Analysis of excavations and peripheral retaining wall structures in urban areas

Case study: Residential building in *Rua do Benformoso*, in Lisbon

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Abstract: In recent years there has been a growing need to take advantage of the urban underground space to create new structures and infrastructures, especially in noble and historic city zones. The use of deep excavations and peripheral earth retaining walls is a common way to address this issue and to maximize the occupation of those spaces.

In this context, the current thesis presents a case study of an excavation and earth retaining walls for the construction of a residential building located at *Rua Benformoso* (*Largo do Intendente*), in Lisbon's downtown. The monitoring/supervision of this project included the analysis of the adopted solutions to stabilize the centenary building original façades, as well as the analysis of the constructive procedures adopted for the excavations and peripheral retaining walls (Berlin-type retaining walls and reinforced concrete walls with buttresses). This analysis allowed the conclusion that these techniques are greatly dependent on the ground geological and geotechnical properties, as well as the construction process.

A numerical model was developed using the finite element software, Plaxis 2D, in order to analyse the behaviour of retaining walls structures. This numerical model was validated with topographic measurements of the retaining wall structures on the construction site.Additionally, numerical models of alternative solutions were also developed, and their results were compared with the performance of the adopted solutions. At the end, all the alternatives solutions proved to verify both ultimate and serviceability limit states (displacements and limit stress requirements typical for these type of structures), and therefore could also be considered as a possible solution.

Keywords: Excavations; Historic building façades; Peripheral retaining wall; Numerical modelling.

1. Introduction

Usually, there is a high demand to maximize the utilization of urban areas in historic cities. This demand leads to taking advantage of the underground spaces to create new structures such as basements or underground car parks. To do so, there is an unavoidable need to rely on excavations and peripheral retaining walls to explore the buildings in underground spaces. These buildings, sometimes of some historical value, need to be preserved. Hence, façade stabilization structures need to be taken into account, during the construction phase, in order to maintain the identity and exterior façades of the buildings.

Ground anchors are widely used as additional supports to the retaining walls providing an efficient way to control the displacements of such retaining walls. However, after finishing the construction, these tempurary ground anchors are no longer needed as the slubs at those levels provide sufficient diaphragm effect to bruce the underground peripheral walls of the building.

The current document presents a case study related to the construction of a residential building located in Rua Benformoso (Largo do Intendente), in Lisbon's downtown. This building is situated in an historic urban area and its construction took into account several of the above mentioned constraints, typical for these types of interventions. During the construction of the building it was possible to monitor and analyse the adopted solution to stabilize its façades and to study the constructive procedure of the excavations and the peripheral retaining walls (Berlin-type retaining walls and reinforced concrete walls with buttress).

Additionally, numerical models were developed using the finite elements model Plaxis 2D to recreate some sections of the peripheral retaining walls of the studied building. These models were validated with topographic measurements made on the construction site, during different construction phases.

Several alternative solutions to the retaining walls used in the construction project were studied. These alternative solutions present different types of retaining walls and supporting elements, and were defined in order to optimize the retaining wall structure adopted in the studied building. An optimized solution should present lower displacements and lower economic costs. Numerical models were developed to study those alternative solutions and an economic analysis was performed. These alternative solutions were designed in accordance with Eurocode 7 and comply with the Ultimate Limit States (ULS) and Serviceability Limit States (SLS), present in that document.

A brief state of the art of the rehabilitation in urban areas, of the excavations and the retaining walls used in such projects is presented in section 2 of this document.

The case study, including the analysis of the adopted solutions and the monitoring of the wall's performance, are presented in section 3 of this document.

Section 4 presents the numerical analysis of both the adopted and alternative solutions, while section 5 presents a comparative analysis of those solutions, comprising structural performance indicators as well as an economical analysis.

At last, section 6 presents the main conclusions that derived from this work, and a suggestion for future developments in this area.

2. State of the Art

This state of the art is dived into the following subsections: (i) rehabilitation of old buildings in urban areas; (ii) the use of gound anchors in peripheral retaining wall structures; (iii) flexible retaining walls; (iv) construction technologies of peripheral retaining walls, an (v) excavation support structures.

2.1 Rehabilitation of old buildings in urban areas

The urban rehabilitation in historic city zones presents an increasing trend and is deemed as the future of construction in these historic areas [1]. This consideration stems from the need to rehabilitate degraded old buildings in generally made of stone masonry walls, or even moderately old buildings made of reinforced concrete, that present severe degradation at to the structural elements.

The main key aspects regarding these interventions are geological and geotechnical aspects of the surroundings. As expected, there is a high concern about the performance of these solutions, as they can influence the behaviour of the surrounding structures.

One of the first precautions of these interventions is the preservation of the facades of the buildings, due to their inherent historical value. As expected, this need only appears in areas that are classified of national interest or historic value.

The basis of these rehabilitations are, not only the preservation of the built patrimony, but also the optimization of the human occupation in those areas. In order to do so, it is common to use underground spaces to create new structures with the use of excavations and construction of retaining walls, which requiring certain precautions that are discussed in detail in the following subsections.

2.2 The use of anchors in peripheral retaining wall structures

The use of ground anchors started to appear in the 1960's, after the World War II. Its usage in retaining walls allowed a reduction of the soil (deformations), which justified its widespread adoption in this context.

These anchors are considered as a support for excavation activities, and present as main goal the restraint of the displacements of retaining walls. The anchors can be either permanent or temporary, depending on the removal of the tension of the anchors tension loud, after the end of the construction project. The use of permanent anchors is reducing, as it is difficult to maintain and monitor them, in the long term, and as there are several hazards that come from their occupation of the soil, beneath surrounding structures.

The presence of anchors in urban areas is creating difficulties in the construction of new structures, as they occupy space of adjacent terrains and difficult any excavation activities.

Due to these restrictions, it has become necessary to study alternative solutions such as: (i) slab bands; (ii) struts, and (iii) partially removable ground anchors.

The partially removable ground anchors are different from the permanent ground anchors, as it is possible to remove the tensioned steel cables, and only the bonded length of the tendon is left in the soil.

Two different partially removable ground anchor systems were analysed in this context: (i) DYWIDAG system [2], and (ii) VSL Ground system [3].

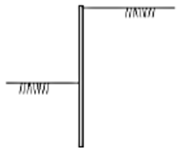
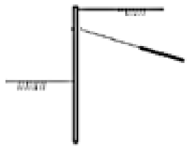
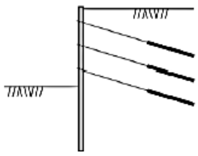
2.3 Flexible retaining walls

The retaining wall structures are used to optimize the space occupation of the underground floors. In this sense, these structures are designed to occupy the building overall area, whilst supporting the surrounding soils, water or rocks. The permanent loads of the retaining walls can be ignored, and they behave mainly to bending. The acting soil pressures for the design of these elements depend mainly on the flexibility and boundary conditions of the walls [4].

Table 1 presents three different types of embedded flexible retaining walls.

The most commonly used retaining wall type for the construction of underground floors is the Multi-supported flexible retaining wall, which was used in the present case study. These retaining walls may take advantage of passive supporting elements (struts) or of active supporting elements (ground anchors) in order to control lateral displacements.

Table 1 – Different types of embedded flexible retaining walls [EC7].

Embedded retaining wall type	Schematic representation
Cantilever wall	
Single-support wall	
Multi-support wall	

The behaviour of these structures depends on the behaviour and properties of the surrounding soil. In order to determine the earth pressures acting on wall, the following theories were used: (i) Mohr-Coulomb theory, (ii) apparent lateral earth pressure distribution theory, by Terzaghi and Peck.

The Mohr-Coulomb theory allows the estimation of the earth pressures acting on the retaining walls. This theory assumes the existence of a rotation at the base of the structure or a lateral displacement of the whole structure.

Terzaghi and Peck developed a theory to determine the apparent lateral earth pressure distribution due to the existing limitations of the Mohr-Coulomb theory, and in order to determine the acting pressure of flexible retaining walls with horizontal braces.

The diagrams of the apparent lateral earth pressure distribution may vary, depending on the soil type, and allow the estimation the loads acting on the braces.

2.4 Construction technologies of peripheral retaining walls

Some construction technologies of peripheral retaining walls were analysed: (i) berlin-type definitive retaining walls; (ii) piled retaining walls, (iii) reinforced concrete walls with buttress.

The berlin type wall is a flexible retaining wall, consisting of reinforced concrete panels beeing constructed in several phases. These walls are usually supported by steel profiles or micropiles and can also be anchored or braced with struts. They act as means of transmitting vertical loads to the soil [6]. This solution is adequate to cohesoil soils and requires the monitoring of the displacements of the supported soil, because it is generally used in the proximity of other buildings.

The piled retaining walls are composed by a series of piles, to be concreted on site, against the soil, and are connected with each other by a top reinforced concrete beam and a lower distribution reinforced concrete beam. The stabilization of the piled retaining walls can be performed with struts and ground anchors.

The reinforced concrete walls with buttresses are considered to be a stiff retaining wall solution. They are made of regular reinforced concrete and they have a wide support base. In this type of solution the wall has three supports borders, enabling a higher stiffness when compared to the others. The main advantage of these structures is the lower associated construction cost, when dealing with significantly high retaining walls.

2.5 Excavation support structures

This subsection identifies the excavation support structures that can be used when constructing retaining walls. These support structures compress the wall against the soil, resisting to the soil pressures, and stabilizing the wall. There are three types of excavation support structures: (i) struts; (ii) ground anchors, and (iii) slab bands.

These structures help mitigate the horizontal displacements of both the walls and the supported soils.

Struts are a simple and effective method for supporting structures during excavations. They are considered to be temporary elements, as they may be removed when they are no longer needed. They only resist to compressive stresses and should be braced properly. They are mainly used in corners, supporting adjacent and perpendicular walls.

The ground anchors are usually used to restrain the horizontal displacements of flexible retaining walls. The pre-stress is applied to the steel tendons, enabling the anchor to transmit such stresses to soil, by friction through the bonded length of the tendon. These anchors can be either permanent or temporary.

The slab bands are not described in this document, as they were not used in the case study.

3. Case study: Residential building at *Rua do Benformoso*, in Lisbon

3.1 Location and brief description

The case study refers to a rehabilitation intervention on a residential building in Lisbon. The building is located at nº 278-294 of Rua do Benformoso, at Largo do Intendente, and it is presented in Figure 1. Since 2012, this area has been a target of several rehabilitation interventions.

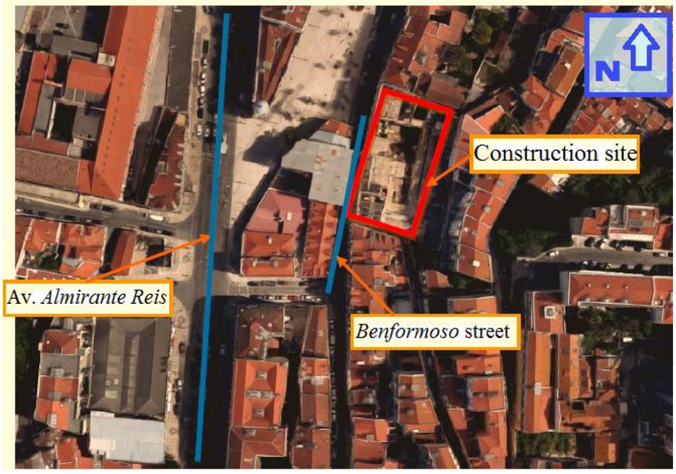


Figure 1 – Location of the residential building.

In this construction project there was the need to preserve the façades of the building with the use of a steel retaining structure. This project also contemplated the demolition of the interior building structure. In these cases, the façades remain identical to the original ones, and a totally new structure is constructed in the interior areas of the building. For this construction project, the implantation area was of about 1795 m^2. The building had six floors above the ground. In plant, this building has a U shaped format, with transversely irregular elevation of the floor levels. At the beginning of the monitoring of this construction project only the façades remained erected and some alignments of stone masonry walls that were responsible to retain some soil volumes. At these stages, most of the interior building structure had already been demolished, and all the demolition activities were concluded.

3.2 Constraints

This construction project had three types of constraints: (i) construction process constraints; (ii) geological and geotechnical constraints; (iii) urban envelope constraints.

The residential building is located in an area that is considered to be of national interest, by the *Direção Geral o Património Cultural*. Hence, there was the need to preserve the original façades of the building to maintain the historic value and identity. The urbanistic rehabilitation operations are currently specified on a website of Lisbon's' Municipal Council [7], which allows the creation of new openings or modification of spans of the new structure at ground level. These guidelines also impose that any architectural element of historic and patrimonial value should be preserved.

Regarding the geotechnical and geological constraints, it's necessary to establish that the building is located at the right side of an underground river stream. The building is located at the base of a hill, with a steep inclinator. The lithostratigraphic constraints were determined, based on the geological map. A Miocene rock formation, made of limestone from Entrecampos, was identified beneath the location of the building. This rock formation is covered by a controlled backfill layer.

Regarding the geotechnical characterization of the rock layers, geological site investigation surveys were performed in 2016. These surveys included: (i) five boreholes with Standard Penetration Tests (SPT), (ii) six shifts, and (iii) water level reading with a piezometer. The water level reading verified that no aquifer passed beneath the construction area. Based on the results of the geological prospection surveys, five geotechnical layers were identified. The properties of those layers are presented in Table 2.

Considering the urban envelope, the proposed solutions were designed in order to minimize the interference of the construction activities with regular activities of the neighbourhood buildings. In order to guarantee that consideration, instrumentation and monitoring campaigns were conducted.

3.1 Façade stabilization structure

The façade stabilization structure was a structure, made of steel profiles (UNP120) that were fixed to several lattice steel towers, along the façade of the building. This is considered to be a temporary structure, which supports the façade of the building, until the new interior building structure is constructed. At the corners of the façade, the structure was strengthened with diagonal steel struts, which connected perpendicular façade walls.

Figure 2 presents the façade stabilization structure during the excavation works, seen from the interior of the building area.

Table 2 – Properties of the geotechnical layers.

Layer	N_{SPT}	Ø' [°]	C' [kPa]	γ[kN/m^2]	E [MPa]
G1	1 - 5	25	0 - 5	16-17	<40
G2	30-60	25-30	5-10	19-20	80-200
G3	>60	25-30	10-20	20-21	200-300
G4	≥ 60	25-30	20-40	21-22	300-400
G5	>60	42-45	30-50	22-23	400-500

Figure 2 – Façade stabilization structure.

3.2 Peripheral retaining walls

The peripheral retaining walls were built through the definitive berlin type methodology, at the underground levels (MS2 and MS3 zones). The MS1 and MS2 zones had a retaining wall of reinforced concrete, with buttresses.

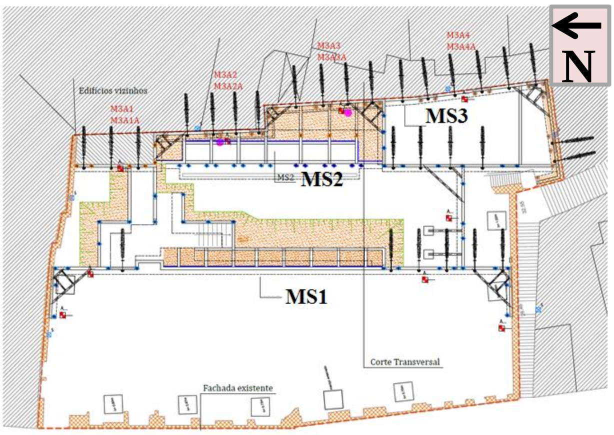


Figure 3 – Peripheral retaining wall zones.

3.2.1 Retaining wall solution for underground floors

As previously stated, a berlin type definitive wall was chosen for this zone. The Berlin type wall presents a top reinforced concrete beam that connects all the micropiles, and allows them to function as a whole. As expected, this beam is responsible to reduce the horizontal displacements of the piles and the wall panels to be constructed. Usually, the excavation activities start after the construction of that top beam.

The micropiles steel tubes (ϕ127×9 mm and ϕ139.7×9 mm) were executed close to the alignment of the retaining wall, and they were fixed to the wall with steel elements, along their height.

The berlin wall was constructed in three different phases, starting from the top to the bottom, with wall panels of reinforced concrete with 0.3 m thickness. These panels were concreted directly against the soil and they were connected to the micropiles. When necessary, temporary ground anchors were installed and the tendons pre-stressed during the construction of the walls. These ground anchors and additional diagonal struts applied to the corners were responsible by the stabilization of the retaining walls.

3.2.2 Retaining wall solution for the public area

The retaining wall solution for the public area was built by reinforced concrete walls with buttresses. This solution was chosen for this area due to the impossibility to consider ground anchors, at this level. This retaining wall was supported on micropiles, similarly to the berlin type retaining wall. The MS2 zone retaining wall is the only connected to the berlin type retaining wall.

The execution of these walls comprised, primarily, the construction of the footings. The reinforced concrete wall panels and the buttresses were constructed with the traditional method. The buttresses of the MS2 zone had a nominal thickness of 0.30 m (equal to the walls), a height of 7.8 m and were spaced 3 m apart. While, the buttress of the MS1 zone had the same thickness and spacing, but a different height of 5.1 m.

3.3 Instrumentation and monitoring plan

The instrumentation and monitoring plan was designed in order to manage the uncertainties of the soil properties, as well as the risks associated with excessive deformation of the retaining wall structures during the construction project.

The instrumentation plan focussed on monitoring the following parameters: (i) vertical and horizontal displacements of the retaining wall structures and of the neighbourhood buildings; (ii) loads at the ground anchors tendons; (iii) vibrations at the neighbourhood buildings. The parameters were measured with the help of topographic targets, load cells and a seismograph.

These measured values were constantly compared certain warning and alarm criteria. The warning criteria were the following: (i) maximum horizontal displacement of 25 mm/ 10 m of gradient; (ii) maximum vertical displacement of 15 mm/ 10 m of gradiend, and (iii) maximum difference of 10% on the pre-stress of the ground anchors. The alarm criteria, which more demanding that the warning criteria, were the following: (i) maximum horizontal displacement of 40 mm/ 10 m of ground anchors; (ii) maximum vertical displacement of 30 mm/ 10 m of depth, and (iii) maximum difference of the pre-stress of 20%.

4. Numerical analysis

This section presents the numerical analysis developed with Plaxis 2D software, in order to simulate the behaviour of the retaining wall structures present in the construction project of the case study. The Plaxis 2D software is widely used to perform geotechnical analysis and allows stress-strain analysis of both soil and of the retaining structures.

4.1 Model description

This subsection provides a brief description of the numerical models developed. It is relevant to point out that the model assumes a plane strain state, as expected of these types of analysis where one dimension of the element (depth of the wall and soil) is much larger than the other two dimensions (dimensions of a section cut of the wall). The hardening soil model was used, which is based on the Mohr-Coulomb, assuming a non-linear stress-strain relationship.

Two section cuts were modelled during this analysis and are presented in Figure 4. The section 1 (S1) refers to a section cut of a berlin type retaining wall on the MS3 zone, while section 2 (S2) refers to a section cut that comprises three different berlin type retaining walls of the MS1, MS2 and MS3 zones.

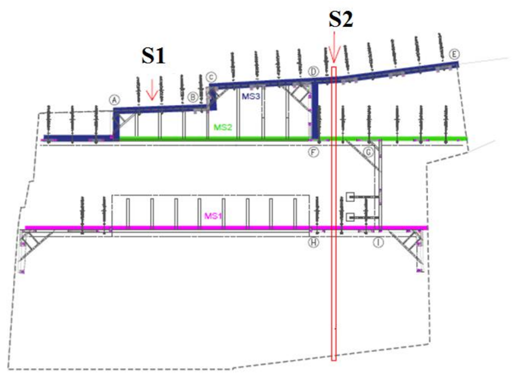


Figure 4 – Sections modelled in this numerical analysis.

4.1.1 Geometrical properties, mesh and discretization

In this analysis, the soil was modelled with triangular shaped elements of 15 nodes and the walls were modelled with plate elements that considered three degrees of freedom for each node and had 5 nodes. The ground anchors were modelled with two different linear elements: (i) the node-to-node anchor to simulate the unbonded length of the tendon (acting as a spring), and (ii) a geogrid element to simulate the bonded length of the tendon. The micropiles were modelled with a plate element, similarly to the walls.

Five differently refined meshes were automatically generated by the software. A mesh sensitivity study was performed and even the coarse meshes retrieved good results. As an example, Figure 5 presents the adopted mesh, with a fine refinement near the wall elements

The dimension of the modelling window was a relevant factor to the precision of this analysis. Hence, a study was performed regarding this aspect and it was concluded that a modelling window of 80×35 m^2 was sufficient.

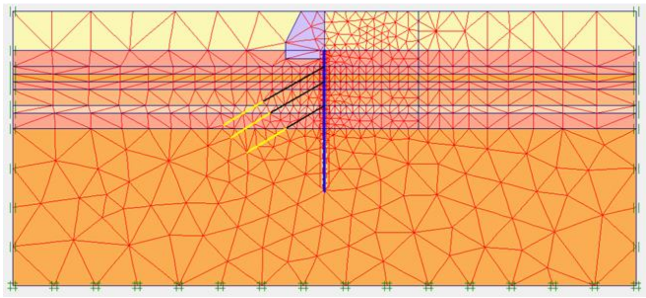


Figure 5 – Finite elements mesh with medium refinement and a fine refinement near the wall elements.

4.1.2 Mechanical properties

The Hardening soil parameters of the geotechnical layers are presented in Table 3.

The Berlin retaining wall was modelled with: (i) an axial stiffness per meter of depth of EA/m = 9.00×106 kN/m; (ii) a bending stiffness of EI/m = 6.75×105 kN.m^2/m; and (iii) a weight of W/m = 7.2 kN/m/m.

The micropiles were modelled with: (i) an axial stiffness of EA/m = 6.5×105 kN/m; (ii) a bending stiffness per meter of depth of EI/m = 1.127×103 kN.m^2/m; and (iii) a weight of W/m = 7.35×10-4 kN/m/m.

4.1.3 Loading and support conditions

Lateral sliding supports were considered on the sides of the modelled window, allowing vertical displacements over those limits but restricting horizontal displacements. A horizontal sliding support was considered on the bottom surface of the model.

In order to represent the action of the neighbourhood building at the soil, a load of 10 kN/m^2 was considered for each floor above the ground, totalling a uniformly distributed load of 50 kN/m^2 , acting at the soil surface.

4.2 Main results

The numerical models allowed the estimation of the of the retaining walls displacements. After, these numerical results were compared with the warning and alarm criteria, which are presented at Table 4. As a simplification, the soil criteria were considered the same as the retaining wall criteria. In this subsection, the deformations, the stresses and the displacements of different construction phases, will be analysed in detail for the S1 and S2 retaining wall sections.

Table 3 – Geotechnical layer properties.

Hardening Soil parameters	G1	G2	G3	G4	G5
Υ_{unsat} [kN/m3]	17	20	21	22	23
$E_{50\ ref}$ [kN/m2]	35000	120 000	250 000	350 000	400 000
$E_{oed\ ref}$ [kN/m2]	35000	120 000	250 000	350 000	400 000
$E_{ur\ ref}$ [kN/m2]	105000	360 000	750 000	1 000 000	1 200 000
c´ [kN/m2]	0	7	15	30	40
Φ´[º]	29	30	30	30	43
Ψ [º]	0	0	0	0	0
M [-]	1	0,5	0,5	0,5	0,5
Material type	Drained	Drained	Drained	Drained	Drained
R_{inter}	0,7	0,7	0,7	0,7	0,7

Table 4 – Warning and alarm criteria.

Displacement	Warning	Alarm	
δ_h, retaining wall	25	40	mm
δ_v, retaining wall	15	30	mm
δ_h, soil	25	40	mm
δ_v, soil	15	30	mm

4.2.1 Section 1 (S1)

Figure 6 presents the numerical results of the horizontal displacements of soil close to S1, where it is possible to observe that the maximum displacement (16.8 mm) occurs at close to the top of the wall. From the top to the bottom of the wall, the horizontal displacements of the soil decrease. The positive displacements are presented in the interior of the excavation. The maximum vertical displacement of about 12 mm occurred in the alignment of the retaining wall structure, along its height. Upwards vertical displacements were observed at the base of the excavation, due to the reduction of weight of the soil that was removed.

The maximum horizontal displacement of the retaining wall structure S1 was of 12.3 mm and occurred at the top of the element. The maximum horizontal displacement of the soil is higher than that of the retaining wall because it was measured at a height of 5 m above the top of the wall.

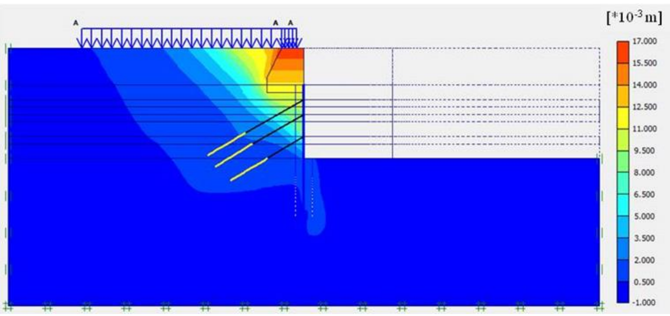


Figure 6 – Horizontal displacements of the soil around the retaining wall S1.

Figure 7 presents the displacements of the retaining wall structure S1 during the construction process, at different construction phases, at the end of each phase.

During the 1st phase of the construction process, after the first excavation, the wall deformed towards the excavation zone due to the stress release caused by the extraction of the soil excavation. During the tensioning of the ground anchors, the wall structure is pulled towards the soil, and almost went back to the initial position. The next phases of excavation and ground anchor tensioning, the wall did not recover to the initial position, and the displacement tended to increase. The maximum displacements occurred between the third excavation and the tensioning of the third ground anchor, which means that the structure rotate with a pivot at the second anchor level, which caused an increase on the displacements of the top of the wall. To sum up, during the constructive process the retaining wall shows a rotational and translational motions due to the relief of stress cause by the excavation and due to the action, of the anchors are prestress.

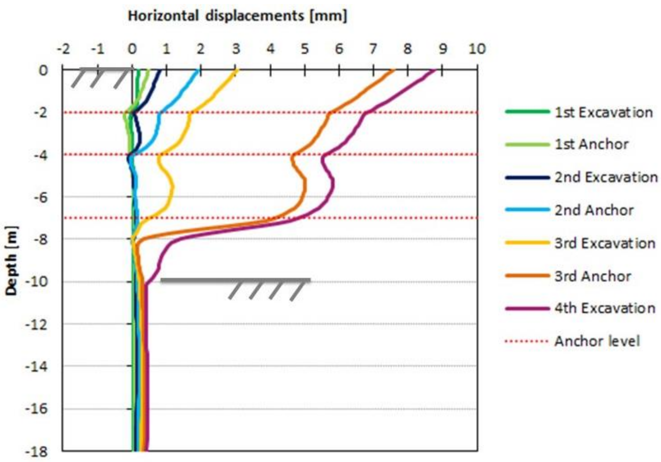


Figure 7 – Displacements of the retaining wall during the construction process.

Figure 8 presents the axial force, the shear force and the bending moment diagrams experienced by the retaining wall S1. The maximum axial force occurs at the 3rd level of anchors and was 662.8 kN/m. In the axial force diagram it is possible to observe three discontinuities at each anchor level. Below the blue line in the diagram, the micropiles are able to transmit by friction the axial force to the soil. The axial force reduces to close to zero values at the bottom end of the micropiles, proving the efficacy of load transmission by lateral friction with the soil.

Regarding the shear forces diagram, it was possible to observe three discontinuities related to the horizontal component of the anchors ground, acting on the retaining wall. Lastly, the bending moment diagram presented a maximum value at above the 3rd anchor level. The maximum value occurs at that height because the soil pressure is higher at that depth and the distance between anchors (2nd and 3rd) is higher.

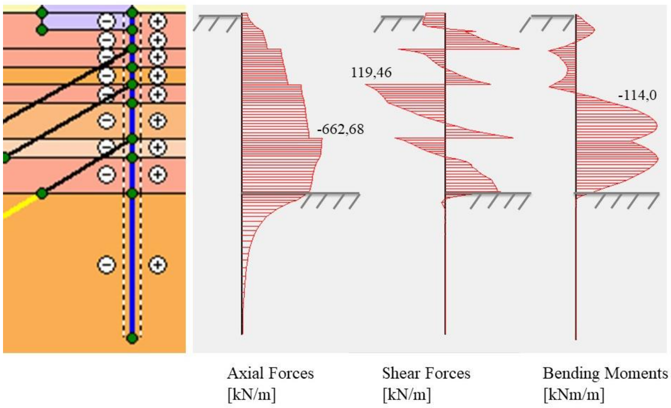


Figure 8 – Axial forces, shear forces and bending moments of the retaining wall structure S1.

4.2.2 Section 2 (S2)

S2 refers to a retain wall zone composed by three different walls, which confer a higher bending stiffness, leading to being easier to perform a multiple bench excavation than a vertical excavation. The analysis method for S2 was similar to the S1. Figure 9 presents the numerical results of the horizontal displacements of soil close to S2, with a maximum of 10.7 mm, near the top of the wall MS2.

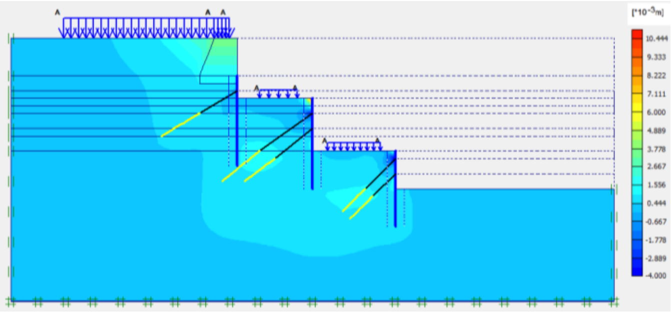


Figure 9 – Horizontal displacements of the soil around the retaining wall S2.

The maximum axial forces, shear forces and bending moments for each wall of S2 retaining wall are presented in Table 5.

Table 5 – Maximum axial forces, shear forces and bending moments.

Wall [-]	N [kN/m]	V [kN/m]	M [kNm/m]
MS3	-232,19	-353,22	-168,09
MS2	-383,69	395,59	201,50
MS1	-445,01	269,03	82,49

4.2.3 Soil stresses

The stress field of the soil, namely the vertical stresses (σyy) and the tangential stresses (σxy), was also analysed and the maximum values, for both sections (S1 and S2), are presented in Table 6.

Table 6 – Vertical and tangential stresses of the soil.

Section [-]	σ_{yy} [kN/m^2]	σ_{xy} [kN/m^2]
S1	766,35	176,50
S2	761,47	126,50

4.3 Numerical results *vs. in situ* instrumentation

This subsection presents a comparison of the results of the numerical model, in terms of displacements, with the results of the instrumentation plan that measured displacements of the structures throughout the construction process. Not all the instrumentation data was available. Figure 10 presents the instrumentation data (displacements) of the S1 wall during the construction phase. According to these measurements the maximum displacement of the S1 wall (M3A1 – measure at the top of the wall) was around 11 mm, similar to the displacement predicted through by the numerical model, thus validating its results.

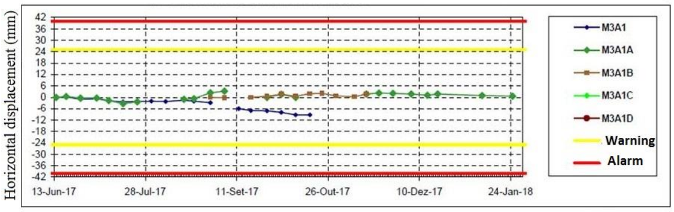


Figure 10 – Horizontal displacements obtained from topographic measurements.

4.4 Alternative solutions results

Five alternative solutions to the S1 wall with different ground anchor levels and wall types where analysed with numerical models and the results where compared. Table 7 presents the modifications of the S1 wall that lead to the definition of the alternative solutions studied in this subsection. Solution A2 comprised two different inclinations and loads of the anchors. These solutions were designed considering the corresponding ULS and SLS, and were studied in detail regarding: (i) displacements along the height of the wall;

(ii) forces and moment acting on the wall (axial, shear and bending), and (iii) stress field of the soil.

Table 7 – Alternative solutions.

Solution	Modification
A1	2 anchors (-1)
A2	2 anchors (-1) different pre-tension & inclination
B1	RC wall with buttresses (spaced 3 m)
B2	RC wall with buttresses (spaced 4.5 m)
C	Piled wall (ϕ=0.8 m and ΔL=1.2 m)

Table 8 presents a comparison of the wall and soil displacements of the alternative solutions with the ones of the adopted solution and the warning and alarm criteria. As expected, all the solutions verified the warning and alarm criteria, proving their application in such context. Solution B1 presented the lowest wall horizontal displacement, due to the high stiffness provided by the buttresses. Solution C presented the lowest soil horizontal displacement as it was the solution that provided a more continuous support to the soil. The removal of one level of anchors in alternative solution A1 caused an increase in displacement of the soil and the wall. Solution A1 was the only alternative solution that presented a lower performance than the adopted solution.

Figure 11 presents a comparison of the final horizontal displacements of the alternative solutions with the adopted one and the warning criteria. It is important to stress that the displacements of all the alternative solutions and the adopted one are far below the warning criteria.

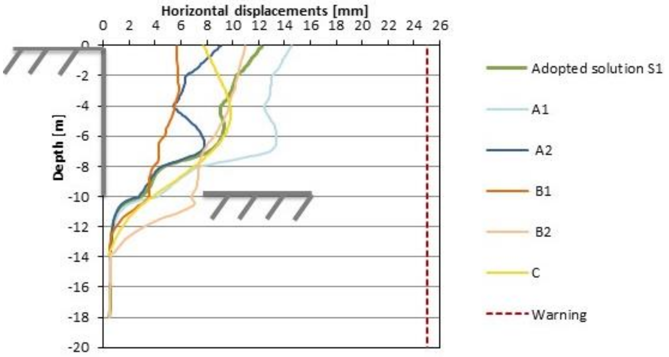


Figure 11 – Comparison of the horizontal displacements of the alternative solutions with the adopted one

Table 9 presents a comparison of the vertical and tangential maximum stresses of the soil for the alternative solutions with the adopted one.

The maximum soil stresses occur at the bottom of the model for all the alternative solutions, with the exception of the piled wall, where the maximum stresses occur at the base of the piles and gets distributed in the surrounding soil. Solution A1 and A2 present lower vertical stress values due to the removal of one ground anchor level.

The alternative solution B1 and B2, being made of reinforced concrete walls, have greater weight and smaller cross sections and thus present greater values of vertical stresses than the adopted solution. Lastly, solution C presents the highest value of vertical stresses for it is the one that presents the highest weight, inherent to the construction process. The maximum tangential stresses present in Table 9 all occur at the bottom of the wall, on the excavation side. There is no significant differences on the tangential stresses presented by the studied solutions.

5. Comparative analysis of the alternative solutions with the adopted one

The economic comparative analysis is important as it allows the comparison of the costs of each alternative solution. This analysis refers to the section S1 only. This section presents a width (in plan) of 12.5 m and an excavation height of 10 m. The calculation of the cost of the definitive berlin retaining wall solutions (adopted, A1 and A2) considered the following costs of: (i) concrete (100 €/m^3); (ii) steel rebars (1 €/kg); (iii) formwork (25 €/m^2); (iv) footings (considers concrete, steel rebar and formwork); (v) ground anchors (75 €/m), and (vi) micropiles (80 €/m). The cost calculation for solutions B1 and B2 considered the following general cost of: (i) concrete; (ii) steel rebar's; (iii) formwork; (iv) footings (considers concrete, steel rebar and formwork); and (v) micropiles (80 €/m), equal to solutions A1 and A2. Solution C considered the following costs: (i) concrete for piles (110 €/m^2); (ii) shotcrete (100 €/m^2); rebars for piles (1.2 €/kg); (iii) piles drilling with Kelly (50 €/m); (iv) concrete for distribution beam (100 €/m^3); (v) rebar for the distribution beam (1 kg); (vi) formwork (25 €/m^2), and (vii) anchors (75 €/m). Table 10 presents the total cost per square meter view of each retaining wall solution. It is concluded that solution A1, A2 and B2 are cost competitive to the adopted solution. As an example, solution A1 could save 4100 € compared to the adopted one, for this wall (S1) with a height of 10 m and a width of 12.5 m. However, considering the costs and the structural performance of the walls (displacement), it was concluded that the retaining wall of alternative solution B2 presented the best overall performance, since it had a low cost, lower displacements and did not include ground anchors, which might be beneficial.

Table 8 – Comparison of the wall and soil horizontal displacements of the alternative solutions

Solution	S1	A1	A2	B1	B2	C	Warning	Alarm
δh, Wall [mm]	12,3	14,5	7,3	5,8	10,9	9,8	25	30
δh, Soil [mm]	16,8	17,7	12,1	11,4	17,1	9,8	25	30

Table 9 – Vertical and tangential stresses of the soil for the alternative solutions.

Total Stresses	Adopted solution	A1	A2	B1	B2	C1
σyy [kN/m^2]	-766,35	-765,69	-765,53	-777,42	-777.29	-860,65
σxy [kN/m^2]	176,50	168,34	164,43	141,95	176,51	171,52

Table 10 – Cost per square meter of retaining wall per alternative solution (in euros).

Solution	Adopted solution	A1	A2	B1	B2	C
Cost [€/m^2]	207,1	174,2	174,2	246,3	198,6	245,2

6. Conclusions and future developments

6.1 Remarks

A literature review was performed in order to better understand the function, construction process and restrains associated with the rehabilitation in urban historic zones. The monitoring of this case study during all the construction process allowed a better understanding of the adopted solutions, which were compared to possible alternative solutions to conclude and understand the choices behind this decision making process.

It was concluded that the rehabilitation in urban historic areas is evolving and the optimization of the occupation of these spaces must be fulfilled. The optimization is made by preserving the historic value of the zone and maximizing space occupation with the building of underground structures.
Several numerical models of retaining wall structures were developed in Plaxis 2D software in order to estimate their displacement and forces. These models also allowed the study of the soil behaviour during different construction stages. Two models where developed to simulate two sections (S1 and S2) of the retaining wall structures present at the case study.

Several alternative solutions (five) to the definitive berlin type retaining wall S1 were developed to assess the benefits of considering different walls typology. Two of the alternative solutions varied the number of anchor and allowed the conclusion that reducing the number of ground anchors also reduces the total cost of the wall but increases the displacements of the wall. Two different alternative reinforced concrete wall, with buttresses with different spacings, where studied. Solution B2 was proved to be the best overall performance solution and presented low cost, reduced displacements and did not utilize any anchors. A last solution of a piled wall (C) was developed and presented the lowest displacement and highest cost.

6.2 Future developments

This thesis allowed the proposal of the following future developments:

(i) the creation of a more rigorous monitoring plan, with more topographic targets and a higher measurement rate, in order to better control the displacements of both the retaining walls and the neighbourhood buildings. This enhancement of the monitoring plan could allow for a better comparison of the numerical results with the *in situ* measurements.

(ii) the comparison of the studied solutions with a cutter soil mix wall, an innovative retaining wall structure.

(iii) the development of more refined three-dimensional finite elements models to better depict the effects along the width of the retaining wall structures, studied herein, and to retrieve results that should be closer to the real case scenario.

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