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Observations of Borehole Deformation Modulus Values Before and After Extensive Heating of a Granitic Rock Mass

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1 ABSTRACT

An extensive campaign of in situ deformation modulus measurements was recently completed using a standard NX borehole jack. These results were obtained in a granite intrusive where spent nuclear-fuel assemblies and electrical heaters had raised the rock temperatures 10°C to 40°C above ambient. We present an analysis of temperature effects based on 41 preheat and 63 post-heat measurements in three boreholes. Using analysis of covariance statistical techniques, we found that the deformation modulus is affected by heat, loading direction, and position within the borehole. The analysis also uncovered a significant interaction between the effects of heating and loading direction.

We used 123 measurements from the same boreholes to evaluate the "Draft Standard Guide for Estimating the In Situ Modulus of Rock Masses Using the NX-Borehole Jack" which was recently proposed by Heuze. In particular, we examined the criterion for screening measurements in those cases where contact between the jack platen and the borehole wall was incomplete. We found that the proposed screen appears to operate randomly on the data and is therefore ineffective.

2 INTRODUCTION

A test of deep geologic storage of commercial spent nuclear fuel assemblies was recently completed at the Spent Fuel Test-Climax (SFT-C). The SFT-C was conducted to demonstrate the technical feasibility of deep geologic storage and to evaluate the acceptability of granites as a medium for permanent disposal of nuclear wastes (Ramspott, et al., 1979).

Rock deformability characteristics were used in calculating displacements and stress changes that occurred as a result of excavating and heating the facility. Young's modulus values of intact cores range from about 50 to 70 GPa (Pratt et al., 1979).

The impetus for the present study was the need to determine what changes in large-scale deformability characteristics occurred as a result of elevating the temperature of the facility 10 to 40°C above the ambient. The heating caused thermal expansion of the rock which acted to change the stresses as much 40%, as discussed below. The spacial variability in deformability was also examined in detail. In addition, the study resulted in a data set which is large enough to support a statistical evaluation of the recently proposed "Standard Guide for Estimating the In Situ Modulus of Rock Masses Using the NX-Borehole Jack" (Heuze, 1984).

3 SITE DESCRIPTION

The basic geometry of the SFT-C facility is three parallel drifts which are connected at their ends (Fig. 1). The center drift is 6.1 m high x 4.6 m wide x 65 m long and has 17 storage boreholes in the floor that held 11 spent nuclear fuel assemblies and 6 electrical heaters during the three-year heated phase of the test. Parallel heater drifts measuring 3.4 m square are located on either side of the center drift. Each of these heater drifts had 10 electrical heaters located in the floor during the three-year heated phase of the test. Within the repository-model cell, this combination of heat and radiation sources simulated the thermal effects of a panel of a full-scale repository, raising rock temperatures to 85°C near the storage boreholes in the center drift and to well over 300°C near the electrical heaters in the two side drifts (Patrick et al., 1984).

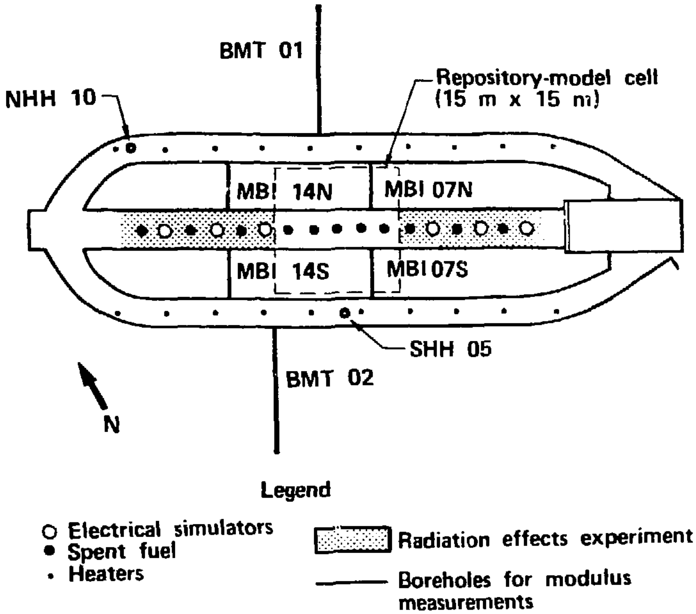

Figure 1. Plan view of Spent Fuel Test-Climax facility showing location of thermal sources, principal experiments, and boreholes.

The SFT-C is located 420 m below ground surface in the quartz monzonite unit of the Climax stock. The medium-grained ground mass contains scattered alkali feldspar crystals up to 150 mm long. The test level is about 150 m above the regional water table and is unsaturated but not dry.

Wilder and Yow (1984) report four dominant joint sets which account for about 93% of all joints mapped. They are oriented N44°W/20°NE, N24°W/vertical, N59°W/vertical, and N48°E/80°SE. The rock mass is moderately jointed with frequencies ranging from 0.90 to 2.2 joints/m. In addition to these systematic joint sets, there are several shears and faults present in the test area.

4 MEASUREMENT TECHNIQUE

We measured rock deformability in nine boreholes located throughout the SFT-C facility (Fig. 1) using a Slope Indicator Co. Model 52101 hardrock borehole jack and associated equipment. Although the "Draft Standard Guide" (Heuze, 1984) had not yet been proposed at the time of these measurements, our procedures were nearly identical to those recommended (Patrick, Yow, and Axelrod, 1984). The equipment was calibrated by the manufacturer or by LLNL, as appropriate. The depth and angular position of the borehole jack platens were established by means of scribe marks on the BX-size drill casing that was used to insert the jack into the borehole. Depths are accurate to one centimetre and angular position to about five degrees.

The borehole diameter at each test location was determined from the average of the two LVDT readings at a nominal seating pressure of 0.3 to 0.8 MPa. In general, we found that the MBI-series boreholes were undersized by as much as 1.52 mm because they were drilled with surface-set diamond bits and were not reamed. On the other hand, the BMT-, NHH-, and SHH-series boreholes were drilled with diamond impregnated bits and, therefore, were oversized as much as 1.52 mm.

5 DATA REDUCTION TECHNIQUES

The fundamental method of analysis was that suggested by Heuze (1984). The calculated deformation modulus E_c (psi) is

$$E_c = 0.86 \cdot 0.93 \cdot D \cdot \frac{\Delta Q_h}{\Delta D} \cdot T^* \qquad (1)$$

where D is the borehole diameter (3.0 in.), ΔD is the change in borehole diameter (inches) produced by a change in line pressure ΔQ_h (psi), and T^* is a function of Poisson's ratio and the half contact angle between the jack platen and the rock. Based on previous studies, we determined Poisson's ratio to be 0.246 and used a T^* value of 1.438 from Heuze and Amadei (1984).

Values of $\Delta Q_h/\Delta D$ were obtained graphically as the slopes of the linear portion of plots of jack gauge pressure versus the average of the two LVDT readings. For most tests, the low-pressure end of each curve was nonlinear but became linear at pressures of 20.7 MPa (6000 psi) or less. It is interesting that linear relationships were observed even where boreholes deviated substantially from the 76 mm (3.0 in.) ideal diameter.

To expedite the correction for longitudinal bending of the jack (Heuze and Salem, 1976, Meyer and McVey, 1974), we fitted an equation to the curve of "true" modulus E_t versus calculated modulus E_c which Heuze presented (1984). For a Poisson's ratio of 0.25, the equation is

$$E_t = 0.030320 + 0.979484E_c - 2.042103 \times 10^{-8}E_c^2 + 1.792758 \times 10^{-13} E_c^3 \quad (2)$$

We considered screening the data according to the full platen seating criterion proposed by Heuze (1984). However, the proposed screen (as discussed below) fails to eliminate many implausibly high values which are obvious statistical outliers. Instead, we calculated all modulus values using the linear portion of the pressure versus displacement curves and deleted modulus values calculated to be greater than 85 GPa, the maximum modulus value obtained in testing 143-mm diameter cores of intact rock. Since these cores possessed no open fractures, which in situ reduce the deformation modulus, the laboratory modulus represents a physical upper bound. This physical argument is supported by a statistical analysis of the modulus distributions which shows that values greater than 100 GPa are part of a long tail of outliers.

We found the following factors to be influential: position within the borehole, location within the facility, loading direction, and heat. The appropriate variable to describe the position within the borehole is the distance of the measurement from the center of the borehole, a quantitative variable. The other factors are all qualitative, therefore an analysis of covariance model is convenient (Searle, 1971). If all the variables were quantitative, we would use regression analysis. Each of the qualitative factors has only two levels: north or south pillar, vertical or horizontal loading, and preheat or post-heat, respectively. Significant interactions between heat and loading direction and between heat and pillar location were detected. The following linear statistical model applies to the data from MBI07N, MBI07S, and MBI14S.

$$E_i = \mu + \beta d_i + \sum_{j=1}^{10} X_{ij} \gamma_j + \varepsilon_i \quad (3)$$

Where E_i= deformation modulus (GPa), d_i = distance of the measurement from the borehole center, and the X_{ij} are factor variables. When the j^{th} factor is present X_{ij} = 1, when absent X_{ij} = 0. The model parameters are μ, β_i, and γ_i, and the ε_i represent residual errors. The parameterization of the model is not unique, but all parameterizations will give the same results. The model parameters cannot be estimated separately, as is the case for regression. Instead only certain meaningful linear combinations are estimated, using the numerical technique of the singular value decomposition. The three factors at two levels require six terms, the two sets of interactions require four additional terms and the constant and slope coefficient add two more for a total of 12 terms.

6 RESULTS AND CONCLUSIONS

6.1 An Evaluation of the Screening Criterion

Heuze (1984) proposed a method for rejecting data when the jack platen is determined to be incompletely seated against the wall of the borehole. We evaluated this proposed screen using data from MBI07N, MBI07S, and MBI14S. The screen removes 67 of the 123 measurements in these boreholes, but fails to eliminate modulus values as high as 446 GPa, which are physically implausible. Only four of the 19 measurements greater than the physically realistic cut-off of 85 GPa are rejected by the screen. Moreover, the inclusion of these extreme values would distort the parameter estimates for the model given by Eq. 3.

We can investigate the behavior of the screen for the 104 measurements below the 85 GPa cut-off by enlarging the model given in Eq. 3 to include a "screening" effect. The screen is another qualitative factor with two levels, thus two terms are added to the model. Using the F test on the model estimates, we could detect no screening effect. This suggests that the intercepts for screened and unscreened data are identical. As an additional diagnostic, we plotted quantiles of the model residuals associated with screened points versus the residuals associated with unscreened points (Fig. 2). The points exhibit good conformity to a straight line with unity slope, indicating equality of distributions (no increase in variance).

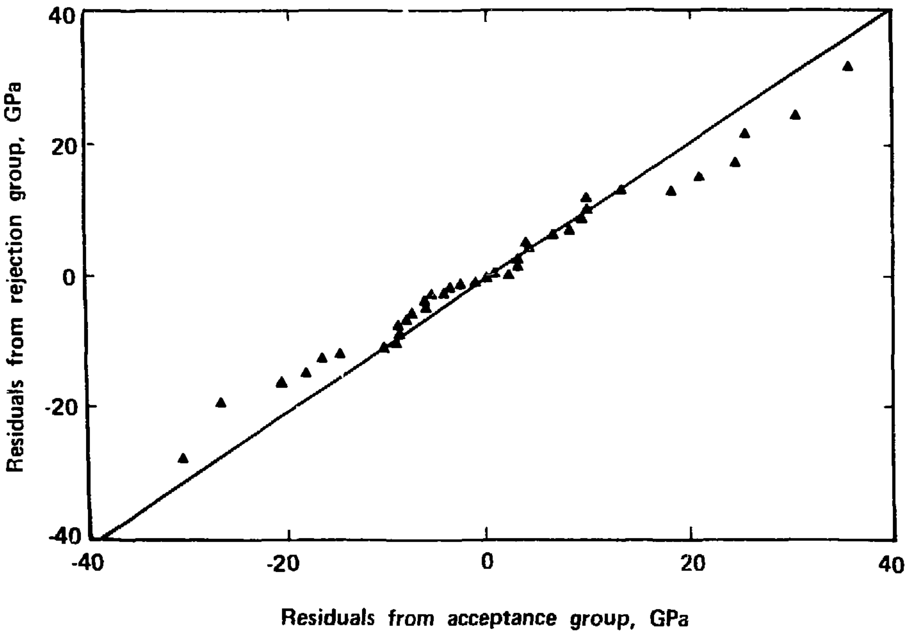

Figure 2. Quantile-Quantile plot comparing distributions of model residuals of data accepted (abscissa) and rejected (ordinate) by the screen. Conformity to a straight line with unity slope implies that the distributions are identical.

The proposed screen appears to randomly reject 63 of the 104 values below 85 GPa, and fails to reject values that are unrealistically high. We conclude that this proposed method is ineffective as a screen.

6.2 Data Analysis

To examine the affect of heating on the rock mass deformability, we analyzed 41 pre-heat and 63 post-heat modulus values. Table 1 lists the "intercept" terms for the various data subsets which were analyzed with the 12-term linear model described in Section 5. These intercepts represent the mean modulus values at the pillar center. The overall slope of the 104 data is -7.00 GPa/m. The physical interpretation of these coefficients is straightforward. For example, the predicted values of post-heating modulus under horizontal loading in the north pillar is 52.87 GPa at the pillar center and it decreases 7.00 GPa for each metre from the center in either direction. The data and associated line for this typical example are shown in Fig. 3.

Table 1. Intercept coefficients calculated using a 12-term general linear model for deformation modulus(GPa).

Time of Measurement	North Pillar		South Pillar	
	Vertical Loading	Horizontal Loading	Vertical Loading	Horizontal Loading
Pre-heating	46.54	57.23	26.26	36.96
Post-heating	62.71	52.87	54.63	44.80

Since this model uses a common slope, it is relatively easy to interpret the effect of various factors. First, there is a strong anisotropy in the modulus. Before heating, the rock mass modulus is about 10.7 GPa less in the vertical loading direction, indicating that the more frequent low angle joints (infilled with pyrite, sericite, and quartz) tend to affect the modulus more than the high-angle joints (which appear "open" at free surfaces but are typically clean or infilled with calcite). Second, while the anisotropy remains after the episode of heating, the modulus is now about 9.8 GPa greater in the vertical loading direction. This is consistent with a hypothesis that the stresses increase as a result of thermal expansion of the rock, and thereby increase joint stiffness. Thermomechanical calculations show that vertical stresses increase by about 5 MPa (40%) and horizontal stresses decrease by as much as 2 MPa (20%) in the pillar center as a result of the episode of heating (Butkovich, 1981). Third, note in this context that the modulus for vertical loading increased by 16.2 to 28.4 GPa while the modulus for horizontal loading in one case decreased by 4.4 GPa and in the other increased by only 7.8 GPa. This is compatible, in concept, with our understanding of the influence of stress changes on individual joints (Goodman, 1980, and Yow, 1985).

These data provide strong field evidence that extensive heating of a rock mass to moderate temperatures may induce significant changes in the deformability of the rock mass as a result of changes in the stress regime. Depending on the extent of heating and the geometry of the underground facility, deformability may increase or decrease.

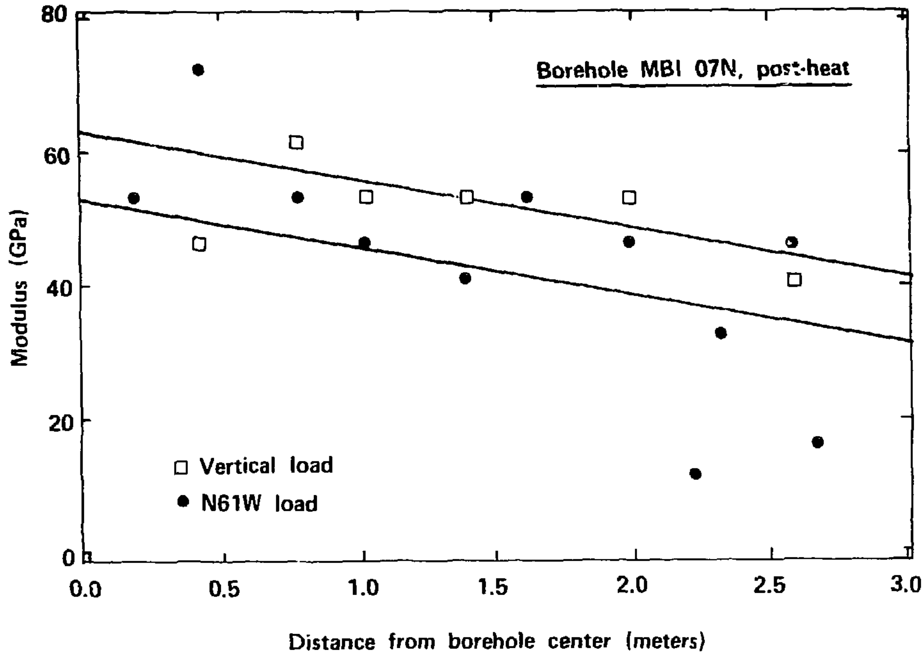

Figure 3. Typical example of relationship between borehole modulus value and distance from pillar center. The slope and intercepts of the lines were developed from a 12-term general linear model.

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