Solutions of Earth Retaining Walls for City Applications

Case Study – Palácio Vila Garcia

David Filipe Oliveira Pereira

Department of Civil Engineering, Instituto Superior Técnico, Lisbon University – PORTUGAL

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Abstract: The constant increase of the population in the urban centers causes excessive pressure on the existing infrastructures which were not originally designed for such demand.

Nowadays, the demand for spaces for retail, services and living causes a new approach regarding the spaces use, leading to the exploration of the underground spaces, mainly for infrastructures as car parking, increasing the profitability of the investments.

The advancement of theories regarding the analysis of flexible earth retaining walls, through the progress of computer technology and new construction technologies and equipment, facilitates the construction of basements in urban environments. As of so, the construction of basements for parking of both residential or services buildings is increasing in cities like Lisbon.

This work is focused on the construction of the housing project *Palácio Vila Garcia*, in Bélem, Lisbon, pointing out the excavation phase and execution of the earth retaining walls to create structural conditions, needed to build the basements.

Firstly, were studied the solutions that best adapt to the local conditions through its design, using the Plaxis 2D finite element software, where the displacements and stresses resulting from the various stages of the excavation works, mobilized at the retaining walls, neighboring structures and ground.

It was performed an integral follow-up of the excavation and peripheral earth retaining structures through the analysis of the construction methods, being these, King Post walls and bored piles earth retaining walls.

KEYWORDS: Earth Retaining Walls, King Post Walls, Bored Piles Wall, Temporary Ground Anchors, Modelling

1. Introduction

With the development of urban centers and the increasing of the demographic pressure, the transport and parking infrastructures also suffer from excessive pressure due to over demand.

The underground space is increasingly valued by the use of the surface areas for housing spaces, trade and services leading to the traditional parking space methods at surface to less common.

In order to be able to accommodate the existing demand for car parking spaces, the engineers tried to profit the use of the subsoil, so that basements are taken care of that need. With a limitation of neighborhood conditions in urban centers, becomes difficult to build earth retaining structures compatible with the neighboring structures and infrastructures.

The present dissertation is focused in the study of the excavation and peripheral earth retaining works at the Palace Vila Garcia, located at Belém, Lisbon west zone. The residential development in analysis has a luxurious character so it is not acceptable the lack of parking spaces.

In first place and contrary to the order as the topics are presented, the design of the solutions was carried out in order to make possible its technical and economical selection.
Secondly and of greater importance considering the civil engineering profile of the student, were studied the proposed solutions in the work environment and the implications of setbacks as the construction continue in order to have a direct and real contact with the work environment.

1.1. Flexible Earth Retaining Walls

Flexible earth retaining walls can operate in two different ways, depending on the type of bracing used, for example, struts, their high rigidity is responsible for the control of the wall deformations passively. In the case of temporary ground anchors, as they are not as stiff, the stability of the structure is guaranteed by the installed prestress, anticipating any movement of the terrain through its active component. The application of the prestress causes two very important phenomena in the future performance of the support element because of the state of alteration of the soil at the back of the retaining wall, causing an increase of the horizontal tensions and consequently diminishing of the loss of tension of the excavation phases. On the other hand, the prestress also causes the movement of the wall to the extruder which causes a displacement contrary to that caused by the excavation which makes it also easier to control the settlements in the neighboring structures [2].
Another component of extreme importance for the good behavior of earth retaining walls is the interaction between wall and the soil in the back of it. Because the resistant elements are concreted directly against the ground, a cooperative interface is formed between the concrete and the ground that can convey vertical load to the ground through the cut, and this component increases when there are temporary ground anchors because of the existence of the horizontal component. The technique of the King Post walls rests on a principle of great value, which is related to the order that the construction of the panels is done and is called Arc Effect. Arc Effect is the phenomenon of gradual redistribution of stresses to the more rigid zones when, for whatever reason, they are altered as conditions of support of the terrain.

2. Case Study – Palácio Vila Garcia

The case study that will be addressed within the scope of this dissertation is named "Palácio Vila Garcia", located in Belém, specifically the phase of excavation and retaining walls.
The palace is a building dating from the end of the eighteenth century located in one of the areas of excellence of the Portuguese capital with the river Tagus in background, great proximity to the gardens and calming of this housing area.
The development has a total area of 7452m^2 (of which 5032 m^2 are gardens) and consists of two sub-projects, the "Casas do Palácio" to be built in the existing zone and to be rehabilitated and the "Casas do Jardim" to be build where the old garden was. As so, the interior of existing buildings will be demolished and the exterior walls will be preserved.
Given the need for parking that we face and its offer in this neighborhood, the existence of parking spaces associated with the property is a very interesting value, which meant that there was a need to build a basement properly connected to all buildings to accommodate such a need.

2.1. Geological and Geotechnical Conditions

In order to characterize the soil involved and the foundation of existing elements that could affect the design of the earth retaining structures and the overall project, a geological-geotechnical study was carried out by GEOTEST.
The prospecting program proposed by the owner "SIT - Sociedade Imobiliária do Tejo" consisted of the following works [1]:

- 6 mechanical boreholes with Ø76mm, characterized from S1 through S6 with until depths of 12m;
- Standard Penetration Tests (SPT) spaced each other from 1,50m in the same boreholes;
- 10 foundation's observation trenches;
- Installation of standard piezometers (Ø50mm) in 2 in the boreholes S1 and S6;
- 8 Laboratory analyses on disturbed and undisturbed samples;

From the mentioned tests, three geological layers, designated ZG1 and ZG2, have been defined, and ZG2 can be divided into two sub-layers, A and B. In the Table *1* are presented the parameters adopted for the geological units considered.

Table 1 - Adopted geotechnical parameters for each geotechnical zone

Geotechnical Zone	Geological Era	Lithology	N_{SPT}	ϕ' (°)	E' (MPa)
ZG1	Recent	Fills and sands	7 - 60	25 – 28	5 – 15
ZG2A	Cretaceous	Weathered basalts	24 – 29	30 – 33	40 – 60
ZG2B		Basalts	>60	35 - 38	90 – 120

With regard to the ground water table level, through the piezometers installed, it was possible to confirm at depths ranging between 3.45m and 4.15m, already expected considering the proximity of the river Tagus. Although were adopted the parameters above, it is important to confirm the assumptions initially considered, relating to the conditions of integrity, state of conservation and the level of the foundation walls in the later stages of the design project and during construction phase.

2.2. Initial Solution

The initial solution studied for the Villa Garcia, used in its entirety the construction method called "King Post walls", temporarily anchored or propped. Considering that the water table is above the final level of the excavation and it is located in medium to high permeability soils, it was foreseen the treatment of the layers with grout columns, properly sealed in the low permeability soils, corresponding to the ZG2 geotechnical zone to enable this constructive technique. This solution allows, through the effect of cofferdam, so that the flow retraction cone will be located inside the excavation area, significantly reducing the probability of damages occur in the buildings. At the final stage, the slabs forming the buildings will be responsible for the horizontal bracing of the wall against the impulses caused and the peripheral pad foundation responsible for the foundation of the same wall, whereby the micropiles, temporary ground anchors and struts will be deactivated after construction of the final structure [3].

2.3. Adopted Solution

Immediately after the conclusion of the tender, the contractor, DST S.A., sought to study alternative solutions in order to increase the performance of the work, thus reducing its costs. Since DST is a company with geotechnical roots, they proposed to the designer a solution that included two constructive processes, a King Post wall solution (with columns of cement slurry) and secant pile wall to guarantee the effect of a cofferdam.

It was also sought, at the request of the contractor, to optimize the solution of temporary ground anchors. The most direct way to decrease the number of temporary ground anchors is to decrease the thrust on the wall by reducing the excavation height. Thus, it was possible to dispense all the temporary ground anchors of the DE cross section, operating the wall with a cantilever behavior. In the HI cross section, also through the reduction of excavation height, it was also possible to optimize the number of temporary ground anchors by increasing their spacing.

Another modification proposed by the general contractor, DST, was the change of grout columns to soil-cement with the same diameter and spacing, considered as also acceptable by the designer.

2.4. Bored Piles Wall

The constructive process adopted for the execution of the pile wall is presented in the chart of Figure 1.

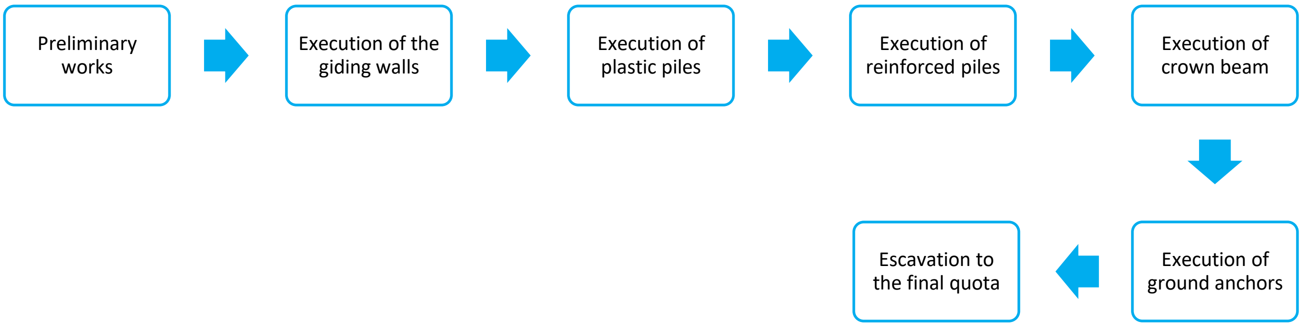

Figure 1 - Phases of the execution of bored piles wall

The execution of a piles wall involves the execution of piles molded in the ground under CFA method through a secant solution consisting of reinforced piles with Ø500mm diameter spaced apart from 800mm between axes interspersed by plastic piles of the same diameter and spacing, Ø500mm away from the 800mm. After the piles are executed, the capping beam and the temporary ground anchors are executed so that the excavation can be carried out to the final cross section.

Before the execution of these elements, the platform was demoted to reduce the height of soil to be supported by the wall conditioned by the water table and by the maximum inclination of the slopes. Thus, the lowering of the work platform by excavation under slopes varied between 0.60m (in the entrance area of the palace) and 2.70m (in the garden area).

The guiding walls are extremely important elements in earth retaining walls of tangent or secant piles to guarantee the verticality and implantation of the piles. They were executed using metallic formwork pieces placed in a trench.

The drilling was followed and its stability during the drilling process was assured through the soil retained in the flight auger. When the final level of the pile was reached, as the boring tool was being removed from the boring hole, the concrete was placed through an auxiliary pump from the bottom up and the exit speed controlled by the operator so that there was no collapse of the hole.

Because they are only of a constructive nature, the plastic piles were built in a meter in ZG2A and constituted by concrete of worse characteristics than the one of the armed piles.

With the plastic piles done were executed the reinforced piles using the same constructive method, the CFA method. These piles were executed between the plastic piles with an embedding that varies between 3m and 4m in ZG2A but as these delivery lengths must be fulfilled in order to guarantee the structural feasibility of the wall, the drilling point was used was specific to drill rock.

After the concreting of the pile, the reinforcement is placed in the hole, which is lifted and suspended over the hole using a winch integrated in the drilling machine and introduced only by its own weight without the need for auxiliary equipment. With the piles completed and in order to execute the capping beam, the approximate height of the capping beam was first excavated and then the head of the piles was demolished so that it was possible to make a structural connection between the beam and the reinforcement of the piles. This demolition was carried out in two different ways, by manual demolition using an electric hammer and by mechanical equipment with a pneumatic hammer.

Once the demolitions were completed, the surrounding land was regularized and the bottom concrete was placed. With all the pile bars that integrate the capping beam in view, the plastic sheaths were removed, so that they could now adhere to the concrete. Thus, the beam was assembled and coffered, leaving the negatives for the subsequent execution of the temporary ground anchors and the necessary reinforcement to the joint with the other surrounding elements (Figure 2).

Figure 2 – Execution of the slabs that will assure the definitive horizontal wall bracing

2.5. King Post Walls

The constructive process adopted for the execution of King Post walls is presented in the chart of Figure 3.

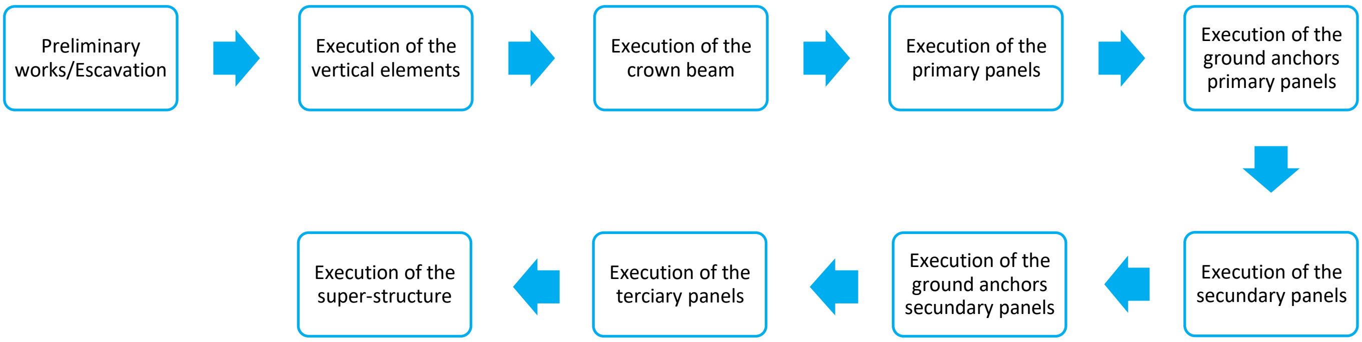

Figure 3 - Phases of the execution of King Post walls

Before any important work was done, the work platform was demoted to again lower the excavation height, but only inside one of the buildings. In this building, the excavation was carried out in all its area whereby, the pre-excavation had in attention the level of foundation of the walls to be conserved, thus being able to be executed the capping beam to a lower level.
After the lowering of the work platform and the execution of the soil-cement columns, were executed the elements responsible for the vertical stability of the wall.
Such vertical elements can be "I" or "H" metal profiles or circular metal profiles such as N80 type micropiles, which were used in the present case study.
In all cross sections N80-type micropiles were used as vertical resistant elements implanted in the axis of the future earth retaining wall. In the cross sections braced only with struts micropiles Ø88.9x7.5mm were used and as of in cross sections braced with temporary ground anchors micropiles Ø114.3x7.5mm were used. As far as their spacing, it was such that the micropiles were implanted at each end of the primary panels resulting in alternating spacing of 1.60m and 4.40m.
Thus, in order to avoid any damages and unforeseen in the work and by using micropiles, it was used a method that consists of previous drilling a hole in the place where the tubes were placed through a borehole of 8 "/ 203.2mm.
The drilling was performed through a drilling rig using rods and bit and temporary coating pipe. The drilling / coating pipe has at its base a cutting tool, which together with the drilling bit performs the hole.
After drilling, the micropiles were placed in the hole, and, similarly to the coating pipe, they were assembled by sections joined by threaded joints "male-female" type.
The profiles are then sealed by the IGU method in order to create a sealing bulb on competent ground.
As in the pile earth retaining walls, also in the execution of King Post walls exists the necessity to have a capping beam. In the base of these beams was placed an earth cushion so that it is possible to leave the starter bars for the several panels of the lower level. The concreting was done against the formwork in its overlay and in the extruder against the foundation of the exterior walls.
Taking into account the tight deadline of the work, the capping beam was executed by sections compatible with the panels, that is, firstly was executed the part of the capping beam that gives the start of the primary panels, so that, when building the part of the beam corresponding to the secondary panel the execution of the panels could already underway.
In the execution of the primary panels the excavation corresponds to the width and height of the panel defined in project. In addition to the corresponding dimensions, an additional excavation was carried out so that the starter bars could be placed on the lower panels and the secondary panels. For each side of the excavation, stools were left so that the thrust previously supported by the excavated soil could be mostly redistributed through the "bow effect" to these thrusts.
The assembling reinforcement of the panels began by preparing the starters bars left on the capping beam, followed by the assembly of the extruder reinforcement of the panel and the reinforcement bars dedicated to punching. Lately was assembled the reinforcement of the wall inlay.
The formwork used was maritime plywood since it has the clear advantage of being able to several uses, have quick assembly and disassembly and are not as expensive as the metal formwork. It is important to note that no formwork was used at the back of the wall so that the panels could be concreted against the ground or against the soil-cement

columns. In order to be able to concrete the panels, an opening was left in the upper part of the formwork called "duck's mouth".

After the completion of the primary panels, the secondary panels were executed, respecting exactly the steps of the primary panels (Figure 4). Tertiary panels are panels that can be done at the same time as the primary panels with the slightest difference being that this panels make up the corners or changes of direction of the earth retaining wall so they should be executed before the secondary panels to confine the more sensitive areas of the excavation.

As corner panels, the bracing of these panels is carried out by metallic struts such as "H" type profiles. This replacement allows taking advantage of the proper balance of a concave zone and the proximity of the panels through a strut. In the convex zones, the proximity between panels was utilized through tie rods composed by pre-stressed "GEWI" type bars.

Figure 4 - Assembling of the reinforcement cage at a King Post Wall panel and beginning of the super-structure execution

2.6. Temporary Ground Anchors

The constructive process adopted for the implementation of the temporary ground anchors is presented in the chart of Figure 5.

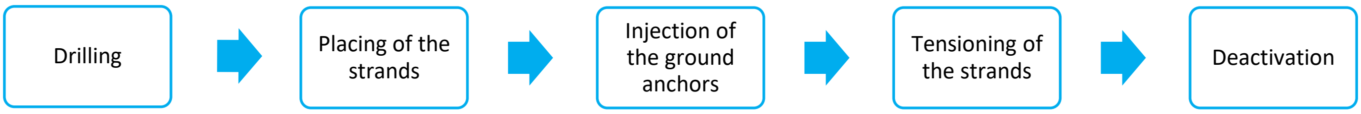

Figure 5 - Phases of the execution of temporary ground anchors

The execution of the temporary ground anchors begins immediately upon execution of the elements, whether the King Post walls or the capping beams of the pile wall, by putting a PVC negative in the element.

The temporary ground anchors responsible for the bracing, for the most part, spaced from 3.20m, implanted only in the capping beam, and in the DE cross section, due to the optimization mentioned above, it was executed with a cantilever behavior. This decision led to an increase the delivery length of the reinforced piles of the wall (to increase its liability), the increase in the reinforcement of the pile and the reduction of the slope behind the wall. In the HI cross section the optimization was carried out at the level of the anchorage spacing.

As for the King Post wall, the temporary ground anchors were placed at the center of the primary and secondary panels resulting in spaces of 3.00m.

In the two types of retaining walls used, all the temporary ground anchors were executed with a slope of 30 degrees.

In the present study case, the drilling method used was roto-percussion of rods and bit and outer casing of the hole. This choice was due, as in drilling for the micropiles, to the poor characteristics of the layers of soil crossed by the drilling.
Once the drilling was completed and stabilized, the strands that materializes the anchorage was placed manually by the workers.
In the present case, the temporary ground anchors used were pre-assembled at the factory and supplied in rolls, consisting of 4 prestress strands, injection tubes and spacers.
By request of the contractor, an intermediate system was used between the IGU system, used in the micropiles, and the IRS system, called IR. The IR system, repetitive injection, is similar to the IRS system with the major difference being the lack of selectivity of the injection tube.
After the cement grout had gained the resistance established in the design, the ground anchors cables were tensioned through a hydraulic jack.
The application of the prestress must only be performed after the cement grout has gained the resistance defined to be able to withstand the tension, by adherence of the cables, to which it will be subjected to the tension. Thus, after 7 days of the sealing operations, the temporary ground anchors were prestressed. This activity is controlled by gauges placed on the jack and by increasing the length of the cables. When pulling, a simplified ground anchor test is performed. Upon completion of the slab and the gain of its resistance, the temporary ground anchors were deactivated by cutting the cables with a torch causing the recess of the cables in the hole and lose all the prestress to which they were subjected.

2.7. Modelling

The modelling of the earth retaining structures was done with numerical calculation software that uses finite elements to simulate the nonlinear behavior of the soils and the influence of the constructive phase in the design of the structure. This software is very competent in regard to stress-deformation and soil stability analyzes and used the latest version of *Plaxis* software, PLAXIS 2D 2017.0.
In order to model the existing earth retaining walls in the present case study, three cross sections were studied, two with piles wall, in cantilever behavior (section 4 - cross section DE) and mono supported (section 6 - cross section HI) and one with King Post wall (section 2).
Firstly, the characteristics of the soil layers were determined through a critical analysis of the elements of the site investigation campaign carried out, in particular, through the values considered for the several layers presented in the geological and geotechnical report, the parameters presented in *Table 2* were considered.
Following, are defined and presented in Table *3* the properties of all structural elements used in both types of retaining walls.

Table 2 - Adopted parameters for each geotechnical zone

	Geotechnical layers		
Parameters	Fills (ZG1)	Weathered basalts (ZG2B)	Basalts (ZG2A)
γ_{unsat} (kN/m3)	18	20	21
γ_{sat} (kN/m3)	19	21	22
E_{50}^{ret} (kN/m2)	15.000	50.000	110.000
E_{oed}^{ret} (kN/m2)	15.000	50.000	110.000
E_{ur}^{ret} (kN/m2)	45.000	250.000	330.000
c_{ref} (kN/m2)	3	3	3
ϕ' (°)	28	32	37
k_0	0,53	0,47	0,40
υ	0,2	0,2	0,2

Table 3 – Properties of the structural elements used

Parameters	Pile Wall	Reinforced concrete wall	Micropiles	Micropile bonding length	Anchorage free length	Ground anchor bonding length
EA (kN/m)	14.030.000	8.250.000	211.300	-	117.600	-
EI (kNm2/m)	211.400	42.970	302,6	-	-	-
E (kN/m^2)	-	-	-	30.000.000	-	30.000.000
w (kN/m/m)	10,63	6,25	0,076	-	-	-
υ	0,2	0,2	0,2	-	-	-
γ (kN/m3)	-	-	-	20	-	20
Ø (m)	-	-	-	0,20	-	0,13
L spacing (m)	-	-	-	3	3	3

The different phases used in the design of the pile earth retaining walls are present below with the exception that in the cross section with cantilever behavior the phase 6 was not considered:

- Phase 0: Creation of the initial stresses in the soil layers;
- Phase 1: Activation of the overload of 10kN/m^2;
- Phase 2: Working platform lowering;
- Phase 3: Execution of the pile wall;
- Phase 4: Excavation for the capping beam;
- Phase 5: Execution of the capping beam;
- Phase 6: Execution of the ground temporary ground anchors;
- Phase 7: Excavation to the bottom level.

As far as the King Post wall was concerned, its execution was simulated through the stages below:

- Phase 0: Creation of the initial stresses in the soil layers;

- Phase 1: Activation of the overload of 10kN/m^2;
- Phase 2: Execution of the micropiles;
- Phase 3: First level excavation;
- Phase 4: Execution of the concrete retaining wall and the ground temporary ground anchors;
- Phase 5: Excavation to the final level;
- Phase 6: Execution of the concrete retaining wall and the mat foundation.

3. Final Remarks

The dissertation was focused on the design and follow-up of the excavation and peripheral retaining wall works allowing the student to have a direct contact with the professional life and understand not only the part of project as everything which involves the execution of the proposed solutions, either at the design or at the execution phase.

Thus, considering the scope of the construction processes involved, through the site visits made during the work, direct involvement in the design and selection of the adopted solutions, both at the initial and at the alternative solutions, discussed directly with the contractor, it was possible to understand and internalize all the steps that involve the design and the execution of this type of solutions. This experience was also complemented by a direct contact with the contractor, allowing to understand their concerns regarding the initial project elements and how they can be subsequently shaped to the real needs of the work.

In the first place, the design of the solutions was carried out to guarantee the safety conditions of both the temporary and definitive phases, as well as the mitigation of possible damages in the neighboring structures and infrastructures, with the support of several analysis, performed using the finite element software, Plaxis 2D. In regard to the difficulties encountered in the design phase, it was possible to conclude that extensive knowledge of geological and geotechnical conditions intersected by excavation works, as well as the neighborhood conditions, such as the foundation geometry and level of adjacent buildings, are extremely important for an optimized and well-defined project and construction.

With the project concluded, it was done a follow up on the execution of the previously recommended solutions, as well as the adaptation of the same solutions, in order to better face some unexpected situations, with the support of the monitoring and survey plan, giving rise to the need for revisions and changes of the initial solutions.

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