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# MECHANICAL ANALYSES OF WIPP DISPOSAL ROOMS BACKFILLED WITH EITHER CRUSHED SALT OR CRUSHED SALT-BENTONITE

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## ABSTRACT

Numerical calculations of disposal room configurations at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM are presented. Specifically, the behavior of either crushed salt or a crushed salt-bentonite mixture, when used as a backfill material in disposal rooms, is modeled in conjunction with the creep behavior of the surrounding intact salt. The backfill consolidation model developed at Sandia National Laboratories was implemented into the SPECTROM-32 finite element program. This model includes nonlinear elastic as well as deviatoric and volumetric creep components. Parameters for the models were determined from laboratory tests with deviatoric and hydrostatic loadings. The performance of the intact salt creep model previously implemented into SPECTROM-32 is well documented.

Results from the SPECTROM-32 analyses were compared to a similar study conducted by Sandia National Laboratories using the SANCHO finite element program. The calculated deformations and stresses from the SPECTROM-32 and SANCHO analyses agree reasonably well despite differences in constitutive models and modeling methodology. These results provide estimates of the backfill consolidation through time. The trends in the backfill consolidation can then be used to estimate the permeability of the backfill and subsequent radionuclide transport.

## 1.0 INTRODUCTION

The U. S. Department of Energy is planning to dispose of transuranic wastes (TRU) at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. The current mission of the WIPP is to provide a research and development facility to demonstrate the safe management, storage, and disposal of TRU wastes generated by U. S. government defense programs. Sandia National Laboratories is conducting procedural and technical activities to assess WIPP compliance with regulatory requirements. Performance of seal, barrier, and backfill materials is being studied as part of these activities. A key candidate component of the room backfill system is crushed salt. Crushed salt is an attractive backfill material because it is readily available from the mining operations, it is compatible with the host rock, and it is expected to reconsolidate into a low permeability mass comparable to the intact salt as a result of the creep closure of the surrounding rock mass. Therefore, an understanding of the mechanical behavior of backfill is important at the WIPP. Optimization of the backfill emplacement is necessary to promote room stability, to enable sufficient backfill consolidation to reduce brine flow and retard the transport of soluble radionuclides, and to maintain sufficient gas permeability to avoid gas pressurization [1].

The study presented herein was conducted to investigate the consolidation of crushed salt and a crushed salt-bentonite mixture in disposal room configurations at the WIPP. Numerical simulations of the backfill and creeping host rock system to 200 years were performed. The finite element program, SPECTROM-32 [2], was modified [3] to incorporate a crushed salt consolidation model [4]. The model selected for implementation combines nonlinear elastic behavior and volumetric creep consolidation. The creep consolidation model was modified to include a deviatoric component. Results from these analyses are compared to results from similar analyses obtained with the finite element program SANCHO [5]. A notable difference between the two codes is that the SANCHO finite element program is based on finite strain theory and the SPECTROM-32 finite element program is based on infinitesimal or small strain theory.

## 2.0 PROBLEM DESCRIPTION

### 2.1 Problem Parameters

The basic problem parameters consist of the room and pillar geometry, depth of the room, mesh refinement of the modeled region, temperature, and boundary conditions (see Figure 2-1). Except for a variation in the mesh refinement, the basic problem parameters in the SPECTROM-32 analyses are identical to the SANCHO analyses. The total strain rates in the crushed salt and the intact salt were assumed to be the sum of elastic and inelastic components as discussed in the next sections. The initial state of stress in the SPECTROM-32 analyses was established by excavating the room instantaneously into an initially lithostatic stress field. Subsequently, the room was assumed to be completely backfilled with either crushed salt or crushed salt-bentonite.

### 2.2 Backfill Consolidation Model

Development of the creep consolidation constitutive equation used in SPECTROM-32 was guided by general considerations with specific functional forms taken from empirical relations matched to available laboratory data. From the application of thermodynamic concepts, the three-dimensional generalization for creep strain rates is given by [6]. Following this approach, two continuum internal variables were assumed, the average inelastic volumetric strain, $\epsilon^c_{eq_1}$, and the average equivalent inelastic shear strain, $\epsilon^c_{eq_2}$.

$$\dot{\epsilon}^c_{ij} = \dot{\epsilon}^c_{eq_1} \frac{\partial \sigma^f_{eq_1}}{\partial \sigma_{ij}} + \dot{\epsilon}^c_{eq_2} \frac{\partial \sigma^f_{eq_2}}{\partial \sigma_{ij}} \qquad (1)$$

For the volumetric portion of Equation 2-1, the invariant strain-rate measure is

$$\dot{\epsilon}^c_{eq_1} = \dot{\epsilon}_v \left(\sigma_m\right) \qquad (2)$$

The sign convention adopted assumes that tensile stresses and elongation (dilation) are positive. The volumetric strain rate $\dot{\epsilon}^c_v$ is described empirically [4] based on laboratory test data on hydrostatic consolidation of crushed salt as

$$\dot{\epsilon}^c_v = \frac{\left(1 + \epsilon_v\right)^2}{\rho_0} B_0 \left[1 - e^{-B_1 \sigma_m}\right] e^{\frac{A \rho_0}{1 + \epsilon_v}} \qquad (3)$$

where

$$
\begin{aligned}
\epsilon_v &= \epsilon_{kk}, \text{ total volumetric strain} \\
\epsilon_v^c &= \epsilon_{kk}^c, \text{ volumetric creep strain} \\
\sigma_m &= \tfrac{\sigma_{kk}}{3}, \text{ mean stress} \\
\rho_0 &= \text{initial density} \\
B_0, B_1, A &= \text{material constants.}
\end{aligned}
$$

The invariant stress measure is given by

$$\sigma^f_{eq_1} = \sigma_m \tag{4}$$

For the deviatoric portion of Equation 2-1, the invariant strain-rate measure is taken to be

$$\dot{\epsilon}^c_{eq_2} = \beta \dot{\epsilon}^c_{eq_1} = \beta \dot{\epsilon}_v (\sigma_m) \tag{5}$$

and the invariant stress is assumed to be a scalar multiple of the octahedral shear stress

$$\sigma^f_{eq_2} = \sigma_e = \sqrt{3J_2} \tag{6}$$

where $J_2$ is the second invariant of the stress deviator ($J_2 = \frac{1}{2}S_{ij}S_{ij}$). Substituting into Equation 2-1 and performing the required differentiation gives

$$\dot{\epsilon}^c_{ij} = \dot{\epsilon}^c_v \frac{\delta_{ij}}{3} + \beta \dot{\epsilon}^c_v \frac{3S_{ij}}{2\sigma_e} \tag{7}$$

$\beta$ is selected such that in a uniaxial test the lateral components of $\dot{\epsilon}^c_{ij}$ equal zero. This requires that $\beta = -\frac{2}{3}$. After substituting for $\dot{\epsilon}^c_v$ in Equation 2-7, the strain rate components are given by

$$\dot{\epsilon}^c_{ij} = \frac{(1+\epsilon_v)^2}{\rho_0} B_0 \left[1 - e^{-B_1\sigma_m}\right] e^{\frac{A\rho_0}{1+\epsilon_v}} \left\{\frac{\delta_{ij}}{3} - \frac{S_{ij}}{\sigma_e}\right\} \tag{8}$$

Obviously, this creep consolidation equation will allow unlimited consolidation. Therefore, a cap is introduced that eliminates further consolidation when the intact material density $\rho_\infty$ is reached. As an option, the crushed salt material may behave either as a nonlinear elastic material or creeping intact salt following complete consolidation.

## 2.3 Intact Salt Constitutive Model

A recently proposed WIPP reference constitutive relation for intact salt creep [7] and the previous WIPP reference law [8] were used in the calculations. The WIPP reference elastic-secondary creep model [8], along with a Mises-type flow potential, represented the mechanical behavior of the intact salt in the SANCHO analyses. The SPECTROM-32 analyses used the Munson-Dawson constitutive relation [7] for intact salt creep along with a Tresca flow potential. This combination was recommended [7] because of favorable comparisons with WIPP field tests in a previous study [9].

## 2.4 Elastic Model

The elastic models used in the SPECTROM-32 and SANCHO analyses were identical. The crushed salt was described using a nonlinear elastic model [3, 4] and the intact salt was assumed to be linear elastic. However, corresponding elastic material constants for crushed salt and intact salt used in the SANCHO analyses were reduced by a factor of 12.5 [5]. This reduction in elastic properties stems from a recommendation [10] that is based on the usage of the early version of the reference constitutive relation for salt creep [7] that produced good agreement between calculated and measured deformations of WIPP field experiments. Since test data do not exist for crushed salt-bentonite mixtures, its elastic properties were assumed to be identical to those of crushed salt. Specific values for the elastic constants may be found in references 3, 4, and 11.

# 3.0 RESULTS

Results from the SPECTROM-32 analyses of the disposal room backfilled with either crushed salt or crushed salt-bentonite are compared to previously reported results using the SANCHO finite element program [5]. Results from the SANCHO analyses were plotted by digitizing the graphical results.

## 3.1 Room Closures

Figure 3-1 compares the SPECTROM-32 and SANCHO vertical and horizontal closures along the room periphery corresponding to the roof/floor centerline and the rib midheight, respectively. During the initial 15 years, the closures predicted by SPECTROM-32 are greater and, thereafter, are less than the closures predicted by SANCHO. The closure curves from both analyses for crushed salt backfill are nearly flat after the density of the crushed salt reaches the density of the intact salt. This behavior is not exhibited for the crushed salt-bentonite analyses since full compaction is not reached. Generally, agreement in the calculated deformations from the SPECTROM-32 and SANCHO analyses is within 10 percent (except when the crushed salt becomes fully consolidated) despite distinct differences in the constitutive relations, mesh refinement, material constants, and theoretical basis (finite versus small strain).

## 3.2 Average Void Fractions

Figure 3-2 provides the time history of the average void fraction remaining in the backfill. The average void fraction [5] is essentially a measure of porosity in the backfill. The trend and magnitude of the average void fractions from both codes in the two analyses agree closely during the initial 5 years. Thereafter, the rate of consolidation is considerably slower in both SANCHO analyses. The crushed salt backfill consolidates completely in 25 years in the SPECTROM-32 analyses; whereas, the corresponding consolidation takes 65 years in the SANCHO analyses. Full consolidation of the crushed salt-bentonite backfill is not reached in either the SPECTROM-32 or SANCHO analyses. The average void fraction remaining in the crushed salt-bentonite backfill after 200 years of simulation is 5.0 and 7.5 percent for SPECTROM-32 and SANCHO analyses, respectively.

### 3.3 Mean Stresses

Comparison of mean stress (pressure) is of interest since mean stress is the driving force in the backfill consolidation process. Figure 3-3 shows the mean stress history corresponding to the center of the disposal room. During the initial 5 years, pressure rise in the crushed salt is negligible throughout the disposal room. Over the next 50 to 75 years, the magnitude of the mean stress increases more rapidly in the SPECTROM-32 analyses than the SANCHO analyses. This response is indicative of the deformational behavior plotted in Figures 3-1 and 3-2 which show that closure (consolidation) occurs more rapidly in the SPECTROM-32 analyses. The cusps appearing in Figure 3-3 occur after full consolidation of the crushed salt. At this point, the consolidation process ceases. Cusps do not appear in the crushed salt/bentonite curves because full consolidation is not reached within the 200 year simulation period as shown by Figure 3-2. Mean stresses determined in the SPECTROM-32 analyses are 2 to 4 time greater than the mean stresses determined in the SANCHO analyses during the initial 80 years and only 1 to 1.5 greater in the final 100 years. This difference can be attributed to more than an order of magnitude difference in the elastic constants used in the two codes with the SPECTROM-32 constants being the greater of the two. Despite some disparity in magnitude, the trends of the mean stress determined from the two analyses compare favorably. Both analyses of crushed salt backfill show a significant increase in mean stress once full compaction is reached.

## 4.0 CONCLUSIONS

Based on the comparison of results from the SPECTROM-32 and SANCHO analyses of a disposal room backfilled with crushed salt and crushed salt-bentonite, void fractions in the backfill material are shown to decay significantly such that the backfill becomes an integral part of the sealing system. The creep consolidation model provides a method to estimate the long-term behavior of backfill materials in a disposal room. The calculated deformations and stresses from the two analyses agree reasonably well despite differences in methodology such as the consolidation model, intact salt creep model, strain theory, and material properties. The volumetric behavior of the backfill is based on hydrostatic laboratory tests, but the deviatoric response included is hypothetical. Deviatoric testing of crushed salt specimens is presently underway. Data obtained from these tests will be used to refine the deviatoric response included in the crushed salt constitutive model.

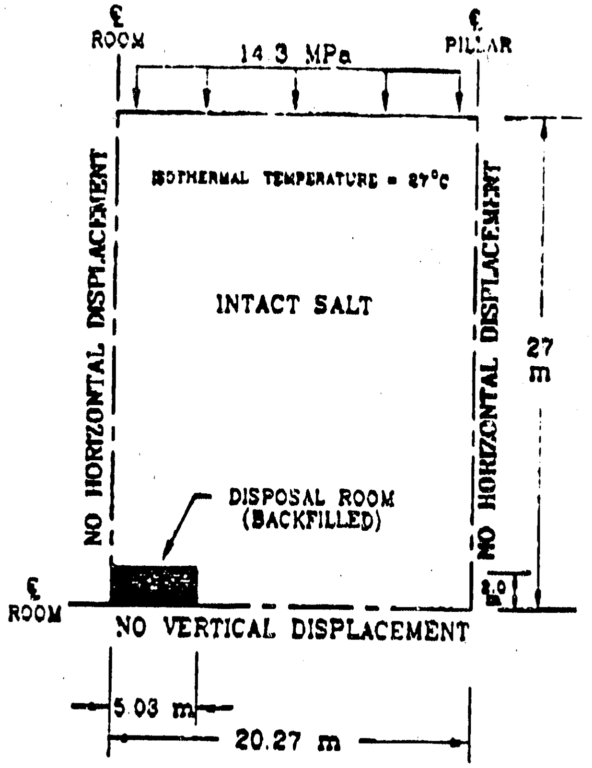


Figure 2-1. Description of Basic Problem Parameters.

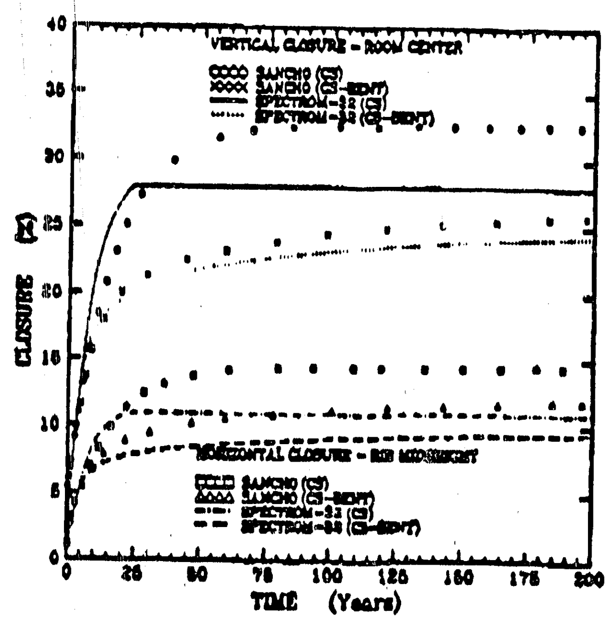


Figure 3-1. Vertical and Horizontal Room Closures for a Backfilled Disposal Room.

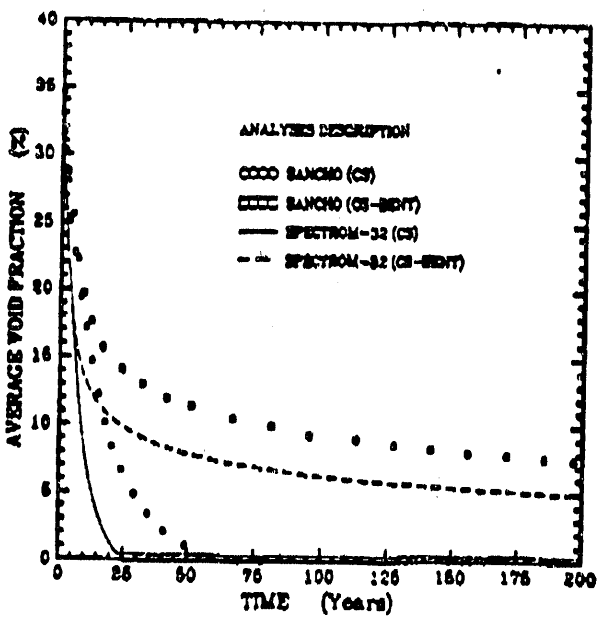


Figure 3-2. Average Void Fraction for a Backfilled Disposal Room.

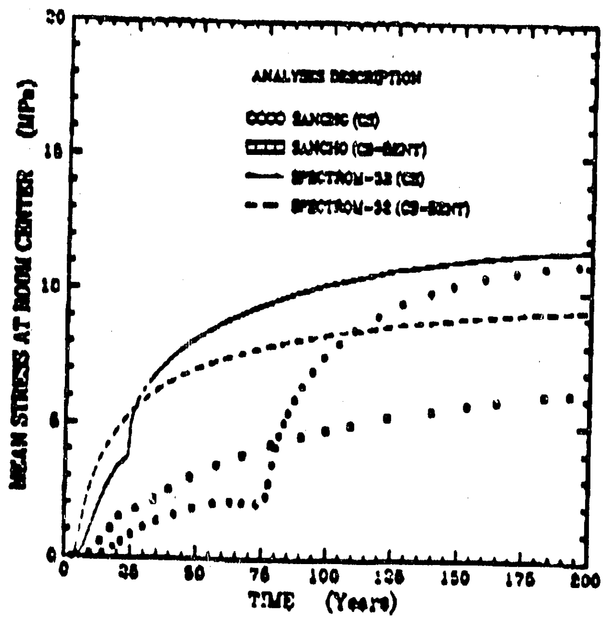


Figure 3-3. Mean Stress (Pressure) at the Center of a Backfilled Disposal Room.

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