WTC 2013
Switzerland - Geneva

World Tunnel Congress 2013 Geneva
Underground – the way to the future!
G. Anagnostou & H. Ehrbar (eds)

ISBN 978-1-138-00094-0

Large deformation analysis for a planned tunnel crossing heavily squeezing ground

A. Vrakas[(1)], G. Anagnostou[(1)]

[(1)]ETH Zurich, Switzerland

ABSTRACT: A large strain analytical solution is presented for the short-term Ground Response Curve (GRC) in saturated squeezing ground and this solution is applied to a geotechnically demanding part of the planned Gibraltar tunnel. Squeezing, the appearance of large, usually time-dependent deformations in tunnelling, is associated with high overburden in combination with poor mechanical properties and often high pore pressures. Here the focus is on the short-term response of the ground. It is characterized by the condition of constant water content and is important for the deformations and stability near the tunnel face. Two large breccia zones in the middle of the planned Gibraltar tunnel typify saturated, weak, low permeability ground under high pore pressure. Motivated by preliminary computational investigations, which indicated extremely large convergences, here the short-term ground response in these regions is investigated by applying an analytical solution that takes into account large strains. The computational results underline the importance of large strain formulation for extreme squeezing conditions, show the favourable effect of plastic dilatancy and support the hypothesis that heavy squeezing may occur in the breccia zones of the Gibraltar tunnel.

1 Introduction

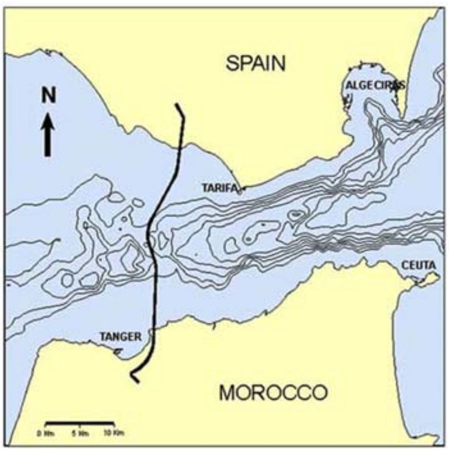
Squeezing phenomena have been encountered in a great variety of underground projects. Extended reports exist in the literature, inter alia from several tunnel cases in Japan (Aydan et al. 1996), the Gotthard base tunnel in Switzerland (Kovári et al. 2000) the Bolu tunnel in Turkey (Dalgıç 2002) and the Lyon-Turin base tunnel in France (Bonini and Barla 2012). As indicated by the empirically known stabilizing effect of an advance-drainage (Steiner 1996, Kovári 1998, Barla 2002), high pore pressures favour the development of squeezing.

From a theoretical point of view, the presence of water leads to a gradual increase of tunnel convergences. Initially (t=0), the instantaneous or short-term ground response is undrained, i.e. it occurs under constant water content. During this phase excess pore pressures develop (negative in the case of the conventional Mohr-Coulomb model) due to the hydro-mechanical coupling. Then, the pore volume and the water content change, more or less rapidly depending on the seepage flow rate. This time-dependent process leads to additional displacements around the opening and reaches steady state after a period of time (theoretically t=∞), which may be long or short depending on the permeability of the ground. Under certain excavation and drainage conditions, which imply a specific stress history (Anagnostou 2009b), the long-term or steady state response can be handled analytically via an uncoupled approach facilitating its mathematical description (Lembo Fazio and Ribacchi 1984, Graziani and Ribacchi 2001, Anagnostou and Kovári 2003). In general, the transient phase that precedes the long-term constitutes a complex process, which is highly affected by the hydraulic as well as the mechanically imposed conditions. The a priori assumed stress history in combination with the stress path dependency of an elastoplastic material has been examined in the past by Giraud et al. (1993), Graziani and Ribacchi (2001), Anagnostou (2009b) and Graziani and Boldini (2012).

On the other hand, the instantaneous response of saturated ground around a deep opening under conditions of either spherical symmetry (spherical cavern) or axial symmetry (cylindrical tunnel in plane strain) can be treated mathematically in an exact way, especially assuming both grains and fluid as incompressible. The first complete elastoplastic solutions to the problem of a contracting cavity in an infinite medium are attributed to Salençon (1969), who presented closed-form expressions using the Mohr-Coulomb (MC) and the Tresca failure criteria. The latter can be used for the equivalent total stress analysis of an isotropic elastoplastic material (with E_u, v_u=0.5, s_u, φ_u=0^o) to model its undrained behaviour under zero volumetric deformations. In retrospect, the excess pore pressures can be evaluated from the variation in the mean total stress. This process was utilized by Mair and Taylor (1993), who reproduced the previous solution and applied it to the prediction of short-term deformations around tunnels driven in London and Boom clay. Mair (2008) showed recently the usefulness of the aforementioned model through various comparisons with field measurements highlighting its attraction, which is based on its simplicity. Yu (2000) also included this solution in his thorough review of cavity expansion methods in Geomechanics, suggesting further a rigorous large strain one, by making use of the appropriate incompressibility condition in the plastic region that is formed around the opening. Anagnostou (2009a) performed a comparative effective stress analysis considering infinitesimal deformations in combination with the MC model without dilatancy, while the respective complete expressions that account for a non-zero dilation angle can be found in the dissertation of Vogelhuber (2007). The analytical relationships that are used in this paper have been derived lately by Vrakas and Anagnostou (2013), taking into consideration finite strains in the whole medium as well as an elastic-perfectly plastic material with a non-associated flow rule.

2 Experimental studies on breccias around the proposed Gibraltar tunnel

The proposed Gibraltar tunnel is an undersea option for the creation of a fixed link between Europe (Spain) and Africa (Morocco), as can be seen in Figure 1a. The tunnel solution prevailed over the bridge one for several reasons (Pliego 2005), but is still a very demanding and challenging project from an engineering point of view. Two main alignments have been considered, the B1 and the B2 (Fig. 1b). The main formation that the tunnel will cross is flysch, but there are two disturbed zones filled with clayey breccias of very low quality presented in Figure 1b (Dong et al. 2013). The combination of poor ground conditions, high overburden and high pore pressures can result in extremely difficult tunnelling conditions (Kovári 1998), referred commonly as heavily squeezing. Another characteristic of these breccias is their very low permeability, which makes the ground response strongly time-dependent.



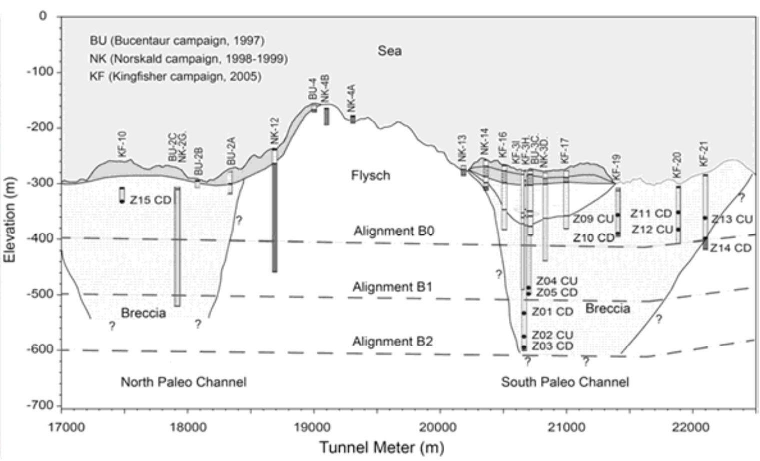


Figure 1. (a) Location map of the proposed Gibraltar Strait tunnel (Pliego 2005) and (b) geological profile with the breccia zones as well as the depth of the tested samples (Dong et al. 2013)

Dong et al. (2013) carried out consolidated drained (CD) and consolidated undrained (CU) triaxial tests on almost fully saturated breccia samples (average degree of saturation equal to 95%) retrieved from various depths (Fig. 1b). Two main zones were considered for the assessment of the experimental results according to the location of the samples: an upper (20-120 m undersea, 7 specimens Z09-Z15) and a lower one (200-320 m undersea, 5 specimens Z01-Z05). After careful processing of the test data and making the appropriate corrections, values for the cohesion, *c*, and the friction angle, *φ*, were obtained in compliance with the MC failure model. The respective curves are displayed in Figure 2. A minimum, a maximum and a mean envelope has been determined for each zone in order to capture the range of the test results. The values of the ground parameters are given in Table 1 in combination with the elastic properties (Young's modulus *E* and Poisson's ratio *v*) and the in situ stress field. The total stresses, σ_o, and the pore pressures, p_o, which will be used in the calculations, correspond approximately to the mean depth of each breccia zone.

Table 1. Estimated data for the calculations

Breccia zone - envelope	c [MPa]	φ [deg°]	E [MPa]	v [-]	σ_o [MPa]	p_o [MPa]
Upper - min	0.076	20.4	500.	0.30	4.5	3.5
Upper - max	0.375	26.0	500.	0.30	4.5	3.5
Upper - mean	0.226	23.2	500.	0.30	4.5	3.5
Lower - min	0.327	9.0	300.	0.30	8.0	5.0
Lower - max	1.306	9.4	300.	0.30	8.0	5.0
Lower - mean	0.817	9.2	300.	0.30	8.0	5.0

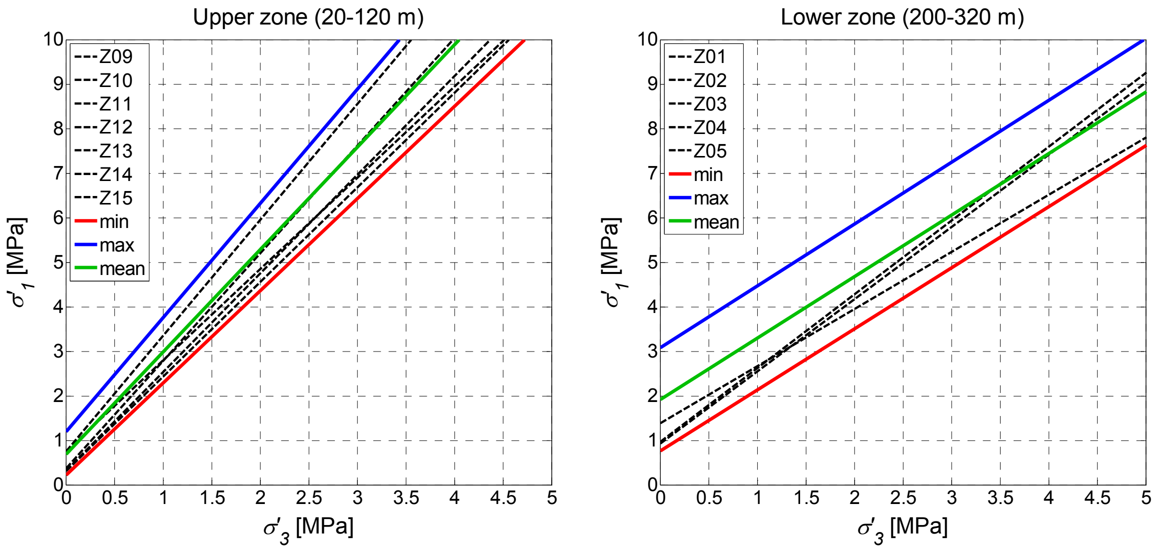


Figure 2. Strength envelopes of the tested samples (dashed lines, Dong et al. 2013) and MC envelopes considered in the computations (solid lines)

3 Analytical solutions for the GRC under short-term conditions

Analysing the ground – support interaction by considering the Ground Response Curve (GRC), which relates the support pressure with the wall displacement, is a widely used method in tunnelling. As has been previously described, the breccias exhibit very low permeability and consequently the short-term response, which is examined in this paper, becomes critical for the stability and deformations in the vicinity of the advancing tunnel heading. Preliminary investigations by Floria et al. (2008), Panciera (2009) and Anagnostou (2010) indicated the possibility of extremely large short-term convergences, which violate the underlying small strain assumption and become physically meaningless. This motivated the Authors to study the short-term response of the breccias to the tunnel excavation within the framework of the large deformation theory.

The behaviour of a deep circular tunnel away from the face can be assumed to fulfil the axisymmetric plane strain conditions facilitating to a large degree the mathematical operations. As a result, a cylindrical cavity in an infinite homogeneous and isotropic medium is considered, unloaded from an in situ uniform state of stress under undrained conditions, i.e. the volumetric strain ε_{vol} is equal to zero. The ground behaviour is linearly elastic-perfectly plastic obeying the MC failure criterion with a non-associated plastic flow rule. The correct relations for the instantaneous response of the ground based on the small deformation theory can be found in the dissertation of Vogelhuber (2007), while the necessary relations for the construction of the GRC in compliance with the large deformation theory are presented concisely below, for the sake of completeness. They constitute part of the general relations, which account for spherical or cylindrical cavities as well as elastic-brittle plastic materials, developed by Vrakas and Anagnostou (2013).

A circular tunnel with an initial radius a_o is considered. The in situ total stresses are assumed equal to σ_o, while the in situ pore pressures equal to p_o. The effective stresses are defined as the difference between the total stresses and the pore pressures, while the convention of compression positive is used in the relationships of this paper. A radial displacement u_a (= a_o-a, positive inwards) is imposed at the tunnel wall leading to the derivation of a corresponding support pressure σ_a. An effective stress analysis is performed based on the theory of large deformations. The equilibrium of each infinitesimal element is considered in the current configuration, the stresses correspond to Cauchy (or true) stresses (i.e. force per current unit area), while an appropriate strain definition, Hencky (or logarithmic) strains, is adopted. The ground behaviour around the opening during unloading can be either purely elastic or elastoplastic forming a plastic ring of outer radius ρ (Fig. 3). The subscript zero in a_o is used for the initial configuration in contrast to the current one, where the radii a and ρ are written without subscripts.

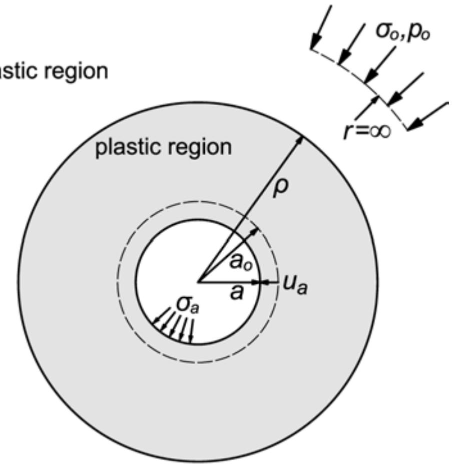


Figure 3. Computational model for a deep circular tunnel (cylindrical cavity)

The critical value of the displacement u_a, i.e. the displacement at the onset of plastification, is given by

$$u_a^{cr} = \left(1 - \frac{1}{\sqrt{1-M_{cr}}}\right) a_o \,, \tag{1}$$

where

$$M_{cr} = 1 - \exp\left[\frac{2(1+v)}{E}\left(\sigma'_o - \sigma'_\rho\right)\right]. \tag{2}$$

The stress value σ'_ρ appearing in Eq. (2) is equal to the effective stress at the elastoplastic interface:

$$\sigma'_\rho = \frac{2\sigma'_o - \sigma_D}{m+1} \,, \tag{3}$$

where

$$m = \frac{1+\sin\varphi}{1-\sin\varphi}, \tag{4}$$

$$\sigma_D = \frac{2c\cos\varphi}{1-\sin\varphi} \,. \tag{5}$$

In the case of elastic response, i.e. if u_a is smaller than the critical one given by Eq. (1),

$$\sigma_a = \sigma_o + \frac{E}{2(1+v)} \mathrm{Li}_2(M) \,, \tag{6}$$

where

$$M = 1 - \left(\frac{1}{1 - u_a/a_o}\right)^2 \;\leq\; 0 \,, \tag{7}$$

while Li_2 is the Euler dilogarithm function, expressed as (Lewin 1981)

$$\mathrm{Li}_2(M)=\begin{cases}\sum_{n=1}^{\infty}\frac{M^n}{n^2} & , \quad -1\le M\le 0\\ -\frac{\pi^2}{6}-\frac{\ln^2(-M)}{2}-\sum_{n=1}^{\infty}\frac{(1/M)^n}{n^2} & , \quad M<-1\end{cases}. \tag{8}$$

It should be noted here, that the infinite series converges rapidly. Hence, the first few terms may be used to provide satisfactory results.

In the case of elastoplastic response, i.e. if u_a is larger than the critical value given by Eq. (1),

$$\sigma_a=\sigma_p'+p_p+\frac{(m-1)(\kappa-1)}{4\Omega_1}\left[\mathrm{Li}_2(M)-\mathrm{Li}_2(M_{cr})\right]-\frac{\Omega_2}{\Omega_1}\ln\left(\frac{\rho}{a}\right), \tag{9}$$

where

$$p_p=\sigma_o-\sigma_p'+\frac{E}{2(1+v)}\mathrm{Li}_2(M_{cr}), \tag{10}$$

$$\Omega_1=\frac{1+v}{E}\left[(1-v)(m\kappa+1)-v(m+\kappa)\right], \tag{11}$$

$$\Omega_2=\frac{1+v}{E}(1-2v)(\kappa+1)\left[(m-1)\sigma_o'+\sigma_D\right], \tag{12}$$

$$\kappa=\frac{1+\sin\psi}{1-\sin\psi}, \tag{13}$$

$$\frac{\rho}{a}=\sqrt{\frac{M}{M_{cr}}}. \tag{14}$$

4 Application to the Gibraltar tunnel

4.1 The GRC considering zero dilatancy

Figures 4 and 5 show the GRCs and the radius of the plastic zone, respectively, for the three MC failure envelopes of each breccia zone plotted in Figure 2.

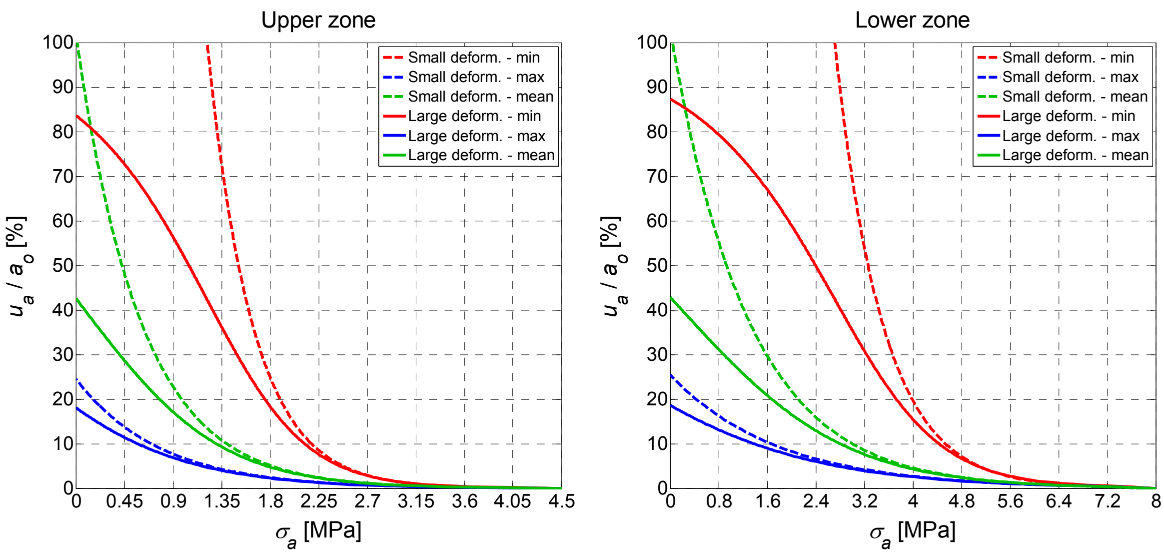


Figure 4. Ground response curves (ψ = 0°)

The error arising from the small deformation theory for convergence values u_a/a_o greater than ten percent is obvious in these graphs. Note that in the case of the worst ground properties considered, the infinitesimal strain theory fails to provide a rational result within the theoretical allowable area of displacements, which is between zero and a_o. Another interesting observation is that the size of the plastic region is not proportional to the cavity wall convergences. Specifically, although the upper zone provides smaller displacements than the lower one, it presents larger plastic radii, demonstrating in the clearest way the contribution of all the material properties (*E*, *c and φ*) and the in situ stress field. However, heavily squeezing conditions could occur in both zones.

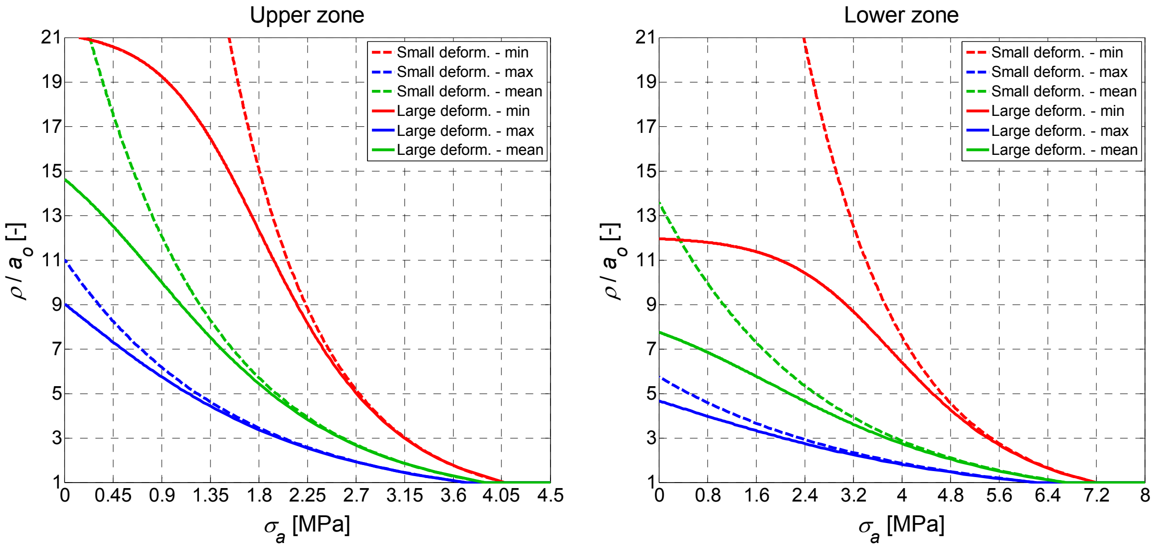


Figure 5. Normalized radius of the plastic zone as a function of the support pressure (ψ = 0°)

4.2 The influence of dilatancy on the GRC

Figures 6 and 7 demonstrate the effect of dilatancy, i.e. non-zero plastic volumetric strains, on ground behaviour for the mean strength envelope. As can be observed, even a small dilation angle has a favourable effect with respect to convergences: the higher the dilation angle, the lower the support pressure for a given tunnel radial displacement. This result can be explained by taking into consideration the stress and pore pressure fields around the cavity, which are presented in Figure 8 for the mean MC envelope of the lower breccia zone.

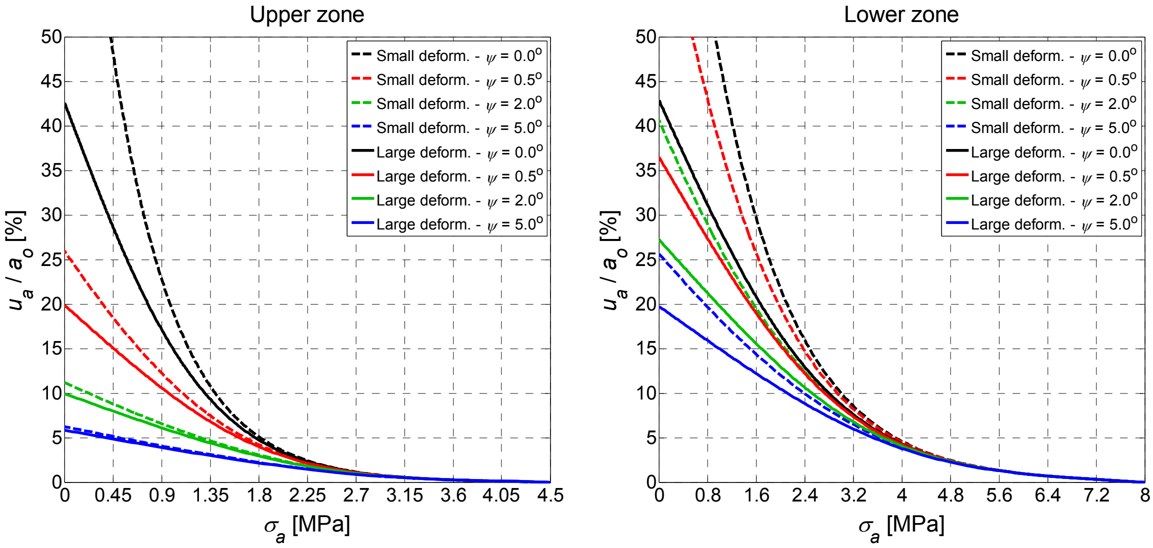


Figure 6. Ground response curves (strength parameters according to the mean MC envelope of the breccias)

A dilatant material tends to expand during plastic yielding. As the expansion is constrained by the pore water in the short-term, negative excess pore pressures develop, which are higher than for non-dilatant behaviour. The pressure drop within the plastic zone, which is more pronounced in the case of dilatancy, is favourable because it increases the effective stresses and thus the resistance to shearing. Figure 8 confirms these considerations demonstrating the favourable effect of the dilation angle according to the MC model (small convergences, less extended plastic zone around the opening).

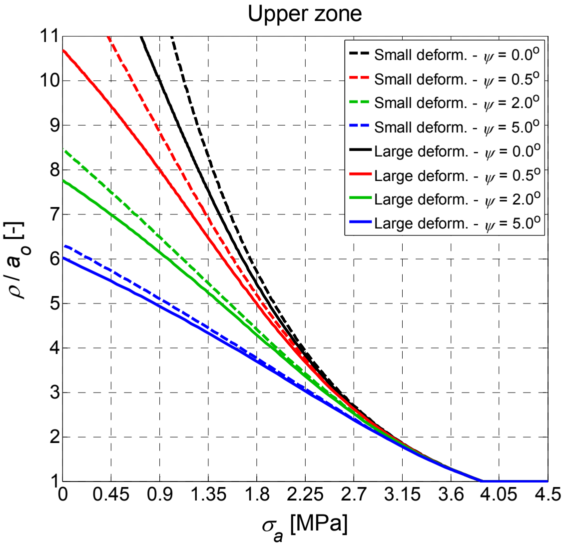


Figure 7. Normalized radius of the plastic zone as a function of the support pressure (strength parameters according to the mean MC envelope of the breccias)

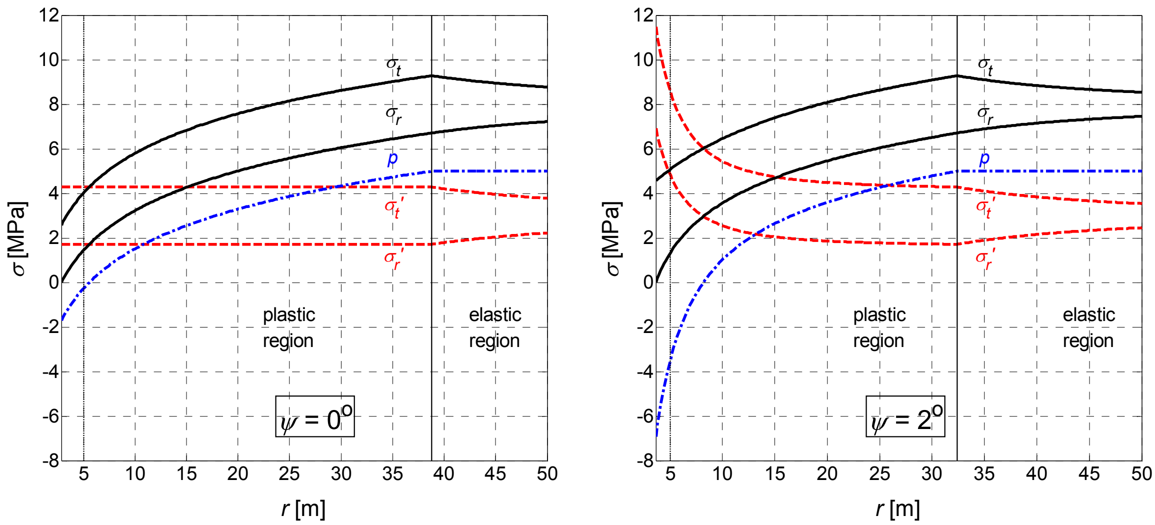


Figure 8. Stress and pore pressure distributions along the radial direction (large strain analysis, material constants of the lower breccia zone, σ_a = 0 MPa, a_o = 5 m)

5 Conclusion

The short-term GRC in compliance with experimental data, obtained from tests on breccias from the Gibraltar Strait, leads to extraordinary results emphasizing the expected presence of heavily squeezing ground conditions throughout these critical zones.

The short-term GRC that accounts for elastoplastic material behaviour as well as large strains, is useful for convergence assessments in the case of extreme squeezing, demonstrating in combination with the results obtained using small strain theory, the limited validity of the latter. It can offer a complete scientific and rational approach to the problem of a contracting cavity through an effective stress analysis under undrained conditions without imposing any restriction on the magnitude of displacements.

The existence of dilatancy affects to a great extent the short-term response of the ground around a circular opening, decreasing tunnel wall convergences, causing a non-uniform distribution of the effective stresses within the plastic region and increasing the negative excess pore pressures.

6 References

Anagnostou, G. 2009a. The effect of advance-drainage on the short-term behaviour of squeezing rocks in tunneling. ComGeo I, Pietruszczak et al. (eds), 668-679, International Centre for Computational Engineering.

Anagnostou, G. 2009b. Pore pressure effects in tunneling through squeezing ground. EURO:TUN 2009, Meschke et al. (eds), Vol. 1, 361-368, Aedificatio Publishers.

Anagnostou, G. 2010. Some rock mechanics aspects of subaquaeous tunnels. Rock Engineering in Difficult Ground Conditions – Soft rocks and Karst, Vrkljan (ed), 1-12, Taylor & Francis Group, London.

Anagnostou, G., Kovári, K. 2003. The Stability of Tunnels in Grouted Fault Zones. Publications of the Division of Geotechnical Engineering, Vol. 220, Swiss Federal Institute of Technology, Zurich.

Aydan, Ö., Akagi, T., Kawamoto, T. 1996. The squeezing potential of rock around tunnels: Theory and prediction with examples taken from Japan. Rock Mech Rock Eng 29, 3, 125-143.

Barla, G. 2002. Tunnelling under squeezing rock conditions. In: Tunnelling Mechanics: Eurosummerschool, Innsbruck 2001 – Advances in Geotechnical Engineering and Tunnelling, Kolymbas, D. (ed), Logos Verlag, Berlin.

Bonini, M., Barla, G. 2012. The Saint Martin La Porte access adit (Lyon-Turin Base Tunnel) revisited. Tunnelling and Underground Space Technology 30, 38-54.

Dalgıç, S. 2002. Tunneling in squeezing rock, the Bolu tunnel, Anatolian Motorway, Turkey. Engineering Geology 67, 73-96.

Dong, W., Pimentel, E., Anagnostou, G. 2013. Experimental investigations into the mechanical behaviour of the breccias around the proposed Gibraltar Strait tunnel. Rock Mech Rock Eng, DOI 10.1007/s00603-012-0350-y.

Floria, V., Fidelibus, C., Repetto, L., Russo, G. 2008. Drainage and related increase of short-term strength of low permeability rock mass. Building Underground for the Future; AFTES International Congress Monaco, Monte Carlo, 281-284, AFTES Paris.

Giraud, A., Picard, J.M., Rousset, G. 1993. Time dependent behavior of tunnels excavated in porous mass. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 30, 7, 1453-1459.

Graziani, A., Boldini, A. 2012. Remarks on axisymmetric modeling of deep tunnels in argillaceous formations. I: Platic clays. Tunnelling and Underground Space Technology 28, 70-79.

Graziani, A., Ribacchi, R. 2001. Short and long-term load conditions for tunnels in low permeability ground in the framework of the convergence-confinement method. Modern Tunneling Science and Technology, Adachi et al. (eds), Vol. 1, 83-88, Swets & Zeitlinger.

Kovári, K. 1998. Tunnelbau in druckhaftem Gebirge – Tunnelling in squeezing rock. Tunnel 5,12-31.

Kovári, K., Amberg, F., Ehrbar, H. 2000. Mastering of squeezing rock in the Gotthard Base. World Tunnelling 13, 5, 234-238.

Lembo Fazio, A., Ribacchi, R. 1984. Influence of seepage on tunnel stability. Design and Performance of Underground Excavations, Brown, E.T., Hudson, J.A. (eds), 173-181, British Geotechnical Society, UK.

Lewin, L. 1981. Polylogarithms and associated functions. Elsevier North Holland.

Mair, R.J. 2008. Tunnelling and geotechnics: new horizons. Géotechnique 58, 9, 695-736.

Mair, R.J., Taylor, R.N. 1993. Prediction of clay behaviour around tunnels using plasticity solutions. Predictive soil mechanics, Houlsby, G.T., Schofield, A.N. (eds), 449-463, Thomas Telford, London.

Panciera, A., 2009. Gibraltar Tunnel – Herausforderungen bei der Planung eines Tunnels an der Grenze der Machbarkeit. Colloquim “Tunnelbau in druckhaftem Gebirge”, ETH Zürich, 7 May 2009.

Pliego, J.M. 2005. Open Session – The Gibraltar Strait tunnel. An overview of the study process. Tunnelling and Underground Space Technology 20, 558-569.

Salençon, J. 1969. Contraction quasi-statique d'une cavité a symétrie sphérique ou cylindrique dans un milieu élasto-plastique. Annales des Ponts et Chaussées 4, 231–236.

Steiner, W. 1996. Tunnelling in squeezing rocks: Case histories. Rock Mech Rock Eng 29, 4, 211-246.

Vogelhuber, M. 2007. Der Einfluss des Porenwasserdrucks auf das mechanische Verhalten kakiritisierter Gesteine. Dissertation Nr. 17079, Institut für Geotechnik, ETH Zürich.

Vrakas, A., Anagnostou, G. 2013. Large deformations research project – Finite strain ground response curves, Report No 133201, ETH Zurich.

Yu, H.S. 2000. Cavity Expansion Methods in Geomechanics. Kluwer Academic Publishers.