Performance of steel strut bracing systems in urban excavations

Case Study – Building at Av. 24 julho, Lisbon

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Abstract:

This dissertation deals with the performance of steel strut bracing system of a flexible earth-retaining structure in a urban area.

The initial goal was to understand the impact of this system in a earth retaining diaphragm wall at Avenida 24 julho, Lisbon, intended for a residential and hotel building with two to three basements, important to control the horizontal displacements as well as the axial forces at the struts as the excavation works proceed. The analysis is carried out with the help of numerical programs *SAP2000* and *Plaxis 2D*, studying, in terms of design, the problem of prestressing steel elements, reaching the conclusion that, in case of no prestress, the performance of the earth retaining structure in service limit states is a lot more risky for the safety of the adjacent buildings.

The results also proof that thre is an opportunity to change the initial constructive method in terms of timing of casting the basement after the removal of the strut, so for that a new solution that intends to evaluate the risk of the new method is presented. Furthermore, it is interesting to study the problem from a different point of view, which is the influence of less stiff supports in all levels, concluding that it turns out to be more advantageous, while apllying the same presstress forces to optimize the horizontal behaviour of the structure.

Key-words:

Flexible earth retaining structures, steel struts, prestress, axial stiffness, buckling effects, basement concrete slabs

1. Introduction

It seems that there is an enormous increase in the population moving from their home towns to live in the big cities, looking for a better life quality. This of course would have an impact in the way civil engineers design their structures. That's because with the amount of people increasing every day, it turns out to have more traffic in the streets, less space to park the cars, and of course the land valuation, it's almost impossible nowadays to think of a solution that doesn't have a direct connection to places under the ground where people can be at. So knowing how to use the underground space and to build retaining structures becomes very important. With that, in very dense cities, the chances to have a building next to the excavation area with two, three or more basements are very high, so it's becoming very difficult to execute ground anchors. Hence, the need to think of a solution that does not interfere with the neighbor space will lead to understanding even more the performance of strut support systems, being this the reason of the theme of this work.

2. Flexible Earth-retaining Structures

First of all, the Eurocode 7 [1] refers that a flexible earth-retaining structure must comprehend a support system to ensure the stability of the excavation. Peck [2] also states that the deformations of the retaining wall in service will change the earth pressures acting on the wall, so it becomes extremely hard to predict the forces that will be applied in struts elements, which ends up complicating the design problem.

Terzaghi [3] stated that a braced excavation should complete two crucial criteria: no collapse of horizontal steel elements, and a good performance in terms of movements of the retaining wall and settlements of the upper surface of the ground behind the wall.

Figure 1 shows the distribuition of earth pressures with the deformations of the retaining wall in the end of the excavation process.

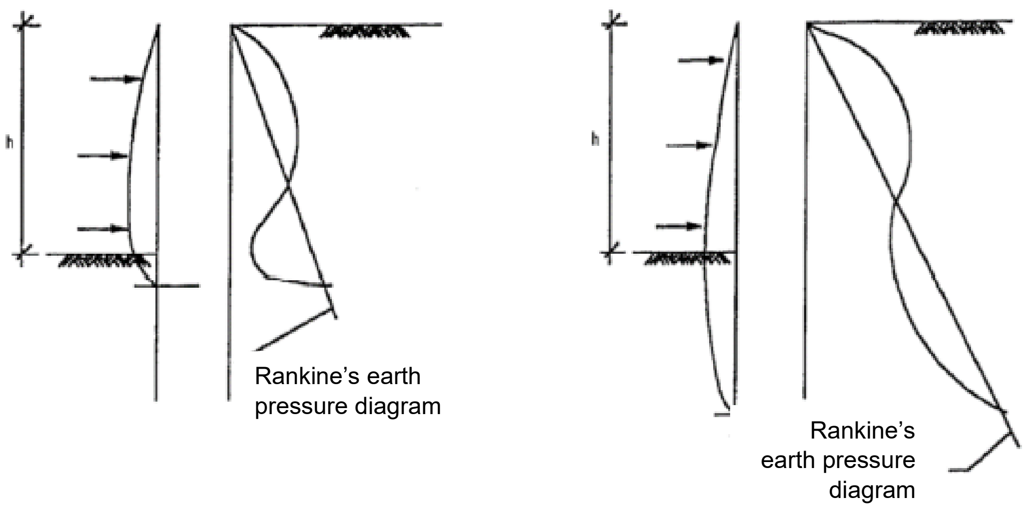

Figure 1 – Earth pressure distribution with horizontal displacements of the Wall [4]

The results prove that the theories of Rankine and Coloumb should not be applied in this case, because this is a problem of soil-structure interaction, which means that more stress fields will be changed near the supports, and where the displacements are higher the pressure of the soil will be smaller. However, the way stresses change in the back of the wall are dependent on several factors related to the axial stiffness of the struts, the evolution and time of the excavation process, etc. The finite element method brought a new way of analyzing geotechnical problems, being easier to model the excavation and to evaluate the performance of the structures along the process, allowing to perform parametric studies.

3. Case Study – Av. 24 julho, Lisbon

The case study presented in this paper is the excavation and the execution of a permanent retaining wall with 50 centimeters thick with temporary steel support struts for the construction of a building in Av. 24 julho in Lisbon, close to Tejo's River, with two to three basements, so the cut will have to be supported by two to three levels os struts. The location of the construction site and the neighborhood conditions are represented in figure 2, with a visual landscape of the retaining structure, with a photo taken in the south side of the area, with three levels of steel struts

Figure 2 – Plan view of the construction site area and neighborhood conditions (left); Struts and diaphragm walls (right)

As was mentioned before, the construction site is located in a densely urbanized area with several buildings nearby. To design a good solution it is necessary to take into account the geotechnical conditions. This is a district where the Tejo River is very close to the excavation pit, so it is expected a very poor geotechnical scenario in terms of resistance and stiffness parameters of the soil. Field and laboratory tests were performed, allowing the identification of four different geological units: landfill deposits of sand (ZG3) at surface, with thickness between 5 and 6 meters laying over a muddy aluvial soil (ZG2) with 4 to 6 meters of thickness, which is laying over a very competent silty clay from the Miocene period (ZG1A), with discontinuities of fractured silty clay (ZG1B), with a medium SPT result of 40 blows.

4. Design Solution Analysis

SAP2000, version 22, was used to obtain the equivalent axial stiffness of the supports and the maximum compression forces in each element. On the other hand, *Plaxis 2D, version 19*, models were very important because they allowed to create the geometry of the problem and analyze the displacements of the retaining wall and the reactions per meter on each level of support.

The constructive method was based on, first, remove the soil to a certain level, then install the strut, and after prestress it, and repeat the process until the end of the excavation. The soil was modeled as a continuous plan divided in several elements, using the hardening soil method, wich gave a really reasonble simulation of the ground because of its real stiffness becoming much higher in cases of stress relieve, very typical in excavations problems. The soil parameters adopted are presented in Table 1.

Table 1 – Estimated values of geotechnical parameters

	γ_{unsat} [kN/m³]	γ_{sat} [kN/m³]	c'_{ref} [kPa]	$S_{u,ref}$ [kPa]	Φ' [°]	ψ [°]	E_{50}^{ref} [MPa]	E_{oed}^{ref} [MPa]	E_{ur}^{ref} [MPa]	Power (m)	R_{inter}
ZG3	18	19	12	-	30	0	38	38	190	0,5	0,8
ZG2	15	16	-	30	-	0	24	24	120	1,0	0,7
ZG1B	19	21	50	-	35	0	90	90	450	1,0	0,7
ZG1A	20	22	60	-	40	0	95	95	475	1,0	0,7

The results shown a really good performance in service limit states of the excavation, with a 5mm maximum horizontal displacement in Section 1 (two levels of struts), below the maximum defined at the original project of 14mm and 16mm in Section 2 (three levels of struts), also smaller than the maximum of 21mm defined at the original solution. Figure 3 identifies each Section of analysis in *SAP2000* model, while figure 4 shows the deformed shape on both models

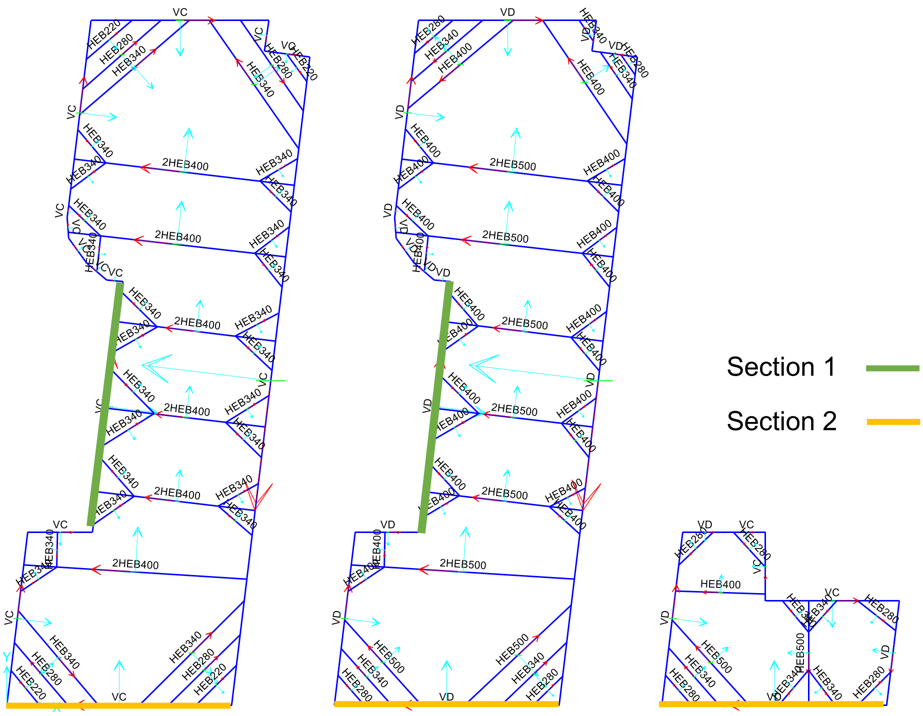

Figure 3 – *SAP2000* models: Floor 1, 2 and 3

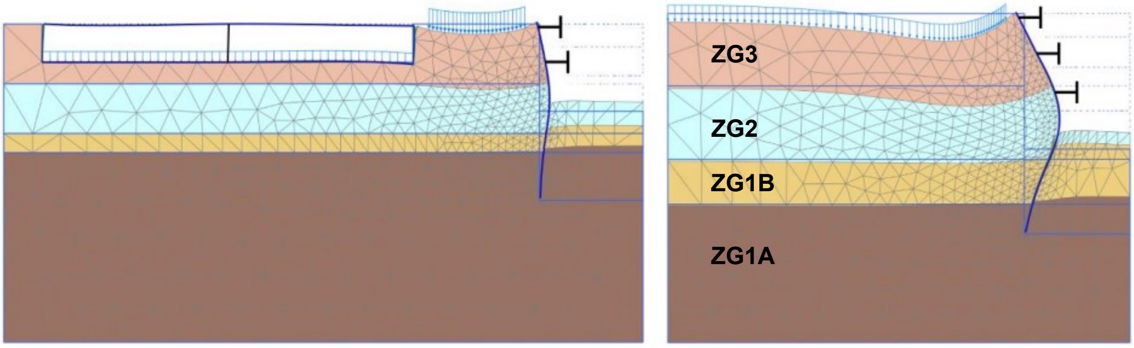

Figure 4 – Deformed Shape in *Plaxis 2D*: Section 1 (left); Section 2 (right)

In terms of the maximum forces applied on each steel strut element, it was confirmed the safety at ultimate limite state of resistance to buckling effects, checked in the accordance with Eurocode 3 – steel structures, with a medium resistance mobilized of only 30% at the material.

Extra calculations were made in this subject: either changing the bending stiffness of the wall, or even evaluating the constructive method of casting the basement concrete slabs before the struts were removed (which practically had no influence on final results), but the most critical scenario came when it was tested a new solution of struts with no presstress. That did not lead to a collapse of the struts, with, by the way, resulting in almost the same results, but it lead to a critical situation where the maximum horizontal displacement reached 22mm, above the maximum estipulated. This is a clear sign that the use of prestress force may be fundamental in these type of situations, mostly for deformations control.

5. Alternative Solution – Optimization of the Design Solution

Considering the site monitoring results at the original solution excavation final level, an alternative solution was studied. This one is, firstly, based on the optimization of the steel members in terms of reducing the section areas, resulting in a solution with a significant reduction of axial stiffness, however it will be maintained the same presstress forces that were defined in the original design solution. This brings to the work a very interesting discussion about the importance of presstress vs. axial stiffness of the struts.

Also, the alternative solution intends to study a new method envolving the timing of the construction of the basement slabs, trying to evaluate the effects of removing the temporary strut before casting the basement slabs, which will work as permanent bracing elements.

The results have shown that is, actually, possible to change the initial method with no damaging consequences on structural performances of the elements, and also on the horizontal and vertical movements of the ground.

In terms of reducing the axial stiffness of steel struts, comparing to the initial solution, the resultant axial forces on each level turns out to be very similar in both cases, because the prestress force continued to be very significant. However, comparing the situation where there was no prestress with the new solution the displacments of the earth retaining structure are much less important in case of a great prestress force, even if the axial stiffness decreases.

Figure 5 and 6 presents a comparison between the maximum horizontal displacements checked during the whole construction (until the final stage of casting the last basement slab), concluding that, in both cases, for each Section of the problem, the safety in service limit states is fullfield.

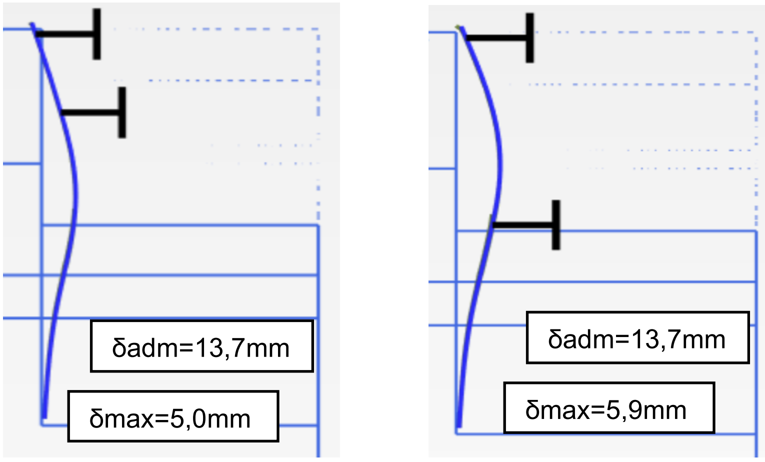

Figure 5 – Section 1: Maximum horizontal displacements: Original (left); Alternative (right)

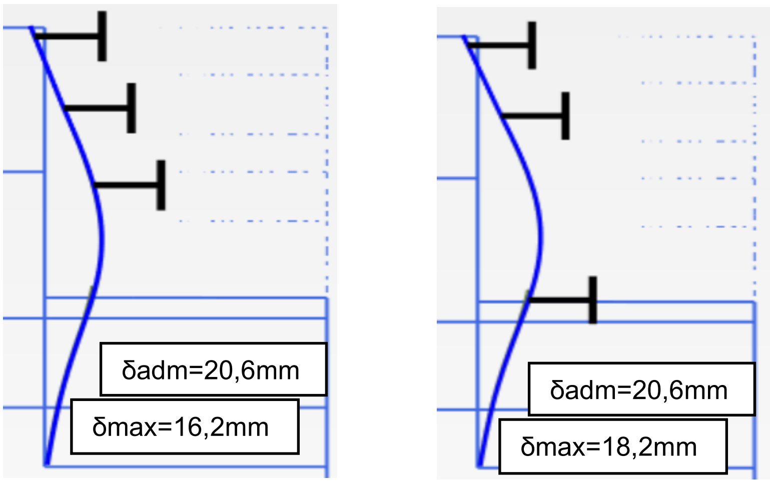

Figure 5 – Section 2: Maximum horizontal displacements: Original (left); Alternative (right)

6. Final Remarks

Considering the objetives proposed initially it is possible to conclude that a new way of casting the slabs should be implemented, having been checked the safety of service and ultimate limite states.

From an economical pont of view, the alternative solution contributes saving approximately 400.000€, including the optimization of the steel structure, like it is presented on table 2.

Table 2 – Economic study

	Original solution				Alternative Solution				Differences	
	Quant. [unid.]	Cu [€/unid.]	Ctotal [€]	[%]	Quant. [unid.]	Cu [€/unid.]	Ctotal [€]	[%]	Ctotal [€]	[%]
Steel Struts										
HEB180 [kg]					3279,83	1,40 €	4 592 €			
HEB200 [kg]					6621,79	1,42 €	9 403 €			
HEB220 [kg]	1338,22	1,42 €	1 900 €		10896,47	1,42 €	15 473 €			
HEB240 [kg]					2296,79	1,43 €	3 284 €			
HEB260 [kg]					22501,17	1,43 €	32 177 €			
HEB280 [kg]	9666,55	1,43 €	13 823 €		20725,30	1,43 €	29 637 €			
HEB300 [kg]					25764,99	1,43 €	36 844 €			
HEB340 [kg]	33206,18	1,54 €	51 138 €							
HEB400 [kg]	60616,26	1,54 €	93 349 €							
HEB500 [kg]	49625,15	1,57 €	77 911 €							
Total [kg]	154452,36		238 121 €	23%	92086,34		131 410 €	21%	106 712 €	26%
Basement slabs										
formwork [m2]	4710	56,23 €	264 843 €	25%	4710	29,24 €	137 720 €	21%	127 123 €	31%
Reinforcement bars [kg]	160140	3,41 €	546 077 €	52%	160140	2,32 €	371 525 €	58%	174 553 €	43%
Total			810 921 €	77%			509 245 €	79%	301 676 €	74%
Global cost			1 049 042 €	100%			640 655 €	100%	408 387 €	100%

It is clearly demonstrated the excellent efficiency of using prestress in struts as a bracing solution to control the deformations of the earth retaining structure, having in that case a reduction of the axial stiffness no meaning in final results. With that being said, it might be convenient to design a solution of steel struts envolving a good prestress force on each level, and taking that opportunity to optimize the struts section as much as possible, leading to a good performance in terms of safety of the excavation to collapse and to control de movements in adjacent buildings, as studied by Terzaghi [3].

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