Analysis of Cavities in salt formations

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ABSTRACT: Analyses have been conducted of the movements in drifts at 290 and 400 in a Spanish potash mine. The constitutive behaviour observed has then been used to make predictions at larger depths. The agreement found between analyses and observations at the shallower levels supports the calculations made at greater depths.

1 INTRODUCTION

The availability of an important amount of geotechnical data from a Spanish potash mine has made it possible to conduct interesting comparisons between measurements and analyses. The latter have been conducted using the program PR2D (Principia, 1985), which has proved very adequate in similar analyses in the past (Blanco et al 1986; Marti et al 1986). It has also provided an opportunity to study the mechanical behaviour of Spanish salts and their performance in relation to underground operations such as mining and, eventually, radioactive waste storage.

One of the major problems in modelling salt masses arises from its creep behaviour, that is, its tendency to flow in time when subjected to deviatoric stresses. As is well known, creep behaviour is strongly influenced by temperature changes, which will necessary occur in the case of high-level waste storage. Temperature changes have therefore an effect on the problem, both by the process of thermal expansion and by modifying the creep behaviour of the salt.

From this point of view, it becomes necessary to solve a coupled thermomechanical problem. For the case of the mine considered here, available data are primarily of a mechanical nature with some measurements of constant ambient temperatures. Hence, the present study restricts temperature influences to effects on the mechanical properties which appear in the constitutive law.

2 RHEOLOGICAL ASPECTS

Evaporitic salts (halite, gypsum, sylvine, etc.) display rheological properties. They undergo viscous flow at room temperature under almost any continuously applied deviatoric stress. This phenomenon is usually called creep and has been studied at scales ranging from laboratory tests to geological observations (Langer 1981; Lidner and Brady 1981). However, it is difficult to propose precise mathematical models which represent this behaviour with generality in a satisfactory manner.

Isothermal creep tests tend to show a region, generally described as secondary creep, where strainrates remain constant for a given applied load. Consequences of this behaviour can also be observed in underground openings. Secondary creep rates have been related to the effective stress by means of empirical power-law relationships (see, for example, Langer 1981), where the main justification for the choice of functional relationship lies in its becoming a straight line in the log-log plot. Typical stress exponents range from 2 to 5.

It was already mentioned earlier that temperature increases produce an acceleration of the creep rate. As could be expected, the mathematical representation of this influence includes an activation energy associated with the energy barrier which must be overcome with the help of thermal agitation.

The combination of the above considerations yields expressions for secondary creep of the type:

\[ \dot{\varepsilon} = A \sigma^n \exp \frac{H}{kT} \]  

(1)

where \( \dot{\varepsilon} \) is the effective strain rate in secondary creep, \( \sigma \) is the effective stress, \( H \) is the activation energy, \( k \) is the Boltzmann constant, \( T \) is the absolute temperature, \( A \) and \( n \) are empirical constants (A has peculiar dimensions arising from the empirical character of the relationship).

Neglecting transient creep behaviour, the problem thus becomes one of modelling a material characterised by the above stress-strainrate-temperature relationship.
3 MATHEMATICAL TOOLS

The numerical procedure selected has been that of dynamic relaxation, based on a central finite-difference scheme. The discretization in time and space uses explicit integration in time and finite difference zones referred to a Lagrangian frame in space. The space semidiscretization follows the mixed discretization procedure first proposed by Marti and Cundall (1982) and later refined by Gocolea (1985). The integration timestep is automatically calculated to guarantee stability of the integration using the Courant condition, since explicit integration schemes are only conditionally stable.

The constitutive laws are used incrementally. First, a hypoelastic prediction is made:

\[ \dot{\varepsilon}_{ij} = \lambda D_{kk} \varepsilon_{ij} + 2\mu D_{ij} \]  

(2)

where \( \dot{\varepsilon}_{ij} \) is the Jaumann rate of Cauchy stress, \( D_{ij} \) is the rate of deformation tensor, \( \lambda \) and \( \mu \) are the Lamé constants.

The resulting Cauchy stress tensor is then modified by the procedure of radial return if the corresponding effective stress exceeds the criterion given in eq. 1.

For the rest, the program PR2D selected for studying the problem works in the usual manner. The integration of stresses around grid nodes yields acceleration via the momentum conservation laws. Explicit integration gives new velocities and displacements, which then allow calculation of strainrates. The constitutive laws finally produce new stresses for recommencing the cycle.

Previous experiences of salt creep analysis with PR2D/3D (Blanco et al 1986; Martí et al 1986) have shown that the procedure is robust and stable. A recent optimisation of the code for operation on a Convex C1-XP computer has also yielded great savings in computer time with respect to previous versions of the code.

4 MODELLLED PHENOMENA

The field data used in this paper come from a potash mine which exploits a relatively thin mineral-bearing strata. It is located in an evaporitic basin of eocene age. The 2m thick sylvinite seam sinks smoothly towards the West. Mining operations are carried out by a room and pillar method. A number of geotechnical measurements are routinely taken. Those of special interest here are:

- Vertical and horizontal convergence measurements, which monitor the decreasing dimensions of the opening under the state of stress imposed.
- Relative displacements around drifts, which allow studying the progressive ground deformations.

Convergences are obtained using a tape extensometer. Expansion measurements are carried out by means of multi-point strain-wire borehole extensometers.

The measurement stations selected for the present investigations were located at drifts not influenced by other drifts or extraction pannels. Two groups of stations were chosen: one of them at 290m depth and the other one at 400m depth. The drift dimensions were identical in both cases: 3.2m high and 4.6m wide.

In order to simplify the model, a single equivalent material was used to represent the thermomechanical behaviour of the sylvinites and carnalite salts together with the thin marl interbedding. The mesh constructed consisted on half section of the drift, limited on one side by a vertical plane of symmetry and extended on the other to represent a homogeneous environment. The model geometry is shown in Fig. 1.

The mesh was constructed so as to make it possible to obtain results at measurement locations and to input bolts in the model at their actual positions in the mine.

The research program undertaken has included two successive phases:
- First, the parameters appearing in the constitutive law were validated by comparing the model predictions with actual measurements at the two referenced depths. Initial values for the parameters were obtained from previous investigations (Blanco et al 1986), based on measurements from a nearby mine on the same basin.
- Then, using the constitutive behaviour and properties obtained, calculations were carried out in order to predict the behaviour of drifts in deeper parts of the deposit (600m).

5 RESULTS AND DISCUSSION

As mentioned above, the validation of the constitutive parameters was conducted by means of two analyses simulating the conditions of the drift at depths of 290m and 400m, respectively. The same temperature was considered in both cases and the same values of constitutive parameters were used. For modelling with PR2D, rate dependence is described by the formula:

\[ Y = Y_0 (1 + B \varepsilon^m) \]

(3)

\( Y_0 \) is the static yield stress, \( B \) and \( m \) describe the rate sensitivity.

From Blanco et al (1986) the following values were initially taken for the parameters: \( Y_0 = 10 \text{kPa}, B = 2.43 \times 10^6 \text{ s}^{-1/3} \) and \( m = 1/3 \). Notice that only the product of \( Y_0 \) and \( B \) is important and not their individual values.

Although overburden effects were taken into account gravity was ignored in the model. Density scaling was used to accelerate the runs, as static solutions are independent of inertial masses.

Slight modifications were made in the constitutive parameters to reproduce the measured
results. The best fit was achieved with $m = 0.367$, a parameter to which the solution is very sensitive. Table I provides a comparison between the results of the numerical model and the experimental measurements when quasi-steady conditions are reached.

The overburden pressure was applied gradually in order to minimise dynamic effects. This can be noticed in the time histories shown in Figs. 2 and 3. Eventually, the system reaches steady state with almost constant velocities. The scale of time has no physical meaning because of density scaling. The interest of the analysis rests primarily with the values of the final velocities.

The model was then applied to a drift at a depth of 600m. The properties were corrected consistently with eq. 1 by means of an activation energy. As its value was unknown for this salt, it was taken from similar analyses conducted elsewhere (Langer 1981).

The geothermal gradient at the mine is low, about 7.9°C/km. Introducing the temperature influence through a modification of the static yield strength gave the latter a value of 7945Pa.

The predictions are given in Figures 2 and 3. The rates of displacement are on the order of ten times higher than those calculated and measured at 290m. Measurements will be carried out in the future in order to verify the predictions.

Several runs, not reported here for reasons of space, were conducted to study the influence of bolting. However, these supporting elements did not particularly affect the bulk convergence rates. This agrees with mining experience and practice, where bolting is used to avoid loose rock blocks or other localised failures, but not to retard closure of a salt cavity.

6 SUMMARY AND CONCLUSIONS

A number of studies have been carried out using information about rock displacements from a Spanish potash mine. Firstly, an inverse problem was solved to obtain in situ mechanical properties of the salt at 290m depth. The model was then applied to a drift at 400m, where field data were also available to check the model. Finally, the procedure was used for analysis at depths of 600m to assess the likely evolution of an opening at that depth.

The comparison between predictions and measurements can be considered very reasonable for the kind of problem studied. The methodology can therefore be considered adequate for analysing creep problems of this type.

It has also been found that, as could be expected, bolting has little influence on the overall mass movements and closure rates. Its practice is recommended nevertheless to prevent local failures.

Finally, the vectorized version of PR2D for the Convex C1-XP has allowed a great improvement in speed of processing while maintaining its
Fig. 3 Predicted horizontal velocities at 600m depth at distances inside the wall of a) 0 b) 0.5m c) 1.5m d) 3.0m

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REFERENCES


