Modelling rock mass conductivity changes in disturbed zones

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ABSTRACT

New methods of describing rock joint behaviour in normal and shear loading allow the physical and conducting joint apertures to be tracked in the course of complex loading histories, i.e. during closure, shear, dilation, shear reversal, cyclic normal loading, with asperity wear etc. This joint behaviour model has been incorporated as a sub-routine in the universal distinct element code (UDEC) for studying the changes in joint geometries that can occur in jointed reservoirs under drawdown, and in the rock mass surrounding tunnel excavations, with and without internal or external fluid pressure. Examples of joint behaviour in disturbed zones are illustrated by several recent tunnel studies. The graphical presentation of behaviour in the disturbed zone includes plots showing the magnitude and location of joint shearing, and the corresponding magnitudes of joint conducting apertures. In the various numerical studies illustrated, conductivity changes are caused by stress relief, by instability-related shearing in tunnels, or by high internal pressures in caverns. Ongoing studies of a special tunneling problem in Oslo include analyses of joint conductivity changes caused by initial excavation, leakage control by subsequent systematic bolting, followed by final concrete lining with build-up of full external ground-water pressure.

1 JOINT DEFORMATION COMPONENTS

A simplified picture of the two fundamental joint deformation components; closure and shear, are illustrated in Figures 1 and 2. The obviously non-linear behaviour results in concave-shaped curves under closure, and convex-shaped curves under shear. As shown in Figure 2, the latter may depend on the size of block sheared; more complex peak-residual behaviour may be exhibited by smaller block sizes.

When these two components are coupled during the deformation of a rock mass, the resulting load-deformation behaviour may exhibit curves that are concave, linear or convex. This will be determined by the dominance of one of the components (N) or (S) as illustrated in Figure 3.

The increasing degree of hysteresis exhibited by rock masses A, B and C is a function of the irreversible shear components (S) and of

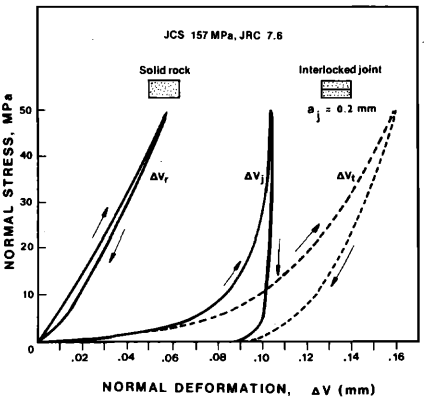


Figure 1. Concave normal stress-closure behaviour after Bandis et.al. (1983).

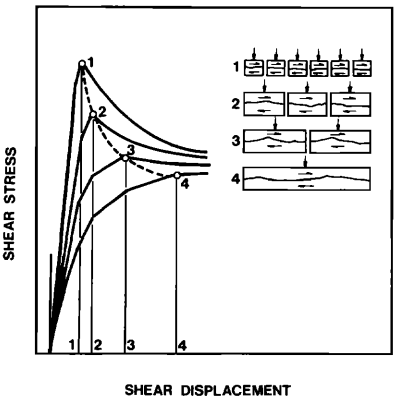


Figure 2. Convex shear stress-displacement behaviour after Bandis et.al. (1981).

accompanying dilation (if the joints are non-planar and stresses are moderate).

Increasing levels of sophistication can be envisaged depending upon the boundary conditions operating. For example, rock mass C with steeply dipping conjugate joints will not deform in shear if sufficiently high lateral stresses are operating. Likewise, if one-dimensional strain conditions are imposed (zero lateral expansion) the joints would once again be prevented from significant shear. However, a large increase in effective stress caused by an internal reduction in pore pressure, might provide enough shrinkage of the matrix to accommodate significant joint shears. An example of such behaviour from NGI's Ekofisk reservoir studies is illustrated in Figures 4 and 5. These figures were produced by UDEC, utilizing a simplified bi-linear joint model for the joints in the chalk (NGI, 1985, 1986).

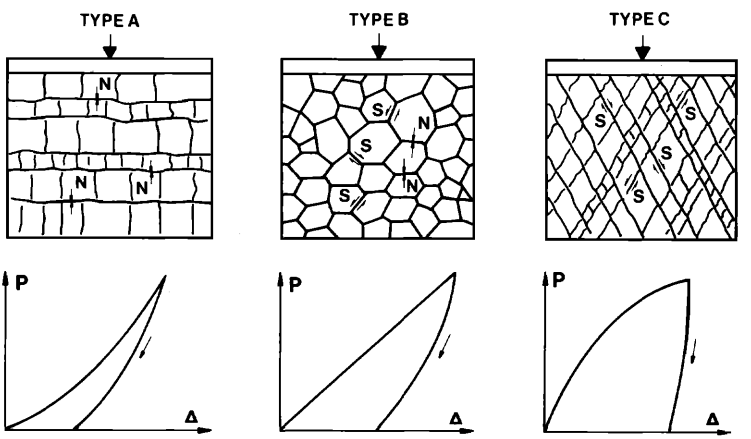


Figure 3. Concave, linear and convex load-deformation behaviour for three classes of rock mass. (Barton 1986).

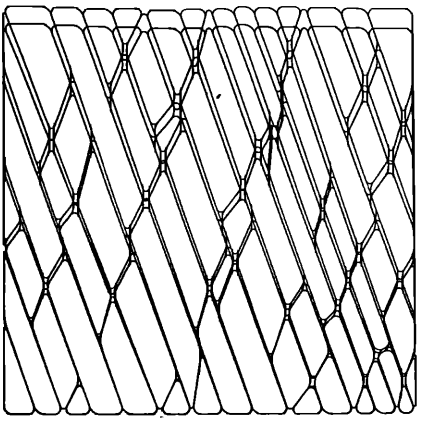


Figure 4. One-dimensional compaction in a fractured petroleum reservoir caused by 20 MPa drawdown of fluid pressures.

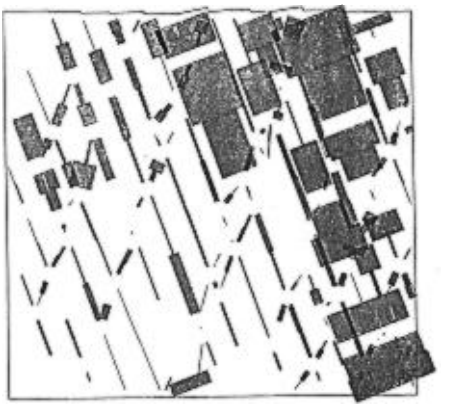


Figure 5. Corresponding locations of joint shearing and associated dilation help to maintain reservoir productivity in a compacting environment. (Barton et.al. 1986).

2 JOINT APERTURES

The objective of this paper is to demonstrate the modelling of conductivity changes in rock masses. The preceeding observations on joint closure, shear and dilation need therefore to be interpreted as joint aperture changes. At the same time, consideration must be given to the fact that joints under stress have varying degrees of contact. Any fluid flow will tend to be channeled around these contacting areas, although fluid pressures may be transferred throughout the whole joint plane.

A joint of a given physical aperture (E) will have a corresponding theoretical smooth-wall (parallel plate type) conducting aperture (e). The conductivity (K_j) of the joint will be given by:

$$K_j = e^2/12 \qquad (1)$$

where $e < E$, and where $e << E$ at high stress, due to large areas in contact.

An empirical model of the relationship between (e) and (E) and the influence of joint roughness (JRC) is illustrated in Figure 6. Rough joints that are under very high stress, and therefore have extremely small apertures, can show (E/e) ratios greater than 10 as indicated in current Stripa waste isolation studies in Sweden.

In field applications, an initial value of (e) and its statistical variation, is obtained from analysis of permeability tests using for example Snow's (1968) statistical method. This initial value of e_o which is depth dependent) is converted to a physical aperture E_o

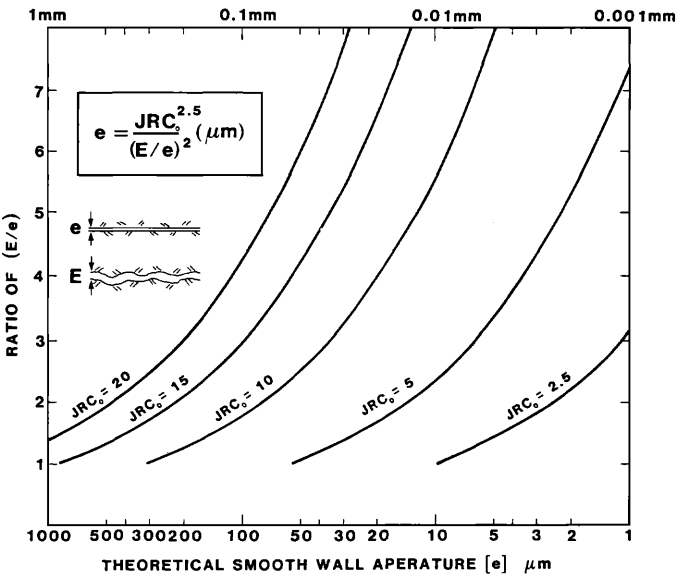


Figure 6. Physical (E) and conducting apertures (e), and their approximate relationship with joint roughness JRC. (Barton et.al. 1985).

(using Figure 6) for use in subsequent modelling of any changes (ΔE) caused by shear, dilation closure, or shear reversal, where:

$$E = E_o \pm \Delta E \tag{2}$$

3 CONSTITUTIVE JOINT MODEL

A brief summary of the constitutive joint sub-routine that is now in operation in the special version of UDEC operated by NGI will be given here, with appropriate references to the fuller treatment to be found elsewhere.

The shear strength-displacement-dilation behaviour are described in principle by the following two generalized equations:

$$\phi_{mob} = JRC_n \text{ (mob) } \log \left(\frac{\sigma_1 - \sigma_3}{\sigma_n'} \right) + \phi_r \tag{3}$$

$$d_n\text{(mob)} = 1/2 \text{ JRC (mob) } \log \left(\frac{\sigma_1 - \sigma_3}{\sigma_n'} \right) \tag{4}$$

where ϕ_{mob} = the mobilized friction angle at any given displacement

$JRC_n(mob)$ = the full-scale mobilized joint roughness coefficient at any given displacement

$(\sigma_1 - \sigma_3)$ = the confined asperity strength, simplifying to JCS_n (full-scale joint wall compression strength) at low stress (Barton 1977)

ϕ_r = residual friction angle

σ_n' = effective normal stress

$d_n(mob)$ = full-scale dilation angle mobilized at any given displacement

Fuller details of this joint constitutive model are given by Barton et.al. (1985).

The normal stress-closure behaviour is also based on the index parameters (JRC) and (JCS) using the Bandis (1980) hyperbolic formulation:

$$\frac{\Delta V_j}{\sigma_n'} = a - b\Delta V_j \qquad (5)$$

where ΔV_j = joint closure

a/b = asymtote to hyperbola = V_m (maximum joint closure)

a = reciprocal of initial gradient = K_{ni} (initial normal stiffness)

Empirical exressions for K_{ni} and V_m based on JRC and JCS complete the modelling of normal closure (see Bandis et.al. 1983).

4 INPUT PARAMETERS

The basic index parameters (JRC) and (JCS) are obtained from tilt tests (Figure 7) and Schmidt hammer tests conducted on the jointed core. Such tests might appear absurdly simple in comparison to the sophisticated use to which the parameters are put. This, however, is one of the strengths of the method; data can be obtained from large numbers of inexpensive index tests which gives a sound statistical base to the final values used as input.

Relevant stress levels needed to define the modelled boundary conditions are either measured by NGI (using the hydraulic fracturing technique) or are given by the client.

5 JOINT SUB-ROUTINE OUTPUT

Typical sets of stress-closure-conductivity and shear-dilation-conductivity curves will be presented here, so that the reader becomes familiar with the physical appearance of the constitutive model described by equations 1 to 5.

Figures 8 and 9 illustrate appropriate sets of curves that were generated on an HP 41 CV programmable calculator and peripherals by Bakhtar, using the program described by Barton and Bakhtar (1984). The particular input data was obtained from tilt test and Schmidt hammer

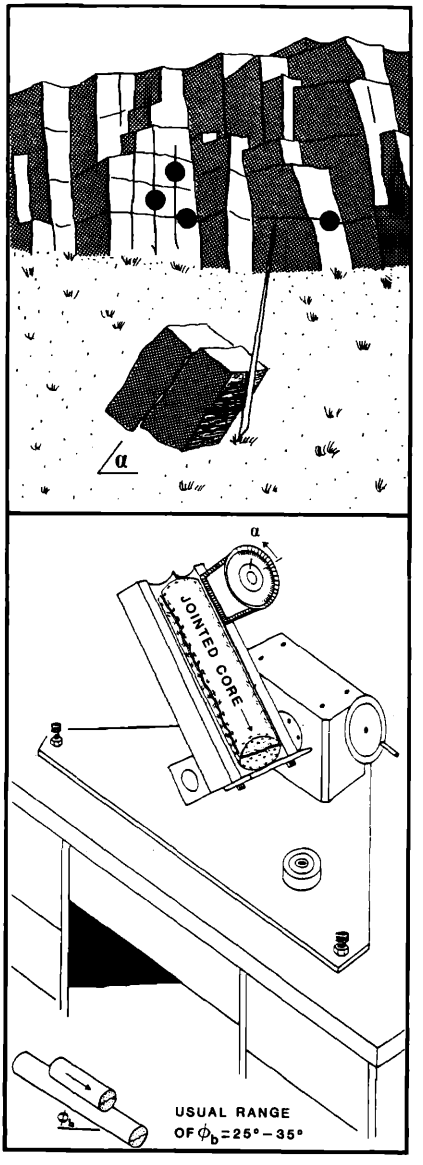


Figure 7. Inexpensive tilt tests for obtaining the statistical variation in joint roughness for the various sets of joints involved.

characterization of the welded tuff in G-Tunnel, Nevada Test Site, in a contract for Sandia National Laboratories.

The calculator program has since been expanded in FORTRAN by Christianson (1985) for use as a sub-routine in UDEC. A spread sheet LOTUS version also developed by Christianson, helps the user select appropriate input data to match available joint permeability data.

6 EXAMPLES OF DISTURBED ZONE ANALYSES

a) Sub-sea circular tunnels

A useful starting point for the evaluation of disturbed zones around tunnels are the UDEC studies of highly stressed, circular sub-sea tunnels performed by Christianson and Hårvik (1985). Figure 10 illustrates the zones of joint shear caused by excavation of tunnels in isotropic and anisotropic stress fields.

Note that joints that are BETWEEN the sectors 3, 6, 9 and 12 o'clock suffer shear, while those that FOLLOW the theoretical lines of zero shear (at 3, 6, 9 and 12) do indeed show zero shear. As one might expect, the joints in the sectors 2 to 4 o'clock and 8 to 10 o'clock tend to be closed rather than sheared by the higher vertical stress in the second example (σ_v = 1.5 σ_h).

The zones of joint shear will clearly represent potential increases in conductivity. The magnitudes of these increases depends on the ratio (JCS/σ_n') and on the joint roughnes (JRC), since these determine the initial joint apertures and the

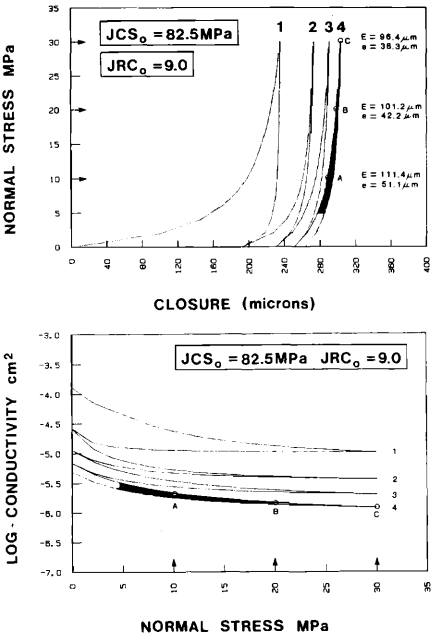


Figure 8. Stress-closure-conductivity modelling for joints in welded tuff. Note physical and conducting apertures (E, e). Characterization of the joints was made in tunnel exposures and on drill core.

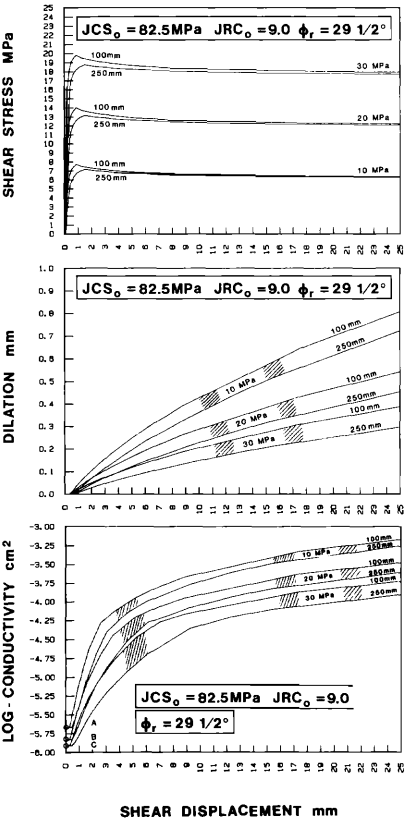


Figure 9. Shear-dilation-conductivity modelling for joints in welded tuff.

magnitude of potential dilation if shearing occurs. There is a certain balance between joints that are too rough to shear, and joints that can shear, but dilate less.

b) Rock caverns for high pressure oil and gas separation

A novel method of high pressure separation of oil and gas ("Prorock") utilizing rock caverns is being studied by Berdal Offshore Engineering A/S. NGI was asked to perform some initial UDEC studies of the rock mechanics feasibility of containing a high internal fluid pressure (10 MPa) in a rock cavern located in a rock mass loaded externally by much smaller magnitudes of rock stress.

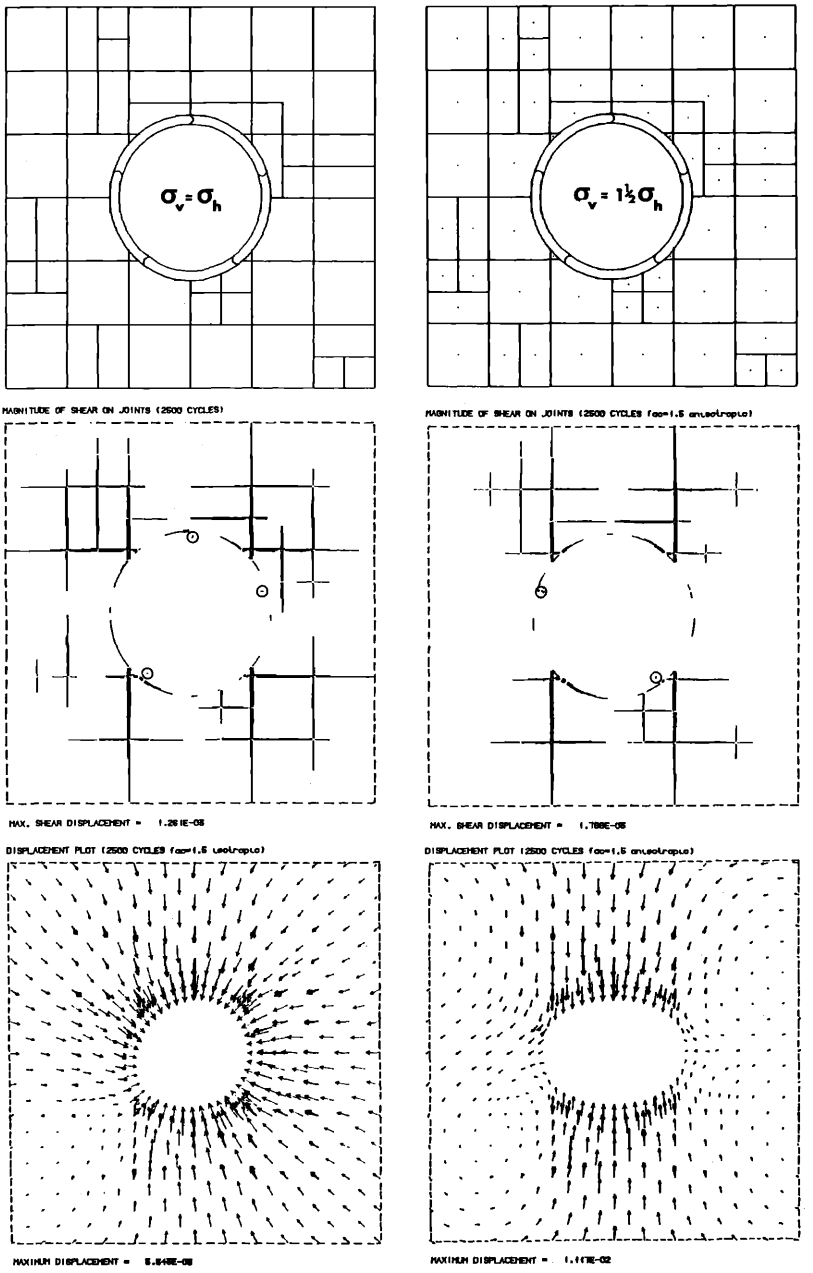


Figure 10. Studies of a hypothetical sub-sea tunnel. ("Troll i Fjell") for a North Sea oil field (Christianson and Hårvik, 1985). Line thickness (centre diagram) is proportional to shear displacement magnitudes (max. 1.79 mm).

The construction sequence assumed was

1. Excavation with no support applied
2. Lining with concrete or shotcrete and a water-tight membrane
3. Application of 10 MPa internal pressure

The rock mass was assumed to be efficiently drained surrounding the cavern so that lining resistance to external water pressure would not be required. The internal pressure was assumed to cause cracking of the light concrete or shotcrete lining; cracks which would need to be bridged by a stretchable membrane. In essence the problem was to choose a cavern location in a sufficiently massive rock mass to limit the concrete cracking to acceptable magnitudes.

The three diagrams in Figure 11 illustrate the assumed jointed cavern geometry, the joints that have sheared more than 50 μm, and the resulting joint conducting apertures (e). The latter forms the basis of conductivity calculations (equation 1).

Co-author Makurat's UDEC modelling of this problem show that apertures reduce with depth, as required. Furthermore when the internal pressure is applied, apertures increase somewhat around the opening, and some subtle changes occur many diameters away from the opening. It is of interest to note that at the locations of most joint shear (max. 1.68 mm) one does not see corresponding increases in conducting aperture. This is because the rock mass is quite massive. The large block sizes result in delayed dilation, as shown by Bandis' work on scale effects (Bandis et.al. 1981). The modelling of this delayed dilation, even for small blocks, can just be seen in Figure 9.

c) Leakage control for sub-urban road tunnels (Fjellinjen)

The final numerical model of disturbed zones to be discussed is incomplete at the time of writing. However, it is already a useful illustration of the potential for investigating disturbed zones in realistic geological environments. Figure 12 (upper diagram) illustrates the geometry of the problem. Two 14 meter span tunnels (3 lane motorways) will be driven at a depth of 20 to 50 meters beneath Oslo. Extensive pre-grouting ahead of the tunnel faces will be used to limit inflow of water during tunnel driving. Final concrete linings are designed for full water pressure. A limit of 2 to 3 litres inflow/minute/100 meters of tunnel has been set in order to limit groundwater drawdown and differential settlement in overlying clay and alun shale.

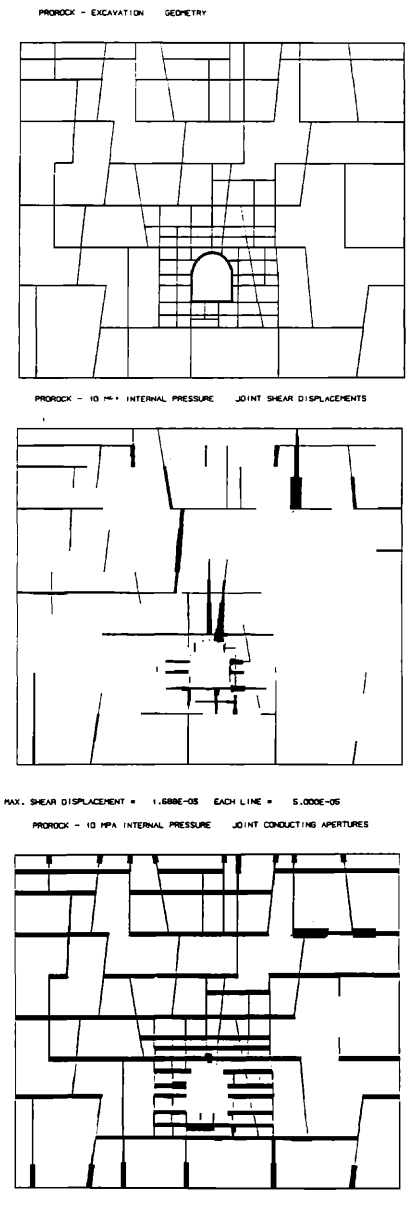


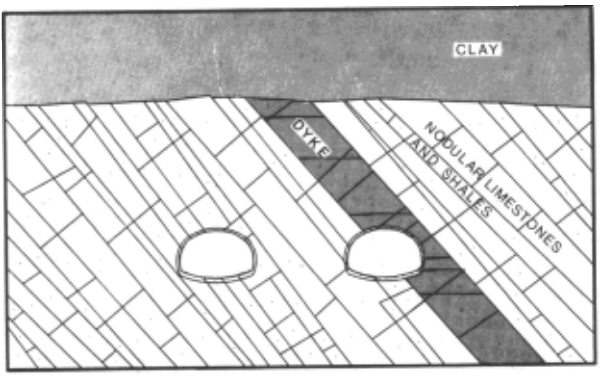
Figure 11. Studies of joint aperture changes and concrete liner cracking for high pressure separation of oil and gas in rock caverns. (Makurat and Barton, 1986).

NGI's engineering geologists and rock mechanics engineers have mapped and characterized the jointing, analysed the water pumping tests using Snow's (1968) method, conducted tilt tests on jointed core, measured stresses using the minifrac technique, and set up the necessary joint input and output for the UDEC sub-routine. The latter involves generation of joint performance curves such as those illustrated in Figures 8 and 9. An important detail is the matching of the depth dependent joint apertures with those derived from water pumping tests.

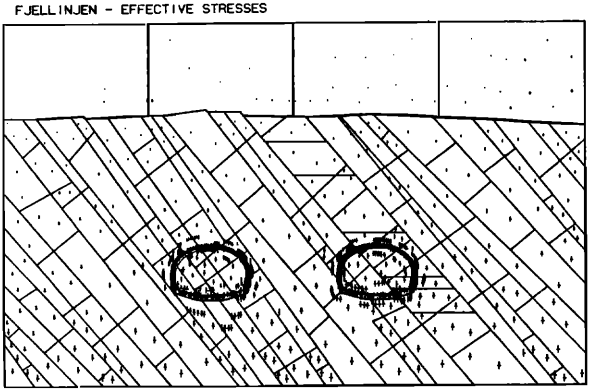
The dipping nodular limestones and shales are modelled with two different joint properties to present the foliation and cross-joints, and joints in the igneous dyke have a third character. Along dyke boundaries low friction surfaces are modelled.

Figure 12 (centre) shows the levels of effective stresses, and the lower diagram shows the resulting distribution of conducting apertures which also are seen to match the values of (e) of 30 - 50 μm derived from pumping tests.

The next step in the modelling is the excavation of the tunnels, followed by installation of systematic bolting using Lorig's (1985) sub-routine. Aperture disturbances will be tracked over successive calculation cycles, so that the bolting can be put into early operation if necessary (i.e. bolting close to the face). Finally the soft pre-zoned concrete liners will be given correct stiffness properties after some further rock deformation (to allow for face advance) at which stage full exernal water pressure will be applied. Results of the studies will be reported elsewhere.

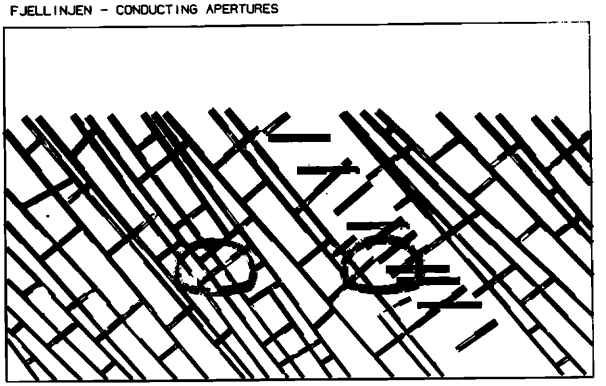


FJELLINJEN - EFFECTIVE STRESSES



MAX. STRESS = 7.910E-01

FJELLINJEN - CONDUCTING APERTURES



MAX. JOINT APERTURE = 6.973E 05 EACH LINE = 1.000E-05

Figure 12. Studies of joint aperture disturbance by excavation, for twin motorway tunnels (Fjellinjen, Oslo Road Authority). Plots show geometry, effective stresses and initial conducting apertures.

7 CONCLUSIONS

1. The modelling of conductivity changes in disturbed zones requires continuous tracking of the larger physical aperture changes caused by joint closure, shear, dilation, or tensile opening.
2. Joint shear and resulting conductivity increases can occur ever around stable circular tunnels excavated in isotropic stress fields.
3. Some joint shear can probably be accommodated without significant increases in conductivity if the rock mass is massive due to large block sizes. Rough joints which would dilate most and cause greatest permeability changes, will also be less likely to shear when tunnel excavation occurs. Consequently the smoother joints may cause greatest changes.
4. A useful starting point for numerical modelling of disturbed zones is the matching of the measured, undisturbed conducting apertures, as obtained from pumping tests.

REFERENCES

Bandis, S. (1980). Experimental studies of scale effects on shear strength, and deformation of rock joints. Ph.D., Dept. of Earth Sciences, Univ. of Leeds, 385 p.

Bandis, S., A. Lumsden and N. Barton, 1981, "Experimental studies of scale effects on the shear behaviour of rock joints," Int. J. of Rock Mech. Min. Sci. and Geomech. Abstr. 18, pp. 1-21.

Bandis, S., A.C. Lumsden and N. Barton (1983) Fundamentals of Rock Joint Dedormation. Int. J. Rock Mech. Min. Sci. and Geomech. Abstr. Vol 20, No. 6, pp. 249-268.

Barton, N.,1976, "The shear strength of rock and rock joints," Int. Jour.Rock Mech. Min. Sci. and Geomech. Abstr., Vol. 13, No. 9, pp. 255-279. Also NGI-Publ. 119, 1978.

Barton, N. and Bakhtar, K. (1983) Rock Joint Description and Modelling for the Hydrothermomechanical Design of Nuclear Waste Repositories. Terra Tek Engineering TRE 83-10, Submitted to CANMET Mining Research Laboratories, Ottawa, 268 p.

Barton, N., Bandis, S. and Bakhtar, K. (1985) Strength, Deformation and Conductivity Coupling of Rock Joints, Int. J. Rock Mech. & Min. Sci. & Geomech. Abstr. Vol. 22, Nr. 3, pp. 121-140.

Barton, N., L. Hårvik, M. Christiansson, S. Bandis, A. Makurat, P. Chryssanthakis and G. Vik (1986). Rock Mechanics Modelling of the Ekofisk Reservoir Subsidence Proc. 27th U.S. Rock Mech. Symp., Univ. of Alabama.

Barton, N. (1985) Deformation Phenomena in Jointed Rock. 8th Laurits Bjerrum Memorial Lecture, Oslo. Publ. in Geotechnique, Vol. 36, No. 2, pp. 147-167, (1986).

Christianson, M. (1985). NGI research contract, 54210.

Christianson, M. and L. Hårvik (1985). NGI research contract, 54210.

Lorig, L.J. (1985). A simple numerical representation of fully bonded passive rock reinforcement for hard rocks. Computers and Geotechnics, Elsevier Publ. 1, pp 79-97.

Makurat, A. and N. Barton, (1986). Prorock: High Pressure Oil and Gas Separation in Rock Caverns. NGI Contract Report for Ing. A.B. Berdal A/S.

NGI (1985, 1986). Ekofisk Reservoir Subsidence - An Investigation using Continuum and Discontiuun Computer Modelling. Confidential Contract Reports 85612-1,2,3 for Norwegian Petroleum Directorate.