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RHEOLOGICAL CHARACTERIZATION OF A CLAY FORMATION FROM DRIFTS EXCAVATION : ELASTIC AND ELASTOPLASTIC APPROACH

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ABSTRACT
An extensive scientific programme has been carried out by Andra (French Agency in charge of radioactive waste management) for investigating feasibility of High Level Activity Waste disposal in deep geological formation. An Underground Research Laboratory (URL) is currently being constructed in North-eastern France to assess the adequacy of a hard-clay argillite layer (Callovo-Oxfordian formation) situated between 420 m and 550 m of depth. Geotechnical measurements have been carried out during the shafts and drifts excavation and particularly upon the main level of the laboratory (-490 m). The drifts are "horseshoe section" type with about 17 m² in area mainly supported by metallic ribs and rock bolts. The digging has been performed with classical pneumatic hammer. Measurement sections have been instrumented very close to the front face using convergencemeters and radial extensometers. This paper presents a comparison between in situ measurements and numerical modelling. Elastic calculations are not in agreement with the measured deformations. An elastoplastic constitutive model considering damage and using Hoek & Brown criteria has been developed and implemented in the FLAC^{3D} numerical code. Mechanical parameters came from lab tests performed on core samples. For the first meters, model provides consistent displacements. Beyond 4 meters, a time dependent convergence takes place and has to be integrated in the model to take into account creep and/or hydromechanical behaviour.

RÉSUMÉ
Un important programme scientifique a été conduit par l'Andra (l'agence française de la gestion des déchets radioactifs) afin d'étudier la faisabilité d'un stockage de déchets de haute activité et à vie longue dans une formation géologique profonde. Un laboratoire de recherche souterrain est actuellement en cours de construction dans le Nord-Est de la France pour évaluer les propriétés d'une roche indurée argileuse (argillite du callovo-oxfordien). Cette roche se situe entre 420 m et 550 m de profondeur. Des expérimentations géomécaniques ont été mises en oeuvre lors de la construction des puits et des galeries en particulier au niveau principal (-490 m). Une méthode classique de creusement au marteau piqueur a été utilisée pour excaver les galeries de type 'section fer à cheval' d'une surface de 17 m^2 environ avec un soutènement se composant de cintres métalliques et de boulons aciers. Des sections de mesures ont été équipées au plus tôt près du front avec des plots de convergence et des extensomètres radiaux. Dans cet article, une comparaison entre modèles mécaniques et mesures in situ est présentée. Les résultats d'une approche purement élastique ne sont pas en accord avec les déformations observées. Une loi rhéologique élastoplastique utilisant les critères Hoek & Brown a été développée et implémentée dans le code numérique FLAC^{3D}. Les paramètres du modèle ont été ajustés sur des essais sur échantillons. Le modèle prédit bien les déplacements mesurés lors des 4 premiers mètres d'excavation. Après, la convergence est dominée par les effets différés, nécessitant l'intégration d'une loi de fluage ou d'un comportement hydromécanique dans le modèle.

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1. INTRODUCTION

In November 1999, having completed the preliminary work phase, Andra started construction work of an underground research laboratory (figure 1) in the district of Bure (Meuse département), located in the North-eastern of France. From 2000 to 2005, the construction of the experimental site has allowed to study radioactive waste storage possibilities in deep geological formation (Delay, 2003 ;Andra, 2005a).

The target horizon for the laboratory is a 130 m thick layer of argillaceous rocks that lies between about 420 and 550 meters below the surface at the URL site. From a lithological view point, the depositional period straddles the Callovian and Oxfordian subdivisions of the middle to upper Jurassic. Argillaceous rocks contain a mixture of clay minerals and clay-sized fractions of other compositions. The clays, which constitute 40 % - 45 % on average of the Callovo-Oxfordian argillaceous rocks, offer groundwater isolation and radionuclides retention. Silica and carbonate-rich sedimentary components strengthen the rock to contribute to stability of the underground construction.

The stratigraphy of the URL is one of alternating limestone-rich and clay-rich units. On the upper part, the Oxfordian limestones lie from about 150 to 400 meters depth. Between the surface and the Oxfordian limestones is a 150 m thick sequence of mixed argillaceous rocks,

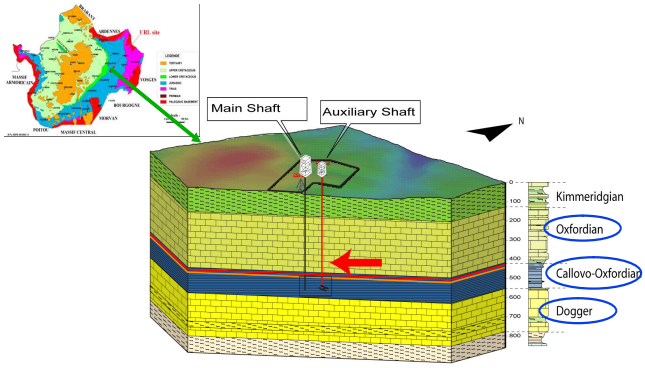


Figure 1. Localization of the underground research laboratory at the Meuse/Haute-Marne site

marls, and limestones of the Kimmeridgian. Underlying the Callovo-Oxfordian argillaceous rocks are the Bathonian and Bajocian-age Dogger limestones and dolomitic limestones (Vigneron *et al.,* 2004).

The state of in situ stress at the Meuse/Haute-Marne site has been measured by comprehensive combined methods. The vertical stress profile is presently well known on the site. The orientation of the σ_H stress (N155°E) is consistent with the regional stress field. The horizontal stress anisotropy is estimated between $1.1 < K_H = \sigma_H/\sigma_h < 1.3$ and the vertical stress and minimum horizontal stress have been directly measured close to the main level (-500 m depth) respectively equal to 12.7 MPa and 12.4 MPa (Wileveau, 2005).

The main purpose of the geomechanical in situ investigation is to understand the rock response to the excavation of underground engineered structures and to the development of the damaged zone. The damaged zone characterization during shafts and drifts excavations will not be developed in this paper. Mechanical measurements are grouped in drift sections and within specific shaft excavation monitoring experiments so-called “mine by tests”. These geomechanical experiments include a set of boreholes or convergence sections designed to monitor the behaviour of rock when openings are restarted.

Figure 2 presents the overall layout of the underground network of excavated rock in the Meuse/Haute Marne laboratory and the location of the experimental drifts constructed in the clay formation. The first geomechanical mine by experiment is located in the -445 m experimental drift, corresponding to the upper layer of the Callovo-Oxfordian layer, where the mechanical response is mainly elastic (Wileveau et al., 2005). After an important instrumentation carried out from the – 445 m level, the vertical mine by test has been monitored between -465 m and -480 m during the main shaft sinking (Armand et al., 2006). The third geomechanical experiment, dealing with this paper, is the drift excavation tests at the main level of the URL, which is around -490 m beneath the surface. SMR1.1 and SMR1.3 sections have been respectively installed in april 2005 and august 2005 during the works

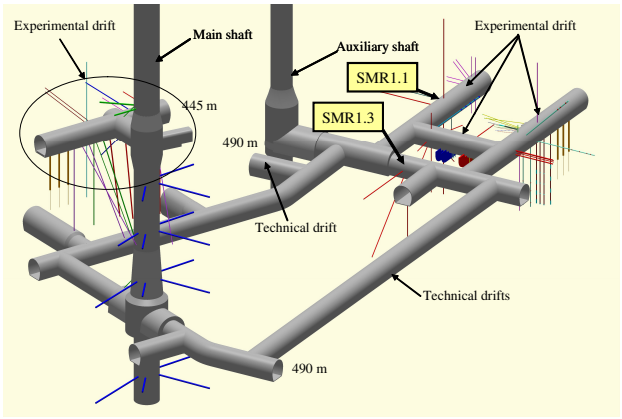


Figure 2. General layout drawing of the Meuse/Haute-Marne URL showing SMR1.1 and SMR1.3 locations

of drift excavation conducted in the direction of the maximal and minimal horizontal stresses.

2. EXPERIMENTAL RESULTS

The two instrumented sections have been put in place very close to the front face (around 1.5 meter) in order to investigate the maximal deconfinement from drift excavation. The sections are composed of radial extensometers for which the end point is fixed at 20 m far from the wall, and convergence measurements with 6 points on the section (see figure 3).

One notice that the feature of the drifts is “horseshoe section” with about 17 m^2 in area mainly supported by metallic sliding arches composed of three parts and rock bolts of 2.4 m length. The floor is also covered by a concrete slab of 0.7 m of thickness. Classical pneumatic hammer has been used to dig the galleries.

The convergences have been measured manually using a system of invar wire along 9 directions of bases. The accuracy of this method is +/- 0.2 mm. The reading frequency has been adapted to the excavation advance rate in order to obtain a high density of measurements within a distance of 12 meters from the section, corresponding approximately to 3 times the excavation diameter. The convergence measurements are given on figure 4 for the two sections SMR1.1 and SMR1.3 until early October 2005. The convergence is still monitored. It is not presented in this paper.

Obviously, the behaviour of these two perpendicular sections is very different and strongly linked with the in situ stress anisotropy. The evolution of convergence in the SMR1.3 is very similar in the vertical and horizontal direction (respectively, measured on bases 6-3 and 1-5) (Fig. 4b). On the SMR1.1 section (Fig. 4a), the vertical convergence is much higher than the horizontal one what is in good agreement with the stress concentration due to the maximum horizontal stress σ_H acting on the walls. These values are given below (the convergence is reset to zero just before the excavation starting).

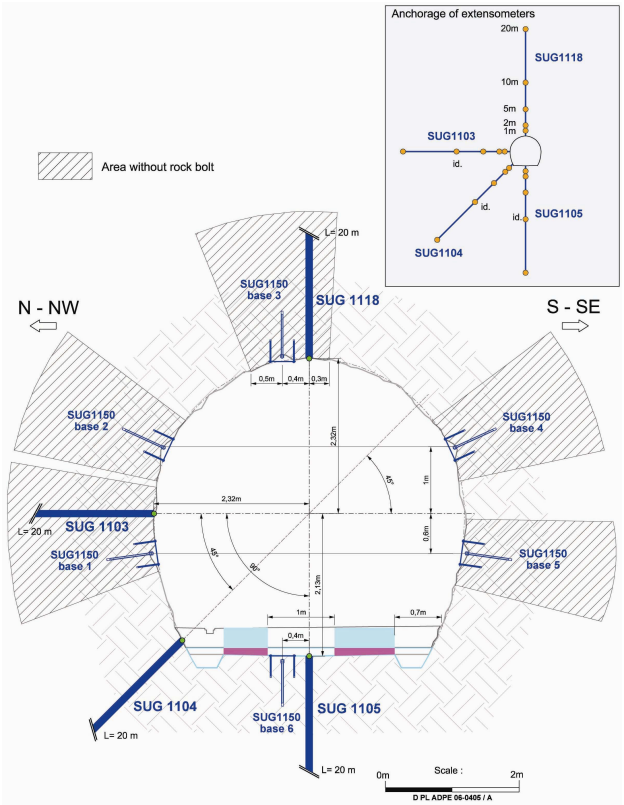


Figure 3. Example of instrumented section SMR1.1 with combined extensometer and convergence measurement at the same location. Base “n” indicates the reference number of convergence point.

The extensometers, on the same section than the convergence measurements, have monitored the deformations of the rock mass automatically (frequency : 4 data/hour) during the excavation advance of the drifts. Figure 5 shows the measurements for the cases of vertical downward and horizontal extensometers. Several names are used (e.g. GMR, GLE, GKE, GNI) for the drifts dug in the experimental area. PM indicates the distance between the workface and the axis of the previous gallery. Only 4 curves by extensometer are presented (0 m, 2 m, 5 m, 10 m relatively to the anchor installed at 20 m which is considered as a fixed point.

One observes the deformation rate reacts gradually with the progress of the face. Moreover, in the particular case of SMR1.3 section where the history of excavation is more complex, the effect of the others openings is clearly measured. Such interaction between drifts is mainly due to the general layout of the URL designed to have a rapid access to the facilities for the time schedule constraint. The smallest distance between parallel galleries is equal to 4 times the diameter of the gallery between the GLE and GKE drifts. This effect has not been identified on the SMR1.1 section.

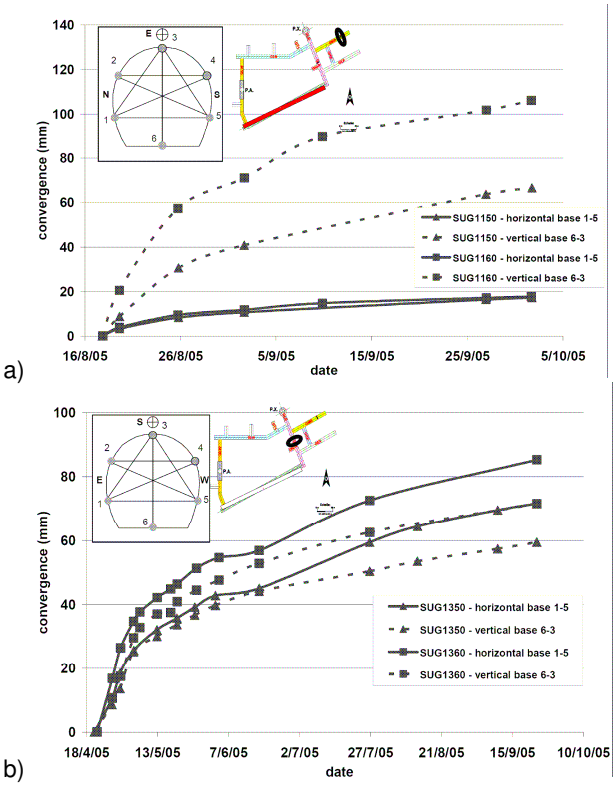


Figure 4. Convergence measurements on sections SMR1.1 (a) and SMR1.3 (b)

The magnitude of extension at the wall relatively to the reference point taken at the 20 m anchor is comparable to the convergence measurements, even if the starting date of measurement are differed of few days. The table 1 shows the value for both instrumentations.

The values obtained by convergence and extension make up a consistent set of data, even though the deformations obtained by the convergence method give in most of the case a larger deconfinement. This difference can be explained by the delay to install the extensometer compared to the convergence section or also by the non measurable part of deformation in place up to 20 m from the wall of the openings. In the following chapter, one takes the convergence values to compare the results obtained by modelling.

3. INTERPRETATION OF CONVERGENCES

3.1 Results of elastic model

The first analysis has been made using a classical approach in the framework of linear elasticity assuming a plane strain approach developed by Panet & Guellec (1974). More complex calculations including a 3D simulation of the drift excavation is presented in the next chapter.

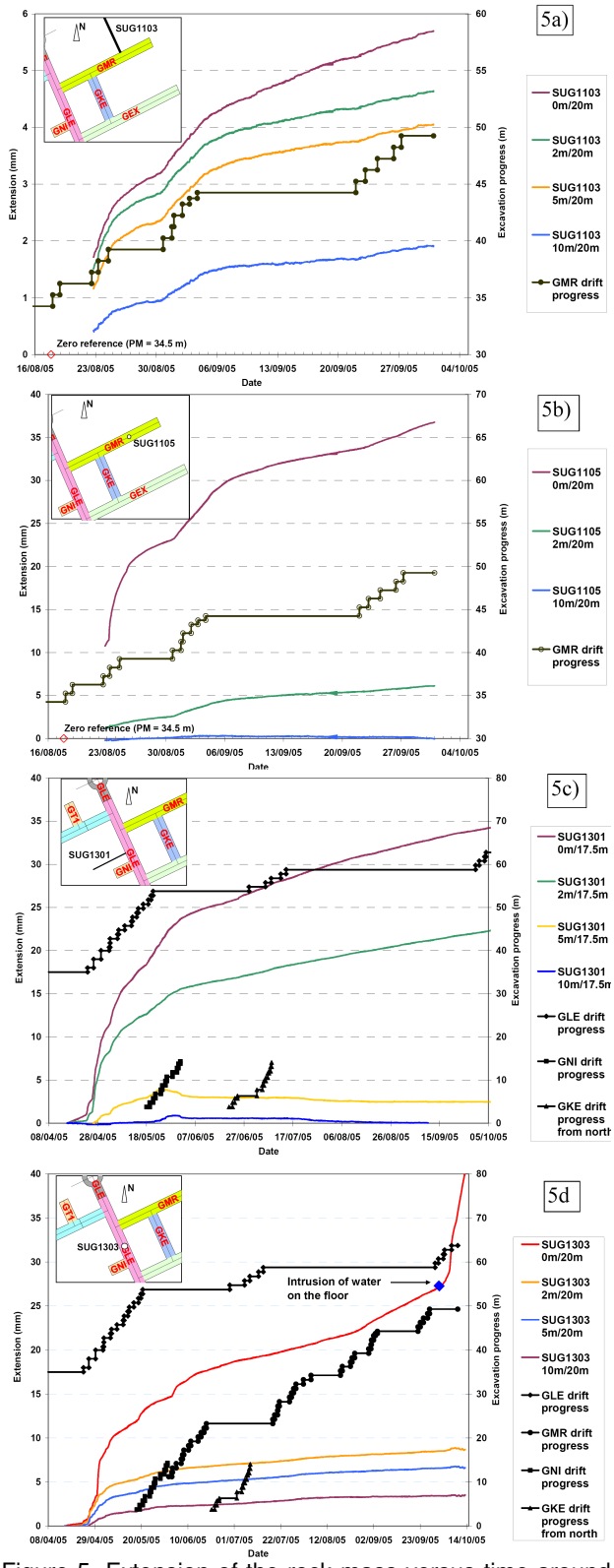


Figure 5. Extension of the rock mass versus time around the drift during the drifts progress – 5a) and 5b) SMR1.1 section – 5c) and 5d) SMR1.3 section – the values are calculated considering the fixed point at 20 m.

Table 1. Comparison between convergence and extension measurements (SMR1.1 and SMR1.3).

	Ref. number	Drift axis	Period[1] (days)	type	Value[2] (mm)
SMR1.3	SUG1350	σ_H	163	base 1-5 horiz.	35.8
				base 6-3 vertical	39.7
	SUG1360	σ_H	163	base 1-5 horiz.	42.7
				base 6-3 vertical	39.8
	SUG1301	σ_H	163	horiz. extens.	33.8
	SUG1303	σ_H	163	vertical extens.	27.0
SMR1.1	SUG1150	σ_h	45	base 1-5 horiz.	8.6
				base 6-3 vertical	33.2
	SUG1160	σ_h	45	base 1-5 horiz.	8.9
				base 6-3 vertical	53.0
	SUG1103	σ_h	45	horiz. extens.	5.7
	SUG1105	σ_h	45	vertical extens.	37.2
	SUG1118	σ_h	45	vertical extens.	23.6

[1] Period of observation calculated until the 1st October 2005

[2] The values given are the half-convergence measured between two bases

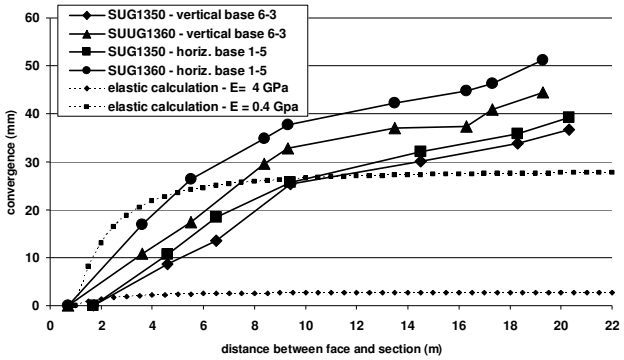


Figure 6. Comparison between the results of convergence measurements of SMR1.3 and plane strain modelling

Considering isotropic mechanical behaviour of the argillite, the elastic parameters Young modulus (E = 4.0 GPa) and Poisson's ratio (v = 0.3) are taken from the Andra's labtests on samples coming from deep boreholes drilled on the Meuse/Haute-Marne site (Andra, 2005b).

The results are not in agreement with the observations as it is shown in figure 6 for the case of SMR1.3 where the in situ stresses are nearly isotropic around the gallery. A better agreement is obtained while reducing Young modulus up to one order of magnitude. This assumption is inconsistent with the mechanical behaviour observed usually on samples subjected to lab tests and can not be validated. Moreover, the significant elastic deconfinement in the first meters from section predicted by plane strain model is not reproduced.

To better represent the complex behaviour of the argillite, one also needs to consider a damageable rock. The fracture network has clearly detected within the first 2 meters from the gallery wall by several direct methods (geological survey on cores samples, resin injection within the fracture network followed by overcoring, borehole camera) and indirect methods (velocity measurement, tomography). The application of elastic model, combined with in situ observations, leads us to consider (as it was previously forecasted) an elastoplastic approach for the argillite lying at this depth.

3.2 Results of elastoplastic model

Numerical calculations were carried out in 3D to simulate the drift progress (in 5 phases) of a horseshoe gallery at 490 m of depth (figures 3 and 7) according to the two orientations of the galleries with respect to the stress tensor : σ_h and σ_H. A first phase allows to reach the fine grid zone. Then, 3 phases of drift advancing (1 meter by 1 meter) are simulated. Finally, the drift advancing is continued to have a complete deconfinement until the end meshed zone.

The geometrical model extends on 49.4 m in X direction, 25.3 m in the direction Y and on 50.6 m height (Z direction). It consists of 627183 gridpoints and 605784 zones. The used mesh is sufficiently fine for highlighting the characteristics of the zones exceeding the damage or failure criteria. In the same way, nodal points were selected in various directions (in front of the face, at the walls side, in vault and under floor) to follow the evolution of displacements (figure 8) and stresses during the phases of drift advancing. These points also allowed easy confrontation with in situ measurements on the two sections SMR1.1 and SMR1.3.

3.2.1 Modelling assumptions

The commercial computation software used for this study is delivered by Itasca (2002): FLAC^{3D} 2.1 v251.

The boundary conditions are as follows:

- null normal displacements are prescribed on the lower face of the model (Z = -515.3), on the face corresponding to the gallery symmetry plane (Y = 0) and on the “left” face of the model (X = -23.0);
- stress conditions are prescribed on the upper face of the model (Z = -464.7), on the “back” face of the model (Y = 25.3) and on the right face of the model (X = 26.4).

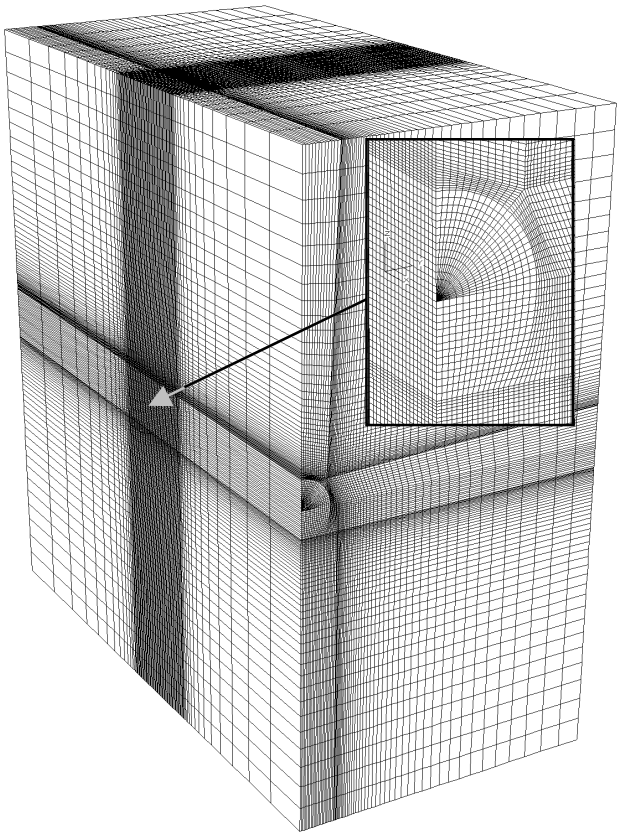


Figure 7. Mesh of the model including horseshoe shape and refined mesh around the drift (see zoom)

The state of natural stresses (at -490 m depth) is as follows: σ_v = 12.7 MPa, σ_h = 12.4 MPa and σ_H = 1.3 xσ_h. From the assumptions on natural stress field, the worst case has been considered (K_H = 1.3).

3.2.2 Geomechanical properties

Numerical calculations are carried out with a damageable elastoplastic model with hardening (as developed by Hoek and Brown). Table 2 indicates the parameters of this model used as reference parameters for studied zone (named B&C zones) of argillite (Andra, 2005b).

Figure 8 illustrates the isovalues of total displacement obtained by the numerical calculation at the end of the 3 steps of one meter excavation. The higher extrusion on the workface is clearly represented, as well as the corner effect. In order to compare the SMR1.1 and SMR1.3 sections to the modelling results, we have put the tracked point at one meter before the initial face. The zero displacement is then considered when initial face is reached.

Table 2. Reference values of B & C zones (used in the modelling (S and m: parameters of the Hoek & Brown criterion, α and β: parameters characterising the residual strength evolution)

Elastic parameters	
Young's modulus (MPa)	4000
Poisson's ratio	0.3
Criteria of the Hoek & Brown model	
Failure criterion	
S (rup)	0.128
m (rup)	2
σ_c (rup) in MPa	33.5
Damage initiation	
S (dam)	1
m (dam)	1.5
σ_c (dam) in MPa	9.6
Residual strength	
α	2.8
β in MPa	3

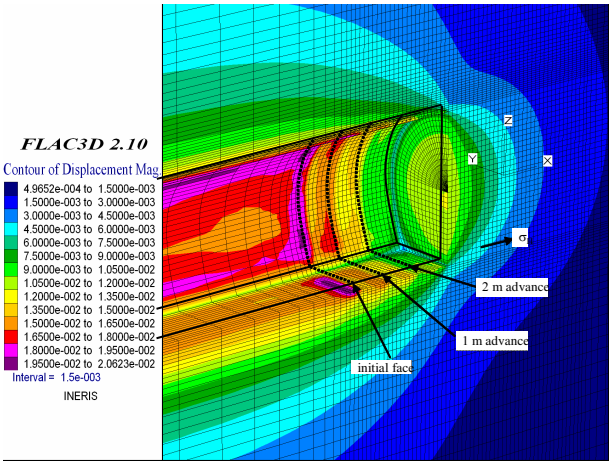


Figure 8. Variation of total displacement for a 3 m advance

3.2.3 Comparison between convergence measurements SMR 1.1 and SMR 1.3 and modelling

Figure 9 illustrates the comparison between the results of numerical modelling and the convergence measurements at sections SUG1350, SUG1360 and SUG1170 (whose axis is parallel to σ_H) and sections SUG1150, SUG1160 and SUG1180 (whose axis is parallel to σ_h) according to the face advance.

The calculation results corresponding to 3 m of excavation with respect to the initial face show a value of vertical convergence of about 10 mm in the direction of the major stress and of 25 mm in minor stress direction, that is to say a ratio of 2.5 between these two directions.

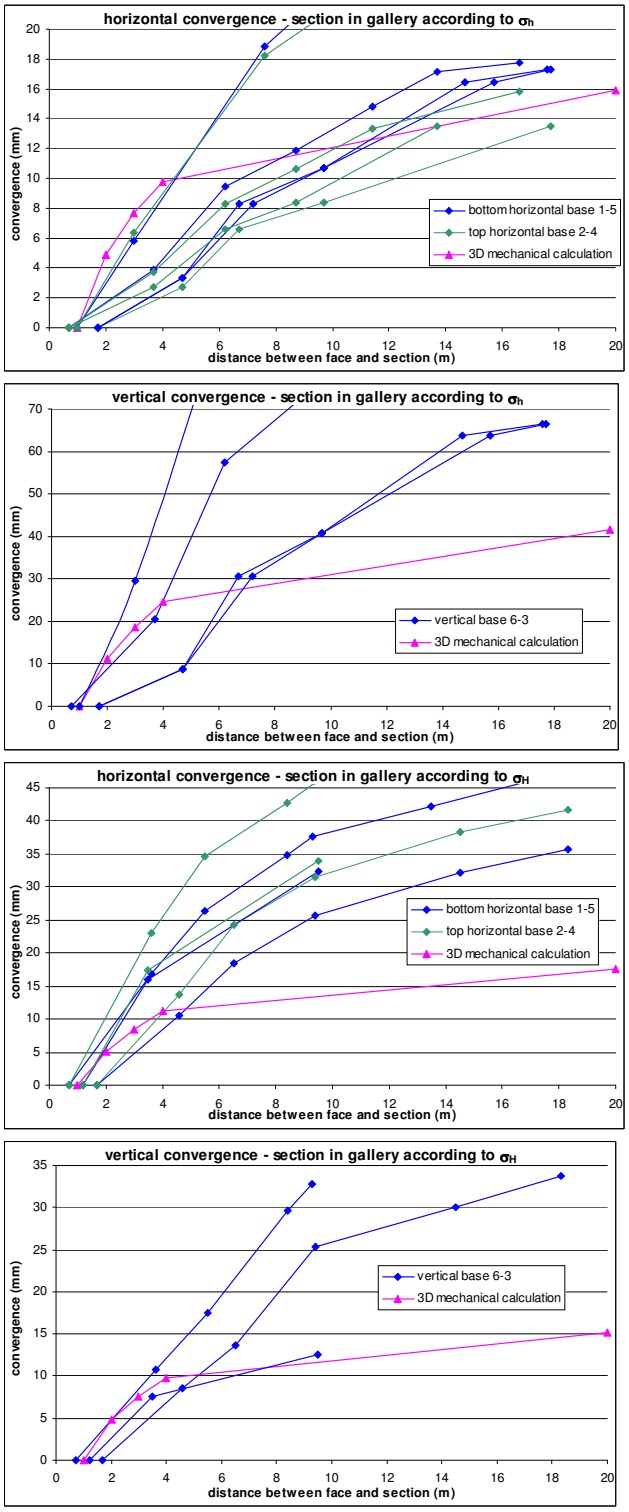


Figure 9. Measurements comparison between horizontal and vertical convergences and modelling results

We notice that this tendency is also observed for the measurements, even if the ratio of displacements is not exactly the same.

The differences between the displacements calculated in the four configurations depicted on Figure 9 show a relative good agreement of modelling with the measurements on the 4 first meters of face progress.

In spite of the fact that the results of displacement calculation are rather well correlated with the measurements in the case of drift advancing for a gallery oriented according to σ_H, the model predicts displacements higher than the measured values for the other direction (σ_h). This is natural, since the model does not integrate neither creep, nor hydraulic coupling. Therefore, long-term convergences cannot be reproduced by the model.

4. CONCLUSION

The main purpose of this paper is to assess the classical approach of tools used in geomechanics to interpret the in situ displacements measured on experimental mine by test conducted by Andra in the Meuse/Haute-Marne URL. For such hard clay lying at 490 m of depth in the Callovo-Oxfordian formation, a complex behaviour is observed, including different phenomena as elastoplastic behaviour, time dependent effect, and hydro-mechanical coupling.

On one hand, the elastic approach has not successfully provided reasonable comparison when the global elastic mechanical response of the clay has been confirmed at the 445 m of depth (Wileveau et al., 2005). On the other hand, a damageable elastoplastic constitutive model using Hoek & Brown criteria has been used. Main conclusion of this analysis is that for the first meters only, displacements observed are consistent with the elastoplastic model. After, the time dependent mechanisms take effect as a predominant part of deformations.

One notices that the elastoplastic modelling presented here has been carried out in the framework of studies on 3D complexity of URL (real geometry of drifts, anisotropy of horizontal stress, and working phases). Thus, we voluntarily simplified the argillite behaviour by neglecting the effects related on creep and hydraulic couplings. Some other numerical modelling are in progress to better understand the strong hydro-mechanical coupling observed in this clay, the real geometry and possible interaction between drifts, the role and link between plasticity and creep.

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