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CIGEO radioactive waste repository project – An observation-based model of claystone behavior for thermomechanical *FLAC3D* simulations

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1 INTRODUCTION

In addition to reference design studies of the CIGEO French radioactive waste repository, complementary analyses have been performed on some specific galleries to enhance the justification of their support design. These analyses involve coupled thermo-mechanical models of large diameter tunnels (about 10m) excavated by TBM and in which exothermic intermediate-level long-lived waste canisters are disposed of. The work focuses on the design of the segmental lining. It integrates a compressible layer on the outer surface, to accommodate rock creep deformations while limiting, at the same time, the stresses developed in the concrete. The main objective is to analyze the influence of creep and thermal loadings on the stability of the tunnel during the 100 years reversibility period of the disposal facility, for a tunnel oriented along the major principal horizontal in-situ stress and for the reference design as obtained from previous studies.

2 MODELLING OF CLAYSTONE BEHAVIOR

The underground disposal facility will be located in the Callovo-Oxfordian claystone formation, at a depth of approximately 500 meters below the surface. Modelling of the mechanical and creep behavior follows a preliminary work (Saitta et al. 2017) in which a new approach based on a coupled Mohr-Coulomb/Power law has been calibrated to properly reproduce the displacements developed around tunnels of the near-by URL of Meuse/Haute-Marne. Extensive data from in situ tests and monitoring allowed to characterize very finely the extension and shape of the EDZ region developed during the excavation, depending on the tunnel direction relative to the major and minor horizontal stresses. For a tunnel excavated along the major stress, the vertical and horizontal extensions, measured from the excavation boundary, are respectively in the order of 0,4D and 0.1D, where *D* is the excavation diameter (Fig. 1). Geological observations indicate that these values are substantially independent of the excavation size: they have been observed for *D* varying from a few centimeters (around boreholes) to several meters (around tunnel of the URL). This conceptual model is therefore also used for modelling large diameter disposal tunnels.

Given the softening behavior of the claystone, with a drop in rock strength once the peak is reached and fractures are formed, the short term behavior is modelled by a Mohr-Coulomb criterion using two different sets of parameters for the intact mass (peak parameters) and the EDZ (residual parameters).

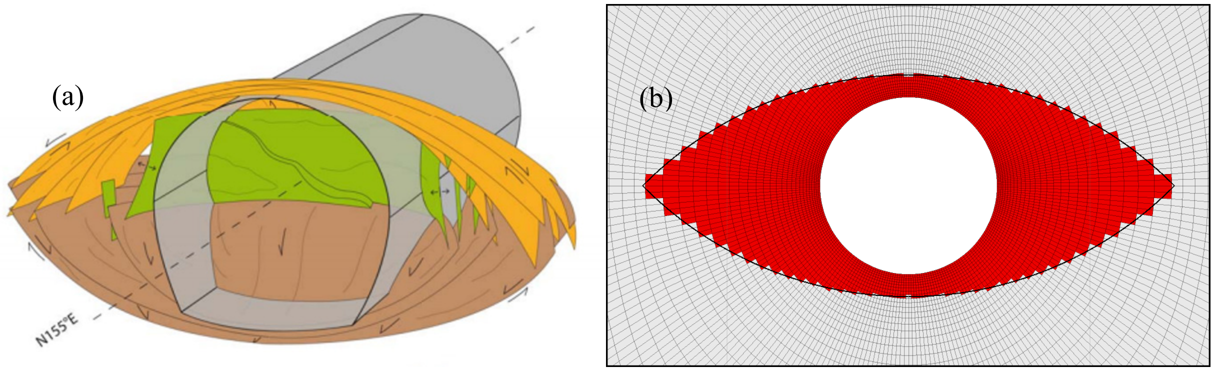

Figure 1. (a) Conceptual model of the EDZ developed during excavation for tunnels oriented along the maximum horizontal stress σ_H (Armand et al. 2014) and (b) its representation in the *FLAC3D* model.

3 MODELLING OF THE COMPRESSIBLE LAYER OF SEGMENTAL LININGS

The compressible layer considered in this study is made up of an assembly of beads composed of a clay/cement mixture. Results of oedometric tests performed in the laboratory indicate an initial elastic phase followed by a high compressibility phase, in which vertical strains increase up to 25-30% while the vertical stress remains almost constant, in the order of 2MPa. Once the beads are crushed, the samples show a progressive increase in material stiffness. This behavior is modelled using the "Double-Yield" elastic plastic model, by calibrating a hardening table relating the cap pressure, p_c, to plastic volume strain, e^{pv}: a plastic plateau reproduces the high compressibility phase. In this study, the length of the plastic plateau is reduced compared to the one used for the reference design studies of the repository, leading to a pessimistic behavior.

4 *FLAC3D* MODEL AND THERMO-MECHANICAL COUPLING

The *FLAC3D* (Itasca 2017) model reproduces a vertical section perpendicular to the tunnel axis. Lateral model boundaries are placed 25m from the tunnel axis, half the distance between two adjacent tunnels in the future disposal facility. Excavation is modelled by progressively relaxing tunnel boundary forces. Segmental linings are activated at 90% relaxation, which, according to the previous study (Saitta et al. 2017), corresponds to the distance from the tunnel face at which lining is installed. Relaxation is then completed and a creep time of 4 years is simulated. Heat-generating waste canisters are then introduced and taken into account through a thermo-mechanical calculation.

The problem is partially decoupled by first performing a thermal calculation and then injecting the resulting temperature map into a mechanical calculation. This approach is possible because of the low kinetic energy associated with mechanical deformation processes and the unidirectional thermo-mechanical coupling. This technique allows the use of two different meshes for the two calculations, resulting in optimized calculation times and grid geometries for the two types of computations. Indeed, the significant extension of heat diffusion within the claystone mass requires a thermal model with upper and lower boundaries very far from the tunnel whereas these same conditions may be closer to the tunnel during mechanical calculation. On the contrary, the mechanical calculation requires a fine discretization of segmental linings, for a reliable estimation of the stresses, whereas in the thermal model a coarser discretization only marginally affects the results and allows, at the same time, higher timesteps and shorter calculation times.

Figure 2 shows the two *FLAC3D* models. For the thermal one, waste thermal power is uniformly distributed on inner disposal chamber faces and varies over time. In the mechanical model, only segmental linings are modeled inside the rock excavation, the primary aim of the study being their design in terms of thickness.

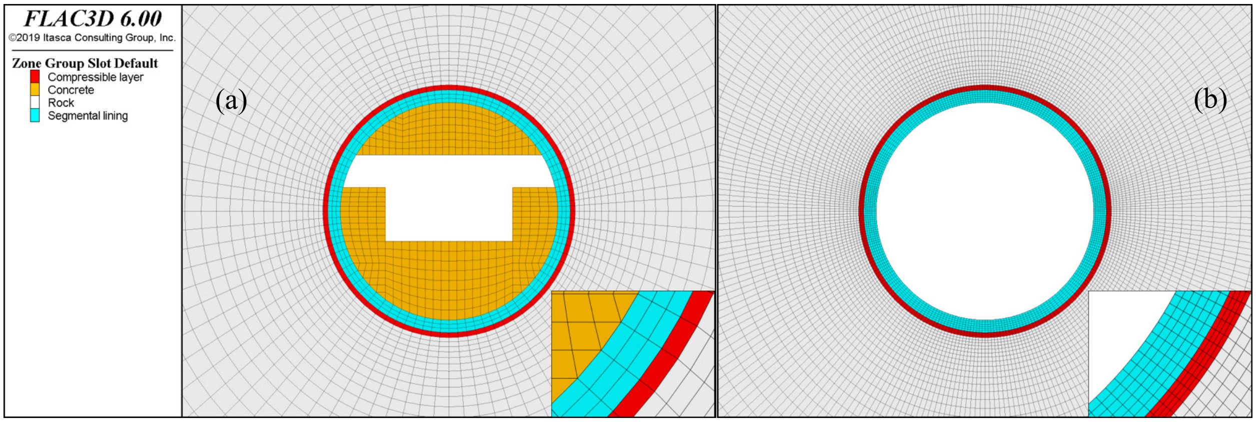

Figure 2. (a) *FLAC3D* mesh for the thermal model, and (b) thermo-mechanical model.

5 THERMAL AND CREEP EFFECTS ON TUNNEL BEHAVIOR

Amongst the various simulations, some calculations used the reference model to highlight the contributions of the thermal and creep processes on the long-term behavior. Results are illustrated in Figures 3 & 4, respectively in terms of convergence evolution and of stress resultants in linings after a hundred years of disposal. Four different configurations are compared, with the following differences:

- **M**: creep-only model (thermal coupling deactivated) with the *A* parameter of the Norton law (viscosity parameter) taken constant and equal to the claystone value for a temperature of 23°C (initial temperature of the medium);
- **TM – A=f(T) – A80/A23=3**: thermal-mechanical calculation in which both thermal and creep processes are activated, and the *A* parameter is multiplied by 3 for a temperature increase from 23°C to 80°C, as observed from creep laboratory tests;
- **TM – A=f(23°)**: thermal-mechanical calculation in which the *A* parameter is taken independent of temperature and equal to the value at 23°C;
- **TM – A=0**: thermal-mechanical calculation in which the creep calculation is deactivated.

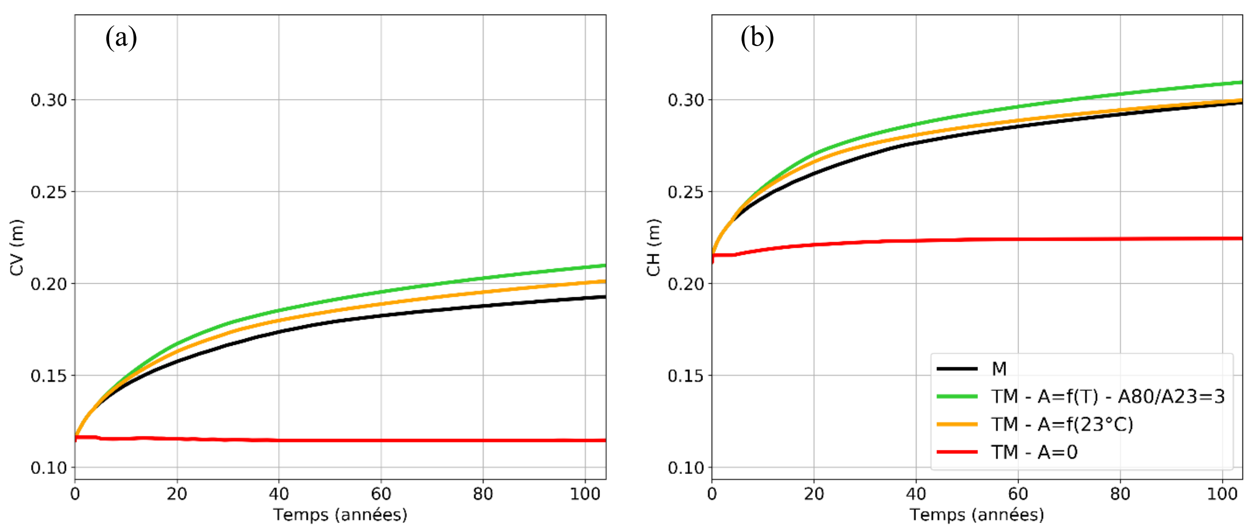

Figure 3. Vertical (a) and horizontal (b) convergences comparison for studied models.

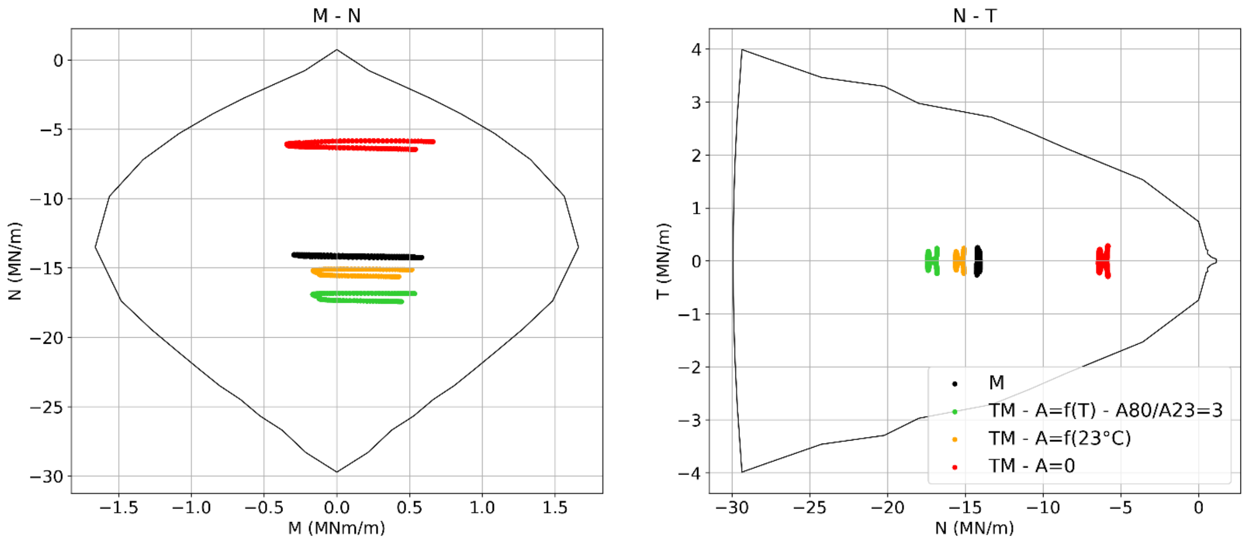

Figure 4. Interaction diagrams comparison for studied models.

Comparison of convergences and resultants leads to similar conclusions. The creep effect on tunnel behavior is much higher than the thermal one. When only the thermal process is active (red curves), convergences are only slightly affected by the thermal changes induced by the waste, whereas in case of a creep-only calculation (black curves), convergences progressively increase with time, leading to higher stress resultants. When both thermal and creep processes are activated, convergences and resultants become higher and their values mainly depend on the evolution of the viscosity parameter *A* with temperature.

6 CONCLUSIONS

FLAC3D thermo-mechanical analyses are performed for the design of CIGEO disposal tunnels with exothermic waste canisters. The claystone EDZ is indirectly modeled through a zone of weaker properties, whose size and orientation reproduce in situ measurements of the fractured mass. Analyses are carried out for the reference tunnel configuration, in which the thickness of the lining concrete and compressible parts are respectively 50 et 20 cm. The effect of creep and thermal processes on convergences and lining stress resultants are investigated for the reference tunnel configuration. Clearly, for the realistic range of parameters used in this study, creep is a much more critical phenomenon than thermal loading.

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