Anisotropy Effects on the Response of Deep Tunnels Excavated in Claystone

Miguel A. Mánica
Instituto de Ingeniería, Universidad Nacional Autónoma de México, México City, México

Antonio Gens
Universitat Politècnica de Catalunya-CIMNE, Barcelona, Spain

Jean Vaunat
Universitat Politècnica de Catalunya-CIMNE, Barcelona, Spain

Gilles Armand
Meuse/Haute Marne Underground Research Laboratory. ANDRA R&D, Bure, France

Minh-Ngoc Vu
ANDRA R&D, Chatenay-Malabry, France

ABSTRACT: Tunnelling in argillaceous rock is very common because of the widespread occurrence of those materials in the earth crust. Research on argillaceous rocks have been further stimulated in recent times because of their suitability as host rocks in deep geological repositories for radioactive waste. The paper presents a numerical analysis, using an especially developed constitutive model for argillaceous rocks, that reproduces successfully the observations obtained in the excavation of tunnels in Callovo-Oxfordian claystone at the Meuse/Haute-Marne underground laboratory. Particular attention is given to the configuration of the fractured zone and its dependence on the orientation of the tunnel. Using this analysis as reference, the effects of stiffness and strength anisotropy as well as of the in-situ stress anisotropy are examined. The analyses reveal that either strength anisotropy or the initial in-situ stress state have a dominant influence depending on the alignment of the tunnel.

Keywords: anisotropy, tunnels, claystone, fractured zone, numerical modelling, in-situ stresses.

1 INTRODUCTION

Argillaceous rocks are very prevalent in nature; it has been estimated that they may constitute as much as 50% of the global sedimentary rock mass and that they outcrop in about one third of the emerged earth surface (Gens 2013). Therefore, tunnelling and underground excavations in this type of materials will occur frequently. Interest on argillaceous rocks has been further enhanced by the fact that they are considered suitable host materials for the safe geological disposal of high-level and long-lived radioactive waste, because of their low permeability, significant retention properties and limited economic value. This has prompted the construction of a number of underground research laboratories that allow the observation of their behaviour under controlled and realistic conditions. The amount of data and information available in these facilities usually surpasses what is generally available in more conventional civil engineering projects.

In the context of radioactive waste disposal, the existence of a fractured zone around the tunnels is a key issue, as they affect the hydromechanical response of the rock. Notably, the fractures that develop lead to an increase of permeability that may favour the eventual migration of radionuclides although argillaceous rocks do exhibit a capacity for self-sealing with time (Tsang et al. 2005). In addition, the development of a fractured zone weakens the rock adjacent to the tunnel and affects the requirements for temporary support and permanent lining.

This paper is based on observations obtained in the Meuse/Haute Marne (MHM) Underground Laboratory, located in Eastern France (Delay et al. 2007). The Laboratory is excavated in Callovo-Oxfordian claystone and the main experimental level is located 490 m below the surface (Figure 1). The determination of the state of in situ stresses revealed a vertical stress of about 12 MPa, consistent with overburden. The horizontal stresses are, however, not isotropic; the minor principal stress has a value similar to the vertical one whereas the major principal horizontal stress is approximately 30% larger.

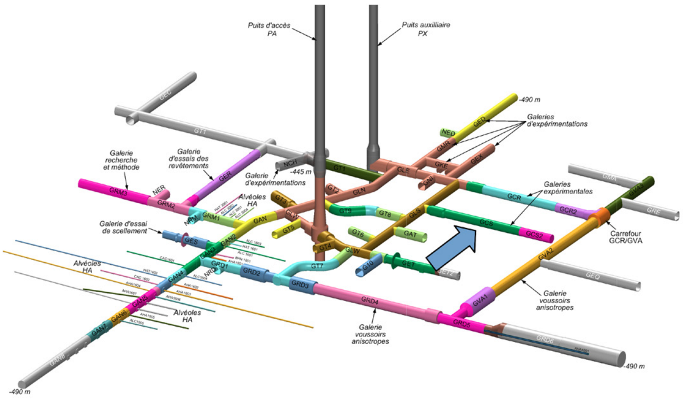


Figure 1. Layout of the MHM Underground Laboratory.

Tunnel excavations in two perpendicular directions will be examined. The excavations were performed using a road header followed by the installation of a relatively flexible support. After excavation, the extent of the fractured zone was carefully determined. It was found that the fractured zone configuration depended very strongly on the orientation of the drift (Figure 2). The in situ stresses in a cross section of the tunnel excavated parallel to the major principal horizontal stress is practically isotropic. However, the fractured zone is very far from being isotropic, extending considerably more in the horizontal direction. Evidently, the anisotropic properties of the rock must affect the fractured zone development. Interestingly, the geometry of the fractured zone for the tunnel excavated in the perpendicular direction is very different, displaying a much larger extension in the vertical direction than in the horizontal one. In this case, however, the in-situ stresses in a tunnel cross section is anisotropic and, therefore, likely to play a role in the generation of the fractured zone. Effects of rock anisotropy are also apparent, for instance, in the measured convergences in the tunnel parallel to the major horizontal principal stress where, again, horizontal displacements are significantly larger than horizontal ones.

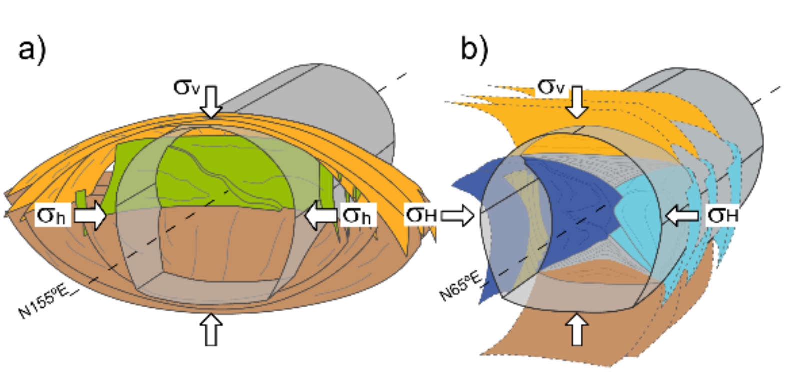


Figure 2. Observed fractured zone in tunnels excavated in the MHM underground laboratory (modified from Armand et al. 2014). a) Tunnel excavated parallel to the major horizontal principal stress. b) Tunnel excavated parallel to the minor horizontal principal stress.

In the next section, a numerical model capable of reproducing satisfactorily the observations made in the MHM underground laboratory is briefly presented. Adopting this Base Case as a realistic representation of the system, the effects of rock and in-situ stress anisotropy will be examined afterwards.

2 NUMERICAL MODEL. BASE CASE

2.1 Constitutive model

A constitutive model for argillaceous rocks has been especially developed in order to reproduce the most characteristic features of behaviour of those materials. It is an elasto-viscoplastic model that incorporates a family of non-linear hyperbolic Mohr-Coulomb yield surfaces, hardening and softening behaviour on either side of peak strength, stiffness and strength anisotropy and time-dependent effects arising from both viscoplasticity and an additional long-term creep component. Hydromechanical coupling is defined by an appropriate Biot coefficient. In addition, the observed increase of permeability with damage is introduced via a relationship between hydraulic conductivity and plastic shear strains. Further information on the constitutive model and the parameters used in the analysis are given in Mánica et al. (2022).

2.2 Numerical model

Tunnelling was simulated under 2D plane strain conditions, Because of the great excavation depth, gravity-induced gradients can be neglected so that it is sufficient to consider one quarter of the problem (Figure 3a). The actual tunnel excavation was approximated by a deconfinement curve that depended on the distance of the excavation front to the analysis section (Figure 3b). The tunnel pressure was reduced to 0.32 MPa, the estimated radial stress provided by the support system. No flow through the runnel boundary was assumed before the excavation front reached the analysis section and zero water pressure afterwards. In order to simulate the phenomena of strain localization and fracturing, avoiding pathological mesh-dependence, a non-local integration formulation was incorporated in the analysis (Mánica et al. 2018). This requires a very fine discretisation in the vicinity of the tunnel where the fractured zone is likely to occur (Figure 3a).

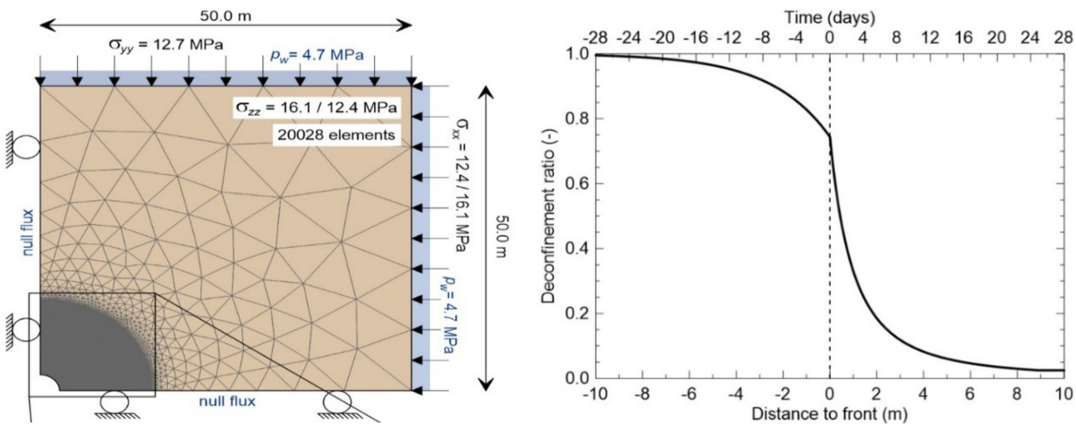


Figure 3. a) Domain of analysis and discretization. b) Deconfinement curve.

2.3 Results

For brevity, only the configurations of the fractured zone obtained in the analyses of tunnel excavation in two perpendicular directions are presented (Figure 4). The successful reproduction of strain localized zones can be noted. It can be observed that the shape and extension of the computed fractured zone resemble closely those observed in the field (indicated by an outline). The analyses were also able to predict successfully rock displacements, convergences and the evolution of pore pressures throughout (Mánica et al, 2022).

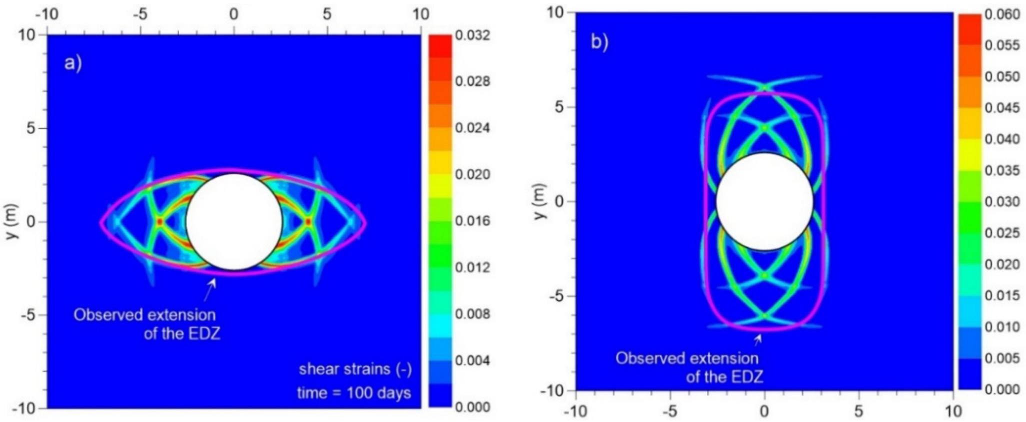
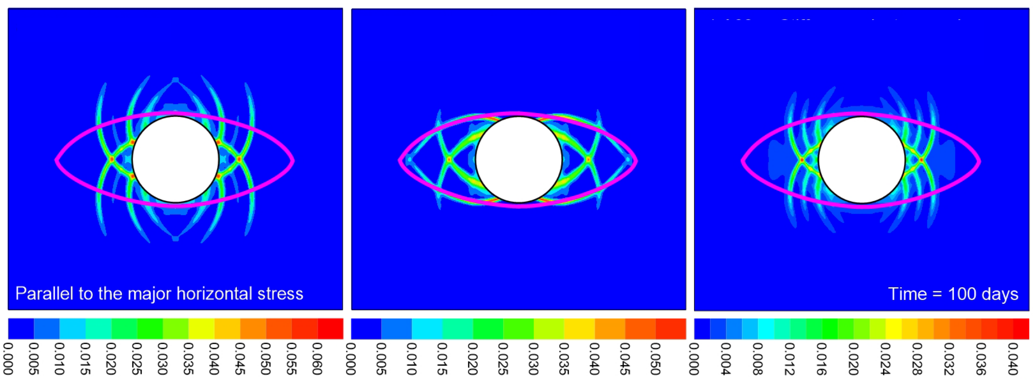


Figure 4. Computed fractured zone configurations. a) Tunnel excavated parallel to the major horizontal principal stress. b) Tunnel excavated parallel to the minor horizontal principal stress. The purple outline is the extension of the fractured zone observed in the field.

3 EFFECTS OF ANISOTROPY

In the Base Case, anisotropy of strength and stiffness has been considered. As indicated above, the in-situ stress state of the tunnel excavated parallel to the major horizontal principal stress is also isotropic whereas it is anisotropic in the perpendicular direction. As the Base Case analysis has proved able to reproduce satisfactorily the field observations, it can be used as a reference to check on the effects of individual anisotropy components. Three different analyses have been performed for the two tunnel orientations: i) isotropic model, b) considering strength anisotropy only, and iii) considering stiffness anisotropy only. The fractured zones obtained for the tunnel parallel to the major horizontal principal stress are shown in Figure 5. The isotropic case (5a) naturally leads to a uniform development of the fractured zone different from that observed in the field. The configuration obtained assuming stiffness anisotropy only (5c) also differs significantly from observations. However, the fractured zone computed using strength anisotropy only is very close to that determined in the field. It is evident therefore that strength anisotropy is the dominant factor underlying the observed development of the fractured zone.



a) b) c)

Figure 5. Configuration of the fractured zone obtained for a tunnel excavated parallel to the major principal horizontal stress. a) isotropic model, b) strength anisotropy only, c) stiffness anisotropy only. The purple outline indicates the extension of the fractured zone observed in the field.

The same set of analyses have been carried out for a tunnel excavated parallel to the minor principal horizontal stress. The results in terms of the computed fractured zones are shown in Figure 6. It is apparent that now, although the fractures developed vary between the different cases, the fractured zone size is very similar in all the analyses and quite close to the observed one, i.e. with a much larger extension in the vertical direction. In this case, therefore, the anisotropy of the initial in-situ stresses has a dominant effect over the anisotropy of stiffness and strength.

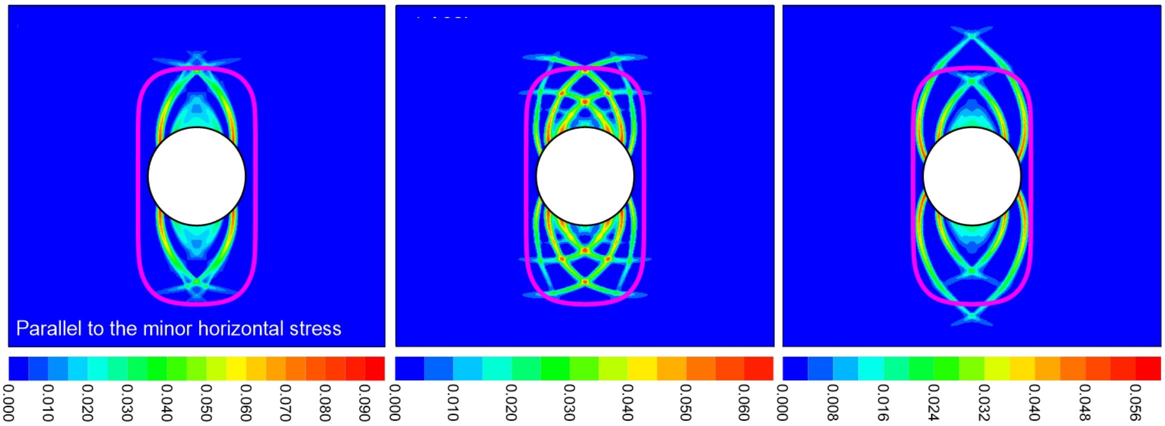


Figure 6. Configuration of the fracture zone obtained for a tunnel excavated parallel to the minor principal horizontal stress. a) isotropic model, b) strength anisotropy only, c) stiffness anisotropy only
The purple outline indicates the extension of the fractured zone observed in the field.

The effect of different kinds of rock strength anisotropy has also been examined. Three analysis have been performed using the variations of rock strength with loading orientation that are shown in Figure 7, together with that used in the Base Case. Due to space limitations, only the case of the tunnel excavated in the direction of the major principal horizontal stress is presented (Figure 8). The analysis B01 uses a strength variation that, as in the Base Case, the maximum strength is when the rock is loaded parallel to bedding. It results in a fractured zone also consistent with observations. However, in cases B02 and B03, where the rock strength loaded parallel to bedding is equal or even lower than the strength when loaded perpendicular to bedding, the computed fractured zone differs from the field one. It appears, therefore, that the fractured zone observations offer also useful information on the type of strength anisotropy of the rock; an especially valuable information as it is derived from field data. It can also be noted that, in all the cases considered, the minimum strength occurs when the loading is oblique to bedding, a quite well-established fact.

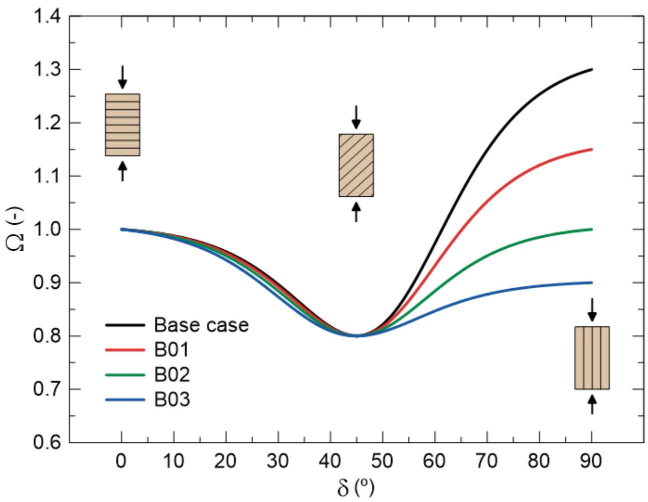


Figure 7. Variation of strength with applied load orientation used in the analyses.

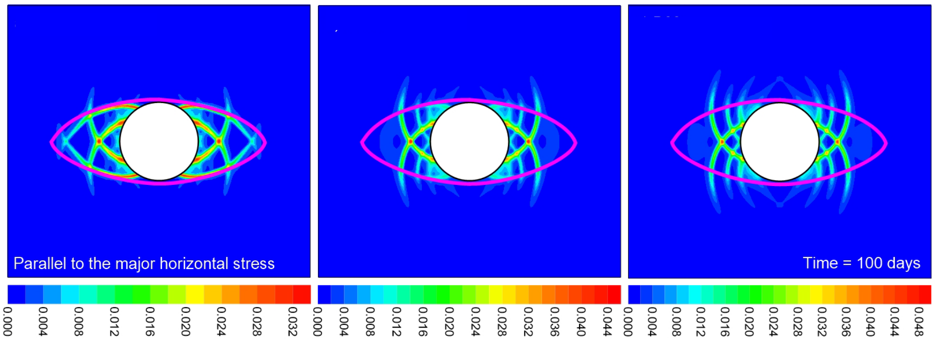


Figure 8. Configuration of the fractured zone obtained for a tunnel excavated parallel to the major principal horizontal stress using different variations of rock strength with applied load orientation. a) B01 strength variation, b) B02 strength variation, c) B03 strength variation. The purple outline indicates the extension of the fractured zone observed in the field.

4 CONCLUSIONS

A numerical analysis using an especially developed constitutive model for argillaceous rock has proved capable of reproducing successfully the observations obtained in the excavation of tunnels in Callovo-Oxfordian claystone at the MHM underground laboratory. Particular attention has been given to the configuration of the fractured zone and its dependence on tunnel orientation. Using this analysis as reference, the effects of stiffness and strength anisotropy as well as of the in-situ stress state have been examined. It has been found that, under an isotropic stress state, strength anisotropy is dominant but the effects of in situ stresses are more influential when a non-isotropic stress state is present. The effect of different variations of strength with loading orientation have also been explored.

ACKNOWLEDGEMENTS

The authors are grateful for the financial and technical assistance of the French national radioactive waste management agency (ANDRA).

REFERENCES

Armand, G., Leveau, F., Nussbaum, C., de La Vaissiere, R., Noiret, A., Jaeggi, D., Landrein, P., & Righini, C. 2014. Geometry and properties of the excavation-induced fractures at the Meuse/Haute-Marne URL drifts. *Rock Mechanics and Rock Engineering*, 47(1), pp. 21–41.

Delay, J., Vinsot, A., Krieguer, J.-M., Rebours, H., & Armand, G. 2007. Making of the underground scientific experimental programme at the Meuse/Haute-Marne underground research laboratory, North Eastern France. *Physics and Chemistry of the Earth*, 32(1–7), pp. 2–18.

Gens, A. 2013. On the hydromechanical behaviour of argillaceous hard soils-weak rocks. *Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering - Geotechnics of Hard Soils - Weak Rocks*, IOS Press, Athens, pp. 71–118.

Mánica, M. A., Gens, A., Vaunat, J., Armand, G., & Vu, M.-N. 2022. Numerical simulation of underground excavations in an indurated clay using non-local regularisation. Part 1: formulation and base case. *Géotechnique*, 72(12), pp. 1092-1112. doi.org/10.1680/jgeot.20.P.246.

Mánica, M. A., Gens, A., Vaunat, J., & Ruiz, D. F. 2018. Nonlocal plasticity modelling of strain localisation in stiff clays. *Computers and Geotechnics*, 103, pp. 138–150. doi:10.1016/j.compgeo.2018.07.008

Tsang, C. F., Bernier, F., & Davies, C. 2005. "Geohydro-mechanical processes in the excavation damaged zone in crystalline rock, rock salt, and indurated and plastic clays - In the context of radioactive waste disposal. *International Journal of Rock Mechanics and Mining Sciences*, 42(1), pp. 109–125