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# Scoping Calculations of TBM Advancement in Flysch and Breccias of Strait-of-Gibraltar Tunnel

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## Abstract

The planned railway tunnel of the Strait of Gibraltar is destined to be one of the most challenging underground structures ever built, given the depth, exceptionally high pore pressures and very poor rock quality at several stretches of the tunnel alignment. The more critical issues of the on-going study are large water in-flows when intercepting fractured arenaceous layers within the flysch formation and excessive deformations in the breccias of the two paleo-channels. The countermeasures designed for the first risk are grout injections and drainage in advancement. For the second risk a consolidation by drainage before the advancement is executed is proposed. Given the limited knowledge of the distribution of rock units and related mechanical parameters, different scenarios have been investigated with respect to undesirable effects as huge water venues, large plastic zones and convergences. FLAC 2D and 3D in the framework of hydro-mechanical coupled and uncoupled analyses have been utilized and the results are illustrated herein.

**Keywords:** Numerical analysis, tunnel excavation, consolidation, water in-flow

## 1 INTRODUCTION

A selected group of international geo-engineering companies and experts, under the general coordination and management of the two leading companies, SECEG and SNED, appointed by the Governments of Spain and Morocco, respectively, are actually carrying out an update of the conceptual design aimed both to confirm the feasibility of the tunnel and at the same time to identify the optimal design solution for the project from the different points of view (construction, safety, maintenance, time & costs, etc.). Intuitively, such an optimal technical solution can only be selected based on an adequate risk analysis, which is also the basic input to and guideline for the whole design process, from the actual preliminary phases to the construction details. On the basis of the performed risk analysis [1], two main risks for tunnel construction appear clearly dominant as primary consequence of the geomechanical and hydrogeological setting:

- the risk associated to large water in-flow/water pressure in correspondence of fractured (permeable) rock masses, or unforeseen lenses of sands and gravels (chapter 2);
- the risk of trapping of the TBM for very high squeezing behaviour in coincidence with poorest flyschiod rock masses and, overall, of the clayey breccias in the two paleo-valley (chapter 3).

This paper will focus on the numerical analyses performed by Geodata as contribution for evaluating these two main risks and the possible mitigation measures related to the feasibility of this challenging work.

## 2 TBM ADVANCEMENT IN FRACTURED ARENACEOUS LAYERS

Two aspects have been studied in detail by numerical analysis (FLAC 2D-3D):

1) the potential water in-flow during TBM advancement,
2) the stability of tunnel face approaching to a water bearing and high permeable rock mass.

In the first case (1), taking into account the available information, the hypothesis of an oblique intercepting of a 20m thick water bearing layer of fracturated sandstone, have been modelled, as well as the mitigation measures, consist of grout injection and drainage in advancement (Figure 1). The hydraulic characterization of the arenaceous layer has been derived by stochastic generation of the inner fracture network (see Figure 2), obtaining an average conductivity in the order of $K=10^{-6}$ m/s. Nevertheless, given the high uncertainly a large variability of the hydraulic conductivity has been considered ($K$ from $10^{-8}$ to $K=10^{-4}$ m/s). In figure 1 the FLAC model is also presented. The results of the numerical analysis in terms of total discharge $Q$ (in l/s) are given in Figure 3.

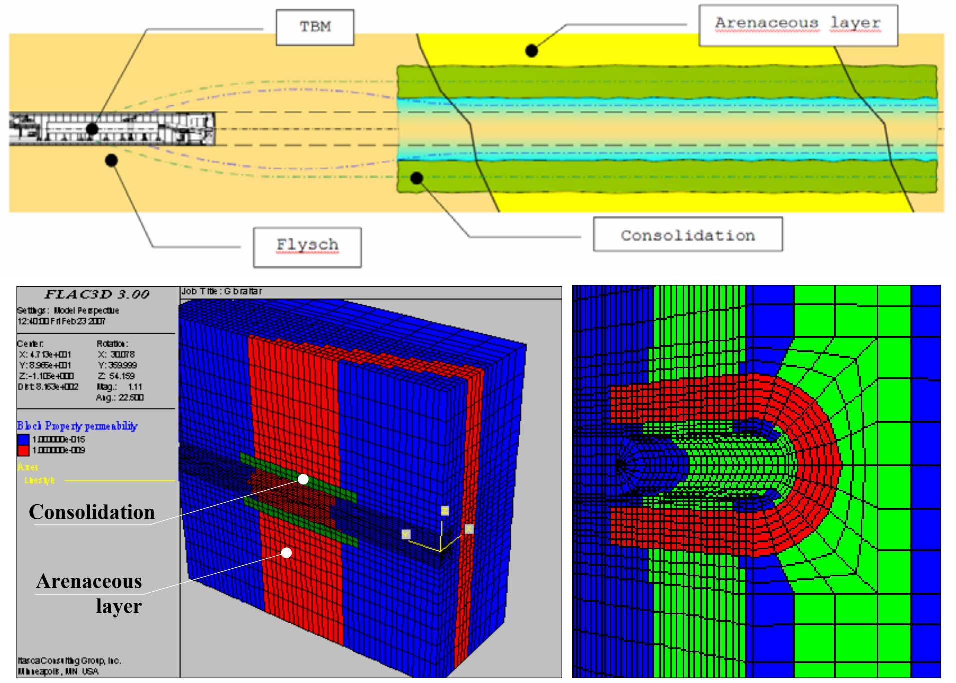

**Figure 1:** Scheme of the solution and FLAC 3D model for the study of the water inflow

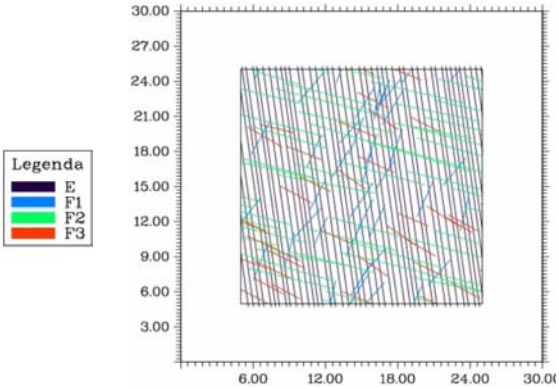

**Figure 2:** Stochastic generation of the inner fracture network derived from available geostructural information

The main results obtained are the following:

- for the average hydraulic conductivity ($K=10^{-6}$ m/s) a unitary discharge of about 3l/s is expected. Such a value increases for about 20l/se and 300 l/sec for $K=10^{-6}$ m/s and $K=10^{-4}$ m/s respectly;
- after grouting the tunnel inflow in the arenaceous layer is one order of magnitude less than the inflow in intrinsic conditions, irrespective of the value of hydraulic conductivity *K*.

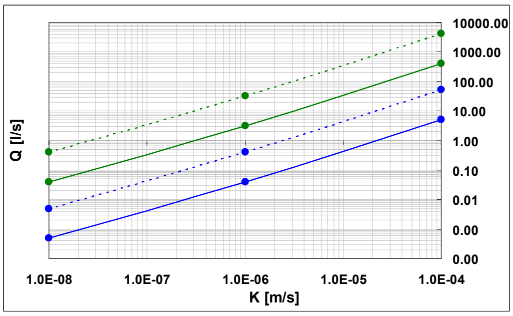

**Figure 3:** Numerical analysis results Q (in l/s): unitary discharge for both the natural condiction and the reduced permeability by ground; cumulative water in-flow by considering the total interference with the arenaceous layer of 80m

For the case 2) a mechanical analyses was performed in radial axial-symmetry conditions by FLAC5 code. The extension of the disturbed (plastic) zone (*d*) beyond the front does not exceed 10 meters (see Figure 4).

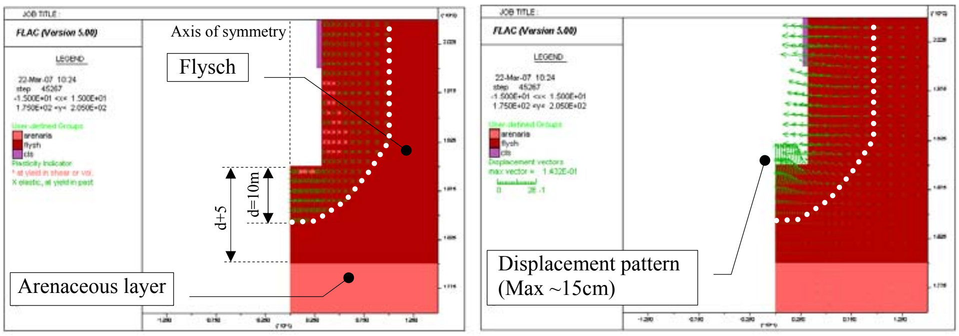

**Figure 4:** Mechanical response to the excavation: deformation induced and extension of the plastic zone

The grout injections for the consolidation the arenaceous layer may be activated at *d*+5 m from the beginning of the arenaceous layer (where 5m is a safety margin), so that no consistent disturbance is produced on the arenaceous layer and no increase of conductivity is expected.

## 3 ADVANCEMENT IN THE PALEO-CHANNELS

The most critical sections of the tunnel should be located at 475m below the sea level, covered by 175m of flysch and paleo-breccias alternatively. Given the poor geotechnical context and very high pore pressure, the excavation appears very problematic particularly in the last formation, which might extend up to 3-4km (Figure 4). The trapping of TBM when crossing the breccias is one of the main potential risks, therefore several technical solutions to avoid it have been investigated. A reasonable solution appears the drainage of the rock that brings to an increase of the effective stress dominant around the excavation and produces a corresponding increase of the short-term strength. The solution analyzed consists of a crown of 50m-long horizontal drains inserted ahead of the face to spill water from the rock in a prescribed time span.

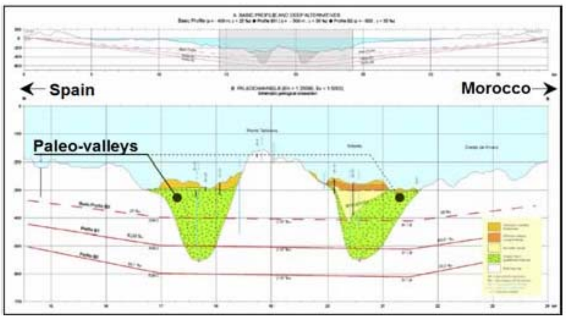

**Figure 5:** Geology with indication of the paleo-valleys (after Pliego, 2005 [1]). According the most recent studies, the relative extension could be larger than depicted (total length=3-4km)

### 3.1 The Numerical Models

A plane-flow/plane-strain fully hydro-mechanically coupled model and an axial-symmetric uncoupled one have been performed (Figure 5). The first model simulates the evolution of pore pressure, strain and stress with time ahead of the tunnel face along a vertical section normal to the tunnel axis. The second one simulates the TBM advancement. Only a quarter of the cross section is considered. A crown of boreholes is located at 4.5m from the center and a nil pore pressure is imposed along the boundaries. At the far boundary the *in situ* pore pressure $p_i$ is imposed. The following mechanical parameters have been utilized: unit weight $\gamma$=23KN/m$^3$, drained elasticity modulus $E$=300MPa, Poisson coefficient $\nu$=0.30, hydraulic conductivity $K$=$10^{-10}$m/s. In Figure 6 the evolution of both pore pressure $p$ and effective isotropic stress $\sigma'_0$ is shown at a location 30cm far from a drain. The increase of isotropic effective stress brings to an associated increase of short-term resistance $c_u$.

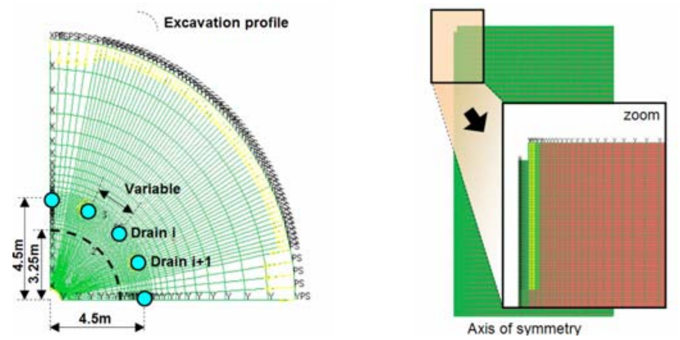

**Figure 6:** The two FLAC models: *Left*) Plane strain. *Right*) Axial-symmetrical grids

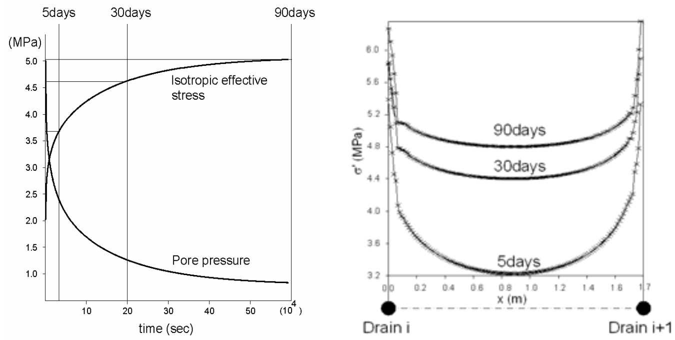

**Figure 7:** *Left*) Evolution of pore pressure and isotropic effective stress in a location 30cm far from a drain. *Right)* Isochrones of the isotropic effective stress at 5, 30, 90 days along the line joining two drains

The effect of drainage brings to an increase of $\sigma'_0$. Given the symmetry, the excavation produces theoretically only deviatoric stresses; if we assume a purely poroelastic behaviour, no excess of pore pressure is therefore produced before the onset of failure. Under these conditions the short-term strength $c_u$ assumes with time the following value:

$$c_u = \left[\sigma'_0\left(t_D\right) + \frac{c'}{\tan\phi'}\right]\sin\phi'$$

where σ'$_0$ ($t_D$) is the effective isotropic stress at a time $t_D$ after the activation of the drains. The formula comes from trigonometric considerations.

In Figure 7 the pattern of cu at 5, 30 and 60 days for 5 drains is reported. The benefit is consistent strictly close the boreholes. However, the increase of strength is required mainly at the front for TBM advancement under safe condition.

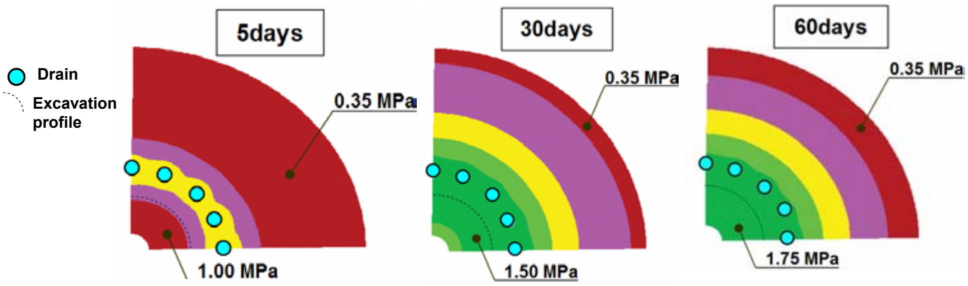

**Figure 8:** Patterns at 5, 30, 60 days of cu for 5 drains per quarter

Therefore the solution at 30 days for 9 drains per crown and per quarter seems more effective. Given the pattern of $c_u$ for this layout of drains, tha second model (axial-symmetric – Figure 8) has been performed. The analysis is in total stresses (undrained condition). The benefit of the drainage is evident if compared to the case without any treatment. The optimal construction solution can be found by sensitivity analysis, analyzing the effect of the change of two main variables, i.e. the number of installed drains and the relative activation time.

## 4 CONCLUSIONS

The advancement of TBM in the flysch formation can be safely executed if grouting is performed before the arenaceous layers have been encountered. Through the numerical analyses the effect of a grout belt is assessed with respect to the water venue and prescription about the activation of grouting can be defined. As far as the advancement in the breccias of the paleovalleys is concerned, the consolidation by drainage of the material before the excavation takes place is recommended, as elicited by the interpretation of the numerical analyses. Consolidation implies an increase of short-term strength and a more favorable excavation response. It may be realized by means of a crown of horizontal drains ahead of the tunnel face. Despite the low permeability of the rock, the progress of consolidation is rather fast, as a consequence of the high gradients.

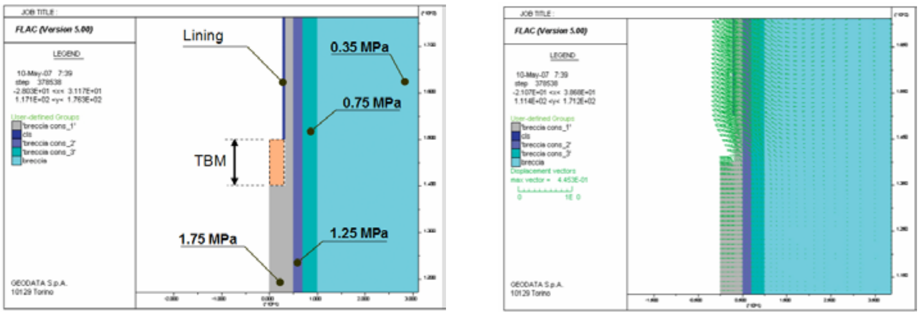

**Figure 9:** *Left*) Axial-symmetrical model: groups and $c_u$ assumed *Right)* Displacement vectors

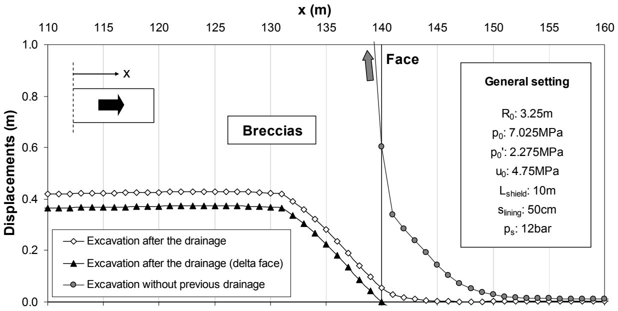

**Figure 10:** Axial-symmetrical model: longitudinal profile of radial displacement

## REFERENCES

[1] Russo G., Grasso P., Bensaid A. (2008): A framework for the risk analysis of the Gibraltar strait railway-link tunnel. ITA-AITES World Tunnel Congress, India (19-25 September 2008)

[2] Floria V., Fidelibus C., Repetto L. and Russo G. (2008): Drainage and related increase of short-term strength of low permeability rock mass. AFTES, International Congress of Monaco (October, 2008)

[3] Pliego J.M., (2005), Open Session – The Gibraltar Strait tunnel. An overview of the study process, Tunnelling and Underground Space Technology, Vol. 20, N° 6, pp. 558-569