

Thermo-Mechanical Analysis of High Level Nuclear Waste in Various Rocks

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INTRODUCTION

The storage of high-level nuclear waste in rocks generates an important variation of the existing temperature, which induces displacements and stresses in the rock mass. These quantities must be evaluated for two main reasons :

- to guarantee the stability of the storage galleries and shafts during construction and handling of the wastes.

- to appraise the safety of the whole storage, for long periods (thousands of years) by studying the thermo-hydro-mechanical phenomena due to the heat transfer.

Of course, the phenomena strongly depend on the type of rock under consideration. The French National Agency for Waste Management : ANDRA is considering the possibility of high-level wastes storage in four deep geological formations : salt, clay, granite and shale.

The purpose of this paper is to present specific models and tools adapted to a certain number of thermo-mechanical analysis of such media. However, it will not be possible here to give an exhaustive description of all the problems encountered in these media. Therefore, we will restrict ourselves to two types of behaviour :

- viscoelastic behaviour, which is of primary concern for salt and some clays.
- brittle behaviour, which is of primary concern for granite and shale.

ANALYSIS IN SALT AND SOME CLAYS

Material models

The main problem arising for a storage in salt or in some clays, from a thermo-mechanical point of view, is the creep, which can cause important convergence of the galleries in the short term and important movement at the ground level in the long term.

The basic material models are of viscoelastic type : the total strain is partitionned into an elastic and a creep strain :

$$\epsilon_{ij} = \epsilon_{ij}^e + \epsilon_{ij}^c$$

which are related to the stress through the following expressions :

$$\epsilon_{ij}^e = D_{ijkl}^{-1} \sigma^{kl}$$

$$\frac{d\epsilon_{ij}^c}{dt} = \frac{\partial \sigma^*}{\partial \sigma_{ij}} \frac{d\epsilon^*}{dt}$$

where D is the Hooke's matrix, σ^* is the Von Mises equivalent stress and ϵ^* is the equivalent inelastic strain.

Variations between the models come from the evolution law for the rate of ϵ^* . For exemple, a simple Norton law, corresponding to secondary creep, can be assumed :

$$\frac{d\epsilon^*}{dt} = A(T) (\sigma^*)^n$$

where T is the temperature.

More sophisticated laws have recently been proposed by TIJANI, on the basis of experiments performed on the ASSE mine salt, which account for some strain hardening and enable a description of primary and secondary creep stages : [3]

$$\frac{d\epsilon^*}{dt} = \alpha X^{\alpha-1} \frac{dX}{dt} + \frac{dY}{dt}$$

with $\frac{dX}{dt} = A_1 (T) (\sigma^*)^n$

$$\frac{dY}{dt} = A_2 (T) (\sigma^*)^n$$

The capacity of these models to describe what happens in the storage has been appreciated thanks to benchmark problems like the SANDIA benchmark and the COSA benchmark [2],[3].

SANDIA benchmark [1]

The SANDIA benchmark has been organised in the frame of the WIPP (Waste Isolation Pilot Plant), and is an intercomparison between the results predicted by a certain number of computer codes on the following problem :

A gallery is located at a - 650 m depth in a salt layer, in the WIPP test site. A heat source is placed just under the gallery, to simulate the presence of waste canisters (see figure 1), and supplies a power :

$$P = 169,5 e^{-\frac{1,365}{t} 10^9} \text{ watts, with } t \text{ in seconds.}$$

A Norton type creep law has been assumed for the salt, while the other rock layers are supposed to have an elastic behaviour. Sliding movements are possible between some layers.

Material data were derived from laboratory tests done by SANDIA. The calculation is performed on a 10 years period. The main results, which were compared are the evolutions of temperatures at some specific locations (bottom of the gallery, middle of the heat source, etc...) the vertical convergence of the gallery, the repartition of stresses along some lines (vertical symmetry axis).

Figures 2 et 3 show the predictions of temperatures and gallery convergence. Except for two thermal calculations with wrong data, we can note a general good agreement between the various results. For such problems, the stress must be laid upon the creep law and the material data, and in particular their dependance upon temperature.

ANALYSIS IN GRANITE AND SHALE

Material models

In the case of brittle materials like granite and shale, it is first important to take into account the existing discontinuities in the rock, which can be classified as :

- well identified major faults, the thickness of which being small in comparison with the dimensions of the rock-mass.
- minor faults, which can be considered as uniformly distributed, like diaclasis.

Secondly, it is important to predict the formation of new discontinuities due to the storage, which will affect the resistance of the rock mass and the possibilities of migration of radionucleids.

The models and methods used to deal with these two aspects are described below.

Modelisation of major faults

Special finite elements have been formulated to model major faults. Geometrically, they are made of two identical lines (in 2-D) or two identical surfaces (in 3-D) along the fault.

The generalized strains of the elements are the relative normal and tangential displacements of the two faces, for exemple in 2-D :

$$\text{normal strain } \epsilon_n = \frac{\Delta u_n}{e}$$

$$\text{shear strain } \gamma = \frac{\Delta u_t}{e}$$

where e is the thickness of the joint, which is not geometrically defined, but which is specified by the user, in order to calculate the element stiffness matrix.

Concerning the material behaviour, many laws have been proposed by various authors [5], [6], [7]. We present here a simple Coulomb's law :

- the joint offers no resistance under traction loads.
- under compression loads, a bilinear stress-strain curve is assumed : the first part corresponds to a crush of the joint faces, the second part to the remanent elasticity.
- under shear loads, the model has an elasto-plastic response : the yield surface is defined by a Coulomb's criterion, and the flow rule may be non associated.

The features are depicted on figure 4.

This technique has been applied to study a generic storage configuration, where two major faults have been identified. Of course, such a configuration is very pessimistic and is not representative of a real storage but it was chosen to maximize the effect of the discontinuities. Figure 5 shows the initial and deformed rock mass after 1000 years. Results obtained indicate that joints sliding is more important than opening : the joints open in the region located above the wastes, because of the deformation imposed by the heat source, whereas sliding occurs on both sides of the source. The maximum values of the opening and sliding at the ground level, for the central fault are respectively 3.6 mm and 11 mm, obtained at 1000 years.

Modelisation of uniformly distributed minor faults

The main assumption in this case is to suppose that the material can still be treated as a continuum, the presence of the faults resulting in a decrease of the traction and shear resistances in some directions. For example, in the case of shale, these directions can often be clearly identified.

In order to model such a material behaviour, we have assumed the existence of one or two directions of diaclasis.

The basis of the model consists in defining plasticity evolution rules, on quantities defined in local reference systems attached to each direction :

Thus, noting σ_{ni} and τ_j the normal and shear stresses along the diaclasis i , a yield surface is defined by a Mohr-Coulomb criterion :

$$f_i(\sigma_{ni}, \tau_j) = \sigma_{ni} \cdot \operatorname{tg} \psi_i + |\tau_j| - C_i \leq 0$$

with a non associated flow rule.

When two directions of diaclasis are specified, the yield surface is defined by the two functions f_1 and f_2 , and the corresponding plastic flows must be coupled.

Formation of new discontinuities

The simplest way to create new discontinuities in a rock-mass which is supposed to be initially sane, is to use a "no-tension" type model, based on a maximum principal stress criterion : the material remains elastic until the greatest principal stress reaches a traction limit R_T . Then, some strain-softening is possible, which corresponds to a progressive reduction of normal and tangential stiffnesses, up to limit strain ϵ_R (see figure 6).

The case where $\epsilon_R = R_T/E$ corresponds to the elastic perfectly brittle material.

Once R_T has been reached, the material is supposed to be cracked and the corresponding direction is memorized. New cracks will be orthogonal to this one.

Under reverse loadings, the cracks will close and then the material will offer its initial compressive resistance.

The shear resistance is supposed to fall down to a limit value, once the crack is formed.

This model has been applied to the calculation of a generic waste repository in granite (Fig. 7). The rock mass was considered as sane, without any initial crack. Therefore an isotropic elastic behaviour was assumed. Figure 8 shows the cracks pattern at $t = 500$ years, on the deformed configuration. Close to the wastes, compression stresses develop, while on each side, traction stresses lead to two important cracked zones. After 1000 years, the majority of the cracks are closed ; only a few remain open in the vicinity of the ground surface.

CONCLUSION

The exemples presented here have illustrated the possibilities of some models to predict the behaviour of waste repositories in various rock-mass.

However, there are still developments and improvements to incorporate in general computer systems, as for example :

- orthotropic elastic material for shale,
- fracture model in viscoelastic material like salt,
- influence of water pressure in some clays,

- thermo-hydro-mechanical couplings, etc...

Moreover, for strain-softening materials like granite, some problems may arise from the point of view of unicity and stability of the computed solutions. This is still an open question nowadays.

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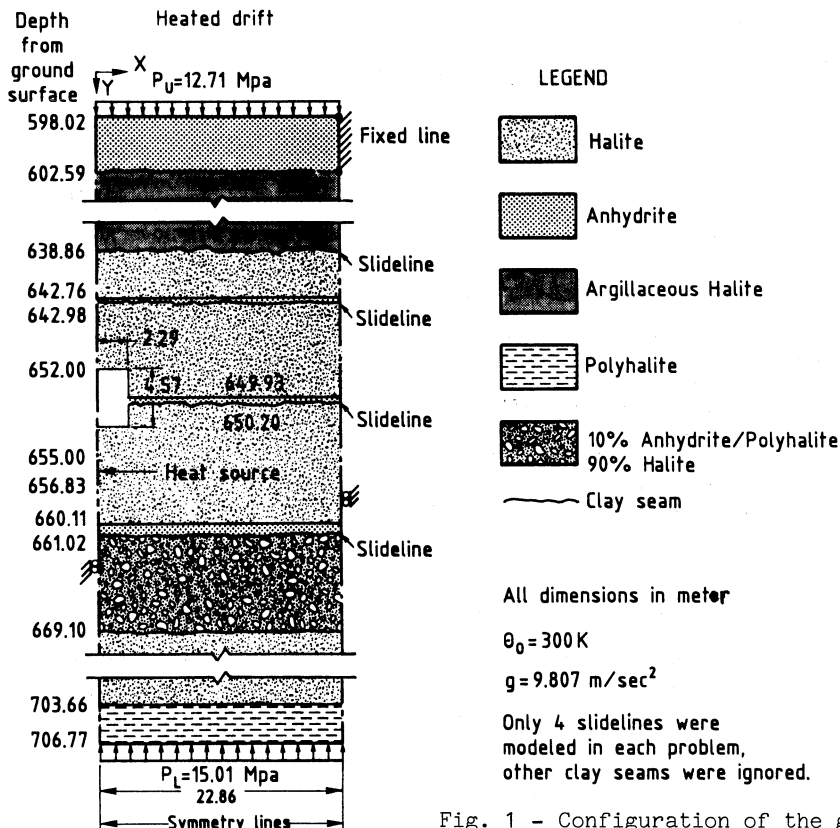


Fig. 1 - Configuration of the gallery

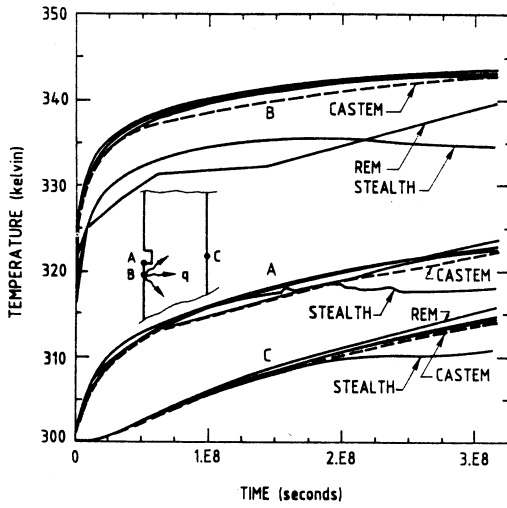


Fig. 2 - EVOLUTION OF TEMPERATURES

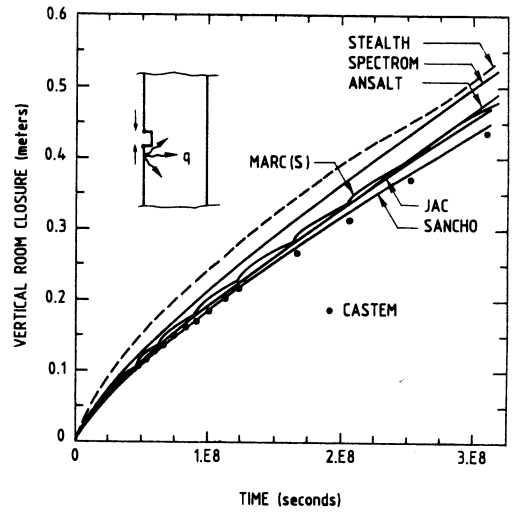


Fig. 3 - VERTICAL CONVERGENCE OF THE GALLERY

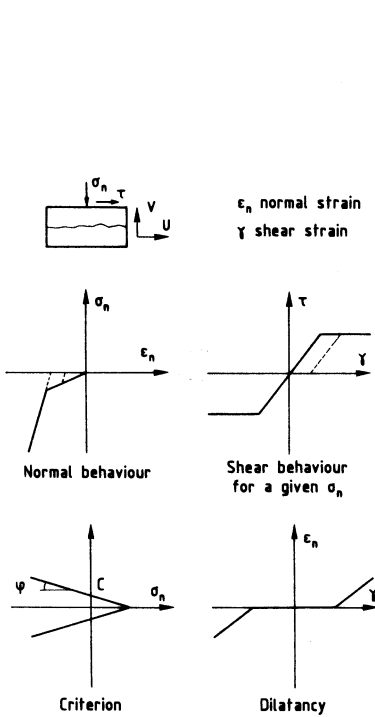


Fig. 4 - COULOMB'S MODEL

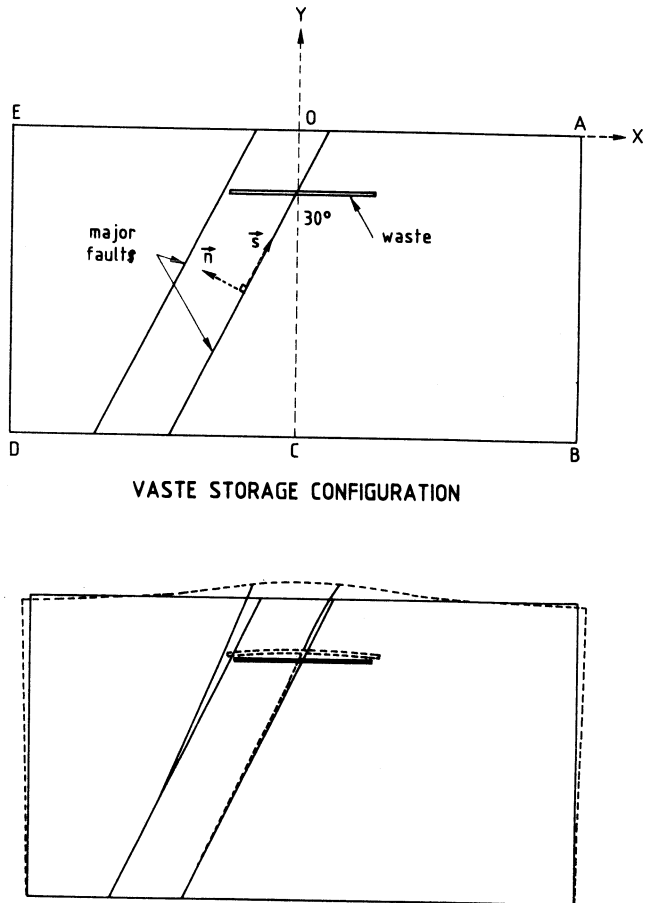


Fig. 5 - DEFORMED CONFIGURATION AT T=1000 YEARS

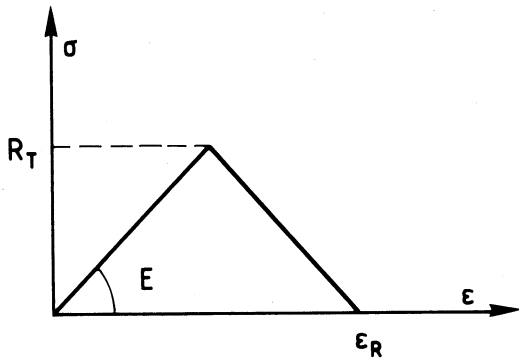


Fig. 6 - UNIAXIAL BEHAVIOUR

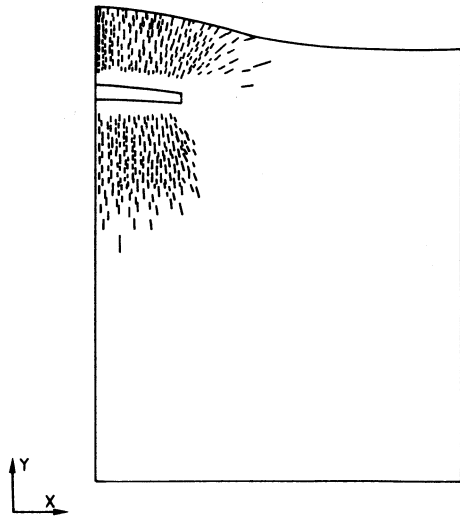


Fig. 8 - CRACKS PATTERN AT T=500 YEARS

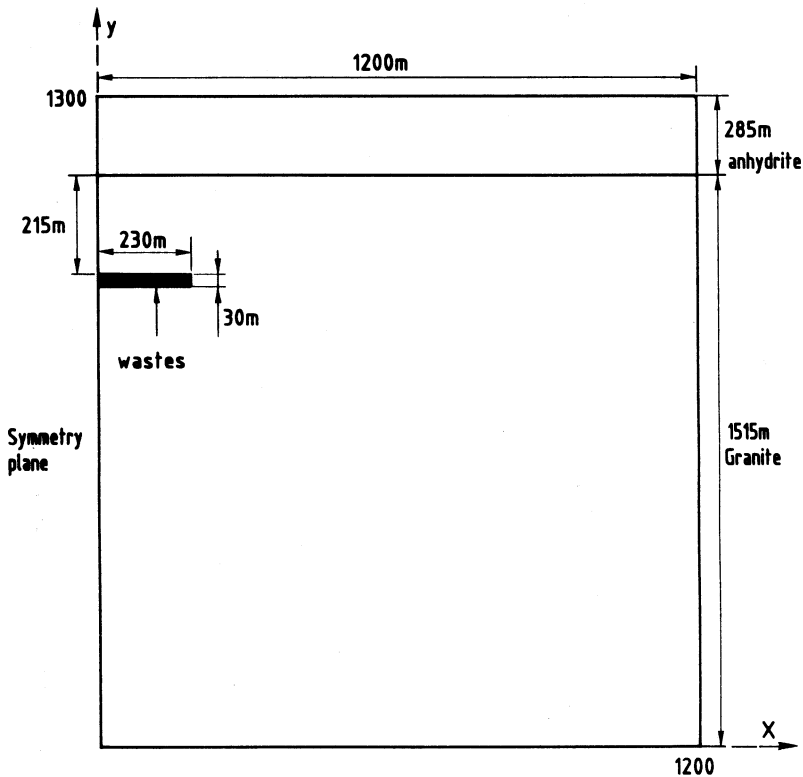


Fig. 7 - GENERIC WASTE REPOSITORY IN GRANITE
(ONLY ONE HALF IS CONSIDERED IN THE
CALCULATION)