France – Spain High-Speed Rail Link, Perthus Base Tunnel:
Crossing Very Difficult Terrains with Two Double Shield 10m-Diameter TBMs

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1 Introduction

The international Perthus tunnel is part of the new international high-speed rail link between Perpignan (France) and Figueras (Spain). The tunnel is about 10 km long and comprises two tubes with an inside diameter of 9.40 m and an excavation diameter of 9.96 m. The distance between these tubes is 20 to 35 metres, depending on the geotechnical conditions of the ground, and they are connected with bypasses every 200 metres. The main tunnel direction is N-S. Work was carried out by a joint venture involving EIFFAGE (FR) - DRAGADOS (ES) based on a planning and construction scheme within the framework of a B.O.T. type Contract Concession. The tunnel was excavated between October 2005 and February 2008 (28 months), with an average production of roughly 350 metres per month, although there were long sections where DSTBM could advance by up to 550 metres per month. The final result was significantly affected when crossing a very critical central zone where production decreased to 50 metres per month. Two slightly conical 9.96 m diameter Double Shield TBMs were specifically installed by Herrenknecht. Mucking was carried outside using a band conveyor, while supplies were delivered to the face by rail. The bypasses were excavated by D&B methods in accordance with advancement of the tubes.

Figure 1a

Figure 1b

Figure 1 – The head of the Herrenknecht 52 cutter equipped with 9.96 m diameter conical Double Shield TBM ready to drive from the Spanish entrance portal (1a) and a view of French side exit portal (1b).
2 Geological overview

From a geological point of view, the Perthus Base Tunnel is located in the Pyrenees Chain and passes through the Axial zone close to the western limit of the Alberas Massif. The terrain primarily comprises Paleozoic granites and metamorphic schistose rocks subjected to significant tectonic action during the formation of the Pyrenean chain. The orogenetic structuring was subsequently affected by significant fragile tectonic action that gave rise to a number of regional faults, the most important of which are the Boulou fault, the Sant Climent fault and the Mas Anglade fault. These are high angle dipping faults in an E-W direction (Boulou, Mas Anglade) and NNW-SSE (Sant Climent).

2.1 Expected geological conditions

In the course of several investigation stages, carried out between 1997 and 2003 by the Grantor and subsequently integrated into the Joint Venture after 2004, 9200 metres of cored boreholes were drilled and integrated with geotechnical tests, geophysical investigations and hydro-geological studies in order to foresee and understand better the geometry and geo-mechanical features of the geological bodies to be excavated.

In the central sector alone, about 2000 metres long and the subject of this article, a further 2500 metres of cored boreholes were drilled. This imposing number of investigations revealed that crossing the central sector would be particularly critical, not the least because the presence of the above-mentioned Sant Clément and Mas Anglade faults - acting as hydraulic barriers - would have seen huge quantities of pressurised water enter both excavating tubes.

It was therefore decided to create an access tunnel leading to two recognition and treatment galleries from which the fault zones could be treated with massive injection interventions. Briefly, the expected model envisaged excavating the base tunnel inside a sequence of granites and schists crossing a central zone characterized by a fault system which would be preventively treated before the passage of the TBM. The Boulou fault zone, comprising by gouge and cataclastic rocks for a thickness of almost 80 m located approximately 500 m before the breakthrough (north side), was also expected to be treated specifically before the passage of the TBM.
2.2 Geological conditions encountered

In June 2004, during TBM assembly, the excavation of the Les Cluses access tunnel to the recognition and treatment galleries was started in order to inject and treat the Sant Clement and Mas Anglade faults zones. The initial rock mass actually presented much poorer geo-mechanical conditions than those anticipated and, above all, was characterised by a fragile sub-horizontal structure affected by significant tectonic action.

Systematic analyses of the geo-mechanical conditions of the rock mass at the excavation faces, together with a new investigation campaign, identified the presence of a sub-horizontal thrust within the metamorphic schists, characterized by the pervasive presence of impermeable argilled (clay) layers of extremely poor mechanical quality. In 2005, geological knowledge was significantly improved thanks to the excavation of galleries that allowed a critical review of all borehole data. The resulting new model showed a completely different picture to what was initially expected: the original risk of having to deal with very permeable ground to be treated with injection became the risk that TBMs would have to cross geo-mechanically poor material, potentially subject to squeezing.

Figure 4 – Photos of the Les Cluses treatment adit tunnel driven into the unforeseen sub-horizontal shear zone: 4a: a preserved paragneiss level within the clay-rich sheared schist; 4b) quartzite sill faulted and sheared by low angle planes

Figure 5 – Detailed geological cross-section along the Les Cluses section revised on the base of new geological information provided by excavation of the adit tunnel and deep re-analysis of borehole logs and surface outcrop surveys.
Moreover, the heterogeneity of the rock mass proved to be a major problem, because of the simultaneous presence of argilled and cataclastic layers enveloping more compact and harder blocks or rock mass sectors. The unequivocal signals that the geologic context was significantly different and decidedly worse that the expected situation were already clear during the excavation of the Les Cluses access tunnel and bifurcation to the treatment galleries.

During these excavation phases, very significant convergences were recorded, suggesting the choice of heavy section application and the need for a systematic new evaluation of already excavated gallery sections supported by contrasting beams placed at the base of steel arches. Since the geological conditions appeared to be significantly different to those expected, all efforts focused on indentifying the procedures needed to manage and control the risks associated with the passage of TBM through the critical zone.

Injection tests were performed on the advancing faces of the treatment galleries in order to verify if it would be possible to improve the geo-mechanical conditions of the rock mass but, because of the low permeability of the rock mass itself due to the high percentage presence of clayey material, such action did not seem to be feasible.

Moreover, since the critical zone span was much wider than the extension of the treatment galleries, a method was investigated in order to minimise the risk of TBM blockage in a swelling and squeezing rock mass. It was therefore decided to define operational procedures considering:

1) The features of the mucked rock mass (relative proportions of hard rock/clay, etc),
2) The weight of mucked material for every stroke,
3) The TBM excavation parameters recorded, particularly:
   3a) torque,
   3b) power absorption for each motor groups,
   3c) thrust and advancement ratio.

Finally, three risk levels were defined:

a) low risk: excavation in a rock mass characterised by prevalence of the rock component over the clayey component, weight of mucked material equal to the expected figure plus 5% and TBM driving in accordance with standard procedures, reduction of rotation speed to 3 rpm.

b) medium risk: excavation in a rock mass characterised by prevalence of the clayey component over the rock component, weight of mucked material equal to the expected figure plus 15%, increase in thrust of group C motors (lower one) and reduction of rotation speed to 2 rpm.

c) high risk: excavation in a rock mass characterised by a clayey component significantly prevailing over the rock component and weight of mucked material equal to the expected figure plus 20%, reduction of rotation speed to 1 rpm, injection of polyurethane foam at the face and injection of resin in the event of over-excavation.
Significant changes in recorded parameters were observed at the transition point from the granite unit to the sheared area, affected by both strong convergence (re-gripping) and decreasing mechanical characteristics of the rock mass (increased piston thrust on lower side of group C).

Steel pipe umbrella execution, through which foam was injected above the TBM heads, was planned in the case of clayey, water saturated and unstable faces.
On crossing the critical zone, the following situations arose:

1) crossing the critical zone without the presence of the treatment galleries or at some distance from them was tackled without encountering particular problems, with reduced advancement speeds in the order of 10 m/day.

2) crossing the critical zone within the sector affected by the presence of the treatment galleries involved significant problems associated with the persistent plasticization of the rock mass caused by the realization of the galleries themselves. The first of two TBM's barely managed to advance at a slow but constant speed, with a daily rate in the order of 5 m/day. However, its passage produced a further increase in rock mass plasticization, generating widespread instability of the faces that the second TBM had to excavate.

3) crossing the critical zone by both TBM's was finally possible only after injection of more than 5,000 cubic metres of foams and resins within a loosened rock mass which, at that point, because of generally increased permeability, required such injection.

French – English translations: risque de attrapage = risk of locking/staking; risqué de cloches = risk of over excavation; failles = faults; augmentation permeabilité = permeability increasing; venues d’eau = water inflow; grossier = coarse grain muck; fin=fine grain muck