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**ABSTRACT:** Fiber reinforced shotcrete has been widely used as part of permanent tunnel support during the last 15 years especially in connection with the application of the Norwegian Method of Tunnelling (NMT). The interaction of the fiber reinforced shotcrete and the rock bolt reinforcement can now be numerically modelled with the Distinct element method (DEM). The discontinuous code UDEC (Universal Distinct Element Code) is used to investigate the overall stability of an excavation, to predict the expected stresses and deformations caused by the excavation and to investigate the optimal excavation sequence to be followed. The jointed rock geometry of Hyundai's shallow test tunnel in jointed biotite gneiss has been considered for demonstrating the fiber reinforced shotcrete, S(fr), subroutine. The results have shown that by using S(fr) and subsequently rock bolts as primary support in the tunnel, the load attained by some of the rock bolts is reduced by approximately half compared to the case where only rock bolts were used.

## 1 INTRODUCTION

The Norwegian Geotechnical Institute (NGI) of Oslo has been involved in a joint effort with Itasca Consulting Group for establishing an algorithm for improved simulation of the behaviour of fiber reinforced shotcrete S(fr) in multiple layers in underground structures. A special S(fr) subroutine that was developed by Itasca and financed by NGI has been incorporated in UDEC (the two dimensional Universal Distinct Element Code). In NGI's modelling work the UDEC-BB version is generally used. This is a special version of UDEC that includes the Barton - Bandis joint constitutive model (Barton and Bandis 1990).

A project that NGI and Hyundai Institute of Construction Technology (HICT) were involved in 1996 in Seoul has been chosen as an example to demonstrate the use of S(fr) in UDEC-BB. Modelling work was performed simultaneously in NGI and Hyundai and in situ measurements have been taken to be compared with the numerical results. The work involved a tunnel in Hyundai's test station (span 5.4, height 6.4 m) in biotite gneiss.

## 2 THEORETICAL BACKGROUND FOR THE FIBER REINFORCED SHOTCRETE

The structural elements in UDEC can be used to model the effect of fiber reinforced shotcrete on any rock surface. The area of application of the shotcrete is specified and UDEC automatically creates the elements necessary to represent a uniformly applied layer. The material behaviour model associated with the structural element formulation in UDEC simulates the inelastic behaviour representative of many common surface-lining materials. This includes non-reinforced and reinforced cementitious materials, such as concrete and fiber-reinforced shotcrete, that can exhibit either brittle or ductile behaviour as well as materials such as steel, that behave in a ductile manner. The behaviour of the material model used for S(fr) can be shown on a moment-thrust interaction diagram, see Figure 1. Moment-thrust diagrams are commonly used in the design of concrete columns. These diagrams illustrate the maximum force that can be applied to a typical section for various eccentricities ( $e$ ). The ultimate failure envelopes for non-reinforced and reinforced cementitious materials are similar. However, reinforced materials have a residual capacity that remains after failure at the ultimate load. Non-reinforced cementitious materials have no residual capacity.

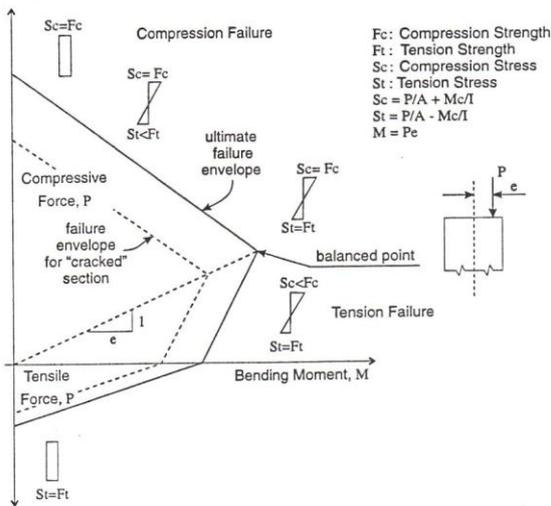


Figure 1. Behaviour of S(fr) as a moment - thrust interaction diagram.

### 3 BRIEF DESCRIPTION OF THE FIBER REINFORCED SHOTCRETE IN UDEC

The numerical code used at NGI, is a UDEC-BB version 3.0 dated November 1996 with the newly developed S(fr) subroutine implemented. This new version 3.0 is a further developed version of Cundall's original distinct element two-dimensional code (Cundall 1980). Examples of application of this code can be found in (Makurat et al. 1990, Barton et al. 1992). The main characteristics of the fiber reinforced subroutine in UDEC are as follows:

- Possibility to apply S(fr) not only on idealised (geometrical shape) tunnel peripheries but also in uneven peripheries (i.e. after a blasting operation with uneven overbreak).
- Possibility to model the variation in adhesion between the S(fr) and rock interface (e.g., model the difference in adhesion to schist and granite).
- Possibility to model the bolt reinforcement piercing the S(fr). The last feature has a limitation since the S(fr) and bolts are fixed in one single point only.
- Possibility to model the fiber reinforced shotcrete in multiple layers.

Seven different types of graphs can be produced in connection with the S(fr) subroutine in UDEC-BB. These are: axial and shear forces on the S(fr), normal and shear forces on the S(fr)/rock interface, moments on the S(fr), failure plot of the S(fr), and tensile failure plot of the S(fr)/rock bond.

The necessary choice of suitable input data to represent bond strength has resulted in the discovery of potentially very high frictional strength between

the shotcrete and rock surface, when the latter is a fresh blasted (or road-header excavated) surface with normal high roughness. Figure 2 shows the principles of the method for selecting relevant values of cohesion and friction in the rock-shotcrete interface, once a designed bond strength (of say 0.5 or 1.0 MPa) has been chosen. The method is based on the non-linear stress dependent BB model (Barton and Bandis, 1990) and on the linear Mohr-Coulomb model of shear strength. The latter is used in describing the bond strength in UDEC-S(fr) using the parameters JTENS which signifies the bond strength, JCOH for the cohesion of the interface, and JFRIC for the friction angle.

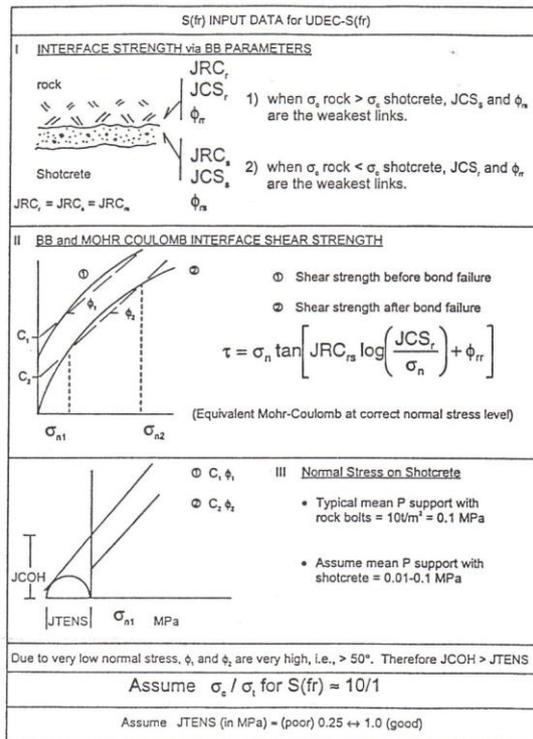


Figure 2. Estimating rock/S(fr) interface strength.

### 4 EVALUATION OF ROCK QUALITY, TUNNEL SUPPORT AND STRESS SITUATION

#### 4.1 Rock mass characterisation

Rock mass classification systems provide guidelines for the estimation of support pressure and for the design of tunnel reinforcement. The Q-System of Barton et al., 1974, Grimstad and Barton 1993, developed at the Norwegian Geotechnical Institute (NGI), has also been applied extensively to derive

the geotechnical parameters needed for predicting the performance of rock masses. As mentioned earlier the modelled tunnel section illustrated in this paper is located in biotite gneiss with varying degree of weathering. The upper 10 to 15 m of the modelled section are assumed to be weathered (shaded area in Figure 3) with the lower part strongly altered. The following points can be summarised for the gneiss .

- Two to three joint sets plus random joints, with mostly non-continuous joints in the upper and lower part of the section are observed. Equal weighting regarding frequency and extent, for sub-vertical joints.

- The mean spacing of all joint sets is 0.20 to 0.25 m.

- The continuity of joints is less than the tunnel span.

- Joint roughness is described as smooth to rough undulating.

- Joint weathering varying from nearly fresh with surface stains only to small amounts of clay for the foliation joint set.

Detailed engineering geological mapping of the rock and core logging has been carried out. The same geotechnical logging chart used in this project has been used extensively as an aid in data collection and presentation for the design of underground caverns for radioactive wastes in England (Barton et al. 1992) and for the mapping of large underground openings (Bhasin et al. 1993, Barton et. al. 1994, Grimstad and Barton 1995). The Q-values, range from 0.4 to 3.1 for the different weathering degrees of gneiss. The gneiss has sufficient joint sets for kinematics block release (three or more on average at one location) and will require systematic bolting after the application of fiber reinforced shotcrete. The joint structure of the gneiss in the model contains a wedge at the tunnel crown. A weak zone runs diagonally through the tunnel demonstrating the worst case scenario.

#### 4.2 Support requirements, fiber reinforced shotcrete

The estimated support requirements for this tunnel which were derived by the Q-system suggest a total thickness of S(fr) about 10 cm. The S(fr) can be applied in two layers of 5 cm each. The first layer which will be applied immediately after the excavation will be followed by systematic bolting in a  $1.5 \times 1.5$  m pattern, 25 mm in diameter and 2.5 m in length followed by the second 5 cm S(fr) layer.

### 5 DESCRIPTION OF THE NUMERICAL MODELS

Four numerical models were run and compared in an attempt to get a better understanding of the performance of the fiber reinforced shotcrete in the tunnel.

The analysis of the results in this paper focuses on the behaviour of the S(fr) and the rock bolts. All four models have exactly the same joint geometry (Figure 3), intact rock, joint properties, boundary conditions (roller boundaries) and in-situ rock stresses. The tunnel was excavated in a single excavation step. The S(fr) was applied on the models when approximately 50% of the total expected deformation had occurred to be followed by the installation of bolts at about 60% of the total expected deformation. This was done in an attempt to allow for the elastic deformation that had already occurred at the face of the tunnel. In model 2 where only rock bolts were applied, these were applied at about 50% of the total deformation. The differences between the numerical models are:

- The 1st model (Model 1) was run unsupported, no S(fr), no bolts

- The 2nd model (Model 2) has no S(fr) applied only bolts.

- The 3rd model (Model 3) has total S(fr) thickness of 10 cm applied in two layers of 5 cm each with bolting between these stages.

- The 4th model (Model 4) has a S(fr) thickness 10 cm applied in a single layer followed by rock bolts.

For the numerical modelling a rather conservative ratio of  $\sigma_h/\sigma_v = 0.75$  has been used. The deformation modulus for the intact rock is assumed to vary between 0.4 (weak zone) and between 1 and 4 GPa for the upper and lower part of the model, Poisson's ratio varies between 0.27 (weak zone) and 0.3 for the intact rock and density varies between  $2300 \text{ kg/m}^3$  (weak zone) and  $2500 \text{ kg/m}^3$  for the intact rock.

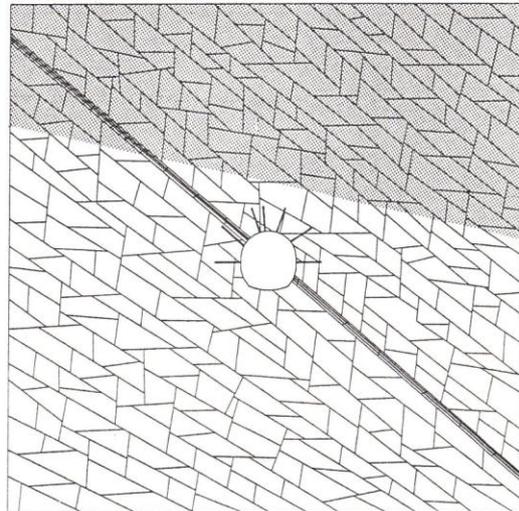


Figure 3. Jointed rock mass geometry, and bolt pattern used in the models.

Table 1. Jointed rock properties for the sub-horizontal joint set and joint sets 2 & 3.

Parameter	Joint set 1	Joint set 2	Joint set 3
	sub-horizontal 0°-40°	Sub vertical I 90°-140°	Sub vertical II 40°-90°
JRC <sub>0</sub>	5.4	2.3	3.8
JCS <sub>0</sub> MPa	98.0	114.0	136.0
φ <sub>r</sub> deg.	28.5	30.5	30.5
σ <sub>c</sub> MPa	190.0	190.0	190.0
L <sub>0</sub> m	0.1	0.1	0.1
L <sub>n</sub> m	0.4	0.3	0.3
Aper mm	0.192	0.110	0.137

Table 2. Fiber reinforced shotcrete parameters used in the modelling work.

Parameter	All Models
Modulus of elasticity, E (GPa)	15
Poisson's ratio, ν	0.15
Density, ρ (kg/m <sup>3</sup> )	2,500
Compressive yield strength, (MPa)	30
Tensile yield strength, (MPa)	3
Residual tensile yield strength, (MPa)	2
Friction in S(fr)/rock interface, (deg.)	60
Cohesion in S(fr)/rock interface, (MPa)	0.86
Tension in S(fr)/rock interface, (MPa)	0.50

Table 3. Summary of the numerical results for model 1, 2, 3 and 4.

Parameters	Model 1	Model 2	Model 3	Model 4
Maximum principal stress, (MPa)	1.41	1.39	1.42	1.53
Maximum displacement (mm) arch crown	4.59	4.17	3.92	4.06
Maximum shear displacement (mm)	2.90	2.56	1.46	2.05
Maximum axial forces on bolts (tnf)		14.76	12.48	13.09
Maximum axial forces on S(fr) (tnf)			32.30	32.60
Maximum moment on S(fr) (tnf)x m			0.18	0.54
Maximum shear forces on S(fr) (tnf)			3.54	4.34
Maximum normal forces on S(fr)/rock (tnf)			7.72	5.51
Maximum shear forces on S(fr)/rock (tnf)			6.77	9.43

The jointed rock properties for all joint sets in the model are shown in Table 1. The necessary UDEC - S(fr) properties for modelling the S(fr) and their values used in this modelling work are listed in Table 2. The rock bolt pattern (bolts of 25 mm diameter) that was applied in reality in the crown and the walls of the tunnel was also modelled numerically (bolt spacing 1.5 m; length 2.5 m). The rock bolt pattern is also shown in Figure 3, UDEC results in Table 3.

## 6 NUMERICAL RESULTS - UDEC-BB

### 6.1 Rock mechanics effects

There is a little change between different models in the magnitude and direction of principal stresses. In order to study the effects of a falling wedge on the tunnel support system, a wedge has been formed numerically on the tunnel crown. When the tunnel was run unsupported, this wedge was loosened and eventually fell. When the tunnel was run with S(fr) and steel bolts the wedge remained in place. For practical reasons, a single "temporary" bolt was used to keep the falling wedge in place immediately after the numerical excavation and before the application of the S(fr) and the ordinary bolt pattern on the model.

The shearing associated with the active wedge in the tunnel crown for model 1 is significant. S(fr) which was modelled in three of the models will effectively secure smaller blocks from falling, something that will very likely happen in reality.

### 6.2 Development of deformation vectors during excavation

The unsupported tunnel in model 1 exhibits the highest deformation values (Table 3). There is a difference in the deformation magnitudes of about 15% between model 1 and model 3. The maximum deformation value occurs in the invert arch of the tunnel. The application of S(fr) on the tunnel in layers of 5 cm with reinforcing bolts in between (model 3) reduces the maximum shear displacement on the joints by approximately half. Due to the presence of massive blocks around the opening the S(fr) has little effect on the overall stability of the tunnel.

### 6.3 Axial forces on bolts

As expected the use of S(fr) lessens the load on the rock bolts. One of the model shows axial bolt forces approaching or even exceeding the scaled bolt yield limit (14.7 tnf). It is clear that, due to the presence

of the unstable wedge in the arch, this particular bolt is heavily loaded, with some others bolts approaching yield limit. It is worth mentioning the 15% decrease of the maximum bolt forces in model 3 where two layers of S(fr) 5 cm each were applied, and maximum bolt load reached 12.5 tnf, (Figure 4, left) and in model 2 where no S(fr) was applied. The yield limit in the bolts is derived from the 22 tnf yield limit for the 25 mm bolts times the reduction factor of 0.67 (bolt pattern 1.5 x 1.5 m) for the UDEC model of 1 m thickness.

It is interesting to note also the development of bolt forces in the models with different thickness of S(fr), models 3 and 4. It is obvious that the application of 2 layers of S(fr) 5 cm each, instead of a single layer of 10cm, contributes to a better distribution of the bolt forces in the rock mass.

#### 6.4 Forces and moments on the S(fr), failure mode

There is a substantial difference between the results obtained between model 3 and 4. The area of application of the forces on the S(fr) is 1 m (depth of model) x 10 cm (e.g. for S(fr) thickness) = 0.1 m<sup>2</sup>. The thinner S(fr) layer in model 3 (1st layer) shows a rather uniform distribution of shear forces around the arch and the tunnel walls, while the thicker S(fr) layer in model 4 attains shear forces mainly on the tunnel arch. This can also be observed from the shear plot in Figure 5. The second S(fr) layer of 5 cm on the arch and walls in Model 3 attains about half of the shear forces compared to the 1st applied layer.

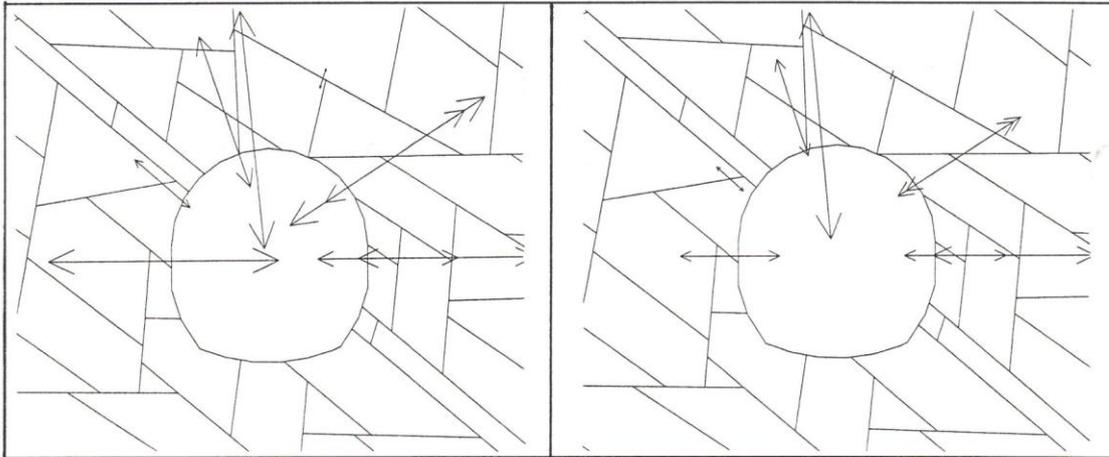


Figure 4 Axial bolt forces for models 2 (left) max. value 14.8 tnf and model 3 (right) max. value 12.5 tnf.

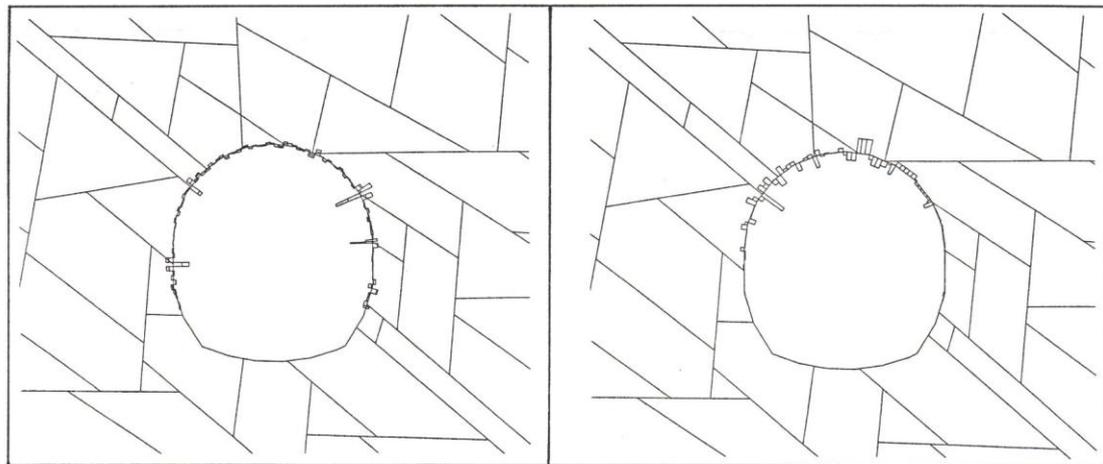


Figure 5. Shear forces plot for model 3 (left) max. value 3.5 tnf and model 4 (right) max. value 4.3 tnf.

## 7 CONCLUSIONS

- Design and construction of Hyundai's shallow test tunnel in relative weak rock has been carried out by using principles from the Norwegian Method of Tunnelling (NMT). The rock quality varies between very poor, to poor. The geo-mechanical properties of these rocks have been assessed based on laboratory and field investigations for input to numerical modelling studies. The rock mass characterisation approach (Q-system) has been applied extensively to predict and evaluate appropriate rock reinforcement requirements tunnels. The estimated Q-values measured ranged between 0.4 and 3.1.

- The input data for the UDEC-BB models have been derived from rock joint and rock mass characterisation. The four numerical models that are presented in this article were similar, with variations mainly in the S(fr) thickness. Models 2, 3 and 4 have also been numerically reinforced by systematic bolting. The bolt properties and bolt pattern were derived by means of the Q-system. The discontinuum code UDEC-BB (Barton - Bandis joint constitutive model) was used for the two-dimensional modelling of the tunnel. This is a rather conservative approach since several features of the in situ rock behaviour cannot be modelled in 2 D (e.g. only the joints parallel or sub-parallel to the tunnel axis have been represented etc.).

- The numerical models 3 and 4 have shown that there is little effect of the S(fr) thickness on the overall deformation of the tunnel. The effect of S(fr) is more evident in the maximum shear displacement values where shear displacement is almost reduced by half in the model where S(fr) was applied prior to bolting. This is mainly due to the fact that the tunnel is lying in a jointed biotite gneiss with rather low JRC values especially in the foliation joint set. The load on some of the rock bolts was reduced by about 15% to 50% when S(fr) was used prior to bolting. This is mainly due to the fact that the rock mass deforms rather little. The S(fr) thickness applied on the tunnel was 5 + 5 cm and 10 cm for models 3 and 4 respectively.

- The use of S(fr) in relatively weak rocks with unstable wedges on the tunnel crown reduces significantly the load attained by the rock bolts. The implications for the use of S(fr) as tunnel support in intensively jointed tunnel conditions are obvious.

- The modelled values of axial and shear forces in the shotcrete and forces along the rock-shotcrete interfaces as well as bolt capacity, can each be compared with Q-system designed assumptions, Hyundai's detailed deformation monitoring of tunnel sections and modelling of the tunnel by using ITASCA's FLAC code (Fast

Langragian Analysis of Continua). These comparisons will be a subject of a future article.

## 8 REFERENCES

- Barton, N., R. Lien, and J. Lunde 1974. Engineering classification of rock masses for the design of tunnel support. *Rock Mech.*, 6: 189-236.
- Barton, N., F. Løset, R. Lien and J. Lunde 1980. Application of the Q-system in design decisions concerning dimensions and appropriate support for underground installations. *Int. Conf. on Sub-surface Space, Rockstore, Stockholm, Sub-surface Space*, Vol. 2, pp. 553-561.
- Barton, N., F. Løset, A. Smallwood, G. Vik, C.P. Rawlings, P. Chryssanthakis, H. Hansteen and T. Ireland 1992. Geotechnical core characterization for the UK radioactive waste repository design. *Proc. ISRM Symp. EUROCK*, Chester, UK.
- Barton, N., T.L. By, P. Chryssanthakis, L. Tunbridge, J. Kristiansen, F. Løset, R.K. Bhasin, H. Westerdahl and G. Vik 1994. Predicted and measured performance of the 62m span Norwegian Olympic Ice Hockey Cavern at Gjøvik. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* Vol. 31, No. 6, pp. 617-641.
- Barton, N. and S.C. Bandis 1990. *Review of predictive capabilities of JRC-JCS model in engineering practice. International Symposium on Rock Joints*. Loen 1990. Proceedings, pp. 603-610.
- Bhasin, R., N. Barton and F. Løset 1993. Engineering geological investigations and the application of rock mass classification approach in the construction of Norway's underground Olympic stadium. *Eng. Geol.*, 35:93-101.
- Cundall, P.A. 1980. *A generalized distinct element program for modelling jointed rock*. Report PCAR-1-80, Contract DAJA37-79-C-0548, European Research Office, US Army. Peter Cundall Associates.
- Grimstad, E. and N. Barton 1993. Updating of the Q-System for NMT. *Proc. Int. Symp. Modern use of wet mix sprayed concrete for underground support*, Fagernes 1993, Norway, 46-66.
- Grimstad, E. and N. Barton 1995. Rock mass classification and the use of NMT in India. *Proc. Conf. on design and construction of underground structures*, 23-25 February 1995, New Delhi, India.
- Makurat, A., N. Barton, G. Vik., P. Chryssanthakis and K. Monsen 1990. Jointed rock mass modelling. *International Symposium on Rock Joints*. Loen 1990. Proceedings, pp. 647-656.