Consideration of Creep Deformation in Deep Underground Gallery Excavation in Claystone

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ABSTRACT: This article deals with the numerical analysis of long-term behaviour of deep underground tunnel structures in claystone with “ductile lining” using PLAXIS 2D. The constructed gallery is a 2.6 m radius circular made of yielding sprayed concrete lining and is constructed at a depth of 500 m in a uniform claystone mass subjected to creep deformations. A visco-elastoplastic model has been used for describing the mechanical behaviour of the claystone. To prevent the development of excessive axial forces in the lining, yielding elements within the sprayed concrete lining have been used. They are modelled using a user-defined material model and special attention is dedicated in this article to the numerical formulation of such constitutive modelling. This article will finally present the short-term and long-term closure evolution results obtained in this context and highlight the good agreement between experimental measurements and numerical predictions, indicating the accuracy of the implemented creep law.

Keywords: PLAXIS 2D, creep model, tunnel, rock.

1 INTRODUCTION

Deep excavation in squeezing grounds for tunnel engineers normally implies large sometimes excessive tunnel convergences. The development of such deformations usually takes slowly lasting for one week, several months, or more than one year, after tunnel excavation is completed. Conventional rigid tunnel shotcrete linings, where rock deformations are strictly limited, are unable to work against great overburden pressure the excavation of which will almost systematically lead to considerable rock deformations and associated phenomena such as shotcrete falls or cracking, or even serious tunnel collapse.

To avoid shotcrete lining failure in deep excavation through squeezing grounds, the use of yielding elements in shotcrete lining, leading to the so-called “ductile lining”, has gradually gained more attention. Yielding elements show a stronger deformability than shotcrete, providing shotcrete lining with high possible resistance and able to accommodate the controlled rock deformations through their compressible deformations.

Structural design of shotcrete lining with yielding elements requires the proper consideration of initial stresses in the rock mass as well as a correct evaluation of delayed deformation that will develop through time after the excavation process and support installation have taken place. This requires the use of appropriate constitutive models for the rock mass in which irreversible strains associated with creep effects as well as possible local shear failure can be considered. Proper consideration of soil-structure interaction is also essential for reliable assessment of structural force development over time. Finally, an accurate representation of the yielding elements and its effect on reducing the normal forces within the lining with acceptable safety margin must be achieved.

This article deals specifically with the numerical analysis of the evolution of the convergence (short-term and long-term) following the underground excavation of a circular tunnel in claystone. Due to the considerably large initial stress values (due to the large depth of the excavation) and to limit the development of excessive normal forces a yielding sprayed concrete lining of high bearing capacity is being placed. In this context a visco-elastoplastic model based on the classical Norton' law has been used for describing the mechanical behavior of the claystone. The claystone constitutive model will first be briefly presented. The setup-up of the numerical FE analysis will be presented in a second part in which strong emphasis will be given on the modelling of the yielding elements (hiDCon®). This example deals with the evolution of the convergence (short-term and long-term) following the excavation of a circular tunnel in claystone Numerical results will finally be presented and compared with experimental measurement obtained on site along with some of the results obtained using other simulation software package in the first place.

2 CLAYSTONE CONSTITUTIVE BEHAVIOUR

The model used in PLAXIS is known as the N2PC-MCT model. This model was primarily developed as the N2PC model and solely intended for studying the time-dependent (long-term) deformation of rock structures (for example subsidence analysis for solution mining). To better predict failure and damage of the structures, the model has been further extended by including a Mohr-Coulomb with Tension cut-off (MCT) failure mechanism (PLAXIS (2022)). The extended model, called N2PC-MCT model, allows modelling more adequately both instantaneous plastic deformation and stress evolution related to rock plastic strength parameters and will be now shortly presented.

In the most general framework, the rock is modelled as an isotropic visco-elastoplastic material in which the total strain tensor is decomposed as an elastic part, a creep part and a plastic part:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{e} + \dot{\boldsymbol{\varepsilon}}^{cr} + \dot{\boldsymbol{\varepsilon}}^{p} \tag{1}$$

The elastic strains $\dot{\boldsymbol{\varepsilon}}^{e}$ obey the classic Hooke law. The creep strains $\dot{\boldsymbol{\varepsilon}}^{cr}$are modelled as follows:

$$\dot{\boldsymbol{\varepsilon}}^{cr} = |\dot{\varepsilon}^{cr}|\frac{3\boldsymbol{s}}{2q} \tag{2}$$

where q is the Von-Mises shear stress and $|\dot{\varepsilon}^{cr}|$ is the intensity of the creep strain rate, defined by the following double-power law:

$$|\dot{\varepsilon}^{cr}| = A_1\left(\frac{q}{q_0}\right)^{N_1} + A_2\left(\frac{q}{q_0}\right)^{N_2} \tag{3}$$

where q is the deviatoric stress, q_0 is a reference stress value N_1 and N_2 are two stress exponent parameters while A_1 and A_2 are two-viscosity-like parameters. The plastic strain $\boldsymbol{\varepsilon}^{p}$ is the time-independent irreversible strain characterized by the well-known Mohr-Coulomb failure criterion governed by standard strength parameters (cohesion, friction angle, tensile strength). When the failure criterion is violated, stress state stays on the yield contour and plastic strain is generated following a perfectly plastic non-associative law (governed additionally by a dilation angle). The detailed presentation of this model can be found in PLAXIS Material Models Manuals (2022).

3 NUMERICAL ANALYSIS OF THE UNDERGROUND EXCAVATION

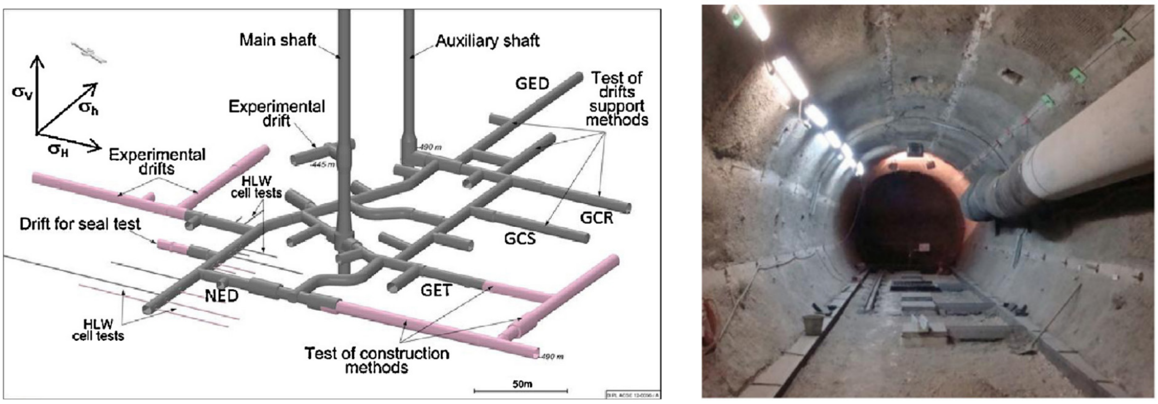
3.1 *Project presentation*

The Meuse/Haute-Marne Underground Research Laboratory (URL) at Bure, France, was established by the French National Radioactive Waste Management Agency (ANDRA) in 2000 to investigate the feasibility of a radioactive waste repository in a claystone formation. The host formation consists of Callovo-Oxfordian argillaceous rock located at depths between 420 m and 550 m.

As part of the research program, a series of experimental studies were conducted to understand the response of the claystone host rock to various excavation and construction methods for shafts and drifts. The primary objective was to study the claystone formation and the evolution of the Excavation Damaged Zone (EDZ) around the structures, with a focus on the impact of these factors on repository safety.

During the construction of the laboratory drifts, extensive experiments and direct measurements were carried out. The extent of the drift network can be seen in Figure 1(a), and more detailed information on the experimental results can be found in a publication by Armand et al. (2007).

Previous analyses of the research data utilized different numerical analysis software, as described in studies by Saitta et al. (2017) and Ribeiro et al. (2020). The specific focus of this article is the finite element analysis of the GCS drift (shown in Figure 1(b)). The GCS drift was excavated in the direction of the major horizontal stress from the south drift (GLS drift) using the PLAXIS 2D software.



(a) *Meuse/Haute-Marne URL drifts network* (b) *GCS drift with yielding elements*

Figure 1. Project presentation.

3.2 *Finite Element Model Setup*

The studied gallery section (GCS drift) has been constructed at a large depth (over 500 m) in a uniform claystone mass. The tunnel is placed at model center and is surrounded by an 80 m × 80 m rock mass. In order not to physically model the entire overburden, the assumption of a uniform state of stress around the tunnel (at the considered stress situation at the construction depth) will be made with $\sigma_V =$ -12700 kPa, $\sigma_h = K_{0,x}.\sigma_V$ = -12400 kPa and $\sigma_H = K_{0,z}.\sigma_V$ = -16200 kPa.

The constructed gallery is a 2.6 m radius circular made of yielding sprayed concrete lining. In situ, it has been observed a zone a fractured rock which has been numerically approximated by an ellipse of major and minor axis respectively equal to 6.02 m and 2.80 m. The claystone material properties are summarized in Table 1.

The tunnel lining is modelled by means of an 18 cm thick sprayed concrete interspaced with yielding elements (hiDCon®) to prevent the development of excessive normal during excavation. The shotcrete segments are modelled as linear elastic material with $E = 20$ GPa and $\nu = 0.2$. The in-between 0.18 m × 0.18 m yielding elements have been modelled also using continuum elements but with an elasto-plastic compression-only behavior. This has been achieved through the implementation of a specific UDSM (User-Defined Soil Model) in PLAXIS such that the following conditions are always satisfied:

Elasto-plastic behaviour in compression: $$p = \min(K\epsilon_v^e, p_{max}) \tag{4}$$

Elastic behaviour in shear: $$\boldsymbol{s} = 2G\boldsymbol{e}_d^e \tag{5}$$

Compression-only behaviour: $$\min(\sigma_1, \sigma_2, \sigma_3) \geq 0 \tag{6}$$

where p is the mean effective stress, K and G are respectively the rock bulk and shear modulus, ϵ_v^e is the elastic volumetric strain, $\boldsymbol{e}_d^e$ and $\boldsymbol{s}$ are the elastic deviatoric strain and deviatoric stress tensors and $\sigma_1, \sigma_2, \sigma_3$ are the principal stress values.

Table 1. Claystone model parameters summary.

Material Name	Intact rock	Fractured rock
Elastic shear modulus G (kPa)	1.54E6	1.54E6
Poisson ratio ν	0.3	0.3
Stress exponent N_1	6.8	6.8
A_1 (day^{-1})	0.136E-12	0.136E-12
Stress exponent N_2	0	0
A_2 (day^{-1})	0	0
Cohesion c (kPa)	6000	800
Reference stress q_0 (kPa)	1000	1000
Friction angle φ (°)	20	25
Dilatancy angle ψ (°)	0	2
Tensile strength f_t (kPa)	900	0

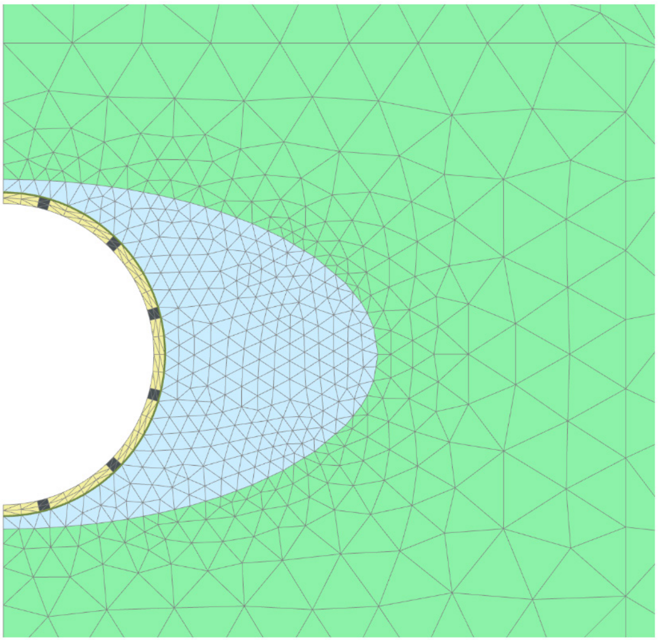


Figure 2. Finite element mesh presentation.

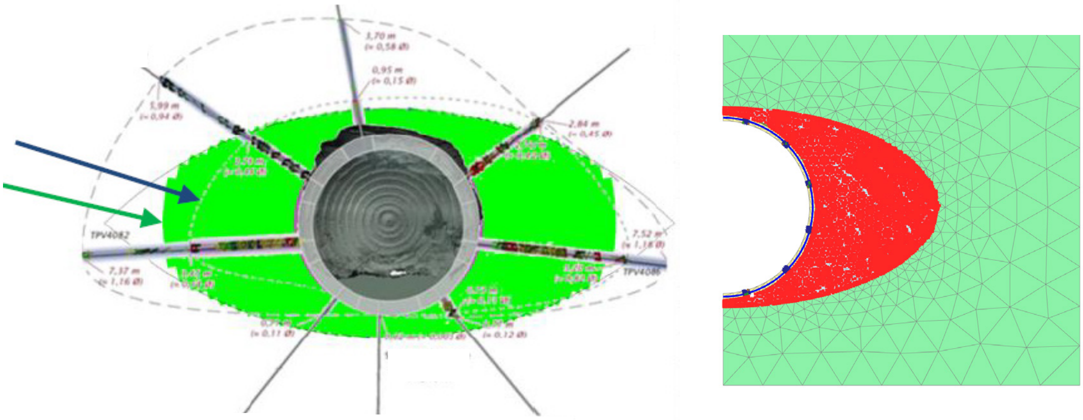
The elastic parameters K and G are derived from $E = 1$ GPa and $\nu = 0$. The maximum mean pressure $p_{\max}$ has been set to 1333 kPa. Such material parameter values have been defined based on available experimental data for hiDCon® yielding elements.

The FE mesh is presented in Figure 2. 15-noded elements have been used for the soil and lining elements. Interface elements also have been considered between the lining and the surrounding claystone mass. The analysis has been performed by considering the following 4 construction phases:

- Initial stress definition: Initial field stresses are being initialized in the model.
- Rock mass deconfinement: The level of deconfinement at the installation of the yielding sprayed concrete lining is taken equal to 0.75.
- Tunnel lining installation: The shotcrete lining along with yielding elements are wished in place and will support the remaining 25 % of the in-situ stresses.
- Creep: Creep analysis for 20 years.

3.3 *Analysis results*

The analysis of excavation-induced fracturing is presented in Figure 3. The experimental results in Figure 3(a) depict the extension of the fractured zone, which was obtained from a similar tunnel section in a different drift (GRD4 gallery). These results were initially compared with a different and independent numerical analysis conducted by Zghondi et al. (2015) using finite difference method. Figure 3(b) illustrates the extension of the plastic zone obtained from the numerical calculation using the PLAXIS software. The red zone represents the simulated plastic zone by the PLAXIS model, which exhibits a generally similar shape to the dotted zone representing the observed fractured zone in situ. However, occasional deviations can still be observed. These deviations are likely attributed to the irregular nature of the fracturing phenomenon, which involves discontinuities in the rock mass.



(a) (b)

Figure 3. Comparison between (a) the extension of the fractured zone computed by (green dots) and (b) PLAXIS predicted plastic points (red dots).

The closure evolution of the GCS drift gallery is presented in Figure 4, where the experimental results are represented with symbols at various locations along diametrically opposed measuring points. The ratio between the two displacements at the end of the excavation is approximately 2, consistent with observations made for galleries oriented according to the major horizontal constraint. However, short-term horizontal convergences are overestimated by around 2 cm (equivalent to 1 cm on the radius). On a long-term perspective, the numerical results are considered highly satisfactory as they provide a close envelope to the experimentally measured data, encompassing the range from maximum horizontal to minimum vertical tunnel closure values. These findings indicate that the implemented creep law in the elasto-plastic model is appropriate for accurately assessing the closure evolution.

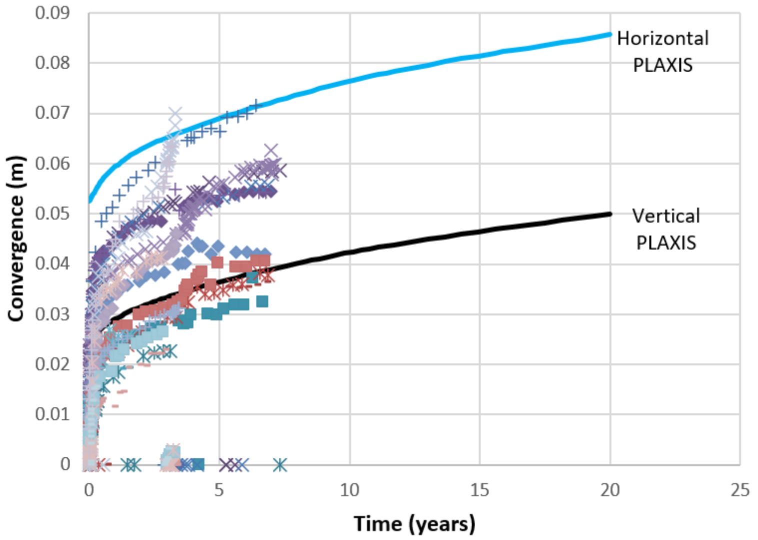


Figure 4. Tunnel closure evolution around the GCS drift. PLAXIS calculated values against measured data.

4 CONCLUSIONS

This article deals with the evolution of the short-term and long-term convergence following the deep underground excavation of a circular tunnel in claystone. In this context, a visco-elastoplastic model based on the classical Norton's law for describing the time-dependent mechanical behavior of the claystone has been used. The setup-up of the numerical FE analysis done with PLAXIS 2D has then be presented. Particular attention has been dedicated to the mechanical behavior modelling of the hiDCon® yielding elements. the analysis reveals the extension of the fractured zone and the plastic zone obtained from both experimental observations and numerical simulations. The numerical results exhibit a generally similar pattern to the observed data, with occasional deviations possibly due to the irregular nature of the fracturing phenomenon. Additionally, the closure evolution of the GCS drift gallery demonstrates a good agreement between experimental measurements and numerical predictions, indicating the accuracy of the implemented creep law in the elasto-plastic model.

REFERENCES

PLAXIS 2022. User Defined Soil Models: N2PC-MCT: A Viscoplastic Creep Model including a Plastic Failure Mechanism for Rocks, *PLAXIS Material Manual CONNECT Ed. V22.00.*

PLAXIS, 2022. PLAXIS 2D Material Model Manual, *PLAXIS User Manual CONNECT Ed. V22.00*.

Delay J., Vinsot A., Krieguer J.M., Rebours H., Armand G., 2007. Making of the underground scientific experimental programme at the Meuse/Haute Marne URL, North Eastern France. *Physics and Chemistry of the Earth,* Parts A/B/C;32(1–7):2–18.

Armand G., Noiret A., Zghondi J., Seyedi D.M., 2013, Short- and long-term behaviors of drifts in the Callovo-Oxfordian claystone at the Meuse/Haute-Marne Underground Research Laboratory, *Journal of Rock Mechanics and Geotechnical Engineering 5, pp 221–230.*

Zghondi J., Carraretto S., Noiret A., Armand G., 2015, Monitoring and behavior of an instrumented concrete lining segment of a TBM excavation experiment at the Meuse Haute-Marne Underground Research Laboratory, *CONCREEP-10.*

Saitta A., Lopard G., Petizon T., Armand G., 2017, Projet Cigéo (France): Modélisation du comportement des argilites de la galerie GRD du laboratoire souterrain de Meuse/Haute-Marne / Cigéo project (France) *–15th AFTES International Congress*, Paris, France.

Ribeiro, V.A., Bruchon, J.F., Burlon S., 2020, Accounting for long term effects for the structural design of deep tunnels in claystones *–5th Int. ITASCA Symposium*, Vienna, Austria.