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Reliability Assessment of Underground Shaft Closure*

A.F. Fossum[1] and D.E. Munson[2]

Abstract

Advanced reliability and structural analysis techniques are used to determine the probability of time-to-closure of a hypothetical underground shaft located in an argillaceous salt formation and filled with compacted crushed salt. Before being filled with crushed salt for sealing, the shaft provides access to an underground facility. Reliable closure of the shaft depends upon the sealing of the shaft through creep closure and recompaction of crushed backfill. Appropriate methods are demonstrated to calculate cumulative distribution functions of the closure based on laboratory determined random variable uncertainty in salt creep properties.

Introduction

Modern advanced reliability techniques coupled with the generality of the nonlinear finite element method provide a much needed and cost-effective tool that can be used in quantitative assessments of the role design variables play in the reliability of a component, and hence the reliability of an engineered system. In this paper, the iterative advanced mean value algorithm (*AMV+*) (Wu and Wirsching, 1989) is coupled with an efficient finite-strain, finite-element algorithm (Roy et al., 1992) to provide a method that computes *CDF* (cumulative distribution function) creep data without resorting to expensive Monte Carlo simulation. The structural component of interest is a long-term shaft seal that forms part of the *WIPP* (Waste Isolation Pilot Plant) seal system. The intent of the *WIPP*, being constructed in the bedded geologic salt deposits of Southeastern New Mexico, is to provide the technological basis for the safe disposal of radioactive Transuranic (*TRU*) wastes generated by the defense programs of the United States. Should this facility prove

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[1]Vice Pres., Mat & Mech., RE/SPEC Inc., P.O. Box 725, Rapid City, SD 57709
[2]Distng. Mem. Tec. Staff, Sandia National Laboratories, Albuquerque, NM 87185

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to comply with the regulations governing long-term performance, it may become a repository for *TRU* wastes in the future.

Structural Model

In earlier work to demonstrate the feasibility of the *AMV+* method, Fossum and Munson (1994) constructed a hypothetical shaft model to represent a man-made opening to provide exploratory or operational access to the underground. After remaining open during the 50-year operational period of the repository, the shaft was filled with compacted crushed salt with an assumed initial density equal to 80% of solid-salt density. The response of interest was the time necessary to compact the crushed salt to a level sufficient to reduce the seal system permeability to acceptable levels. Because the structural calculations give crushed salt compaction in terms of relative densities, rather than permeabilities, an end-point density of 95% of solid-salt density was used in this demonstration calculation as a measure of acceptable compaction. A nonlinear finite-element code was used to obtain structural sensitivities with respect to the material parameters considered to be random in a clean-salt creep material model. An *FPI* (fast probability integration) technique was used to construct the probabilistic response given the structural sensitivities and the random variable uncertainties. The analysis was made using the *AMV+* algorithm to obtain the *CDF* for the time to shaft closure. In this paper we extend these results by including the demonstration case in which a shaft is surrounded by argillaceous salt, a material known to creep somewhat faster than clean salt. The probability density functions are determined and presented for the parameters considered to be random variables in the argillaceous material salt creep calculation, and a comparison is made of the *CDF's* for the calculations made with clean- and argillaceous-salt materials.

Material Response

The salt creep equations are the Multi-Mechanism Deformation (*M-D*) model, so-called because dislocation induced creep is the sum of the effects of three different micromechanisms, depending upon temperature and stress level. Transient behavior is accounted for through an internal variable satisfying a first order differential equation.

The parameters considered to be random in the clean-salt calculation have already been presented elsewhere (Fossum et al., 1994) from a database comprising 29 triaxial compression creep tests. The new parameters determined here for argillaceous salt include A_2 from the expression for the undefined steady-state mechanism, K_0 from the expression for the transient strain limit, and α and β from the expression for the stress dependent workhardening parameter. The probability density functions shown in Figures 1–4 for these parameters were determined from a database comprising 17 triaxial compression creep tests on *WIPP* argillaceous salt. Also shown in these figures are the means and standard deviations for the parameters.

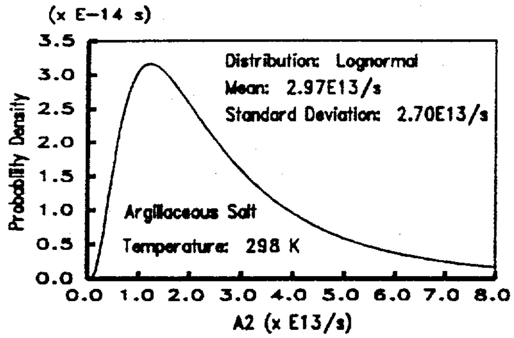

Figure 1. Probability density function for A_2.

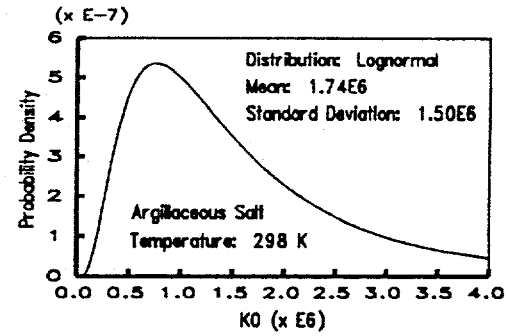

Figure 2. Probability density function for K_0

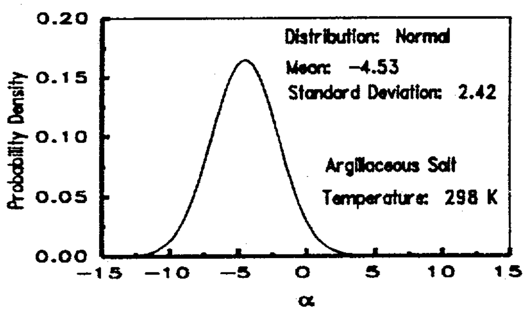

Figure 3. Probability density function for α

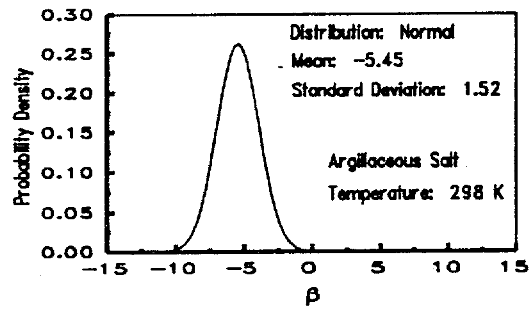

Figure 4. Probability density function for β

The crushed salt material model includes the sum of a nonlinear elastic strain component and a plastic strain component. In the elastic part, the bulk and shear moduli are formulated as exponential functions of the current crushed-salt density. The plastic strain component depends on the current crushed-salt density and the mean stress. Currently the database is sparse and no attempt is made to determine probability density functions for the parameters of this model.

Results

Because the results presented here represent a demonstration of the method, they do not reflect the actual parameters planned for use in WIPP shaft calculations. Figure 5 shows the *CDF*'s of the time it takes, after emplacement, for the density of the crushed salt to reach 95% of solid-salt density, for the two cases in which the shaft is either surrounded by clean salt or by argillaceous salt. At a probability level of 50%, the argillaceous case will take 56 years or less while the clean-salt case will take 104 years or less. The times calculated for these two cases are important because they represent the time that short-term seals (concrete plugs) in the shaft must be effective. The calculational results for the demonstration case illustrate the method for calculating the *CDF*'s using *FPI* and *AMV+* and suggest the method is applicable to the actual conditions of shaft seal design when these conditions are defined. While no suitable level of risk has yet been defined to correspond to the success or failure of a seal design system, the results developed here will be required in the future for certification to a defined level of reliability.

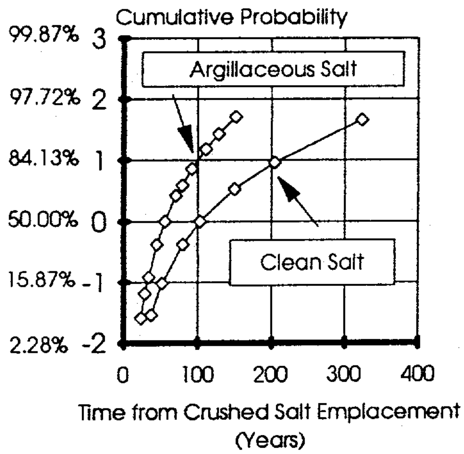

Figure 5. Cumulative distribution function of time to reach 95% fractional density

Application of these reliability tools throughout the seal design process potentially provides quantitative assessments of the role each of the design variables plays in the reliability of the crushed-salt component, and thus in the reliability of the sealing system. For example, the analysis results showed that the uncertainty in the response was driven almost exclusively by the uncertainty in parameter A_2 associated with one of the steady-state salt creep mechanisms. This information can be used to assess quantitatively the importance in decreasing the uncertainty in the parameter through further testing on the reliability of the design.

Summary

The goal of the current study has been to apply new technology that will enable the designer to apply plausible parameters to actual underground WIPP openings and to account for each of the design sources of uncertainty accurately in evaluating structural reliability and risk assessment. It is envisioned that component and system risk sensitivity factors will be used to identify critical design reliability factors.

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