*Fractured and Jointed Rock Masses, Myer, Cook, Goodman & Tsang (eds)* © *1995 Balkema, Rotterdam. ISBN 90 5410 591 7*

# Radioactive waste repository design using Q and UDEC-BB

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***Abstract***

The NGI methods of characterising joints (using JRC, JCS and $\phi_r$) and characterising rock masses (using the Q-system) are being utilised in a current geotechnical consultancy project for UK Nirex Ltd. Present geotechnical characterisation activities include the logging of six kilometres of 100mm drill core.

Preliminary rock reinforcement designs (systematic bolting and unreinforced or fibre-reinforced shotcrete) are derived from the Q-system statistics, which are logged in parallel with JRC, JCS and $\phi_r$. Discrete element UDEC-BB modelling provides a check on the performance of the proposed excavations with Q-system reinforcement, giving predicted bolt loads and rock deformations, together with joint shearing and hydraulic apertures to better define the disturbed zones.

## INTRODUCTION

The NGI methods of characterising joints (using JRC, JCS and $\phi_r$) and characterising rock masses (using the Q-system) are being utilised in a current geotechnical consultancy project for UK Nirex Ltd. This organisation is responsible for the safe disposal of solid low and intermediate level radioactive waste in the UK. Present planning and site investigation is now focused at Sellafield in NW England where extensive deep drilling, downhole testing, geological and geophysical investigations are progressing. According to present plans, approximately 2 million $m^3$ of low and intermediate level radioactive waste may eventually be disposed of at Sellafield, utilising large rock caverns at depths in the region of 800m. Present plans are for caverns of 25m span and heights of 15m (low level waste) or 35m (intermediate level waste) (refer to Ireland, 1992) [9].

The NGI/WS Atkins/Taywood Engineering work as Geotechnical Consultants to UK Nirex Ltd has included field mapping and core logging, using newly developed geotechnical logging charts which combine Q-system parameter histograms with more detailed joint and rock mass descriptions suitable for use in the distinct element code UDEC-BB (Cundall, 1980 [6], Makurat et al., 1990 [11]). Extensive numerical analyses of access tunnel and cavern excavation response are being carried out to investigate rock reinforcement requirements and the extent of the disturbed zones. The latter is graphically represented by UDEC-BB plots of stress, deformation, joint shearing and joint aperture distributions and magnitudes.

## GEOTECHNICAL LOGGING CHART

As a first step in the rock mechanics design process, data of relevance to cavern and tunnel design studies are collected from field mapping and from current logging of some 6 km of oriented drill core. The methods used by BGS for core orientation are described by Horseman et al. (1992). [8]

The NGI/WSA team has utilised newly developed geotechnical logging charts for describing jointing in the drill cores. The chart used in the field mapping is illustrated in Fig. 1 for a hypothetical data set. A brief explanation of each parameter logged is given below.

Since the stability of excavation in hard rock masses depends largely on jointing, much of the data concerns such features as joint geometry and the surface characteristics of the joint planes. Included in the charts are also some data concerning permeability, rock compressive strength and rock stresses, as obtained by other Nirex contractors.

Data for the six Q-system parameters are given on the left hand side of the geotechnical chart. In the histograms drawn for each Q-parameter, values plotting on the right hand side of the chart are favourable for good stability, while values plotting more on the left hand side imply poorer stability.

To the right of the six Q-parameters in the geotechnical chart, there are other parameters which express rock mass character in related ways. These additional data are necessary in order to give a more complete description of the rock mass and rock joints, especially for the performance of subsequent numerical modelling.

The upper third of the chart (including RQD and $J_n$) describes geometrical factors of the ***rock mass*** as a whole. The middle third of the chart (including $J_r$ and $J_a$) describes ***joint character***. The lower third of the chart (including $J_w$ and

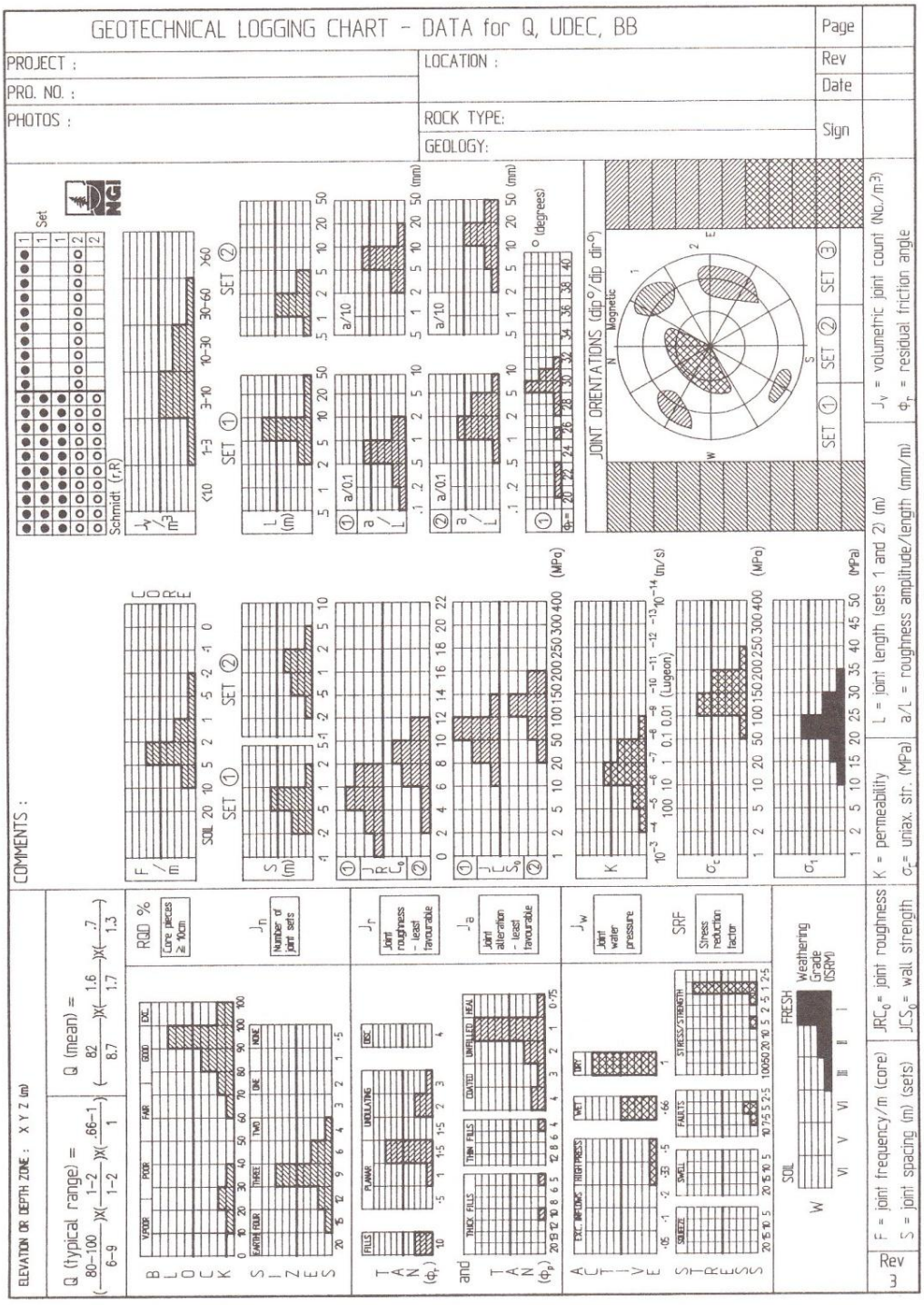


*Fig. 1 Geotechnical logging chart for recording rock mass quality (Q), rock joint character (JRC, JCS, $\phi_r$) and related data for UDEC-BB design studies.*

SRF) includes such factors as ***permeability, rock stress*** and ***strength***.

The parameters presented in the geotechnical logging chart are as follows:

*I ROCK MASS STRUCTURE*

1. RQD (Deere et al. 1967) [6] (Q)
2. $J_n$ = joint set number (Q)
3. F = joint frequency (per metre)
4. $J_v$ = volumetric joint count (Palmstrøm, 1983) [9]
5. S = joint spacing (in metres)
6. L = joint length (in metres)
7. w = weathering
8. $\alpha/\beta$ = dip/dip direction of joints

*II JOINT CHARACTER*

9. $J_r$ = joint roughness number (Q)
10. $J_a$ = joint alteration number (Q)
11. JRC = joint roughness coefficient
12. a/L = roughness amplitude of asperities per unit length (mm/m)
13. JCS = joint wall compressive strength
14. $\phi_r$ = residual friction angle

*III WATER, STRESS, STRENGTH*

15. $J_w$ = joint water reduction factor (Q)
16. SRF = stress reduction factor (Q)
17. K = rock mass permeability (m/s)
18. $\sigma_c$ = compressive strength
19. $\sigma_1$ = major principal stress

Further details of these parameters are given by Barton et al. (1992). [5]

## JOINT CHARACTERISATION AT SELLAFIELD

Present geotechnical characterisation activities are focused on the logging of six kilometres of nominal 100mm drill core.

Selected joints recovered in the drill core are subjected to index tests to determine JRC (using tilt tests and profiling), JCS (using Schmidt hammer tests) and $\phi_r$ (using tilt and Schmidt hammer tests).

The NGI methods of tilt testing and Schmidt hammer testing of joints have been described in detail by Barton and Choubey (1977) [1] and by Barton and Bandis (1990) [3] and will not be elaborated upon here.

This index testing is performed in the NGI/WSA laboratory kindly provided by BGS at Keyworth, Nottingham. Joint behaviour is checked at NGI using Direct Shear Tests (DST) and Coupled Shear Flow Tests (CSFT). The three parameters are subsequently used as part of the direct input for discrete element UDEC-BB modelling of access tunnel and cavern performance.

Examples of a set of data for JRC, JCS and $\phi_r$ obtained from a section of one of the Sellafield boreholes is shown in Figure

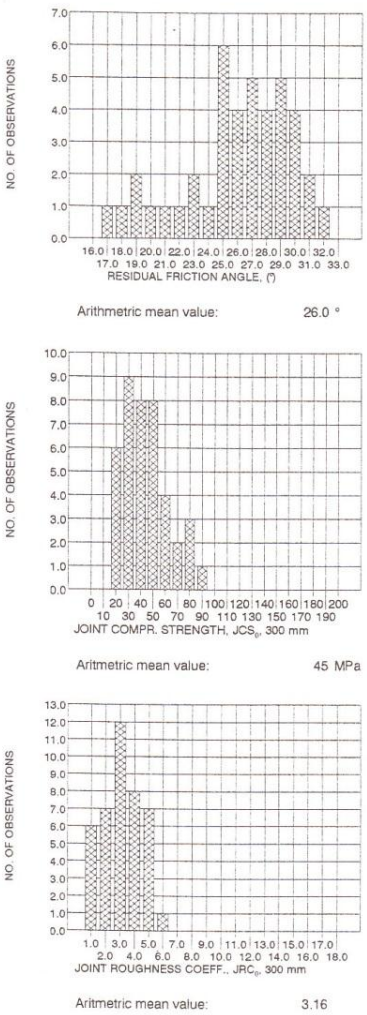


*Fig. 2 Example of JRC, JCS and $\phi_r$ joint statistics for a section of a borehole at Sellafield.*

2. The mean values of JRC, JCS and $\phi_r$ of approximately 3.2, 45 MPa and 26° can be used directly as input data in UDEC-BB models of excavations. In practice, NGI/WSA are logging joints of different sets separately, and UDEC-BB models (shown later) are given different sets of input data according to the numbered joint sets modelled in any particular case.

## VALIDATION OF SELLAFIELD JOINT DATA

The extensive core logging performed for UK Nirex Ltd in this project is providing significant data concerning the statistical variation of joint parameters and the potential variation of data from joint set to joint set. These data, which are obtained from index testing of joints from several kilometres of drill core, are also supplemented with selected laboratory testing, in order to validate the JRC, JCS and $\phi_r$

data. The objective here is to verify that the measured shear behaviour of the joints, the normal stiffness behaviour, and coupling between closure and water flow, and shearing and water flow, are each reasonably well described by the non-linear BB joint behaviour model which is a sub-routine of the discrete element code UDEC developed by Cundall (1980). [6] The UDEC-BB code is used in subsequent modelling of rock excavations at Sellafield, as shown later.

The statistically representative data set obtained from many hundreds of joint samples that undergo tilt testing and Schmidt hammer testing is complemented by a lesser but significant number of laboratory tests. Direct Shear Testing (DST) and Coupled Shear Flow Testing (CSFT) performed in NGI's laboratories indicate satisfactory agreement between prediction and practice.

## ROCK MASS CHARACTERISATION AT SELLAFIELD

The large amount of data generated in this characterisation programme has necessitated computerised data handling. All the geotechnical joint logging performed on core at BGS by the NGI/WSA team is therefore recorded on a PC. Lotus format plotting of data in the form of tables and histograms is thereby readily achieved, and combination of data from specific depth zones or from borehole to borehole is facilitated. The charts are supplemented and updated by data from other Nirex contractors where appropriate; for example concerning rock strength, rock mass permeability, rock stress, and joint orientation.

The comprehensive set of data such as that shown in Fig. 1 is subsequently used in an integrated design exercise. In each case, data obtained from relevant field mapping is noted, so that the bias introduced by vertical boreholes is minimised.

In principle, the Q-system data logged in the left hand side of the chart (see parameters RQD, $J_n$, $J_r$, $J_a$, $J_w$, SRF) is used to make preliminary designs for rock reinforcement for tunnels or waste disposal caverns. The recommended rock reinforcement (i.e., bolts of specific length, diameter and spacing) is subsequently modelled discretely in the UDEC-BB models of the specific excavations (Cundall 1980) [6], to check on the adequacy and predicted performance of the excavation both with and without reinforcement.

Logged data concerning joint frequency, joint spacing and orientation are utilised when assembling the joint geometries for the numerical models. This important exercise is performed by the same engineering geologists who have mapped relevant exposures in the field, logged the core and analysed the data sets. The rock mechanics modellers who also have logging experience, "take over" the joint models for UDEC-BB analysis, after integration with the engineering geologists' final stages of work.

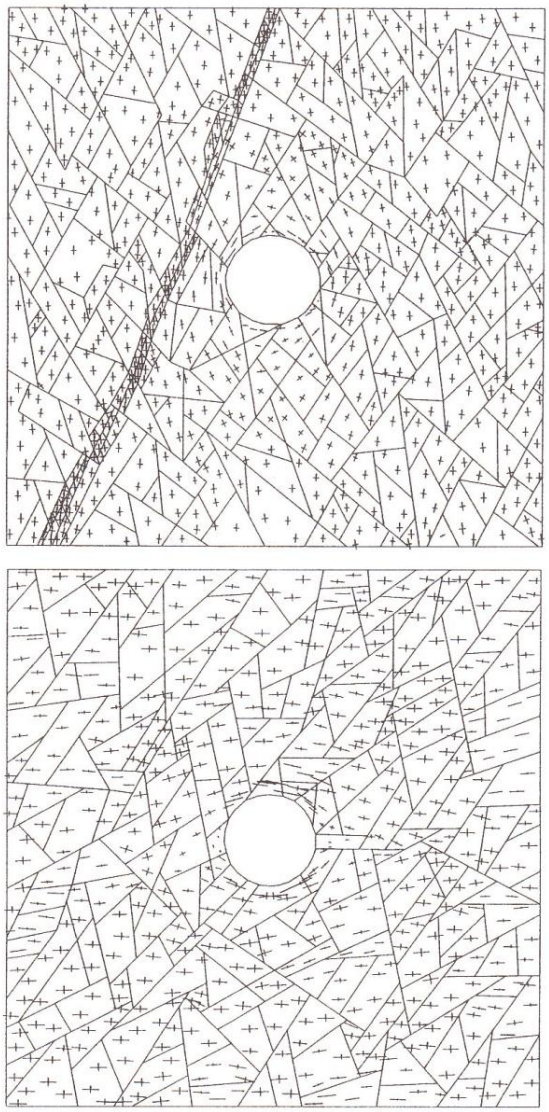

*Fig. 3 Simulation of an 8.4m diameter TBM access tunnel a) parallel and b) perpendicular to the major stress.*

## NUMERICAL MODELLING OF TBM ACCESS TUNNELS

A present concept for access to the repository depth, which will probably be in the region of 800m, is by inclined spiral tunnels which may be driven by hard rock TBM of about 8m diameter. Some preliminary studies of tunnel stability which demonstrate the use of the core logging data in discrete element (UDEC-BB) models are shown in Figures 3, 4 and 5.

The lower horizontal rock stress around one side of the spiral (Fig. 3, top) contrasts with the higher horizontal rock stress around the side of the spiral at right angles to the principal stress (Fig. 3, bottom). The contrasting influence of

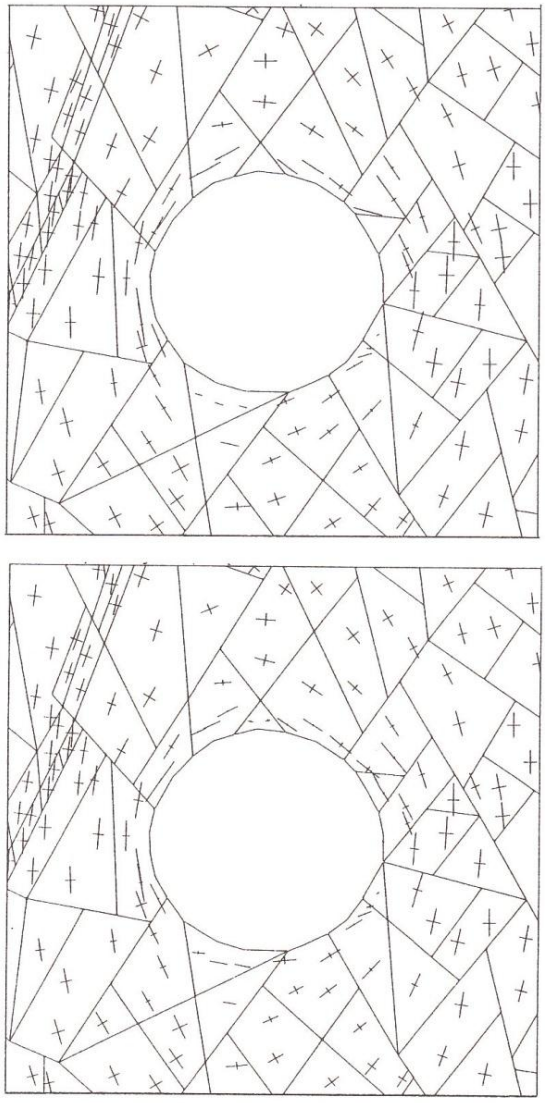

*Fig. 4 Low stress model showing unstressed wedges a) when unbolted, and stressed wedges (and reduced displacements) b) when bolted.*

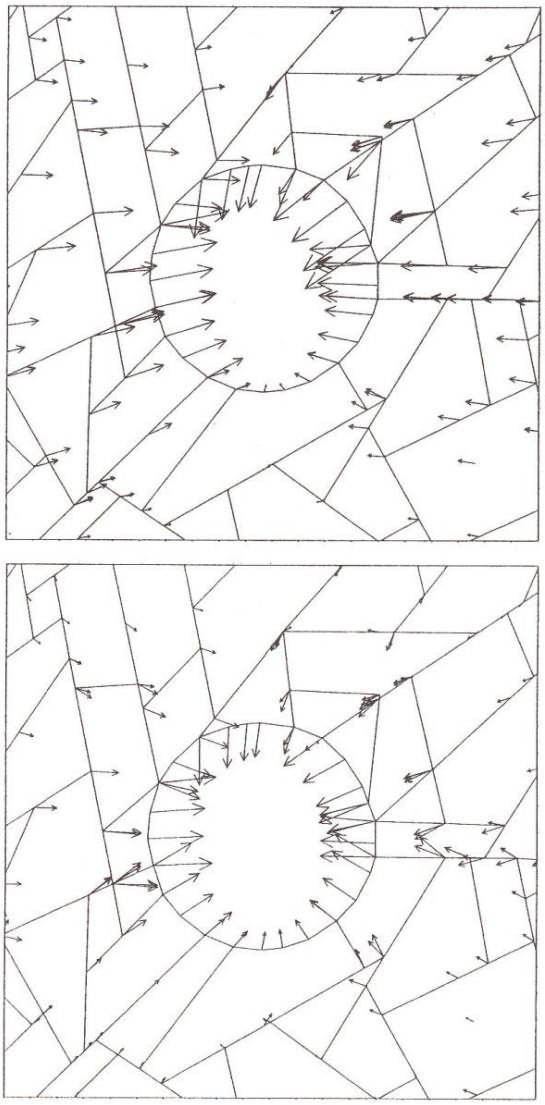

*Fig.5 Higher stress model showing the displacements a) without bolting (max. 14.8mm) and b) with Q-system bolting (max. 7.4mm).*

bolting on stresses is shown in Fig. 4. The upper diagram shows two unstressed wedges in the unbolted case, and the lower diagram shows renewed stress transfer in these wedges when bolted, using Q-system designs of B 1.5m c/c, L = 3.0m, $\phi$ = 20mm. Fig. 5 shows displacement vectors in the higher stress model (Fig. 3b) for the case of no bolting (Fig. 5a) and with bolting (Fig. 5b).

The models illustrated were first run to equilibrium with no modelled rock reinforcement. Q-system designed rock bolting was subsequently installed at the "instant" (tens of thousands of cycles) when approximately 50% of the maximum deformation had occurred. This corresponds roughly speaking to the earliest possible installation of bolting through trailing fingers some few metres behind the crown of the TBM. The models are then run on to equilibrium. This causes axial loading in the bolts, usually tensile in nature. Other UDEC-BB plots include bolt loads at joint crossing (using Lorig's 1985 [10] bolting sub-routine in UDEC), joint shearing (Fig. 6a) and mechanical and hydraulic joint apertures (Fig. 6b).

On occasion, the UDEC-BB verification of the Q-system reinforcement design shows the need for minor adjustments to bolt spacing or bolt diameter. This is an important aspect of quality control which is followed systematically. A further check on the performance of the UDEC-BB models with the

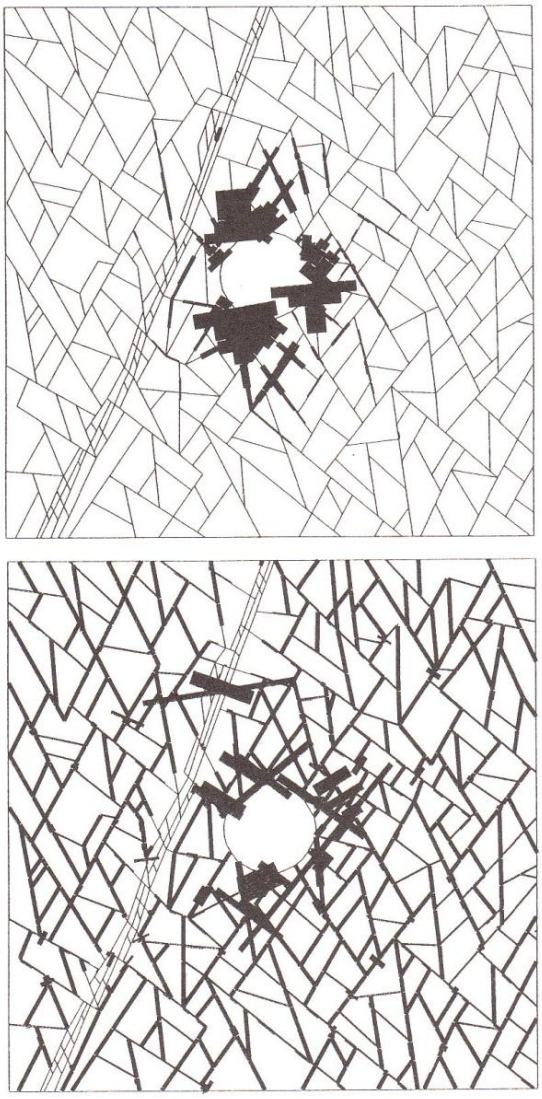

*Fig. 6 Shear displacements on the joints (upper) and hydraulic apertures (different for three joint sets) indicate the extent of the disturbed zone.*

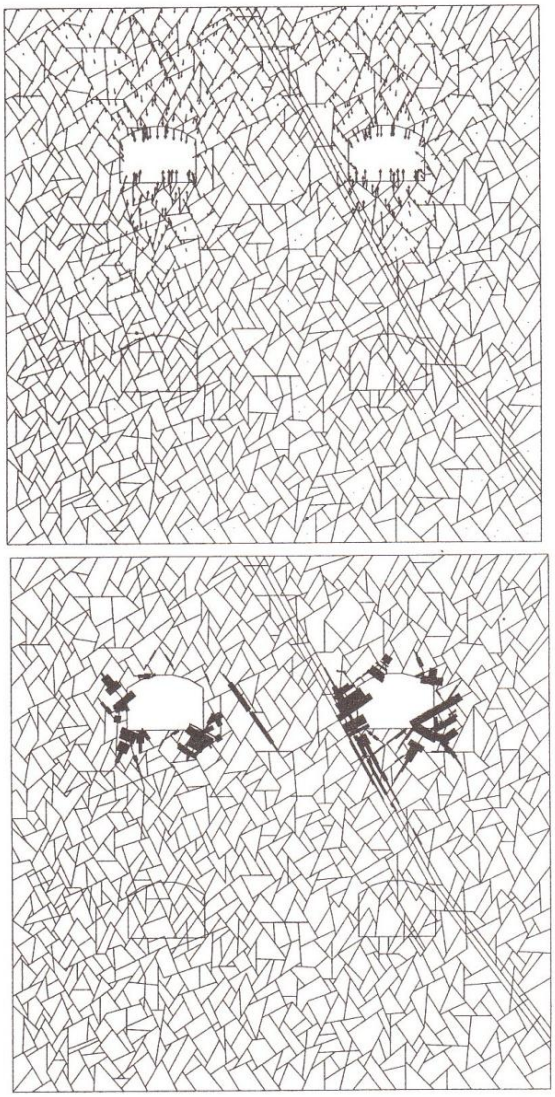

*Fig. 7 Low level waste caverns (upper level) if excavated with axes parallel with the major horizontal stress and left unbolted. Magnitudes of the displacement vectors (max. 29.2mm) and joint shearing (max. 24.9mm) are shown.*

Q-designed reinforcement is to compare the wall and arch displacements with Q-system case records of measured deformations in excavations of equivalent size and Q-value. The "normalised" plot of Q/span or Q/height versus measured deformation given by Barton et al. (1980) [2] forms the data base for this verification exercise.

It is noted that the UDEC model records the total deformation as compared to the partial deformation usually recorded in instrumented tunnels. There are exceptions to this such as the 62m span Olympic ice hockey cavern excavated at 25 to 50m depth in Gjøvik, Norway for the 1994 Games (Barton et al. 1992). [4]. In this case, the MPBX extensometers were installed from the surface prior to construction and subsidence of the surface was also measured. The total downwards deformation of 4 to 8mm recorded by a range of instruments was matched by 4 to 9mm in UDEC-BB models using core logging and stress measurements.

## NUMERICAL MODELLING OF LOW LEVEL WASTE CAVERNS

Low level waste caverns (LLW) are presently planned as 25m span by 15m high excavations on two levels in the repository. NGI is performing scoping studies with UDEC-BB

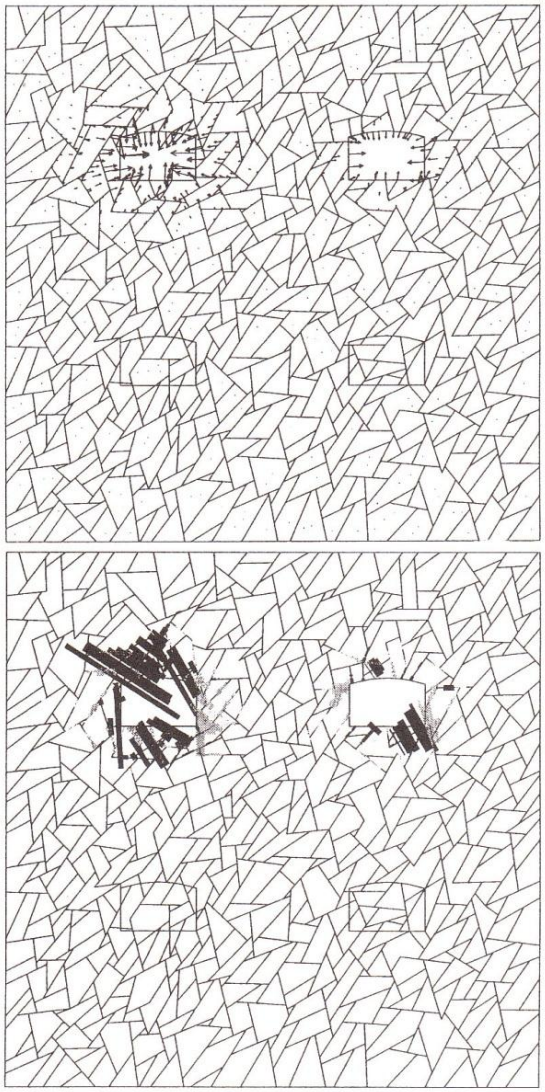

*Fig. 8 Low level waste cavern (upper level) if excavated with axes perpendicular to the major horizontal stress. Magnitudes of the displacement vectors (max. 13.8mm) and joint shearing (max. 11.6mm) are shown.*

to investigate the effects on various pillar widths and crown pillar thicknesses of the disturbed zones surrounding each cavern. Different cavern orientations are also being investigated, in order to minimise construction difficulty, cost and disturbed zone development.

An example of one of the LLW scoping studies is shown in Figs 7 and 8. The studies shown here were first run without bolting as worst case scenarios. The more frequently jointed model in Fig. 7 is a simulation with cavern axes parallel to the major stress and sub-parallel to many of the joints. Larger disturbed zones are indicated in this case with maximum deformations and joint shearing of 29.2mm and 24.9mm respectively.

The less frequently jointed model in Fig. 8 is a simulation with cavern axes perpendicular to the major stress. More localised disturbed zones and less deformation (max. 13.8mm) and shear (max. 11.6mm) are indicated, even for this unbolted, worst case condition.

## CONCLUSIONS

1. A systematic method of recording relevant geotechnical data during field mapping and core logging has been described. The method serves as a check list of important parameters, and allows the all important variability of rock masses to be recorded and taken account of in design.

2. The integrated use of Q-system rock mass parameters and the more detailed joint descriptors JRC, JCS, and $\phi_r$ have been demonstrated. The parameters $J_r/J_a$ from the Q-system allow the shear strength of filled discontinuities to be estimated. These supplement the use of JRC, JCS and $\phi_r$ for describing the behaviour of the unfilled joints.

3. The utilisation of geotechnical data obtained from logging several kilometres of oriented drill core from Sellafield in discrete element models has been illustrated. UDEC-BB discrete element models of TBM driven access tunnels and low level waste caverns demonstrate the capability for realistic modelling of excavations in jointed rock.

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