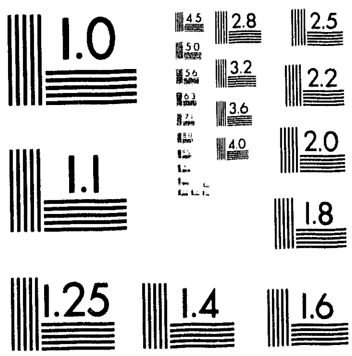
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Dilation-induced permeability changes in rock salt

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ABSTRACT: A model of permeability changes in rock salt is developed and implemented in a time-dependent finite element code. Model parameters are developed from laboratory tests. The model is used to predict permeability changes adjacent to excavations in rock salt.

1 INTRODUCTION

The permeability of rock salt is the single most important parameter in its viability as a medium for hydrocarbon storage and waste disposal. Although intact or undisturbed rock salt has a very low permeability, there is growing evidence of a region surrounding excavations in which the permeability can be dramatically increased. The permeability of the bedded rock salt which is the host material for the Waste Isolation Pilot Plant (WIPP) in SE New Mexico has been extensively studied. Beyond a few meters from most excavations, the rock salt has a brine permeability of about 10^{-21} m^2, a porosity on the order of 0.1%, a formation pore pressure less than the lithostatic state of stress, and no measurable gas permeability (Stormont et al., 1991). Within about one-half effective radius of an excavation, however, a Disturbed Rock Zone (DRZ) forms. In this zone, the formation becomes partially saturated and both the brine and gas permeability can exceed 10^{-16} m^2 (Stormont et al., 1991). The formation of a DRZ has been principally attributed to inter-crystalline boundary microcracking accompanied by dilation, and is the result of relatively high deviatoric and low mean stresses in the salt surrounding excavations (Stormont, 1990a).

One approach to predicting the extent of the DRZ is to identify the regions surrounding an excavation in which the stress state is sufficient to dilate or microcrack the rock salt. Reasonable agreement has been reached between the amount of rock which is predicted to have dilated and that interpreted from various in situ measurements (Stormont, 1990b). However, this approach provides no information on the magnitude of the permeability within the DRZ.

A second approach seeks to quantify the permeability increase within the DRZ, most conveniently by developing a stress-permeability relationship. The majority of research and interest on this subject pertains to changes in permeability as a function of hydrostatic stress, such as related to a material's depth of burial. These permeability changes are due to recoverable changes in the pore structure, and have been modeled assuming elastic deformation of the pore structure (e.g., Walsh, 1981). Permeability changes are also possible due to the creation of new porosity (or inelastic dilation or damage). These permeability changes are due in part to deviatoric stresses, and may or may not be recoverable. The dramatic permeability changes observed in the DRZ are of this type, that is, they are due to microcracking and dilation.

A phenomenological model of permeability changes in rock salt resulting from damage has been developed by Stormont et al. (1992). The model begins with the equivalent channel model, which gives the permeability as a function of the porosity, hydraulic radius (flow path aperture) and empirical constants. The permeability model is recast in terms of easily calculated or measured quantities, i.e., stress and strain. The model parameters are developed from permeability measurements during quasi-static compression tests. Predictions of permeability changes are made by incorporating this model into a time-independent plasticity finite element code.

When compared to in situ measurements, this model is found to somewhat underpredict the permeability of the rock salt in the DRZ.

In this paper, we extend the model of Stormont et al. (1992) to include the effect of the pronounced time-dependency (creep) of rock salt. The model is modified in order to be incorporated into a time-dependent finite element code. The adequacy of the model is assessed by comparing simulation results with in situ measurements around an opening in bedded salt. The paper describes the theoretical derivation and numerical simulations for time-dependent changes of salt permeability. Agreement and discrepancies are discussed, and future development needs are recommended.

2 PERMEABILITY MODEL

Our model for permeability changes in rock salt is based on a series of measurements of gas permeability during quasistatic compression tests (Stormont and Daemen, 1992). The result of the deviatoric loading tests (CTC - conventional triaxial compression) can be summarized as follows. Initially, under hydrostatic stress, the rock salt has no measurable gas permeability. As the deviatoric load is increased, the permeability and porosity increase as a result of sliding and dilation along grain boundaries. Continued loading results in the growth and coalescence of the secondary tensile cracks. The pore structure is largely interconnected virtually as soon as the rock salt begins to dilate and as a result the gas-accessible porosity is equal to the dilation of rock salt. The pore structure of rock salt consists of narrow microcracks with large aspect (length to width) ratios (Stormont and Daemen, 1992).

From the equivalent channel model (e.g., Walsh and Brace, 1984), permeability k can be expressed as (Stormont, 1990a)

$$k = \frac{w^2 \phi^s}{b} \quad (1)$$

where w is the hydraulic radius, Φ is the porosity, s is related to the flow path tortuosity, and b is a constant related to the pore shape. For rocks in which the flow is through narrow channels such as microcracks, b is 3 (Wyllie and Spangler, 1952).

To link the predicted mechanical response and the permeability, Equation (1) must be cast in terms of calculable quantities (i.e., stress and strain). It was found that during CTC tests, the inelastic volume strain is nearly identical to the gas-accessible porosity because the pore structure which develops is largely interconnected (Stormont, 1990a). Therefore, changes in the porosity are taken to be equal to the calculated inelastic volume strain or dilation

$$d\phi = \varepsilon_v^{in} \quad (2)$$

The gas-accessible porosity of undisturbed rock salt is immeasurably small, so Equation (2) can be rewritten as

$$\phi = \varepsilon_v^{in} \quad (3)$$

Because the hydraulic radius (i.e., one-half of the flow path aperture) was not measured directly, w must be replaced with a measured parameter such as stress σ. The aperture of a microcrack is a nonlinear function of the stress across it (Goodman, 1976), and can be expressed as

$$w = Cp\ \sigma^{\lambda} \quad (4)$$

where Cp is a constant related to the deformability of the microcrack and λ is an (negative) exponent which accounts for the nonlinearity. For a three-dimensional state of stress, the most relevant stress measure which corresponds to σ is the minimum principal stress because microcracks, and consequently the flow paths, develop preferentially normal to this direction.

By substituting Equations (3) and (4) into Equation (1), the permeability is expressed as (Stormont et al., 1992)

$$k = A\sigma_3^{'\lambda'}(\varepsilon_v^{in})^s \quad (5)$$

where A is an empirical constant and λ' is equal to 2λ. σ' represents the nondimensionalized minimum principal stress, σ_3/P where P is a constant used to non-dimensionalize stress, here taken as 1 MPa.

The results of the CTC tests indicate that fundamentally different pore structure develop depending on the confining pressure. The original model of

Stormont et al. (1992) accounted for this by making both λ and s linear functions of the minimum principal stress. In this work, we found that a somewhat better back-fit to the laboratory data could be achieved with a constant value of λ and expressing s as a function of minimum principal stress (σ'), plastic transition pressure (P) and an empirical constant (n). When there is no dilation, the permeability is set to a default value which represents the permeability of the undisturbed rock salt. We use a value of 10^{-21} m^2 as this is about the lower limit of most laboratory and field measurements of rock salt permeability (Stormont et al., 1991).

Equation (5) has been implemented into the finite element code GEO. GEO is capable of describing elastic, viscoelastic, viscoplastic, strain-softening and dilation behavior of rock salt. The program carries out an explicit time-domain integration. The permeability, therefore, can be calculated for each element and each time step using the current values of $\sigma^{3'}$ and ε_v^{in}. Since σ'_3 and ε_v^{in} are updated for each time step, the change of salt permeability from one time step to another is due to the change of stress state and creep deformation and dilation.

The GEO model defines volumetric dilation as:

$$\varepsilon_v^{in} = F\{exp[C(\gamma_o-\gamma_c)/\gamma_c]^{-1}\}$$
$$exp[-H\sigma_m/(P-\sigma_m)] \ ; \ \gamma_o>\gamma_c \ and \ \sigma_m<P$$

where F, C and H are coefficients related to dilation, strain softening and confinement, respectively, γ_o and γ_c are induced and critical octahedral shear strains, σ_m is the mean stress, and P is the plastic transition pressure. Detailed formulation of the constitutive equation and the finite element code GEO is given elsewhere (Serata et al., 1991; Serata and Fuenkajorn, 1993).

3 CALIBRATION OF MODEL PARAMETERS

The laboratory permeability-CTC test data are used to determine the numerical values for the coefficients in the permeability model and the volumetric dilation equation. Finite element analyses are performed to simulate the mechanical behavior and permeability changes during the CTC tests under confining pressures of 2.4, 4.1, 5.9 and 7.6 MPa. The elastic, viscoelastic, viscoplastic, and strength parameters for the simulations were those developed by Serata and co-workers (Serata et al., 1991; Serata and Fuenkajorn, 1991; Serata and Fuenkajorn, 1993). The back analysis is performed by adjusting the coefficients in the volumetric dilation function and permeability model until the results of the simulation agree as closely as possible with all the experimental results. The parameters which provide the best fit to the test data are given in Table 1.

Table 1. Model Parameters

Permeability parameters	
A	2 x 10^{-3} m^2
λ	3.9
n	40
P	41.3 mPa
Dilation parameters	
F	0.05
C	0.2
H	3.1
γ_c	0.0085
P	41.3 mPa

The volumetric strains from the simulations are compared with the test results in Figure 1. The simulated volumetric strain tends to overestimate the test results, particularly after the samples are deformed beyond 8 to 10% axial strain at the lower stress levels. Figure 2 compares the simulated permeabilities with the experimental results. Deviation of predictions from the permeability test results is usually less than an order of magnitude, except for those tested with a 7.6 MPa confining pressure. The variation of the measured permeability suggests that a realistic objective for the permeability model is to provide an order-of-magnitude estimate of permeability.

4 AN ASSESSMENT OF THE MODEL PREDICTABILITY

We constructed a finite element model to simulate the geometry, boundary loading conditions and history of Room D, a well-instrumented experimental WIPP drift. A hydrostatic pressure of 14.5 MPa is initialized into the model before excavation, which represents the assumed in situ stress state at a depth of about 600 m. It is assumed that the room is excavated instantaneously. The simulations extend from before excavation to 52 months after excavation (when in situ gas permeability tests were conducted). Detailed boundary and loading conditions for the Room D simulation are given elsewhere (Serata and Fuenkajorn, 1991).

Figure 3 provides a comparison of the permeability prediction and the in situ permeability test data measured at 52 months after excavation. The permeabilities are presented as a function of horizontal distance from the wall of Room D. A few meters away from the excavation, the gas permeability of the formation was below the resolution of the test system. A maximum value of the permeability, dependent on the test duration and conditions, is given in the figure in those cases when the permeability is below the test resolution. The model tends to overpredict the measured permeabilities, particularly near the room boundary. The model predicts that at a distance of 4.6 m and beyond, no dilation occurs and consequently the permeability is assumed to be the default value associated with undisturbed rock salt. This result is consistent with the gas permeability measurements in the rock salt at these locations being below the resolution of the measurement system.

The time-dependent behavior of the rock salt has very little impact on the predicted permeability. A prediction soon after excavation (<1 month) and at 52 months are virtually identical and overlie one another in Figure 3. This result is a consequence of the very strong dependence of the permeability on the amount of dilation. Because creep tends to reduce the deviatoric stresses, the greatest potential for such dilation occurs immediately upon excavation.

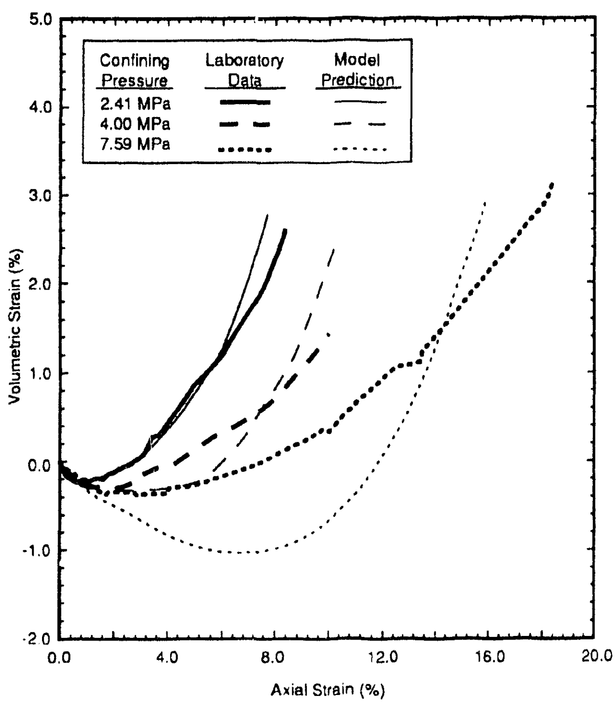

Figure 1. Volumetric strain as a function of axial strain, laboratory results versus prediction.

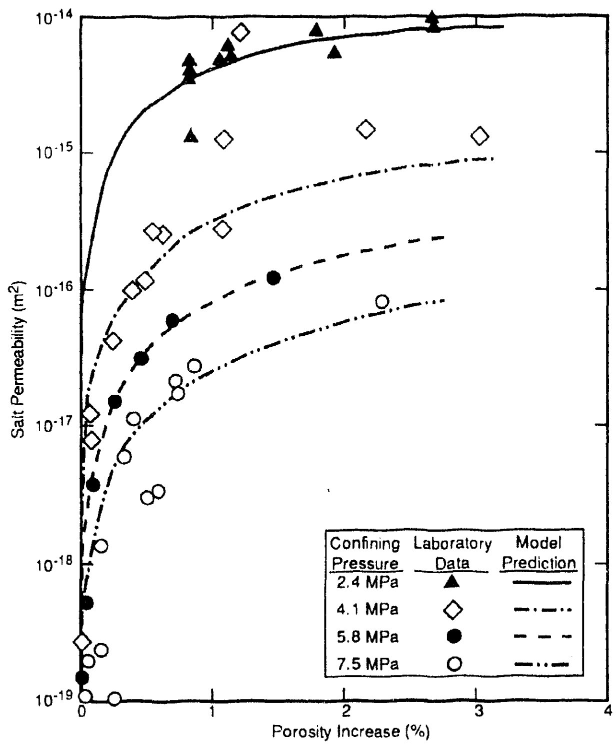

Figure 2. Permeabilities as a function of dilation, laboratory results versus prediction.

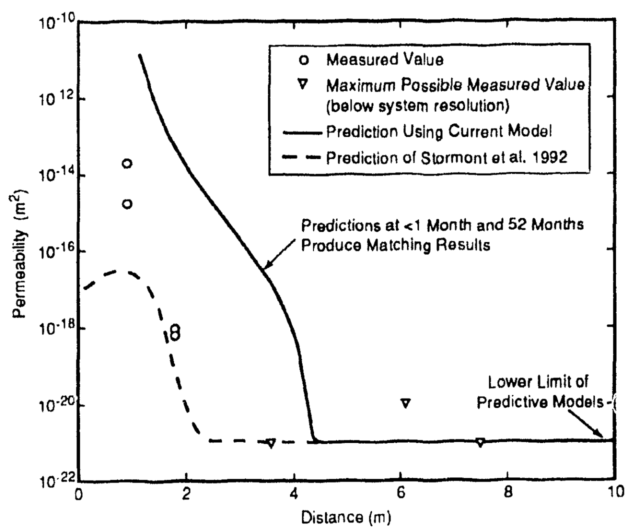

Figure 3. Comparison of permeability along permeability test borehole between model prediction (lines) and measurements.

The prediction using the quasi-static model of Stormont et al. (1992) is also given in Figure 3. This prediction is consistently lower than that based on Equation (4), attributable to a somewhat different form of the model and parameters. The two predictions bracket the experimental results. The discrepancies between the simulation and the in situ measurements may be caused by factors related to (1) the permeability model and parameters, (2) the mechanical model and parameters, and (3) details of the simulation (e.g., boundary and initial conditions, discretization). An improvement in the predictive ability of the model would result if both mechanical and permeability parameters were derived from tests conducted with loading paths more representative of that which the rock actually experiences. Permeability data for which the flow direction is normal to the direction of the minimum principal stress (i.e., normal to the majority of microcracks) are also desirable, primarily to investigate the degree of anisotropy of the dilation-induced permeability. Simulations which incorporate the periodic horizontal layers of anhydrite and clay may alter the stress-strain distribution in the rock and consequently the predicted permeability.

5 CONCLUSIONS

The proposed permeability model describes an increase in permeability of salt as a function of volumetric dilation, minimum principal stress, and plastic transition pressure. Implementation of the model into the finite element code where the volumetric dilation is calculated in an explicit time domain allows one to predict the time-dependent changes for salt permeability under various boundary and loading conditions. The representativeness of the model coefficients is speculative because they have been calibrated from a limited amount of test data with a relatively high intrinsic variability and under a narrow range of test conditions (loading path, stress rate, confining pressure). Laboratory data from a broader range of test conditions are needed to provide a more rigorous calibration for the coefficients.

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