COUPLED FLUID-FLOW MODELING OF BRINES FLOWING THROUGH DEFORMING SALT AROUND THE EXCAVATIONS FOR THE WASTE ISOLATION PILOT PLANT (WIPP), IN THE PERMIAN SALADO FORMATION*

M. Wallace, J. Pietz, J. Case, and D. Deal
International Technology Corporation
5301 Central Avenue, N.E., Suite 700
Albuquerque, NM 87108

B. Lauctes
Geoscience Consultants, Ltd
500 Copper Avenue, NW
Albuquerque, NM 87102

ABSTRACT

Small brine weeps have been observed on the exposed surfaces of the otherwise dry repository horizon excavations at the Waste Isolation Pilot Plant (WIPP). Furthermore, it is known that creep of the surrounding salt will enhance permeabilities and porosities in the region encompassing the excavations, offering the potential for increased brine inflow. This study is part of an ongoing effort through the Brine Sampling and Evaluation Program (BSEP) to evaluate the coupled processes of salt creep and brine inflow. The previous phase of this project involved the development of a comprehensive mathematical formulation of multiphase (brine and nitrogen), temperature-dependent flow through deforming rock. Aspects of that formulation were employed in the current implementation of a salt-creep brine-inflow simulator. The coupled processes were investigated through the integration of a finite element rock mechanics code with a finite element groundwater flow code. Preliminary analyses applied to a hypothetical circular excavation showed the development of a zone of disturbed rock having enhanced permeability and porosity. This development was accompanied by the outward propagation of an unsaturated zone. For the excavation geometry considered, the development of this unsaturated zone appears to be primarily sensitive to strain rates.

INTRODUCTION

The WIPP facility is located approximately 42 kilometers east of Carlsbad, New Mexico, and 655 meters underground in the bedded salt deposits of the Salado Formation, part of an evaporite sequence over 1000 meters thick. Although the excavations at the site are apparently dry, small amounts of brine have been observed to weep from exposed surfaces in the repository horizon and seep into boreholes in the underground excavations. These occurrences have been the focus of the Brine Sampling and Evaluation Program (BSEP) at the WIPP (4, 7). The assessment and understanding of the brine occurrences become important when considering what the long-term effects of brine seepage might be on the rates of resaturation and repressurization of the excavations after closure.

Excavations at the WIPP create openings at atmospheric pressure and the resulting pressure gradients induce fluids (contained in the salt) to flow toward the excavations. The excavation also creates a stress differential between atmospheric pressure and the virgin rock stress in the intact salt. This stress differential causes salt to creep into the excavations. Gases (mostly nitrogen) dissolved in the brine, exsolve and also move toward the excavation. The result is that excavation-induced flow of three phases (represented by salt, brine, and nitrogen) may occur simultaneously.

To a certain extent, the above phenomena are coupled. For example, the deformation of salt may change the permeability and porosity of the salt itself, which in turn results in fluid pressure changes. Fluid pressure in rock pores then affects stresses in the rock and consequently changes the salt creep rate (10). The presence of exsolving gas may couple with brine flow by providing a gas driving force for brine flow.

It is the objective of this study to formulate a coupled numerical model for the investigation of brine inflows to the underground repository. These simplifications take the form of several assumptions.

In the first assumption, the presence of fluid does not affect the creep rate or the elastic deformation of the rock; in other words, the effective stress acting on the rock is essentially equivalent to the total stress. This assumption is supported by the low porosity (.001) (8) of salt. In the second assumption, the steady state creep law is assumed to

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* Work supported by the U.S. Department of Energy Assistant Secretary for Defense Programs, Office of Defense Waste and Transportation Management, under DOE Contract No. DE-AC04-86AL31950

be an adequate model for salt creep. In the third assumption, all gas evolution and gas-driving forces on fluid flow are ignored. The precise gas content of the brine is not known, though estimates based on the solubility of nitrogen in sea water yield volume changes of 20 percent for a saturated brine that is depressurized (15).

To implement the model, a coupled finite element computer code was developed from two existing computer codes. The computer code is written in modular form such that if further refinements, such as modeling saturated/unsaturated fluid flow, become necessary, they can be easily accommodated. The two computer codes used were VISCOT (9) for salt creep modeling and SUTRA (1) for porous media fluid flow modeling.

In performing the pilot analysis described in this report, there are several key issues that are addressed to provide guidance in future modeling efforts. These include the development of the disturbed rock zone (DRZ) around the excavation, the relationship of rock strain to changes in porosity and permeability, and the nature of flow into the excavation cavity.

EQUATIONS FOR FLUID FLOW

The general fluid-flow equations were developed from the continuity equations and then expanded based on several proposed constitutive relationships, such as porosity versus stress.

The salt is assumed to be an equivalent porous media in which Darcy's law applies. Visual inspection of the repository walls and corners reveals obvious fractures. Without detailed information about fracture geometries and layouts, however, the more complicated fractured media approach may not provide greater accuracy than the equivalent porous media approach.

To describe the flow system for deforming media, both the fluid and the rock mass must be incorporated into the continuity Eq. (1) (11):

$$\frac{1}{\rho} \cdot \frac{\partial}{\partial x_i} \left[\frac{k}{\mu} \rho \left(\frac{\partial p}{\partial x_i} + \rho g_i\right)\right] = \phi \beta \frac{\partial p}{\partial t} + \frac{\partial}{\partial t} \left(\frac{\partial u_i}{\partial x_i}\right) \tag{Eq. 1.}$$

where:

ρ = Fluid density $[M/L^3]$,
ϕ = Rock porosity $(0 \le \phi \le 1)$,
t = Time $[T]$,
x_i = Distance $[L]$,
i = Coordinate index $(1,2,3)$
k = Permeability tensor $[L^2]$,
p = Pressure of fluid $[M/LT^2]$,
g = Gravitational acceleration $[L/T^2]$,
μ = Dynamic viscosity $[M/LT]$.
β = Compressibility of fluid $[LT/M]$, and
u_i = Displacement (elastic only) $[L]$.

Assuming that the pressure potential is large relative to the elevation potential at the repository horizon, one can neglect the pgi term. Then, given constant density and viscosity for a two-dimensional analysis, Eq. (1) simplifies to:

$$\frac{1}{\mu} \left[\frac{\partial}{\partial x} \left(\frac{k \partial p}{\partial x}\right) + \frac{\partial}{\partial y} \left(\frac{k \partial p}{\partial y}\right)\right] = \phi \beta \frac{\partial p}{\partial t} + \frac{\partial}{\partial t} \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y}\right) \tag{Eq. 2}$$

The second term on the right-hand side of the equation is defined as the source term, Qd, in Eq. (3).

where:

$$Q_d = \frac{\partial}{\partial t} \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y}\right) \tag{Eq. 3}$$

This term represents the time rate of change of elastic strain and represents the compression or expansion of the void space due to changes in stress, in the salt. For the unidirectional coupling used in this paper, this term in the flow equation was computed by the salt-creep module.

CONSTITUTIVE RELATIONS FOR CREEP DEFORMATION

Rock salt is known to be a rheologic material. Deformation of rock salt around underground excavations is dependent on time, stress, and temperature. Induced fractures in the vicinity of excavation rooms complicates the stress-deformation analysis. As a simplification, salt is analyzed as a continuum which follows the stress equilibrium and displacement-continuity conditions.

The finite-element code VISCOT (9), a two-dimensional nonlinear transient thermoviscoelastic and thermoviscoplastic code for modeling time-dependent viscous mechanical behavior of a rock mass was selected to simulate the rock deformation process. For this analysis, three sets of equations are needed; the equations of equilibrium, the displacement-continuity equations, and the stress-strain constitutive equations. The first two sets of equations apply to a general continuous media and are not presented here. The third set describes the stress-strain constitutive relations.

The constitutive relations for elastic deformation and secondary creep which encompass the stress-strain relations involve the following assumptions:

1. Elastic deformation occurs under hydrostatic compression,
2. Viscoelastic, time-dependent deformation is neglected,
3. Thermal elastic deformation is neglected since temperatures at the repository horizon are constant,
4. The yield stress for viscoplastic deformation is equal to zero, and
5. The influence of moisture and pore pressure on salt creep are neglected.

In this analysis, constitutive relations as given by Krieg (12) are used. These relations are well known and have been used in performing analyses such as the WIPP benchmark problem under isothermal conditions.

CHANGING POROSITY AND PERMEABILITY OF ROCK SALT

With the strain tensor calculated by VISCOT, it is desired to change strain components into volumetric change and update porosity of the deforming media. Reference 16 suggests Eq. (4) for volumetric change:

where:

$$\Delta V \doteq V_o(\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_1\varepsilon_2 + \varepsilon_2\varepsilon_3 + \varepsilon_3\varepsilon_1 + \varepsilon_1\varepsilon_2\varepsilon_3) \qquad \text{(Eq. 4)}$$

ε_1, ε_2, and ε_3 = Principal strains [L/L], and

V_o = Initial volume [L^3].

For infinitesimal strains, the higher order terms are small in Eq. (5).

$$\Delta V \doteq V_o \quad (\varepsilon_1 + \varepsilon_2 + \varepsilon_3) \qquad \text{(Eq. 5)}$$

$$\Delta V_v = \Delta V$$

Letting the volume of solids in a rock element be constant, we have in Eq. (6).

$$\phi = \frac{V_v}{V} = \frac{V_o\phi_o + \Delta V}{V_o + \Delta V} \qquad \text{(Eq. 6)}$$

where:

V = Volume of a rock element [L^3],

V_v = Volume of pores in the same rock element when strains are very small [L^3]

ϕ = Porosity, and

ϕ_o = Initial porosity.

For infinitesimal strains, Eq. (7) is used.

$$\phi \doteq \frac{\phi_o + (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)}{1 + (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)} \qquad \text{(Eq. 7)}$$

In the current model, it is assumed that only the elastic strains affect porosity. Although creep strains are assumed not to affect porosity, they will function to relax stresses near the excavation. To relate porosity with permeability for rock salt, the following Eq. (8) is suggested, which is obtained through laboratory tests (2):

$$\frac{\phi^3}{(1-\phi)^2} = \frac{k^a}{b} \qquad \text{(Eq. 8)}$$

where:

k = Intrinsic permeability [L^2],

a = Empirical constant, and

b = Empirical constant.

Lai's experimental tests were conducted in a high-pressure, triaxial cell with confining and seepage pressure held constant. Salt samples were prepared in the laboratory and were free of visible fractures. Due to experimental limitations, Eq. 8 probably does not completely describe the relationship between porosity and permeability found in the vicinity of a repository excavation. However, although it lacks field testing confirmation, this equation is suggested for the time being, subject to future modifications when better relationships between rock deformation and permeability are available.

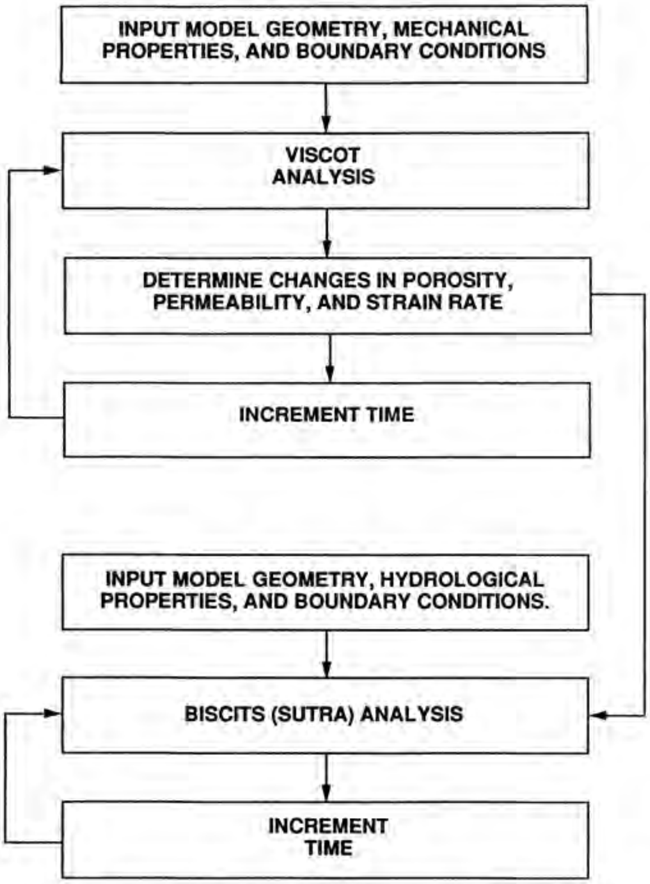

Fig. 1. Flowchart of Coupling Between Rock Mechanics

MODIFICATION OF SUTRA

SUTRA is a finite element code for fluid density-dependent groundwater flow simulations. In the current solution of the fluid flow problem, the conductance matrix must be continuously updated to account for changes in permeability and porosity in the disturbed zone. The coupling illustrated in Fig. 1 is in one direction; i.e., salt creep affects Qd and porosity, but changes in moisture content of the salt do not affect salt creep.

The numerical implementation of SUTRA for confined flow was manipulated by the authors to allocate all parameters but pressure on an element-wise basis. In addition, only the terms pertinent to this analysis were utilized. Furthermore, the strain term was substituted as an equivalent Qd term since it can be treated in the same sense as a source term. Porosities are also updated on each time step for each element as obtained from the VISCOT output. The modifications made to SUTRA were deemed significant enough to justify a new acronym, BISCITS (Brine-Inflow Salt-Creep Integrated Transient Simulator).

SAMPLE PROBLEM AND RESULTS

In order to demonstrate the current computer code capabilities and to perform a sensitivity study, an analysis of a circular opening in homogeneous salt was performed. The results of the analysis can be compared against closed form solutions for elastic/viscoplastic deformation. The results provide an indication of phenomenological behavior of the disturbed zone and its modification in space and time.

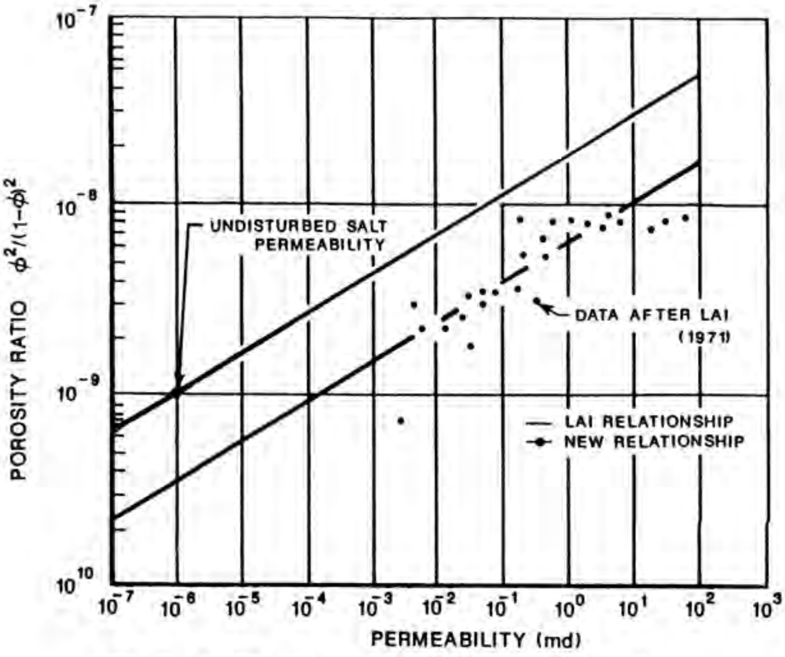

Fig. 2. Modification of Lai's Original Relationship.

The circular excavation has a radius of 1.8 meters, which corresponds approximately with the radius of the salt handling (SH) shaft. The analysis ignores the effects of surrounding excavations. The finite element model composed of 400 elements models one quadrant surrounding the excavation. The model utilized an initial lithostatic stress field corresponding to a depth of 671 meters. The initial stresses on the inner boundary were relaxed to zero over the first time step to simulate excavation.

For the fluid-flow analysis, the far-field and inner boundaries were fixed pressure boundaries. An initial hydrostatic pressure equal to a lithostatic pressure of 15 MPa was assumed. The inner boundary was fixed at atmospheric pressure.

The material properties for performing the coupled analysis include the elastic properties and secondary creep properties of the salt, the compressibility of the brine, and the best estimate for permeability of the undisturbed rock salt. Wherever possible, reference properties for the WIPP repository were used in the analysis.

Predictions of the zone of increased permeability at the WIPP have been made using the porosity-permeability relations modified (2).

$$\log \left[\frac{\phi^3}{(1-\phi)^2}\right] = a \log k - \log b \quad \text{or} \qquad \text{(Eq. 9)}$$

$$y = ax + B$$

where:

$$y = \text{Log} \left[\frac{\phi^3}{(1-\phi)^2}\right], \text{ and}$$

$$x = \text{Log } k.$$

If it is assumed that the empirical constant "a" which represents the slope in the above relation is the same as in Lai's experimental work (2), then the point slope equation can be used, assuming that for undisturbed salt the intrinsic permeability is 10-6 millidarcies at a porosity of 0.1 percent (8). This modification to Lai's original relationship is shown in Fig. 2.

It was anticipated that the stress analysis of the excavation for the circular opening should initially follow the elastic solution of Kirsch (13). At the excavation, the boundary or tangential stress should increase to approximately twice the value of the initial stress, while the radial stress should decrease to zero. In the absence of creep, this stress state would be maintained throughout time. However, in response to the high deviatoric stress, the salt will creep inward and the radial and tangential stresses will relax with time. The tangential stress will form a stress abutment zone in the salt. The stress abutment zone propagates radially outward with time. The elastic response to this changing stress produces changes in porosity and permeability.

Figure 3 illustrates the simulated concurrent stress and porosity distributions with time. Initially, a small increase in porosity occurs near the excavation. As boundary stresses relax and the stress abutment zone moves outward into the salt, a distinct zone of enhanced porosity develops. The maximum increase in porosity is approximately 40 percent over the undisturbed porosity.

The development of permeability with time is illustrated in Fig. 4. The far-field permeability is approximately 1.0 nanodarcy. At the earliest time shown, there is very little permeability enhancement. As salt creep relaxes the built up stresses, the sum of the strains is no longer zero, and porosity and permeability increase with time. Because only

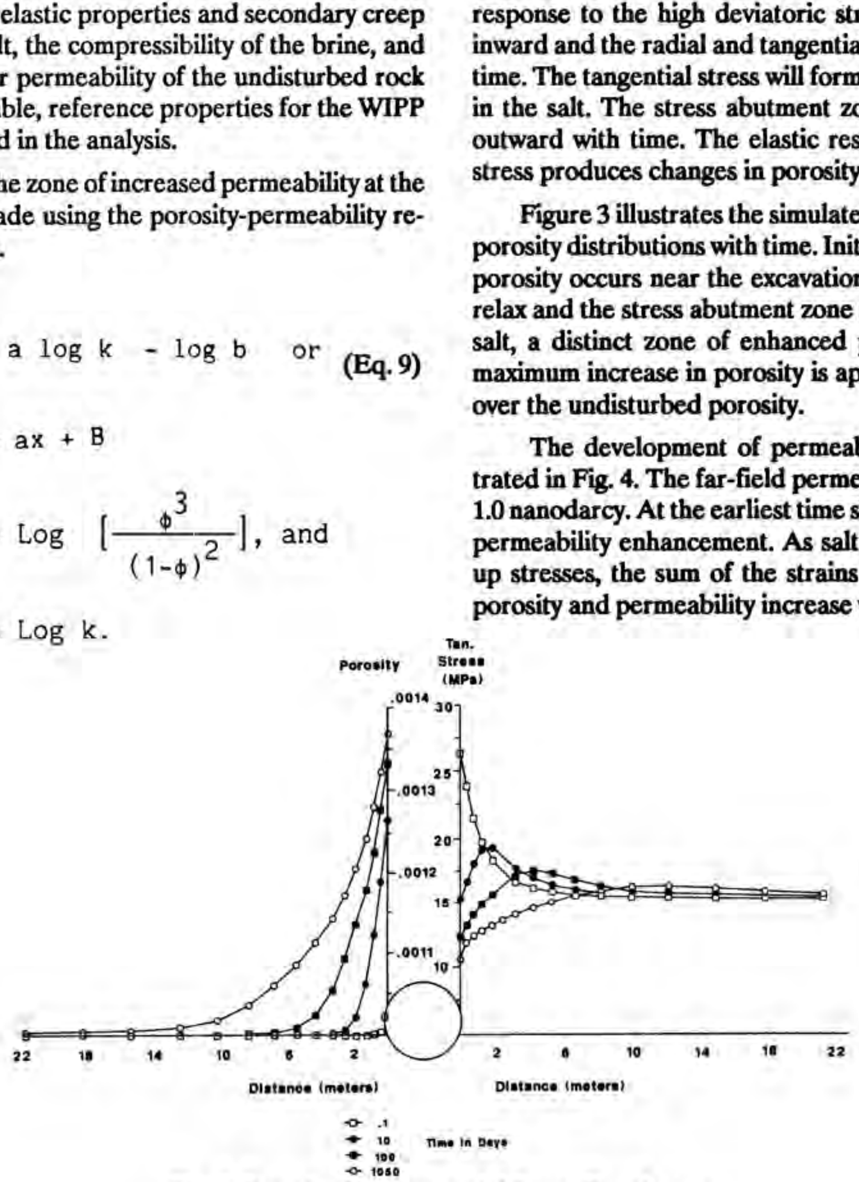

Fig. 3. Porosity and Tangential Stress Development

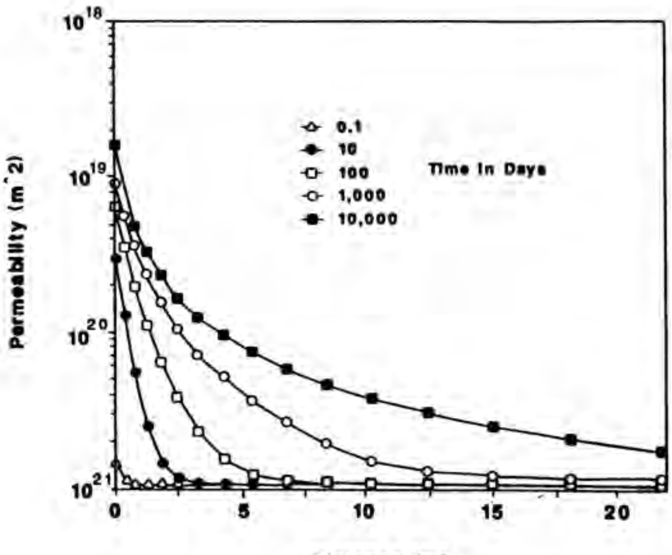

Fig. 4. Development of Permeability with Time.

changes in permeability in the model may be chiefly attributed to changes in tangential stress.

Following 1,000 days, at a distance of 12 meters from the excavation, the model predicts insignificant increases in porosity and permeability. The trend of the predicted permeabilities appears to agree reasonably well with in situ measurements. The model predicts a radius for the DRZ of approximately 12 meters for a circular excavation. The data (8) suggest a radius for the DRZ of approximately ten meters, while the data (6) describe the DRZ radius as approximately one to five meters. The radius of the DRZ may be dependent on the size and geometry of the excavation.

Shortly after the base case simulation begins, pressure values for nodes near the excavation opening drop to near atmospheric. These results suggest the development of an unsaturated zone near the excavation. This may be a consequence of the increases in porosity due to stress relaxation, the relative impermeability of the salt, and the inability of fluid flow and fluid expansion to fill the void space. This conclusion was borne out in subsequent parametric analyses.

Furthermore, observations of moisture content suggest that unsaturated conditions do exist within at least the first five meters of the salt (6). The extent of propagation of this zone is not possible to predict with the current model, since it was not designed to simulate variably saturated (or multiphase) flow. However, the parametric analyses have shown that when strain rates are several orders of magnitude lower than the maximum predicted rates, desaturation does not occur.

Strain rates are the only parameters in the analyses which vary significantly with time or distance. Therefore, their distribution in time and space likely play a singular role in determining the ultimate extent of the unsaturated zone. One could conclude by this that the unsaturated zone would extend no further than the boundary of substantial strain rates. That boundary is coincident with the boundary of the disturbed rock zone, which as implied in Fig. 3, extends approximately on the order of 10 meters into the host rock. Beyond that radius, the rock may remain saturated with brine.

SUMMARY OF MAJOR LIMITATIONS AND ASSUMPTIONS

This exercise was not an effort to derive a totally new code based on a global derivation such as that of Niou and Deal (14), but rather was an attempt to couple two existing codes to obtain an initial feel for the effects of deformation of initially very impermeable salt on the flow of brine to a segment of a circular shaft with a radius of 1.8 meters, excavated at a depth of 655 meters. The results are constrained by limitations that exist in both codes and in the assumptions necessary to couple them. The following limitations and assumptions apply:

1. Volumetric deformations do not significantly affect model geometry. Both models (VISCOT and SUTRA) are fixed-grid models.
2. The governing equation for fluid flow is taken from the soil consolidation equation of Huyakorn and Pinder (11), in which changes in local strain affect fluid pressure.
3. Effective stress equals total stress in the rock. The porosity is so small in the deforming salt that the change in pore pressure is assumed not to affect total stress. This allows unidirectional coupling from VISCOT to SUTRA, eliminating the need to input the change in pore pressure from SUTRA into each iteration run of VISCOT.
4. Only elastic strain (no plastic strain) is considered in the calculation of changes in porosity.
5. Elastic strain of the salt is entirely converted to change in porosity.
6. The rock is assumed to be saturated with fluid.
7. Creep strain (plastic deformation) is included in the stress state calculated by VISCOT and although it indirectly affects the magnitude of Qd through the

relief of stress, the plastic strain is not directly considered in calculating porosity.

8. Permeability is calculated from a relationship derived from the empirical relationship found by Lai (2), that was modified to more closely simulate the salt at the WIPP.
9. Neither microfracture nor macrofracture porosity were considered.

CONCLUSIONS AND RECOMMENDATIONS

This work has described a coupled model for the simulation of salt creep and fluid flow for the near-term. After excavation of the circular opening, the tangential stress predicted by the model is equal to the stress given by the elastic Kirsch solution. Salt creep serves to relax this stress buildup, and the relaxation of this stress buildup causes the propagation of a stress abutment zone into the salt. This stress abutment zone in turn causes elastic deformation of the salt, which is assumed to increase porosity and permeability.

The model results appear to concur with measured results in two important areas. First, a radius of 10-12 meters for the disturbed rock zone appears roughly to correspond to the radius indicated by permeability measurements conducted by Peterson et al. (7) and DRZ measurements conducted by Borns and Stormont (6). Secondly, the modification of Lai's empirical relationship appears to accurately predict the trend of the permeabilities as measured by Peterson et al. (7). From this standpoint, the assumed relationship between elastic strain and porosity, where all of the elastic strain is converted into porosity, appears to yield at least a qualitative fit to the observed permeabilities and radius for the DRZ.

For the base case simulation using reference properties, the model results show the development of an unsaturated zone near the excavation. This unsaturated zone results from an increase in void volume and the inability of the fluid to flow and expand into the new void volume within the time frame of the simulation. A sensitivity analysis has shown that strain rates play a singular role in determining the extent of the unsaturated zone. Therefore, it is possible that the unsaturated zone does not extend substantially beyond the DRZ.

Future work may involve the construction of a grid which includes heterogeneities of the salt, as well as more realistic room geometries. Were it desired to more closely follow the theoretical development of Niou and Deal (14), further enhancements of the code system could include more elaborate relationships of stress-strain-porosity-permeability and the multiphase flow of brine, nitrogen gas, and the salt rock itself.

REFERENCES

1. C. I. VOSS, "SUTRA Saturated-Unsaturated Transport: A Finite-Element Simulation Model for Saturated-Unsaturated, Fluid-Density-Dependent Ground-Water Flow With Energy Transport or Chemically-Reactive Single-Species Solute Transport," U.S. Geological Survey Water Resources Investigations Report 84-4369, prepared in cooperation with U.S. Air Force Engineering and Services Center, Washington, D.C (1984).
2. C. S. LAI, "Fluid Flow Through Rock Salt Under Various Stress States," Ph.D. Dissertation, Michigan State University, East Lansing, Michigan (1971).
3. D. E. DEAL, "Brine Seepage into the Waste Isolation Pilot Plant (WIPP) Excavation," Proceedings of Waste Management '88, Vol. II, Tucson, Arizona, pp. 649-657 (1988).
4. D. E. DEAL and J. CASE, "Brine Sampling and Evaluation Program, Phase I Report, June 1987," DOE-WIPP-87-008, prepared for the U.S. Department of Energy by International Technology Corporation and Westinghouse Electric Corporation (1987).
5. D. E. DEAL and W. M. ROGGENTHEN, "The Brine Sampling and Evaluation Program (BSEP) at WIPP: Results of Four Years of Brine Seepage Data," Proceedings of Waste Management '89, Tucson, Arizona (1989).
6. D. J. BORNS, and J. C. STORMONT, "An Interim Report on Excavation Effect Studies at the Waste Isolation Pilot Plant: The Delineation of the Disturbed Rock Zone," SAND87-1375, Sandia National Laboratories, Albuquerque, New Mexico (1988).
7. E. W. PETERSON, P. L. LAGUS, and J. C. STORMONT, "Permeability Measurements at the Waste Isolation Pilot Plant (WIPP)," Proceedings of the Waste Management Symposium, Tucson, Arizona (1986).
8. E. W. PETERSON, P. L. LAGUS, and K. LIE, "WIPP Horizon In Situ Permeability Measurements Final Report," SAND85-7166, Sandia National Laboratories, Albuquerque, New Mexico (1985).
9. INTERA Environmental Consultants, Inc., "VISCOT: A Two-Dimensional and Axisymmetric Nonlinear Transient Thermoviscoelastic and Thermoviscoplastic Finite-Element Code for Modeling Time-Dependent Viscous Mechanical Behavior of a Rock Mass," ONWI-437, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio (1983).
10. J. B. CASE, P. C. KELSALL, and J. L. WITHIAM, "Laboratory Investigation of Crushed Salt Consolidation," Proceedings of the 28th U.S. Symposium on Rock Mechanics, Tucson, Arizona, pp. 189-196 (1987).

11. P. S. HUYAKORN and G. F. PINDER, Computational Methods in Subsurface Flow, Academic Press, New York, 473 pp. (1983)

12. R. D. KRIEG, "Reference Stratigraphy and Rock Properties for the Waste Isolation Pilot Plant (WIPP) Project," SAND83-1908 (1983).

13. R. E. GOODMAN, Introduction of Rock Mechanics, John Wiley & Sons, New York, 478 pp. (1980)

14. S. NIOU and D. E. DEAL, "Migration of Brine and Nitrogen in Creeping Salt," Proceedings of Waste Management '89," Vol. I, Tucson, Arizona, pp. 329-404 (1989).

15. W. ROGGENTHEN, "Solubility of Nitrogen in WIPP Brines," International Technology Corporation Memorandum, Albuquerque, New Mexico (1988).

16. Y. C. FUNG, Foundations of Solid Mechanics, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1965).