MINING IN RHEOLOGIC MATERIALS

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ABSTRACT

Rheologic materials, such as salt, potash and ice exhibit the characteristic of flowing under any level of deviatoric stress. It is important to control the velocity gradients of this flow to ensure the safety of personnel and facilities, as well as the structural integrity of geological barriers which prevent water intrusion and flooding.

Special problems are caused by the intersection of galleries in underground mining operations, which generate complex geometries and states of stress. The quasi steady-state problems generated by the secondary creep of salt and potash are treated by the dynamic relaxation process. Two such geometries are investigated for a range of vertical loading conditions since the load path is often modified by the formation of stress-relief arches over mining galleries.

The results obtained are satisfactory despite the apparent incompatibility between the long times required for the onset of steady-state flow and the short timesteps imposed by an explicit integration procedure.
1.0 INTRODUCTION

Evaporitic salts such as rock salt and potash display rheological properties. This is characterised by viscoplastic flow occurring at room temperature under almost any continuously applied deviatoric stress. This phenomenon is usually called creep and has been studied extensively from laboratory tests to in-situ geological observations [1,2].

The design of salt cavities will require a material model capable of simulating creep behaviour in order to represent the progressive closure of the excavations. The determination of the rate of closure is of particular importance for such a mining operation.

The progressive closure of the salt cavities will also have an indirect consequence on the mining system where there is a possibility that the overlying strata will be unable to adapt its bottom boundary at the salt interface without failure. Failure of the overlying strata may then provide pathways for water, with potentially disastrous consequences for various mining activities.

In this paper DYNA3D [3] is used to study the influence of salt creep on the overlying strata for a potash mine. In this particular mine, the salt thickness above the mining horizon is approximately 30 m and the depth of the ore bed is approximately 1000 m below ground level.

It was not practical to construct a finite element model that represents the complete mining continuum to study the evolution of ground subsidence and the resulting stress field in the overlying strata. Hence, a localised model of the mining area is created with a boundary condition law, at the top of the salt strata, relating the vertical stress to the vertical closure velocity.
DYNA3D has been used to obtain the vertical stress-velocity laws at the top of the salt stratum. This paper describes the way in which the analysis has been performed and the results obtained.

2.0 OUTLINE OF THE MINING PROBLEM

The mining system considered is the room and pillar method, in which long rooms are mined in the potash ore bed leaving long support pillars between the rooms (Figure 1). Access to the rooms is gained through perpendicularly mined galleries. A geological section of the salt stratum, including the potash bed, is shown in Figure 2. The rooms are mined only in the potash and are 2.60 m high.

After an initial phase, isothermal creep tests on salt samples tend to show a region of the strain-stress curve where strain rates remain constant for a given applied load (secondary creep). In this region, the behaviour of the salt is usually described by means of a power-law relationship of the type:-

\[
\dot{\varepsilon} = A \sigma^n
\]  

(1)

Where:

\[
\dot{\varepsilon} = \text{Effective strain rate.}
\]

\[
\sigma = \text{Von Mises effective stress.}
\]

A, n = Material constants.

In the present work it has been assumed that the behaviour and potash in the mine corresponds to (1) with A = 9.33 \(10^{-16}\) MPa\(^{-n}\) sec\(^{-1}\), n = 5. This is a reasonable assumption as only the steady-state situation is of interest.
The study concentrates on areas where galleries cross at right angles. The aim is to obtain a law relating the vertical stress at the top of the rock salt and the corresponding downwards velocity as a function of the galleries dimensions in the mine below.

For this purpose a block of rock salt (Figure 3) is modelled. In order to keep the model size within reasonable limits, four vertical planes of symmetry are considered. The introduction of symmetry is equivalent to the assumption of a repetitive room-pillar structure. Also, since the model height is small compared to the mine depth, a fifth plane of symmetry has been placed at the mean level of potash.

The parameters a, b, c, d and e define the geometry of the crossing galleries. By varying these parameters several different configurations can be analysed.

The effect of the overlying strata has been introduced by simply applying a uniform pressure at the top of the salt strata. Each value of the pressure $p_i$ leads to a different steady-state velocity field due to the creep of the salt and potash. The average downwards velocity across the top of the salt gives a value $v_i$ in the velocity versus vertical stress law for the particular geometry considered. Four or five points are sufficient to define the law if logarithmic fitting is used to construct an exponential relationship of the form:

$$v = Kp^m$$  \hspace{1cm} (2)

where $K$ and $m$ are constants.
For this study two configurations have been considered with the geometrical parameters presented below.

\[ a = 5.85 \text{m}, \ b = 19.50, \ c = 7.80, \ d = 12.35, \ e = 13.65 \]

and

\[ a = 8.45 \text{m}, \ b = 17.55, \ c = 9.10, \ d = 12.35, \ e = 13.65 \]

In order to obtain the \( v-p \) law (2) for each configuration, the overburden pressure was varied between 17 and 27 MPa.

3.0 DYN3D MODEL AND RESULTS

The finite element model used to study one of the configurations is illustrated in Figure 4. The model consists of 5249 eight-noded brick elements and 7164 nodal points. The mesh is divided into three distinct layers with element sizes increasing in coarseness from the mean level of the potash ore to the top of the salt stratum. The layers are connected using the tied option of the sliding interface facility.

The most difficult part of the modelling was representing the rheology of the materials. The secondary creep of the potash and the salt is introduced using a strain rate dependent isotropic plasticity material model (material 19 in DYN3D). In this model the yield stress \( \sigma_y \) was specified as a function of the effective strain rate \( \dot{\varepsilon} \) and the hardening modulus \( E_t \):

\[
\sigma_y = g (\dot{\varepsilon}, E_t)
\]

(3)

The material yields when the stress state corresponds to a point on the yield surface:

\[
\sigma = \sigma_y
\]

(4)
If the stress state is maintained on the yield surface equations (4) and (1) can be combined:

\[
\sigma_y = \left( \frac{\dot{\varepsilon}}{\varepsilon} \right)^{1/n}
\]

which determines the function g.

Hence, if the material constantly yields with time, the constitutive secondary creep law (1) will be satisfied and the plastic flow computed by DYNA3D will model the creep of the materials.

To ensure that the material continually remains in a state of yield, the initial yield stress \((\sigma_y_0)\), corresponding to a zero effective strain rate, is set to a very low value while the hardening modulus is set to zero. If the stress state always satisfies the yield condition, the elastic constants \(E, \gamma\) will not influence the response. DYNA3D uses these constants to compute an elastic stress predictor for each computational cycle. This predictor should always be outside the yield surface and hence a very high \(E\) value is selected.

For such problems, the velocities encountered are only several millimetres per year and hence inertial forces are negligible and densities can be artificially increased to reduce the number of cycles necessary to reach the steady-state. The selection of an optimum density for the materials is not a trivial task and usually requires some experimentation. It depends on the geometry of the model, on the \(A\) and \(n\) coefficients in the creep law and also on the overburden pressure. Low values of the density produce spurious oscillations in the response that make the solution invalid. While high densities increase the number of cycles required to achieve the steady-state.
The velocity time histories for nodes located at the top of the salt strata are presented (Figure 5) for a typical configuration. It can be seen that the velocities reach a steady-state solution. The time scale has no physical meaning.

Once the steady-state velocities of the nodes at the top of the model have been averaged to produce a mean downwards velocity $v_i$. In order to determine enough $(p_i, v_i)$ points to construct the $v$-$p$ law for the particular geometric configuration the problem is re-analysed for a different overburden pressure $p_{i+1}$. By least squares fitting the following constants were determined for the two configurations studied.

$$ K = 1.74 \times 10^{-3} \text{ MPa}^{-m} \text{ mm yr}^{-1}, \quad m = 4.01 \text{ for the first configuration and }$$

$$ K = 3.73 \times 10^{-3} \text{ MPa}^{-m} \text{ mm yr}^{-1}, \quad m = 3.94 \text{ for the second configuration.}$$

These laws were used to construct boundary conditions for further analyses of the overlying strata.

4.0 CONCLUSIONS

DYNA3D has been used to model the steady-state flow of a rock salt strata over a potash mine. The flow was governed by a secondary creep power law that makes the salt behave as a very viscous non-Newtonian fluid. The results obtained were satisfactory.

The traditional domain of application for explicit codes such as DYNA3D is the modelling of high speed dynamics problems. The robustness and speed of explicit algorithms allows simulation of a wide range of highly non-linear low speed problems, as presented in this paper.
5.0 REFERENCES


Figure 2. Geological Section.

Figure 3. Schematic View of Geometric Configuration.
Figure 4. Perspective Views of Finite Element Model.
Figure 5. Velocity Time Histories at the Top of the Stratum (Overburden Pressure = 17 MPa).