THERMO-MECHANICAL MODELLING OF A SIMULATED HIGH-LEVEL WASTE REPOSITORY IN SALT

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ABSTRACT

Thermo-mechanical coupled phenomena due to heat generated by radioactive waste in salt formations with caverns are studied with explicit computer codes PR2D-PR3D\(^1\). Results for 2 and 3-D analyses are compared with measurements taken at Asse Mine, FRG. The suitability of the above codes for such modelling as well as the dominance of thermal expansion effects on the solution are concluded.

1. INTRODUCTION

Salt formations constitute one of the main options presently under consideration for siting of high-level waste repositories. Their stability and evolution under the coupled effects of waste-generated heat and cavity-induced stresses is consequently a major consideration.

Due to the importance of those effects, a large number of analytical and experimental efforts have been undertaken in various countries, including the operation of underground laboratories in which thermal and mechanical effects of waste emplacement are simulated.

The problem considered here is generally that of a cavity opened in salt rock. Within the salt, not far from the
bottom of the cavity, a heat source is activated at some point in time.

A number of physical mechanisms are triggered by the above sequence of events. The opening of the cavity alters the natural stress distribution. The resulting deviatoric stresses are linked to a pattern of salt flowing into the cavity. The relationship between those deviatoric stresses and their associated strain-rates is governed by the isothermal constitutive law.

The generation of heat under the cavity has two main effects. As the natural temperature distribution is altered, some stresses and displacements are directly induced by the temperature changes through thermal expansion phenomena. The second effect is to modify substantially the isothermal constitutive law: for given deviatoric stresses, creep processes accelerate with temperature.

The suite of programs PR2D and PR3D\(^1\), which solve the coupled equations of thermal and mechanical phenomena, are here demonstrated against measurements taken at the underground laboratory located in the Asse salt mine, FRG.

2. BEHAVIOUR OF SALT

Polycrystalline salt rocks are usually taken to behave as visco-elastic-plastic solids. A number of reviews of their
behaviour has been carried out in recent years, specially in relation to their potential for storage of energy resources, such as oil and gas, and as a possible repository for radioactive waste (see, for example, Langer\(^2\), Lindner and Brady\(^3\), Munson and Dawson\(^4\) and Horseman and Passaris\(^5\)).

The long-term response of salt is best represented by the steady-state equation of secondary creep, in the form:

\[
\dot{\varepsilon} = A \bar{\sigma}^n \exp(-H/kT) \tag{1}
\]

where \(\bar{\sigma} = [3/2 s_{ij}s_{ij}]^{1/2}\) is the effective stress \\
\(\dot{\varepsilon} = [2/3 d_{ij}d_{ij}]^{1/2}\) is the effective strain-rate \\
\(s_{ij}\) is the deviatoric stress tensor \\
\(d_{ij}\) is the rate of deformation tensor \\
\(A, n \) and \(H\) are material constants \\
\(k\) is the Boltzmann constant \\
\(T\) is the absolute temperature.

Isotropy considerations lead to the component formulation of the previous equation as:

\[
d_{ij} = (2/3) A \bar{\sigma}^{n-1} \exp(-H/kT) s_{ij} \tag{2}
\]

The ability to represent the sort of behaviour mentioned is common to programs which intend to solve creep problems in salt, e.g. PR2D/PR3D\(^2,6\), ANSALT\(^7\), etc.
3. OTHER THEORETICAL AND NUMERICAL CONSIDERATIONS

The mechanical field equations express the balance of momentum. Integrated over a small volume V, surrounded by an area S and enclosing a mass M, they can be expressed

$$\ddot{u}_i = \left\{ \int_S \sigma_{ij} n_j ds + M f_i + F_i \right\}/M$$

(3)

where $\ddot{u}_i$ is the acceleration

$n_j$ is the outer normal

$f_i$ are the body forces

$F_i$ are the concentrated forces applied.

Equations 2 and 3 essentially define the mechanical problem. The coupling with thermal equations can be seen in two terms: the exponential factor in eq. 2 and the thermally induced strains. The latter are introduced best by modifying the rate deformation tensor $d_{ij}$ to account for the temperature change:

$$d_{ij} = (\dot{u}_{i,j} + \ddot{u}_{j,i})/2 + \alpha \dot{T}_{ij}$$

(4)

where $\alpha$ is the coefficient of thermal expansion.

This rate of deformation tensor is used in the formulation of the constitutive laws (eq. 2). In an updated Lagrangian numerical approach, with explicit time integration, the
constitutive relations are best formulated in a rate form. Firstly, a hypoelastic incremental prediction is made:

\[ \Delta \sigma_{ij} = d_{kk} \delta_{ij} + 2\mu \Delta d_{ij} \]  

(5)

where \( \Delta \sigma_{ij} \) is the Jaumann rate of Cauchy stress.

The resulting stress tensor is then tested against a viscoplastic yield locus which is immediately obtained from inverting eq. 1. For convenience, the formulation adopted here follows the dynamic effects correction of Bodner and Symonds:\n
\[ Y = Y_0 \left(1 + \left[ \frac{\dot{\varepsilon}^P}{B} \right]^{1/n} \right) \exp(H/kT) \]  

(6)

where \( Y \) is the current yield stress

\( Y_0 \) corresponds to a static yield stress

\( B = A Y_0^n \) on the assumption that \( Y_0 \) is small.

The above equations pose the mechanical problem. Two equations represent the thermal problem: Fourier's law of heat conduction

\[ h_i = KT_i \]  

(7)

where \( h_i \) is the heat flux

\( K \) is the isotropic heat conduction coefficient

and the energy balance which, again integrated over a small volume \( V \) surrounded by surface \( S \) and enclosing mass
\[ \dot{T} = \left( \int_S h_i n_i ds + \int_V s_{ij} \pi_{ij} dv + M \dot{Q} \right) / C_p M \]  

(8)

where \( Q \) is the heat source per unit mass 
\( C_p \) is the specific heat.

The second term of eq. 8, corresponding to temperature increases due to plastic energy dissipation, is negligible in the present calculations.

The equations presented are integrated explicitly in the time domain. The field equations permit obtaining motions (eq.3) and temperatures (eq.8). These results are then fed to the material equations to compute stresses (eq.5,6) and heat fluxes (eq.7).

Each time that the equations have been solved as indicated, a computational cycle is completed and the time is incremented.

4. EXAMPLE OF APPLICATION

The above methodology has been applied to the analysis of an example of a simulated JLW repository in rock salt. The example selected for this validation was the experiment conducted at Test Site 2 in the Asse Mine, FRG. This example has been documented by Rothfuchs\textsuperscript{10}. 

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The problem geometry is that of a gallery, 10m x 7.5m in section, opened in rock salt at a depth of about 800m. The corresponding natural overburden at this location is 17MPa. Test Site 2 has electric heaters under the room floor at ambient pressure. A central heater extends from 2 to 5m below the room floor, and 8 guard heaters are arranged around the central heater at radii of 1.5m. Heating power was constant in the guard heaters (total of 7.22KW). In the central heater it changed from the initial 2.53KW to 3KW after 110 days.

The following material properties were used based on data reported by Hunsche and Chabannes et al. 

- Young's modulus $E$ (MPa) = 15.000 - 40T ($^\circ$C)
- Poisson's ratio $\nu = 0.27$
- Density $\rho = 2.100$Kg/m$^3$
- Constitutive parameters $Y_0 = 100$Pa
  (see eq.6) $B = 136.9 \times 10^3$ sec$^{0.2}$
  $n = 5$
  $H/k = 6495^\circ$K

Thermal conduction $K$ (W/m$^0$K) = 6.1/ [1 + 0.0045T($^\circ$C)]
Specific Heat $C_p$ (J/Kg$^0$K) = 810 + 0.23T ($^\circ$K)
Thermal expansion $\alpha = 4.1 \times 10^{-50}$ K$^{-1}$

The problem is that of predicting the temperature, stress and displacement fields which, as a function of time, will result from the imposed condition.
The calculations were conducted with PR2D and PR3D\textsuperscript{1}, which had been used previously in the analysis of deformations of salt\textsuperscript{6}, as well as in problems involving coupled thermo-mechanical phenomena and strain-rate dependence\textsuperscript{12}.

5. RESULTS AND DISCUSSION

Although some partial 3D results are presented, our attention is centred mainly on axisymmetric (2D) calculations. The discrete model used (figure 1) represents an axisymmetric section around a salt cavity, subjected to uniform pressure, with symmetry Boundary conditions imposed in the plane through the centre of cavity.

The analysis was performed in two phases. Firstly, the overburden loads were applied under isothermal conditions, until a steady-state of creep is achieved through dynamic relaxation. At this point the heaters are switched on generating temperature increases (figure 2) and associated mechanical effects.

A Constant Temperature was enforced at the cavity walls to represent the ventilation cooling. This may be appreciated in the temperature distribution (figure 3). Deformations in the thermal phase (figure 4) are due to several effects: firstly, to the continuing flow of material from the applied overburden, now accelerated from thermal softening effects; secondly, to the thermal expansion. Thermal
expansion causes dilatation movements in unconstrained areas, and thermal atresses in constrained locations, which in turn generate extra creep deformations. Displacement time-histories are plotted in figure 5, including results from an analysis without any thermal expansion ($\alpha = 0$). It may be appreciated that the majority of the displacements are due to thermal expansion effects.

Finally, some partial results of 3-D calculations are included in figure 6, showing a transient temperature distribution from a thermomechanical analysis. Work continues in this area, which will allow a more realistic representation of the effects of concentrated heaters on a long gallery than 2D analyses.

CONCLUSIONS

The viscoplastic creep behaviour of salt with coupled thermo-mechanical effects from concentrated heat sources has been modelled for formations including cavities. The suitability of non-linear explicit codes such as PR2D and PR3D is demonstrated for such modelling.

From the results of the analyses it is concluded that thermal expansion effects rather than thermal softening effects dominate the solution.

Finally, work in progress for 3D modelling will allow a more realistic representation of these phenomena. The cost
of 3D analysis is viable in explicit integration models, due to the reduced storage, whereas in other cases it would probably be prohibitive.

REFERENCES


Figure 1: Mesh used for axisymmetric Asse mine calculations

Figure 2: Time-histories of temperatures
Figure 3: Temperature increments (200 days)

Figure 4: Displacements \times 20 (365 days after start of heating)
Figure 5: Floor heave after start of heating

Figure 6: Temperature distribution for 3-D model (100 days)