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Investigation of an empirical creep law for rock salt that uses reduced elastic moduli

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1 INTRODUCTION

Early attempts to predict the creep response of rock salt around underground rooms at the Waste Isolation Pilot Plant (WIPP) produced closure estimates that were one-third to one-fourth of values measured in situ (Morgan et. al., 1985). A subsequent study (Morgan, et. al., 1986) of the WIPP reference elastic secondary creep model (Krieg, 1984) used to make these predictions revealed that room closures and even closure rates could be increased by reducing the elastic constants. This study also indicated that a vertical cylindrical shaft configuration could be substituted for more complicated and expensive rectangular room configurations in studying constitutive parameters for rock salt. Sjaardema and Krieg (1986) used these results to determine how much the WIPP reference value of Young's modulus E had to be reduced to increase the creep closure and closure rate of a hypothetical borehole in rock salt by factors of 3.5 to 4. They found that E had to be divided by 12.5 to produce the desired results.

Motivation for this empirical "fix" to the creep model was to provide realistic room closures in examining the consolidation of crushed salt, a proposed backfill for rooms at the WIPP. The empirical model was not intended to replace more scientifically based models for predicting the creep response of rock salt. Instead it was an expedient that allowed crushed salt investigations to proceed while other creep models were being improved. However, the empirical model was subsequently used to predict the response of several different WIPP room configurations, and the resulting closure estimates were surprisingly good when compared to field measurements (Munson et. al. 1986, Morgan & Krieg, 1988). Consequently, the model has received more use than was originally intended, and various hypotheses have been made as to why it produced such good results. One hypothesis was that damaged or microcracked rock, known to exist near the surfaces of WIPP excavations (Borns & Stormont, 1989), dominated room closure, and the reduced elastic modulus captured its behavior. Other speculation implied that the degraded modulus increased the elastic strains in the salt mass remote from room surfaces to such an extent that the integrated effect produced the increased closures. However, none of these hypotheses explained the observation that the moduli reductions increased *closure rates* as well as closures.

In this paper, we present the results of shaft calculations, similar to those used by Sjaardema and Krieg, to investigate why dividing E by 12.5 "works." The goal of this investigation is not to justify or promote the empirical model, but instead to explore possible physical phenomena that it captures better than the WIPP reference and other

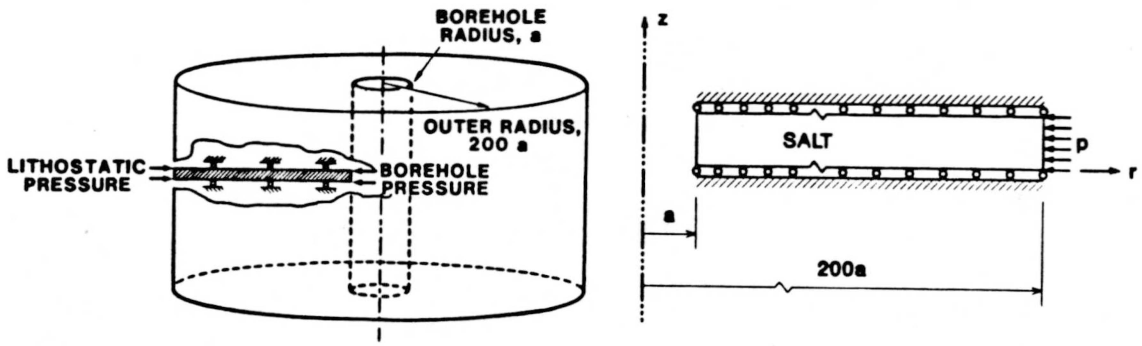

Figure 1. Structural model of a vertical shaft in rock salt.

creep models. This in turn is intended to give direction to improving more scientifically based models. The shaft calculations indicate that the empirical model and the WIPP reference model produce different unloadings of salt near an underground openings. This result leads to a study of each model's abililty to predict the unloading behavior observed in a laboratory stress relaxation test. The paper concludes with a comparison of shaft closures computed with two unified creep plasticity (UCP) models, one with parameters determined from a fit to only constant stress laboratory creep data and the other with parameters obtained by fitting laboratory stress relaxation data in addition to the creep data.

2 SHAFT GEOMETRY AND BOUNDARY CONDITIONS

The geometrical idealization of the hypothetical shaft used in this study is shown in Figure 1. In this model, a circular hole of radius a is assumed to be drilled vertically into a semi-infinite mass of rock salt which is represented by a hollow cylinder with an outer radius that is 200 times larger than a. The value of the outer radius is arbitrary but should be chosen large enough to prevent creep displacements at the inner surface from being influenced by the location of the outer boundary. For the problems examined here, an outer radius of $200a$ is large enough. Axially, the cylinder is assumed to be in a state of plane strain so only a thin axisymmetric strip of finite elements, with vertical displacements constrained on the top and bottom surfaces, is needed to determine creep displacements at the borehole surface. Here both the inner radius of the borehole and the height of the strip are assumed to be 1 m. Lithostatic pressure p at the depth of interest is applied as an initial isotropic stress field everywhere in the salt and also as the boundary condition at the outer surface of the cylinder. For this study p has a value of 15 MPa, the approximate lithostatic pressure at the working horizon of the WIPP. The inner surface of the hollow cylinder is stress free, and the shaft is assumed to be excavated instantaneously.

3 REFERENCE ELASTIC SECONDARY CREEP MODEL FOR WIPP ROCK SALT

The WIPP elastic secondary creep law is used as the constitutive model for the salt. In this model, the components of the total strain rate $\dot{\epsilon}_{ij}$ can be expressed, using conventional summation notation (with indices from 1 to 3), in terms of the stress rate components $\dot{\sigma}_{ij}$ as

$$\dot{\epsilon}_{ij} = -\frac{\nu}{E}\,\dot{\sigma}_{kk}\,\delta_{ij} + \frac{1+\nu}{E}\,\dot{\sigma}_{ij} + \dot{\epsilon}^c_{ij} \tag{1}$$

where E is again Young's modulus , ν is Poisson's ratio, and δ_{ij} is the Kronecker delta. The first two terms in this equation represent the elastic contribution to the total strain rate. The inelastic component $\dot{\epsilon}^c_{ij}$ is purely deviatoric and is composed of only the secondary creep strain rate. Von Mises flow is assumed so $\dot{\epsilon}^c_{ij}$ can be expressed in terms of the equivalent secondary creep strain rate $\dot{\bar{\epsilon}}^c$, the deviatoric stress components, $s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}$, and the equivalent von Mises stress, $\bar{\sigma} = \sqrt{1.5 s_{pq}s_{pq}}$, as $\dot{\epsilon}^c_{ij} = 1.5\dot{\bar{\epsilon}}^c s_{ij}/\bar{\sigma}$ where

$$\dot{\bar{\epsilon}}^c = A\,\bar{\sigma}^n \exp\left(\frac{-Q}{R\theta}\right) \tag{2}$$

In Equation 2, θ is the absolute temperature, and R is the universal gas constant (1.987 cal/mole·K). The parameters A, n, and Q are determined from fitting this expression to secondary creep data, and for WIPP salt they have reference values of 5.79×10^{-36} $\text{Pa}^{-4.9}$/sec, 4.9, and 12 kcal/mole), respectively. The elastic constants E and ν have reference values of 31 GPa and 0.25 that were determined from laboratory quasistatic and ultrasonic tests (Wawersik & Hannum, 1980, Wawersik et. al., 1976). The empirical model is exactly the same as the reference model except that E is divided by 12.5 to give a value of 2.48 GPa.

4 EVALUATION OF NEAR FIELD DAMAGE AND FAR FIELD STRAINING HYPOTHESES

The near field damage or microcracking hypothesis and the far field straining hypothesis for explaining the success of the empirical creep model were evaluated based on a set of shaft calculations in which part of the strip was modeled with the reference value of E while the remainder was modeled with $E/12.5$. An increasingly larger portion of the rock mass was modeled with $E/12.5$ in each calculation. Displacements computed in these simulations were compared to similar displacements computed in two other calculations that had the entire configuration modeled with either E or $E/12.5$. The temperature in these and all other calculations presented here was assumed to be 27°C (300K).

In evaluating the near field damage hypothesis, the first calculation had the salt within one shaft radius a of the inner surface modeled with $E/12.5$ and the remainder modeled with E. The one shaft radius over which the modulus was degraded corresponds roughly to the extent of the damaged or disturbed rock zone around WIPP excavations (Borns & Stormont, 1989). In nine additional calculations, the salt within $2a$, $5a$, $10a$, $20a$, $50a$, $100a$, $125a$, $150a$, and $175a$ of the inner surface was modeled with $E/12.5$ while the remainder was modeled with E. Radially inward displacements computed in these simulations at the shaft surface as shown in Figure 2a for the first year of simulation time. All of the curves in this figure fall between the lower bound corresponding to the calculation in which all of the salt was modeled with E and the upper bound corresponding to the calculation in which all of the salt was modeled with $E/12.5$. The lower bound displacement after one year is about four times less than the upper bound displacement. If E is degraded for only a distance of $1a$ from the free surface, the displacement after one year is about twice that computed without degrading E. However, this increase represents only 25% of the increase needed to attain the displacement computed with all of the salt having the degraded modulus. The all $E/12.5$ solution is approached asymptotically as the amount of salt with the degraded modulus increases, but $E/12.5$ must be used for a distance at least of $50a$ from the inner surface before the solutions are indistinguishable.

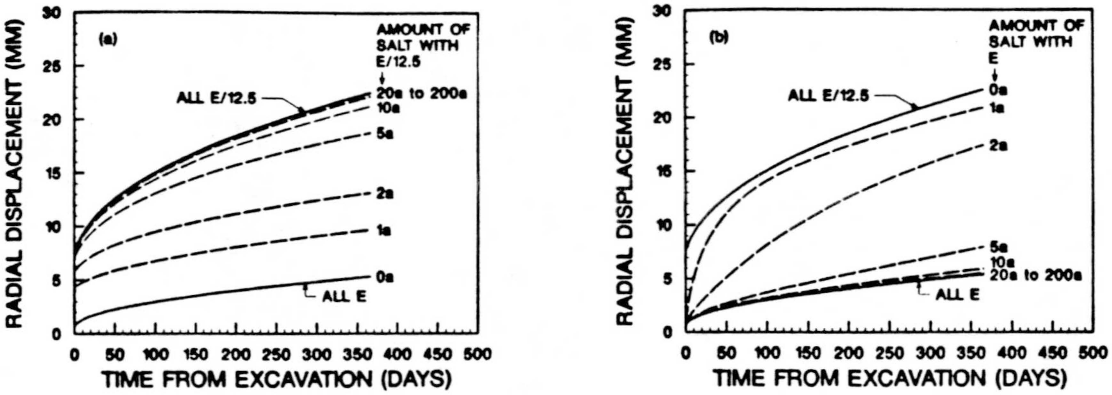

Figure 2. Radially inward displacements of the shaft surface computed with various parts of the salt having a degraded modulus; (a) salt has near field modulus of $E/12.5$ and far field modulus of E; (b) salt has near field modulus of E and far field modulus of $E/12.5$.

The observed disturbed zone certainly does not extend this far so the near field damage hypothesis alone does not explain the success of the empirical model.

Similar calculations were used to evaluate the far field straining hypothesis. In these calculations, salt extending from the surface of the shaft to a prescribed distance into the rock mass was considered intact with a modulus of E while the far field salt was given a modulus of $E/12.5$. The extent of the salt having modulus of E started at $1a$ and was increased to $175a$ in the same manner used to evaluate the near field damage hypothesis. The resulting radially inward displacement histories are shown in Figure 2b. These displacement histories indicate that almost all of the salt, not just the far field salt, must have a degraded modulus before the all $E/12.5$ solution is obtained. Thus, the far field straining hypothesis does not seem to be valid.

5 STRESSES NEAR THE SHAFT SURFACE

Examination of the stresses near the shaft surface, as computed in the simulations with all of the salt having a modulus of either E or $E/12.5$, provides some additional insight into the empirical model that helps to formulate a completely different hypothesis for explaining why the model works. The von Mises stresses computed with E and $E/12.5$ are plotted as a function of the radial distance from the shaft surface in Figure 3a for simulation times immediately after excavation and one year later. The stress field immediately after instantaneous excavation is elastic, and the models with E and $E/12.5$ produce identical profiles because the elastic stresses for a hollow cylinder do not depend on Young's modulus (Timoshenko and Goodier, 1934). After one year, however, the profiles have changed from the elastic solution and are quite different from each other. The profile computed with $E/12.5$ has a steeper gradient near the surface than the one computed with E. Furthermore, the stress at the surface computed with $E/12.5$ has reduced to a value of 10.5 MPa compared to a value of 8.25 MPa computed with E. An alternate presentation of the stress differences is shown in Figure 3b where the von Mises stresses in the salt at the shaft surface are plotted as a function of time for the two different simulations with E and $E/12.5$. Although the stress computed with $E/12.5$ is only about 30% to 40% higher than that computed with E, the resulting

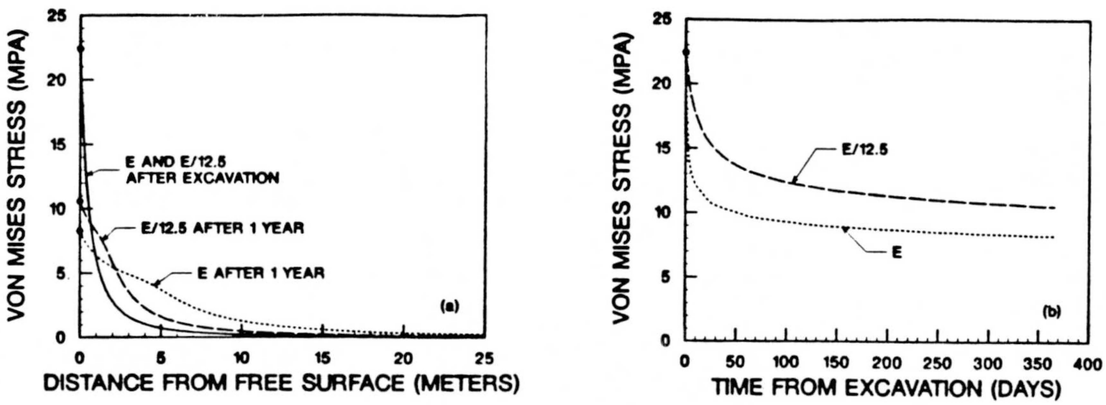

Figure 3. Von Mises stresses around the shaft opening for cases in which all of the salt is modeled with a modulus of either E or $E/12.5$; (a) stress as a function of distance from the free surface; (b) stress near the inner shaft surface as a function of time.

differences in creep rates are much larger due to the 4.9 stress exponent in Equation 2. These results imply that although displacement and stress fields are interdependent, the different unloading behavior produced by the empirical model may be responsible for its success.

6 SIMULATIONS OF A LABORATORY STRESS RELAXATION TEST

In order to study unloading in more detail, the reference creep model with E and the empirical model with $E/12.5$ were used to simulate one of the few laboratory stress relaxation tests available for rock salt (Wallner, 1986).[1] In this test, a solid cylindrical sample of salt was first loaded axially to approximately 40 MPa under a confining pressure of 10 MPa and at a temperature of 27°C. Then the axial displacement and confining pressure were held fixed, and the change in axial stress was monitored for a period of about six days. The resulting axial stress history is shown in Figure 4a along with simulations of the test computed with E and $E/12.5$. The empirical model with $E/12.5$ captures the measured stress relaxation behavior much better than the reference model with E. Thus, a model's performance in simulating laboratory stress relaxation appears to be a good indicator of its ability to simulate closure of underground excavations.

As a further test of this hypothesis, a unified creep-plasticity (UCP) model for rock salt (Krieg, 1980) was also used to simulate the stress relaxation test. This UCP model, which treats only kinematic hardening, produces about the same secondary creep response as the WIPP reference elastic secondary creep model, but it also accounts for transient creep behavior. For the shaft problem shown in Figure 1, closures computed with the UCP model were somewhat larger than those computed with the reference model but were still substantially less than those computed with the empirical model (Morgan & Krieg, 1988). Thus, as might be expected, using this UCP model to predict the response of the relaxation test results in a stress history that falls between those computed with the WIPP reference and empirical creep models. The stress relaxation history computed with this UCP model is shown in Figure 4b where it is labeled "Old UCP Model."

[1]Other existing tests are somewhat ambiguous because they were either run without confining pressure or at higher temperatures than those appropriate for this study.

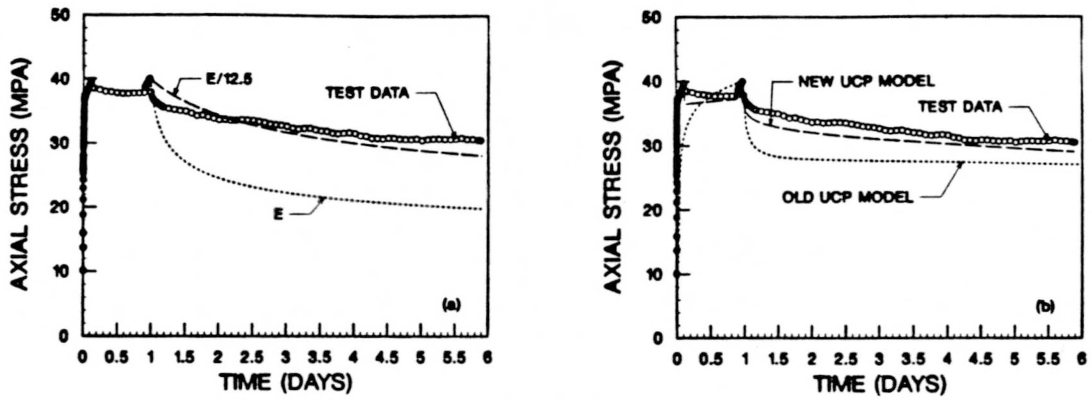

Figure 4. Axial stress change during a laboratory stress relaxation test as computed with (a) the elastic secondary creep model with E and $E/12.5$ and (b) two UCP models.

Attempts were made to determine new parameters for the UCP model that would provide good fits to both creep data and the stress relaxation data. However, the form of the model was too restrictive to produce the desired results. Consequently, a new UCP model containing provisions for both kinematic and isotropic hardening was formulated. In order to compare the new model directly to the old model, parameters for the new model were determined by fitting simulated creep behavior computed with the old UCP model and the relaxation data in Figure 4. The new model thus had the same creep behavior as the old UCP model but improved stress relaxation behavior. The curve labeled "New UCP Model" in Figure 4 represents the improved relaxation behavior.

The new UCP model was then used to compute closure of the shaft in Figure 1. The resulting borehole displacement history is shown in Figure 5 along with those computed with the old UCP model, the WIPP reference model, and the empirical model. The transient portion of the new UCP history is about the same as that computed with the old UCP model, but the long term slope (closure rate) computed with the new UCP model is much higher. In fact, it is almost the same as the slope computed with the empirical model. The improvement in both displacement and displacement rate strongly supports the contention that stress relaxation or unloading of rock salt is an important phenomenon that must be modeled correctly in addition to creep behavior if the in situ response of rock salt is to be predicted accurately.

7 CONCLUSIONS

In this paper, calculations of the response of rock salt around a hypothetical shaft configuration have been used to study explanations of why degrading Young's modulus E in an elastic secondary creep law produces good predictions of the in situ behavior of rock salt. The study revealed that near field damage and far field straining hypotheses could not explain the model's success, especially in producing increased closure rates. However, the study did reveal that the empirical model produced quite different unloading behavior around openings in rock salt than the reference model without the modulus reduction. Further examination indicated that the empirical model also captured unloading behavior observed in laboratory stress relaxation tests more accurately than the reference model. This result led to the conclusion that performance under laboratory

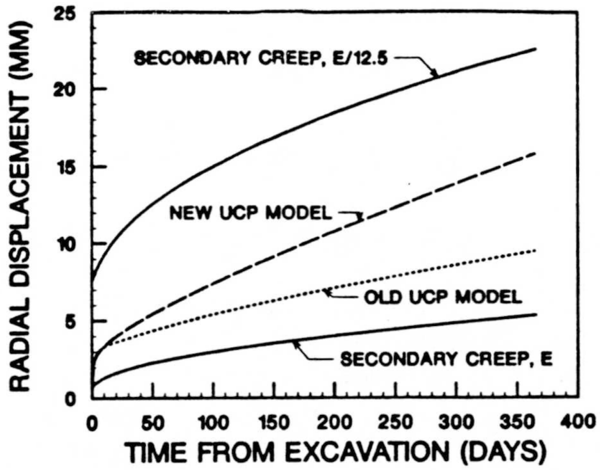

Figure 5. Radially inward displacements of the shaft surface computed with the elastic secondary creep model with E and $E/12.5$ and with two UCP models.

unloading conditions might be indicative of a model's ability to predict underground response of rock salt. This hypothesis was tested with a UCP model that was fitted to both creep and stress relaxation data. The UCP model produced much better closures and closure rates for the shaft problem than a UCP model fit only to creep data.

These results are encouraging because they imply that the in situ behavior of rock salt can possibly be modeled accurately with creep models based on behavior observed in laboratory tests as long as stress relaxation or unloading tests are used in addition to constant stress creep tests. However, this optimism is based on only one stress relaxation test. Additional relaxation and other laboratory unloading tests are needed to investigate the hypothesis in greater detail. The hypothesis must also be reconciled with other proposals for increasing in situ closures, such as the use of a Tresca instead of a von Mises flow potential for the creep of rock salt (Munson et. al., 1989). In addition, other creep models, such as the one currently proposed by Munson, et. al., 1989, should be fit to the unloading data to determine if doing so also improves their predictive capabilities.

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