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APPLICABILITY OF BOREHOLE STRESS MEASUREMENT INSTRUMENTATION TO CLOSELY JOINTED ROCK

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ABSTRACT

INTRODUCTION

A field testing program is currently being conducted at the Hanford Site in southeastern Washington in order to characterize the thermal and mechanical behavior of the Columbia River Basalts at conditions similar to those expected in a nuclear waste repository. This testing is being performed in the Near-Surface Test Facility (NSTF) by the Basalt Waste Isolation Project under the direction of the U.S. Department of Energy.

One of the major objectives of the program is to develop and evaluate instrumentation which will allow the characterization of the in-situ stress state and deformation properties of the rock mass. The closely jointed and fractured nature of the rock mass, as well as the anticipated temperature and hydrologic conditions of the repository environment, have raised serious questions as to the applicability of most of the currently available geotechnical instrumentation. This paper presents the results to date of the development effort of the borehole deformation gage (BDG) and the vibrating wire stressmeter (VWS). This effort has included laboratory testing, numerical modeling and in-situ testing at the NSTF and has resulted in several significant modifications to the instruments designs and algorithms.

BOREHOLE DEFORMATION GAGE

The borehole deformation gage currently in use at the NSTF has undergone extensive modification from the original U.S. Bureau of Mines design to improve the instrument's reliability when used in conditions of elevated temperature and humidity.

The design changes were incorporated into the BDG as a result of the high failure rate experienced during testing at the NSTF and primarily included improvements of the sealing system to prevent moisture intrusion.

Calibration testing of the BDG was also revised to improve characterization of the gage response to thermal conditions. The thermal and mechanical behavior of the gage is unique to the strain gage bridge in question and while deformational testing is straightforward, thermal compensation is complex and involves several factors. Characterization of thermal expansion of the gage components is the most

critical factor related to temperature changes and a new testing apparatus was developed specifically for this purpose. Testing consists of placing the BDG in a stepped fused-quartz calibration cup whose increments are representative of the anticipated in situ borehole deformation.

The algorithm used to convert voltage output to stress change comprises three parts which include calculating borehole deformation, free-field expansion of the borehole and stress change magnitudes and direction.

Calculating borehole deformation includes accounting for the bridge sensitivity, changes in sensitivity with temperature, and compensating for the thermal expansion of the gage and associated strain dependent behavior. So that stresses can be estimated directly in the rock mass, as opposed to a borehole, corrections are made for free-field expansion of the borehole in a heated environment based on the thermal expansion coefficient of the rock. Lastly, the maximum and mimimum principal stress changes and the direction of the maximum principal stress change are calculated, based on the work of Lawrence Berkeley Laboratories which takes into account the influence of thermally induced stress changes along the borehole axis.

VIBRATING WIRE STRESSMETER

The vibrating wire stressmeter senses uniaxial stress change, therefore three are installed in a borehole at 60° intervals (corresponding with the three BDG axes) to determine the maximum and minimum principal stress changes in a plane normal to the borehole axis. The VWS was modified to improve reliability by plating components to reduce corrosion and by replacing o-rings with metal inserts which are electron-beam welded to the gage body to prevent moisture infiltration.

Characterization of the VWS consisted of the following four stages in order to characterize gage response to stress changes:

- *Design screening test*
- *Calibration testing*
- *Analytical study*
- *Aluminum uniaxial test*

The design screening test examined the influence of six potential factors on the VWS response in order to determine the scope of further testing. These factors, gage type, basalt sample, VWS initial wire stress, change in wire stress during installation, temperature, and in-situ stress on installation, were studied at the extremes of the anticipated range. Calibration testing consisted of determing the optimum setting preload for gage installation and gage sensitivity as a function of temperature and biaxial pressure. To study the behavior of a stressmeter in anisotropic stress fields, a number of linear elastic, finite element analyses were performed in which the effects of anisotropic stress changes, elastic properties of the rock mass, and preload settigs were investigated. Finally, tests were conducted in an aluminum block to study the influence of gage orientation with respect to uniaxial stress changes, to further examine thermal effects, and to validate the results from the analytical study.

The VWS algorithm used to evaluate the changes in the stress field in the rock mass consists of three parts. First the wire stress in each of the three stressmeters is evaluated and then corrections are made for changes in temperature. Lastly, the Newton Raphson method utilizing an iterative approach is used to simultaneously solve three *independent nonlinear equations to determine the maximum and minimum principal stress changes and the angle of the maximum principal stress change.*

BLOCK TEST RESULTS

The Block Test currently underway at the NSTF consists of a cube of basalt two meters on a side confined in the three orthogonal directions by flatjacks and a cable anchor system. The dimensions of the test block were selected to incorporate a sufficient number of structural discontinuities so that the deformational response will be representative of the rock mass. This arrangement allows the application of a known triaxial stress field in the test region and, by measurement of the displacements across the block, an evaluation of the deformation response of the rock mass. This test set-up also provides an opportunity to investigate the response of borehole stress measurement instrumentation to a known stress field input. Five borehole deformation gages and eight vibrating wire stressmeters were installed in four boreholes within the test block and their response was monitored during deviatoric loading in the vertical and horizontal directions.

The results generated by both types of instruments over several loading cycles were somewhat surprising. During loading in the vertical direction the instrument outputs correlated quite well with the applied stress, while loading in the horizontal direction produced gage responses with little similarity to the flatjack pressures. This discrepancy is initially attributed to the effect of the major joint set in the vertical direction. Agreement between all gages was quite good, especially with the VWS, however, the malfunction of two BDGs reduced the number of available data points.

CONCLUSIONS

Based upon the results of the analytical studies and in-situ testing involving the BDG and VWS, the following conclusions have been made with regard to the applicability of these instruments to stress measurement in closely jointed rock:

- *Instrument measurements of stresses performed while the rock mass exhibited a linear elastic response (i.e., vertically) were quite good, while measurements performed when the rock mass exhibited inelastic behavior (i.e., horizontally) deviated significantly from the predicted stresses. This phenomenon was attributed to the influence of the large aperture vertical joint set.*

- *Stress results from the VWS were generally in closer agreement to the applied stresses than were those from the BDG.*

- *Hermetic sealing improved VWS reliability significantly while BDG performance, although somewhat improved, will require future work to adequately seal the gage.*

- *The thermal expansion testing of the BDG has improved the calibration significantly, but the technique requires some refinement.*

This analysis was based upon the results from the Block Test loading cycles conducted at the ambient rock temperature. Future testing will continue the evaluation at elevated temperatures up to 200°C.