

Changes in in situ rock joint flow characteristics caused by mechanical displacement

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ABSTRACT--Joints provide paths for fluid flow through rock. Prediction and control of contaminant transport in ground water requires understanding the process of fluid flow in fractures.

In this study, a natural fracture was isolated from a low-permeability rock mass within a prototype in situ test block (volume 8 m³). Three-dimensional displacement monitors surrounded the test fracture and a borehole probe monitored the fracture's gas conductivity. The fracture was loaded by hydraulic flatjacks in the block's boundary slots.

The results showed that rock displacement and fracture conductivity often changed in contradictory ways under load. The lower-than-expected correlation between mechanical and flow responses of the test fracture apparently was due to the presence of a large number of semi-independent rock subblocks; the test fracture behaved as two flexible tiled walls rather than two rigid plates. The subblocks were defined by seemingly minor, discontinuous joints. The instrumentation grid was too coarse and arbitrarily placed to allow satisfactory characterization of the behavior of the joint network.

Minor fractures thus appear to be a major cause of behavioral unpredictability. However, these fractures are extremely difficult, if not impossible, to map or characterize in detail. This leads to the fundamental question of whether confident modeling of jointed rock masses is feasible with current deterministic approaches to both modeling and field instrumentation.

1 INTRODUCTION

The overall hydraulic conductivity of the rock mass surrounding any excavation is affected by the excavation's presence as well as by long-term tectonic events. Stress concentrations around the periphery of an opening cause rock displacements that in turn alter the effective hydraulic conductivity of the near-field rock mass.

Prediction of changes in conductivity of a given rock volume caused by changes in the acting stress field is an integral part of the engineering design process. The basis of most predictive methods is a relatively straightforward conceptualization of the behavior of a single fracture under changing load: a gap between two blocks of intact rock that narrows as the loading component normal to the fracture increases.

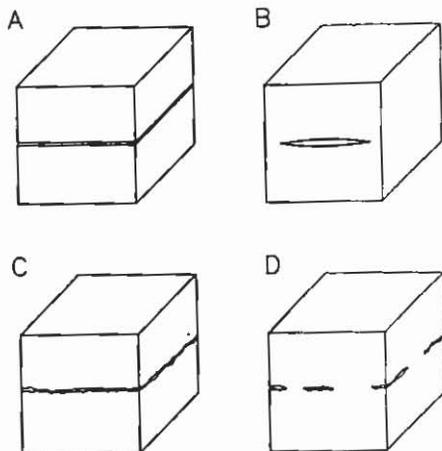


Figure 1. Structural and geological map of test block surface and sides (after Richardson, 1986).

(The conceptualization becomes less clear when load is applied parallel to the fracture.) According to this model, points within the rock on opposite side of a fracture should move toward each other when compression is applied to the fracture. Since fracture conductivity is a function of the width of the gap (the fracture aperture), the conductivity of the fracture itself should decrease in turn.

The details of this conceptualization become important when it is applied to the real world. The simplest model—two smooth, infinite parallel plates a constant distance apart (fig. 1A)—is easiest to deal with mathematically. However, real fractures are rough, finite, and contain significant areas of contact between their walls (fig. 1B through 1D). Some of these deviations from the parallel-plate model have been addressed (e.g., Iwai, 1976; Gale, 1982; Long, 1987; and others), often with the aid of laboratory experiments and/or numerical models. These studies have added much to the understanding of fluid flow through fractures and the coupling of fluid flow with mechanical behavior.

The next step in predicting conductivity in situ is to check the utility of the parallel-plate model with field experiments. A major difference among numerical models, laboratory experiments, and field experiments is the difference in uncertainty of the boundary and initial conditions. Unknown components contribute more to experimental results as conditions approach those in the real world. Field studies evaluate the appropriateness and effectiveness of measurement methods to a greater degree than do more controlled experiments. The effects of choice of conceptual model and the effects of measurement methods cannot be separated. This is not necessarily a flaw. Rather, this situation should be considered as part of the calibration of a model. The utility of a model is related directly to the feasibility of collecting the data required.

This paper presents the results of some experiments performed in situ with a large block of fractured rock. The goal was to determine whether accurate, precise measurements of the coupled behavior (deformation and flow) of a single fracture could be obtained with an in situ test block.

2 METHODOLOGY

The experiments were performed with the Colorado School of Mines (CSM) in situ test block, a 2-m cube of gneiss drilled out in the floor of a drift inside the CSM Experimental Mine in Idaho Springs, CO. The test block was surrounded on four sides by hydraulic flatjacks to control

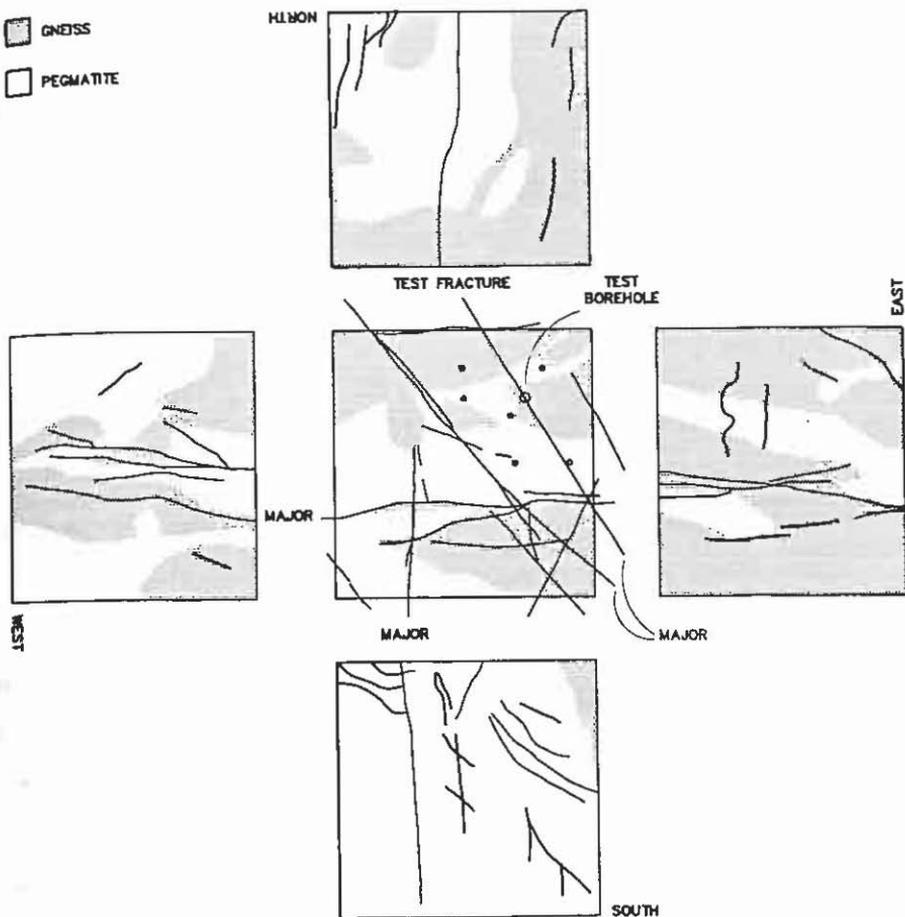


Figure 2. Some conceptualizations of fractures: A) infinite, smooth parallel plates at constant aperture, B) finite, C) rough, D) significant contact area.

boundary pressure. In this way, a portion of the control normally associated with laboratory experiments was retained.

Prior to the experiments, the test block was mapped in some detail. Each of the 24 boreholes in the block was recorded on videotape with a borehole camera, and the surface and sides of the block were photographed and mapped (fig. 2). Four major fractures and many lesser ones (tight, irregular, or apparently not interconnected) were discovered. One of the major fractures was chosen as the test fracture. It was vertical, undulating, and moderately rough; a 7.2-cm diameter borehole followed the fracture to a depth of 1.6 m. Six smaller boreholes in the vicinity of the test fracture served as sites for rock stress and movement sensors. A system to monitor the three-dimensional movement of points 1 m below the surface was installed in each small borehole. The borehole that followed the test fracture was used to characterize

hydraulic conductivity and local deformation of the fracture. Gertsch (1989) discusses the instrumentation in detail.

Four configurations of boundary loading were used during the course of the experiments, but only the "equal biaxial" portion (equal loading of all four sides) is discussed here. The maximum boundary pressure of 6.8 MPa was reached in eight load increments. The mechanical response of the rock surrounding the fracture was monitored continuously, and a full suite of flow tests was conducted at each load level. For the sake of brevity, only the response of the region of the fracture between 43 and 97 cm deep is discussed. Complete results are in Gertsch (1989).

3 RESULTS AND DISCUSSION

Equal biaxial loading of the test block had been expected to cause nearly pure compression of the test fracture, resulting in closure of the fracture and an associated decrease in hydraulic conductivity. Translated to the expected responses of the instruments, this meant that, as the boundary pressure on the test block increased, 1) the boreholes on opposite sides of the test fracture were expected to move toward each other (all moving toward the block center), 2) the local deformation monitors were expected to register closure of slightly smaller magnitudes, and 3) the hydraulic conductivity was expected to decrease.

Figure 3 illustrates the actual responses of the test fracture and the surrounding rock. Each row of drawings represents the behavior due to the latest boundary pressure increase (a running total of the load is on the left side of the figure). The three-dimensional movements and tilting of the six instrumented boreholes and the relative fracture movements within the large borehole are magnified and plotted on sketches of the test block. Block boundaries and the major fractures are shown for reference. Note that relative fracture deformation (dashed line) is plotted as movement of the upper right side of the fracture, as if the lower left side had remained stationary. The accompanying change in hydraulic conductivity (ΔK) is listed below the load total.

At lower boundary pressures, the test block behaved mechanically much as expected, with minor deviations in tilting and in vertical movement. Until fracture compression reached 2.5 MPa, the outer wedge moved relatively consistently toward the block center. The tilt vectors, however, already showed differential rotation, and the rock surrounding the test fracture generally dropped instead of rising. Curiously, the conductivity increased consistently to this point.

When the load reached 2.5 MPa, the outer wedge began to rotate and the conductivity finally decreased, although not to preload levels. Conductivity began to increase again with the next load increment and continued increasing for the remainder of the equal biaxial configuration. This increase in conductivity occurred despite some wild swings in mechanical behavior. At 3.9 MPa, the fracture opened dramatically, then, after little response at 5.3 MPa, closed again as suddenly at 6.8 MPa. This abrupt behavior was especially noticeable in the local fracture movements, although the other instrumentation sites also showed contradictory movements (e.g., compare the movements of the two leftmost boreholes at 3.9 and 6.8 MPa). Significant gradients of

shear must have existed within the test fracture, despite the absence of applied shear loading.

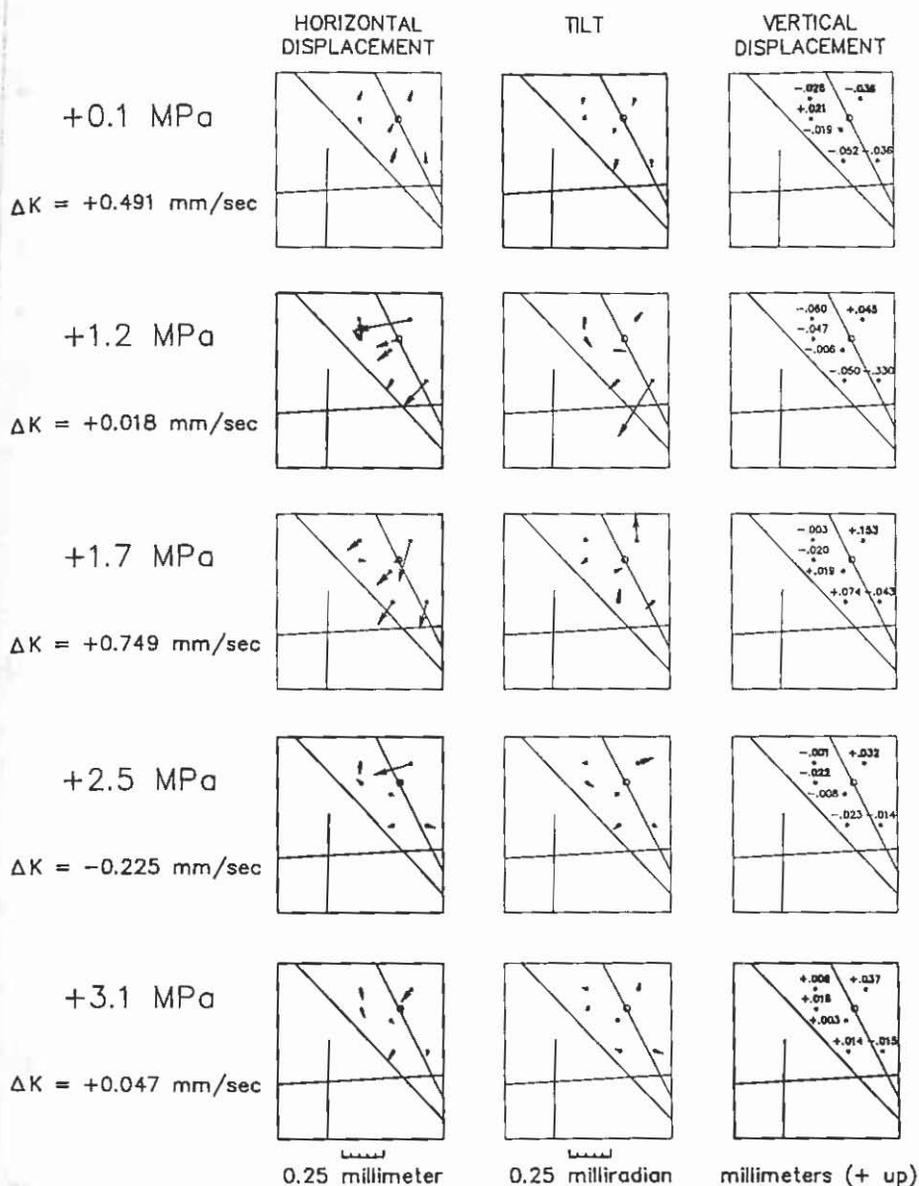


Figure 3. Measured incremental responses to equal biaxial load steps. Movements are shown by magnified vectors originating at the boreholes where the measurements were taken.

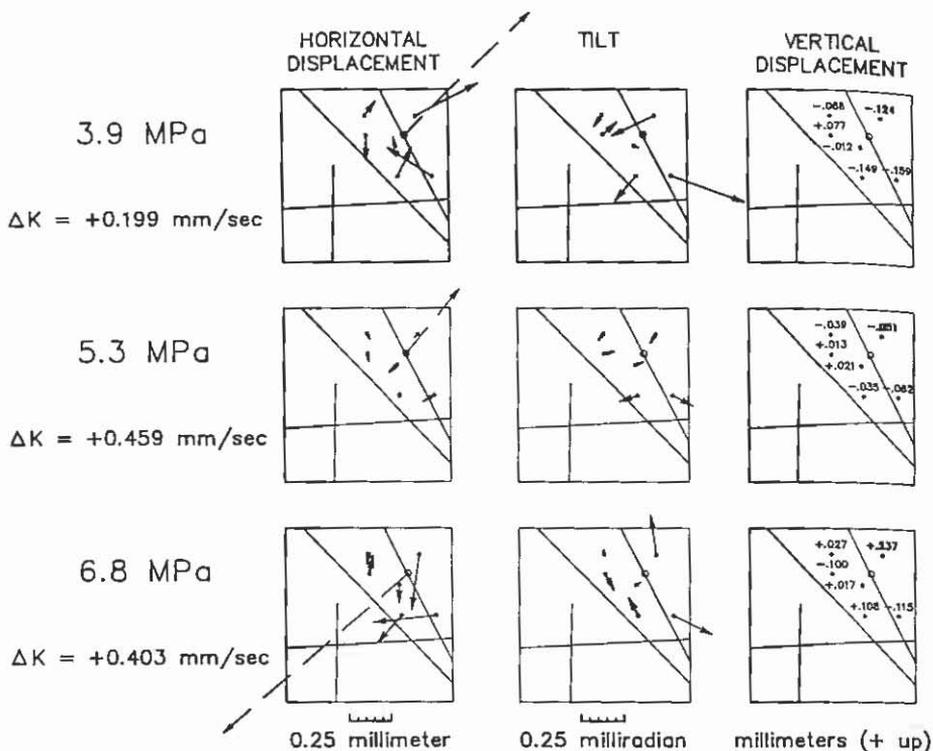


Figure 3.--Continued

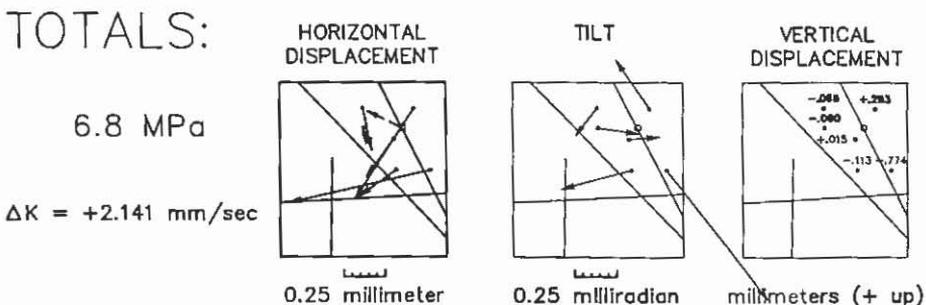


Figure 4. Measured total responses to maximum equal biaxial load.

Figure 4 illustrates the vector sums of all the incremental responses shown in figure 3; in other words, the total response of the test block to the maximum equal biaxial boundary pressure. Note that this figure gives no hint of the behavioral complexities apparent in figure 3.

4 CONCLUSIONS AND RECOMMENDATIONS

The test fracture characterized in this study did not behave as a simple interface between two intact rock blocks. Rock movement a small distance from the test fracture did not agree consistently with rock movement near the fracture. The conductivity of the test fracture often changed in contradiction to the sense of the rock movements. Apparently, an unmapped network of discontinuous fractures influenced both the mechanical response of the rock and the conductivity response of the test fracture to different extents, depending on the relative rock volume involved in each type of measurement (fig. 5) and on the different sensitivities inherent in each measurement. The contributions of each of these unexpectedly important fractures varied unpredictably with applied load and, in an apparently nondeterministic manner, with load history.

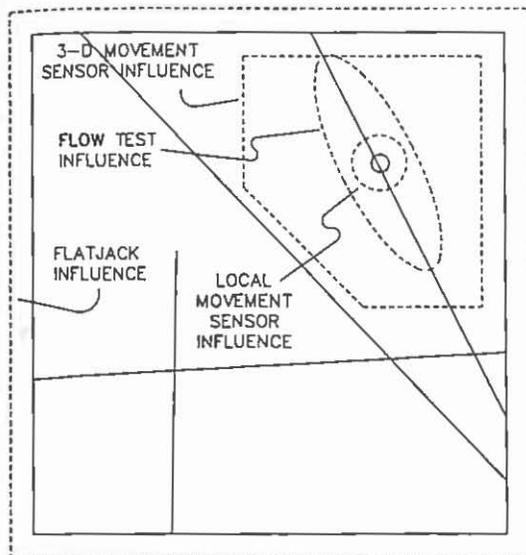


Figure 5. Relative volumes of influence of different measurement and testing systems.

obtain. Therefore, the conceptualization of a rock fracture as a simple void between two rock blocks may be unworkable for field use. The large amount of uncertainty in determining the initial conditions even within a small, carefully mapped volume of rock may preclude deterministic modeling of all but the very simplest situations.

The ability of numerical models to simulate reality has exceeded the ability of current field characterization techniques to provide accurate input data. It may be counterproductive to continue increasing the power of numerical models without guaranteeing that the input data is worthy of the models' accuracy.

The structure of the test block has been modeled previously (Sour et al., 1987; Brown, 1986). In both cases, the block structure was simplified to make model formation feasible. Mapping information was not used to its fullest extent because of the very large amount of time that would have been required to incorporate it. Yet, the field data collected in previous (Brown, 1986; Richardson, 1986) and present studies indicate strongly that undiscoverable discontinuities play important roles in governing rock mass response. The immediate conclusion is that deterministic modeling is not practical for predicting the behavior of jointed rock masses; the models may be accurate, but the data to calibrate them is nearly impossible to

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