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Lisbon new circular Metro underground line: Centenary buildings underpinning

Nouvelle ligne circulaire du métro de Lisbonne: Reprise en sous-œuvre des bâtiments centenaires

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ABSTRACT: The new Lisbon metro line will cross a densely urbanized part of the city, connecting Rato station located at one of the hills of the city and Cais do Sodré station at the Tagus River right bank. Thus, the underground excavation intersects a wide range of materials, from rock mass to soft soils. The new Santos Station will be located partially beneath XIX century buildings with a cover depth of about 15 m, being these structures highly sensitive to differential settlements given its masonry and timber composition with multiple structural pathologies. Given the building conditions, its heterogeneous soil foundation and the level of surface settlements induced by NATM excavation, an underpinning solution was needed aiming to mitigate the buildings potential damages. Hence, high length micropiles, concrete reinforced beams and walls were executed from the building ground floor aiming to transfer buildings loads to the soils located underneath the tunnel excavation. This paper presents an overall description of the adopted solutions, how they were implemented and the buildings' behaviour during the underground works.

RÉSUMÉ: La nouvelle ligne de métro de Lisbonne traversera une partie densément urbanisée de la cité, reliant la gare de Rato, située sur l'une des collines de la cité, et la gare de Cais do Sodré, sur le Tage fleuve. Ainsi, l'excavation souterraine recoupe une large gamme de matériaux, de la masse rocheuse aux sols meubles. La nouvelle station de Santos sera située en partie sous des bâtiments du XIXe siècle avec une profondeur de couverture d'environ 15 m, ces structures étant très sensibles aux tassements différentiels compte tenu de sa maçonnerie et du bois avec de multiples pathologies structurelles. Compte tenu des conditions du bâtiment, de l'hétérogénéité de la fondation du sol et du niveau de tassement de surface induit par l'excavation NATM, une solution de reprise en sous-œuvre était nécessaire afin d'atténuer les dommages potentiels du bâtiment. Par conséquent, des micropieux de grande longueur, des poutres et des murs renforcés en béton ont été exécutés à partir du rez-de-chaussée du bâtiment dans le but de transférer les charges des bâtiments vers les sols situés sous l'excavation du tunnel. Cet article présente une description globale des solutions retenues, de la manière dont elles ont été mises en œuvre et du comportement des bâtiments lors des travaux souterrains.

Keywords: Metro; underpinning; centenary buildings; excavation.

1 INTRODUCTION

The new Lisbon circular metro line will include a new Station in Santos that will be partially located beneath some XIX century buildings with a cover depth of about 15 m, being these structures highly sensitive to differential settlements given its masonry and timber composition while presenting already multiple structural pathologies.

The underground excavation of this tunnel, using the technology known as New Austrian Tunnelling Method, was analysed with numerical models and surface settlements were estimated considering the geological scenario previously accessed. This information was used to evaluate the building vulnerability to those settlements also considering their structural condition and it was concluded the deficient structural conditions of those structures to support the estimated settlements without major damage. Given this scenario, a buildings underpinning solution was proposed mitigating the impact of the underground excavations on those centenary buildings.

2 AFFECTED BUILDINGS

Considering the vulnerability analysis conducted, two buildings with masonry walls and timber floors were classified with a moderated potential damage induced by the underground excavation. Those XIX century buildings have 3 and 5 upper floors and had a superficial foundation (see Figure 1).

Figure 1. Centenary buildings located above de tunnel.

The buildings are located on a hillside on the area where a monastery collapsed due to a strong magnitude earthquake that took place in 1755. Therefore, is it possible that the superficial foundation is located on top of debris fills which worsen its foundation conditions and can justify the differential settlements that were already visible.

Considering this scenario and the settlements estimation from the underground excavation numerical analysis, using Burland's (1997) classification it was concluded that those building, without reinforcement, would potentially suffer moderate to severe damage.

3 MAIN CONSTRAINS

3.1 Geological-geotechnical constrains

The geological investigation campaign included the execution of multiple boreholes that allowed the characterization of the soil units underneath the buildings (see Figure 2). It was possible to confirm that its superficial foundation was on top a 10m thickness Anthropocene fill layer. Bellow that layer, Miocene and Lisbon Vulcanic Complex materials were found showing satisfactory resistance and deformation characteristics.

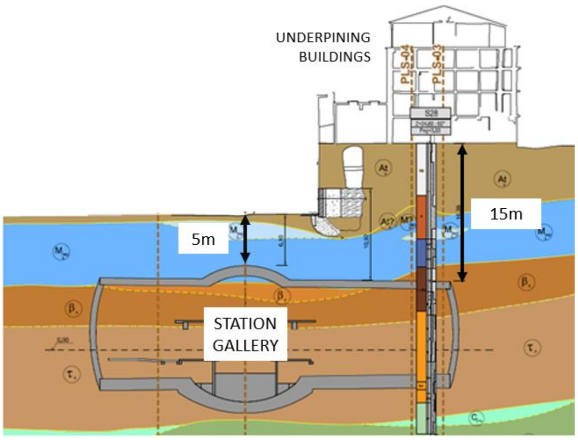

Figure 2. Geological scenario.

3.2 Constructive technologies constrains

The reinforcement solutions must respect the local constraints regarding the accessibility of equipment. Considering the need to work inside the buildings, the solutions must be compatible with equipment that can operate with a minimal ceiling height of about 2,5m.

3.3 Underground works constrains

Underground works consider the excavation using the NATM method which include the use of reinforcement elements such as umbrella soil nails and geodrains that go beyond the tunnel section. The position of those elements must be considered on the underpinning solution to avoid intersection of those elements.

4 UNDERPINNING SOLUTION

To materialize the solution of buildings underpinning, it was proposed the execution of the following elements at the ground floor level:

- Reinforced concrete beams grid, connected to the masonry walls with prestressed threaded bars to promote an effective load transfer do micropiles (see Figure 3) [concrete beams 60cmx80cm | ϕ32mm GEWI bars];

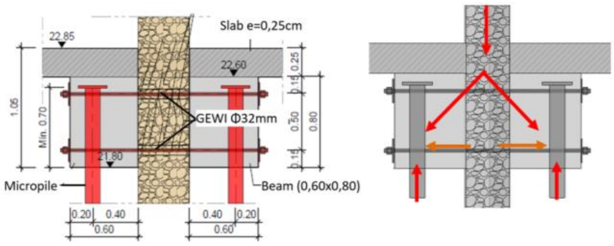

Figure 3. Underpinning solution – Load transfer beams.

- Reinforced concrete lining walls connected to the masonry peripheral walls with stell bolts to promote an effective load transfer [30cm thickness wall];
- Reinforced concrete slab on beam grid for materialization of the ground floor, overall rigidification of the solution and control of torsional forces in the beams [25cm thickness slab];
- Application of sprayable reinforcement mortars reinforced with carbon fibre meshes on internal masonry walls for their confinement and structural reinforcement [S&P ARMO-mesh | S&P ARMO-crete w] (see Figure 4);

Figure 4. S&P ARMO system application.

- Micropiles, vertical and sub-vertical, executed in the alignments of the walls and connected to the beams grid. Its 6m bond length materialized with repetitive selective injection (IRS) is placed outside the excavation influence area, in materials from the Lisbon Volcanic Complex geological unit (see Figure 5) [N80 tube 127x9mm].

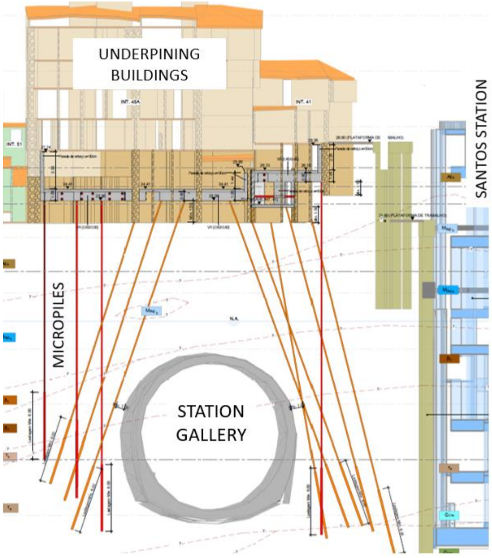

Figure 5. Underpinning solution - Cross section.

The underpinning solution was design to transfer the totality of the buildings load to Lisbon Volcanic Complex competent materials through micropiles with lengths from 20m to 25m, totalling about 4000m of micropiles tubes. That load transfer will occur when the underground works induces a settlement at build foundation level so it is expected that the load transfer can occur gradually with the tunnel excavation progress.

5 SOLUTION DESIGN

The underpinning concrete beam grid was designed using structural models within the SAP2000 software. The grid joint support was placed on micropiles location considering its inclination and using a spring to simulate the axial stiffness of the micropile free length. Those models made it possible to estimate beams structural forces as well as its elastic deformation (see Figure 6).

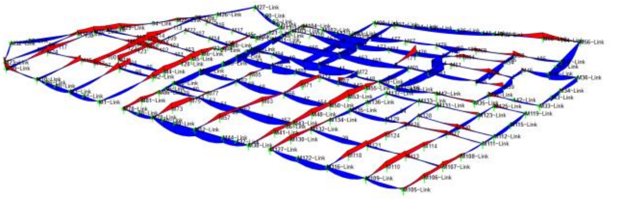

Figure 6. Beams grid SAP2000 analysis – Bending moments.

Considering the joint support springs on the structural model, the maximum design axial load on each micropile was estimated, allowing the safety validation of those steel elements. Since the micropiles free length is placed on influence excavation area it was necessary to account for second order effects so a 20mm as the maximum eccentricity a micropile can be subjected and therefore its design accounted for axial-bending moment verification. A numerical model considering NATM excavation phasing allowed the confirmation of displacements on micropiles to be less than 20mm (see Figure 7).

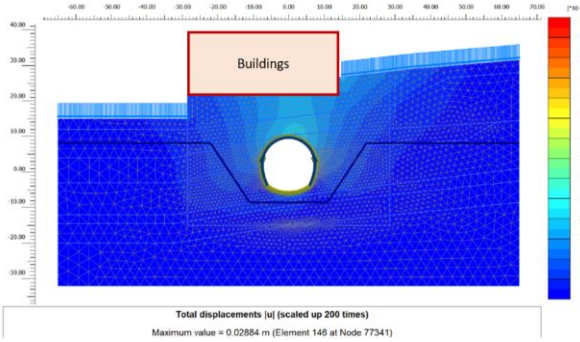

Figure 7. Plaxis 2D – Total displacements.

6 MONITORING AND SURVEY PLAN

Given the highly complexity of the present solution as well as the geotechnical substantial risk scenario a reinforced monitoring plan was implemented. Regardless of the underground excavation typical monitoring plans, at surface inside and outside the underpinning buildings multiple devices were installed such as inclinometers, topographic targets, tiltmeters, crack meters and liquid level sensors. Automated total stations (ATS) were used to access data daily aiming the access of in real-time building behaviour while the underground excavation is implemented and allowing for risk mitigation measures promptly if needed (see Figure 8).

The monitoring and survey plan the establishment of threshold values included for each monitoring device. The numerical analyses results were used to determine reference values for measured parameters that were used to set warning and alarm values, considering warning alarms thresholds as 80% and 120% of the reference values, respectively. Thus, the reach of warning limit means the approximation of the estimated behaviour and alarm means it was surpassed by 30% and therefore the works must stop, and reinforcement measures must be taken.

Figure 8. Automated total stations.

Up to this date, the monitoring survey plan has been implemented with daily measures and the buildings behaviour during the underpinning works and later with underground excavation has been proven as expected, with low settlements reaching a maximum of 3mm (see Figure 9).

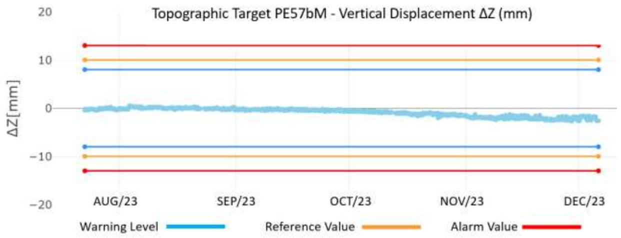

Figure 9. Topographic target - Vertical displacement.

Since the underpinning buildings are located on a hill the mass movements of the soil were also a concern since the station and tunnel underground excavations are taking place at the hill bottom. Thus, inclinometers with 35m long were installed behind those buildings to access deep horizontal soil movements that cloud indicate any global stability issue (see Figure 10).

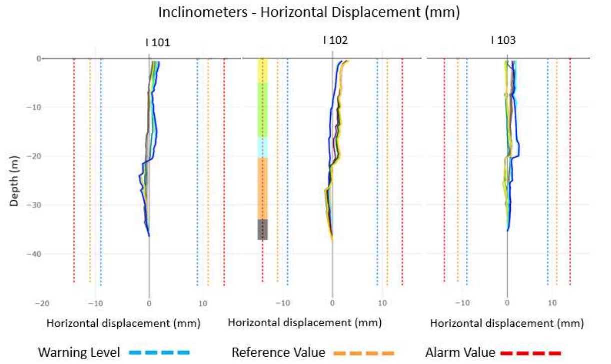

Figure 10. Inclinometers - Horizontal displacement over.

7 CONCLUSIONS

Underground excavations can lead to surface settlements that can impact the structural safety of buildings, particularly centenary buildings were multiply pathologies can already be observed. The use of numerical models for settlement estimation combined with Burland's method to access a buildings potential damage is crucial to determine the necessity of additional reinforcement measures. For extreme scenarios, such as the one presented, an underpinning solution can be most suitable way to maintain the building integrity despite this type of solution often as multiple constrains regarding equipment access and operation (see Figure 11). An adequate monitorization plan is essential to confirm an effective load transfer to the underpinning system while the underground excavation take place.

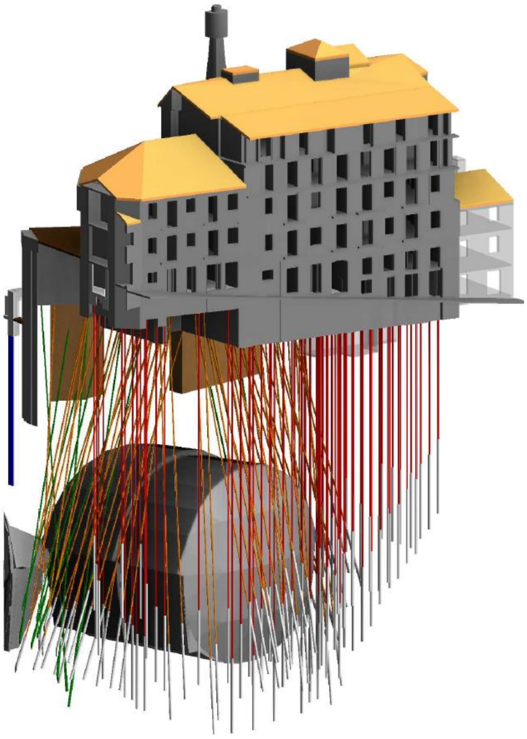

Figure 11. Buildings underpinning view.

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