Solutions of Excavation and Peripheral Earth Retaining Structures in Urban Environment: Avenida Fontes Pereira de Melo, 41 in Lisbon

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May 2017

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Nowadays, in the urban centres, the construction has increased exponentially, such a thing is an example of what is happening in Lisbon. The high occupation rate in the city centre, forced the use of subsoil for the infrastructures construction. This use of the subsoil is not only conditioned by the geotechnical characteristics of the subsoil, but also by the use of the neighbouring subsoil. Even though, most of the times the usage of the neighbouring subsoil is not allowed, the use of peripheral earth retaining structures with internal supports, as is the case of shoring and slab strips, can be an alternative.

In this dissertation, it is intended to accompany the work of a construction in Avenida Fontes Pereira de Melo, nº39 to 43, in the centre of Lisbon. In this construction support structures, which did not occupy the neighbouring underground spaces, as it is the case of slab bands, were executed.

Throughout this thesis, a modelling of the section was made based on the earth retaining structures solution which resorted to slab bands. In order to perform the modelling, the program of finite elements, Plaxis 2D, was used. The purpose of this modelling was to perform a critical analysis of the results obtained and compare them with the values of the real displacements.

Key words: Excavation in urban areas, bored piles curtain, slab bands.

Introduction

This dissertation appears in the context of underground constructions regarding the peripheral earth retaining structures in a highly dense urban environment, at a time when the densification of the construction has grown exponentially, especially in urban centres.

Due to the increasing need to obtain useful area, inevitably, the subsoil and the volumetric are used. They allow the removal of soil below the surface level. Moreover, new constructive technologies and new materials have been developed in order to be able to solve the most diverse problems that arise today and to present quality and cheap solutions that are at the same time competitive in an aggressive marker and where the customer is more selective.

In this work it will be taken into account the different earth retaining structures works, the reasons taken decisions and the possible changes when comparing to the initial project.

The study case of this dissertation is in one of the most urbanized areas of Lisbon, between Avenida 5 de Outubro and Avenida Fontes Pereira de Melo, and it is also near the underground of Lisbon. It should be taken into account that in the vicinity there are also buildings. All these conditions require a previous study and a detailed monitoring of the behaviour of the displacements.

Peripheral earth retaining structures

Throughout this work different methodologies used for earth retaining structures of urban soils will be presented. These methodologies can benefit from the support of slab bands. In this construction “Berlin walls” and bored pile Curtains were used. Strips of slabs were also used near the curtain of piles in Avenida Fontes Pereira de Melo.

The **bored pile wall** is a discontinuous piles wall, really close to each other, and sometimes they may even intersect each other [9]. The bored pile are executed directly inside the ground, against the field and this deforms the piles, regardless of whether or not a temporary casing tube is being used. This work is performed prior to the excavation work.

The bored pile technique can be used in two ways:

1. Peripheral earth retaining structures resistant element;
2. Structural Foundation element.

The “Berlin walls” are elements of earth retaining structures which possess small rigidity and they are perpendicular to its plane. They are also constituted by vertical profiles, generally metallic, and between these profiles, generally estivation in wood is placed. This type of earth retaining structures is an economical method. It presents ease of manoeuvring and construction, good daily yields in the wall area and it allows simultaneously the realization of the excavation and the earth retaining structures execution. As a disadvantage it requires a consistent field and in term of depth is a method with some limitations.

Temporary bracing solutions

The **shoring’s** are temporary structures. They are removed when the ground anchor structure has sufficient capacity to self-sustain. The most common type of shoring’s consists of a set of metal pieces that connect to each other. In general, this solution is more economical than the one with ground anchors and it is mostly used to sustain structures placed in corners or between opposing walls, as shown in Figure 1.

Figure 1: Steel Corner Shoring [FPM41].

The ground anchors can be provisional or definitive. Its constitution depends on several factors, such as the specific life time in project, the constructive characteristics and the surrounding environment, particularly the protection against the corrosion and the possible creep phenomena.

In urban settings, the ground anchors that present a temporary character are chosen, since the cares taken into account are much less than any other solution [6, 16].

The ground anchors usage in many cases is the ideal solution, because these have a positive impact not only in the work progress, but as well as in the construction quality.

The shoring slab of bands consists in the rigid locking of excavations, using structural elements [20]. This solution is advantageous, because it can be executed for environmental, legal, economical and constructive reasons when the traditional methods can't. Another advantage that it presents is not only the movement reduction that would happen if the deactivation of ground anchors or shoring (as support systems) would not be done correctly, but also the transmission of impulses exerted by the ground to the buried floors, i.e., the mobilization load phase occurs during the excavation phase. This earth retaining structures method consists on the execution of the locking slab bands, concreted against the ground, before proceeding to the next excavation level. Its construction offers high stiffness to the earth retaining structures and it saves times, since there is a good compatibility between the provisional elements and the definitive ones, taking into account that the locking elements will already be part of the definitive structure.

Preliminary studies and work

The following diagram (*Figure 2*) describes the steps taken by the designer to choose the types of peripheral earth retaining structures used in the work under study:

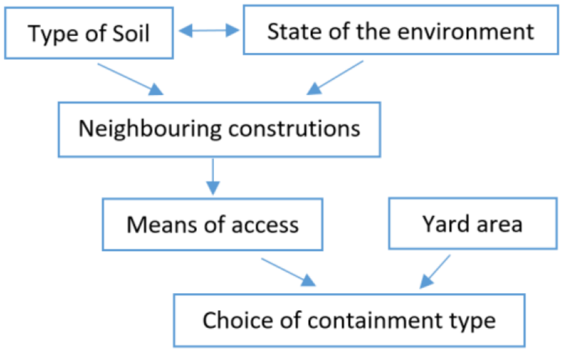

Figure 2: Scheme to choose the peripheral earth retaining structures type.

Case Study - Avenida Fontes Pereira de Melo 41

The construction that was monitored and studied throughout this dissertation is located between Avenida Fontes Pereira de Melo (East) and Avenida 5 de Outubro (West), *Figure 3*. It has a total area of 2134,84m^2, with the building implantation area equal to 2037,25m^2, and the gross building area equal to 32406,93m^2.

Figure 3: Site location FPM41.

To the north of the construction there are two building with different ages and construction types. To the west there is an underground car park with 3 floors. The Figure 4 represents the neighbouring structures/services of the construction under study.

Figure 4: Representative scheme of neighbouring structures and services.

Geotechnical-geological conditions

Having as a base the data extracted from the surveys, it can be concluded that the geological formation, defined as fill Depot (At), has a thickness that varies between 2 and 5 meters, S1 and S5, respectively. This layer of fill material consists essentially of clay-sandy and clay materials, as well as lithic fragments and ceramic remains, making it a very heterogeneous layer. In this field, the formation of “Argila dos Prazeres” (M_Pr) was also detected. This formation is represented by a succession of horizontals silty and marl layers interbedded with carbonaceous clay layers. The upper levels consist of gray clays. These levels extend for 6 to 9 meters of depth. Based on the results, it was proposed the parameterization and estimation of geotechnical parameters for the lands in the area studied (Table 1).

Structural design of the building-Generalities

The building floors are constituted by reinforced concrete slabs. The columns form a regular mesh of approximately 7,5 x 7,5 m^2, except in a zone of level 1, where the pillars are 12 meters apart in one direction.

Peripheral foundations and earth retaining structures

The proposed solution for the foundations consisted of a mixed solution of indirect foundations, using reinforced concrete bored piles in the ground and direct foundations, using reinforced concrete footing. The piles usage in the North half of the Building resulted from the proposed construction process, which forced the construction of "top down" construction piles. In the southern half of the Building the foundations were performed with footing. In all the perimeter of the building, a diaphragm wall with 60 cm thick was built. This wall would ensure the land earth retaining structures along the provisional and definitive phases of the work. In some cases it would be built near neighbouring constructions (for example the underground station), reason why the ground horizontal displacements would have to be minimized.

Ground	NSPT	ϒ(kN/m^3)	ϕ' (º)	c' (kPa)	E (MPa)
At	4-19	19	25	-	5
M_{PR}	13-24	19	26-28	5	10-20
	25-37	20	30-32	10	20-30
	41-60	20	32-34	20	35-50
	>60	20	38	20	60

Table 1: Estimated parameter values based on the tests carried out at the site FPM41.

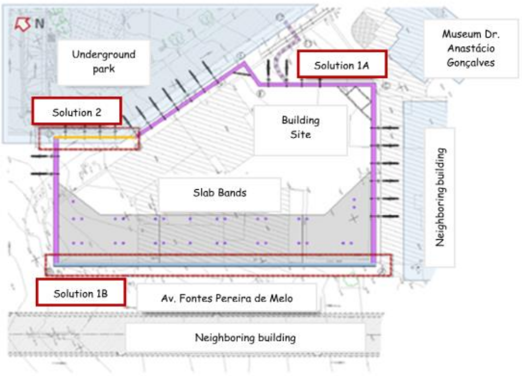

Figure 5: Earth retaining structures plant and zoning solutions [26].

In solution 1B, taking into account the neighbourhood conditionings in the elevation AB, bored piles were produced. These bored piles consisted in reinforced concrete, ø600mm, with a spacing of only 0,80m, and the length of the piles ranged from 25 to 28m. This length allowed a minimum of 7m (in general) or 10m (AB elevation) to be fitted below the final excavation level below the excavation level.

In solution 1A (Figure 8), several levels of ground anchors and struts will also be used in order to ensure the horizontal balance of the provisional earth retaining structures. In order to allow a better distribution of forces in the curtain and to avoid the excessive concentration of loads, distribution beams and crown beams will be constructed in connection with the shoring and ground ground anchors. In the DE elevation a wall will be built at the compatible levels with the EMPARK underground park and at level -3 a curtain of piles with the characteristics used in the BC elevation will be constructed. In solution 2, the excavation extends to the boundary of the EMPARK underground park and the vibration caused by this method could cause instability in the neighbouring structure. Moreover, Berlin walls were used. They consisted in reinforced concrete panels, with a minimum thickness of 30cm, so that structural problems in the EMPARK infrastructure were avoided.

Monitoring and Survey plan

The Topographic Targets are devices that measure the movements in the horizontal plane, according to two orthogonal directions, and movements in the vertical direction.

In Figure 6 the location of the 6 topographic targets of the elevation AB can be observed in 3 different depths. Every week readings were performed. This periodicity only decreased in cases in where the observed displacements approach the alert criteria.

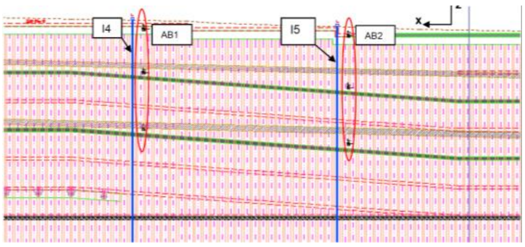

Figure 6: Inclinometers location and topographic targets at the AB elevation [35].

The **inclinometers** are a complement to the topographic targets. They are constituted by an inclinometric tube, a torpedo and a reading unit. There are two types of inclinometer, the vertical inclinometer that measures horizontal displacements and depth and the horizontal inclinometer that **measures the settlements that can occur.** The vertical inclinometer is the one used in this type of works because it gets the movements evolution of the piles curtain in depth.

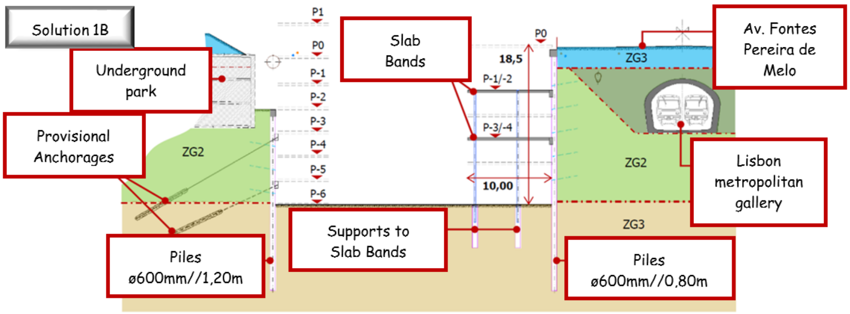

Figure 7: Illustration of solution 1B, in the elevation AB.

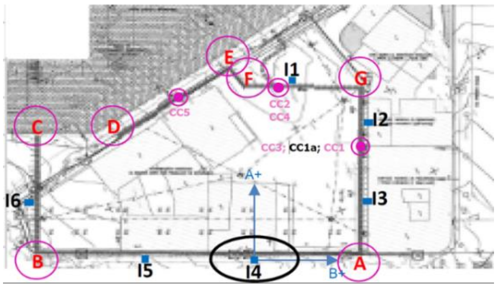

Figure 8: Inclinometers localization.

Through the readings, it was possible to conclude that in the first weeks of motorization the inclinometers of the elevation AB showed high displacements values regarding the first meter of excavation. These values did not correspond to the reality. Comparing these results with the readings obtained through the topographic targets, it was possible to see the reason for the value discrepancy, and this was due to the fact that in the construction of the pile, the tube that protects the inclinometer was not damaged. In the following depths, the measured values are closer to reality.

When studying displacements and their evolution it is necessary to take into account the excavation level that is in the construction (Figure 9).

The **load cells** are installed on the ground anchors head, allowing the monitoring of the installed pre-stress load. In this work it was proposed the installation of electric charge cells by induction. The reading of this apparatus is carried out using a monomeric device. To ensure the correct placement, each cell was placed on metal plates of stress uniformization.

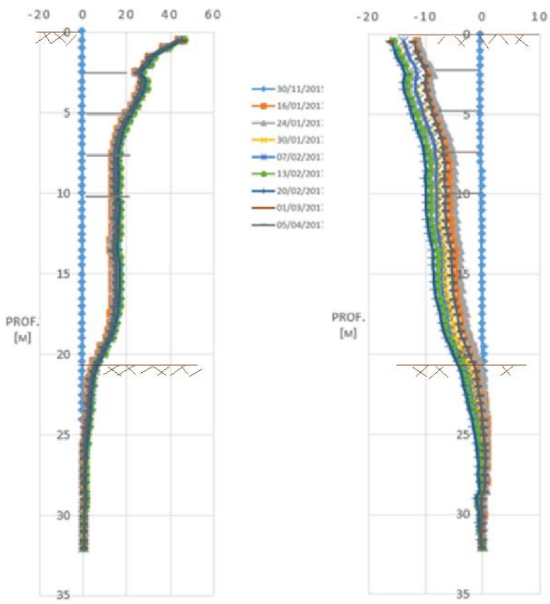

Figure 9: Accumulated displacements in the perpendicular direction to curtain (A) and parallel (B), inclinometer I4.

Lisbon Underground Monitoring

Regarding the monitoring of the Lisbon Underground, when a new excavation or intervention is performed in the ground with less than 25m, the tunnel structures must match certain requirements.

Through the Lisbon Underground 18 topographic stations were installed. They were displayed along the side AB (with 62m) of the Figure 10.

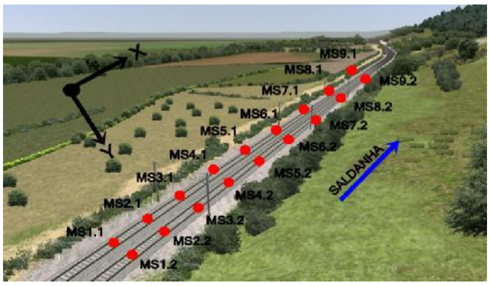

Figure 10: Surface marks location along the line of ML.

The MS4.1 and MS5.1 stations were the stations that had the largest displacements along the YY axis, reaching the alarm criterion. Due to this phenomenon the readings were doubled, being two times in each week. After this, a reinforcement measure was designed, using the pre-stress applied in the slab band of the floor -3. However with biweekly readings it was possible to realize that the displacements tended to stabilize. These results corresponded to the construction phase of the shoe and later stabilized due to the concreting of the last slab (Figure 12).

Numerical modelling of the slab ban solution

The peripheral contention was scaled using a finite element calculation program, Plaxis 2D, version 8.5.

The modelling presented in this work refers to a cut of the elevation AB of the earth retaining structures structure. The section will have an excavation height of 18m, with a curtain earth retaining structures structure of spaced piles.

A parameterization of the materials occurred in order to accomplish this analysis. It was based on the information gathered in the campaign of geological-geotechnical prospecting, previously executed. For the purpose of modelling the massif, the parameters presented in Figure 13, were used.

In order to define the mesh, triangular elements of 15 hodes were considered. This mesh had the following dimensions: 45m wide and 50m high. In order to improve the representation of the soil deformations, the distance of the curtain to the left window limit is equal to the excavation height. From the piles curtain to the right limit the window has 50m in order to allow the tunnel to be centred on both sides. In this model, an overload of 10KPA was considered, which is defined in the Descriptive Document and Justification of Excavation and Peripheral Earth retaining structures of the Work FPM41. Also the water table was considered at a depth of 22.4m. As it can be seen in Figure 11 the water table is below the excavation base, so it will not have a high influence on the calculations.

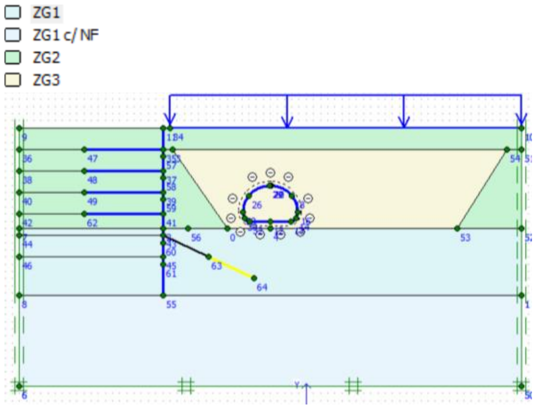

Figure 11: Modelling, Plaxis 2D.

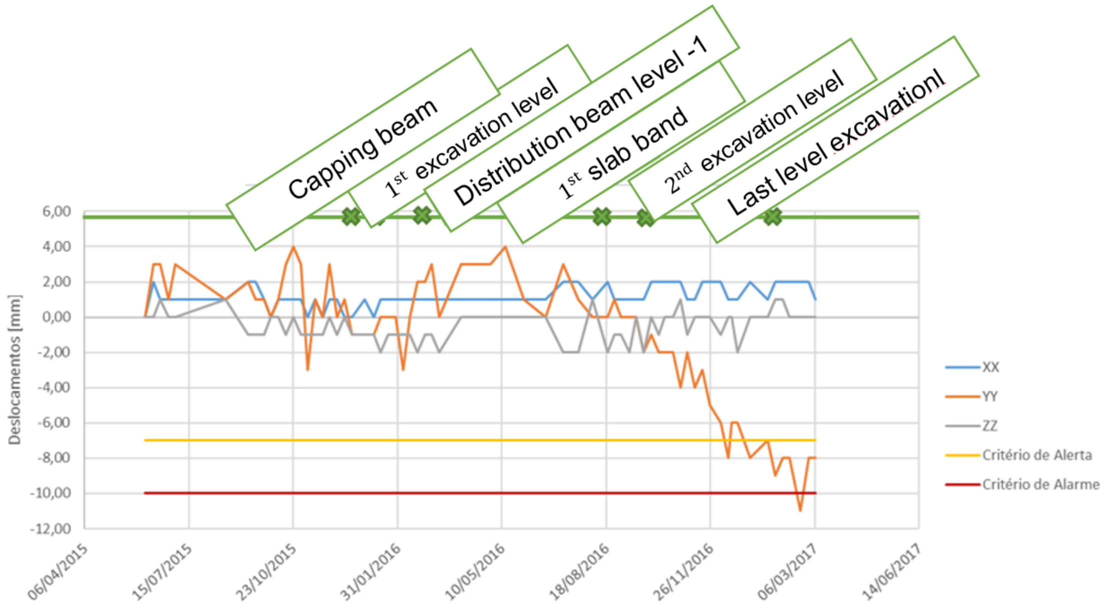

Figure 12: Displacements evolution in station MS5.1.

Geotechnical Zone	Formação	ϒ (kN/m^3)	ϕ' (º)	c' (kPa)	E (MPa)
ZG3	Landfills and yellow Clay soil	17	28	5	10
ZG2	Calys and a Limestones of "Prazees" (NSPT lower to 60 strikes)	24	30	40	15
ZG1	(NSPT higher to 60 strikes)	24	35	75	60

Table 2: Geomechanical parameters of the different geotechnical zones.

Reinforced concrete bored piles wall, braced by slab bands (elevation AB)

The constructive process of the AB elevation consisted in the construction of a piles curtain along the elevation by level, excavation and concreting of the slab bands against the ground.

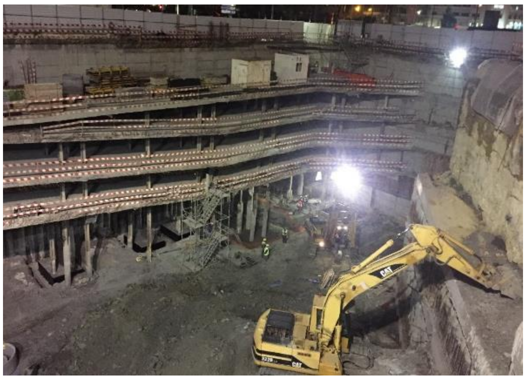

Figure 13: Slab bands at 19/01/2017.

After the blocking of the earth retaining structures, which was constituted by slab band at the floor -1, the same slab is concreted against the ground. In order to allow the subsequent execution of the supporting slab profiles, negatives with 50x50cm should be provided. Through this negatives a drilling will be carried out (minimum length of 5.0m below the final excavation level) and installation. Then drills with a diameter of 400mm are executed in order to install and seal the HEB260 profiles that will support the sections of slab. This whole process is repeated in the following two levels, i.e., up to the floor -3. From the4th floor to the end the entire construction process is identical. The excavation up to floor -5 is set with the GA and BC elevations and to the 6th floor in conjunction with the GA elevation, the walls of the GA and BC elevations are concreted.

Through the 2D model it was concluded that the **maximum horizontal deformation** occurs during the excavation of the floor -2, with a value of 6.4 mm towards the interior of the excavation. This value is lower than the alert criterion, which does not lead to reinforced measures. But it should be noted that this value does not correspond to the reality, since this construction was stopped for 2 months in the excavation phase of the floor -1, which led to reach the alert and alarm criteria and consequently to act with reinforced measures. These measures were used to inject projected concrete against the curtain and to carry out the execution of the slab band. The program used has some limitations, which is the case of the representation of this work stoppage.

It was possible to observe displacements in the interior of the excavation. These displacements happened in all the direction due to the fact that the slab bands had a passive support structure function.

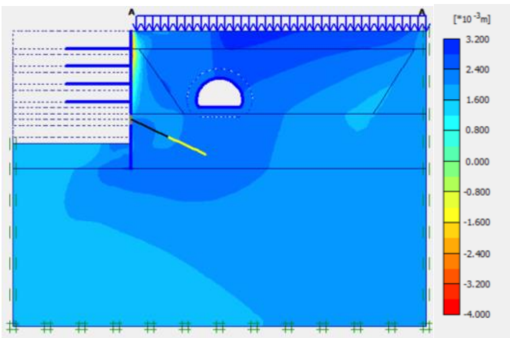

Figure 14: Horizontal deformation at the end of the excavation.

Concreting of the slab band (level -4):

In the concreting slab phase of the floor -4 a maximum displacement between the 2nd and 3rd slab band was detected and it had approximately 3.4 m. Analysing this result and similar ones it is possible to notice that the increase of the displacements at about 2.5 m depth is in agreement with the displacements presented in the inclinometer readings.

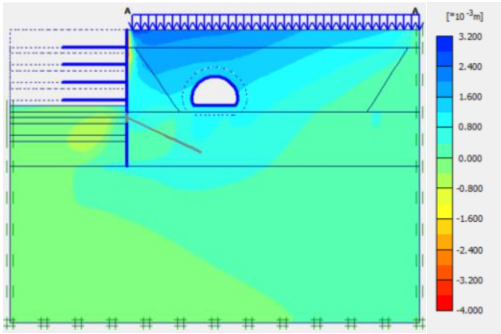

Figure 15: Horizontal deformations corresponding to the phase nº11.

Final Remarks

The visits to the construction allowed verifying the conditions present in the place, to observe the difficulties felt in order to follow the constructive process of all the excavation outlined in the project. The most relevant aspects regarding the difficulties experienced during the follow-up of the construction were the interpretation of the data from the weekly readings. Through this interpretation it was possible to detect problems in the earth retaining structures wall and to apply security measures, sometimes preventive, others of reinforcement.

It is also important to highlight the difficulty felt regarding the data read in the underground of Lisbon, and it is also worth noting the hypothesis of placing an electric station in the metropolitan of Lisbon in order to measure the hourly displacements. Although this measure would be more cost-effective in economic terms, taking into account the downtime of the work and, consequently, the increase in the duration of this excavation, this reinforcement measure would have been an advantage in the interpretation of the displacements at the underground of Lisbon.

As for the chosen model, it was chosen the most conservative, and it was verified that the results would never reach the alert criteria, in case the work was carried out according to the projected time.

Figure 16: Slab bands at 17/08/2016.

Figure 17: Slab bands at 20/09/2016.

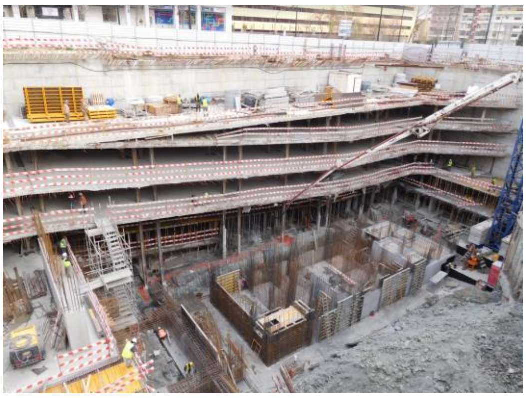

Figure 18: Slab bands at 23/02/2017.

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