

Rock joint and rock mass characterization at Sellafield

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ABSTRACT: The NGI methods of characterizing rock joints and rock masses were utilized extensively in geological investigations undertaken by United Kingdom Nirex Limited (Nirex) at Sellafield to determine whether it was suitable as the location for a deep geological repository for radioactive wastes. In addition to the standard rock mechanical laboratory testing of joints, coupled shear flow testing (CSFT) was also performed on natural rock joints for obtaining the magnitude of joint conducting apertures. The objectives of the CSFT tests were to produce site specific data, albeit on small scale samples, so that the effects of normal and shear stress changes, closure and shearing, could be evaluated and compared with the patterns of behaviour predicted by numerical modelling of the disturbed zone which would be caused by excavation of disposal caverns.

Preliminary rock reinforcement designs for the conceptual disposal caverns were derived from the Q-system statistics. Numerical modelling using UDEC-BB was carried out for predicting the behaviour. The purpose of numerical modelling was to investigate the potential stability of various sizes of rock caverns and in particular the rock reinforcement (predicting bolt loads and rock deformations), the extent of the disturbed zone (joint shearing and hydraulic aperture) with respect to cavern orientation, the effect of pillar widths, and the effect of cavern excavation sequence.

1 INTRODUCTION

The NGI methods of characterizing rock joints (using JRC, JCS and ϕ_r) and characterizing rock masses (using the Q-system of Barton et al, 1974) formed the basis for NGI's participation in the site characterization programme at Sellafield to determine whether the site was suitable as the location for a deep waste repository for the disposal of the UK's intermediate-level and certain low-level solid radioactive wastes (Nirex, 1997). A special geotechnical logging chart (see Fig. 1) was developed for recording and presenting key engineering geological parameters including the data required for rock mass classification purposes (Q-system). This PC based chart has allowed the data logged from different areas around the project site to be combined enabling input data files to be set up for numerical modelling of sections of the underground excavations. Advanced rock mechanics testing of joints which include coupled shear flow conductivity tests (CSFT) were performed on natural joints from the sedimentary and volcanic rocks. The CSFT testing apparatus, which was designed by NGI, helped derive the experimental data needed to quantify the effect of joint

deformation on conductivity (Makurat et al, 1990). Rock reinforcement designs were evaluated using the Norwegian Method of Tunnelling (NMT) concepts (Barton et al, 1992).

2 JOINT CHARACTERIZATION AT SELLAFIELD

2.1 Joint shear strength parameters

Index tests to determine JRC (tilt tests, pull tests and profiling), JCS (Schmidt hammer tests), ϕ_r (tilt tests, pull tests and Schmidt hammer) were carried out on joints recovered in the 96 mm diameter drill core. The NGI methods of tilt testing and Schmidt hammer testing are described in detail by (Barton and Choubey, 1977 and by Barton and Bandis, 1990).

The original form of the non-linear «JRC - JCS» criterion for predicting the shear strength of rock joints (Barton and Choubey, 1977) is written as:

$$\tau = \sigma_n \tan \left[JRC \log \left(\frac{JCS}{\sigma_n} \right) + \Phi_r \right] \quad (1)$$

where σ_n = normal stress and τ = shear stress. The residual friction angle ϕ_r for unfilled joints is determined from Schmidt hammer and tilt tests using the following equation (Barton and Choubey, 1977):

$$\Phi_r = (\Phi_b - 20^\circ) + 20 \left(\frac{r}{R} \right) \quad (2)$$

The parameter ϕ_b is termed the basic friction angle for flat, sawn, but unpolished, unweathered surfaces of the rock in question.

Computerized data handling using the geotechnical core logging charts has enabled visualization of both the lateral and depth variation of the various parameters for the jointed rock masses at the site.

2.2 Geotechnical logging chart

A convenient method of recording and presenting key geotechnical parameters including the data required for rock mass classification purposes was developed at NGI for systemizing the data logged from Sellafield (see Fig. 1). The basis of the engineering geological data is the six different parameters in the Q-method: RQD (rock quality designation), J_n (joint set number), J_r (joint roughness number), J_a (joint alteration number), J_w (joint water reduction factor) and SRF (stress reduction factor). Histograms for these parameters are shown in Fig. 1.

The Q-system parameters, along with other important engineering geological data, form a set of information required for the design and modelling of underground structures. The Q-system parameters occupy the left-hand side of Fig. 1. This chart is arranged in a special manner for convenience in field mapping, in core logging and in subsequent use of the information.

In the middle section of the chart there are histograms for joint frequency F , joint spacing S , joint roughness coefficient JRC, joint wall strength JCS, permeability K , rock strength and rock stress. On the right side of the chart, there are histograms showing Schmidt hammer readings R , r , volumetric joint count J_v , joint length L , joint roughness amplitudes a/L , residual friction angle and joint orientation. This method of recording the six Q-system parameters and other geotechnical information during field work for small or large areas has been found to be very useful. Incorporating all the information in a PC-based spreadsheet (Lotus or Excel) makes it possible to see at a glance the variation in the different parameters from borehole to borehole and at different depths. Hence, data from different areas may be selected and combined. The geotechnical chart contains information for setting up input data files for

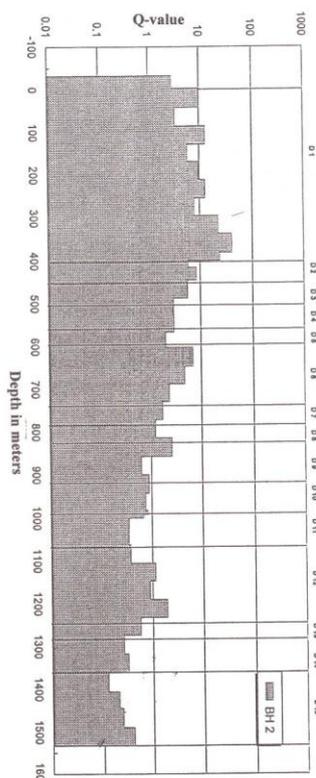


Fig.2 Q-value depth log for a borehole

numerical modelling using the distinct element codes UDEC-BB or 3DEC (Cundall, 1980, 1988). A description of all the above parameters which are considered to be of importance when performing field mapping and core drilling is given by Bhasin, 1994.

2.3 Depth Logs

Based upon the data recorded in the geotechnical logging charts, depth logs were prepared for the various boreholes. Figure 2 shows an example of a Q-value depth log for one of the logged drill core. Similarly, the depth variation of other parameters such as permeability, porosity, unconfined compression strength and the six individual Q-system parameters could also be visualized.

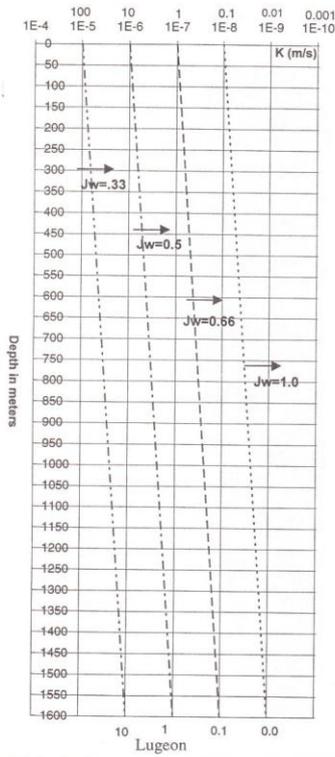


Fig.3 Relation between J_w and measured permeabilities and depth

During the logging of drill cores the Q-system parameters J_w (joint water reduction factor) and SRF (stress reduction factor) were initially estimated based on the characteristics of the cores. These parameter values were later revised based on the results obtained from the rock mechanical tests conducted in the field and in the laboratory. The J_w -values were revised based on the permeability tests carried out in the field. NGI's experience from Lugeon testing of boreholes in projects related to underground construction works were utilized for revising the J_w -values (see Fig. 3).

In this figure the results from permeability tests conducted at various depth intervals were plotted for estimating the J_w -values. The SRF-values were updated by plotting the ratio σ_2/σ_1 with depth (see Fig. 4) and correlating these values with the Q-system rating table for SRF.

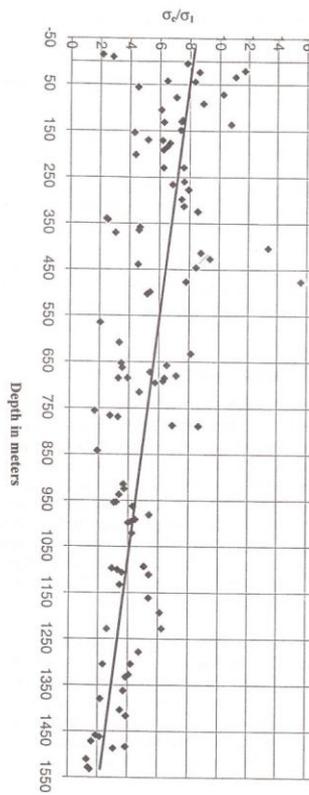


Fig.4 SRF updating procedure, σ_2/σ_1 versus depth

3 EXPERIMENTAL DETERMINATION OF ROCK JOINT CONDUCTING APERTURE

3.1 Coupled shear flow testing

One of NGI's rock mechanics testing programmes that complements corelogging activities at Sellafeld comprised experimental determination of rock joint conducting apertures through CSFT tests. Figure 5 shows NGI's biaxial cell which is primarily used for coupled shear flow temperature testing of natural joints. Samples for the CSFT tests are selected so that the joint passes approximately through the middle of cast epoxy block. The joint samples used for the tests at Sellafeld were 96 mm in diameter and 150mm in length. Detailed data from characteriza-

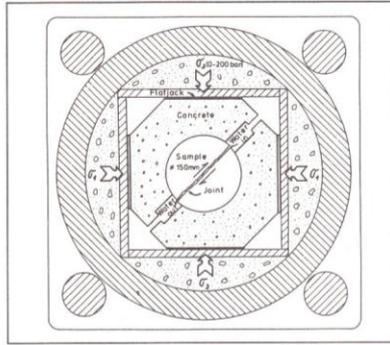


Fig. 5 NGI's biaxial apparatus for CSFT testing of rock joints

tion of individual samples are given in Table 1. The methods of characterization were based on tilt testing and Schmidt hammer testing of adjacent sections of the chosen joint. The CSFT section remained closed before the flow test. The jointed samples were cast into a reinforced epoxy block and then mounted into the apparatus with flat jacks acting on each of the four sides as shown in Fig. 5.

By applying the same oil pressure to all four flat jacks, only normal stress is applied over the joint. This stage is the consolidation stage. The shear displacement along the joint is very small during this stage as minor seating adjustments/interlocking is taking place. Several cycles of normal stress are followed by a shear stage where shear displacement along the joint is created by reducing the oil pressure in two opposite flat jacks and increasing it in the other, so that the normal stress acting along the joint remains approx. constant. Displacements normal to and along the joint are measured during all stages of the test. Fluid conductivity is measured by measuring the amount of fluid that passes through the joint (in a horizontal direction) under a constant pressure head. The stress paths for all the tests consisted of 3 load-unload cycles of consolidation (normal stress alone) at stresses ranging from 26 to 30 MPa. The fourth cycle consisted of approx. 3mm shearing at a normal stress ranging from 8.5 to 17 MPa depending upon the depth of the samples. Table 2 summarizes the effect of normal and shear displacements on the joint conducting apertures for the tests performed.

Excavation of a cavern results in unavoidable disturbance of the rock mass immediately surrounding the excavation. Small amounts of shear displacements (1-2mm) can cause dilation of the joints, which, in the absence of gouge production can result in nearly

Table 1 Characterization data of individual samples for the CSFT tests

No.	Rock type	Depth (m)	Joint dip °	JCS MPa	JRC	ϕ_r °
1	Sand stone	106.72	85	60.7	4.18	28.2
2	Sand stone	106.45	86	67.2	4.38	26.4
3	Ignimbrite	503.57	70	87.1	5.44	28.7
4	Sand stone	1032.35	73	86.8	3.97	24.8
5	Tuff	609.92	75	264.5	4.22	25.3
6	Tuff	691.71	59	*	3.0	*
7	Tuff	805.54	72	*	4.0	*

* Preliminary tests not conducted due to delicate infills

Table 2 Magnitudes of joint conducting apertures after consolidation and shearing

No.	Depth (m)	Normal stress stage		Shearing stage		
		σ_n MPa	Joint cond. aper. on 3 rd cycle μm	Shear disp. mm	σ_n MPa	Joint cond. aper. after shearing μm
1	106.72	26	6	2.8	8.78	47
2	106.45	26	16	2.3	13.27	25
3	503.57	24	125	2.8	14.98	75
4	1032.35	26	170	3.8	17.89	114
5	609.92	31	8	3.1	9.73	13
6	691.71	30	6	3.0	17.35	40
7	805.54	30	5	5.5	16.61	15

two orders of magnitude increase in conductivity (Barton, 1982). Since the flow through a joint is proportional to the cube of its hydraulic aperture, the joint flow dominates the permeability of jointed rock masses and therefore special attention must be paid to the aperture and its change.

The volumetric flow rate through a joint can be expressed using the theoretical smooth wall conducting aperture (e) in the following equation:

$$e = \sqrt[3]{\frac{Q \cdot 12 \cdot \nu}{g \cdot w \cdot i}} \quad (3)$$

where e=conducting aperture assuming laminar parallel plate flow (m)
w=width of flow path (m)
 ν = kinematic viscosity (m^2/s)
Q=flow rate (m^3/s)
i=hydraulic gradient
g=acceleration due to gravity (m/s^2)

The change in aperture can result from both normal stress and shear displacement. The mechanical aperture (E) is usually larger than the corresponding smooth wall conducting aperture (e) because of the roughness of the joint (Barton, 1982):

$$e = \frac{E^2}{JRC^{2.5}} \quad (4)$$

where JRC= Joint roughness coefficient

The numerical modelling of disturbed zone effects, which would result from excavating access tunnels and disposal caverns, provide estimates of joint apertures before and after excavation of the tunnel caverns. The apertures are affected by normal stress changes, shearing, dilation and even tensile opening. NGI's BB model (Barton-Bandis) simulates stress and size dependent coupling of shear stress, displacement, dilation and conductivity thus enabling the prediction of jointed rock mass behaviour. The magnitude of joint conducting apertures obtained through the CSFT tests have been found to be in close agreement with those predicted by the discrete element modelling of disturbed zones which would result from the excavation of the disposal vaults according to the conceptual design used for this study.

4 NUMERICAL MODELLING OF UNDERGROUND OPENINGS

For the jointed volcanic and sedimentary rocks found at the Sellafield Site, modelling of the rock mass as a discontinuum is the only realistic method to simulate what could happen during tunnel, shaft and cavern excavation. The discontinuum modelling is based on the integrated use of the empirical Q-system, and on Cundall's (1980) Universal Distinct Element Code (UDEC) with the Barton-Bandis (BB) joint model incorporated (UDEC-BB).

The Q-system of tunnel support design provides recommendations for rock bolt spacing and thickness of fibre reinforced (or in some cases, unreinforced) shotcrete. Numerical modelling is utilized in NMT designs made by NGI for helping to understand the potential failure modes thereby improving on the basic empirical design. For the Sellafield repository design studies, modelling was carried out to obtain a better understanding of the stability of the caverns, the rock reinforcement requirements, the extent of the disturbed zone around the cavern areas and the effect of various pillar and crown pillar dimensions. Figures 6 and 7 show examples of the hydraulic apertures and the bolt loadings around the periphery of a cavern of size 26 × 16 m.

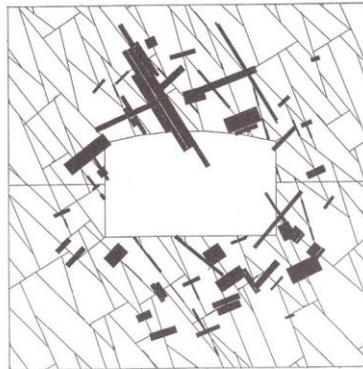


Fig. 6 Thick lines indicating the magnitude of hydraulic apertures around the opening, max. aperture=2.3 mm

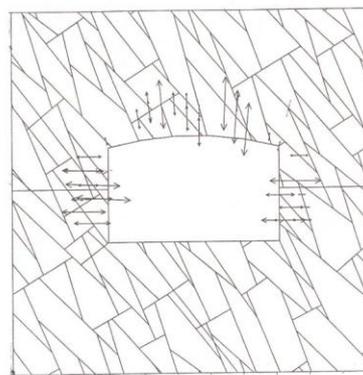


Fig.7 Arrows indicating the magnitude of bolt loading around the cavern, max bolt load=40 tons

A scoping study was also performed to help clarify whether cavern orientation parallel or perpendicular to the major principal stress would result in more stable caverns with less deeply seated disturbed zones. Different joint models were modelled in each case. In addition to the above, sensitivity studies were performed using numerical models to investigate the effects of some disposal cavern design variables for siting in the Borrowdale Volcanic Group of rocks. Depth, orientation and cavern size were investigated in stratified models with variation in rock mass deformation moduli. A total of fourteen models

were performed with the two-dimensional code UDEC-BB, and one with the three dimensional distinct element code 3DEC.

5 CONCLUSIONS

NGI's method of characterizing joints and characterizing rock masses, using a systematic and graphic method for recording and presenting geotechnical data 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 into account in design.

An important element in NGI's rock mechanical testing programme from corelogging activities at Sellafield comprised of experimental tests for determination of rock joint conducting apertures through CSFT tests. The magnitude of joint conducting apertures obtained through the CSFT tests can be compared to those predicted by the discrete element modelling of the excavation disturbed zone.

Discontinuum numerical modelling of the jointed rock mass surrounding underground structures using UDEC-BB was used to predict the rock mass behaviour and assist in the selection of the optimum cavern orientation, excavation sequence, optimum geometry and rock support of the underground excavations. NMT support procedures using the Q-system were applied to support design.

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