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Numerical simulations of tunnelling in soft rock under water pressure

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Abstract

The paper deals with the effect of the groundwater and time on the behaviour of tunnels in soft rocks.
Herewith, a short review illustrates the basic principles governing the influence of the pore pressure on the soft rocks behaviour and underground excavation performance. Then, the main ways for the tunnel equilibrium analysis are presented and discussed by assuming short and long term conditions. This type of analysis allows a first estimation of the tunnel behaviour, but, in many cases, a more exhaustive simulation is required in order to optimise the tunnel analysis and design.
Thus, a 3D simulation of a mechanised tunnelling in soft rock under water pressure is finally exposed. This kind of analysis allows shedding light on the effects of the advancement rate, the permeability, the previous drainage of the soil and other effects on the displacements and stresses along the tunnel.
The paper also describes the main parameters required to continuously ensure the transient equilibrium during tunnel excavation, controlling both processes simultaneously: mechanical and fluid calculations.

Keywords: Tunnelling, soft rock, groundwater, coupled analysis, excavation simulation.

1 INTRODUCTION

The excavation of a tunnel causes changes in the initial state of stress resulting in displacements of the rock mass towards the cavity.
The stress distribution varies in the longitudinal direction up to a certain distance from the face, causing the progressive tunnel closure during the excavation. Sometimes this behaviour leads to the inexact perception that displacements only depend on time while they also develop in function of the distance from the face. Thus, in many cases the blocking of the TBM cannot be avoided just by increasing the rate of advance.

The displacements may be negligible in case of good rock, but very important for the tunnel stability in case of poor rock and high overburden. In cases of squeezing rock, the time dependent behaviour due to creep and consolidation should also be taken into account.
The present paper deals with the time effect due to the consolidation process, that seems to be the most critical issue for evaluating the risk of TBM blocking in the case of soft and very deformable rocks.

2 SHORT TERM, UNDRAINED CONDITIONS

The excavation of a tunnel in a soft and impermeable rock leads to an initial equilibrium that corresponds practically to undrained conditions, i.e. without water flows.
The behaviour of a porous material in undrained conditions may be described with the Biot theory [1]. The Biot coefficient α is the main parameter to describe the rock behaviour:

$$\alpha = 1 - K/K_s \qquad (1)$$

where K is the drained bulk modulus and K_s the bulk modulus of grains (solid component).
From this parameter two basic properties may be defined: the undrained bulk modulus K_u and the Skempton coefficient B:

$$K_u = K + \alpha^2 \cdot M \qquad (2)$$

$$B = \frac{\alpha \cdot M}{K+\alpha^2 \cdot M} \tag{3}$$

where M is the Biot Modulus:

$$M = \frac{K_w}{n + (\alpha - n)(1-\alpha)\frac{K_w}{K}} \tag{4}$$

being K_w the water bulk modulus (2 GPa) and n the porosity.

The use of a Biot coefficient α=1 (i.e. incompressible solid component) and a low porosity leads to very high values of the undrained bulk modulus that should be verified. It has to be noted that the porosity of an ideal material composed of uniform spherical grains ranges between 26% and 48%; in case of a clay it typically ranges between 40-55%.

The Skempton coefficient B, see Eq. (3), represents the ratio of pore pressure increment Δu to mean stress increment $\Delta\sigma$, according to Eq. (5).

$$\Delta u = B \cdot \Delta\sigma \tag{5}$$

During the tunnel excavation, in the short term, the water pressure remains unchanged in the elastic zone, since also the average state of stress does not change from the initial value. In the plastic zone, however, the total stresses will reduce considerably, inducing a reduction of the pore pressure according to Eq. (5). In addition the pore pressure can reduce owing to the volume increase related to the dilation during the rock failure [3].

Negative pore pressures arise when the variation of the total average stress is higher than the initial water pressure. This behaviour usually occurs in soft rocks with a minimum overburden of 100-200 m and is described by different authors (e.g. [2]). The consequence of these negative pore pressures is that, just after excavation, the tunnel walls appears dry and stable while a different behaviour can take place with time.

In order to correctly analyse the tunnel equilibrium in the short term it is necessary to take into account in the calculation model the hydro-mechanical coupling (i.e. effective stresses and pore pressure). A simplified analysis based on total stresses, that considers both the undrained shear strength and the undrained bulk modulus, does not lead to correct results. Figure 1 shows the ground reaction curves determined for both approaches in the case of the Gibraltar tunnel. In this particular case, the water depth is higher than the rock overburden.

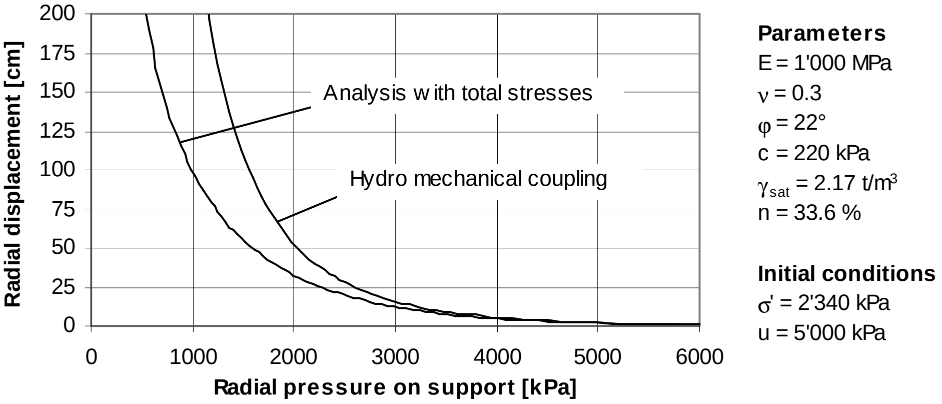


Figure 1: Ground reaction curves for undrained conditions (2D finite difference analysis).

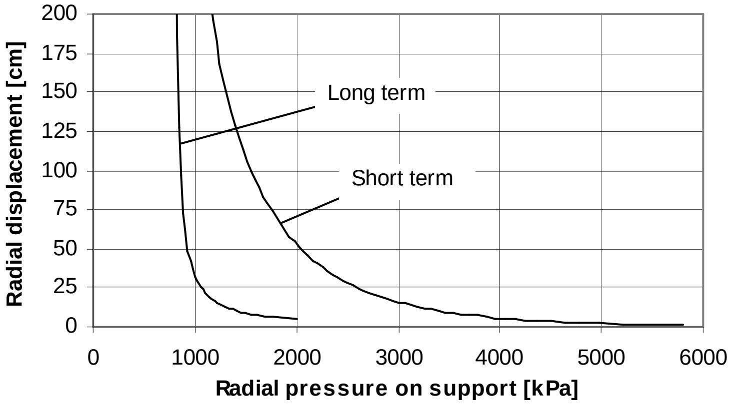
The undrained shear strength adopted in the analysis with total stresses was defined as function of the initial effective stress according to Eq. (6):

$$c_u = (\sigma' + c / \tan\varphi) \cdot \sin\varphi \qquad (6)$$

The results obtained using both approaches show important differences (Figure 1). In fact, the analysis based on total stresses does not take into account the forces resulting from the variation of the pore pressure within the plastic zone.

3 LONG TERM EQUILIBRIUM

The consolidation process produces displacements which increase with time.
Figure 2 illustrates the results in terms of ground reaction curves for undrained (short term) and drained (long term) conditions achieved with the hydro-mechanical coupling approach. The results presented in Figure 2 do not confirm that the long term displacements are higher than the short term ones.



Parameters
E = 1'000 MPa
$\nu = 0.3$
$\varphi = 22°$
c = 220 kPa
γ_{sat} = 2.17 t/m^3
n = 33.6 %

Initial conditions
σ' = 2'340 kPa
u = 5'000 kPa

Figure 2: Ground reaction curves (2D finite difference analysis, hydro mechanical coupling).

It is important to take notice that the simulation in drained conditions (long term) assumes the water pressure within the rock mass being in a state of equilibrium and independent on the radial pressure on support. In fact, this assumption considers to have reached drained conditions before the tunnel excavation. Thus, the displacements calculated for the long term are lower than for the short term ones as consequence of the pre-consolidation effect. If this assumption does not correspond with the actual construction method, the results of the analysis assuming drained conditions become quite unrealistic.

More realistic results can be obtained by starting the consolidation process after the equilibrium in undrained conditions. In this case, the final state is fully different than the one obtained by assuming drained conditions from beginning. This is clearly shown in Figure 3, where radial and tangential stresses are illustrated. It has to be noted that the pore pressures are the same in both cases.

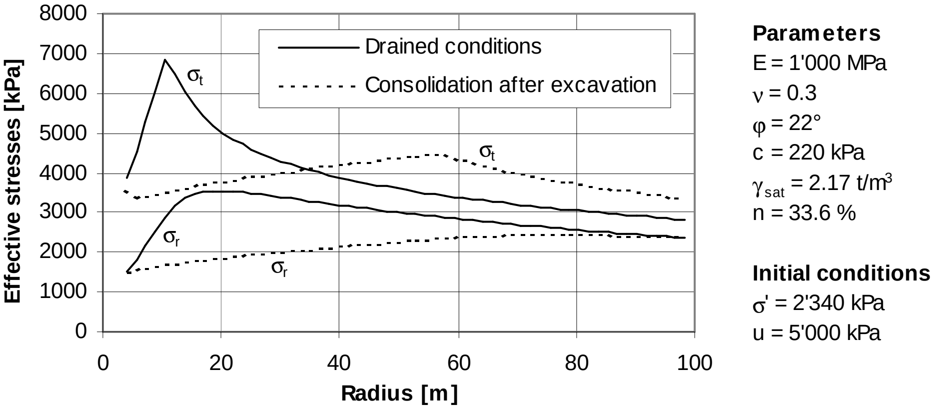


Figure 3: Radial and tangential stresses in the rock mass (support pressure 1500 kPa).

Figure 2 shows quite large displacements also for high values of the radial confinement pressure. In those conditions it is very difficult to state if the tunnel can be excavated with TBM and how fast the displacements develop. The analyses with 2D models, as used to obtain the results shown here above, are limited to preliminary evaluations and are in many cases insufficient.

4 SIMULATION OF THE TBM ADVANCE

In order to verify the feasibility of the TBM excavation in soft and impermeable ground, a 3D analysis is required as a rule.

In these analyses the tunnel advance has to be properly described. A single step advance does not give good results because the support would be activated without having simulated the excavation process (progressive advance of the excavation face through a specific section). As a consequence the displacements would be underestimated.

The fully coupled simulation of the tunnel advance requires managing simultaneously the fluid flow and the mechanical equilibrium.

With an explicit finite differences solution technique, the time interval associated to each calculation step cannot overpass a maximum value in order to assure numerical convergence of the fluid flow analysis.

In case of low permeability, the time interval has also to be chosen in taking into account the mechanical equilibrium. In fact, it could occur that the number of iterations required to achieve the fluid flow time imposed by the excavation advance rate, is insufficient to reach the mechanical equilibrium.

Some results of this kind of analysis are presented in Figure 4 jointly with the ground reaction curves of Figure 2. They were obtained by considering an earth pressure of 1 MPa at the face and along the 10 m long TBM shield.

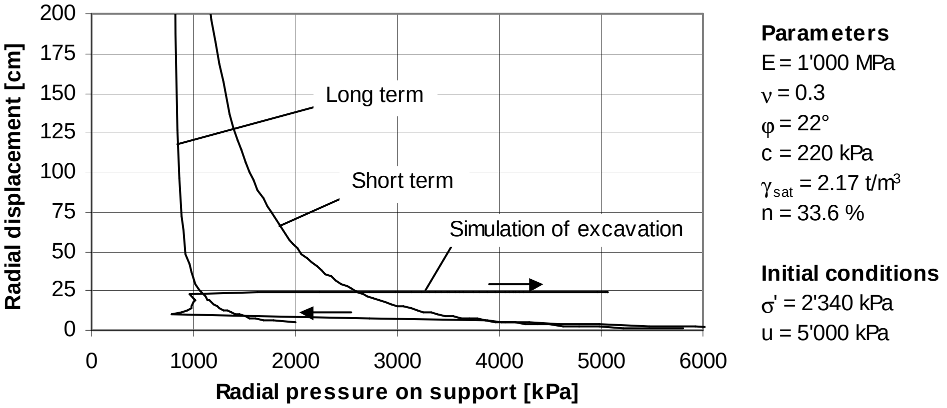


Figure 4: Comparison of results obtained with 3D simulation of tunnel advance and ground reaction curves calculated with 2D models.

The radial displacement reaches 24 cm as maximum value. This clearly indicates, in this case, the feasibility of the excavation by TBM.

It can be noticed that the final load on the support is estimated to 5 MPa owing to the assumption that the support is impermeable. This choice was preferred for Gibraltar since the water inflow would have to be pumped for a height up to 500 m to the sea level.

It is also interesting to note that for the final equilibrium the effective stress are nearly nil since the water pressure corresponds more or less to the total stress.

5 CONCLUSIONS

In order to correctly evaluate the behaviour of a soft and impermeable rock during the tunnel excavation it is necessary to simulate both, the fluid and the mechanical processes.

The long term behaviour of a tunnel cannot be analysed by neglecting the short term equilibrium. The results can be quite misleading.

The analysis with 2D-models, as used for defining the ground reaction curves presented in this paper, is limited to preliminary evaluations of the tunnel stability. More accurate results can be obtained only by simulating the advance of the excavation and the 3D-equilibrium. This type of analysis allows to describe realistically the behaviour of the tunnel during the excavation process. In addition, it allows also to take into account the advance rate, the permeability, the duration of a standstill, the shield geometry, the TBM configuration, and so on.

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