Drainage and related increase of short-term strength of low permeability rock mass

Drainage et relatif accroissement de la résistance à court terme du massif rocheux à faible perméabilité

Vincenza FLORIA - Geodata SpA, Torino, Italy
Corrado FIDELIBUS - Bari Technical University, Italy
Luca REPETTO, Giordano RUSSO - Geodata SpA, Torino, Italy

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. In fact the tunnel profile crosses mostly clayey tectonized flysch and two paleo-valleys filled with weak clayey breccias for 3-4km. Specifically, serious problems might arise with the advancement in the latter formation, given the low short-term strength of the material. A series of numerical analyses have been performed to investigate the risks associated to the advancement by TBM in this problematic geological context. As far as the breccias are concerned, a consolidation before the advancement takes place seems necessary. The conceptual solution may consist of several long drains which produce a dissipation of the pore-pressure in the ground ahead of the face. A plane strain FLAC numerical model has been utilized to simulate the evolution of the consolidation and the increase of short-term strength in a tunnel cross-section. Even if breccias possess rather low values of permeability, the dissipation occurring in the model brings to a benefic increase of the short-term strength and consequently to more favorable excavation response. In fact, as clearly shown by a 2D axial-symmetrical numerical analysis, the convergence when the excavation takes place in the consolidated rock results hampered.

RESUME: Le tunnel ferroviaire sous le détroit de Gibraltar est destiné à être une des structures souterraines les plus ambitieuses jamais construites pour la profondeur, les pressions interstitielles particulièrement élévées et la qualité très faible de la roche le long du tracé. En fait le tunnel traverse des zones tectonisées de flyschs argileux et deux paleo-vallées remplis de brèches argileuses faibles pour 3-4 km. En particulier, les problèmes les plus critiques pourraient se developper avec l'avancement dans la dernière formation mentionnée, à cause de la faible resistance à court terme de brèches. Une série d'analyses numériques a été exécutée pour étudier les risques associés à l'avancement par tunnelier dans ce contexte géologique problématique. En ce qui concerne les brèches, une consolidation avant que l'avancement ait lieu semble nécessaire. La solution conceptuelle peut se composer de plusieurs longs drains qui produisent une dissipation de la pression interstitielle avant du fronte de taille. Un modèle numérique FLAC d'une section transversale du tunnel en déformation biaxiale a été utilisé pour simuler l'évolution de la consolidation et l'augmentation de la contrainte efficace à court terme. Même si les brechès possèdent des valeurs plutôt basses de perméabilité, la dissipation que se produit dans le modèle apporte à une augmentation benefique de la contrainte efficace à court terme et par conséquent à une réponse plus favorable d'excavation. En fait, comme clairement montré par une 2D analyse numérique axial-symétrique, lorsque l'excavation dans les terrains consolidés a lieu, la convergence résulte entravés.

1 - INTRODUCTION

The tunnel of the Strait of Gibraltar is probably the most challenging underground structure to be built in the next decades. 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. A Tunnel Boring Machine will be utilized. Given the poor properties of the ground, the trapping of TBM when crossing the breccias is one of the main potential risk, therefore several technical solutions to avoid this have been investigated. Conceptually, a reasonable solution appears to be the drainage of the rock to increase the effective stress dominant around the excavation and produce 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.

The drainage of low-permeability rock is a rather new technique in ground engineering and, with respect to the specific case, only the simulated effect of the drainage is illustrated in the following. It is worth to remark that the applicability of the technique is still under debate and further studies and in situ experiments will be necessary before it be efficiently engineered and accepted for the final design.

The results of FLAC numerical simulations of the pore-pressure evolution with time and associated local increase of short-term strength are herewith reported and commented, anticipated by a description of the site situation. From the interpretation of the results an opinion about the efficiency of the proposed solution can be eventually given.

2 - SITE DESCRIPTION

In Figure 1 the tunnel profile and geology of the site are shown. There is a limited confidence on the extent and depth of the paleo-valleys filled with quaternary breccias. Given the difficulty in recovering undisturbed samples, some uncertainty on the geotechnical properties of the breccias arises. A value of 0.35MPa for the undrained cohesion c_u has been selected as representative for the numerical simulation, despite the results of the few available laboratory tests indicate even lower values. However, the selected value does not seem to conform with the effective strength parameters and expected effective in situ-stress. This might imply also that breccias are in a 'under-consolidated' (UC) state, i.e. the pre-consolidation pressure is less than the expected value of isotropic effective stress for given overburden and pore pressure. Conventionally an over-consolidation ratio less than 1 is ascribed to a UC material; anyway the material is normal consolidated (NC). Finally, in terms of effective stress, the following ranges of Coulomb parameters have been selected: cohesion c' =0.10÷0.25MPa, friction angle ϕ'= 23÷25°.

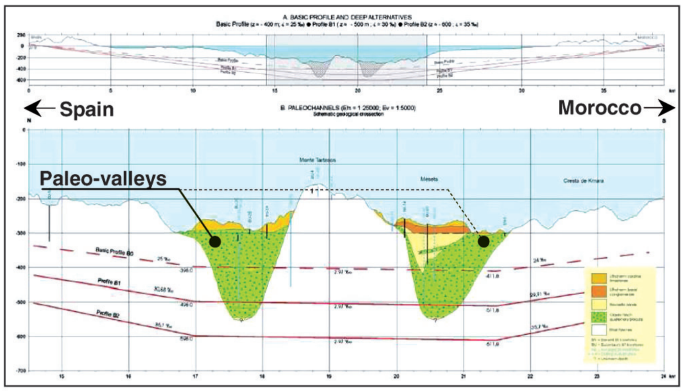

Figure 1 - Geology with indication of the paleo-valleys (after Pliego, 2005). According the most recent studies, the relative extension could be larger than depicted (total length=3-4km).

3 - THE NUMERICAL MODEL

A plane-flow/plane-strain fully hydro-mechanically coupled model has been utilized to simulate the evolution of pore pressure, strain and stress with time ahead of the tunnel face along a vertical section normal to the tunnel axis. Even if an uncoupled analysis would have offered exact results, yet the coupled model has been selected here and resulted computationally non demanding.

The FLAC mesh is shown in Figure 2. 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. As the rock is 'under-consolidated', this pore pressure exceeds the hydrostatic pore pressure. The initial effective isotropic stress σ'_{0i} is therefore reduced with respect to the value expected for a NC under the overburden. In the following analyses σ'_{0i}(UC) is 30% of σ'_{0i}(NC). The following mechanical parameters have been utilized: bulk unit weight γ 23KN/m^3, drained elasticity modulus E 300MPa, Poisson coefficient ν 0.30, hydraulic conductivity K 10^{-10}m/s. Three analyses have been performed by applying 3, 5 and 9 drains respectively for the UC material. In addition a fourth analysis with 5 drains refers to the NC material.

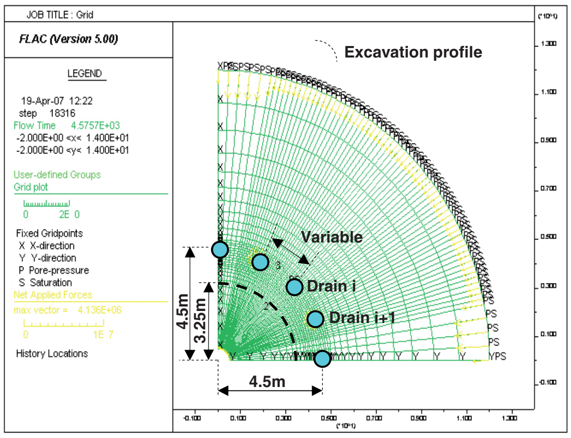

Figure 2 - Plane strain FLAC model

4 - RESULTS

In Figure 4 the evolution of both pore pressure p and effective isotropic stress σ'_0 is shown at a location 30cm far from a drain. The consolidation is faster in the first week. At 30 days the isotropic stress results enough close to the drained value. In Figure 5 the isochrones of σ'_0 along the line joining two drains are also given.

In Figure 6 the comparison between UC and NC is given in terms of evolution of σ'_0 at the center of the line joining two drains. Given the larger gradient for the UC case, the increase of effective isotropic stress is obviously faster. At the same location in Figure 7 a comparison is made the three UC cases. It is worthwhile to remark that the efficiency does not increase proportionally with the number of drains.

The increase of isotropic effective stress brings to an associated increase of short-term resistance c_u. The actual OCR was not assessed directly through an oedometric test, therefore some assumptions necessitate to derive a plausible value.

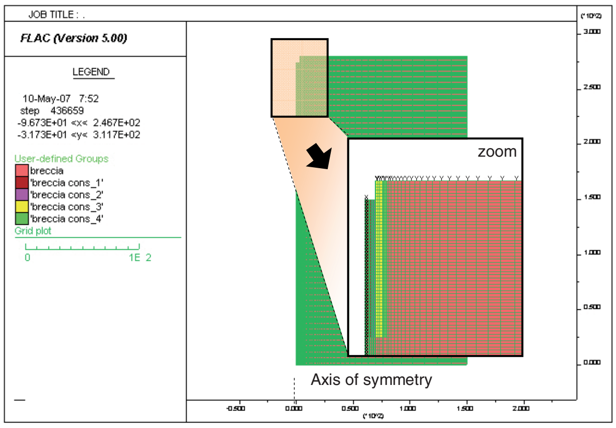

Figure 3 - Axial-symmetrical FLAC model

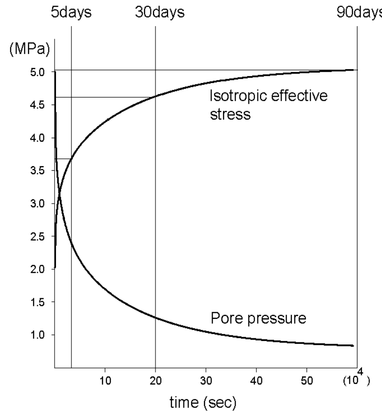

Figure 4 - Evolution of pore pressure and isotropic effective stress in a location 30cm far from a drain

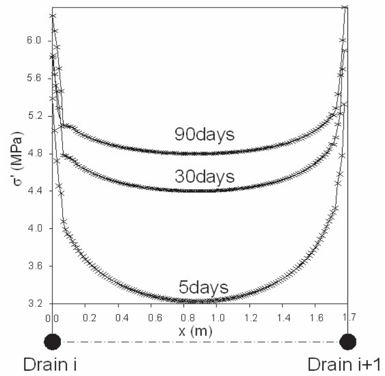

Figure 5 - Isochrones of the isotropic effective stress at 5, 30, 90 days along the line joining two drains

For the maximum overburden the effective stress should be 2.27MPa. The functional relation among the short-term cohesion c_u and the effective strength parameter is (Ladd, 1964):

$$c_u = \frac{c' \cos\phi' + \sigma'_0 \sin\phi'}{1 + (2A_f - 1)\sin\phi'}$$

where A_f is the Skempton pore-pressure parameter, typically 0.7÷1.3 for NC clays (Lambe and Whitman, 1979). For c_u =0.35MPa and c',ϕ' minimum values of the ranges (see Section 2), by inverting the relation one obtains the range 0.80÷1.22MPa for σ'_0. Evidently, this implies a very low value of OCR.

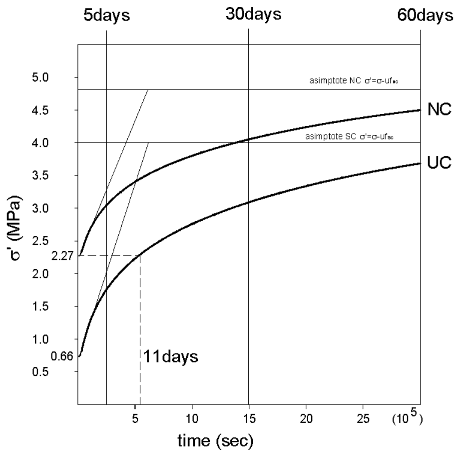

Figure 6 - Evolution with time of isotropic effective stress at the center of the line joining two drains respectively for NC and UC

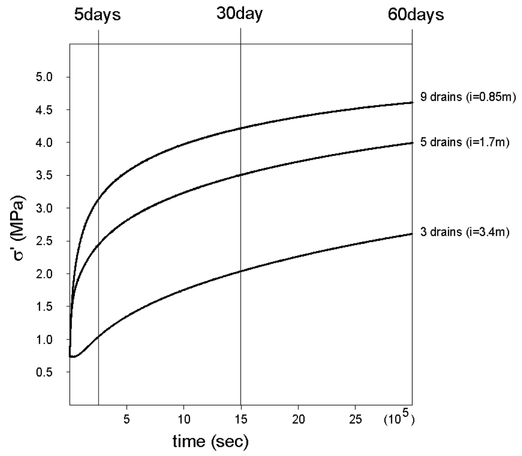

Figure 7 - Trend with time of the isotropic effective stress at a location 30cm far from a drain respectively for 3, 5, 9 drains per quarter.

The effect of drainage brings to an increase of σ'_0. Given the symmetry, the excavation produces theoretically only deviatoric stresses; if we assume a purely poroelastic behavior, 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 $\sigma'_0(t_D)$ 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 c_u 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.
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, a FLAC axial-symmetric analysis has been performed to simulate the advancement (see Figure 9). The analysis is in total stresses (undrained condition). In Figure 10 the displacement vectors are displayed. In Figure 11 the values of radial displacements in the proximity of the excavation face are plotted. Such a values will be compared with the acceptable deformation for the selected TBM.
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.

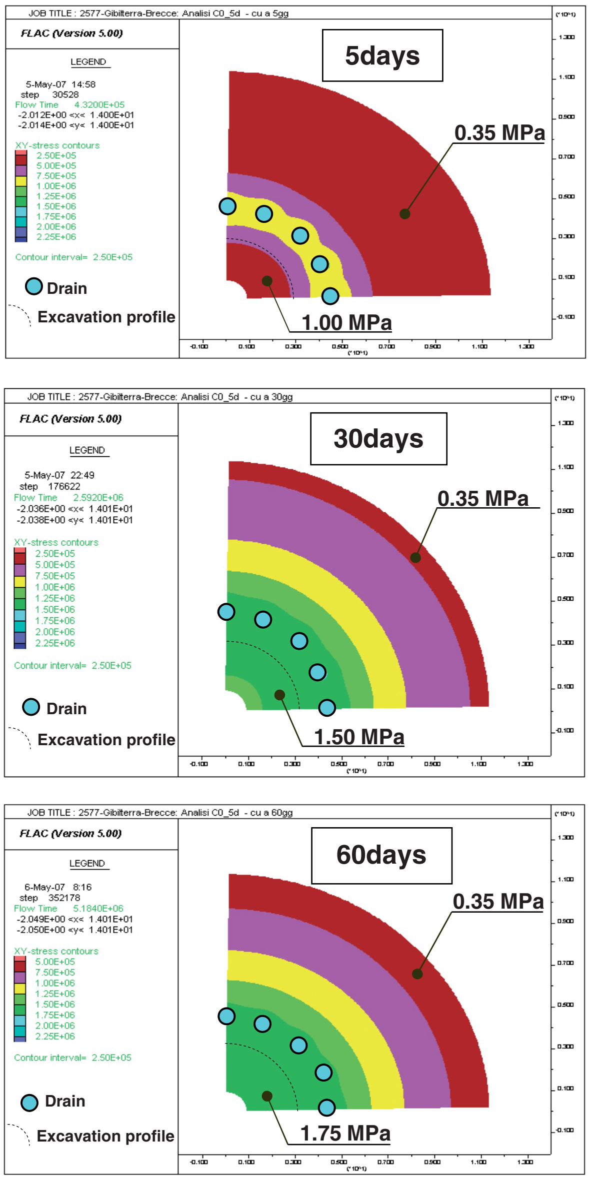

Figure 8 - Patterns at 5, 30, 60 days of c_u for 5 drains per quarter

5 - CONCLUSIONS

The advancement of TBM under safe conditions in the breccias of the paleovalleys of the Strait of Gibraltar might require the consolidation of the material before excavation takes place. Consolidation implies an increase of short-term strength and then a more favorable excavation response. Numerical simulations show that the consolidation may be realized by means of a crown of horizontal drains ahead of the tunnel face. The progress of consolidation around the drains has been presented. Despite the low permeability of the rock, the progress of consolidation appear theoretically rather fast, as a consequence of the high gradients. Even if the functioning of the drains under these extreme conditions is debatable and experience has to be gained before the technique can be applied, the solution appears very promising. The results of applications in other tunnels under construction will assist in giving a definitive opinion on the applicability of the technique to this specific case as well as to other cases where a low-permeability low-strength rock is encountered.

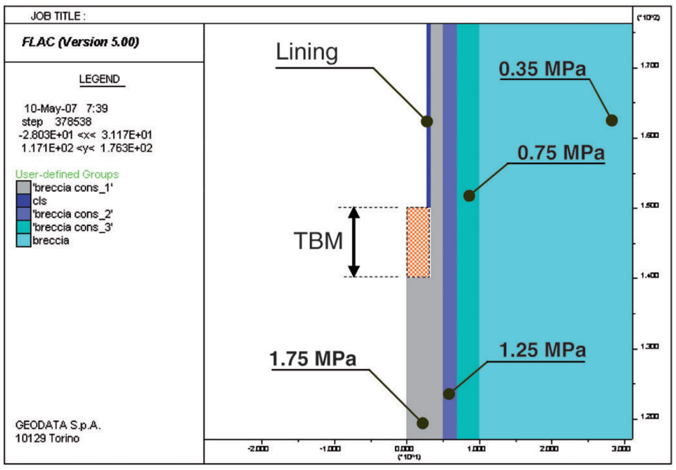

Figure 9 - Axial-symmetrical model: groups and c_u assumed

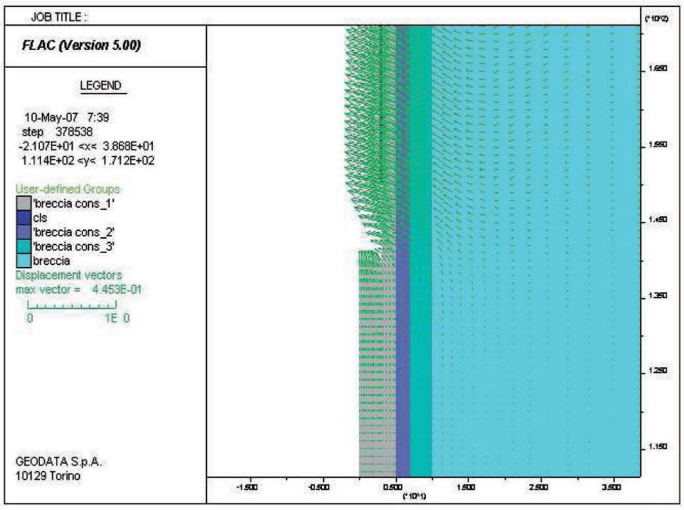

Figure 10 - Axial-symmetrical model: Displacements

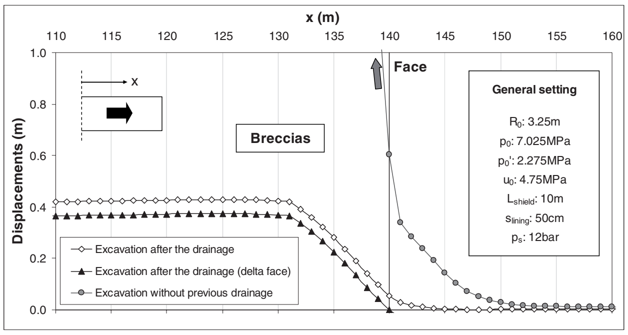

Figure 11 - Axial-symmetrical model: longitudinal profile of radial displacement

REFERENCES

Ladd C.C., (1964), *Stress-strain behaviour of saturated clay and basic strength principle*, Research in Earth Physics, Research Report R64-17, Soil Mechanics Division, Department of Civil Engineering, Massachusetts Institute of Technology.

Lambe W. and Whitman R.V., (1969), *Soil Mechanics*, John Wiley.

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.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Francisco Roca of SECEG SA for the critical review of the manuscript.