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Results of Pressurized-Slot Measurements in the G-Tunnel Underground Facility*

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1 INTRODUCTION

Volcanic tuffs are being considered by the Department of Energy as a medium for disposal of high-level radioactive wastes. The Yucca Mountain Project (YMP) was established in 1977 to evaluate such disposal in geologic formations on or adjacent to the Nevada Test Site (NTS). A rock-mechanics field-testing program is underway at Sandia National Laboratories (SNL) as part of the YMP. SNL has the responsibility for assessing the repository design and performance as well as characterizing the geomechanical behavior of the rock. SNL has conducted field experiments in G-Tunnel in Rainier Mesa at the NTS, where tuffs similar to those at Yucca Mountain, the potential repository site, are found (Zimmerman and Finley 1987). Later experiments are planned as part of the YMP Exploratory Shaft investigations at Yucca Mountain.

Major geomechanical factors in repository developments are determinations of the stress state and the deformability of the rock mass (described by the modulus of deformation). One feature of SNL's rock-mechanics program was the development of a testing program for cutting thin slots in a jointed welded tuff and utilizing flatjacks for pressurizing these thin-slots on a relatively large scale. Goals in pressurized-slot testing were to (1) improve the technology for making field measurements in jointed rock and (2) obtain field data for jointed welded tuff to support YMP repository conceptual design efforts. Objectives in the pressurized-slot testing in G-Tunnel have been to apply and possibly improve methods for (1) utilizing the flatjack cancellation (FC) method (Mayer et al. 1951, Tincelin 1951) for measuring stresses normal to the slot and (2) measuring the modulus of deformation of the jointed rock surrounding the slot (Rocha 1966, Louriero-Pinto 1986). This paper discusses the results of field measurements in and around a single slot and evaluates potential applications and limitations.

2 SLOT-NORMAL STRESS MEASUREMENTS

The basic measurement concept for the FC method is to (1) determine

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initial distances between anchors located on either side of a soon-to-be-cut slot, (2) measure the changes in the anchor distances after the slot is cut, and (3) insert a flatjack in the slot and pressurize it until the initial distances are restored. The pressure in the flatjack can then be mathematically related to the stress normal to the slot. Figure 1 shows the measurement layout for the pressurized-slot testing. A highlight in the testing was the cutting of slots with minimum disturbance to the surrounding rock using a diamond-tipped chain saw (Zimmerman et al. 1987). This cutting process allowed removable flatjacks to be used and reduced the time required to cut the slots.

The flatjacks used were made by SNL out of 18-ga stainless steel. The overall dimensions were 76 x 76 cm and the total thickness was 0.74 cm. The flatjacks were determined to have an effective area of 0.93 x area of outside dimensions based on laboratory measurements. Distance measurements between four pairs of anchors bonded to the rock surface were taken with a Whittemore strain gage, manufactured by Weidmann Machine Co. The gage has a resolution of 0.0025 mm (0.0001 in.), but the actual accuracy was approximately 0.025 mm (0.001 in.) because the gage was operated manually and subject to visual interpretations.

Normal stresses for the FC method were determined from linear-elastic equations derived by Alexander (1960). The simplified version of Alexander's formula is:

$$S_i = a\,P_i + b\,Q_i \qquad (1)$$

where S_i is the rock stress normal to the flatjack, P_i is the flatjack pressure at cancellation, Q_i is the rock stress parallel to the flatjack, i is the cycle identifier, and a and b are coefficients involving the slot geometry and Poisson's ratio. The latter coefficients account for differences in slot and flatjack dimensions and, because of linear assumptions, are independent of the modulus of deformation for the rock. For the dimensions used in the testing and an assumed value of 0.2 for Poisson's ratio, the values of a and b were calculated to be 0.693 and 0.004, respectively.

The quantity P_i can be determined using the measurements:

$$P_i = m_i\,R \qquad (2)$$

where m_i is the average slope of the pressure-deformation data during the flatjack pressurizations and R is taken as the average displacement across all four lines that resulted from the slot cutting. Equation 2 was used so that the value R could be selected as an average or perhaps a single anchor measurement. Three normal-stress measurement cycles, identified as C1, C2, and C3, were used.

Table 1 summarizes the results for the slot closures for the three cycles. Data in Table 1 represent closure distances. The largest closure occurred immediately after the slot was cut and subsequent measurements showed a diverging trend. Table 2 summarizes the results of the pressure-deformation measurements taken during the flatjack pressurizations. Data on loading and unloading were generally linear, and straight lines were regressed to the loading data using the method of least squares. Standard errors are provided in parentheses. The average data is the average for the four measurement lines.

Using equation 2 and the data from the tables, the values of P_1 = 2.7 MPa, and $P_2 = P_3$ = 3.2 MPa are obtained. Corresponding values for the slot normal stresses are S_1 = 1.9 MPa, and $S_2 = S_3$ = 2.2 MPa

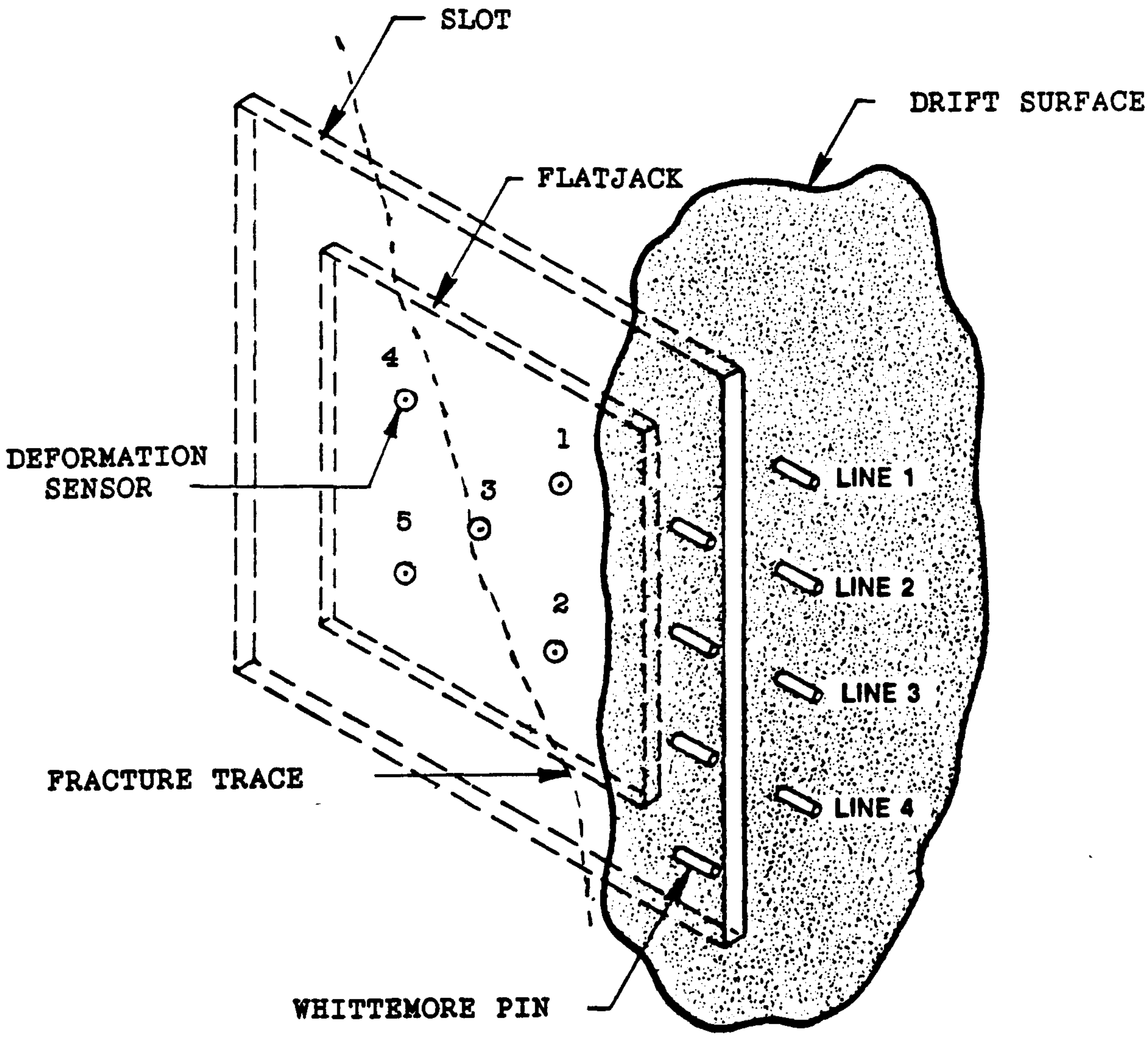

Figure 1. Schematic showing test configuration for all pressurized slot measurements.

Table 1. Summary of slot closure initial displacements for flatjack cancellations

Meas	Condition	Days	Displacements (mm) Lines 1	2	3	4
1	Before Slot Cutting	-	0	0	0	0
2	After Slot Cutting	0	0.278	0.375	0.260	0.258
3	Before Cycle C1	21	0.230	0.323	0.210	0.216
4	Before Cycle C2	21	0.197	0.276	0.131	0.144
5	Before Cycle C3	22	0.187	0.267	0.121	0.126
6	After Cycle C3	22	0.193	0.270	0.122	0.126

Note: R = 0.293 ± 0.056 mm (Meas 2) for Equation 2

Table 2. Summary of linear regression slopes using Whittemore measurements

Test Cycle	Slopes MPa/mm (± MPa)* Lines 1	2	3	4	Average ±1 std. dev.
C1	11.2 (±0.32)*	8.5 (±0.31)	7.6 (±0.32)	9.1 (±0.45)	9.10 ±1.53
C2	12.8 (±0.17)	9.8 (±0.10)	9.3 (±0.08)	11.2 (±0.25)	10.78 ±1.57
C3	12.9 (±0.09)	9.8 (±0.09)	9.2 (±0.05)	11.2 (±0.15)	10.78 ±1.65

*Standard Error in parenthesis

assuming that the effects of the Q parameter are negligible. For comparison, the in situ stress state in the test area had been estimated from nearby measurements (Zimmerman and Finley, 1987) and the resultant stress normal to the slot can be shown to be 5.9 MPa; the latter is obtained assuming that there are no stress redistributions or relaxations due to the excavation process. The net result was that the average stress as determined by the FC method was 36 percent of this estimated stress.

3 MODULUS OF DEFORMATION MEASUREMENTS

Rocha (1966) pioneered a method to measure rock-mass deformability with the use of an instrumented flatjack containing deformation sensors. The method involved measuring displacements of the slot surface rather than using surface pins, as had been used in the deformability studies of Mayer et al. (1951) and Tincelin (1951). A distinct advantage of the Rocha method was that deformability measurements could be taken at greater depths using a diamond disk cutting technique that he developed. A major difference between Rocha's method and the present study was that a diamond-tipped chain saw was used to cut the slot in this study (Zimmerman, et al. 1987).

Figure 1 also includes a schematic illustrating the major features of the instrumented flatjack testing. Flatjacks were prepared by SNL using 18-gage stainless steel that was welded to a steel perimeter frame. The 76 x 76 cm flatjack contained special strain-gage-cantilever sensors that monitored the displacements of the inside surfaces of the flatjack. The flatjack was placed in the 1 x 1 m slot without the use of a coupling medium. The assumption was made that the sensors measured the relative displacements of the slot surface. The internal sensors operated on strain-gage principles, and data were manually recorded. The sensors had a sensitivity ranging from 180 to 190 $\mu\varepsilon$/mm. Pressure-deformation measurements up to a maximum pressure of 14 MPa were made for two cycles of loading, identified as Cycles D1 and D2.

Analytical efforts are required to make estimates of the modulus of deformation from the pressure-deformation measurements. Rocha and da Silva (1970) expressed the modulus of deformation as:

(3) $$E_d = K_r(\Delta P/\Delta w)$$

where E_d = modulus of deformation, ΔP = change in flatjack pressure, and Δw = change in the displacement sensors located in the flatjack. The quantity K_r is a deformation constant that has the dimension of length and whose value depends on the position of the measurement within the flatjack, the dimensions of the loaded area, the shape of the loaded area, the position of the loaded area in the slot, and Poisson's ratio.

Rocha and da Silva used small-scale model tests and quasi-empirical approaches to arrive at values of K_r. Rocha and da Silva presented two curves that can be used to estimate the deformation constant for these tests. One curve predicted a value of K_r for the position of the flatjack in the slot and the other for the location of the sensors within the flatjack. The analytical solution was for a slot in quarter space. For the G-Tunnel testing, estimates of K_r = 3600 and 3100 mm are applied to the sensors nearest and furthest from the surface respectively. The value is higher nearer the slot surface because there is less rock to resist the pressure. Rocha and da Silva also investigated the effect of rock continuity in the plane of the flatjack. They prepared a set of curves based on axisymmetric geometry to estimate these effects. Continuity was described in terms of the ratio of the slot and/or fractured area (D) to the dimension of the circular flatjack (d). The maximum deformation at the center of a circular flatjack was decreased by approximately 50 percent when the D/d ratio decreased from ∞ to 1.1. Using Rocha and da Silva's curves and a fractured surface dimension of 1.25 (slot length over flatjack length) times the flatjack dimension, the values of K_r obtained previously should be reduced by approximately 30 percent. Thus, final estimates for K_r are 2520 and 2170 mm respectively.

Loureiro-Pinto (1986) suggested a similar formula which is expressed as:

(4) $$E_d = K_1(1-\nu^2)(\Delta P/\Delta w)$$

where ν = Poisson's ratio and a different deformation constant, K_1, depends upon the stiffness, shape, arrangement, and number of flatjacks, the location of the measuring point, the shape of the test drift, and of the depth of the crack (h) formed in the application of the pressure. The depth-of-crack factor is a particularly sensitive quantity that Loureiro-Pinto developed after extensive numerical calculations. The factor is calculated based on the tensile strength of the rock mass and the initial stress. Using data from Zimmerman and Finley (1987), the value of h can be estimated to be 0.25 m. The slot was 0.2 m larger than the flatjack in total dimension. From a visual standpoint, there was no evidence of crack propagation in the plane of the slot so the 0.25 m value may be high. For a value of h = 0.25 and an assumption of ν = 0.2, the deformation coefficients can be estimated to be 1700 and 1670 mm for the sensors nearest and furthest from the surface respectively.

Table 3 summarizes the results of the pressure-deformation measurements for the two cycles. The data were generally quite linear and least squares lines were regressed to the loading portions of the data. The table provides the standard errors for the measurements. Sensors 1 and 2 were nearest the surface and 4 and 5 were furthest. Table 3 shows that the slopes were significantly greater for the deepest sensors.

Table 4 summarizes the applications of equations 3 and 4 to the data in Table 3. Slopes for sensors at the same measurement depth were averaged for presentation in Table 4. The results of the calculations in Table 4 show the differences in the measurements at the shallowest and deepest positions. In all cases, the calculated values of E_d were larger in the deeper positions. In view of uncertainties, which will be discussed later, it seems appropriate to average the values determined from the source equations in determining single values for the modulus of deformation. Thus, an average value of 19.8 GPa is obtained using equation 3 and a value of 14.6 GPa is obtained using equation 4. This range encloses the recommended value of 16.1 GPa (Zimmerman and Finley 1987) for G-Tunnel welded tuffs.

Table 3. Summary of linear regression slopes using internal sensor measurements

Test Cycle	Slope MPa/mm (MPa)* Sensor 1	2	3	4	5	Average ±1 std. dev.
D1	6.0 (±0.08)*	4.9 (±0.12)	9.3 (±0.34)	10.4 (±0.11)	12.6 (±0.21)	8.64 ±3.17
D2	5.6 (±0.24)	4.8 (±0.32)	7.3 (±0.17)	11.3 (±0.15)	13.8 (±0.08)	8.56 ±3.86

*Standard Error in parenthesis

Table 4. Summary of modulus of deformation calculations

Cycle	Sensor position	Ave* slope (MPa/mm)	Equation 3 K_r (mm)	Equation 3 E_d (GPa)	Equation 4 K_1 mm	Equation 4 E_d (GPa)
D1	Shallow	5.45	2520	13.73	1700	9.26
	Deepest	11.50	2170	24.96	1670	19.20
D2	Shallow	5.20	2520	13.10	1700	8.84
	Deepest	12.55	2170	27.24	1670	20.96
			Ave E_d =	19.75 (±7.38)	Ave E_d =	14.56 (±6.41)

*Mean for sensors at same level.

4 DISCUSSION OF MEASUREMENTS AND CONVERSIONS

Comparisons in the results obtained from the measurements and available information showed:

1. The slot opening generally diverged as a function of testing cycles (Table 1).
2. FC method normal stresses were considerably less than those estimated from other in situ measurements.
3. Instrumented flatjack data showed distinct differences in sensor outputs located nearest and farthest from the surface.
4. Average modulus of deformation values were similar to those measured in other testing programs.

It is postulated that observations 1 and 3 reveal significant information that affects the other two. The data in Table 1 show that the slot slightly diverged after the slot cutting. There has been concern about time-dependent closure effects, particularly with FC applications (Deklotz and Boisen 1970, Hoskins 1966). During the slot-cutting process, a small fracture was noted in a plane nominally perpendicular to the slot and near mid-depth. The fracture appeared to predate the slot cutting. The slot surface showed no irregularities and the rock mass appeared to be competent during the C-cycle testing. During Cycles D1 and D2, there was visible evidence on the surface of the flatjacks that the rock was fracturing along the surface. Testing was stopped after Cycle D2 because the fracture had progressed to the point of causing a permanent crease in the flatjack surface (Figure 1). The increased deformation nearer the surface accounted for the larger displacements in Sensors 1 and 2 in Table 3. In retrospect, the divergent trends of the initial values in the C cycles suggests that the fracture activation effect was more dominant than creep.

It is very likely that the fracture became activated and propagated during the C and D cycle testing. The effect would be that the surface pins would open more and there would be an underprediction of the normal stress.

Acceptance of this postulation also suggests that the calculated modulus of deformation using either K_r or K_1 would be somewhat higher if the fracture were not present. The values in Table 4 for the deepest sensor positions may provide values that are more representative. This means that the predicted values using the deformation constant methods would be somewhat higher than the estimated rock-mass value of 16.1 GPa. There are many factors that were not considered in determining the values of K_r and K_1 that should be qualified and evaluated before final E_d values can be defined. There were differences in (1) flatjack and slot sizes and shapes, (2) sensor locations and depths, (3) interpretations of crack propagations in the plane of the slot, (4) slot-cutting methods, and (5) definitions of effective flatjack areas that could have affected the results. Also the normal limitations of linear-elastic model assumptions and material property quantities must be considered.

5 CONCLUSIONS

Results were encouraging in the applications of pressurized slot testing for determining a normal stress and modulus of deformation in welded tuff. The FC and instrumented flatjack methods yielded repeatable data and in combination provided invaluable information on the in-plane fracture behavior. Derived values of S and E_d should be considered preliminary. It is anticipated that additional refinements in the analytical models could produce better estimates of these important rock mass characteristics.

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