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EPB-TBM Face Support Control in the Metro do Porto Project, Portugal

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Abstract

The highly variable nature of the deeply weathered Oporto granite posed significant challenges in the driving of the 8.7km long Metro tunnels with 2 EPBTBMs. Early problems were encountered due to over excavation and face collapse in that extremely heterogeneous geology. Because of the last collapse with fatal consequences the project was interrupted. The difficulties were finally resolved by the introduction of an additional Active Face Support System which involves the injection of pressurized bentonite slurry to compensate automatically for deficiencies in the face support pressure. The project has now been completed with minimal surface subsidence and no face instability.

1. INTRODUCTION

The planned integrated Metropolitan Transport System of Porto includes 70 km of track and 66 stations and excavation of the first section of the C and S lines started in August 2000. This first section, with 6.3 km tunnel and 11 stations, is located under the centre of the picturesque and densely populated city of Porto. The tunnel has an internal diameter of 7.8 m and accommodates two tracks. It was driven by two Earth Pressure Balanced (EPB) TBMs with outside diameters of 8.7 m and 8.9 m. The alignment has a maximum cover of 32 m and a minimum of 3 m.

Fig. 1 Routes of Metro do Porto

Fig.2 Pração dos Aliados

2. GEOLOGICAL AND HYDRO-GEOLOGICAL CONDITIONS

The tunnel passes through the Porto Granite, a medium grained two mica granite which is characterized by deep weathering to a depth of 30 m. It passes through all weathering grades (W1 to W6, as established in the geological classification according to the scheme proposed by the Geological Society of London 1995) altering erratically from fresh granite to residual soil in short distances. A particularly striking feature is that weathered zones of considerable size could be encountered under zones of sound granite.

Fig. 3 Porto Granite all weathering grades

Fig. 4 Borehole samples
Notice: completely weathered granite (left box) encountered under sound granite (right box)

The permeability of the rock mass depends on its weathering grade. In the less weathered rock the flow is primarily related to the fracture system, while in the more heavily weathered material, the ground behaves more like a porous medium. The highly variable permeability of the rock mass has resulted in a very complex ground water regime. Although the overall permeability is of the order of 10^{-4} cm/s or lower, it is considered that preferential drainage paths exist within the granite mass. Because of a lack of cohesion the highly weathered material is vulnerable for erosion under high hydraulic gradients. These extremely heterogeneous geological and hydro-geological facts result in the tunnel being driven in mixed face conditions in which the groundwater loads are difficult to define.

3. EARTH PRESSURE BALANCED (EPB) – TBM

In Porto the complex geological and hydro-geological conditions require tunnel to be driven with pressurized face support. Two TBM types are suitable: Slurry-TBMs or EPB-TBMS. Both types have been applied in comparable ground. The contractor in Porto chose to use EPB-TBMs which provide active support for an unstable face by means of a pressurized earth paste with the consistency of a highly viscous liquid. The earth paste is produced from the excavated soil mixed with additives. Soil conditioning additives such as foam, polymer or bentonite slurry are injected into the working chamber and into the tool gap in front of the cutter head where the excavated material can be mixed with additives.

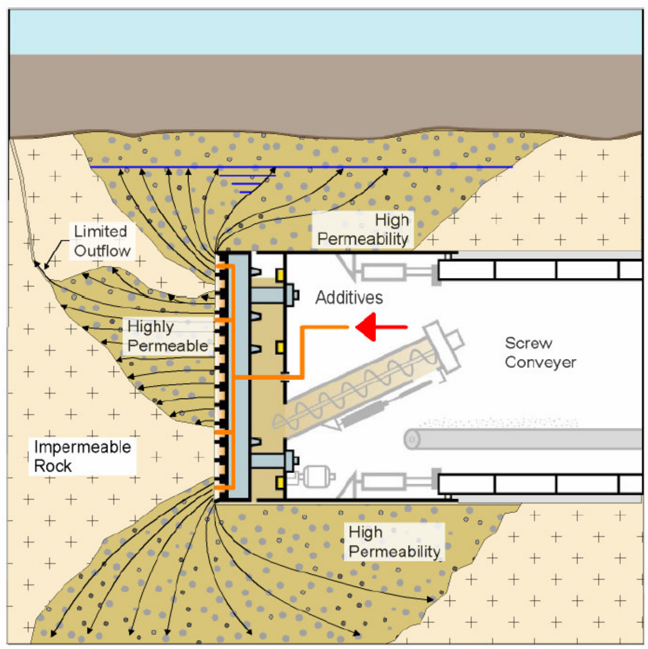


Fig. 5 Complex hydro-geological conditions

Operation Mode

The TBM can operate in different modes. If the EPB-TBM is operated in a so-called closed mode, the working chamber is completely filled with earth paste which is pressurized by the advance jacks via the bulkhead. The pressure level is controlled by the rotation of the excavating cutter head and the rotation of the discharging screw conveyor. Rotation of cutter head and screw conveyor are controlled manually by the operator. More stable ground with sufficient cohesion leads to a temptation to operate the TBM in semi-closed mode. In other words, the working chamber is not completely filled with earth paste. Compressed air support in the empty part of the chamber can prevent local instability of the face. A higher rate of advance, less tool wear and savings on conditioning additives in the semi-closed mode are attractive to the contractor, in comparison with the strictly closed mode operation. Operation of the TBM without any active face support is called open mode. However it is misleading to describe the semi-closed mode and the open mode as an alternate operation procedure of an Earth Pressure Balanced TBM since the earth pressure is not balanced.

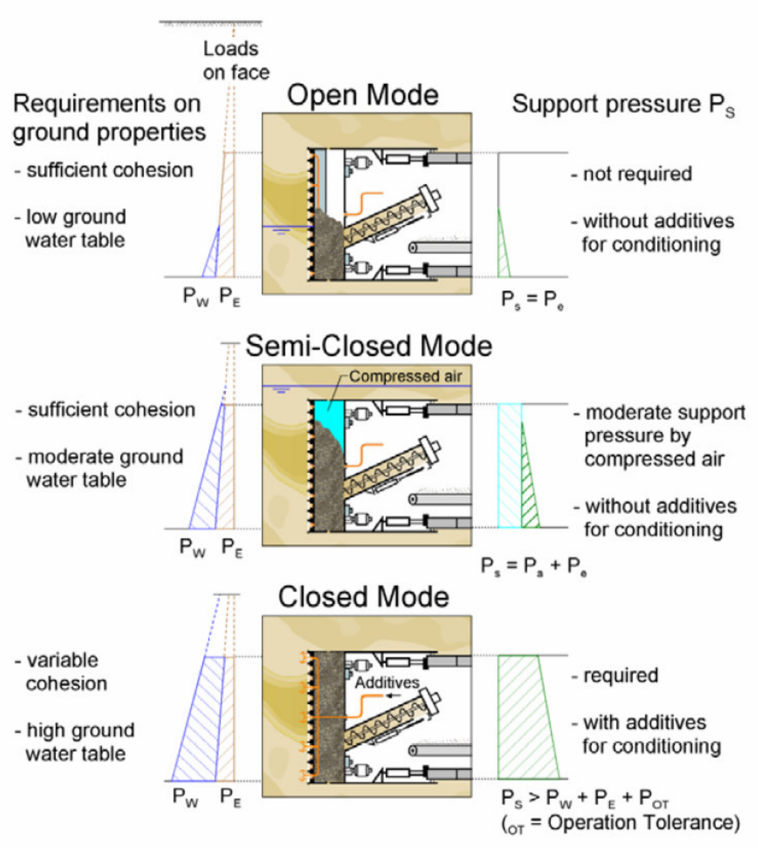


Fig. 6 EPB-TBM Operation mode

4. FACE SUPPORT

A controlled tunnel drive, in ground where the face is unstable because of insufficient cohesion, always depends upon reliable face support pressure to balance the loads on the face. At the beginning of the Porto tunnel drive lack of adequate face support had resulted in over-excavation and local instability of the extremely weathered part of the face with fatal consequences.

Loads on the Face

The loads on the face are generated by ground water pressure and earth pressure. In the Metro do Porto project the stresses at the face were calculated using the model published by Anagnostou and Kovari [1]. For typically shallow Metro tunnels, the water pressure prevails. Consequently intensive investigation of the ground water regime is required. Stresses generated by earth pressure are difficult to determine exactly in heterogeneous ground such as that in Porto. However the values are relatively low and in the range of stresses which have to be taken into account to compensate for the operational tolerances of an EPB-TBM.

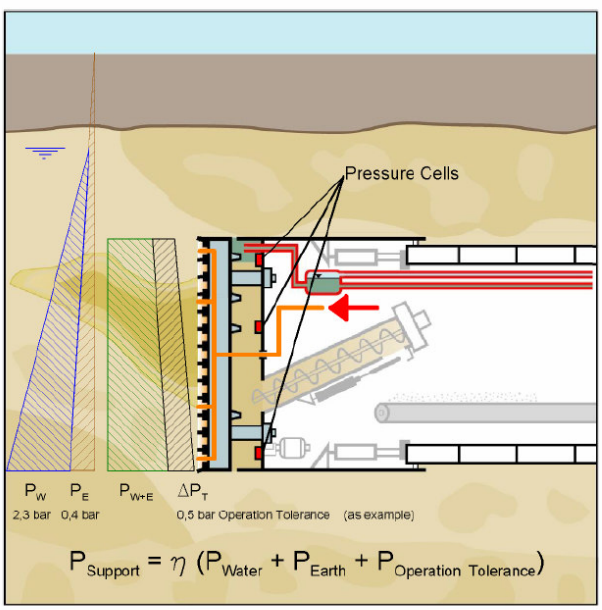


Fig. 7 Stresses at the face

Transfer of Support Pressure

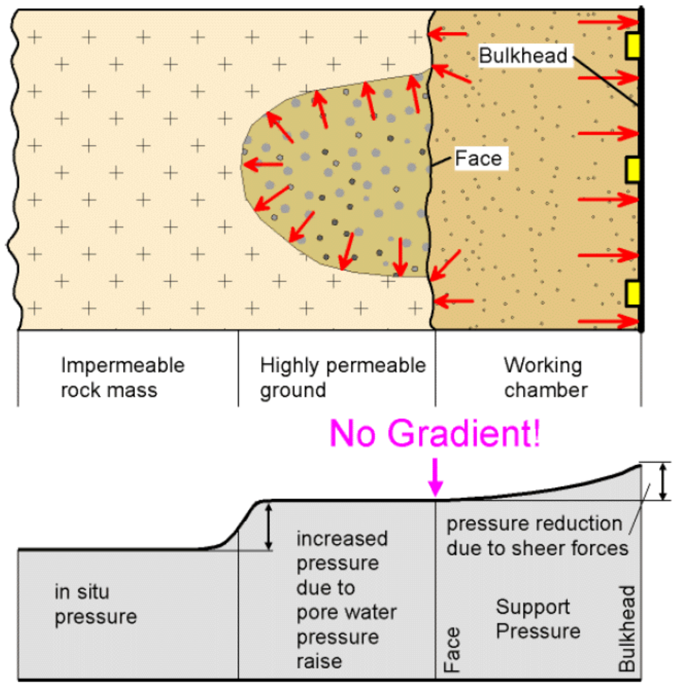


Fig. 8 Transfer of support pressure without membrane

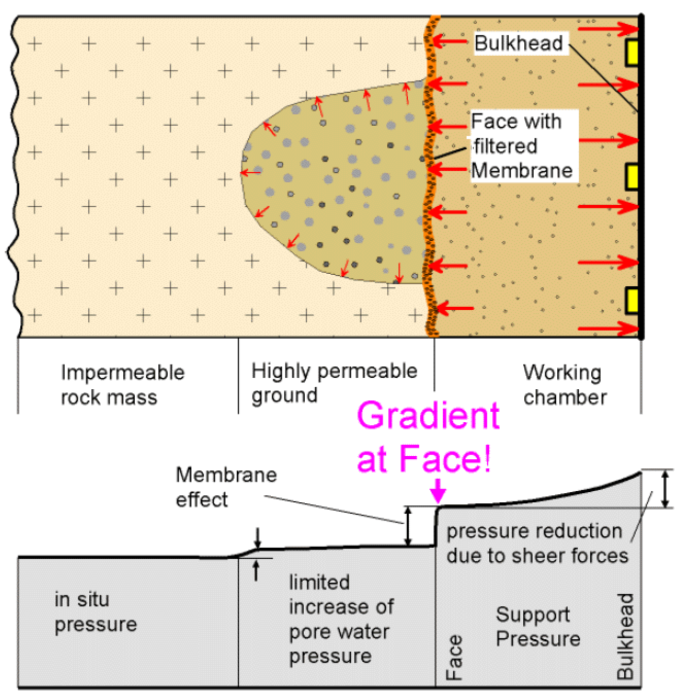


Fig. 9 Transfer of support pressure with membrane

In Porto the complete filling of the working chamber was verified by measuring the pressure in the earth paste by means of pressure cells mounted at three different levels on the bulkhead in the working chamber.

This method satisfied the demand of preventing a sudden collapse of an unstable face, but does not detect a creeping over-excavation or limited face instability. Pressure measurement at the bulkhead, 1.5 m behind the face gives only partial information about the pressure at the face. The support medium, the earth paste created from excavated ground, conditioned by a suspension of different additives, must have the physical properties of a viscous liquid. However, the shear resistance in that viscous liquid reduces the support forces which can be transferred onto the face. This value differs considerably due to the variability of the excavated ground and the conditioning process. Therefore the fluctuation of the face support pressure had exceeded 0.5 bar, which was considered to be unacceptably high.

Areas of high permeability are embedded in the impermeable rock mass as found in the weathered Granite of Porto. It is difficult to transfer support forces via a liquid support medium onto such a highly permeable area of the face unless an impermeable membrane is created on the surface to prevent the ground conditioning fluids from penetrating into the ground and equalizing the pore water pressure and the support pressure. This leaves only the earth pressure to balance the stresses endangering the stability of the face and, given the fluctuations in earth pressure described above; this may be insufficient to maintain the stability of the face. The solution to this problem is to create a nearly impervious membrane on the face by filtration of the solids of the support medium, as described below.

Conditioning of Support Medium

When the ground being excavated consists of a soft clay, the thrust provided by the machine and the controlled removal of the excavated material generates a uniform support pressure on the face. Most soils, particularly those containing rock particles, must be transformed to a highly viscous liquid by mixing additives into the excavated material.

Foam is the most economic additive. It consists of water, air and tensides.. These tensides, mixed with water, readily form bubbles when introduced into the foam generator with compressed air. These air bubbles typically diffuse or break down within 2-3 hours after the foam has been generated. This diffusion process has only limited effect on the face support during a continuous operation of the TBM. However, if the TBM is stopped for a longer period, the diffused air accumulates in the crown area of the working chamber, penetrating partly into the ground and leaving a zone of reduced support pressure. In addition to this effect the air penetrating the soil can increase the pore water pressure in the soil at the face because its relative viscosity is 70 times lower than water. Because the foam contains only gaseous and liquid substances it does not form a membrane at the face to transfer support forces.

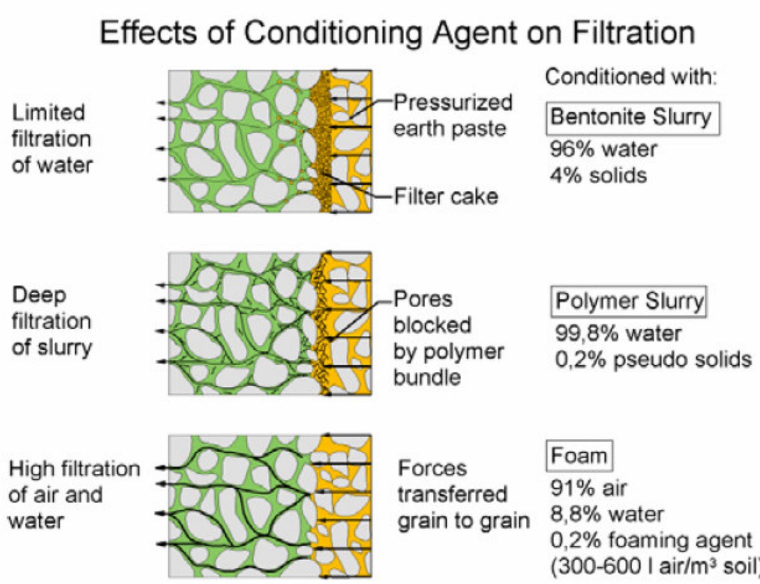


Fig. 10 Effects of different agents

Polymer-Slurry is another common conditioning agent and its properties remain constant during the operation and even if the machine is stopped for a significant time. Because the additives in a Polymer-Slurry are almost liquid, it has a limited capacity to form a membrane on the face. However, it is effective in transforming the soil into a paste and in minimizing large pressure fluctuations.

Bentonite-Slurry acts in a similar way to Polymer-slurry but, because of the presence of solids in the additives, it is able to form a membrane on the face. Therefore it is a favourable conditioning agent for use in pervious granular ground.

5. FACE SUPPORT CONTROL IN PORTO

The nature of the weathered Porto Granite and its extreme heterogeneity combines all the negative elements which influence the ability to control the face support pressure as described above.

Demand for Closed Mode Operation

The variety of the excavated material resulted in a wide range of earth paste shear-strength causing high fluctuation of the support pressure. The complex ground water regime with different grades of permeability reduced the effective support pressure by increasing the pore water pressure in areas with limited drainage. Application of foam as conditioning agent amplified this effect. In addition, the reliance on the machine operator to make adjustments based on observations of the EPB-TBM instrumentation did not contribute to the reliability of the face support pressure. Pressure fluctuations up to 0.5 bar were typical.

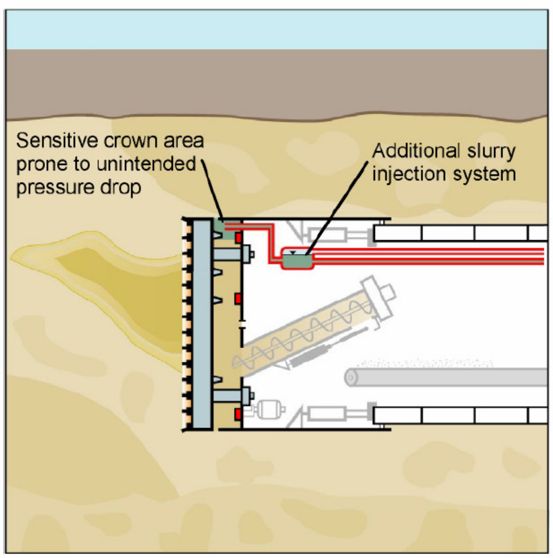
All these features involve some component of risk, particularly when excavating in soils with low cohesive strength. However, operation of the machine in semi-closed mode, as was done in the early part of the drive, increases these risks to an unacceptably high level and several collapses occurred.

These collapses resulted in the project being stopped for several months during which major improvements in the operating process were introduced. The most important of these improvements were:

a. the EPB-TBM was required to be operated exclusively in closed mode and
b. an additional Active Face Support System was installed on the TBM.

Additional Active Face Support System

The Additional Active Face Support System is designed to compensate for deficiencies of the face support pressure. It is positioned on the back-up train and consists of a container filled with pressurized Bentonite-Slurry linked to a regulated compressed air reservoir. The Bentonite-Slurry container is connected with the crown area of the working chamber of the EPB-TBM. If the support pressure in the working chamber drops below a predetermined level the Active Face Support System automatically injects pressurized bentonite slurry until the pressure level loss in the working chamber is compensated. This addition of this Active Face Support System to the EPB-TBM results in an operation similar to that of a Slurry-TBM. This automatic pressure control system reduces the range of fluctuations of the face support pressure to about 0.2 bar.



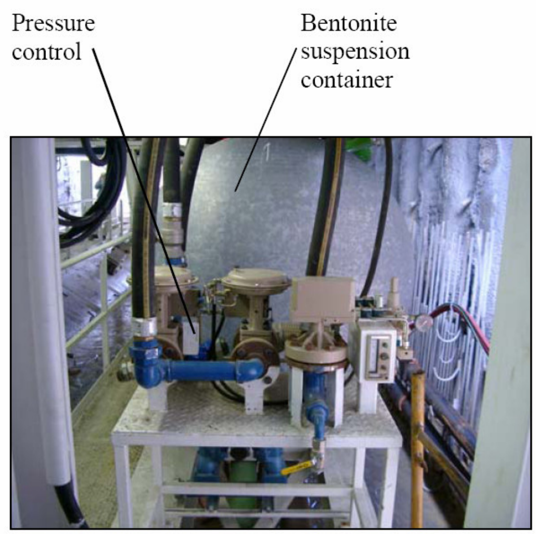


Fig. 11 Additional Face Support System   Fig. 12 Installation of AFSS

The application of the Active Face Support System in the Metro do Porto project was the first time that this system had been used. There was initial concern that the addition of the Bentonite-Slurry would alter the characteristics of the muck to the point where it could no longer be contained on the conveyor system and that additional slurry muck handling facility may be required. This concern proved to be unfounded since the volume of Bentonite-Slurry injected proved to be very small and there was no discernable change on the characteristics of the muck. The predetermined support pressure was determined from calculations using the method published by Anagnostou and Kovari (1996) [1] which proved to be reliable for these conditions. The Active Face Support System was extremely effective in maintaining the predetermined support pressure and no serious face instability or over-excavation problems were encountered after it was introduced. In fact, the system permitted the 8.9 m diameter TBM to pass under old houses with a cover of 3 m to the foundations, without any pre-treatment of the ground. Surface settlements of less than 5 mm were measured in this case. The boring of the section under this shallow cover is described in a paper from Diez and Williams, 2003 [2]. The Active Face Support System was also connected to the steering gap around the shield and the filling of this gap with Bentonite-Slurry provided a reliable means of maintaining a predetermined pressure in the steering gap.

6. CONCLUSIONS

The highly variable characteristics of the weathered Granite in Porto and the erratic changes demonstrated the feasibility threshold of the usual EPB-TBM technology according to the actual state of art in heterogeneous ground. The impossibility of accurately predicting and maintaining the correct face support pressure resulted in significant over-excavation and collapses at the beginning of the drive. The introduction of an additional Active Face Support System which automatically compensates deficiencies in maintaining the predetermined face support pressure proved to be a very effective improvement of the actual applied EPB-TBM technology.

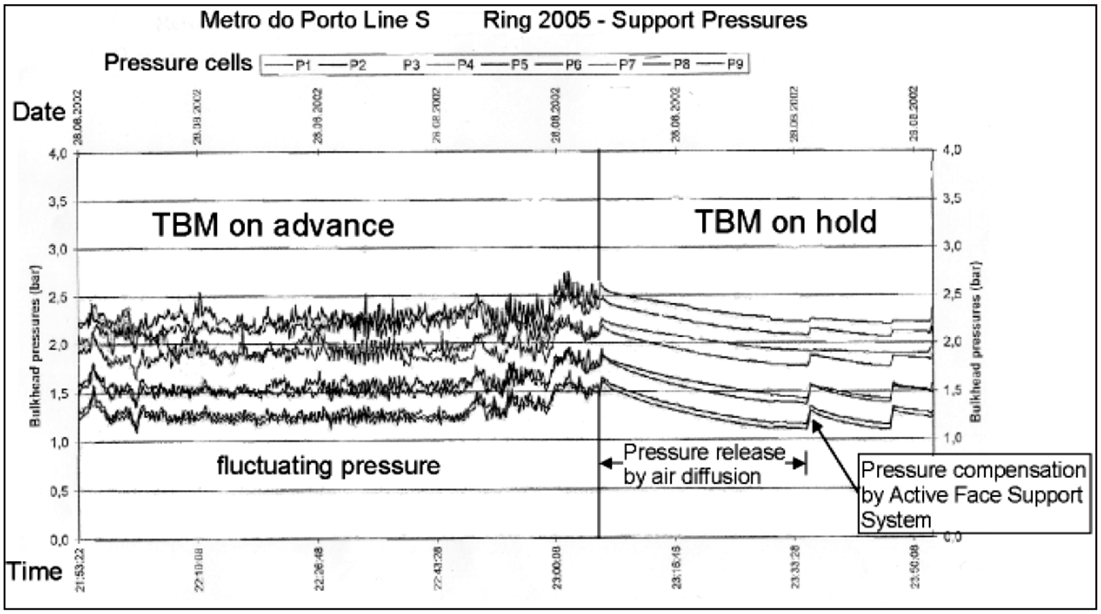


Fig. 13 Typical characteristic of face support pressure

7. ACKNOWLEDGEMENT

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8. REFERENCES

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[2] Diez R. and Williams R. "Tunneling under very low cover - Approach to Trindade station, Porto Metro, Portugal