THE INFLUENCE OF GROUNDWATER PRESSURE ON MINE SLOPE STABILITY ANALYSIS

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ABSTRACT

This paper examines the relationships between material shear strength and groundwater pressures in the context of mine slope design. Problems concerning the incorporation of shear strength and groundwater pressure data into existing stability assessments are discussed. In particular a major hinderence to the mine slope designer is the lack of quantitative data with which to work. A new approach to this problem is outlined and proposed as an effective slope design tool which accounts for some of the uncertainties in these parameters. The technique of back-analysis as an aid to slope design is also discussed.

INTRODUCTION

Problems associated with slope stability can be of vital importance to the working and profitability of surface mining operations. In certain areas of the world a large proportion of surface mine slope instabilities involve groundwater pressures, indeed in many situations stability is acutely sensitive to groundwater pressures. Generally there has been little advance in the integration of groundwater pressure into analytical techniques over recent years. This is undoubtedly linked to the complexity of failure mechanisms and the consequent lack of confidence in analytical methods presently available. A major problem in mine slope stability assessment however is the quality of groundwater data for input to the analysis. Very often, due to the dynamics of mine slope layout and monitoring difficulties, information relating to groundwater pressures is either non-existent or of poor quality.

This paper examines two areas of mine slope stability assessment which are crucial to the slope design process; shear strength assessment and groundwater pressure input. It is in these two catagories where design information is often inadequate. However it is also true that stability is most sensitive to these parameters. The paper presents an approach to the problem which has proven to be an effective design tool and which accounts to some degree for the uncertainties in mine slope design.

SHEAR STRENGTH POWER ENVELOPES

The fact that many natural discontinuities exhibit non-linear shear-normal stress behaviour under field conditions of loading has been known for some time. A number of empirically based failure criteria have been proposed as aids to the selection of shear strength parameters for use in mine slope design, Ladanyi & Archambault (1969), Barton (1973). These criteria have found some difficulty in establishing themselves as practical engineering tools due to the complexity of their formulation. It has been found , Denby (1983), that a simple power equation may adequately and efficiently represent shear failure envelopes for discontinuous rock masses;

$$\tau = A\,\sigma^{B} \qquad (1)$$

where τ = shear strength
σ = normal stress
A & B = index values

The practical employment of a power equation to predict shear strength values for mine slope design required the development of a technique to estimate index values A and B which define the failure envelope. From research carried out at the University of Nottingham an empirical approach was developed based on studies of Coal Measures discontinuities and granular fill in direct shear. Following extensive laboratory testing it was observed that a relationship existed between the two index values A and B, the basic frictional properties of the materials, the surface form of the samples and their material strength. Theoretical studies of the power equation also indicated a relationship between index values A and B of the form;

$$A = M e^{N(1-B)} \qquad (2)$$

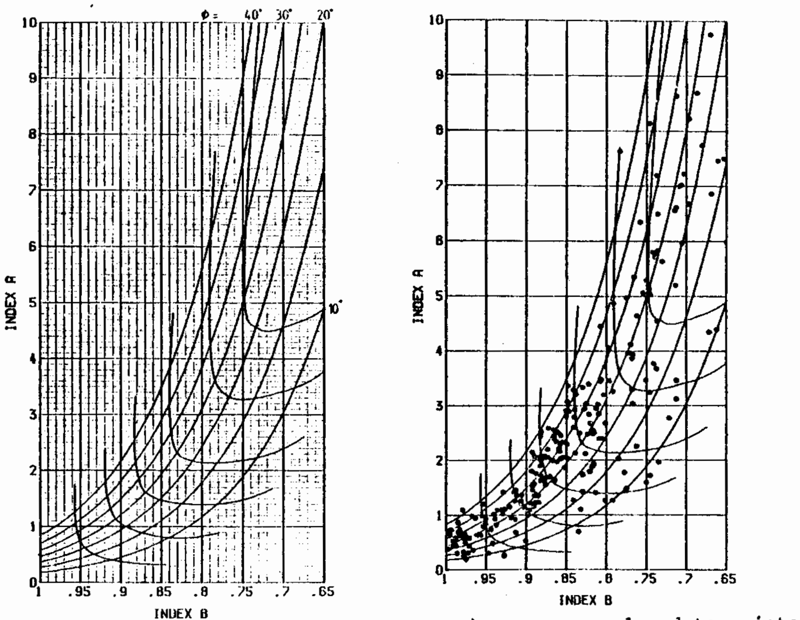
where M = $\tan\phi$
N = 9.491

Thus (2) enables the derivation of A from a knowledge of B and the basic friction angle, ϕ , a fundamental rock property which may be measured or estimated in a number of ways. A more complex problem involves the quantification of index value B which is essential to both equations (1) and (2). Studies by Archard (1958) suggest that index B may be regarded as a function of surface roughness. Differentiation of (1) with respect to σ. provides the instantaneous inclination of the shear strength envelope. Subtraction of the basic friction angle provides a relationship which relates index B to the peak dilation angle, Patton (1966), in the form;

$$i = \tan^{-1}(AB\sigma^{(B-1)}) - \phi \qquad (3)$$

where i = peak dilation angle

The factors detailed above have been combined to produce a nomogram, figure 1a, which may be used to predict index values A and B, Denby and Scoble (1984). With estimates of the basic friction angle and the peak dilation angle, interpolation provides values for the two power indices. As the peak dilation angle, i, is a stress dependent variable the nomogram has used selected constant i values derived at a normal stress of



a) Proposed Nomogram

b) Nomongram plus data points

Figure 1 Proposed shear strength Nomogram (After Denby (1983))

50kPa. At this normal stress it is likely that material strength plays little role in the dilational behaviour of discontinuities and hence surface roughness controls the dilational process. Measurement of field i values has been shown to be extremely dificult and practical employment of the nomogram involves the estimation of a likely range of i values for a particular slope.

A significant amount of data has been collected by the authors from a variety of sources and formed the basis of a shear strength data bank, Denby (1983). This data has been used to test the validity of the nomogram approach to a wide range of discontinuities and fill materials. Figure 1b shows the data analysed using power equations and superimposed on the nomogram. It may be seen that the data generally falls within the bounds of the nomogram.

THE ROLE OF GROUNDWATER IN STABILITY ANALYSIS

Two effects of groundwater upon slope stability have been well documented, namely the reactive effect of water on the materials comprising the slope and the influence of groundwater pressure on the stress regime within the body of the slope. Both these factors are known to have detremental effects on the stability of mine slopes.

The reactive effect of groundwater varies considerably depending upon the material, Van Eckhart (1976), Colback and Wiid (1965), Arscott (1967). Strength reductions of between 15 and 90 % have been noted in British Coal Measures, with argillaceous material more susceptable to degradation in the presence of water. Often part or all of the critical failure surface within a slope will be saturated. Fluctuations in water level may cause slaking of material and contribute to progressive failure of the slope. The role of water as a weathering agent has been noted as an important factor in long term slope stability, Spears and Taylor (1972).

Whilst the authors acknowledge the importance of reactive effects this paper will confine itself to an investigation of the role of groundwater pressures upon stability assessment.

THE EFFECTS OF GROUNDWATER PRESSURE

The effects of groundwater pressure upon stress distributions within a slope have been explained in many publications, Hoek and Bray (1977) , CANMET (1977) for example. Two main effects have been identified;

a) Increased disturbing forces linked to cleft water pressure.
b) Reduced normal stresses acting on the failure surface, leading to reduction in available shear strength.

A combination of increased disturbing and reduced resisting forces within the slope results in reduced stability.

1) Cleft Water Pressures

The presence of cleft water pressures, either within vertical joint sets or tension cracks, is often a contributary factor in the initiation of final collapse of mine slopes. Periods of high precipitation can lead to a rapid build-up in the level of water in such discontinuities, especially if surface drainage behind the slope crest is inadequate. Unless the pressures caused by such build-ups are allowed to dissipate by either natural or artificial drainage the balance in slope forces may be sufficiently altered to initiate failure.

2) Reduced Normal Stresses

The importance of cleft water pressures must not be under-estimated, however generally the greater influence of groundwater pressure upon reduced stability is caused by the reduction in normal stress acting across critical discontinuities within the body of the slope.

The reduction in normal stress may be defined by the effective stress principle which states that;

$$\sigma' = \sigma - u \qquad (4)$$

where σ' = effective normal stress
σ = normal stress
u = pore water pressure

A major consequence of this factor is a reduction in the shear forces available to resist slope deformation. The importance of this factor increases significantly when non-linear failure criterion define the shear strength availability in such slopes.

i) Effects upon Stability Assessment Employing Linear Criterion

The reduction in shear strength with reduced normal stress may be seen in figure 2a. This figure shows a linear failure envelope, traditionally employed in stability assessment, for a rock discontinuity. The shear strength may be quantified by the equation;

$$\tau = c + \sigma' \tan \phi \qquad (5)$$

where τ = shear strength
c = cohesion
σ' = normal stress
ϕ = angle of friction

The shear strength comprises a cohesive and a frictional component. At low normal stresses the cohesive component exerts more influence upon shear strength than the frictional component. It is debatable as to whether this cohesive component exists in a real slope situation. Ground relaxation caused by the excavation process is likely to result in concentrations of stress along discontinuities leading to the rupture of relatively weak cohesive bonds. It may be seen that the reduction in shear strength, for unit reduction in normal stress (n), is a constant equal to n. tan ϕ

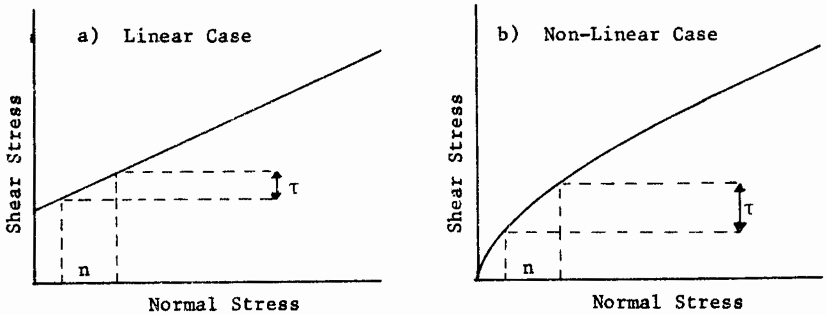


Figure 2 Shear strength reduction for change in normal stress

ii) Effects upon Stability Assessment Employing Non-Linear Criterion

The reduction in shear strength with reduced normal stress is more difficult to define when non-linear failure criterion are employed for shear strength prediction. Figure 2b shows a power envelope which defines the non-linear failure criterion for rock discontinuities or granular fill material. The shear strength may be quantified by equation 1. It may be seen that at low normal stresses the curvature of the envelope increases and that there is no cohesive component at zero normal stress. The rate of shear strength reduction varies and is dependent upon the instantaneous slope of the envelope. This may be obtained by differentiation of the power equation with respect to the normal stress and is given by;

$$\frac{d\tau}{d\sigma} = AB\,\sigma^{(B-1)} \tag{6}$$

It may be seen that the reduction in shear strength, for unit reduction in normal stress (n), is not now constant. The rate of reduction is normal stress dependent and is greater at lower stress levels.

The Effect of Groundwater Pressure upon Normal Stress Levels

It may be seen that the divergence between linear and non-linear envelopes is greatest at low normal stress levels. Stead (1983), following an extensive study of slope instabilities occuring in British surface coal mines, suggests that the majority of slope instabilities fail along surfaces where effective normal stress levels are less than 1000 kPa. It is in this stress range where an accurate representation of the failure criterion is required.

Stead also shows that 60% of instabilities involve groundwater pressures to some degree or other. These pressures contribute significantly to the low effective stress levels present in many mine slopes. Relatively high natural water tables and the increasing depth of surface mine excavations suggest that groundwater pressures will continue to influence stability. Advanced dewatering techniques can reduce these pressures to some extent, Norton (1983), however it is unlikely that they will be used exhaustively in the near future.

Fluctuations in groundwater pressures, due to seasonal variations in rainfall for example, are observed in many surface mine slopes. The resultant fluctuations in effective stress levels within mine slopes are important factors in the development of slope instabilities. These fluctuations become even more important if the critical failure surfaces exhibit distinct non-linear failure characteristics.

The importance of groundwater control also increases if non-linear failure criterion exist. Slight variations in effective normal stress levels have a more profound effect upon the resisting forces developed within the slope than for linear behaviour. These effects can be detrimental if pressure increases occur, however the use of slope depressurisation by drainage to increase stability becomes a more favourable option. For an equivalent amount of drainage the stability increase apparent when analysing with a non-linear shear criterion will be greater than for analysis with a linear criterion.

BACK ANALYSIS OF FAILED SLOPES

Previous sections have demonstrated the influence of normal stress upon stability. It is essential therefore that analytical techniques which incorporate stress variation are used to estimate stability. Present limit equilibrium analyses which employ methods of slices are suitable for this purpose and may be used with non-linear failure criteria. These techniques may also be used to investigate the influence of variation in water pressure on stability.

The selection of shear strength parameters for stability assessment is a crucial part of the slope design process. It is also perhaps the most difficult task facing the slope designer. Samples may be removed and tested in the laboratory, however problems occur due to sample disturbance and scale factors which limit confidence in the results of such tests. In- situ tests are both difficult to perform and expensive. Empirical failure criteria are often difficult to use in practice, requiring sound engineering judgement in the selection of input parameter values. As such a combination of these techniques is often used in the assessment of shear strength parameters for slope design.

In the event that a slope failure does occur it affords the engineer the opportunity to gain considerable knowledge about such factors as failure mechanisms, material strength and groundwater. The technique of back-analysis is crucial to the overall slope design process. Using back-analysis methods it is possible to estimate in-situ values of some of the unknown or un-measurable parameters required for future slope design. In surface mining the parameters estimated by back-analysis are often employed in the design of slopes of similar structure, dimensions and materials. Back-estimated values of input data for slope design often provide the most reliable information to the engineer. In surface mining back-analysis is invaluable to the engineer. In civil engineering the safety factors required for slopes with public access are generally greater than for many mine slopes and as such slope failure is less common.

The monitoring of groundwater pressures in advancing mine slopes is generally not carried out. This factor can cause difficulties when back-analysing slope failures as water pressures have a direct influence upon the mechanics of slope failure and the stresses involved. Back-analysis is also complicated when critical shear surfaces exhibit non-linear normal-shear stress behaviour. As the previous section demonstrated, uncertainty in water pressures will generally result in greater errors when non-linear failure criterion are employed.

Standard back-analysis techniques are available to estimate linear c,ϕ values from slope failures. If however the critical shear surfaces exhibit non-linear shear stress- normal stress behaviour then the results obtained will be of limited use. These effective c,ϕ values are normal stress dependent and the employment of them in slopes where the normal stress levels acting are different, due to differing slope dimensions or altered groundwater pressures, can result in significant errors. The necessity to predict non-linear shear strength parameters, which may be used outside the normal stress range of the back-analysed slope, has resulted in the development of a technique which incorporates the nomogram described earlier. This modified technique should both increase the accuracy of back-analysis and make it a more flexible and powerful tool for the engineer.

Back-Analysis of Non-Linear Shear Strength Parameters and Groundwater Pressure Ratios

The prediction of power index values A and B from the study of failed slopes requires modifications to standard limit equilibrium back-analysis methods. Limit equilibrium based techniques may be used as only relatively simple modifications are necessary to incorporate non-linear shear strength criterion. Also, given the quality of the input data for the analyses, more complex techniques would not often result in better output. The modified back-analysis techniques could only be used, however, in situations with relatively simple failure mechanisms, e.g. planar failure along a major discontinuity, as simplifying assumptions are made in the formulation of the equations. A method for quantifying power indices has been developed by the authors.

The incorporation of non-linear shear strength criterion into standard limit equilibrium analyses was accomplished using a method described by Hoek and Bray (1977) The basic technique involved calculating an effective normal stress level at each point along the failure surface, calculating linear c,ϕ values for the tangent to the curved envelope, figure 3, and then employing these values in a standard limit equilibrium analysis. Back-analysis of index values A and B from failed slopes required estimates of the failure geometry and likely groundwater pressures within the slope. By systematically varying the value of index B a range of index A values could then be calculated, each of which gave an overall factor of safety of one.

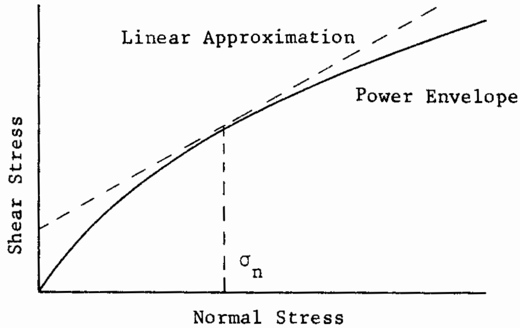


Figure 3 Linear approximation of non-linear shear strength data

In reality little groundwater information was available as input to the back-analysis. In most of the failed slopes no quantitative monitoring had been carried out prior to failure. Generally only a 'ball park' estimate could be made as to the likely groundwater levels at failure. For this reason groundwater pressures for the back-analyses were input using a range of R.U. values. The R.U. value is defined as the ratio of groundwater pressure, at a given point on the failure surface, to the unit weight of material acting on unit area of the failure surface, Smith (1971). Using this method it is possible to incorporate low quality groundwater data into a back- analysis. Typically low groundwater pressures employed R.U. values ranging from 0-0.2 and high groundater pressures employed ranges from 0.2-0.4.

Even this relatively vague groundwater input was of considerable assistance in the back-analysis of power index values A and B. Figure 4 shows how the nomogram given in

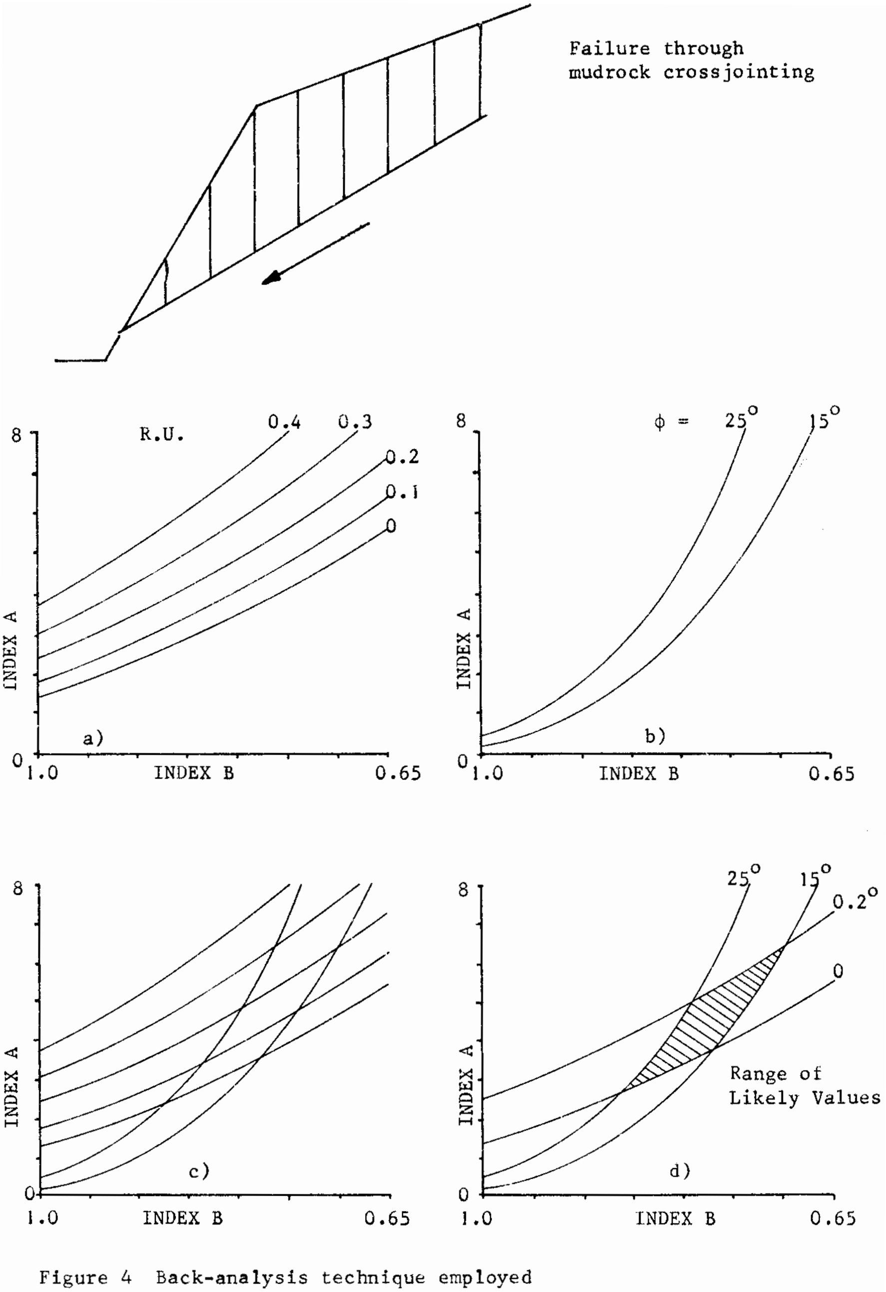


Figure 4 Back-analysis technique employed

figure 1 may be employed to provide reasonable estimates of these indices. Figure 4a shows the typical output from a series of back-analyses using the full range of R.U. values. The relationship between index A and B values may be seen. Figure 4b shows two base friction curves from the nomogram with representing the range of A,B indices expected for the failure surface (in this case mudrock cross-jointing). Using either of these figures in isolation would be of little use as the ranges obtained in each case are excessive. By superimposing the two figures, figure 4c, it may be seen that the area of interference represents the likely range of A and B indices for that failure surface. The likely range of power indices may be reduced further if even a broad range R.U. estimate is available, figure 4d. Obviously better estimates of the groundwater pressures produce smaller ranges and increased confidence.

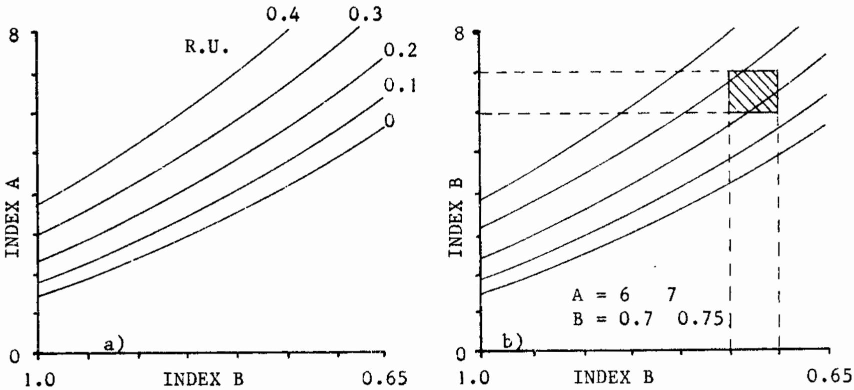


Figure 5 Back-analysis of groundwater pressure ratio

Similar principles may be applied to estimate the likely groundwater pressures involved in a slope failure, given estimates of index values A and B. Figure 5 provides a set of diagrams which illustrate the procedures involved in this process. In this case the ranges of shear index values A and B are known or estimated prior to the analysis. It may be seen from the figure how it is possible to estimate realistic R.U. values, from which groundwater pressures may be calculated, providing adequate shear strength data is available.

CONCLUSION

This paper has outlined a new approach to mine slope stability analysis which has been found to be effective in the U.K. mining environment. The assessment of stability has been clearly demonstrated to be governed significantly by the non-linear shear strength characteristics of the U.K. Coal Measures and groundwater pressures. Difficulties in monitoring groundwater pressures in rapidly advancing mine slopes result in only low quality groundwater information being available as input to stability analysis. Distinctly non-linear shear strength behaviour observed for the constituent slope materials has also complicated stability assessment. The approach reported integrates consideration of both these factors into slope design and is proposed as a realistic method of stability assessment.

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