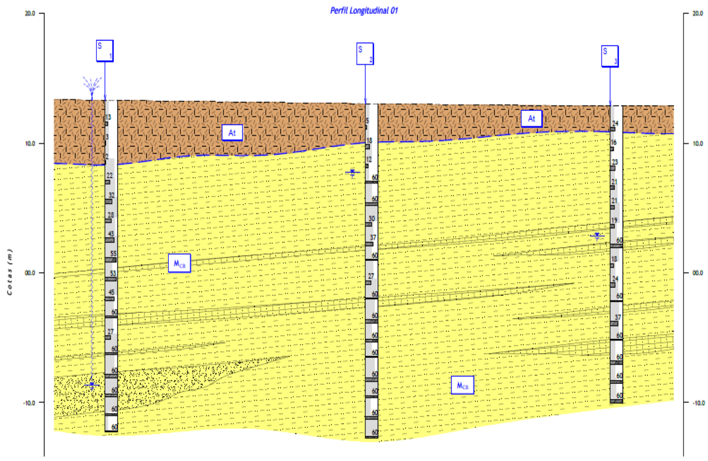

Figure 3 – Geological profile (Geocontrole, 2015)

3.1. Geological and Geotechnical Conditions and Vicinity Constrains

To design a solution that is adequate for the present situation first of all is essential to know the geological conditions and the vicinity constrains.

In order to define the geology of the site, nine mechanical bore holes were drilled, piezometers were installed in the bore holes and some samples were collected and tested in the lab. Based on the results of this work three different geological units were identified: landfill deposits of silty-sand clay, with thickness between 2 and 10 meters laying on a silty clay from the Miocene period that is called “Areolas de Cabo Ruivo” and goes until 13 to 21 meters depth. Bellow, there is a layer of Miocene material with high resistance. In Figure 3 is presented a longitudinal geological profile considered in the case study.

As was mentioned before, the construction site is located in Lisbon, in a densely urbanized area with several buildings nearby. The major constraint was the existing building of CUF Descobertas hospital because was the closest and most sensible structure, so it’s important to ensure the integrity of this structure during the execution of the excavation works and the construction of the retaining wall.

3.2. Executed Solution

Based on all the conditions that were mentioned before, the chosen technology was performed using diaphragm walls, with 17 to 23 meters depth, in order to execute 5 underground floors. To guarantee the horizontal stability of this structure during the excavation works, 4 to 5 levels of pre-stressed ground anchors were installed, as shown in Figure 4 and 5.

Figure 4 - Props and ground anchors in the diaphragm wall

Figure 5 – Executed solution (Synege, 2017)

3.3. Instrumentation and Monitoring Plan

A great level of uncertainty is associated to this kind of construction works. In order to manage the risk and guarantee safety during all the phases, anticipating possible failures and allowing the confirmation of the hypothesis assumed during the design phase, the instrumentation and monitoring plan is installed, with instruments that measure movements of the retaining wall, the ground sustained and neighbor infrastructures as well as the pre-stress acting in the ground anchors.

Also, was defined a range that is acceptable to observe in this instruments called: alert criteria and alarm criteria. If the values obtained are equal to the alert criteria, the structure must be reinforced and if the values are equal to the alarm criteria, all excavation works must stop and the solution should be redesigned in order to meet the desirable safety conditions.

In Figure 6 is presented one of the horizontal displacements measured in one of the inclinometers installed in the retaining structure.

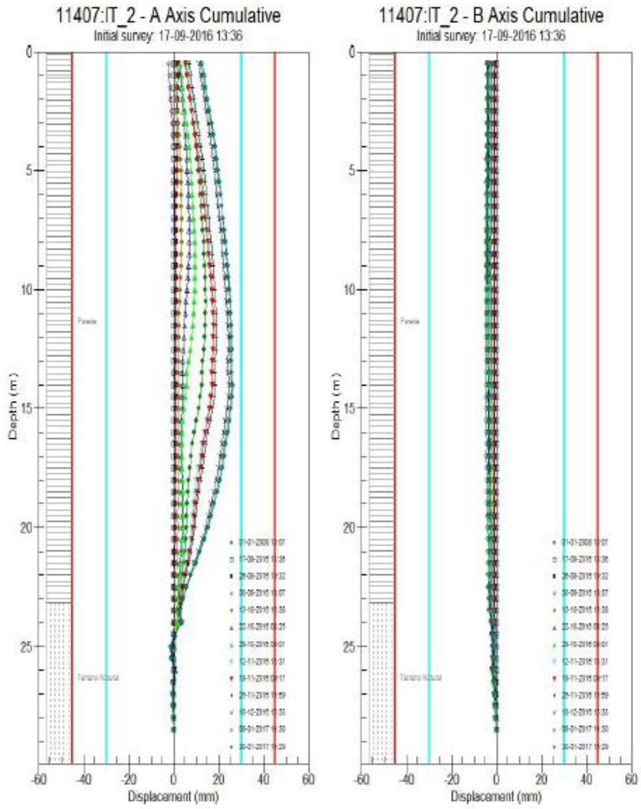

Figure 6 – Horizontal displacements measured in the inclinometer installed in the studied section: max = 25 mm (Teixeira Duarte, 2017)

3.4. Modelling of the Executed Solution

To study the mechanical behavior of the soil and the problem of interaction between the soil and the structure, a specific section of the executed solution was modelled using the finite element software (FEM) Plaxis 2D. The goal is to compare the displacements obtained in this model to the displacement predicted in the plan and installed in the construction, which will result in adjustment of the geological parameters by performing a back analysis.

The model was constructed considering the section closest to the building of the CUF Descobertas hospital. The geometry was based on the design, and aims to simulate the behavior of the diaphragm wall with the contribution of the 5 levels of ground anchors installed. The geological characteristics and thickness of the soil layers presented here were based on the result of the geological preliminary study. Using this kind of models is also possible to maintain all the excavation phases in order to obtain more realistic results.

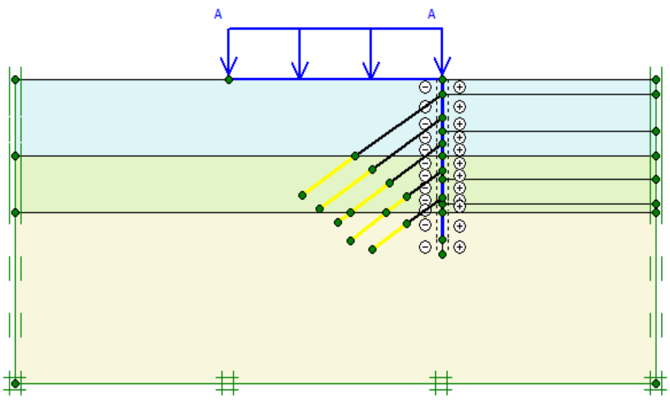

Figure 7 – Geometry of the model simulated in the FEM program Plaxis 2D

To model this solution using Plaxis 2D, besides the characterization of the geometry of the model, it was also necessary to define the geological characteristics of the soil. The model used to simulate the behavior of the soil was the Hardening Soil model and the parameters considered are presented in the following table.

Table 1 – Parameters of the Hardening Soil model

Hardening soil parameters	**Landfill deposits**	**Silty Clay 22<NSPT<43**	**Silty Clay 50<NSPT<60**
γ [kN/m^3]	18	18	18
c' [kPa]	10	20	45
ϕ' [˚]	25	32	36
ψ [˚]	0	0	0
E_{50}^{ref} [kPa]	10000	40000	50000
E_{oed}^{ref} [kPa]	10000	40000	50000
m [-]	0,5	0,5	0,5
E_{ur}^{ref} [kPa]	30000	120000	150000
ν_{ur} [-]	0,2	0,2	0,2
p_{ref} [kPa]	100	100	100
K_0 [-]	0,58	0,58	0,58
R_f [-]	0,9	0,9	0,9

After defining the geometry and the geological and structural characteristics of this model is possible to perform calculations and obtain displacements and acting forces for each of the considered phase. The initial stresses were generated considering the K0 procedure, but after activating the surcharges and the wall, all displacements were reset to zero, to avoid unrealistic results. The horizontal and vertical displacements for the final phase are presented in the following images.

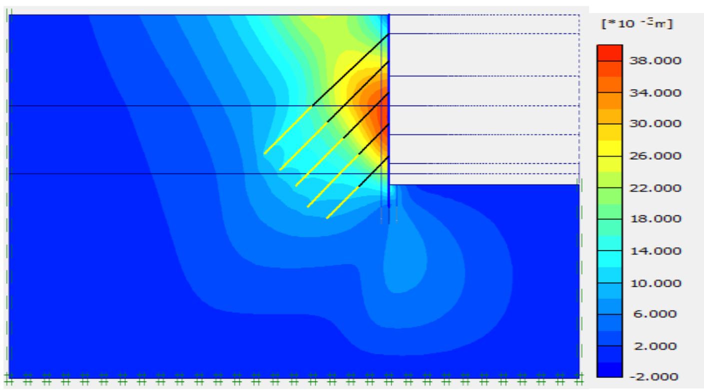

Figure 8 – Horizontal displacements in the last phase (max= 40,14 mm)

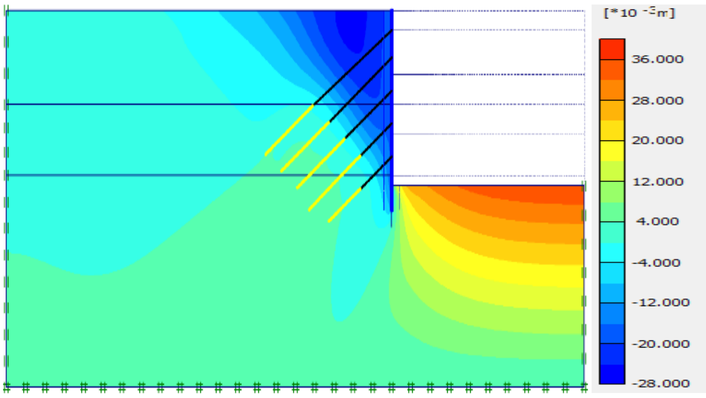

Figure 9 – Vertical displacements in the last phase (max= 28mm)

In the figure 5 was presented the horizontal displacements measured in the inclinometer located in this section. The horizontal deformations of the retaining wall are different from the result of the instrumentation, so a back analysis is going to be performed in order to calibrate this model, obtaining more realistic geological parameters.

4. Back Analysis

Taking advantage of the installed instrumentation plan, the results for the instruments placed on this section, one inclinometer and one topographic target, were analyzed and compared to the displacements that results from the calculations of this model.

This analysis was performed changing only parameters that were previously selected based on the stress state of the soil, mainly Young Modulus, because is the parameter with higher influence in the behavior of the sustained soil, and also the angle of shearing resistance for the second layer.

Several attempts were performed, at first the parameters were changed individually and then all together. The modelling performed follow the same steps as before. The final results can be found in the following table.

Table 2 – Parameters of the Hardening Soil model after the back analysis

Hardening soil parameters	**Landfill deposits**	**Silty Clay 22<NSPT<43**	**Silty Clay 50<NSPT<60**
γ [kN/m^3]	18	18	18
c' [kPa]	10	20	45
ϕ' [°]	25	34	36
ψ [°]	0	0	0
E_{50}^{ref} [kPa]	15000	60000	120000
E_{oed}^{ref} [kPa]	15000	60000	120000
m [-]	0,5	0,5	0,5
E_{ur}^{ref} [kPa]	45000	180000	360000
ν_{ur} [-]	0,2	0,2	0,2
p_{ref} [kPa]	100	100	100
K_0 [-]	0,58	0,58	0,58
R_f [-]	0,9	0,9	0,9

The maximum horizontal displacements after the back analysis is much closer to the value of the maximum horizontal displacement observed in the inclinometer as intended. The displacements for the final excavation phase during the analysis is presented in the next figure.

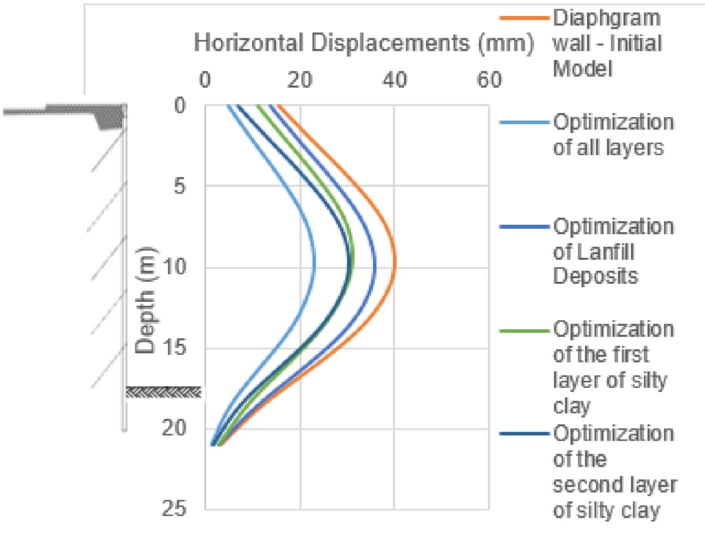

Figure 10 – Horizontal displacements in depth for the model before and after the back analysis

5. Alternative Solutions

Two alternative solutions were studied to understand if it could be possible to find a different solution for this case study, more economical and/or with less deformations.

Because it was observed a small difference in the horizontal displacements during the 3 final stages of the excavation, the first alternative presented is an optimization of the solution by reducing to four the number of levels of pre-stressed ground anchors.

In the second alternative solution presented, the retaining wall will be performed using the bored pile wall technology which, as was said, is a versatile technique. The wall will be made by piles of 600 mm of diameter and with a space of 1,2 meters between the axis of the piles.

The geological conditions considered were the result of the back analysis process and the simulation in the program Plaxis 2D was performed again, considering the differences in the geometry for both solutions and for the second solution the different values for the characteristics of the structural materials.

5.1. Horizontal displacements analysis result

After modelling all the different solutions considered in this analysis using *Plaxis* 2D, the horizontal displacements for the final excavation phase were analyzed in order to understand if all this solutions have the required behavior for the project demands.

In figure 10, is presented the evolution of horizontal displacements in depth for all the different solutions considered and also for the initial solution before the optimization of the model because of the back analysis.

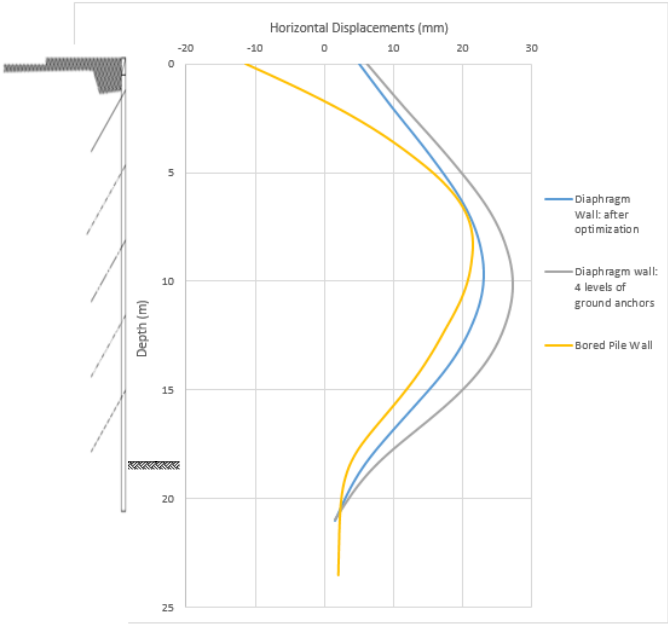

Figure 11 – Horizontal displacement in depth for different solutions presented in this paper

5.2. Economic analysis result

The behavior of the different structures is an important matter in this subject, but is not the only factor to be considered when a specific solution is selected.

Besides the analysis on the behavior of the different structures considered in this paper, an economic analysis was done in order to estimate the costs for each solution proposed in order to be able to conclude which one of best fits the preset problem.

In the following table, the final results for both of the performed analysis are presented.

Table 3 – Comparing different solutions

Solution	Maximum horizontal displacements (mm)	Cost (€/lmw)
Executed solution	23,06	9016,4
Optimization of the executed solution	25,45	8638,4
Bored pile wall	21,36	7102,24

The solution of the retaining wall executed using bored piles technology is the most economical one and also is the solution that presented smaller horizontal displacements which lead to the conclusion that can be the best solution, but is important to consider the possibility of additional works because this solution by itself doesn't guarantee waterproof and the space between piles may need to be reinforced using *Jet Grounting* or Soil-cement mix columns, especially in the first layer of the soil, in the presence of the landfill deposits.

Both solutions using diaphragm walls have more significant overall costs, because this solution demands a higher volume of concrete along with a bigger percentage of steel for the reinforcement which makes the solution more expensive, but there is no additional works to be performed in order for this solution to be waterproof and the good behavior is assured even when the contained soils have poor mechanical characteristics like landfill deposits.

Regarding horizontal displacements, both solutions presented a behavior that is adequate to the present problem. The solution using bored piles demands less space in the construction site than the solution using diaphragm walls because of the equipment used to recycle the bentonite mud, so in urban areas, most of the times, is not possible to use diaphragm walls in the construction of underground floors in buildings.

6. Final Remarks

Considering the objectives proposed initially it is possible to conclude that they were achieved. The study contributed to increase the knowledge about the behavior of flexible retaining walls in urban areas, especially in the presence of soils from the Miocene like was observed in the case study that was followed during this work.

Like is usually performed in this kind of construction works, some instrumentation was placed in the wall in order to measure the displacements of the retaining wall and the pre-stressed acting in the ground anchors. The instrumentation and monitoring plan allow to manage the risk associated to the construction, since is extremely difficult to estimate with precision the geological parameters.

The possibility to obtain the results of the behavior of this structure during all excavation phases from a real case and use a computer program to simulate the response of this structure to the variation of the geological parameters was also very important to this work, since allow the calibration of the numerical model during the back-analysis, comparing the displacements measured in the finite elements model with the displacements measured in the reality. From this comparative analysis, was verified that the parameters of the soil consider in the beginning of this work were very conservative, so the values were optimized in order to be closer to the reality. Was also verified that the parameter with bigger influence in the displacements of the structure was the elasticity modulus and the internal friction angle.

Using the optimized parameters, different solutions were proposed and analyzed from a technical and economical point of view. One of the solution used also diaphragm walls, and consists in an optimization with one less level of prestressed soil anchors and the second solution used bored piles technology.

It was found that the performed solution was appropriate in terms of displacements but is not the most economical solution. The most economical solution is the one that uses bored piles with also good behavior in terms of horizontal displacements verified in the numerical model. However, this analysis has some limitations, because additional may need to be take into account in order to ensure the stability and waterproof of the bored pile structure. Also, this technology is less demanding in terms of space in the construction site, so it's possible to be widely adopted in urban areas.

References

Brito, J. d. (2001). *Ground Anchors (in Portuguese).* Lisboa: Instituto Superior Técnico, Universidade de Lisboa.

Brito, J. d. (2001). *Diaphragm Walls (in Portuguese).* Lisboa: Instituto Superior Técnico, Universidade de Lisboa.

Brito, J. d. (2002). *Bored Piled Walls.* Lisboa: Instituto Superior Técnico, Universidade de Lisboa.

Guerra, N. M. (2012). *Geotecnical Strutures Analysis (in Portuguese).* Lisboa: Instituto Superior Técnico, Universidade de Lisboa.

Matos Fernandes. (1983). *Earth Retaining Strutures. New Scaling Methods (in Portuguese).* Porto: Faculdade de Engenharia da Universidade do Porto.

Meireles, A. B., & Martins, J. G. (2006). *Foundations and Soils Lateral Containment – Bored Piled Walls Execution (in Portuguese).* Pontifícia Universidade Católica de Goiás.