Instability Assessment of Jointed Rock Slopes – A Case Study

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ABSTRACT

This paper deals with the assessment of instability of high wall slopes in a jointed rock mass in the Marulan limestone quarry in NSW, Australia. Laboratory and field investigations were carried out in order to collect the required input data for the slope stability analysis. The methodology of field investigation required for the assessment of the geo-technical parameters affecting the stability of slope faces was based on a three dimensional joint survey of the discontinuities on the slope faces at the quarry. The main emphasis was placed on the collection, compilation and evaluation of engineering geological data, discontinuity characteristics and rock mechanics tests on a highly fractured and semi weathered limestone rock mass at the Marulan Quarry.

A geo-technical assessment of the instability data obtained from geological mapping of the slope faces together with the laboratory assessment of mechanical properties of the rock mass was carried out in order to identify the mode of failure of major slopes within the quarry. Stereographic projection techniques helped in identifying the possible mode of failure for the quarry slope and aided in suggesting appropriate remedial measures to be adopted to ensure future stability.

Keywords: Rock mass classification, Hard rock slopes, Murulan quarry, Stereographic projections, Australia

1. INTRODUCTION

Hard rock quarrying is a major source of raw materials for buildings, roads, railways, and construction industries in Australia. Production of rock aggregates and other hard rock material is currently approaching 350 Million tonnes of output per annum from some 400 different quarrying operations throughout the continent (Hiscock and Mitchell 1993). In order to exploit the rock aggregates economically, it is necessary to keep the quarrying costs low, to minimise the transport cost of material by selecting quarrying operations close to the construction sites and to pay due attention to the stability of the excavations. Instability of hard rock slopes mainly depends upon the open cut geometry, the presence of structural discontinuities like joints, faults or bedding planes and their attributes. The most important intrinsic factors affecting slope stability in hard rocks include:

- Range and extent of discontinuities
- Properties of discontinuities (aperture, roughness, and type of filling material)
- Orientation of discontinuities
- Number of joint sets
- Lithological composition and the mineralogical constituents of the rock; their strength, porosity, density and water content
- Various geotechnical parameters such as shear strength and density of the rock mass
- Rock mass classification used to estimate the behaviour of the rock mass at the quarry slope.

One of the more inexpensive methods of slope stability analysis in a hard rock slope is to carry out joint surveys in the high wall faces in the jointed rock mass and to interpret the results with the aid of stereographic projection techniques. This method can be used to predict the size and shape of the potentially unstable block together with its possible mode of failure by taking into account the shear strength of the natural discontinuities. This paper contains a presentation of the application of this approach in assessing the stability of a slope in the Marulan limestone quarry and suggests a method of remediation of slope instability in the quarry (Khanlari,1996).

2. FACE INSTABILITY AT A LIMESTONE QUARRY, NSW, AUSTRALIA

The site of this investigation was the Marulan quarry located in the Bungonia region, some 10 km. east of the Hume Highway, south east of the NSW capital, Sydney. Based on field observations and geological studies it was concluded that the limestone rock mass at the Marulan quarry is a recrystallised and medium grained, light to dark grey limestone. It is a thickly bedded deposit of a high quality and forming a semi-weathered rock mass. Due to the presence of some major discontinuity sets and a few dolerite dykes that are mainly weathered, instability of the rock slope may manifest itself as discrete unstable blocks.

2.1 Methodology of Discontinuity Data Collection and Analysis

The data relating to the discontinuities of the slope faces in the Marulan quarry was collected based on the scan line method as suggested by ISRM, Brown

(1981). For the stability assessment, the slope faces of the quarry were divided into two sections designated as section A and section B. Geological and geotechnical field investigations were carried out to study the main type of rocks and geological features present. Three dimensional joint survey programs were also carried out to collect geotechnical data from the discontinuities in the slope faces. Some 768 readings were taken from the discontinuities that intersected the scan-line. Discontinuity data collected in this manner were analysed using statistical analysis techniques and were also used as input data for the evaluation of the rock mass quality using different rock mass classifications.

2.2 Discontinuity Data from Marulan Quarry

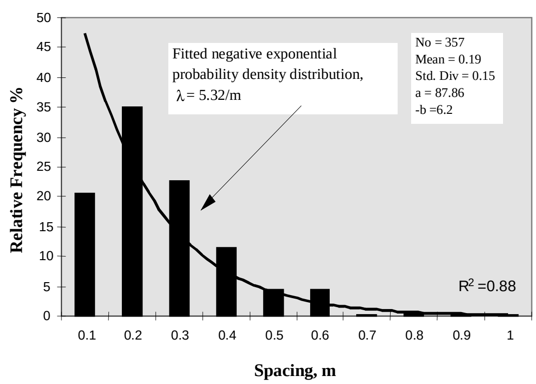
Table 1 shows the statistics derived from the discontinuities measurements and their attributes for section A and section B slopes for the Marulan quarry. The main parameters noted in the table were length, orientation, dip angle, aperture and the nature of the joint infill material. Other attributes of the discontinuities included in the table were discontinuity persistence, joint roughness, joint spacings, joint water inflow and joint compressive strength as derived from the Schmidt hardness rebound test.

Table 1 - Statistics of discontinuity distribution at Marulan quarry

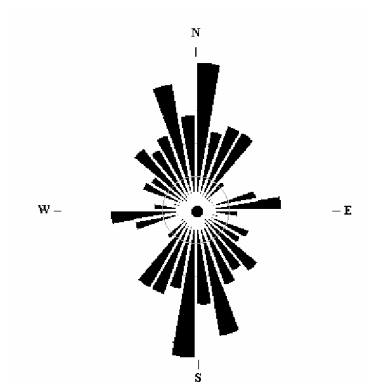
Discontinuity Parameters	Section A	Section B
Number of discontinuity	357	411
Orientation • Mean • Maximum concentration	 $179.24^o \pm 17.1$ (56.6%) 180-200 (14.3%)	 $197.5^o \pm$ (21.2%) $100\text{-}120^o$ (21.2%)
Dip angle • Maximum	70 ± 17^o (17%) $70\text{-}80^o$ (33%)	$57^o \pm$ (27.45%) $80\text{-}90^o$ (34.5%)
Aperture	2-6mm (69%)	2-6mm (72%)
Water inflow	98.6 % dry	78% dry
Discontinuity curvature • Stepped • Undulating • Planar	 46% 11% 43%	 37% 20% 43%
Discontinuity roughness • Roughness	 83%	 100%
Discontinuity persistence • Outcrop • Rock • Beyond exposure	 69% 10% 21%	 70% 10% 20%
Joint Spacing • 0-0.15m • 0.215- 0.25m, • 0.25-0.35	 20% 36% 24%	 26% 47% 15%

• 0.35-0.45m, • >0.45m	12% 8%	5% 7%
Joint compressive strength (Schmidt hammer hardness number)	23±8	23±6
Joint length (m), Range 0.5 to 3.5 m	1.58±0.97	1.56±0.98

The discontinuity data collected from the scan line survey and site investigation were classified to determine the frequency distribution of the discontinuities. The factor analysis of the discontinuity data indicated that the joint spacings, the number of joint sets and their orientation are the main factors contributing to the failure mode of the hard rock slopes. Figure 1 shows the distribution of joint spacings in section A of the Marulan quarry together with the Rose diagram of the discontinuity sets. It can be seen that there are 5 major sets of joints in section A.



(a) Joint spacing



(b) Rose diagram of joints

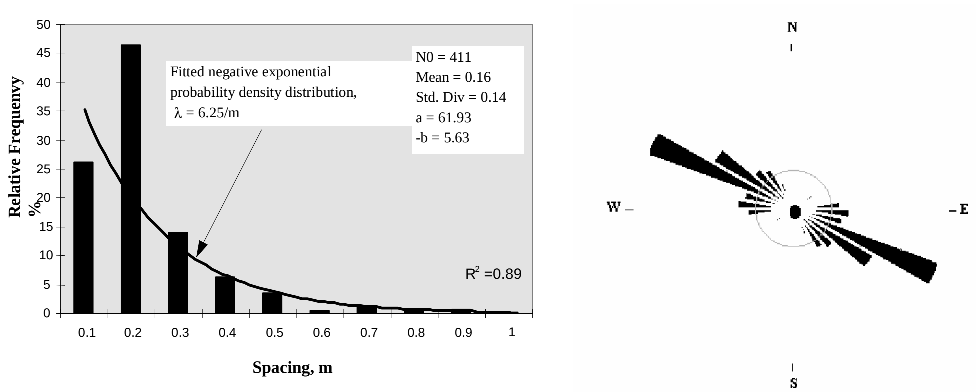
Fig. 1 - Probability density distribution of joint spacing and rose diagram in section A (Khanlari, 1996)

Figure 2 shows the spacing distribution and Rose diagram of discontinuity sets in section B of the quarry indicating four major sets of discontinuities with joint spacing of 0.2m.

3. ROCK QUALITY DESIGNATION (RQD)

Different values of RQD for sections A and B were calculated from joint surveys data and also the theoretical RQD* was calculated from Eq. 1 (Priest and Hudson, 1981) and the results are presented in Table 2. As is clear from Table 2, the measured RQD is within 9% of the calculated RQD* using only the average number of discontinuities per metre (λ):

$$RQD^* = 100\,(0.1\,\lambda+1)\,e^{-0.1\lambda} \qquad (1)$$



(a) Joint spacing at Section B of the quarry (b) Rose diagram of joints

Fig. 2 - Probability density distribution of joints and rose diagram in section B (Khanlari, 1996)

Table 2 - Comparison between measured and theoretical RQD in the limestone rock mass

Source of Data	Total scan line length , L (m)	Average discontinuity frequency, λ	Measured RQD (%)	Theoretical RQD* (%)	Differences in RQD values (%)
Section A	67.80	5.26	83.3	90.27	+6.97
Section B	65.79	6.25	78.32	87.4	+9.08
Total	133.59	5.75	80.68	82.11	+1.43

3.1 Qualitative Assessment of Rrock Mass Properties

Sen (1990) proposed the terms rock quality proportion or percentage (RQP) and rock quality risk (RQR) to define in quantitative manner the following factors:

(i) RQP represents the proportion of each rock, i.e. very good, good, fair, poor or very poor rocks within the same rock mass. However, Sen (1990) has actually used proportions rather than percentages, e.g. (0.04-0.96) rather than (4-96%) in line 1 Column 4 of Table 3. This means that the proportion of good rock is 0.04 and that of fair rock is 0.96.

(ii) RQR is the percentage of risk associated with the actual Rock Quality Designation (RQD) being less than the measured RQD value that is adopted as the design criteria. Thus, rock quality risk is defined as the probability of RQD being less than given design value. Values of both rock quality percentage (RQP) and rock quality risk (RQR) lie between 0 to 1 and they are complementary to each other.

The quality description charts in Fig. 3 developed by Sen (1990) enabled the estimation of Rock Quality Percentage (RQP) and Rock Quality Risks (RQR) for the limestone rock mass.

It can be seen in Table 3 that there is a complimentary relationship between (RQP) and (RQR) and the average number of fractures along a scan line (λ) for a given (RQD) value. It means that the smaller value of (RQR) represents a

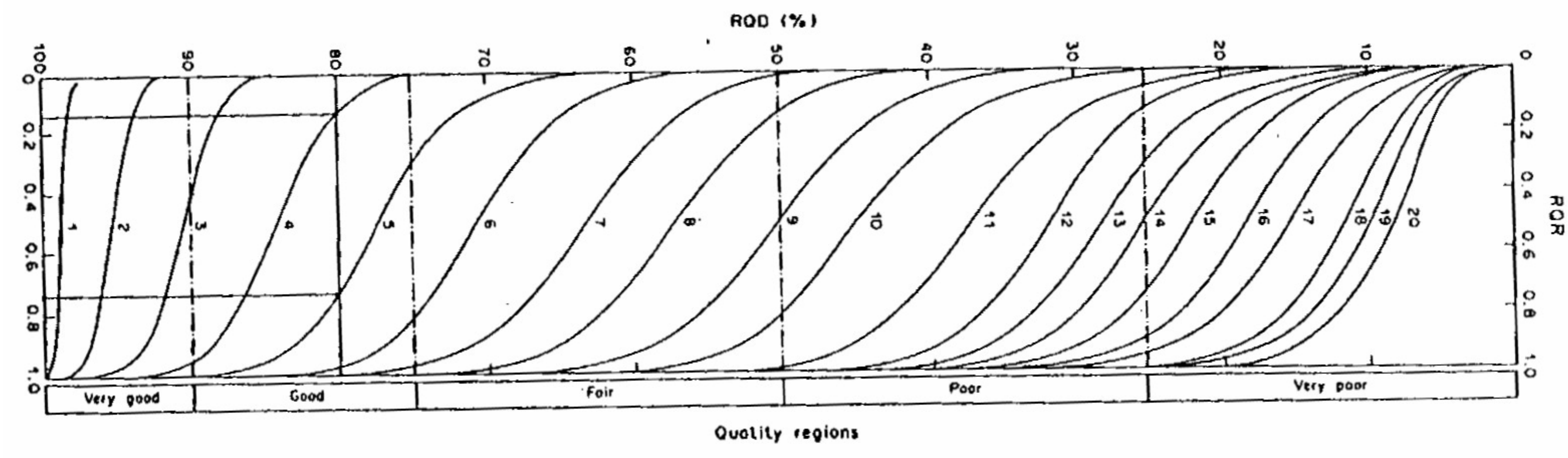


Fig. 3 - Quality description chart (numbers on the curves are λ , mean number of fractures) After Sen (1990)

better quality rock mass. From Table 3, it can also be concluded that the rock mass is of a double quality type with RQP values of 0.04 and 0.96 for good and fair qualities respectively with a RQR equal to 0.96. This present a greatest risk in section A. The results for section B in Table 3 show that the rock mass has a RQP values of 0.02 and 0.98 for 'good' and 'fair' qualities respectively with RQR equalling 0.98 which is rather high.

Table 3 - Different Values of RQD, RQP and RQR for the limestone rock mass

Source of data	Average discontinuity Frequency, λ	RQD (%)	RQP	RQR
Section A	5.26	83.3	Good - Fair 0.04 - 0.96	0.96
Section B	6.25	78.32	Good - Fair 0.02 - 0.98	0.98
Total	5.75	80.68	Good - Fair 0.05 - 0.95	0.95

4. ROCK MASS CHARACTERISATION AT MARULAN QUARRY

For the characterizing of the rock mass at the Marulan quarry, following distinct steps were carried out:

(i) Determining engineering properties of intact rock by laboratory testing

(ii) Estimating rock mass strength from the laboratory and field data and classification of the rock mass using (a) RMR system, (b) Q - system and (c) Weakening Coefficient system.

Table 4 - Engineering properties of intact rock samples from Marulan quarry

Engineering properties of intact rock	Sections A and B
Uniaxial compressive strength (MPa)	77.84
Tensile strength (MPa)	3.81
UCS derived from diametral point load test (MPa)	77.37
UCS derived from axial point load (MPa)	86.13
Poisson's ratio	0.35
Elastic modulus (GPa)	18.45
Friction angle	25^o to 35^o for Section A $< 15^o$ Section B
Cohesion	200-300 Kpa Section A <100 Kpa Section B
Bulk density (kg/m^3)	2660.0

Table 4 presents some of the important properties of the intact limestone samples tested in the laboratory. It should be noted that some of these engineering properties were used as input data for rock mass classification.

4.1 Application of Rock Mass Classification Systems

For the purpose of this work, some currently used rock mass classifications methods such as the Geomechanics Classification or the RMR system of Bieniawiski (1973), Norwegian Geotechnical Institute's (NGI) Q-system (Barton et al., 1974; Barton et al., 1976) and the Weakening Coefficient system (WC) were examined (Singh 1986 & Singh and Gahrooee, 1990). The application of these classifications is described below.

4.1.1 Geomechanics classification system (RMR)

The calculated RMR rating values based on the geotechnical and geological parameters for sections A and B of the limestone quarry are given in Table 5. Results indicate that the rock mass quality in section A is fair and in section B a very poor class rock.

Table 5 - Geomechanics classification or RMR system of the rock mass at the Marulan quarry

Rock Mass Parameters	Section A		Section B	
	Value	Rating	Value	Rating
U. C. S. (MPa)	77.84	7	77.84	7
RQD %	83.3	17	78.32	17
Discontinuity Spacing (m)	0.19	8	0.16	8
Discontinuity Condition	Class III	20	Class II	25
Ground Water Condition	Dry	15	Dry	15
Orientation Rating	Class III	-25	Class V	-60
Total RMR Rating	42		12	
Rock Mass Description	**Fair rock**		**Very poor rock**	

4.1.2 Application of Q system

The Q system was based on the measurement of six geotechnical parameters as described by Barton et al. (1974 & 1976). The Q index can be calculated by the following equation:

$$Q = \frac{RQD}{J_n} x \frac{J_r}{J_a} x \frac{J_w}{SRF} \qquad (2)$$

This system of classification is mainly used in hard rock tunnelling but it is also useful for ascertaining the rock mass quality in open cut mining.

The designation of rock mass parameters in Eq. 2 and results of the Q system of classification for the limestone are given in Table 6.

Table 6 - Rock mass classification Q-system for the Marulan quarry

Rock Mass Parameters	Section (A)		Section (B)	
	Value	Rating	Value	Rating
Rock Quality Designation (RQD%)	83.3	83.3	78.32	78.32
Joint Set Number (J_n)	5	15	4	15
Shear Strength Factor (J_r/J_a)	3/2	1.5	3/1	3
Joint Water Reduction Factor (J_w)	Dry	1	Dry	1
Stress Reduction Factor (SRF)		5		5
Q Value	1.65		3.13	
Description	**Poor**		**Poor**	

4.1.3 Application of weakening coefficient classification system (WC)

The Weakening Coefficient classification system (WC) is used by Singh (1986) for underground coal mining and in the design of rock slopes by (Singh and Gahroohee,1990). The most important discontinuity parameters contributing to this system are; RQD, joint spacing, joint surface index, joint filling materials and, finally, the discontinuity aperture. The weakening coefficient values for the limestone rock mass were quantified according to the discontinuity parameters and the appropriate values are presented in Table 7.

Table 7 - Rock mass weakening coefficient for limestone in the Marulan quarry

Parameters	Section A		Section B	
	Value	Rating	Value	Rating
RQD %	83.3	0.83	78.32	0.78
Discontinuity spacing (m)	0.19	0.7	0.16	0.7
Joint Surface	Rough	0.9	Rough	0.9
Joint types and aperture or infill thickness	Open <5 mm	0.7	Open >5 mm	0.6
Discontinuity Aperture	2 - 6 mm	0.7	2 - 6 mm	0.7
Weakening Coefficient (WC)	0.256		0.206	
Orientation Rating	0.29×0.37		0.13×0.1	
Total Weakening Coefficient (WC)	0.11		0.013	
Description	**Moderate**		**Poor**	

It may be recalled that the relationship between these discontinuity parameters can be represented by the following equation:

$$K = K_1 \times K_2 \times K_3 \times K_4 \qquad (3)$$

where
K_1 = discontinuity aperture,
K_2 = discontinuity spacing,
K_3 = joint surface index, and
K_4 = joint filling index.

The Weakening Coefficient can be calculated by the following equation:

$$WC = RQD \times K \qquad (4)$$

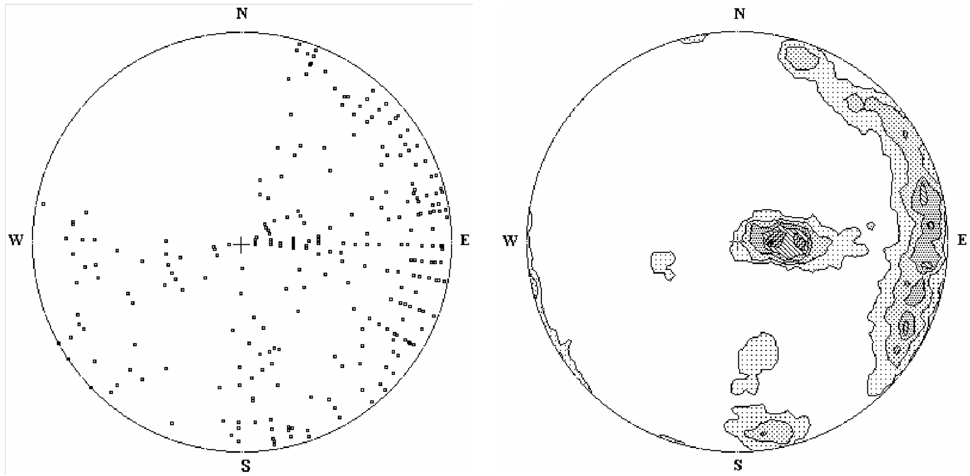
5. APPRAISAL OF FACE STABILITY AT MARULAN QUARRY

In order to assess the stability of the slope faces at the quarry studied, the data collected from the joint surveys were analysed using statistical analysis methods to find the relationship between the various discontinuity parameters. The data from discontinuity orientations were used for the assessment of the potential mode of failure in two different parts of the limestone quarry using a stereographic projection technique as described in sections 5.1 and 5.2.

In order to estimate rock mass strength parameters for the stability evaluation using the stereographic method the inferred results obtained from rock mass classification method were compared with those obtained from the laboratory measurements. From RMR values, the interpreted friction angle for the rock mass in section A of the quarry was in the range 25^o to 35^o and for section B of the quarry < 15^o (Table 4). However, direct shear test results carried out on the natural joint samples from the slope faces of the quarry showed an average friction angle 18.88^o for both sections. Therefore, a judgement was made to use the lower value that was the measured value in this case. To be even more conservative, the cohesion was ignored.

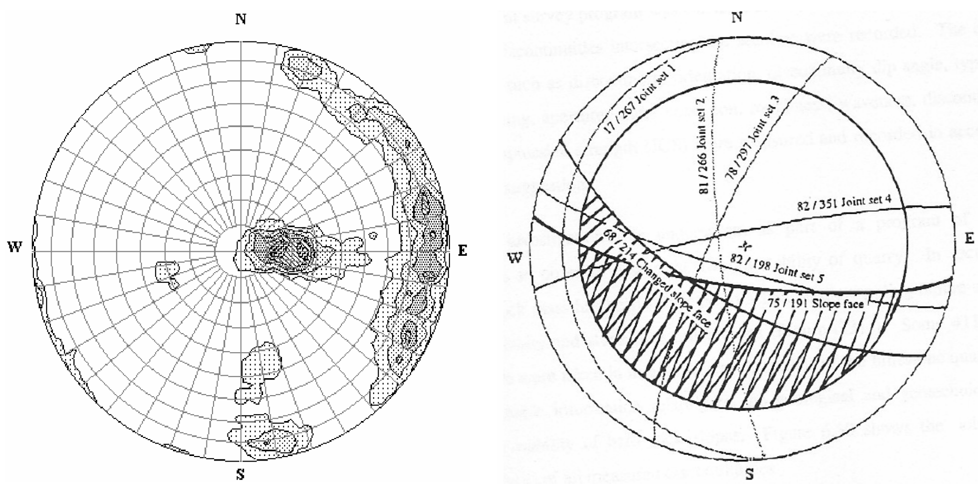
5.1 Stability Assessment of the Slope Face in Section A

Section A is located in the northern part of the quarry and contains six benches. Samples of naturally jointed rocks were collected during the site investigation. From direct shear tests a friction angle of 18.9 degrees and cohesion of 1.91 MPa were determined. The discontinuity dips in this section show that 32.77 per cent of the discontinuities had a dip between 70 to 80 degrees. A lower hemisphere equal area stereographic projection method was used for discontinuity data analysis. Figure 4(a) shows poles of some 357 discontinuities measured from the slope faces of six benches. Figure 4 (b) shows the contoured plot of the discontinuity poles in section A of the quarry using lower hemispherical stereographic net. It can be seen in the diagram that there are 5 discontinuity sets on this part of the quarry.



(a) Pole plot of section A (b) Contoured plot of section A

Fig. 4 - Analysis of discontinuity orientation data of Section A from Marulan Quarry



(a) Contour plot of section A on polar net (b) Stereographic projections of major joint planes

Fig. 5 - Analysis of pole plot data of section A from Marulan Quarry

Figure 5 (a) represents a contour diagram superimposed on a polar net and Fig. 5 (b) represents a stereographic projection of major discontinuity planes. It can be seen in Figure 5 (b) that five major joint sets were prominent, occurring at dip and dip directions of $17^o/267^o$, $81^o/26^o$, $78^o/297^o$, $82^o/351^o$ and $82^o/198^o$ respectively. On this diagram, a great circle of slope face of 75^o with dip direction of 191^o was plotted.

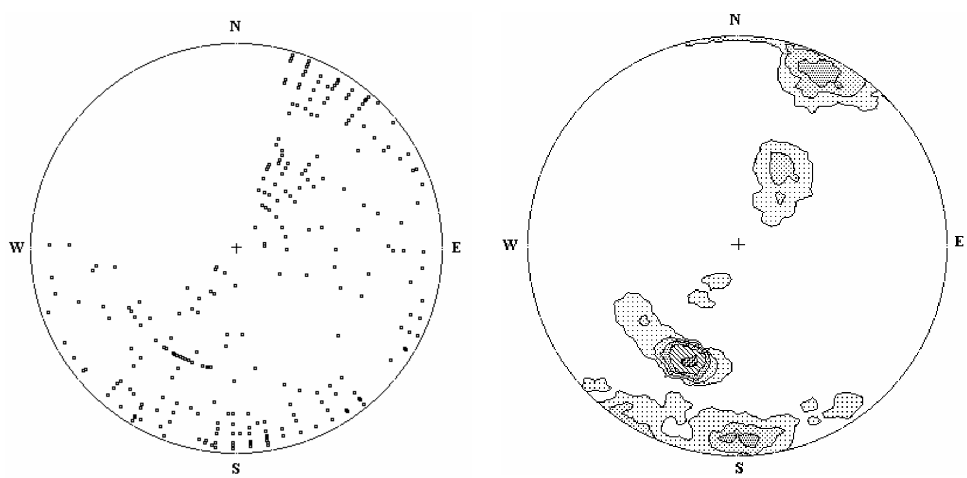
In addition, a circle representing an internal angle of friction of 18.9^o was superimposed on the stereo-net to delineate the unstable shaded area of potential wedge failure. It is recommended that the orientation of the slope face be changed to $68^o/214^o$ in order to eliminate the danger of potential instability.

5.2 Stability Assessment of the Slope Face in Section B

Section B is situated in the western section of the quarry. It contains some dolerite dykes intersecting the limestone rock mass which probably has an affect on the stability of the slope face in this part of the quarry. Results of the statistical analysis of discontinuity data shows that 34.55% of discontinuities are dipping at 80^o to 90^o degrees in section B. It indicates that the joints in this section are high amount of dip. In section B of the quarry, the rock mass has been subjected to a small-scale toppling failure which resulted from discontinuity and slope face orientations.

Figure 6 (a) represents a plot of some 411 discontinuities on a lower hemispherical equal area stereo-net. Figure 6 (b) shows a contour plot of these discontinuities showing the presence of four discontinuity sets in this part of the quarry, occurring at dip and dip directions of $51^o/022^o$, $81^o/205^o$, $82^o/360^{oi}$, and $35^o/208^o$ respectively.

Figure 7 (a) shows a polar net superimposed on contoured pole plot. In order to assess slope stability, a great circle of the quarry face at 75^o dip with a dip direction of 111^o and a friction cone at an angle of 18.9^o was superimposed on the stereo-net (Figure 7 b).

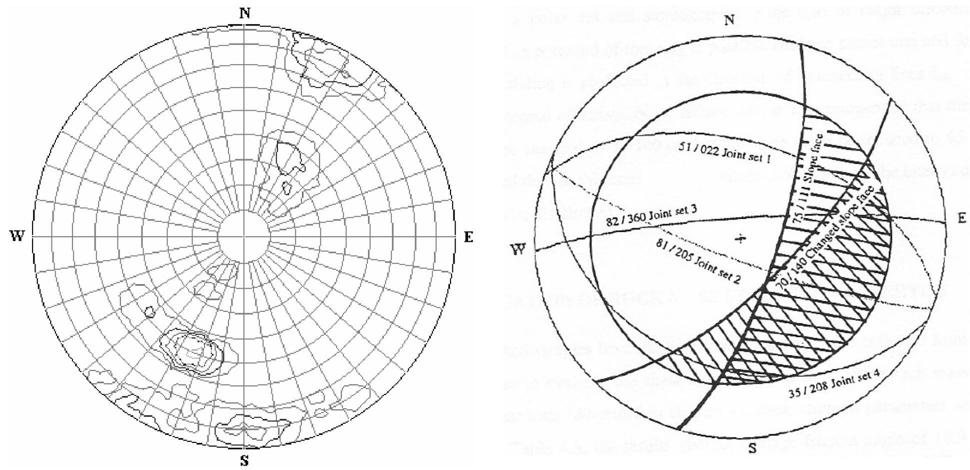


(a) Pole plot net (b) Contoured pole plot net

Fig. 6 - Discontinuity orientation data of section B from the Marulan quarry

The potential for possible toppling type of failure exists between joint sets one and four and also a potential for sliding is predicted in the direction of the intersecting lines. In order to reduce the potential for instability, or to reduce risk, it is recommended that the orientation of the slope face be changed to $70^o/140^o$ or that the slope angle be reduced to 68^o.

The orientations of dominant joint sets are given in Table 8 together with suggested remedial measures to reduce the danger of potential slope instability.



(a) A polar net superimposed on contoured pole plot

(b) Stereographic projection of joint sets

Fig. 7 - Analysis of cluster poles of section B from the Marulan quarry

Table 8 - Orientations of major discontinuity or joint sets and slope faces

Structural Section	(Dip / Dip Direction) Section A	(Dip/Dip Direction) Section B
First predominant joint set	17^o / 267^o	51^o / 022^o
Second predominant joint set	81^o / 266^o	81^o / 205^o
Third predominant joint set	78^o / 297^o	82^o / 360^o
Fourth predominant joint set	82^o / 351^o	35^o / 208^o
Fifth predominant joint set	82^o / 198^o	____
Slope face	75^o / 191^o	75^o / 111^o
Changed slope face	68^o / 214^o	70^o / 140^o

Note: Change in slope angle from 75^o to 68^o increases the stability of the face and also reduces the potential failure volume. The change in the dip direction also reduces the plan area of the unstable block and hence the volume. This becomes clear from the stereo-net analysis.

6. CONCLUSIONS

The frequency distribution of the discontinuity data for the most important discontinuity sets was determined by using statistical analysis techniques. A negative exponential probability density distribution model was proposed for the joint spacing frequency of distribution in both sections of the quarry. It is shown that the length of discontinuity, their dip and dip direction and the frictional properties of joints are the most important factors affecting hard rock slope stability.

Results of different rock mass classifications carried out in Marulan quarry showed that the limestone rock mass may be considered of moderate strength in section A of the quarry and of very poor quality in section B of the quarry. The value of the cohesion for sections A and B was found to be between 200 - 300 kPa in section A and <100 kPa for section B while the value of internal friction angle was found to be 25^o to 35^o in section A and $<15^o$ in sections B respectively. However, in order to be conservative an angle of friction of joint surface was selected as 18.8^o for the stereographic analysis as determined by direct shear test carried out in the laboratory.

Results of the stability assessment in the Marulan quarry showed that five major joint sets in section A and four dominant discontinuity sets in section B are affecting the stability of slope faces of the quarry. It was also identified that there is a possibility of potential wedge type slope failures in section A of the quarry, while section B of the quarry is susceptible to toppling type of failure.

Due to the presence of these major joint sets and also dolerite dykes in different parts of the quarry, changing the direction of slope faces was recommended as a possible remedial measure.

It is concluded that the stereographic projection method incorporating a joint survey technique offers a very inexpensive method of assessment of slope stability in jointed hard rock masses.

References

Barton, N., Lien R. and Lunde, J. (1974), Engineering Classification of Rock masses for the design of tunnel support, Norwegian Geotechnical Institute, pp.1-48.

Barton, N. (1976), Recent experience with the Q-system of tunnel support design, ASTM STP984, American Society for Testing and Materials, Philadelphia, pp. 107-117.

Barton, N., Lien R. and Lunde, J. (1976), Engineering classification of rock masses for the design of tunnel support, Rock Mechanics, 12, pp.1-54

Bieniawski Z.T. (1973), Engineering Classification of Jointed Rock Masses, Transactions, South African Institution of Civil Engineers, Vol. 15, No 12, pp.335-344.

Bieniawski Z.T. (1989), Engineering Rock Mass Classification, John Wiley, New York, p.251.

Brown E. T. (1981), ISRM Suggested Methods, Pergamon Press, Oxford, p. 211.

Hiscock and Mitchell (1993), Stone Artefact Quarries and Reduction Sites in Australia, Australian Publishing Service, p. 94.

Khanlari, G. R. (1996) Application of Rock Mass Characterisation to Slope Stability Problems, PhD Thesis, Department of Civil and Mining Engineering, University of Wollongong, NSW Australia, p. 490.

Priest S. D. and Hudson, J. A. (1981), Estimation of discontinuity spacing trace using Scan line Surveys, International Journal of Rock Mechanics and

Mining Sciences & Geo-mechanics Abstracts, Pergamon Press Ltd., Vol. 18, pp. 183-197.

Sen Z. (1990), Technical Note: RQP , RQR and Fracture Spacings, International Journal of Rock Mechanics and Mining Sciences and Geo-mechanics Extracts, Pergamon Press Ltd, Vol. 27, pp 84-94.

Singh, R. N., Gahrooee, D R, (1990), Application of Weakening Coefficient for Stability Assessment of Slopes in Heavily Jointed Rock Mass, International Journal of Surface Mining, 3(1990), p l3

Singh, R. N. and A. EL.Mherig, (1985), Geotechnical investigations and appraisal of face instability in Jointed Rock in Surface Mining, Proceedings of 26th US Symposium in Rock Mechanics, Rapid City, South Dakota, 26-28 June 1985, pp 31-39.

Singh R. N., R. Khanlari, R. N. Chowdhury AND J. Shonhardt, (1996), A Geotechnical investigation and instability assessments of quarry slopes in heavily jointed porphyry rock mass, The Seventh International Symposium on Landslides (1996), Balkema, Rotterdam, ISBN 909 5410 8185, pp 1835-1841.

Singh T. N (1986), Application of equivalent materials model in mining and tunnelling, Proceedings on workshop on Rock Mechanics and Problems in Tunnels and Mine Roadways, Srinagar, pp 42, 1-27.