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The modelling and measurement of super-conducting rock joints

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1 INTRODUCTION

Rock joints exhibiting exceptionally high conductivity have been responsible for severe inflows (10-50 m^3/min.) and flooding in recent Norwegian tunneling projects. These events may be explained by channeling of flow in partially outwashed mineral fillings, associated with deep weathering in ancient basement rocks. There is also evidence to suggest extensional strain with consistent relationships to regional faulting patterns (Selmer-Olsen 1981).

Hydraulic fractures making connection with joint systems that are sheared as a result of increased fluid pressure, has been deduced as the mechanism explaining unusually large fluid losses in the geothermal project in Cornwall, England (Pine and Batchelor, 1984). Such mechanisms also introduce uncertainty into water flood and MHF stimulation treatment of fractured oil and gas reservoirs, particularly when principal stress and joint orientations are poorly understood due to coring and stress measurement problems in weak, overstressed reservoir rocks.

The possibility of permanent disposal of nuclear waste in crystalline rock, has also focussed attention on highly conductive ("super-conducting") joints in nuclear waste programmes in Canada, the USA and in Europe. The bi-modal distributions of joint spacing, continuity, apertures and conductivities resulting from the discovery of super-conducting joints has important implications for the location of planned repositories, due to their dramatic impact on potential transport times.

In the laboratory a class of super-conducting joints can be created by shear displacement that causes dilation when shearing non-planar features. Recent biaxial shear testing of rock joints recovered in jointed core has identified a strong coupling of conductivity and shear displacement. The theoretical predictions of constitutive relationships for coupled flow in rock joints (Barton et al. 1985) have been broadly verified. However, further work is required to identify the influence of gouge production in shear-flow coupling, when weaker materials or higher stresses are of interest.

2 MAJOR LEAKAGES IN TUNNELS

Recent articles in the Norwegian tunneling literature describe some dramatic cases of water inflows in tunnels, in connection with a dozen or so recent hydro power developments. Løset (1980) describes inflows of

12-15 m^3/minute at a pressure of 2-3 MPa in the Tyrveli-Bordalsvatn tunnel of the Kjela project. Small lakes and streams 250 m above the tunnel were rapidly drained, necessitating plugging of the tunnel and local diversion. In the Saurdal-Sandsvatn tunnel of the Ulla Førre project an initial leakage of 50 m^3/minute was registered in one zone, and 2 1/2 kilometers of tunnel was completely flooded.

A common feature of these leakage zones was the deeply weathered nature of the discontinuitites, even to depths of 400 meters. In general they consisted of partly outwashed sand, gravel and carbonate (mostly calcite) fillings, and leakages often occurred under high terrain. Obvious weakness zones in the terrain tended to be tight at tunnel depth due to clay filling.

The deep weathering of the basement pre-cambrian gneisses and granites, probably occured before the Cambro-Silurian sediments were deposited. The fact that these weathered discontinuities were previously filled with hydrothermal products of alteration may perhaps be explained by the regional stress distributions. Selmer-Olsen (1981) found that in 80 % of the major leakages, the sub-vertical discontinuities were oriented at 45° ±15° to the strike of major faults in the area. This suggests that many of the discontinuities were approximately parallel to the major horizontal stress and therefore extensional features. Other cases reported by Løset (1980) were more complicated, with large leakages registered in discontinuities with various orientations. In some of these cases wide apertures may have been associated with shear displacement.

3 EQUIVALENT JOINT APERTURES

It is of interest to make a preliminary estimate of the theoretical joint aperture required to allow the above maximum level of leakage. We can assume that one major vertical joint intersects a tunnel at right angles, and makes connection to the surface. The flow to, or from, a horizontal equipotential can be described by the following equation:

$$e^3 = \frac{6 \cdot Q\mu \ \ln\ (2D/r)}{\pi \cdot g \cdot (P_r)}$$

where Q = flow rate (cm^3/sec)
μ = dynamic (or absolute) viscosity of water (gm/cm·sec)
D = depth to tunnel (m)
r = tunnel radius (m)
g = acceleration due to gravity (981 cm/sec^2)
P_R = pressure head (gm/cm^2)
e = conducting aperture of joint (cm)

Substitution of the following values; D = 250 m, r = 4 m, P_R = 2.5 MPa, Q = 50 m^3/min, μ = 0.0145 gm/cm·sec, results in a theoretical value of (e) of 1.66 mm. The median aperture of 25 µm back-calculated from Canadian borehole pumping tests, (Davison et al. 1982), would result in 0.17 liters inflow per minute for an 8 m diameter tunnel located 250 meters below the surface as in the previous example. The ratio of apertures (1660/25) when cubed, makes a very significant reduction to the catastrophic leakage of 50 m^3/minute reported above.

Many of the major inflows into these Norwegian tunnels were concentrated along the intersection lines of regional joints where outwash of hydrothermal filling materials (carbonates) had occured. In the

Forsmark tunnel in Sweden, Carlsson and Olsson (1977) found that the locations where most inflow occurred were related to local widening of the joints. This was reportedly related to dilation, or to crushing at joint intersections.

The observations of canal-like flow at tunnel perimeters may nevertheless be a function of the disturbance caused by excavation, and by the very highly eroding flow rates that occur initially upon first exposure to atmospheric pressure. Possibly the parallel plate model of flow is also more valid away from the zone of disturbance because shear stresses and displacements will be less marked.

4 MECHANICAL AND CONDUCTING APERTURES

Modelling the effects of hydraulic fracturing in jointed reservoirs, and thermal effects in planned nuclear waste repositoires, has refocussed attention on the importance of coupling between mechanical and hydrologic processes in jointed rock. A first step in this process is the comparison of real (mechanical) joint apertures (E) and the theoretical smooth wall conducting apertures (e) used in the cubic flow law. The effect of changes in ΔE on Δe, are obviously of prime interest.

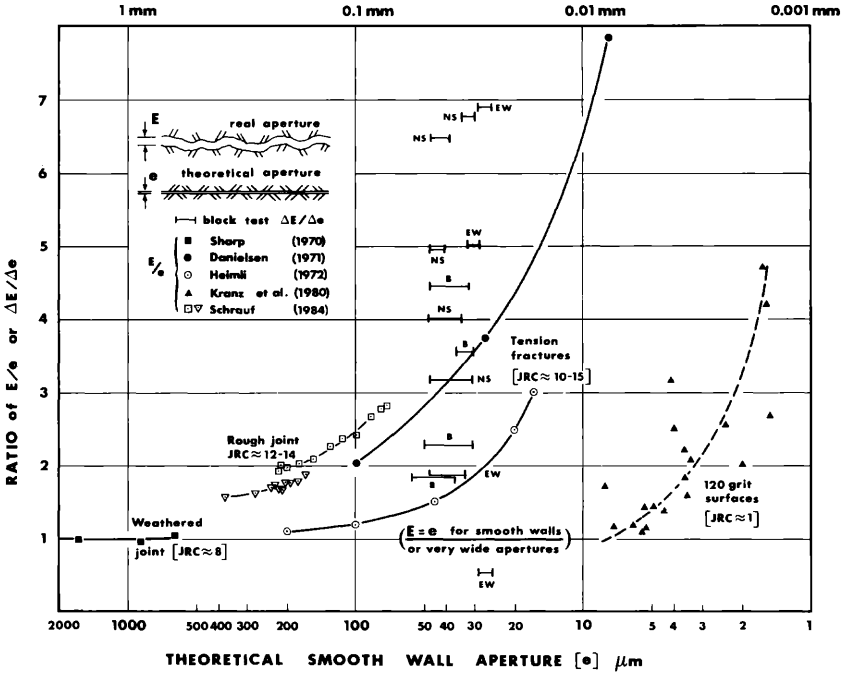

Figure 1. Comparison of real mechanical apertures (E) with theoretical smooth wall conducting apertures (e). The mismatch is caused by flow losses due to tortuousity and surface rough ness. After Barton et al. (1985).

Figure 1 illustrates a recently updated set of experimental data, showing increasing divergence between ΔE and Δe (or E and e) as aperture reduces. Obviously the same effect will be seen as normal stress level increases.

An empirical equation describing the experimental trends shown in Figure 1 can be derived by including the joint roughness coefficient (JRC). This parameter affects joint closure under stress. It also determines the types of contacts, and therefore indirectly the tortuosity of flow and the frictional drag resisting flow between the joint walls. The following relationship is used:

$$E = \sqrt{(e \cdot JRC_o^{25})} \qquad (2)$$

The subscript represents nominal laboratory size 100 mm long samples. JRC_o is obtained from tilt tests as described by Barton and Choubey (1977).

5 MODELLING SHEAR-FLOW COUPLING

The modelling of shear-dilation-conductivity coupling is based on a mechanical model of stress-displacement and dilation-displacement behaviour. The following two equations are general expressions of the friction angle (ϕ'mob) and dilation angle ($d_n$mob) mobilized at any given displacement and for any combination of normal stress/wall strength (σ_n'/JCS) and for any value of mobilized wall roughness JRC(mob). Full scale roughness (JRC_n) is assumed.

$$\phi'(mob) = JRC_n\ (mob)\ \log\ (JCS/\sigma_n') + \phi_r \qquad (3)$$

$$d_n^o\ (mob) = 1/2\ JRC_n(mob)\ \log\ (JCS/\sigma_n') \qquad (4)$$

It is assumed that the initial conducting aperture (e_o) can be obtained with sufficient accuracy from discrete borehole pumping tests (see for instance Davison et al. 1982) or from the statistical treatment of such tests as described by Snow (1968). Such a value of e_o would be converted to the mechanical aperture (E_o) using equation 2. Changes of aperture ΔE caused by dilation are calculated from the shear displacement increment ($\Delta\delta$) as follows:

$$\Delta E = \Delta\delta \tan d_n^o(mob) \qquad (5)$$

The conductivity at any given shear displacement is calculated by converting ($E_o + \Delta E$) into a conducting aperture (e) using equation 2. The familiar relation between conducting aperture and conductivity (k)

$$k = e^2/12 \qquad (6)$$

is used to obtain the final parameter needed for modelling the shear-flow coupling.

An example of typical output from the model is reproduced in Figure 2. We have assumed typical values of joint wall strength JCS_o obtained from Schmidt hammer measurements of partly weathered joint walls, in rock with an unconfined compression strength of 150 MPa. A medium level of joint roughness was assumed. Two different initial apertures were used. These were obtained from the normal closure part of the modelling, as described by Barton et al. (1985).

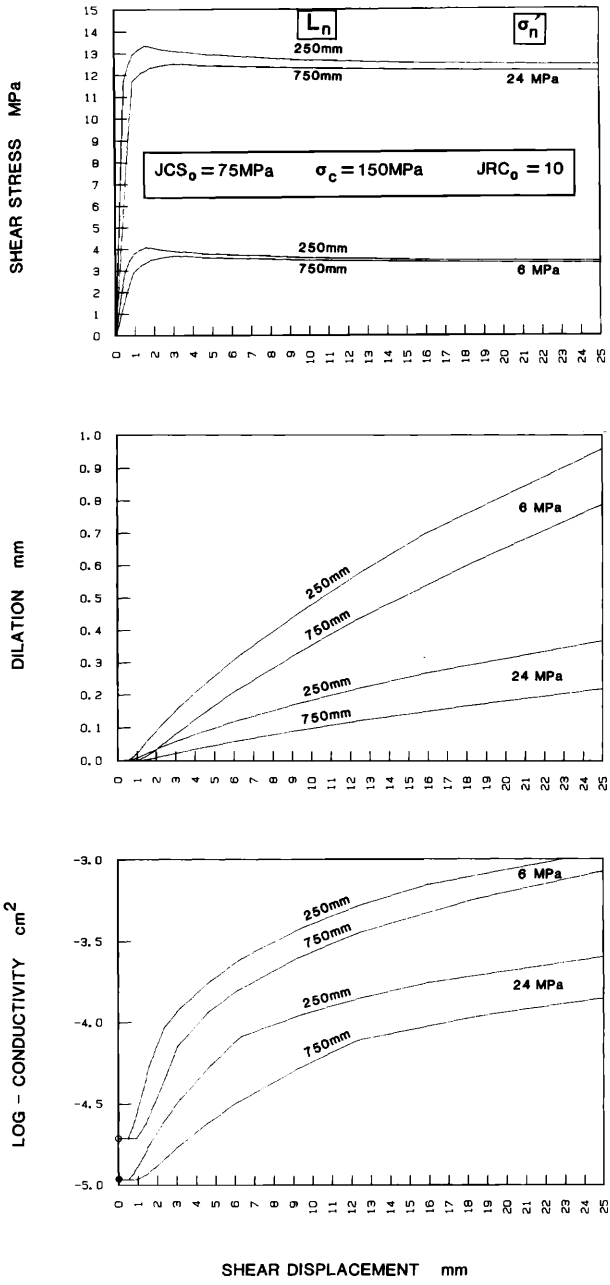

Figure 2. A typical set of model results which demonstrate the coupling of shear, dilation and flow, for two block sizes at two different effective normal stress levels. After Barton et al. (1985).

6 LABORATORY TESTS OF SHEAR-FLOW COUPLING

The dramatic changes of joint conductivity predicted by the numerical model emphasise the importance of obtaining experimental data to validate some of the results we have obtained. NGI has recently developed a special biaxial cell (Makurat, 1985) in which shear-flow coupling can be measured on jointed cores of 150 mm or more in diameter. A cross-section through the cell is shown in Figure 3.

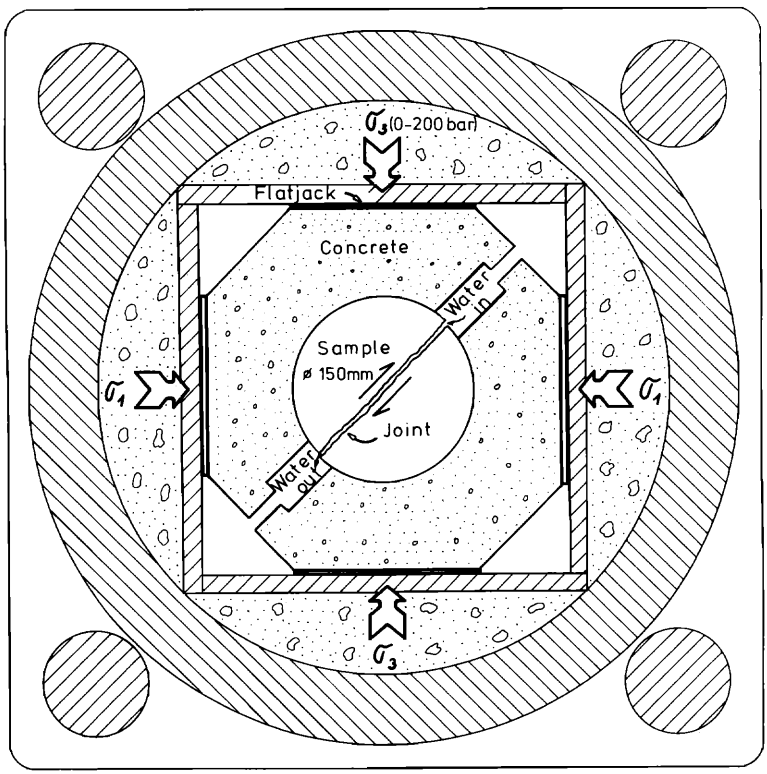

Figure 3. Cross-section of NGI's biaxial flow-deformation cell. After Makurat (1985).

The jointed samples are set in a reinforced molding material, which forms the loading plattens. Normal and shear stress components are developed by flat jacks. Both shear and normal displacements across the joint are measured concurrently with flow rate, using a novel sealing system.

Figure 4 illustrates several sets of data from tests on a joint in gneiss. This joint had the following characteristics: JCS_o = 160 MPa,

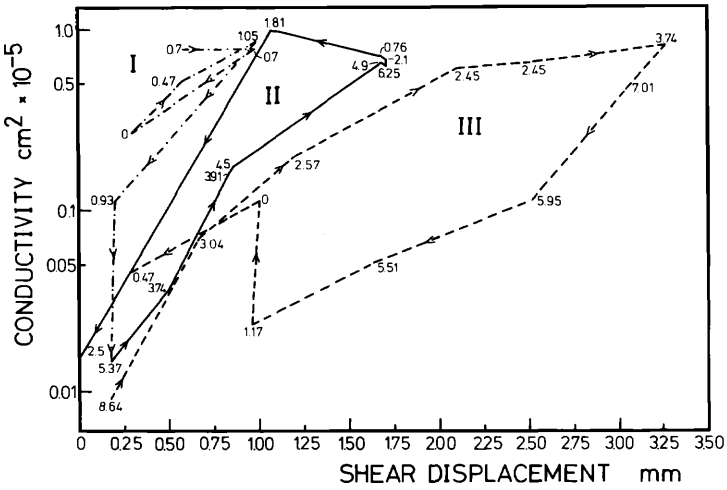

Figure 4. Coupled shear-flow tests performed on a joint in gneiss. Shear cycles I and II were in a forward direction, cycle III was in the reverse direction. The small numbers appended to the curves indicate effective normal stress in MPa. After Makurat (1985).

JRC_o = 6.0. Dilation during shearing caused some limitations on the degree that the normal stress could be held constant during a shearing event, due to the tendency for sudden slip and associated dilation. However, the results indicate a degree of shear-flow coupling similar to the numerical model (Figure 2, lower diagram). Displacements of 1-2 mm were sufficient to cause nearly two orders of magnitude increase in conductivity.

The amount of experimental data obtained from these new coupled tests is at present limited. A second test on a planar foliation surface in schist showed another important effect. Under repeated shearing gouge was produced which reduced conductivity even as dilation was occurring.

Such effects seem likely to be associated with shearing under high ratios of (σ_n'/JCS), and in case where roughness is only a small scale feature superimposed on a basically planar surface.

7 ENGINEERING IMPLICATIONS

Whether super-conducting joints are formed in practice as a result of shearing in a water flood treatment of a petroleum reservoir, in a geothermal hydrofrac stimulation or across a thermally loaded waste repositiory, will depend on the magnitude of effective stress changes, on the roughness and on the stress to strength ratio.

The traditional method of transforming principal stresses into shear and normal stress components along a plane inclined at angle β to the principal stress appears to breakdown when the assumptions of isotropy are in doubt due to the presence of a real fracture, and due to out-of-

plane slip caused by dilation. The net result is a considerably increased shear strength for rough, dilatant features. The formation of artificial super-conducting joints may therefore require the exceptional changes of stress associated with fluid pressure changes. They are perhaps unlikely to occur as a sole result of thermally induced changes in total stress.

The presence of tunnels may, however, cause sufficient increase in shear stress for significant shear displacements to occur around the excavations. In this zone there are lower radial stresses, and dilation will therefore be less constrained. Numerical analyses show that shear displacements may occur along horizontal and vertical joints even when the stress distribution is isotropic and the opening is perfectly circular. This zone will require injection following excavation if the effect of the openings is to be minimized in the overall conductivity.

The presence of anisotropic stress, and steep or shallow dipping joints greatly magnifies the likehood of shear-induced super-conductors. These have been shown to develop in physical models (Barton and Hansteen, 1979) and in numerical models (Wahi et al. 1980). The development of such features is also suspected in a recent case of mine flooding following a magnitude 6.9 earthquake (Barton, 1984). Joints were observed to conduct more water with higher pressure outflows. This was observed in several levels of the mine. The initial increase in flow rate for the whole mine was 250 %. The process was reversible only in the sense that over a six month period the increased inflows gradually subsided, presumeably due to the increased draw-down.

8 CONCLUSIONS

According to Norwegian tunneling experiences super-conducting rock joints may occur in crystalline basement rocks at depths of at least several hundred meters. Hydrostatic pressures of several MPa are likely to be recorded when breaching such features. Theoretical joint conductivities as high as 10^{-2} cm^2 can be deduced from extreme cases.

A model that couples shear displacement, dilation and conductivity predicts increases of joint conductivity of 1 to 3 orders of magnitude in the first few millimeters of shear displacement if joints are non-planar.

Laboratory tests have been performed on 150 mm diameter jointed drill cores using a specially designed biaxial rig. Simultaneous measurement of flow rate and shear displacement under effective normal stress levels of several MPa have indicated similar magnitudes of conductivity enhancement to those predicted in the case of non-planar joints. The effect of gouge production in weaker or more heavily stressed joints requires further work.

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