Abstract: The growing use of the superficial space in densely urbanized areas led to the need to take advantage of the available space at the subsoil, often regardless of the existing geological scenario. Therefore, it is in these cases that the geotechnical works, as excavations and retaining walls, assume great importance. There are some factors associated to geotechnical works, such as the knowledge of the intersected soils and the consequences caused by these interventions in existing neighboring conditions. The aim of this work is then to perform some analyzes that address these issues, thereby contributing to the understanding of flexible structures, whose fundamentals are essentially empirical with the structural performance depending significantly on the geological and geotechnical scenario.

The aim of this thesis is to point out the behaviour of flexible retaining structures, using as case study the underground car parking in Alves Redol Street in Lisbon. In this work, the retaining wall consisted of a set of CFA piles curtains, anchored to the ground. Since it was preconized and executed a plan of instrumentation and observation for this work, an analysis of the displacement was made considering the various stages of the construction process. The next step in this dissertation was to proceed to the numerical modeling of the solution run through the finite element program Plaxis 2D. The deformations estimated through the numerical model were compared with the real ones measured on site by the instrumentation. This analysis allowed to perform a back analysis, which aim was to approximate the most the maximum deformations obtained by instrumentation with the values estimated through the model, both in the final phase of excavation. Lastly, some alternative solutions have been studied; with a different construction technology, in order to realize if the solution performed was possible to become optimized. Besides the study of the alternative solutions, were also presented an analysis of the behaviour of the proposed structure. In order to compare their viability an economic study was made, such as a risk analysis of the excavation in the neighbors buildings

Keywords: Excavations; earth retaining structures; CFA piles; instrumentation; back analysis.

Introduction
The problem of scarcity of space in large urban centers appears as a consequence of the large urbanization, which due to the occupation with spaces for dwelling, services and commerce. There for the space available on the surface does not secures the demand that is required by today’s society. This demand is mainly for car parking and as due to the excess vehicles in large urban centers, the existing surface parks are not enough. This is a situation to which the city of Lisbon is no exception. Although over the years underground car parks were built throughout the various areas of the city but the demand for this service still exists. The implementation of these structures is strongly influenced by the available area for its construction and also by the number of underground floors.

As mentioned, a limitation of space for the construction of underground structures involves solutions that demand the vertical excavation and thus occupy the smallest possible area. The flexible earth retaining walls allow execution of excavation works safely and effectively. There are several types of flexible retaining walls such as curtains of bored piles, sheet piles, Berlin walls or diaphragm walls. The application of these solutions depends on the local geology, the ground water level and also the vicinity conditions. Depending on the geological scenario, some soils may require some
interventions before the implementation of the supporting structure. This results in the soil treatments such as deep soil mixing and jet grouting comprising a mixture of soil with a binder, usually cement, which improves the ground geotechnical behaviour. The flexible supporting structures are extremely interesting due to their behavior in service, and when combined with soil treatment techniques promote retaining solutions unique and challenging for those involved in its realization.

The aim of this thesis is to study the work for the excavation and peripheral earth retaining structure for a car park in Alves Redol Street, which lies in the center of Lisbon, a densely urbanized area. Such constructions are associated with various constraints, but the one that stands out is to ensure the security and integrity of neighborhood conditions. In the case of a Lisbon city with buildings from different decades, it becomes a challenge to know the characteristics and behaviour of the surrounding structures, which may be sensitive to ground movements in its vicinity. During the excavation and execution of the retaining structure a monitoring plan was done which contributed significantly to this work.

Flexible Retaining Walls

According to Peck (1972), flexible support structures are all supporting structures whose deformations induced by the pressure of the soil have a significant effect on the distribution of pressures as well as the magnitude of the pulses, bending moments and shear for that scale. The support structures are also often referred to as curtain or wall. There are several types of flexible support structures, which differ by its components as the materials and the constructive process. (Matos Fernandes M. A., 1983)

Flexible support structures can be anchored or shored depending on whether are used anchors or props, respectively, as a condition of support. The flexible support structure may have one or various levels of support, depending on the geometry adopted. It is also important to mention the great advantage in using anchors instead of props, due to the creation of a free space inside the excavation. That space allows that all construction works occur with greater ease and speed.

Regarding the materials used in the realization of such structures, there are several options, often by passing concrete, as is the case of bored piles, or by using metallic structures, such as sheet pile retaining walls. Other methods, more modern, are those that use grout for executing Cutter Soil Mixing panels or JetGrouting columns.

The performance of this type of structures has been very positive, as they have been highly competent as support and containment 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 (Matos Fernandes 1983).

Multi-anchored Retaining Walls

In the case of anchored curtains the problem of determining the pressures developed beneath the structure does not arise. The question here rests in the values for which scales the prestressing load is applied to the anchors. It is not proper to revise the maximum stress that will be submitted to the anchors, it is before adopting the prestressing to impose in each one so that the behaviour of the system, while supporting structure flexible multi-anchored, is the desired one. This behavior is measured through displacement of the flexible retaining structure presented during successive phases and at the end of excavation (Guerra N. M., 2007).

King Post Walls Retaining Walls

King Post walls are earth retaining structures and consist of metal profiles, usually HE series, whose spacing is defined in relation to height. Between those, profiles of wood or precast concrete panels are placed (Patrício & Teixeira, 2006). These types of retaining walls are temporary when the horizontal elements used are wood material, they are called Berlin walls. Although when the execution of the walls is made of reinforced
concrete panels, this final structure is called often by Munich walls. The former is usually used when the goal consists in earth retaining structures of fast execution, which may be or not reinforced with anchors, also temporary. Depending on the height of the containment structure, the function to which it is intended or the type of soil to retain, it may be necessary to perform one or more levels of ground anchors.

Bored Pile Walls

The bored piles curtains are constituted by a set of reinforced concreted piles connected to each other through a caping beam at the top and several distribution beams in depth, depending on the levels of ground anchors considered. The curtains piles can be performed according to various methods, including using the continuous flight auger or the Kelly bar with recoverable tube or bentonite slurry (Brito, 2002).

The use of these structures is intended primarily to support underground structures, including peripheral retaining walls, whose neighborhood conditions require special care because any disturbance may be critical. However bored piles curtains have other applications, such as slope stability or vertical support and foundation for the construction of tunnels in urban areas.

Cutter Soil Mixing Retaining Walls

The structure of peripheral retaining walls panels performed through soil-cement technology uses the Cutter Soil Mixing (CSM). However it is necessary to mention the Deep Soil Mixing technology (DSM) and their variants to enclose the CSM method.

Deep Soil Mixing is a method for treating the soil in depth without digging or spiking of prefabricated elements, whose purpose would be to increase its load capacity, waterproof and promote confinement, providing the ground new and improved mechanical features. This technique consists in introducing a binder, mixing it with soil and thus modifying its chemical and physical properties. This mixture is run through a vertical hollow shaft with a cutting tool at the end, which allows breaking down the soil and carrying the mixture at low pressure. In this process, the resulting elements are soil-cement columns that can generate the most varied geometries. The DSM method has two variants, the Deep Dry Mixing (DDM) and Deep Wet Mixing (WDM), whether the binder is injected dry or wet. In DDM the binder is injected in the form of powder and its transportation is provided from the tank to the ground through the use of compressed air. In the wet injection the binder, usually cement, is premixed with water to form a plaster fluid, which subsequently mix with the soil (Contente, 2012).

This leads to Cutter Soil Mixing technology as a variant of DSM, where the injection is given wet, combined with certain principles of operation of diaphragm walls. The main difference between the CSM and the DSM is the geometry of the elements executed. The former elements are rectangular pannels and the latter are columns, both of soil cement. Since the sections of the panels are rectangular CSM unions are much less overlap than the DSM elements. This retaining wall also has a sealing function that makes this technique very advantageous.

In all other cases the DSM machine rotates according to a vertical axis, as the CSM makes using equipment such as hidromill, similarly to the diaphragm walls, where the rotation of the gear wheels is made over a horizontal axis, allowing greater cutting capacity of the land.

Case Study: Alves Redol Car Parking

This section is intended to frame the case study of this thesis that it is the construction work of Alves Redol Street car parking, with three underground floors and two ramps. This study focused only in phases of execution of the excavation and peripheral temporary retaining structure.
According to the geotechnical design the section taken as reference in the study of the retaining wall was the closest to the Instituto Superior Técnico stone stairs, named C1 (see Figure 2). The main reason to focus this section was due to the displacements except in the retaining wall being the highest. Another reason was also the proximity with the stone stairs that were in use during all the excavation and construction works.

Geologic and Geotechnical Scenario

The geological and geotechnical conditions were determinate based on information obtained from two bore holes, S1 and S2. According to the information given by the bore hole S1 showed a deposit fill top layer, with approximately 3.2m, whose constitution was heterogeneous and the geotechnical characteristics were relatively weak. The information given by the bore hole S2 consists in a layer of 1.6 meters in clayed sands. Overlapping these two layers is the stone stairs pavement.

Below the deposit fill layers, according to the bore holes S1 and S2, were Miocene soils named “Prazeres clays and limestones” with thicknesses in the range of 16.9 and 18.3 m, respectively. The area of influence of the bore hole S2, the upper zone, consists of very stiff clays with some shell fragments, and interceded rust whose thickness is around 6 meters. According to the information probing the hole S1 below the silty clays, there are very compact clayed sands with a minimum thickness of 4.6 meters (Engiarte & Rodio, 2011).

Regarding the presence of ground water, according to available information, the groundwater table level was coincident with the bottom of the excavation, and therefore not expectable interfering with the work of containment.

Vicinity Constrains

The car park in Redol Alves Street is located in a densely urbanized area of Lisbon. This construction confronts North and South with Alves Redol Street and earth retaining walls of the Instituto Superior Técnico, approximately 3m high. The West constrains consists in João Crisóstomo Avenue. The East constrains are the stone stairs of Instituto Superior Técnico that are 8m high. As seen on Figure 3, there are also a centenary building and another building that is recent. The integrity of those structures must be considered during the excavation works but also during the construction of the bored piles retaining walls.

Instrumentation and Monitoring Plan

The Instrumentation and Monitoring Plan is a crucial tool in the execution of geotechnical structures. Once the flexible containment
structures are extremely sensitive to the displacements caused by the removal of soil or installation of support elements, it becomes essential to know and control their movements. This way this plan is thought since the design stage to ensure safety in the work by making a risk management associated with the constructive solution.

The installation of instrumentation is also essential when it comes to interventions in urban areas, as is the example of this case study due to the possible impacts on neighboring buildings. Some examples of significant impacts in this work are the sags in the streets or walks, the appearance of cracks or even worsening of those that already existed. For the latter purpose are then established criteria and to change alarm, whose purpose is to ensure that no excessive displacements are achieved in both containment structure as in neighboring buildings.

Monitoring besides the confirmation of the hypotheses considered in the design phase, also allows design optimization, with corrective actions due to possible unforeseen situations. The instrumentation plan to be considered as an investment security and, instead of more labor cost associated.

**Solution’s Modeling**

As mentioned before was used a finite element software (FEM): Plaxis 2D, to model the reference section. The results obtained through the software are a good approximation of reality. This happens because it’s possible to respect the model geometry as well as the structure or the geologic settings, and the same for the characterization of the mechanical parameters.

This modeling aims to compare the values of stresses and displacements obtained by a numerical calculation program, with the monitoring displacements. Another goal of this modeling is the calibration issue, considering the reference section, aiming a back analysis. The back analysis results consist in an improved geotechnical and real geotechnical scenario that allows studying other constructive solutions potentially more economical.

The modeling of this case study focused on one reference section of the retaining structure, as previously mentioned was the section that showed more horizontal displacement constraint. This section is about 14m high, and has two retaining structures, a wall of Berlin at the top followed by a bored pile curtain.

**Executed Solution**

The model used in Plaxis software to simulate the soil behavior was the Hardening Soil since it’s the model that replicates the soil response more precisely. In the Table 1 are the parameters used to characterize the soils.

<table>
<thead>
<tr>
<th>Hardening Soil parameters</th>
<th>Geotechnical Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fill Deposits</td>
</tr>
<tr>
<td></td>
<td>Stiff Clays</td>
</tr>
<tr>
<td></td>
<td>High Compacted</td>
</tr>
<tr>
<td></td>
<td>Clayed Sands</td>
</tr>
<tr>
<td>$Y_{unsat}$ [kN/m$^3$]</td>
<td>18 21 21</td>
</tr>
<tr>
<td>$\sigma^0_{ref}$ [kN/m$^2$]</td>
<td>30000 80000 120000</td>
</tr>
<tr>
<td>$\sigma^0_{oed}$ [kN/m$^2$]</td>
<td>30000 80000 120000</td>
</tr>
<tr>
<td>$\sigma^0_{ur}$ [kN/m$^2$]</td>
<td>90000 240000 360000</td>
</tr>
<tr>
<td>$c’$ [kN/m$^3$]</td>
<td>0 0 0</td>
</tr>
<tr>
<td>$\phi’$ [°]</td>
<td>30 20 36</td>
</tr>
<tr>
<td>$m$ [-]</td>
<td>0,5 0,5 0,5</td>
</tr>
<tr>
<td>$\Psi’$ [°]</td>
<td>0 0 0</td>
</tr>
<tr>
<td>Material type</td>
<td>Drained Undrained Drained</td>
</tr>
</tbody>
</table>
As seen in Figure 4 the soil layers were characterize based one the information given by the design and also the retaining walls and respective anchors were defined.

After defining the geometry and the model mechanical properties the next step are the Calculations and the Output results. Since the stairs don’t have an horizontal surface, the initial stresses were not generated considering the K0 procedure. Instead in the calculation process was created a phase, nominated Gravity Loading that generated the initial stresses in the soil before any construction work. After simulated all constructive process the displacements in the soil were obtained and shown in Figure 5 and Figure 6.

The deformations and stresses of the bored pile retaining wall were also studied, and the results were pretty similar to the instrumentation displacements. However the modeled results were much higher than the ones measured by the inclinometers and topographic targets. The back analysis was done based on this significant difference.

Back Analysis

This study was possible due to the installed instrumentation plan. Although only the instruments placed on the curtains that belong to the reference section were studied.

There were two topographic targets in the top of the bored piles retaining wall and two inclinometers, since this section is about 25m long.

The values obtained in Table 2 were the result of several attempts, by changing every value to understand the behavior of the soil.

The modeling process was similar to the executed solution. The geometry and the structures properties remained the same. What was constantly changed were the soil properties, mainly the Young Modulus, until the results provided by the modeling were the closest to the real ones measured by the instrumentation installed on the curtain and soil.
As seen on Figure 7 the grey line is much closer to the black line than the dashed line. The displacements happened around the same depth so the results were quite good.

These results allowed thinking that the executed solution could be improved, so some alternative solutions were considered and proposed.

### Alternative Solutions

Some alternative solutions were studied in order to understand if the adopted solution could be optimized. The first alternative solution consisted in the same bored piles curtain, but with different spacing between piles. Instead 1m apart now the piles are 1,5m apart. This solution was called SA1.

The second alternative solution named SA2 was thought based on the displacements obtain by the inclinometer. Since the displacement after the first anchor in the bored pile retaining wall was decreasing, the last level of anchors was not considered. In order to present an alternative to the bored pile curtain, it was considered a CSM retaining wall with three levels of anchors. This solution was named SA3. At last since the displacements obtained in SA3 modeling were below the real results, to optimize this solution the last level of anchor was removed. And this solution was called SA4.

The modeling process was the exact same one done in the executed solution and in the back analysis. Although the soil characterization used was the one pictured in Table 2, and the structural properties were calculated considering the geometry changes.

In the Figure 8 there are the graphics that show the displacements of each alternative solution, but also the initial modeling displacements and the back analysis results. Observing this graphics the solution that provides less displacements it SA3 and the SA2 is the one with higher displacement values. Although all the alternative solutions brought better values, considering that the executed solution refers to the displacements accepted as reasonable in the design stage.

### Table 2 - Parameters of the Hardening Soil Model Used in the Back Analysis.

<table>
<thead>
<tr>
<th>Hardening Soil parameters</th>
<th>Geotechnical Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fill Deposits</td>
</tr>
<tr>
<td>$\gamma_{unsat}$ [kN/m$^3$]</td>
<td>18</td>
</tr>
<tr>
<td>$E_{50}^{ref}$ [kN/m$^2$]</td>
<td>40000</td>
</tr>
<tr>
<td>$E_{oed}^{ref}$ [kN/m$^2$]</td>
<td>40000</td>
</tr>
<tr>
<td>$E_{ur}^{ref}$ [kN/m$^2$]</td>
<td>120000</td>
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<tr>
<td>$c'$ [kN/m$^3$]</td>
<td>0</td>
</tr>
<tr>
<td>$\phi'$ [°]</td>
<td>35</td>
</tr>
<tr>
<td>$m$ [-]</td>
<td>0,5</td>
</tr>
<tr>
<td>$\psi$ [°]</td>
<td>0</td>
</tr>
<tr>
<td>Material type</td>
<td>Drained</td>
</tr>
</tbody>
</table>

![Figure 7 - Back analysis horizontal displacement results.](image-url)
Economic and risk control analysis result

Besides considering the behaviour of the structure and the displacements shown, an economic analysis was done followed by a risk analysis. It is important to understand how important are the displacements on the curtain versus the cost of the structure and also the possible damages caused in near or sensitive buildings.

**Table 3 – Comparing alternatives.**

<table>
<thead>
<tr>
<th>Maximum horizontal displacements (mm)</th>
<th>Cost (€/m$^2$)</th>
<th>Damage control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executed solution</td>
<td>8,2</td>
<td>160</td>
</tr>
<tr>
<td>SA1</td>
<td>17,14</td>
<td>140</td>
</tr>
<tr>
<td>SA2</td>
<td>25,49</td>
<td>159</td>
</tr>
<tr>
<td>SA3</td>
<td>6,72</td>
<td>196</td>
</tr>
<tr>
<td>SA4</td>
<td>16,41</td>
<td>171</td>
</tr>
</tbody>
</table>

Considering the data presented in Table 3, it can be seen that the SA1 is the most economically advantageous solution, and presents possible damage to neighboring structures characterized as negligible. However it is not the solution that has lower horizontal displacements in the earth retaining curtain.

The solution SA2 is one whose analysis provided the risk of damage to the surroundings as very slight, rather than negligible. However the parameters that characterize the very slight damage yet are very small and can be considered insignificant in a structure as are those stairs. Regarding the displacements shown by the curtain this solution provides the higher displacements. Although this solution compared with SA1 is not competitive at all since the latter has lower displacements, cost and lower damage control.

Regarding the solution SA4, the SA2 only present more viability if there were no neighboring structures, or the movements of the curtain were not all constraints. This is because the difference in
price per square meter of wall is about 12€/m². This solution would not be appropriated for all densely urban areas, compared to other alternatives presented in Table 3.

The solution SA3 is very competitive from the standpoint of displacement the curtain displays. However it is the most expensive solution per square meter of wall. Regarding possible damage to neighboring buildings, this solution like the SA1 presents a classification of damage to neighboring buildings as negligible, so this factor is not an asset in this case.

Similarly to SA3, SA4 is an optimization of the former. However the removal of a level of anchors promotes an increase of the displacements of the structure, more than double the SA3, saving about € 25/m² per square meter of wall. As regards possible damage to adjacent structures they are considered negligible, so this is not a decisive factor when choosing between solutions. In a situation where the vicinity is not a constraint this solution can promote significant economic savings.

Thus the two solutions studied, the curtain wall bored piles and CSM wall as well as their variants or optimizations, it is considered unreasonable to assume that the overall containment solution that uses bored piles is more economical. In contrast, the solutions that involves a wall CSM is further directed to articles whose containment structure includes the final solution, because their displacements are negligible.

In this study case the option SA1 would be quite relevant since analyzing the displacement of this solution compared to the solution performed was still able to gain an advantage over this. Regarding the costs is economically advantageous because it only differs in geometry, the piles are more spaced. In relation to the damage, the possible cracks that could appear in the stair could be perfectly accommodated by the structure without risking the service limit states.

**Conclusions**

It is possible to give an overview of this work, considering the objectives proposed initially described. In general the studies and analyzes proposed in the objectives were achieved and the results were satisfactory.

The first objective described contributed to increase the knowledge about the behaviour of flexible containment structures in urban areas, whose main tool was a computer program which uses the finite element method, the *Plaxis 2D*. Also under perceive the functioning of this type of retaining wall stands out the possibility that it was able to follow the work in all the processes of construction and excavation. This follow-up allowed verifying that the technology executed was fast implementation and practice.

The implementation of the monitoring and observation plan was very important, since the results obtained allowed all the calibration of the numerical modeling, back analysis and the development of alternative solutions. This plan proved to be a great investment rather than a cost as might seem in the beginning. This plan led to very efficient management of constructive timing and safety in the work. Once installed, instrumentation allows knowing the structure movements in all phases of the construction process. Therefore it is possible to perform a controlled management of risk. Even mentioning the advantages of the plan of instrumentation and monitoring, since topographic targets were installed in adjacent buildings, it was possible to perceive and control the effects caused by digging these. However, according to the measured movements of the targets may be said that the solution was very competent performed on soils containing, as demonstrated no visible damage nearby.

Regarding the implementation of the bored piles curtain, this constructive solution presented a very satisfactory behaviour and horizontal displacements. This structure showed good performance either during the construction process or at the end of the excavation where the measured maximum displacement was about 8 mm which is 0.06% of the total height of the excavation. This value is very satisfactory for this type of retaining wall and respects the serviceability limit states.

It also noted the use of numeric calculation program that uses the theory of finite elements,
the Plaxis 2D was crucial in this work. This software allowed for the modeling of the solution running, the shaping of the parametric analysis of soil, back analysis, and finally the entire study of alternative solutions. It was through the displacement results obtained from the program that was possible to compare the model movements with actual movements, measured by instruments installed in the wall. Then through this comparative analysis it was found that the movements were significantly higher than those set initially.

Based on this comparative analysis of the movements made by the FEM analysis in relation to measured instrumentation, it was found that the soil parameters adopted initially were quite conservative. So based on the information provided by the program for the soil was observed that parameters could be optimized in order to bring the maximum results of numerical modeling with actual results. Were then altered the modulus of elasticity and internal friction angle. With these changes it was possible to achieve results very close to the actual, especially in relation to the maximum displacements measured. The maximum displacements were measured considering the maximum value measured by the inclinometer and a topographic target, located on top of the curtain.

In order to show some alternative solutions, the first two could be considered as a solution to the optimization runs and the last two consist of CSM walls reinforced inside with metal profiles. Despite the constructive methodology be quite different in the two solutions, not to mention the rigid quality control panels CSM, this solution was the one that presented the most competitive on the speed of execution, cost of construction and structural performance. The CSM wall reinforced with metal profiles showed the curtain displacement and a deformed configuration slightly different.

It was found that a solution that considers the execution of curtains spaced piles of 1.5 m is the most economic, due to the walls of CSM profiles. The CSM solutions are about 20% to 25% more expensive than the curtain poles spaced 1.5 m, and despite being a difference still reasonable, it was hoped to obtain a solution in CSM extremely economic. It was found that the solution executed could have been optimized, spacing the piles 1.5 m instead of 1 m and that the horizontal displacements were still expected to be lower than those permitted in the design phase. Note that the location of maximum displacement of SA1 occurs at about the same height of the maximum observed.

The Cutter Soil Mixing technology seems to be growing in Portugal since were found several construction works on sites where this technique was successfully employed. This solution showed great advantages as a retaining wall exhibiting smaller deformations than those provided by the bored piles solutions.

References