

Technical Note

The Disturbed Zone Around Tunnels in Jointed Rock Masses

B. SHEN†‡
N. BARTON†

1. INTRODUCTION

The disturbed zone around an excavation is a region where the original state of the *in situ* rock mass, such as stress, strain, rock stability, water flow, etc. has been affected. The definition of the disturbed zone depends on the nature or the purpose of the excavation. For instance, the disturbed zone of a road tunnel normally means the region where rock blocks have undergone notable displacement or the tangential stress shows a major increase. The displacement and stresses are the factors controlling the tunnel stability. For nuclear waste disposal however, the disturbed zone around a deposition tunnel is more frequently considered the area where joint movement (open or sliding) occurs. The joint movement in this case is of more concern than the tunnel's local stability because it changes the water flow, and hence increases the possibility for radioactive material migration.

In both cases, joints in the rock mass play a key role in the development of the disturbed zone. Joints can create loose blocks near the tunnel profile and cause local instability [1]; joints weaken the rock mass and enlarge the displacement zone caused by excavations [2,3]; and joints change the water flow system in the vicinity of the excavation due to the channelling effect [4].

According to the frequency of jointing, a rock mass may be described as "intact" (without joint), "sparsely jointed" (with a few joints), "jointed" (with several intersecting joint sets) and "heavily jointed" (with closely spaced and intersecting joint sets). These descriptive terms are approximate and depend on the joint spacing relative to the dimension of the excavation.

In this study, we have investigated the effect of joint spacing on the size and shape of the disturbed zone around a tunnel. A 2-D distinct element code, UDEC, is used to model the tunnel excavation in a simply jointed rock mass. An analytical method was also used to verify the numerical results. Rock masses ranging from intact rock to heavily jointed rock (joint spacing less than 1/16 of tunnel diameter) are studied. The influence of

boundary condition and *in situ* stress condition on the disturbed zone is also studied.

2. UDEC MODELS

The models have the dimension of 56 × 56 m, which facilitates the excavation of a tunnel with a diameter of 20 m in the centre of the model. Two sets of persistent joints, both dipping 45° but being perpendicular with each other, cut the model into blocks with regular shapes. Joint spacing varies from 7.2 to 1.2 m in different models and the number of blocks in the models ranges from 250 to 10,000. Four models are used in studying the effect of joint spacing. They are (Fig. 1):

Model	Joint spacing (m)	Number of blocks
No. 1	7.2 m	250
No. 2	3.6 m	1000
No. 3	1.8 m	4000
No. 4	1.2 m	10000

In this study, the joints are assumed to be Mohr-Coulomb joints, i.e. elasto-perfectly plastic joints. The blocks are treated as elastic blocks. The properties of the rock blocks and joints are listed in Table 1.

For all the above four models, a stress condition of $\sigma_y = 20$ MPa and $\sigma_x = 5$ MPa is assumed. These values represent the gravity-induced stresses at a depth of about 700 m. For model No. 3, an additional stress state ($\sigma_y = 20$ MPa and $\sigma_x = 10$ MPa) is also applied in order to study the influence of stress state on the disturbed zone.

Models No. 1-4 are assigned roller boundary condition for all the boundaries except the top one on which stresses are applied instead. Two additional calculations are carried out with model No. 3 to study the sensitivity of boundary conditions. The two additional boundary conditions used are: stress boundaries and mixed stress-displacement boundaries. The first one represents the boundary condition usually used in laboratory tests, where the loading stresses are ensured while the block movement is not limited. The second one is to apply a stress boundary for the first few hundred cycles in UDEC (initial loading without equilibrium) and then change to roller boundaries. This is a technique

†Norwegian Geotechnical Institute (NGI), Oslo, Norway.

‡Author to whom correspondence should be addressed at CSIRO, Division of Exploration and Mining, PO Box 883, Kenmore, Qld 4069, Australia.

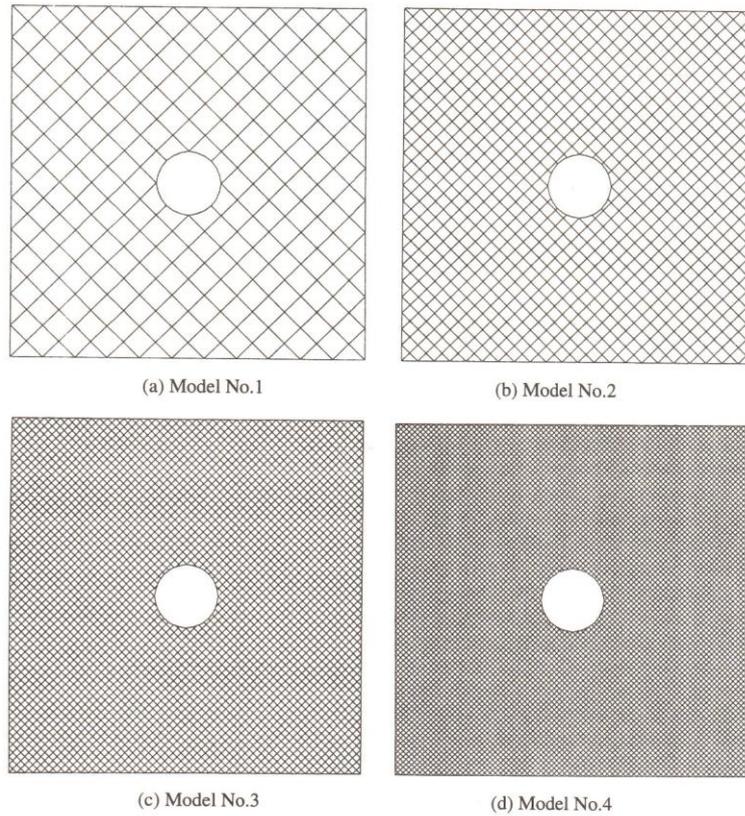


Fig. 1. Four UDEC models with different joint spacing.

with which a general displacement control is achieved but some block movement is allowed. This boundary condition is more close to the reality in the field.

Two additional models are also studied, one without any joints (No. 5) and the other with vertical and horizontal joint sets (No. 6) (Fig. 2). Model No. 5 is designed to investigate whether the continuum approach can yield similar results to the discontinuum approach for heavily jointed rock masses. In this model, the intact rock is considered as an elasto-plastic material which follows Mohr–Coulomb yield criteria. In addition to the elastic properties given in Table 1, strength properties for intact rock are also given:

$$c = 3 \text{ MPa}, \quad \phi_i = 35^\circ, \quad \sigma_t = 0$$

Table 1. Mechanical properties

Young's modulus (E)	25 GPa
Poisson's ratio (ν)	0.2
Density (d)	2740 kg/m ³
Joint normal stiffness (K_n)	37 GPa/m
Joint shear stiffness (K_s)	1.6 GPa/m
Joint friction angle (ϕ)	40
Joint dilation angle (ϕ_d)	2
Joint cohesion (c)	0

Here c is the intact rock cohesion, ϕ_i is the intact rock internal friction angle, and σ_t is the intact rock tensile strength.

Model No. 6 has the same joint spacing as model No. 3, but different joint directions. This model is designed to investigate the influence of joint orientation on the disturbed zone.

3. NUMERICAL RESULTS

3.1. Disturbed zones for different block size

We divide the disturbed zone into three zones; (1) the failure zone, where loose rock blocks are falling into the tunnel; (2) the open zone, where joints open up; and (3) the shear zone, where joints experience a certain shear displacement (3 mm in this study). The failure zone is one of the direct concerns for tunnel stability, while the open zone and the shear zone are of great interest for water flow because both joint opening and shearing change the hydraulic aperture of the joints significantly [5, 6].

(1) *Failure zone* (Fig. 3). There is clearly an increasing risk of local instability when the joint spacing is

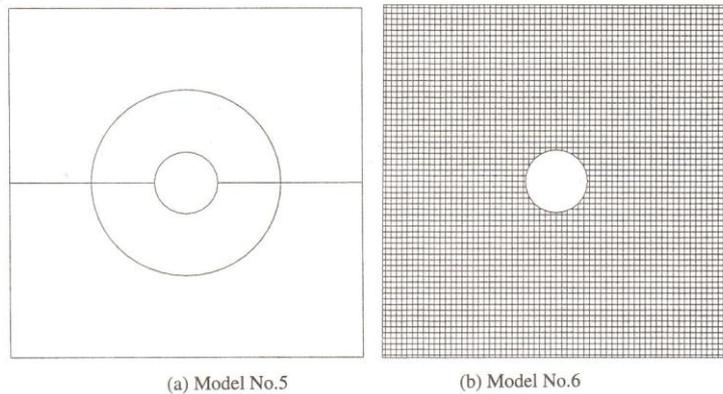


Fig. 2. Two UDEC models, one without joints, and one with vertical and horizontal joint sets.

decreasing. As is shown in Fig. 4, when the joint spacing is small enough so that the excavation of the tunnel creates loose (stress free) blocks in the wall or the roof of the tunnel, those blocks fall into the tunnel due to the force of gravity. With a tunnel diameter of 20 m, the models with joint spacing of 1.8 m (model No. 3) and of 1.2 m (model No. 4) show this type of instability. Larger joint spacing in models No. 1 and 2 prevents any appearance of such loose blocks and, hence, shows no failure zone.

The failure zone caused by block falling is limited to the surface of the tunnel, and it shows only a minor change when the joint spacing is further reduced.

(2) *Open zone* (Fig. 4). Model No. 1 with the largest joint spacing shows no joint opening in the vicinity of the tunnel. When the spacing decreases from 3.6 m (model No. 2) to 1.8 m (model No. 3), there is a clear expansion of the open zone. Obvious expansion, however, is not observed when the joint spacing is further reduced from 1.8 to 1.2 m (model No. 4).

(3) *Shear zone* (Fig. 5). Because of the tunnel excavation, joints in much of the modelled area undergo some level of shear displacement. To identify the change of the joint shearing with different joint spacing, we only consider those joints with shear displacement of 3 mm or greater. Hence, the shear zone here is defined as the region with joint shear displacement ≥ 3 mm. The shear zones around the excavation for models No. 1-4 are shown in Fig. 5.

There is a clear trend for the shear zone to expand with reduced joint spacing. When the joint spacing is 7.6 m, the shear zone includes only a few joints around the tunnel. In contrast, when the joint spacing is 1.2 m, the shear zone expands to the boundary of the model. The shear zones form an X-shape around the tunnel which is coincident with the failure path of brittle rock under biaxial loading in laboratory experiments. Obviously, this X-shape is due to the existence of maximum shearing along it. The 45° dipping orthogonal joint sets is another reason for the X-shaped shear zone.

This will be discussed later in the paper when comparing the shear zones for different joint patterns.

Following the above discussions for joint spacing from 7.6 to 1.2 m, it is natural to question what will happen if the joint spacing becomes very small or if there are no joints at all. Will the shear zone still keep the X-shape? In both cases the material can be treated as a continuum material. The intact material model No. 5 is hence used. The intact material is assumed to be elasto-plastic following Mohr-Coulomb's yielding criterion. The yield zone for the assigned rock strength and stress state is shown in Fig. 6(a). A comparison to the shear zone with shear displacement ≥ 9 mm in model No. 4 can be found in Fig. 6(b).

The yield zone of intact rock takes a shape fairly similar to the shear zone of the heavily jointed rock. The similarity is because of the fact that both yield zone and shear zone are caused by shearing. The slight difference is that the yield zone grows at a smaller angle to the direction of maximum principal stress than the shear zone.

3.2. Disturbed zones for different boundary conditions

In reality, tunnels are often located in an essentially infinite or semi-infinite rock mass. The so-called "boundaries" of numerical models are often just some artificial cutting planes which separate our region of interest from the rest of the rock mass. For this reason the suitability of different boundary conditions in simulating nature should be investigated.

In UDEC models, there are three types of boundary conditions available: roller boundary, stress boundary and elastic boundary. The first two boundary conditions restrict either displacement or stresses on the boundary, respectively. The elastic boundary allows both displacement and stresses which are calculated from the surrounding rock mass by the Boundary Element Method. Although the elastic boundary is thought to be closer to the reality, it is rarely used by modellers because it increases the size of the problem, but reduces the calculation speed significantly. One compromise to

achieve some degree of deformation at a boundary is to use the so-called "mixed boundary". The idea of a mixed boundary is to use the roller boundary and stress boundary alternatively during the UDEC cycles before reaching equilibrium. Using a mixed boundary a specified stress can be applied to the boundary, while a certain displacement on the boundary is allowed.

In this study, all three boundary conditions (roller boundary, stress boundary and mixed boundary) are applied to model No. 3 (joint spacing = 1.8 m, block number = 4000). The difference in results due to different boundary conditions is found to be significant.

When the stress boundary conditions ($\sigma_1 = 20$ MPa and $\sigma_3 = 5$ MPa) are used on three of the four boundaries of the model (the bottom boundary needs to be a roller boundary to avoid rigid movement of the model), tunnel excavation causes collapse of the whole model (Fig. 7(a)). In the lower part of the model, two joints slide with considerable shear displacement (1.3 m) due to the non-limitation of displacement on the boundary. In the upper part of the model, two failure

"kink" bands mark the collapse within which blocks rotate and rearrange significantly. This type of block collapse is very similar to that reported by Bandis *et al.* [7] from laboratory model tests at NGI (Fig. 7(b)). The loading frame at NGI applied designed stresses through air and water filled rubber tubes, and the block displacement on the boundary was not limited, as modelled here.

When the mixed boundary condition is applied, there is no model collapse, except the fall of some loose blocks into the tunnel. There is no significant difference in the disturbed zones between mixed boundary condition and roller boundary condition, although the mixed boundary condition allows a maximum of 6 mm displacement on the model's vertical boundaries.

Such a massive collapse of rock mass as shown in Fig. 7 is probably rarely observed in real engineering cases, because the "boundaries" are confined in their movement by the outside rock mass. This result suggests that, in case the *in situ* stresses are close to the strength of the rock mass (or joints), stress boundary should be

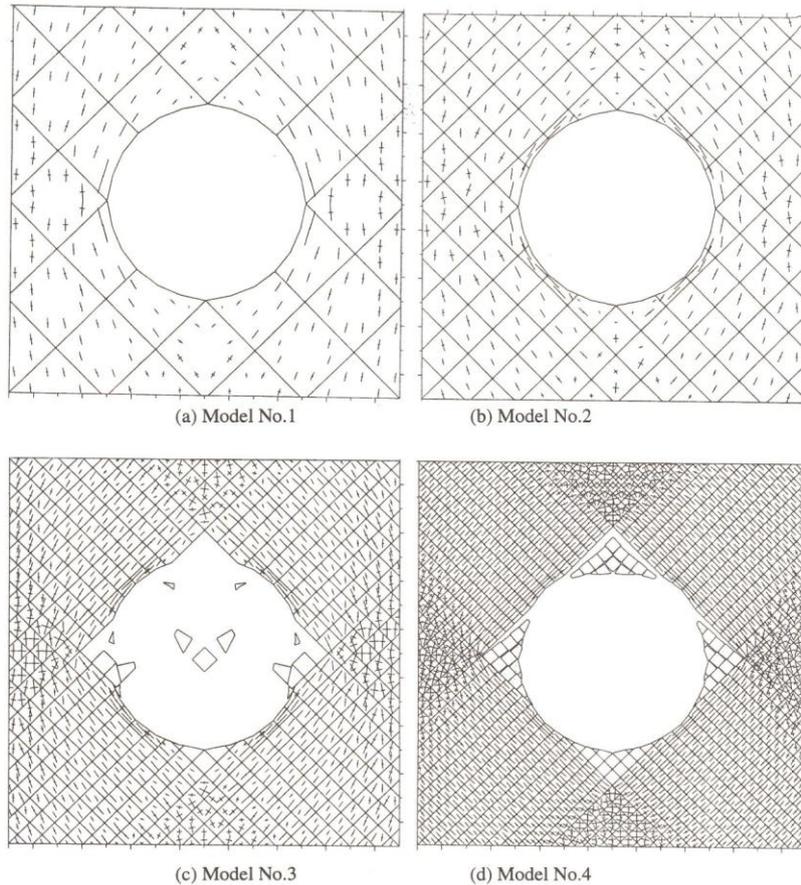


Fig. 3. Overbreak shape and stress. Some loose blocks in models No. 3 and 4 fall into the tunnel.

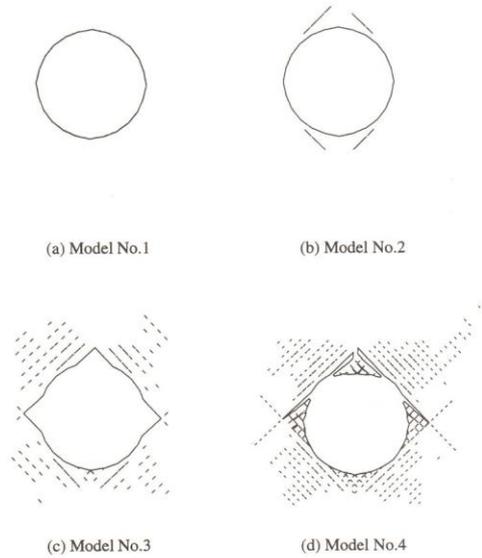


Fig. 4. Open zone around the tunnel.

avoided in order to eliminate the misleading model collapse.

3.3. Disturbed zones for different stress state

For model No. 3, a different *in situ* stress state is applied. The horizontal stress (confining stress) is twice that used previously ($\sigma_v = 10$ MPa). With this stress state those blocks found to be loose earlier are still unstable. However, the open zone has almost vanished and the shear zone around the tunnel becomes much smaller than before (Fig. 8). Differing from the X-type shear zone for lower confining stress, the shear zone for the higher confining stress has a nearly equidimensional shape. Obviously, the higher horizontal stress puts the tunnel under more even

stress, and stops the shear zone from growing in particular directions.

3.4. Disturbed zones for different joint orientation

In model No. 6, we changed the joint orientation from dipping 45° in models No. 1-4 to vertical and horizontal directions, but kept other conditions the same as in model No. 3. The disturbed zones in model No. 6 seem to be different from those of model No. 3, purely because of the change of joint orientation (Fig. 9).

The loose blocks in model No. 6 appear in the upper-left and upper-right corners of the tunnel, instead of the roof and side walls of the tunnel as in model No. 3. As a result of the loose blocks falling down, the final tunnel shape resembles a "cat-face". The shear zone is

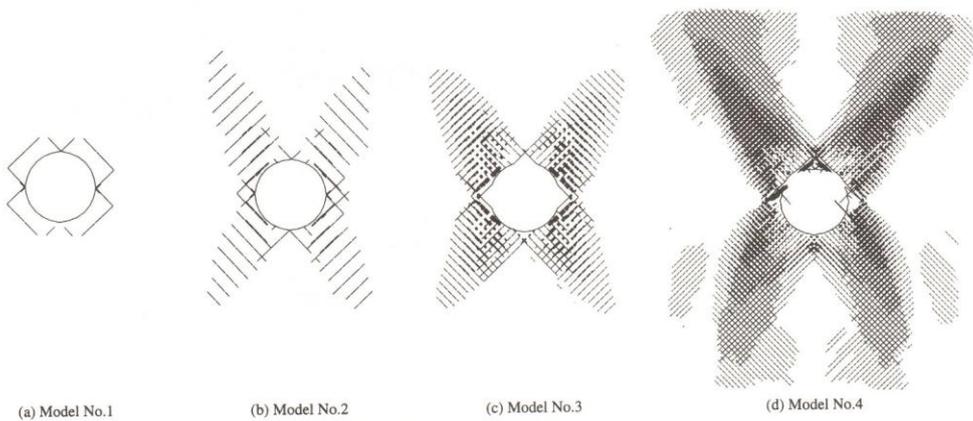


Fig. 5. Shear zone around the tunnel.

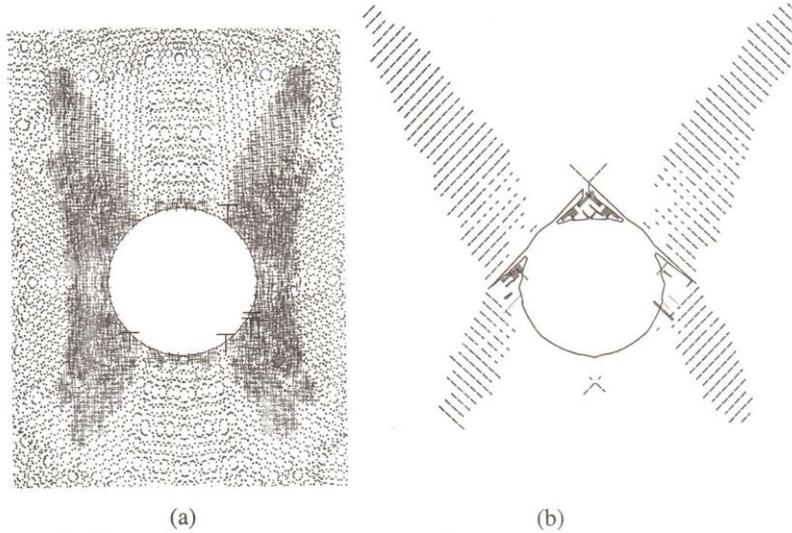


Fig. 6. Comparison of (a) yield zone of intact model No. 5 with (b) Shear zone of model No. 4 (shear displacement ≥ 9 mm).

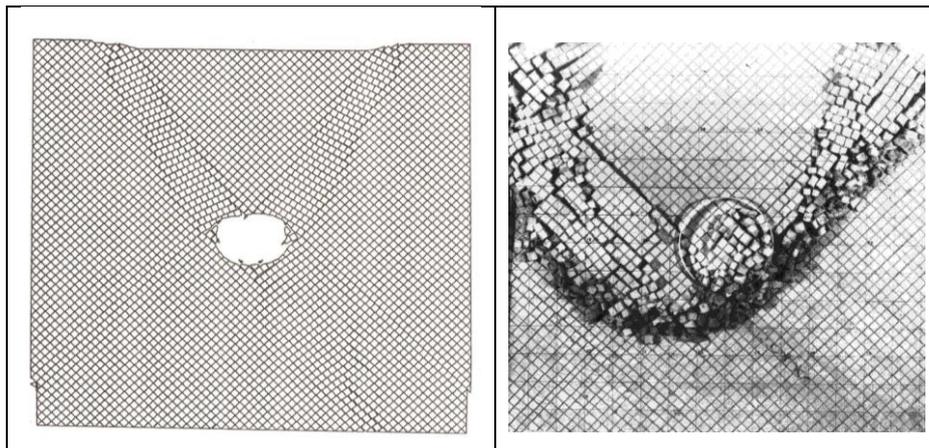
shrunk to a few vertical joints above and below the tunnel.

4. ANALYTICAL STUDY OF SHEAR ZONES AROUND THE TUNNEL

To provide an additional understanding about the shear zone around a tunnel in the general case, in this section we report an analytical investigation of the shear zone in a "heavily jointed" rock mass. We assume a circular tunnel being excavated in the heavily jointed rock mass (Fig. 10). Two joint sets

exist in the rock mass, both dipping α , but in opposite directions. The horizontal and vertical stresses are σ_x and σ_y with a ratio $\sigma_x/\sigma_y = K$. The stresses around the tunnel can be obtained by using the following equations [8].

$$\sigma_{rr} = \frac{\sigma_y}{2} \left[(1+k) \left(1 - \frac{a^2}{r^2} \right) - (1-K) \left(1 - \frac{4a^2}{r^2} + \frac{3a^4}{r^4} \right) \cos 2\theta \right]$$



(a) Numerical model

(b) Physical model

Fig. 7. Modelling results of rock mass collapse due to tunnel excavation in comparison with experimental results reported by Bandis *et al.* [7]. Stress boundaries are used in the simulation and in the physical model.

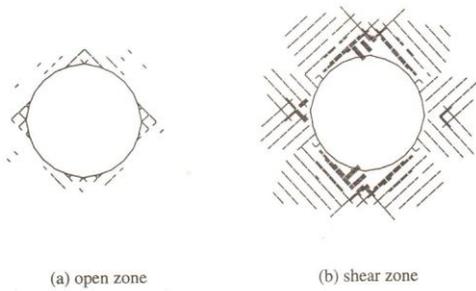


Fig. 8. Open zone and shear zone (≥ 3 mm) for model No. 3 when the applied stresses are $\sigma_r = 20$ MPa, $\sigma_v = 10$ MPa.

$$\sigma_{\theta\theta} = \frac{\sigma_v}{2} \left[(1 + K) \left(1 + \frac{a^2}{r^2} \right) + (1 - K) \left(1 + \frac{3a^4}{r^4} \right) \cos 2\theta \right]$$

$$\sigma_{r\theta} = \frac{\sigma_v}{2} \left[(1 - K) \left(1 + \frac{2a^2}{r^2} - \frac{3a^4}{r^4} \right) \sin 2\theta \right]$$

To facilitate later discussion, we change the polar coordinate system into x - y coordinate system. The stresses in the x - y coordinate are:

$$\sigma_{xx} = \sigma_{rr} \cos^2\theta - 2\sigma_{r\theta} \sin\theta \cos\theta + \sigma_{\theta\theta} \sin^2\theta$$

$$\sigma_{xy} = (\sigma_{rr} - \sigma_{\theta\theta}) \sin\theta \cos\theta + \sigma_{r\theta}(\cos^2\theta - \sin^2\theta)$$

$$\sigma_{yy} = \sigma_{rr} \sin^2\theta + 2\sigma_{r\theta} \sin\theta \cos\theta + \sigma_{\theta\theta} \cos^2\theta.$$

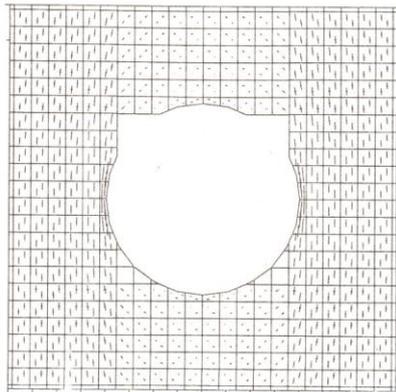
We are interested in the shear and normal stresses on the joint plane. They can be calculated by:

$$\sigma_s = -(\sigma_{xx} - \sigma_{yy}) \sin\alpha \cos\alpha + \sigma_{xy}(\cos^2\alpha - \sin^2\alpha)$$

$$\sigma_n = \sigma_{xx} \sin^2\alpha - 2\sigma_{xy} \sin\alpha \cos\alpha + \sigma_{yy} \cos^2\alpha.$$

For Mohr-Coulomb joints, the sliding condition is

$$\sigma_s = \sigma_n \tan\phi + c$$



(a) tunnel shape and stresses

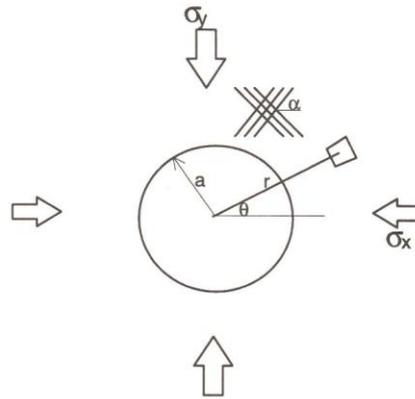


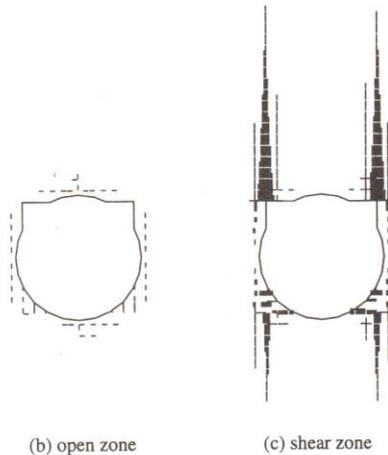
Fig. 10. A circular tunnel in a heavily jointed rock mass under biaxial loading.

where ϕ is the joint friction angle and c is the joint cohesion.

With the above equations, the boundary of the shear zone where joints slide can be obtained analytically or numerically. For simplicity, a short computer program was written to find the shear zone, by checking point by point along the radial direction from the tunnel boundary.

Figures 11-13 show the analytical results of the shear zones around the tunnel, when the joint friction angle, stress ratio and joint orientation are changing, respectively.

Figure 11 shows considerable extension of the shear zone when the joint friction angle is reducing from 35° to 20° . Figure 12 shows a significant difference for the two stress ratios $\sigma_v/\sigma_r = 0.5$ and 0.25 . Lower stress ratio results in less normal stress and greater shear stress along the joint, and hence causes a much larger shear zone around the tunnel. The analytical shear zones shown in



(b) open zone

(c) shear zone

Fig. 9. Results from model No. 6 with vertical and horizontal joint sets.

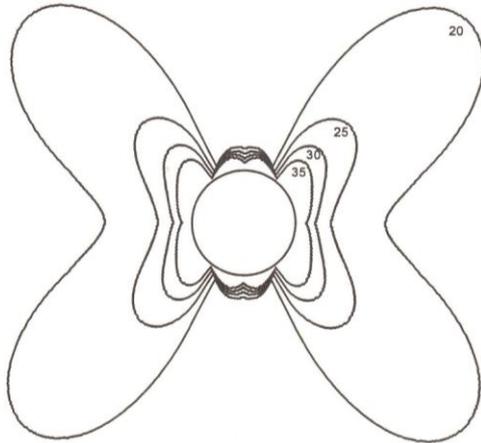


Fig. 11. Shear (sliding) zone around a tunnel when joint friction angle changes from 35° to 20° . The applied stresses are $\sigma_x = 20$ MPa, $\sigma_y = 10$ MPa. Joint orientation is 45° from horizontal direction.

Fig. 12 are very similar to those obtained from UDEC simulation.

Figure 13 shows the shear zone of four different joint orientations: joint dip angles are 45° , 60° , 75° and 90° , respectively. Among them, joints dipping 60° produce the largest shear zone. This is understood because, according to Mohr-Coulomb strength criterion of intact rock, the 62.5° dipping plane is the weakest plane for shear failure.

5. DISCUSSIONS

The excavation disturbed zone is a very general concept which refers to the region disturbed by excavation. In this study we investigated three zones

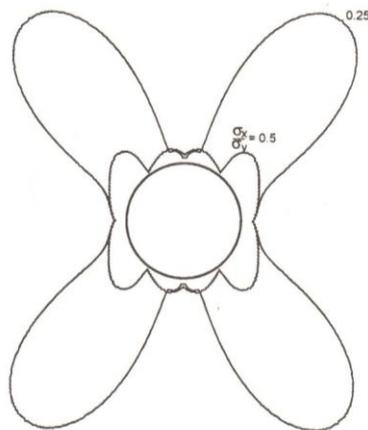


Fig. 12. Shear (sliding) zone around a tunnel at two different stress ratios. Joint friction angle is 35° . Joint orientation is 45° from horizontal direction.

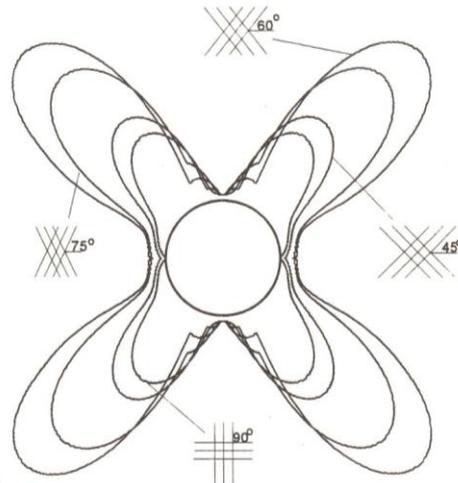


Fig. 13. Shear (sliding) zone around a tunnel when joints in the surrounding rock mass changes orientation. Joint friction angle is 40° , stress ratio is 0.25.

around a tunnel in an ideally jointed rock mass: failure zone, open zone and shear zone. The change of these three zones with different joint spacing and orientation was the main focus of this study.

The failure zone, or the region where rock blocks fall, is found in the immediate vicinity of the tunnel. In this region, due to the effect of stress arches, a local stress-free state may exist. However, this local block falling occurs only when the joint spacing is small enough to create loose blocks, as demonstrated in models No. 3 and 4. We have also seen that the location of the loose blocks is decided by the orientation of the joints. For instance, with two 45° dipping orthogonal joint sets the loose blocks appeared in the opposite walls and the roof of the tunnel, while with the vertical and horizontal joint sets they appeared in the upper-left and upper-right corners of the tunnel. It should be mentioned that this 2-D UDEC simulation only investigated the case with two sets of persistent and orthogonal joints. The results may not cover a more realistic case with non-persistent joints and a 3-D joint structure.

The open zone, i.e. the region where joints open, enlarges with reducing joint spacing and reducing stress ratio σ_x/σ_y . However, with the stress ratio being no less than 0.25, as is often the case in rock masses, the open zone is limited to a distance of the tunnel radius from the tunnel surface. A stress ratio greater than 0.5 can eventually eliminate the open zone.

The shear zone around the tunnel can extend a considerable distance from the tunnel boundary. With 45° dipping joint sets, the shear zone takes an X-shape and expands in the four directions about 60° from the direction of the minimum principal stress. The shear zone is very sensitive to the joint spacing and the stress ratio σ_x/σ_y . Small joint spacing and less stress ratio cause

a considerably increased shear zone which can extend to a distance of 10 times the tunnel radius. A lower joint friction angle and joints dipping at about 60° are also favourable for a wider shear zone.

The division of disturbed zone into failure zone, open zone and shear zone facilitates our study of a tunnel's short-term instability and long-term instability. The failure zone can be regarded as the instability during or shortly after the excavation which calls for immediate support by rock bolts or shotcrete. The open zone can be considered as the region where the long-term instability may occur. It is also a region where the water flow is significantly enhanced. If this open zone extends to a water conductive fracture zone or fault, there will be the potential for a significant increase of the water flow parallel with the tunnel and perhaps into the tunnel, if it is still open or saturated in the long term waste disposal scenario. The shear zone is the region which may be harmful to the tunnel stability by breaking rock bolts or cables. There will also be some disturbances for water flow in this region, because the joint shearing usually changes the joint aperture in the case of non-planar joint surfaces. The shear zone is of particular importance for nuclear waste disposal because it extends much wider than the

failure zone, and hence has more effect on the water flow system.

Accepted for publication 1 August 1996.

REFERENCES

1. Goodman R. E. and Shi G. -H. *Block Theory and its Application to Rock Engineering*. Prentice-Hall International, London (1985).
2. Einstein H. H. and Hirschfeld R. C. Model study on mechanics of jointed rock. *J. Soil Mech. & Found. Div., ASCE* **99** (SM3), 229-248 (1973).
3. Barton N. and Bandis S. The effects of block size on the shear behavior of jointed rock. *Proc. 23rd U.S. Symp. on Rock Mech.* Berkeley, Cal. pp. 739-760 (1982).
4. Desroches J. and Cornet F. H. Channelling and stiffness effects on fluid percolation in jointed rock. In *Rock Joints* (Edited by Barton and Stephansson) *Proc. Int. Symp. Rock Joints*, pp. 535-540 (1990).
5. Barton B., Bandis S. and Bakhtar K. Strength, deformation and conductivity coupling of rock joints. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* **22-23**, 121-140 (1985).
6. Makurat A., Barton N., Rad N. S. and Bandis S. Joint conductivity variation due to normal and shear deformation. In *Rock Joints* (Edited by Barton and Stephansson), *Proc. Int. Symp. Rock Joints*, pp. 535-540 (1990).
7. Bandis S., Lumsden A. C. and Barton N. Experimental studies of scale effects on the shear behaviour of rock joints. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* **18**, 1-21 (1981).
8. Brady B. G. H. and Brown E. T. *Rock Mechanics for Underground Mining*. George Allen & Unwin, (1985).