A viscoplastic model including damage for deep argillaceous rocks : blind predictions of drift behaviour

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Abstract

In order to demonstrate the feasibility of a radioactive waste repository in clay-stone formation, the French national radioactive waste management agency (ANDRA) started in 2000 to build an underground research laboratory at Bure. One of the key issues is to understand long term behaviour of drifts. Souley et al. [4] proposes a new macroscopic viscoplastic model of Callovo-Oxfordian clay-stones based on both laboratory and field observations which aimed to improve the viscoplastic strain predictions around the drifts. An example of a blind prediction of the excavation of a drift parallel to σ_h (using this new model) is presented and compared to in situ measurement. Results show the influence the damage state on viscoplastic strain rates, advantages and disadvantages of this new approach.

Keywords: Long term behaviour, viscoplastic model, damage, deep claystone

1. INTRODUCTION

In November 1999, Andra started the construction work of the Meuse Haute-Marne underground research laboratory (URL) (Figure 1) in the district of Bure, located in the North-east of France. From 2000 until 2005, the construction of the experimental site has allowed us to study the radioactive waste repository feasibility in deep geological formation. The main results are presented in the “dossier 2005” [1].

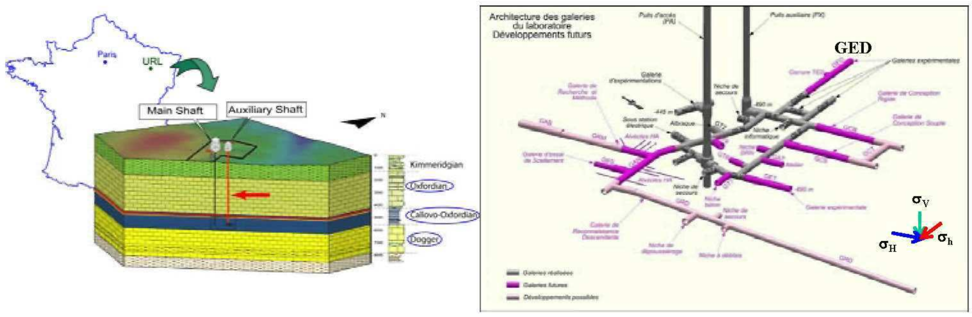
The target horizon for the laboratory is a 135 m thick layer of argillaceous rock that lies between about 420 and 555 meters below the surface at the URL site. Argillaceous rock contains a mixture of clay minerals (40 % to 45 %), silica and carbonate-rich sedimentary.

The construction of the URL itself serves a research purpose through monitoring of the excavation effects (?). The main goal of the geomechanical in situ investigations is to understand the rock response to the excavation of underground engineered structures and to the development of the damaged zone. At short term (during excavation work), the major issues are to understand the rock mass deformations, the hydromechanical coupling, and the effect of excavation works on transport properties in the vicinity of the drifts. The long term behaviour remains also a key issue for repository design and reversibility.

At the main level of the laboratory, geomechanical measurements and EDZ characterization have been performed (convergence, extensometer …) in drifts either parallel or perpendicular to the horizontal major stress. Armand et al. [2] describe the EDZ characterization and the induced fractures pattern observed during the excavation works. They exhibit that high deformation rates appear in the fractured area [2]. Those in situ observations conducted Souley et al. [4] to propose a new macroscopic viscoplastic model for Callovo-Oxfordian clay-stones based on field observations and the previous models (short-term or long-term behaviour) in order to improve the viscoplastic strain predictions around the drifts.

Since the end of 2006, a new research program has started in the URL in which Andra continues to study different excavation and support techniques in order to understand the effect on the EDZ extent and to optimize the excavation method. The feedback of previous experiments shows that “Mine-by-test” experiments are the best way to increase the knowledge on drift behaviour. A “Mine-by-test” provides a large in situ characterization and is a good opportunity to develop and validate constitutive models and numerical tools able to predict the hydromechanical behaviour of

Callovo-Oxfordian clay-stones, as it was performed during the MODEX-REP European project [3] around the main access shaft.
The new excavations (GED drift, figure 1b) performed in 2008 provide the first opportunity to test the new macroscopic viscoplastic model [4] thanks to blind prediction. This paper presents the experimental layout and the associated blind predictions. The authors used this new model to perform 3D calculations using the real construction steps. Those calculations show up the advantage of the new model. Comparisons with in situ data allow checking the efficiency of this numerical approach.



(a) (b)

Figure 1: Meuse Haute Marne URL : (a) Location and geology, (b) Drifts and shaft network (purple: extension forecasted in 2012)

2. BRIEF DESCRIPTION OF THE RHEOLOGICAL MODEL

Numerous campaigns of laboratory tests (uniaxial/triaxial, mono/multi-stage creep and relaxation) have been undertaken for characterizing the mechanical and hydromechanical short and long-term behaviour of the argillites. As a result, several constitutive models were developed in the framework of MODEX-REP European project [3]. The new model [4] can be seen as a unification of two rheological models for clay-stones: one for the short-term response is based on the extension of Hoek-Brown criterion to describe the damage in pre-peak phase (approached by the theory of plasticity), failure and residual phase; the other for the long-term behaviour according to the modified Lemaître's model with creep threshold.
The main characteristic of this model is the coupling of damage with creep behaviour of the argillites based on the obviousness of the damage impact on the viscoplastic

strain rates. In situ measurement exhibits high deformation rate in the fracture zone observed around the drift [2]. Those deformations are mainly due to the induced fractures (EDZ) and their aperture. The modelling is performed in the framework of continuum mechanics, and viscoplasticity in some way will take into account the mechanical behaviour of this fractured zone.

More precisely, in agreement with in situ observations, it was supposed that the post-failure material, in regards to its new microstructure, must have some creep characteristics which differ from those of the intact material. In particular the viscoplastic strain rate and the activation energy must reflect the failure of the clay-stones. For a damaged material (between the intact and failure states), a function of interpolation was proposed for the strain-hardening parameter since sufficient creep tests are not available on the damaged samples of clay-stones. The influence of damage on creep activation energy has been approached by an exponential function.

Finally the coupling between the induced damage and the creep behaviour is only clarified in one way: (damage → viscoplastic strain rates) since for the moment, we do not consider the influence of viscoplastic strains on the damage threshold or more generally on the long-term strength of clay-stones. On the other hand, viscoplastic strains modify the stress field which, in its turn, is corrected while it exceeds damage criterion possibly changing indirectly EDZ extent. The set of constitutive equations and their implementation in FLAC3D© code as well as verification and validation tests are widely presented in [4].

3. EXPERIMENTAL LAYOUT

3.1. In situ stress state and GED drift

The in situ stress state 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 horizontal stress anisotropy σ_H/σ_h is closed to 1.3 close to the main level (-490 m) [5], respectively equal to 12.7 and 12.4 MPa for modelling task.

The drift network grows following both horizontal principal stresses. GED drift is far away from other drifts and excavated perpendicular to the horizontal major stress. It is excavated with a pneumatic hammer. Supports consist of 2.2 m radial bolts, 10 cm of synthetic fibers reinforced shotcrete and sliding steel arches (installed every meter). The front is also reinforced with 11 synthetic anchors (12 m long) emplaced at the front every 6 m. Excavation started in May 2008 and will be finalized by the end of January 2009.

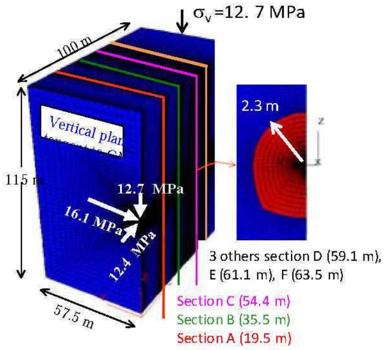


Figure 2: Geometrical model for blind prediction of GED, meshing and boundary conditions

3.2. Experiment layout

The experiment layout consists of 6 convergence sections (with 5 convergence measurements per section, 4 extensometers 30 meter long, with 7 measurements anchors (at 1, 2, 3.5, 5, 8, 15 and 30 m from the wall) and 4 extensometers 1 meter long. A geological mapping of front (every 5 meters) and the structural analysis of all cored boreholes (even in borehole performed for other experiments) have been carried out during excavation work to characterize the fracture zone. Extensometer and convergence section have been installed during the excavation work. The other boreholes will be drilled after the excavation. Multi-packer systems with 3 or 6 chambers from the wall to 6 m deep, have although been emplaced to perform pore pressure measurement and permeability tests. Those data are not presented because the numerical analysis is a purely mechanical analysis.

4. CALCULATIONS AND RESULTS

4.1. Geometry, boundary conditions and excavation sequence

In relation to the symmetry of GED drift (70 m long and considered as isolated) and its orientation with respect to the initial stress state (parallel to σ_h), only the half domain is modelled. The geometrical model (150 m high, 57 m wide and 100 m long) shown in figure 2 consists of 574770 elements with following characteristics: 5 cm radially around the measurement sections A, B, C, D, E and F (located at 19.5, 35.5, 51.5, 59, 61 and 63.5 respectively from the beginning of GED drift) and 40 cm axially on both sides of each measurement section. The real advance velocity during the drilling of GED is used herein: the mean advance velocity is of 1 m/day except the break time to install materials.

4.2. Results

The EDZ distribution around the GED drift is firstly examined. When the face is positioned at sections B and C for example, fractured zones (from peak to the residual behaviour) are not yet formed around the drift. From a face at 5 m after each section (that is to say two radii of gallery) to the end of excavation, the fractured zones extend from 0 to 29 cm depending on the position (floor, roof of drift side) and the section.
Contrary, a damaged zone (pre-peak behaviour) is systematically formed as soon as the GED face reaches the position of a given section (80, 110 and 120 cm, respectively at side, roof and floor of GED). In relation to anisotropy of the in situ stress state, more damage is obtained in the vertical direction compared to the horizontal ones (along σ_H) whereas the difference in EDZ geometry and extent between the floor and the roof is related to their geometries. The extent of damaged zone becomes 170, 260 and 270 cm respectively at side, roof and floor at the end of excavation.
The evolutions of viscoplastic strains in time are also examined along vertical and horizontal boreholes in section C (figure 3). If the maximum of deformation in the horizontal direction is reached at the GED sides, the model predicts a maximum of viscoplastic strain inside the rock matrix in the vertical directions. It is also noted that the amplitude of the viscoplastic deformations is well correlated to the intensity and the extension of EDZ (i.e. high viscoplastic strains occur in the more damaged zones) in accordance with the philosophy of the model and the in situ observations. In particular, at the end of 10 years, the predicted viscoplastic strain rates at 2 m from the GED wall of $2e^{-12}$ and $4e^{-12}$ s^{-1} respectively in the horizontal and vertical directions.

4.3. Comparison with in situ data

The analysis of measured and predicted convergences shows that in the vertical direction and independently of the measurements section: (a) the short-term the velocity of measured convergences are higher than those predicted, but at long-term, we can expect that the measured convergence velocities tend asymptotically towards the predictions; (b) the amplitude of measured convergences are higher than those

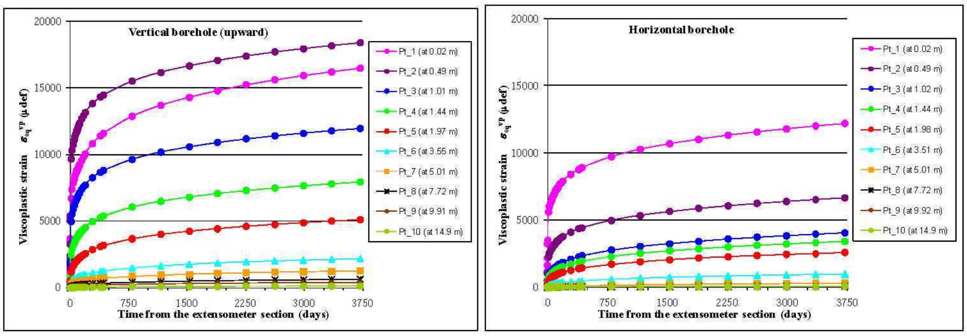


Figure 3: Viscoplastic strains along vertical and horizontal boreholes (section C)

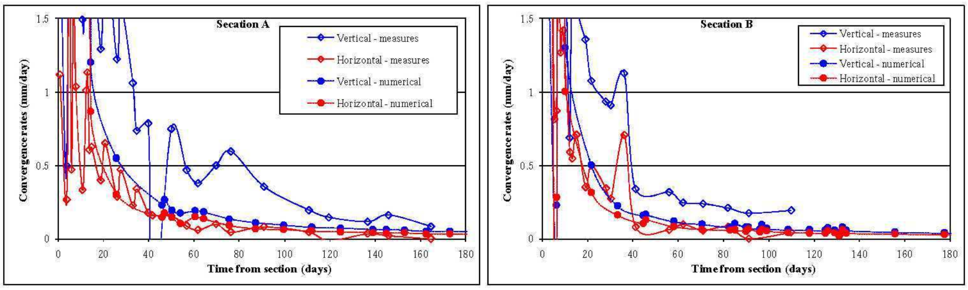


Figure 4: Comparison of calculated and measured convergence rates

predicted. In particular, calculation underestimates from 13 to 44% vertical convergence respectively in sections B and C at the end of 80 days.

For horizontal convergences we note that at 80 days after the passage of GED face to a given section, measured/predicted (in mm) convergences are of: 23/30; 18/39; 33/47 respectively for the sections B and C. This illustrates the over-estimation character of predictive calculations in horizontal direction.

The comparison of horizontal and vertical convergences rate is given as an example for section A and B (figure 4). It is thus noted that contrary to convergences, the predicted convergences velocities are in agreement with those measured at court term. More precisely, of horizontal convergence velocities (average calculated on the "stages" and expressed in mm/j) in the form of measured/predicted are: 0.04/0.05; 0.05/0.05 and 0.09/0.08 respectively in the sections have, B and C.

5. CONCLUSIONS AND PERSPECTIVES

This paper presents firstly a 3D blind prediction of the behaviour of a GED drift oriented parallel to σ_h. The prediction is performed using new macroscopic viscoplastic model of Callovo-Oxfordian clay-stones which includes the impact of damaged and fractured zones in the near field behaviour.
The comparison of the convergence predictions in 6 sections and the first measurements indicates that the model underestimates the values of vertical convergences and over-estimates horizontal convergences. On the other hand, the convergences rates are well produced particularly in the horizontal direction as of the 100 first days. The enriching of the model, particularly for the fractured zones (viscoplastic rates and modules), is in the course of reflexion and will integrate the measurements of convergences and extensometric currently in acquisition.

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