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AN EXAMPLE OF FRACTURE CHARACTERIZATION IN GRANITIC ROCK

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ABSTRACT

A detailed study of geologic discontinuities for an underground heater test in highly fractured granitic rock is reported. Several prominent shear fractures were delineated within a 6x30x15 m rock mass by correlating surface mapping and borehole fracture logs. Oblique-reverse faulting is suspected on at least one of the surfaces, and its inferred borehole intercepts appear to be collinear in the direction of slickensiding observed in the field. Four distinct joint sets were identified, one of which coincides with the shear fractures. Another lies nearly horizontal, and two others are steeply inclined and orthogonal. Fracture lengths and spacings for the four joint sets are represented by lognormal probability distributions.
AN EXAMPLE OF FRACTURE CHARACTERIZATION IN GRANITIC ROCK

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INTRODUCTION

The characterization of geologic discontinuities is an important issue for underground nuclear waste storage. An observational study of natural fracturing in granitic rock was conducted at the Stripsa mine, Sweden, in support of underground thermomechanical experiments by the Lawrence Berkeley Laboratory and the Swedish Nuclear Fuel Safety Board (Witherspoon and Degerman, 1978). Two objectives were involved: first, major geologic features such as faults, shear zones, or dikes were identified and described geometrically for input as discrete elements in numerical models of the rock mass. The second task was to provide statistical information on the jointing between major features from which equivalent continuum properties could be estimated. Of interest here are the distributions of joint orientation, spacing, and persistence as represented by trace length.

The Stripsa mine, located in south-central Sweden, is an inactive iron mine which incorporates a massive, medium-grained quartz monzonite pluton within its workings. The experimental site is at a depth of 338 m in the pluton and approximately 150 m from the contact with the synclinal ore body. As part of an integrated program of rock mass characterization (Witherspoon, et al., 1979), the work described here pertains to a specific heater test, termed the "time-scaled" experiment, designed to investigate long-term thermal effects. A rock volume of roughly 6x30x15 m³ is involved, containing an array of eight 1-kW electrical heaters. The heaters simulate radioactive waste canisters scaled by a factor of 0.32, which according to laws of similarity and heat conduction allows a ten-fold compression of the time scale (see Cook and Hood, 1978). The heater test was concluded in late 1979, and the data reported here are being incorporated into analyses and models of the experiment.

METHODS

Heaters for the experiment were placed at a depth of about 10 m beneath the underground drift according to the pattern of vertical boreholes in Fig. 1. In order to characterize discontinuities at that depth, information from the heater and

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Fig. 1. Layout of vertical boreholes for scaled heater test.

Instrumentation boreholes was combined with detailed fracture mapping of the floor of the drift. Statistics were extracted from both sets of data, and major continuous features were identified on the basis of mapped exposures and cross-correlation of their borehole intercepts. While this approach is entirely standard, our techniques are worth brief mention.

The borehole logs were prepared from oriented core samples, using the device in Fig. 2 to orient each section of core. An estimated error of ±5 degrees was involved in the technique; however, this was not cumulative due to the high degree of core recovery and reconstruction that was possible. Core logs mainly contained information on discontinuities, including the location, orientation, surface characteristics, and mineralization of prominent or open fractures, plus changes in lithology.

Mapping of discontinuities in the floor of the drift was done in considerable detail, sampling fractures down to about 30 cm in length. After the floor was cleaned, it was marked with a 1 x 1-m horizontal grid system. Fracture outcrop traces were then mapped in each square
Fig. 2. Downhole core orientation device.

The mapping, using a reference frame as shown in Fig. 3. The process was inherently biased against nearly horizontal features, and when sampled, their traces were usually very irregular due to the uneven topography of the floor. Errors in location and length of traces were probably on the order of a few centimeters. The resulting fracture map is shown in Fig. 4.

Fig. 3. Mapping of fractures in drift floor.

Fig. 4. Floor fracture map for scaled heater test.
Fig. 5. Subsurface profile of major features along centerline of drift.

DETERMINISTIC RESULTS

As a starting point for finding important discontinuities at depth, the more continuous features in the floor map were identified. Based on orientations measured at their outcrops, each of these was extrapolated downward to its expected points of intersection with the vertical boreholes. Positive correlation in the subsurface was made according to the proximity, orientation, and surface characteristics of discontinuities from the core logs. Not surprisingly, few features were found to extend more than a couple meters into the subsurface.

Some success was achieved, however, in extrapolating and locating several steeply-inclined features striking transverse to the drift. As shown in the profile of Fig. 5, these are minor faults or shear fractures that extend into the heated region of the rock mass. They generally offset or truncate other discontinuities in the floor map, and by inference, in the subsurface as well. The most prominent and well-defined of the faults, labeled no. 3, apparently offsets a vertical 20 cm-wide pegmatite dike at a depth of about 8 m.

Fig. 6 shows 3-D views of the fault surfaces, each formed by triangular planes connected at the correlated borehole intercepts. Boundary points were extrapolated from orientations measured at neighboring borehole intercepts, and thus are subject to more uncertainty than the borehole points. Slickensiding was observed on no. 3, and we would expect the points defining its surface to be nearly colinear in this direction. Fig. 6b demonstrates this by rotating the fault diagram 45 degrees in the direction of shearing. If the extrapolated boundary points are deleted from this view, as in Fig. 6c, the subsurface intercepts for faults indeed line up with minimum deviation. This is an important kinematic consideration in modeling the experiment.

STATISTICAL RESULTS

Jointing between the major features is best described statistically, as evidenced by the pervasive pattern in the detailed fracture map. For the present study, orientations were obtained from the vertical borehole logs. Fig. 7 is a contour diagram of these data, where four distinct joint sets are labeled. Set 1, though poorly defined, corresponds in orientation to the four faults discussed above. Set 2 represents a series of steeply-dipping joints, orthogonal to Set 1, that strike roughly parallel to the drift. The floor map indicates these are usually truncated by the faults of Set 1. Joint Set 3 is orthogonal to Set 2, but few fractures of this orientation appear as continuous traces in the detailed floor map. Subhorizontal joints of the fourth set are not represented in the floor map, of course, due to geometrical biasing.
(a) Plan view; local coordinate system is centered in the plane of the heater array.

(b) 45° rotation of (a) in the observed direction of slickensiding on no. 3.

(c) Same view of no. 3 as in (b), with extrapolated boundary points deleted.

Because of the well-defined joint sets, analysis of fracture spacing can be made according to orientation. Boundaries for the four joint sets are taken as the 1.5 percent (average density) contour of Fig. 7, which allows fractures in the borehole logs to be assigned to particular sets. Vertical spacings between consecutive joints of the same set were computed, and values for all fracture logs produced the histogram plots in Fig. 8. Statistics were determined by plotting the data in lognormal probability form, as shown by Fig. 9. Linear functions through the points indicate that median normal spacings for the joint sets, corrected for the dip angle, range from a quarter meter for Sets 2 and 3 to just over a half meter for Set 1.

Fig. 6. Orthographic projections of shear fractures based on mapped traces and correlated borehole intercepts.

Fig. 7. Stereographic contour plot of fracture poles, based on 827 joints logged in the boreholes. Lower hemisphere projection; counting circle was 1.5% area.

Fig. 8. Histograms of vertical fracture spacings from borehole data.
Fig. 9. Lognormal distributions of vertical fracture spacings.

The persistence of joints, or trace lengths, can be determined from the detailed floor map. Although orientations for only a portion of the mapped fractures were measured, joints were grouped into sets on the approximate basis of their dip directions. Fig. 10 represents the corresponding set boundaries on the stereonet. Fractures dipping less than about 30 degrees were not usually mapped, which eliminated Set 4 from consideration. At the other extreme, fractures dipping more than about 85 degrees were marked vertical in the mapping, enabling the outer boundaries of each set in Fig. 10 to be distinguished. Resulting trace length histograms from the floor map are shown in Fig. 11, and Fig. 12 plots the lognormal distributions. Median lengths range from 0.58 m for Set 3 to 1.28 m for Set 1. Many of the lengths in Set 1 are censored by the size of the drift, and correction for this (Baecher and Lanney, 1978) has not yet been made.

MODELING CONSIDERATIONS

The deterministic results indicate that the four faults and pegmatite dikes in Fig. 5 can be modeled on a discrete basis. Although the experiment is three-dimensional, some initial 2-D finite element calculations could be made to determine the effect of these features on the rock mass behavior. Since their orientations are nearly perpendicular to the long axis of the experiment, it is suggested that a plane-strain model with a profile similar to that in Fig. 5 could be used for scope and studies. The direction of minimum shear resistance along fault no. 3, however, is not in this direction; therefore, it would be best represented with a joint element conforming to the irregular shape in the given profile. Initial 2-D calculations such as this might indicate whether certain major discontinuities will be important in later 3-D models.

An anisotropic continuum model could be used to model the highly jointed rock between the major discontinuities (Goodman, 1976). Required parameters are the joint orientations, spacings, and shear and normal stiffnesses. Laboratory testing would be needed for the latter.
properties, while orientations and spacings could be based on the reported statistics. In regard to selecting specific input values, there is little ambiguity about the dominant set orientations according to Fig. 8; however, the median fracture spacings found in the lognormal distributions have little fundamental significance to the rock mass behavior. While it has been argued that spacings are exponentially, as opposed to lognormally distributed (Baecher and Lanney, 1978; Priest and Hudson, 1976), neither description provides a unique input value for numerical models. A reasonable approach would be to first estimate the sensitivity of a 2-D model to different spacings, then use these findings to guide the selection of parameters for a limited number of 3-D calculations.

Several additional points should be considered in setting up continuum models for the experiment. First, mechanical properties of joints are stress-dependent, and they will thus be influenced by the in-situ state of stress. Stress measurements near the experiment by Carlsson (1978) show that the maximum principal stress is nearly horizontal and oriented ESE-WNW. This suggests that joints of Set 2 are highly compressed, and should therefore have relatively high shear and normal stiffnesses. Alternatively, Sets 3 and 4 are oriented nearly perpendicular to the minimum principal stress, so their influence on the mechanical response of the rock mass may be more pronounced.

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REFERENCES


