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Thermomechanical Aspects of Radioactive Waste Disposal in Rock Salt

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ABSTRACT

Nuclear Waste Disposal in deep salt formations is an option being considered by several countries. Rock salt is a very impervious medium, but can be easily leached ; in selecting an appropriate disposal formation, adequate natural protection from water movements must be found. One must be sure that the initially favorable characteristics will not be affected by the existence of shafts and galleries, or by the important heat output generated by vitrified wastes. The subject is delicate, for a comprehensive rheological model for rocksalt is difficult to establish and to be extrapolated to long time scales ; some methodological problems are raised by use of numerical computations.

1. INTRODUCTION

For applications related to highly-active nuclear waste disposal, Rock Mechanics has been confronted with all the classic problems involved in underground work. Added to these problems met and solved in other industries such as civil engineering, dams, mining, quarries and oil drilling, Rock Mechanics faces radically different difficulties linked, on one hand, with the necessity of confining the radio-nuclides for periods up to 100 000 years, perhaps even longer-up to a million years, and on the other, the release of heat which causes an increase in temperature in the host material around the highly-active nuclear waste.

Disposal of nuclear waste raises a series of scientific and philosophical questions which require a truly "pluridisciplinary" approach : this is a fashionable word but here it covers a deep-rooted reality, since there is intersecting between the requirements of one group and the responses of the other, between the problems of society and the problems of technology. This report will only examine the aspects related to Rock Mechanics, nevertheless keeping in mind the fact that the definition of a waste disposal site requires reflexion from the sociological, psychological, historical, climatological point of view as much as from the geological, hydrogeological, tectonic or mechanical aspects.

2. SALT DISSOLUTION BY UNDERGROUND WATER

2.1 Ground water flow

Ground water flow is a major danger for nuclear waste disposal ; first, it can provoke a premature corrosion of the man-made barriers which protect the wastes ; then ground water

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flow, activated by the temperature gradients generated by the heat output, can transport radionuclides up to what is called biosphere.

For this reason, the host rocks contemplated for high level waste disposal must be the least permeable possible and the regional hydraulic gradient must be very low. In fact, this implies studying the hydrogeology of media where there is no -or minor- flow of water (de Marsily and Feuga, 1984).

Even if the natural properties of the rock formation are, in this regard, extremely favorable, the existence of the disposal itself (galleries, shafts) may deeply modify the initial geological context.

2.2 Salt dissolution

Relationships between rock salt and water are complex. Rock salt permeability to water, or more precisely to brine, is very small at sample scale (Chia Sing Lai, 1971 ; White and Spiers, 1985 ; Lorenz and al, 1981). In situ tests in deep drill holes seem to prove that the permeability remains small even at larger scale, probably in the range of 1 to 100 nanodarcys (Berest, 1990). Recent experiments on the WIPP site (New Mexico, USA) seem to confirm this order of magnitude (Bredehoeft J.D., 1988). Moreover permeability to gas of a rock formation previously saturated with brine is probably extremely small ; and next, rock salt is an auto healing material, i.e the existence of discontinuities allowing for a large localized flow of water through a wide salt formation is very improbable.

However rock salt raises a particular problem due to its solubility. In some extreme geological conditions, the water flow can lead to the destruction of the deposit (J. Goguel, 1967). Conversely the risk must not be exaggerated ; rock salt has remained unchanged for millions of years in numerous deposits whose total surface makes up a significant part of the surface of immerged lands. (E.C. Pendery, 1966). Even in unfavorable conditions -direct contact between rock salt and clear water- the dissolution rates can remain small, various processes bringing to a natural limitation of the efficiency of the solution mechanisms.

Nevertheless in the carrying out of a disposal, the heat emission from the wastes can perceptibly modify the natural conditions. The solution risk is thus an essential factor in the choice of a site and for the design of a disposal system. The underground galleries will remain at atmospheric pressure even after backfilling of the disposal. Gas generation in the wastes will generate a progressive pressure buildup, leading to a balance between fluid pressure inside the disposal and natural water pressure in the surroundings. But during a certain period the disposal will be a "potential pit" for underground waters. Moreover, underground works can create the conditions of an access of ground waters to the disposal : through shafts, exploratory drills ; or joints and faults created or activated by stress redistribution around the disposal.

2.3 A case history

Salt mine flooding is an extreme example of the action of water. This kind of accident is not interesting as such from the point of view of disposal, for deposits (and mining technology) make this accident most unlikely. However, the study of flooding brings in a very useful "model" of dissolution phenomena. The Ronnenberg accident W.G. is a classical example (Figure 1). The water inflow takes place in a zone where salt is divided into two distinct masses by almost vertical marl/anhydrite layers. The cumulative water inflow over the period 1905-1973 amounted to approximately 200,000 m^3 ; then 240,000 m^3 for the year 1974. Later on, the brine flow rate into the mine reached 1 m^3/mn in April 1975 ; 1.5 m^3/mn on June 27, 1975 ; and 3.7 m^3/mn on June 29. In spite of the efforts put forth to reduce the flooding, the flow rate reached 15 m^3/mn on June 30. The mine was then abandonned. The flow rate reached 60 m^3/mn on July 10.

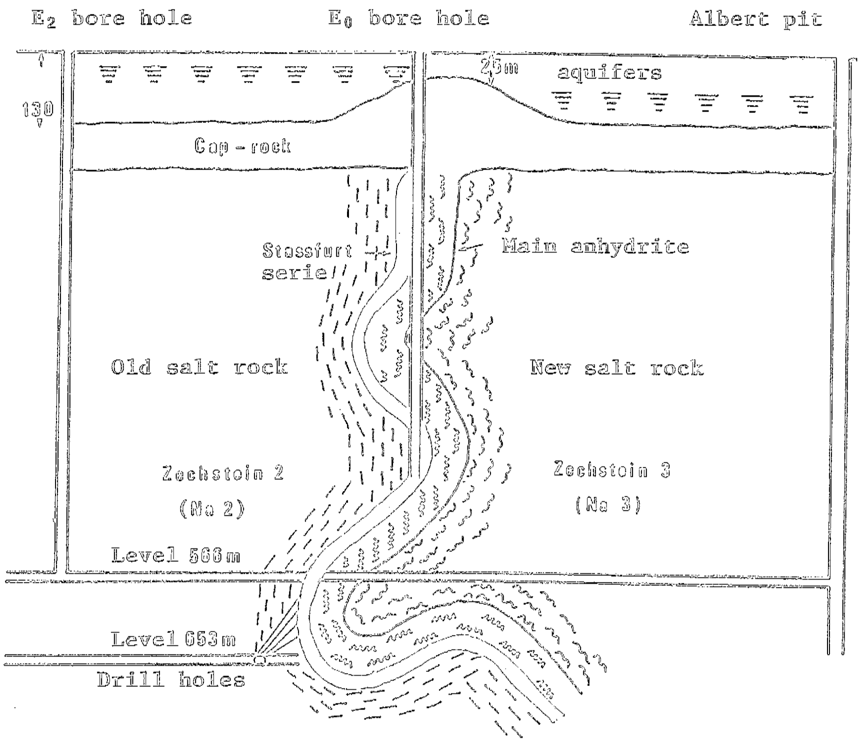

Fig. 1 - Ronnenberg Salt mine.

Some aspects concerning this type of accident should be underlined :

1. The open galleries of a mine build up a hydraulic "potential pit" ; they offer an exsurgence to the water flow. This allows rapid and active dissolution. Indeed, when the salt and the overlying ground water come into contact, a saturated brine layer appears in contact with salt and tends to stagnate because of its own weight. It thus protects the salt. Rapid leaching requires a situation where the brine can flow.

2. When non-saturated brine flow is possible, its flow rate may increase very rapidly. Indeed, the brine enlarges its own flow channel in salt through dissolution.

3. The geological context is unfavorable. The salt is separated by a discontinuity which allows the water flow from the very beginning. Generally speaking, many European salt mines can be found in districts where the presence of salt has been known for centuries owing to the existence of salt springs. These are often fringing deposits, shallow and in lateral or vertical contact with underground water. The deposit is not well protected in these districts ; it leads to natural solution and particular risks for the mines. Accidents due to solution mining, (P. Combes et al, 1984) or even to natural deposit solution (Davies, 1982), bring in similar information. They originate from an unfavorable geologic context or the destruction of natural protection by man-made works.

2.4 Concept of Geological Overburden

Many deposits remain undamaged from any solution for millions of years. This fact proves the efficiency of the natural barriers which separate the deposits from the ground water. The deposit of rocksalt is often followed by a deposit of very thick layers of sediments in which the prevailing materials are those which change into impervious rocks (for example clays). The whole of these layers build up the "overburden" of the salt deposit. From our view point, the existence of such an overburden is a favorable element to be considered in the design of a disposal system. But it must be thoroughly checked whether these favorable conditions will remain unchanged or not, for instance under the effects of the thermal load.

3. THE THERMOMECHANICAL PROBLEM

3.1 Introduction

A salt formation, properly protected from natural solution, exhibits considerable advantages. The major remaining problems concern the evolution hazards, under the effect of external events, or under the effect of shaft and gallery digging and disposal of heat sources. The thermomechanical evolution can be divided in three distinct stages :

- Digging of the galleries will last a few dozen years. Mining operations at the considered depth (800 meters) can be considered as a routine.

- The thermal phase begins when vitrified wastes are disposed. The heat output slowly decreases with time, and the major part of the thermal energy is released after one or two centuries. The attention of Rock mechanicians has been drawn to this phase, because it raises difficult and original problems, temperature changes having a strong influence on rock salt rheology.

- The last phase, whose length is difficult to foretell, is the return to an equilibrium state (if it exists) in which the natural state of temperature and stresses and the continuity of the rock mass are restored.

In the next paragraph, we will discuss some aspects of those thermomechanical problems.

3.2 Thermal effects

Vitrified wastes generate an important heat output, which rapidly decreases with time. As an order of magnitude, the total generated heat will be $6\ 10^{16}$ Joules (in the French program). An accurate description of heat transfer phenomena is then necessary. Except for the case of forced convection due to a thick aquifer, heat diffuses by conduction. The linear approximation of the Fourier law gives excellent results, when compared to actual data, due to the relatively small range of variation of the thermal properties of rocks.

$$\frac{\partial T}{\partial t} = k\ \Delta T\ ,\ K = k\rho C$$

where k is the thermal diffusivity and K is the thermal conductivity.

The power output is a decreasing function of time. At least for the first centuries, the following approximation can be considered

$$q(t) = q_0 \exp(-t/t_0)$$

where t_0 is of the order of 40 years and q_0 in the average heat ouput per unit of horizontal area. Let us try to describe the thermal climax, i.e the instant when the temperature in the disposal reaches its maximum value. It can be shown (Berest, 1989) that the temperature at the center of a not too thick disposal can be expressed as follows :

$$T(t) = q_0 \sqrt{\frac{t_0}{k\rho C}}\quad \theta\left(\frac{t}{t_0}\right)$$

where $\theta(u)$ is the function defined by the differential equation

$$\dot{\theta}(u) + \theta(u) = \frac{1}{\sqrt{\pi u}} \qquad \theta(0) = 0$$

The maximum is reached for $t/t_0 = 0.815$ (about 33 years) and is

$$T_{max} = 0.315\ q_0 \sqrt{t_0/(k\rho C)}$$

i.e 180°C, in the case of a reasonable example ($q_0 = 50$ w m^{-2}).

This very simple calculation illustrates the influence of the q_0 parameter, the only parameter which results from the design of the repository and not from the properties of the surrounding rocks. A low q_0 means that the buried material is "spread" so that the rise in temperature is slight. The numerical value selected above is close to the relatively "compact" design which has been chosen in Germany [Prost, 1983]. In the concept, it is hoped that the remarkable creep properties of rock salt at high temperature will ensure a faster natural sealing of the excavation.

3.3 Mechanical effects

The magnitude of the mechanical effects of heating is not so easy to estimate ; numerical computations are necessary. Nevertheless the global upheaval at ground level can be readily estimated. The uplift becomes important when the wastes have lost the main part of their thermal energy (~ 10^2 years) and will remain important up to the time when a large part of the generated heat has flown through ground level (if the disposal depth is $H = 700$ m, and the thermal diffusivity is $k = 3\ 10^{-6}$ m^2 s^{-1}, this means $H^2/k \sim 10^4$ years). During this period, the generated heat balances the temperature increase in the rock mass, $W = \int \rho CT\ dv$. If the rock has elastic or elasto-viscoplastic homogeneous behaviour of the following type

$$\dot{\underline{\underline{\epsilon}}} = L\ \dot{\underline{\underline{\sigma}}} + \dot{\underline{\underline{\epsilon}}}^p + \alpha\ \dot{T}\ \underline{\underline{1}}\ ,\ \mathrm{tr}\ \dot{\epsilon}^p = 0$$

then the uplift volume at the ground surface is a simple function of the total thermal energy W released at a given time

$$V = 3\ \alpha\ W\ /\ \rho C$$

Assuming the following numerical values : $\rho C = 2\ 10^6$ J/°C/m^3, $\alpha = 4\ 10^{-5}$/°C, $W = 6\ 10^{16}$ J, we get $V = 3{,}6\ 10^6$ m^3 which leads to a significant uplift plumb to the repository (one to three meters). The stress magnitude will be $\sigma \sim E\alpha T$, i.e several dozens of Mega Pascal if the elastic modulus is $E \sim 10^4$ MPa (in fact, those stresses will rapidly relax due to the viscoplastic nature of rock salt behaviour).

3.4 Conclusions

A "compact" design of the disposal leads to relatively high temperature increase and ground level upheaval, which means that the generated stresses and strains in the rock mass will be severe. An accurate estimation and analysis of those mechanical effects is then of major importance ; we will now focus on some difficulties of such an analysis, from the points of view of constitutive law formulations and numerical computations.

3.5 Rock Salt Rheological Behaviour

Many scientific works have been devoted to rock salt mechanics. A master bibliography can be found in Hardy R.H. and Langer M. (1984) ; an interesting state of the art has been prepared by Aubertin M., Gill D.E., Ladanyi B. (1987).

This interest has been motivated by practical reasons (salt mining is an old and widely spread activity) but by theoretical reasons also : rock salt behaviour is highly non linear, includes important viscous effects and is widely influenced by temperature level. These features have led to numerous misinterpretations. Twenty years ago, laboratory tests were relatively rapid (less than 24 hours) ; at this time scale, rock salt exhibits a ductile behaviour but a not so negligible strength. These tests cannot explain the actual behavior of deep mines or underground caverns. Longer tests (several months) have allowed researchers to match actual data and constitutive laws. In particular, creep tests (Langer, 1979) have led to a set of results which are almost universally accepted.

1. Under deviatoric stresses, even moderate ones, the salt creeps without reaching equilibrium even after several months. The behavior of the salt thus resembles that of a highly viscous liquid.

2. A rise in temperature strongly increases the creep rate.

3. The creep rate seems to depend mainly on the second invariant of the deviatoric stress tensor (or of the gap between extreme main stresses) ; the dependency is highly non linear.

Nevertheless some controversial questions remain.

1. Creep tests must be carried out over a period of several months. How can an extrapolation for longer periods be made ? (Heusermann, 1982). Some authors (Hunsche, 1983) propose the concept of stationary creep (the creep rate reaches a constant value after a transient phase) but other laboratories wish to show evidence of a time hardening of rocksalt (G. Vouille, 1983).
2. Is salt a liquid or does it show a certain yield criterion ? The latter, if it exists, is probably weak so that its determination in laboratory is difficult. Nevertheless, the existence of such a yield criterion can have significant consequences from a practical point of view when long term behavior is considered.

4. EXTRAPOLATION OF GEOMECHANICAL CHARACTERISTICS

4.1 Extrapolation in space

The major importance of the scale effect for hydrogeological properties is well known (Brace, 1980). There will be no surprise that, on the contrary, the scale effect is very slight for thermal properties. Thermal conductivity varies little from one rock to another and for heat exchange there is no equivalent of "short circuits" which the open discontinuities constitute for the circulation of water.

The situation for mechanical properties is more contrasted. They are measured in the laboratory, in-situ in underground structures (convergence of tunnels or measurement by specific equipment) and sometimes on a very large scale, for example the effect of depressurizing an underground cavity (E. Hetuin, P. Berest, P.A. Blum, 1989). The scale effect depends on the existence of discontinuities, but also the type of loading and its intensity. The effect will be strong if tension or shear stress are generated along the discontinuities.

Generally speaking, it seems that the scale effect is slight for rock salt as is shown by the good correlation between laboratory measurements and the observations made in-situ in cavities of several 100 000 cubic metres. Naturally, this correlation must be related to the very low frequency of discontinuities open in the salt mass. However, it is to be noted that the mode and geometry of the loading in a buried waste deposit will cause stress in the non-saline overburden as well as in the salt itself. The scale effect can be important for the overburden yet difficult to assess. This results in the necessity for parametric studies in which several hypothesis will be used for the properties of the overburden.

4.2. Extrapolation in time

The incidence of time scale on the physical-mechanical properties of geological media is a problem quite specific to long term deposits of radionuclides. We know for example that short term (1 day) mechanical tests on salt lead to incorrect prevision for the behaviour of real structures after several years of existence. In this precise case, tests over several months make it possible to undertake reasonable extrapolation. What is the situation as regards nuclear deposits ? Mechanical load effects of great intensity (let us say an invariant $(J_2)^{1/2}$ of several MPa) will probably disappear after a few centuries. On the other hand, mechanical load effects of low intensity will straight away affect a large volume of rock (at a distance from the deposit) and will persist a very long time. The most difficult operation is to analyse these effects in the laboratory because of the extremely low deformation rates generated by these small loads. Extrapolation in time is therefore also an extrapolation at very low stresses and rate of deformation. However, the issue is essential, since these very low rates describe the last stage of a return of the mass to its original continuity.

This major difficulty can be dealt with in several ways :
◦ One can increase the complexity of tests ; this has led to developing the means of undertaking creep tests with temperature. These creep tests offer high performance greater than those currently used in Rock Mechanics. They are carried out for example at the Sandia National Laboratory of Albuquerque (U.S.A.), at the B.G.R. in Hannover (G.F.R.), at the Laboratoire de Mécanique des Solides at the Ecole Polytechnique in France (Langer, 1979 ; Wawersick et al., 1981 ; Charpentier, 1984). For example, the B.G.R. in Hannover has developed a creep machine in which the temperature is regulated to 1/1000 degree and deformation rates are measured with an accuracy of 1 % in three centuries. In this way they hope to define tendencies which up to now were not accessible (Hunsche 1984).

Similarly, numerous studies place focus on the discussion of the interpretation of tests. The classical test called "simple compression" is already a test on a relatively complex structure. Apart from the obvious effects of humidity, temperature and inevitable fluctuations of applied load, the effect of the boundary conditions or even the techniques of taking samples have led to abundant literature where one of the issues is to discuss the existence of secondary creep (constant rate of deformation under constant load) which several authors think they have established.

◦ One can study the numerous microphysical mechanisms of deformation on which hope is founded for a theoretical deduction of the laws of creep (Munson and Dawson, 1981). For example, for Langer (1986) these investigations are the only way to identify if the rheological laws established by laboratory tests are transposable to other conditions of temperature, stress or rate of deformation. C. Spiers et al. (1982-1983) have shown the difficulty of this task by emphasizing the original mechanisms of deformation in which the brine contained in the grain joints play an essential role.

◦ It is our opinion that the study of the geological deformations has not been sufficiently used. Although interpretation is often rather complex, the data drawn from observation of geological structures are very rich a priori, since they concern time scales at least equal to those which interest us. A discussion on the case of salt domes is given in L. Charo (1987).

◦ Finally, there is a need to check that the difficult problems referred to are relevant from the point of view of the actual structure studied. It is normal to give priority to uniaxial creep tests, since they are relatively simple to carry out and universally practised, therefore comparison is possible. Nervertheless, these tests are specific and only give an imperfect representation of the loading to which the material is subjected in a deposit. This is in no way similar to creep under constant load (nor pure relaxation). We can then be led to give priority to a close study of certain characteristic phenomena of uniaxial creep leaving aside certain simpler aspects of the rheological behaviour which are, even so, essential for the mechanical problem under study.

5. DESIGN AND CALCULATION OF A WASTE DEPOSIT

The design of structures for radionuclide waste deposit in geological formations requires use of the computer for the calculations in view of the complexity of coupled phenomena and the rheology of materials, especially for salt. The loading is due partly to the weight of the rock mass but essentially it is of a thermal nature. Temperature has the effect of causing expansion of rock mass but also modifying the creep rates as indicated above.

These particular characteristics give rise to specific technical problems : the discerning choice of time scales, the presence of an initial state of prestressing in a medium which is not elastically linear. Moreover, it is obviously necessary to carry out several distinct calculations adapted to the various scales of length (metric for a container, kilometric for an earth mass) and of time (the week for the effect of burying a container in a bored cavity, the century for the return to thermomechanical equilibrium).

Examples of such calculation adapted to French salt formations are to be found in H. Rolnik (1984) M. Ghoreychi and P. Berest (1989). For the case of the Gorleben site, see M. Wallner (1986).

Beyond the problems of calculation techniques however, the use of computer programmes to calculate a waste deposit also raises particular problems of method. Two examples, one of the tests carried out on the Waste Isolation Pilot Plant (WIPP) site and the other of the COSA comparative testing organized by the European Community will illustrate certain problems.

5.1 The WIPP example : Is the objective of "blind forecasting" realistic ?

There are now fields of study where physical modelling has reached an advanced degree of maturity. Numerical calculation has progressed so much that excellent accuracy can be obtained with ordinary software. For a structure composed of manufactured products with fairly homogeneous and known mechanical characteristics, reacting in the linear thermoelastic field under the effect of well identified external loads, we can today expect that the gap between calculation and observation is below one or a few percent. However, precautions must be taken before accepting any extrapolation of this remarkable progress to the field of Earth Sciences.

An example of the difficulties raised by the concern of achieving a perfectly rigourous demonstration is illustrated by the forecasting of results of an in-situ test at the W.I.P.P. site. The reasoning behind this method is summed up as follows :

"In the existing regulatory context, a major requirement is to assure that the public safety is preserved. This requires, in part, the development of technology for the prediction, far into the future, of the structural creep response of salt. In the early development of the structural prediction technology, it was decided to rely where possible on first principles or, where that was impossible, on laboratory empirical data as the proper basis for the technology. Back calculations based on in situ measurements would not be acceptable. Thus, results from the WIPP in situ structural experiments would serve solely for validating the independently developed prediction technology". (D. Munson et Al., 1989).

This method of "blind prediction" can be considered as marked by true intellectual rigour and a real respect for the requirements of the demonstration. In spite of the development of very careful and numerous laboratory measurements, the perfecting of elaborate design codes and the undertaking of a high-performance in-situ test (a circular cylindrical pillar was devised to ensure precise calculation), the results obtained raised numerous queries.

Indeed, the previsions underestimated the intensity of the displacements and the effective rates by a factor of about three. It is interesting to devote a few lines to the subsequent analysis of the factors which led to this under valuation. Munson and Fossum (1986) propose three basic factors :

◦ The evaluation of the parameters : this factor includes the distinction between several types of salt and consideration of deformations generated by the excavation and sampling before the tests were performed.

◦ The flow law : the so-called "triaxial" tests are in fact tests where only two independent forces are applied, an axial load and a confining pressure. They do not offer the possibility of distinguishing between a Von Mises and a Tresca flow law (the latter is independent of the principal intermediate stress whereas the Von Mises law puts the three principal components of the stress tensor to play a symmetrical role). The difference between the two laws is often small as regards the practical consequences, in such a way that the Von Mises law is preferred because of an easier numerical use. In the case of rock salt, the flow potentials are expressed more or less as follows :

$$\Phi = A\,(\sigma_1 - \sigma_3)^6 \qquad \text{(TRESCA)}$$
$$\Phi = A\,\{\, 1/2\,[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2]\,\}^3 \qquad \text{(VON MISES)}$$
$$\dot{e}_{ij} = \partial/\partial\sigma_{ij}\,\Phi$$

The (small) gap between the usual Tresca and Von Mises laws is considerably amplified here to the order of five which intervenes in the expression of the viscoplastic deformation rate.

Subsequent "finer" tests (carried out on hollow cylinders, therefore with a more complex stress distribution than in the triaxial test) have shown that the Tresca law was preferable.

◦ Constitutive equation : it is often accepted in a triaxial creep test that the rate of deformation under constant load reaches a constant value after a transient phase of a few days or some weeks during which this rate, initially high, falls appreciably. One is tempted to simplify the description of this transient phase, for its contribution to total deformation is small in the case of a long term test. This simplification is legitimate for the very simple structure of a cylinder subjected to a homogeneous deformation. For a more complex structure such as an underground tunnel, the stress distribution is much more complicated : the area round the walls is immediately and heavily loaded, but a volume of considerable size, further away, is also progressively affected by the presence of the tunnel (the elastic theory is a very poor guide here since it forecasts that the influence of the tunnel does not exceed a distance of some diameters). In these conditions, the transient creep and more generally the creep under low stress acquires considerable importance for such a structure, whereas the laboratory tests tend to underestimate their importance.

This experience calls for lowering initial ambitions, in other words, the achievement of "blind prediction" is undoubtedly too stringent a requirement for geotechnical calculation. On the other hand, there can be no question of limiting study to "curve fitting". Between the two there exists a method which endeavours to progressively reconcile a very rich set of data (laboratory tests, in-situ tests, observation of real structures, cases history, data from the physics of solid). Considerable progress accomplished over the last ten years gives us grounds to hope that this method will provide reliable previsions at term.

5.2 The COSA European Community exercise : each calculation can require specific modelling

The European Community organized several comparative "tests" on design codes ("Benchmarks") devoted to thermomechanical calculation for rock salt (B. Come, 1987). These exercises on theoretical cases or practical experience in mines were found to be extremely fruitful for the twelve teams which participated : the information retrieved undoubtedly exceeds the specific problems under study.

The calculation of the development of temperature in a rock mass under the effect of buried heat sources generally gives excellent results (the differences between solutions and between solutions and measurements are of the order of a few percent). Two reasons explain this agreement : on one hand, the physical mechanism is perfectly identified (Fourier conduction law), on the other, the number of parameters intervening in this law is low and these parameters (thermal diffusivity, specific heat) have very homogeneous values throughout the rock mass.

The problem of determining stress and displacement is totally different : even in a rather extreme case, differences from one to three appear in the results obtained by various teams. Several factors contribute to such differences : the determination of initial stresses, always difficult to measure in-situ and often disturbed by the structures built for access to the test site, consideration of boundary conditions where "elastic" experience is not to be trusted since it only predicts small radii of influence, following the Saint Venant principle. But the main difficulty arises from the expression of the constitutive equation.

This expression is clearly very complex, since the mechanical properties are very sensitive to temperature and can be scattered throughout a single rock formation. They involve various mechanisms which change according to the scales of time and stress. Moreover, this equation is expressed by very non-linear relationships, so that a small error on an exponent eventually leads to a large error in the calculation of a real structure. Finally, it must be remembered that tests are generally carried out on very simple but specific structures (a cylinder in the case of an ordinary triaxial test) which give priority to a certain family of states of stress. The constitutive equations which are drawn from this are therefore only perfectly valid for this family of states of stress (c.f. the example of the W.I.P.P. above).

Faced with these difficulties we can venture a paradox : the constitutive equation depends on the structure to be studied.

Indeed, the complexity of the behaviour of the material apparently requires setting down a law comprising a large number of parameters. Often the laws concerning rock salt include about 20 parameters ; our conviction is that, in carrying out varied tests, from the point of view of geometry or mode of loading, it would undoubtedly be necessary to increase greatly this number of parameters to take into account all the aspects of behaviour. This introduces in two new difficulties -on one hand, the calculation becomes costly, and on the other, interpretation is even more costly, the links of cause and effect are inextricably intermingled, so the influence of the various mechanisms can only be observed by multiplying the variants of calculation. To sum up, the results of calculation, far from casting light on the phenomena, by themselves become an object of study with a degree of complexity equal to that of real structures. In this case it is wise, for a well-defined problem, to try to identify the parameters which present a real influence on the main calculation results, in other words, the value of the partial derivatives of effective magnitudes in relation to the parameters of the problem. It is generally found that the effective parameters are quite few but depend essentially on the nature of the problem raised.

For example, creep tests show that deferred deformations of a viscoplastic type are rapidly much more intense than instantaneous deformations of an elastic type. We can therefore be tempted to describe the elastic behaviour very briefly and devote more care to a detailed description of deferred effects which are very complex. In a particular structure it can nevertheless occur that the effective magnitudes depend essentially on elastic characteristics, whereas non-elastic characteristics are of secondary importance only. Such is the case for example of the extent of ground surface uplift. The brief calculation presented in the introduction shows that it depends principally on the coefficient of thermal expansion, and very little on the viscoplastic deformations of the salt, because these occur without any variation in volume.

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