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Geotechnical challenges of excavating the deepest metro station in Lisbon - Estrela station

Défis géotechniques pour creuser la station de métro la plus profonde de Lisbonne - station Estrela

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ABSTRACT: As part of the future circular line of the Lisbon Metro System, Estrela Station stands out for being the deepest in the network, with a depth of around 60m. Excavated using the NATM methodology from a shaft with quadrangular and circular sections in Miocene and Cretaceous limestone, it posed challenges inherent to this type of work due to its section size, geological singularities or the need to increase productivity. Production was optimized with the excavation of a pilot tunnel from the T33 track tunnel in order to have another front for debris extraction and also serving for geological reconnaissance. Intercepted rock faults, recognized or not in the previous design phases, were addressed in order to mitigate excessive deformations or even potential instabilities. The presence of the second unit of the "Caneças Formation" in the lower section of the station chamber, of a more marl-clayey nature and potentially more deformable, led to the adoption of complementary support solutions foreseen in the project, as well as specific reinforcements.

RÉSUMÉ: Faisant partie de la future ligne circulaire du métro de Lisbonne, la station Estrela se distingue pour être la plus profonde du réseau, avec une profondeur d'environ 60 mètres. Creusée selon la méthodologie NATM à partir d'un puits à sections quadrangulaires et circulaires dans des calcaires du Miocène et du Crétacé, elle posait des défis inhérents à ce type de travaux en raison de la taille de ses sections, des singularités géologiques ou de la nécessité d'augmenter la productivité. La production a été optimisée avec le creusement d'un tunnel pilote à partir du tunnel ferroviaire T33 afin de disposer d'un autre front d'extraction des débris, partialisant la demi-tronçon et servant également à la reconnaissance géologique. Les failles interceptées dans le massif, reconnues ou non lors des phases de conception précédentes, ont été considérées afin d'atténuer les déformations excessives voire les instabilités potentielles. La présence de la deuxième unité de la « Formation Caneças » dans la partie inférieure de la chambre de la station, de nature plus marne-argileuse et potentiellement plus déformable, a conduit à l'adoption de solutions complémentaires prévues dans le projet, ainsi que de solutions de renforcement spécifiques.

Keywords: NATM; shaft; underground station; deepest Lisbon metro station.

1 INTRODUCTION

The newest Lisbon Metro expansion unites the existing Rato and Cais do Sodré stations from the yellow and green lines, respectively, forming a close ring line. This paper refers to Lot 1 with an extension of 1320m, which includes, the Estrela Station, the T33 and T34 double track tunnels (figure 1). Due to the surface level and the track slope limits, the station had to be located approximately 60 meters below surface, which presented some challenges.

The circular section shaft and the station as whole were excavated and monitored using the principles of NATM.

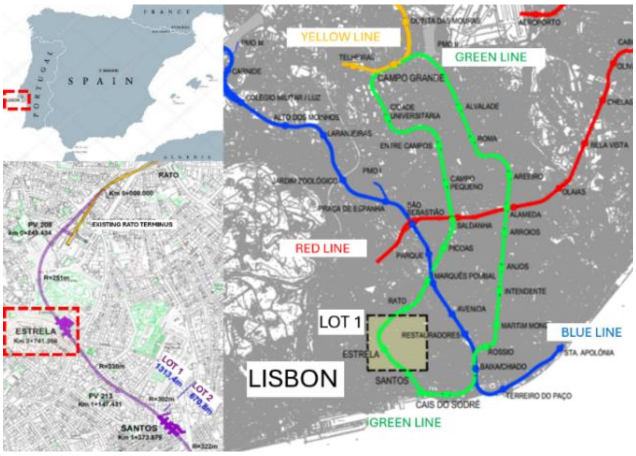

Figure 1. Estrela Station location map.

2 GEOLOGICAL AND GEOTECHNICAL FEATURES OF THE SITE

In the Estrela station area, the geology and geotechnical parameters were previously well known, complemented by a specific survey and in situ and laboratory tests during design phase. Three units were identified with different lithologies and geotechnical parameters (2021a) as shown in figure 2:

-Landfills, with little expression;

-Miocene of Lisbon, namely clays and calcarenites;

-Upper Cretaceous formations having very varied deformability and resistances. Caneças Formation, the lowermost, is characterized by limestones, marls and clays, thus with a wide range in compressive strength and deformability. This formation was intersected at the shaft base and at the northernmost station section. The circular shaft and the station gallery were built within the 40m thick Bica Formation, made of crystalline limestones with high strength and low deformability. All these formations have a 15º tilt to southeast.

Underground water was almost absent and restricted to a level in the Miocene and to sporadic vertical infiltrations in the cretaceous limestones.

Symbology	Formation	Depth (m)	Lithology
Landfill		0-2.0	Landfill, dark brown silty clay with lithic and ceramic fragments
M_{ag}	Prazeres Fm.	2.0-3.4	Brown to grey silty-marly clay, with hardened shell layers.
M_{cal}		3.4-13.0	White to yellowish marly limestone, with levels of calcarenites, somewhat vacuolar.
C_{c1b}	Bica Fm.	13.0-18.2	Yellowish nodular limestone with marls.
C_{c1c}		18.2-25.4	Whitish and very fractured and weathered limestone.
C_{c1c}		25.4-40.0	Yellowish crystalline limestone, very weathered, fractured and slightly karstified.
C_{c1d}		40.0-52.1	Whitish to yellowish compact limestone with veins, weathered and fractured.
C_{c2a}	Caneças Fm.	52.1-60.2	Weathered and fractured marly limestone, with dark gray clay.
C_{c2b}		52.1-68.3	Weathered and fractured marly limestone, with dark gray clay.

Figure 2. Geological-geotechnical profile (M- Miocene; C – Cretaceous).

3 DESIGN FEATURES

The preliminary design defined the need to install the station shaft in a restricted space, limited by buildings and without occupying public roads (figure 3).

Its first level has a square section with dimensions of ~32x32m^2, and containment walls made up of 57 piles with 800mm diameter. On the sides facing the existing buildings, 126 micro piles with 280mm diameter were used, reinforced with HEA160 steel beams. Depending on the height of the containment, between two and four anchoring levels were installed, with variable lengths and net working loads between 365 and 635kN. Their lower section is inbeded in the limestones and locked by a reinforced concrete transition slab to the top of the circular shaft.

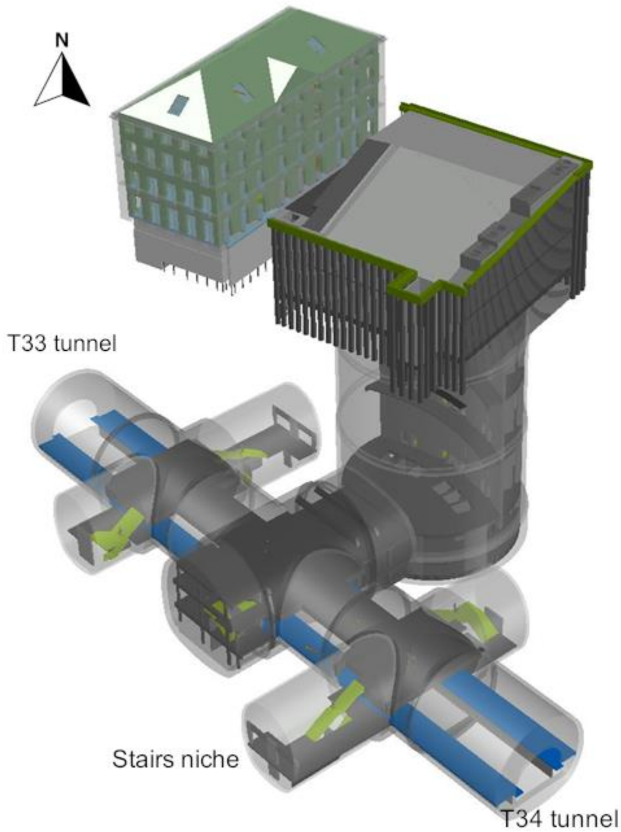

Figure 3. Estrela Station 3D model.

With a diameter of ~30 meters and a stepped and progressively larger section in depth, the primary lining of the circular section shaft is 0.20m to 0.30m thick, consisting of shotcrete and double wire mesh. This was complemented by a mesh of 4.0m long Swellex PM12 rockbolts and occasional 2.0m long geodrains. The advance depth was initially 0.90m, increasing to 2.10m, divided into eight segments, or panels, of the perimeter.

Figure 4. Transition between the square and circular section shafts.

A transversal gallery connects the circular shaft to the station main gallery which is 104m long, 15m high and 16m wide with a total section varying between 220 and 223m2. Four transversal niches accommodate stairs and elevators.

Figure 5. Upper piled wall with temporary ground anchors.

The presence of too closed existing buildings in two sides of the shaft required the use of micro piles with 260mm diameter reinforced with HEB160 steel beams instead of typical 800mm piles. The transition to the circular section shaft was made with a transition concrete slab as illustrated in the following figures.

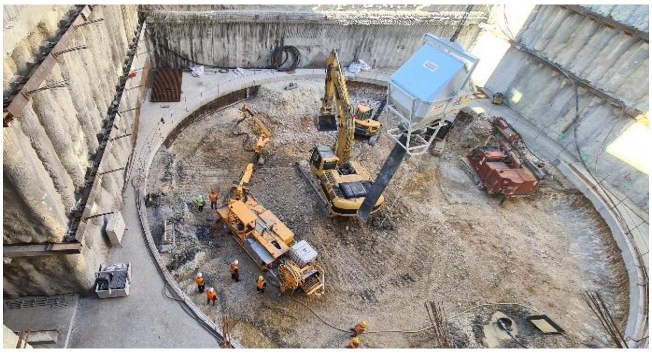

Figure 6. Piled retaining wall and the transition slab to the circular section shaft.

Figure 7. Micro pile retaining wall and beginning of excavation of circular section shaft.

4 SPECIAL OCCURENCES

As the shaft excavation rate was slower than expected, due to limestone with high compressive strength, and as the T33 double track tunnel reached the station face early on, it was studied a smaller section pilot tunnel (figure 8) to attack the station top head section from the double track tunnel. Thus, a considerable volume of rock could be retrieved earlier, leading to an output increase, but also there was the opportunity to make extra geologic mapping since a major fault was a possibility inside the northern station section, as foreseen in the project.

Figure 8. Pilot tunnel section against the station top heading section.

In the south section, an unexpected fault (figure 9), with a *terra rossa* infill, promoted some instability leading to adoption of local reinforcement with extra rockbolts, mesh and shotcrete to smooth the gap. In the falt zone, the transversal niches were also reinforced with longer and less spaced forepoles.

Figure 9. Fault materialized by the reddish-brown clay.

In the station northern section, not only a fault was considered to occur, but also the lower part of the Caneças Formation, with fine bedded grey marls and clays. As the fault was not confirmed during the pilot tunnel survey - it occurred in the final meters of the T33 tunnel- the primary lining that consisted of 0.30m thick lattice girders, shotcrete and, in the bench section, of 6m long Swellex PM16 rockbolts, was maintained.

The Caneças Formation, although dry, were found at the invert level to the middle of the station, and in the bottom of the shaft. This led the designer to request the increase in the reinforcements at the interface with the limestones. These consisted of two lines of 12m long, 25mm diameter steel bars grouted in a 78mm diameter bore with a 30º downward attitude.

Figure 10. Lattice girders extensions at bench height, were the limestone-clay transition is clearly visible.

Figure 11. Southern station section showing in the middle the double track tunnel and side niches for the stairs and elevators.

5 CONCLUSIONS

The executed project was delivered according to expectations, without major issues. We should note that in this kind of underground works underneath urban areas, there are always some uncertainties concerning the rock mass quality, geologic fault occurrences or underground water behaviour, mainly in long tunnels where survey is, sometimes, very spaced with major gaps in between. The few unexpected conditions were addressed by the designer, the designer representative on site and the contractor to successfully adapt the project.

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