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Rock Slope Stability—How far away are reliable design methods?

By

E. HOEK, M.Sc., Ph.D.

(Professor of Rock Mechanics, Imperial College of Science and Technology, London)

SUMMARY - Methods of slope stability analysis are briefly reviewed and it is concluded that the limit equilibrium technique is the only method currently available which offers the possibility of wide application in rock slope design. Discontinuum theories and model studies are seen as areas in which further development is likely to be productive. The problems of obtaining adequate input information on structural geology, rock properties and groundwater conditions are examined and methods of overcoming these problems are discussed. The influence of excavation techniques on the stability of rock slopes is briefly examined.

I - INTRODUCTION

In both civil engineering and mining operations, the increasing size of excavated slopes is such that severe financial consequences as well as loss of life and damage to property can result from slope failure. The seriousness of this problem has been widely recognised and a considerable research effort has been devoted to the study of problems of rock slope stability. Significant advances have been made in these studies and, in this paper, an attempt will be made to take stock of the present position and to examine the question of whether reliable slope design methods are available or are likely to become available in the near future.

II - METHODS OF STABILITY ANALYSIS

(a) - Continuum Theories

Because of the successes which have been achieved in the application of continuum theories, particularly the theory of elasticity, to the design of underground excavations in high stress environments (Refs. 1,2), it is not surprising that attempts should have been made to apply the same theories to problems of rock slope stability (Refs. 3,4,5). Although the results which have been obtained have been interesting from the research point of view, it cannot be claimed that useful slope design criteria have emerged from these studies. This lack of success is due to the fact that, under the low stress conditions which exist in slopes, the behaviour of the rock mass is dominated by the structural discontinuities such as faults, joints and bedding planes. The normal stresses acting across these discontinuities are not high enough to permit the effective transmission of shear stress and hence stress and failure conditions determined on the basis of continuum theories are misleading.

In spite of the fact that some of the limitations of continuum theories have been overcome by the work of Goodman et al (Ref. 6), a detailed study of numerical methods of stress analysis, based on continuum theories, has led the research team working under the author's direction to the conclusion that these

methods are of limited practical value in rock slope design. These methods are useful, however, in the study of problems in which the scale is so large that individual discontinuities do not contribute significantly to the overall behaviour pattern. This applies to the study of the overall displacement or groundwater flow pattern in a large slope.

(b) - Discontinuum Theories

The recognition that the behaviour of a rock mass under low stress conditions is dominated by the structural discontinuities present has resulted in an increased research activity involving attempts to treat the rock mass as a discontinuum. Experimental studies of the mechanical behaviour of interlocking granular systems (Refs. 7,8,9) have produced important results which have contributed to our understanding of this problem. Pioneering attempts to apply discontinuum theories to the design of rock slopes have been made by Trollope (Ref. 10) and, although these techniques have not been developed to the level at which they could be regarded as generally acceptable design tools, the philosophy underlying this approach deserves wider recognition and exploitation by rock mechanics research workers. The results of some recent work by Cundall (Ref. 11) in which the toppling failure of a system of regular blocks, separated by 'joints' having both cohesion and friction, was studied are reproduced in figure 1.

The development of more powerful numerical methods and of larger computers will almost certainly increase the usefulness of these methods which, at present, must be classed as research rather than design tools. The author believes that the most important application of these methods in the near future is the study of the behaviour and progressive failure of relatively simple discontinuous systems in an effort to build up a body of knowledge which can be used as a basis for the development of design techniques.

A discussion on the application of discontinuum theories to rock slope stability would not be complete without mention of the use of models for the study of

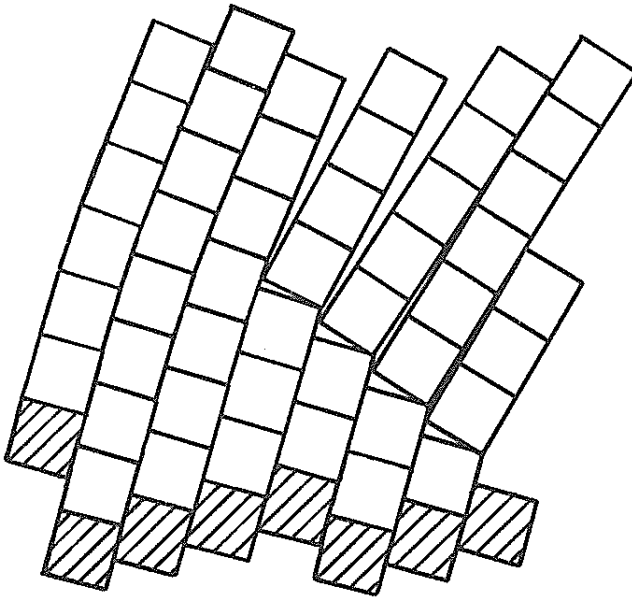


Fig. 1 : Toppling failure in a jointed system.
(After Cundall, Ref 11).

slope failure. Just as the computer produced diagram reproduced in figure 1 can give a useful insight into the mechanics of certain types of slope failure, so models can be used as tools for the communication of ideas and, if sufficient care is taken to satisfy the similitude requirements, for the quantitative study of slope failure. A recent model study by Barton (Ref. 12) provided useful information on both modeling techniques and on the mechanism of failure of a jointed slope.

(c) - Limit Equilibrium Methods

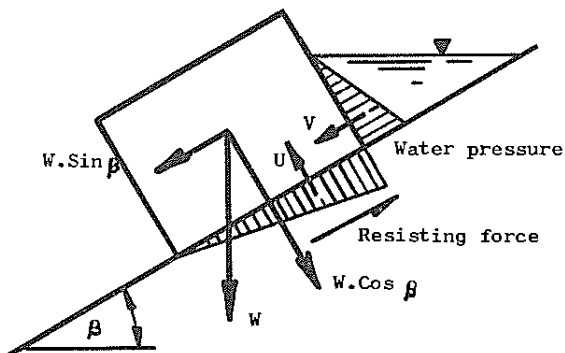


Fig. 2 : Forces acting on a block on an inclined plane.

The only form of slope stability analysis which has been developed to the extent that it can be classified as a widely accepted design tool is the method based upon the concept of limit equilibrium. The principle of this method is illustrated in figure 2

which shows a block of rock resting on an inclined plane and acted upon by the forces U and V generated by water pressure on the base and rear face of the block. The factor of safety against sliding of this block is given by

$$F = \frac{c.A + (W.\cos \beta - U) \tan \phi}{W.\sin \beta + V} \quad (1)$$

where c is the cohesive strength of the base
 ϕ is the angle of friction
and A is the base area of the block .

(i) - Soil slopes

The simple principles illustrated in figure 2 have been successfully applied to the stability analysis of soil slopes for many years and it is worth considering why the method works so well in soil. Skempton and Hutchinson (Ref. 13) have shown that, in most cases, the strength properties of soils, determined by triaxial or shear tests in the laboratory, bear a close relationship to the strength properties of those soils calculated by back-analysis of slope failures. This suggests that there is no serious scale effect in soil testing and that the process of progressive failure which takes place in a soil under laboratory test conditions is similar to the process of failure which occurs under field conditions. Since the laboratory test is an adequate model of field behaviour, one is justified in using the results of these tests as input information for a stability analysis and this convenient separation of the analysis into two relatively simple stages facilitates the production of practical engineering designs.

(ii) - Simple rock slopes

In the case of rock slopes containing planar discontinuities which strike parallel to the slope face and dip into the excavation at an angle greater than the angle of friction, the stability of the slopes can be calculated by means of simple two-dimensional limit equilibrium methods. The author has recently published a set of design charts which can be used to obtain estimates of the factor of safety for simple rock slopes (Ref. 14).

In the case of rock slopes, the intact material plays an almost insignificant part in the failure process since sliding occurs along structural discontinuity surfaces. The definition of the location of these structural surfaces and the determination of their mechanical properties are the most serious problems in rock slope stability and these problems will be discussed in greater detail in a later section of this paper.

(iii) - Three-dimensional slope problems.

The simple slopes discussed in the previous section are the exception rather than the rule and, generally, failure in a jointed rock slope occurs as a result of sliding, on two or more surfaces, of wedges or blocks of rock separated from the surrounding rock mass by a number of intersecting structural features. A relatively simple case of such a failure is illustrated diagrammatically in figure 3 which shows a wedge of rock sliding on two intersecting oblique planes.

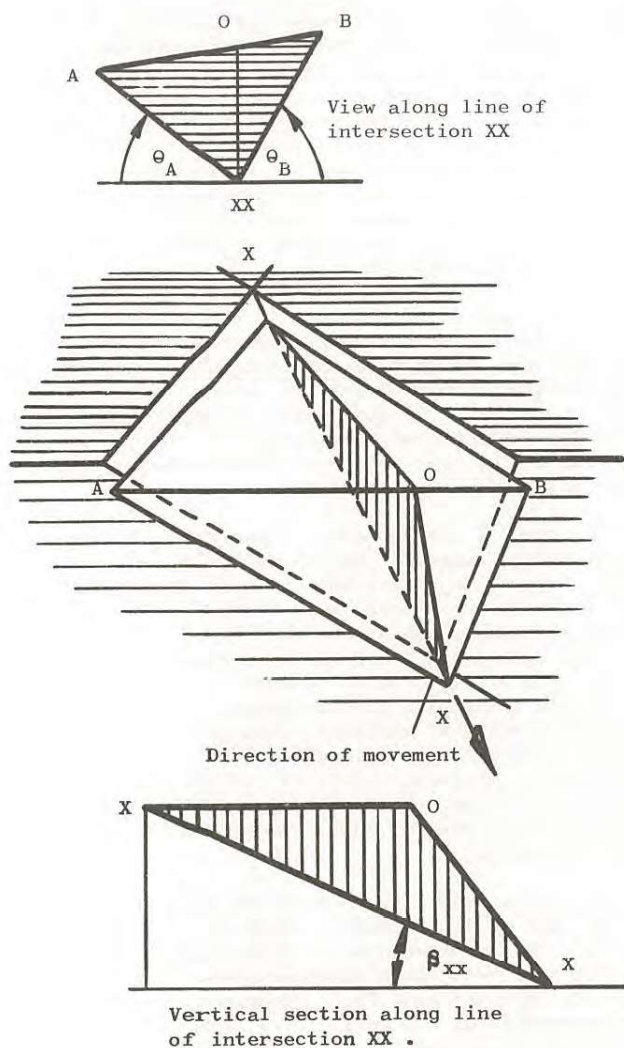


Fig. 3 : Sliding of a rock wedge on two intersecting oblique planes.

The factor of safety for the slope illustrated in figure 3, assuming the material properties of the two planes to be the same and the slope to be drained, is given by

$$F = \left\{ \frac{c \cdot A}{W \cdot \sin \beta_{XX}} + \frac{\tan \phi}{\tan \beta_{XX}} \right\} \frac{\sin \theta_A + \sin \theta_B}{\sin(\theta_A + \theta_B)} \quad (2)$$

It will be seen that this equation consists of three terms - a cohesion term, a friction term and a term which defines the wedging action of the two planes. For some simple slope geometries, the cohesion term can easily be evaluated (Ref. 15) but in many slope design situations it is preferable to ignore the cohesion term and base the design on frictional shear resistance only. Under these conditions, equation 2 reduces to a very simple form and Hoek and Boyd (Ref. 16) have recently published a set of charts

which give the solution to this equation directly from the strike and dip of the two planes. These charts are intended for use where the quality of the input information does not justify a more detailed analysis but where a preliminary assessment of slope stability is required.

A more elaborate set of three-dimensional slope charts has been published by Londe et al (Ref.17) and these charts or the graphical methods based upon the use of stereographic projections (Ref. 18) are powerful tools for three-dimensional slopes stability analysis in cases where the structure of the rock mass has been reasonably well defined. Mathematical techniques for three-dimensional slope stability analysis are also available (Refs. 19,20,21,22) and have the advantage of being readily processed by computer.

(iv) Limitations of limit equilibrium methods

In spite of the fact that limit equilibrium techniques are currently the most satisfactory methods for slope stability analysis, it is important to recognise that these techniques have certain limitations which must be kept in mind when carrying out a stability analysis. The most important of these limitations are as follows:

A mode of failure must be assumed before a stability analysis can be carried out and this means that a judgement has to be made on the position and properties of the surface or surfaces upon which sliding will take place. Unless great care is taken in mapping the structural discontinuities in a rock mass and in checking the stability of a number of possible failure surfaces, it is relatively easy to miss the most dangerous failure mode and to arrive at an over-optimistic assessment of the factor of safety. In one case in which the author was involved, slope failure occurred on a one centimeter thick clay layer which had not been detected during the site investigation and was not, therefore, included in the considerations which resulted in this particular slope being pronounced safe.

Limit equilibrium calculations are restricted to the surface upon which sliding takes place and do not include any consideration of the behaviour of the mass of material resting on this surface. Observation of slope failures suggests that considerable movement can take place within the sliding mass and that this movement could have a significant influence upon the stability of the slope (Ref.23). Similarly, toppling failure of near surface blocks such as that illustrated in figure 1 cannot be incorporated into a normal limit equilibrium analysis.

The factor of safety calculated by means of the limit equilibrium method is only valid for the condition of limiting equilibrium, ie. the condition in which the material above the failure surface is just on the point of sliding. This restriction is due to the fact that the progressive failure of the surface and the changing stress distribution on the failure surface are not taken into account in the analysis. This means that factors of safety other than unity should only be used to give general guidance and their absolute value should not be relied upon too heavily.

Time dependent slope failure resulting from creep or weathering processes cannot be incorporated directly

into a limit equilibrium analysis and the only satisfactory method for dealing with this problem is to estimate the strength properties of the failure surface at various points in time and to use these values in the stability calculation.

III - INPUT INFORMATION FOR STABILITY ANALYSIS

The reliability of any slope stability analysis depends not only upon the method of calculation used but also upon the quality of the input information used in this calculation. The most important items of input information are :

- (a) The geometry of the slope and of the structural discontinuities in the rock mass.
- (b) The mechanical properties of the surfaces upon which sliding can take place.
- (c) The groundwater flow pattern and the resulting water pressure distribution in the slope.
- (d) External factors such as accelerations imposed by nearby earthquakes or large blasts and superficial loads due to the placing of waste dumps or the passage of heavy equipment.

(a) - Site Investigation for Stability Analysis

In the author's opinion, the most difficult problem associated with a rock slope stability analysis is the definition of the structural geology of the site. Surface exposures, where they exist, are frequently altered by weathering and care must be taken in extrapolating the information obtained from these exposures into the rock mass. Core drilling is expensive and, unless rigid specifications concerning core recovery are set out, the value of the information obtained is questionable since the critical weak zones are lost in drilling. The use of down-hole tools such as borehole television cameras and seismic or sonic probes is almost always associated with technical difficulties.

In view of these difficulties, what practical steps can be taken to ensure that an adequate site investigation is carried out before an attempt is made to assess the stability of a rock slope ?

In the first place, the author believes that a great deal of useful information can be obtained from airphotographs or from regional geology maps. All too often a slope problem is approached on the basis of the information available on site only and any information which could be obtained from a consideration of the regional geology of the area is ignored. Major structural features such as faults or folds, which have a significant influence upon the direction and frequency of jointing, are best studied on a regional scale and the maximum benefit is obtained when such a study is carried out by a competent geologist with some idea of the structural features which are important in slope stability.

The mapping of structural features on surface exposures is probably the most fruitful source of input information for a stability analysis and again, a geologist with some appreciation of the basic mechanics of slope failure should be responsible for such mapping if the maximum amount of information is to be obtained. There is considerable controversy upon the question of whether one should attempt to collect all available structural information in order to build up a statistical picture of possible

failure modes or whether one should first decide, from a superficial examination of the site, which structural features are likely to be the most dangerous and then to map only these features in detail. The author tends to favour the latter approach on the basis that the rock mass is not concerned with statistics - it finds the weakest structural plane and fails on that. On the other hand, it must be admitted that this plane may not be visible on the surface and it may only be possible to detect it by mapping a large number of small sympathetic structures which will show up as a cluster on a stereographic projection .

Photogrammetric techniques in which stereoscopic pairs of photographs of rock exposures are used to determine the orientation and inclination of structural features have been used by several research groups (eg. Ref. 24) and it is anticipated that these techniques will become more useful in rock slope engineering as improved methods of analysing and presenting the results are evolved.

On opencast mining sites, diamond drill core is almost always available but on most civil engineering sites, special provision must be made for obtaining such core. During recent years there has been a considerable improvement in the quality of diamond drilling available and a few drilling companies will now accept a contract in which 98-100% core recovery is specified. In special circumstances, use can be made of Rocha's integral sampling technique (Ref. 25) in which a reinforcing rod is grouted into a small pilot hole before the final coring is carried out. The very good core recovery obtained in poor material justifies the additional cost of this technique in critical slope problems.

Even when 100% core recovery is obtained, the orientation of the structural features revealed in the core still represents a difficult problem and a variety of techniques have been used in order to overcome this problem. These techniques range from a reconstruction of the entire core from the collar of the hole (Ref. 26) to the use of commercially available core marking devices. Examination of the walls of the borehole by means of a periscope or a borehole television camera, fitted with an orientation system, can provide useful information for the orientation of the structures in the rock mass. Devices such as the 'Televviewer', a sonic tool used in the oil industry (Ref. 27), have great potential for structural investigations in rock slope sites provided that these tools can be adapted to the conditions found on these sites.

All down-hole tools are expensive and, because of the severe conditions in which they operate, suffer from a high rate a breakdown and damage. Consequently, the use of these tools is probably best left in the hands of specialist consultants who have adequately trained crews available to service and operate the equipment and to interpret the results.

In general, there are no short-cuts in site investigation for rock slope stability analysis. Each site presents its own special set of problems and it is usually necessary to use a number of site investigation techniques and to be prepared to improvise to a considerable extent in order to obtain an adequate picture of the structural geology. Since it is an act

of gross irresponsibility to attempt to carry out a detailed stability analysis without an adequate structural picture of the rock mass, it is essential that provision be made, in terms of both finance and time, for this site investigation.

(b) - Mechanical Properties of Rock Masses

As already stated in this paper, the stability of a rock slope is controlled by the structural discontinuities in the rock mass and by the interlocking of rock elements separated by these discontinuities. Since it is only possible to study the overall strength characteristics of an undisturbed jointed rock mass in a few special cases (Ref. 28), it is necessary to reduce the problem to the following relatively simple steps:

- (i) Determination of the shear strength of the rock surfaces.
- (ii) Correction of these shear strength values for surface roughness.
- (iii) Consideration of the influence of interlocking of elements on rock mass behaviour.

(i) - Shear testing of rock surfaces

Goodman (Ref. 29) has recently published a review of methods of shear testing on rock and it would exceed the scope of this paper to enter into a full discussion on this subject here. In spite of the difficulty of interpreting the results of shear tests (Ref. 14), there does not appear to be any reasonable alternative to these methods available at present and the author believes that it is necessary to carry out some form of shear testing before attempting a slope stability calculation.

Figure 4 shows a large shear machine designed and constructed at Imperial College for the testing of rock surfaces. A small shear machine, designed for use in the field, is illustrated in figure 5. These two machines give very similar results and the author feels that shear strength values obtained from tests carried out in the small machine are adequate for most current forms of slope stability analysis (Ref. 14).



Fig. 4 : 100 ton shear machine at Imperial College.



Fig.5 : 10 ton capacity portable shear machine.

(ii) - Correction for surface roughness

Patton (Ref. 30) demonstrated the influence of surface roughness on the shear strength of structural discontinuities and suggested that a simple correction could be applied to account for this influence. A more refined correction has recently been suggested by Barton (Ref. 12) and the resulting curved relationship between shear strength and normal stress has been applied to the analysis of rock slope stability (Refs. 14,15). Pentz (Ref. 22) has emphasised the importance of the curvature of this relationship at low normal stress and the author believes that research into methods for defining this curvature from simple field measurements is urgently required.

(iii) - Influence of interlocking of rock elements

Examination of any jointed rock mass in the field suggests that the interlocking of individual rock elements plays an important part in determining the strength of the rock mass. Since it is very difficult to study this effect at full scale, most of the information available has been derived from model studies (Refs. 7,8,9,12). These studies show that the influence of interlocking of blocks is similar to that of surface roughness and that a non-linear relationship between shear strength and normal stress is obtained. In terms of slope stability, this effect can be treated in exactly the same way as that due to surface roughness, provided that the shear strength versus normal stress relationship can be established (Ref.28).

(c) - Influence of Groundwater on Slope Stability

Equation (1) shows that the presence of groundwater in a slope can reduce the factor of safety since both forces U and V act in unfavourable directions. Estimates of the influence of water pressure on the stability of typical rock slopes (Ref. 31) suggest that the safe slope angle can be reduced by approximately 10° if a dry slope becomes saturated. If tension cracks in the slope crest become water-filled, the reduction in factor of safety is more serious (Ref. 14).

Although it is widely recognised that water flow in rock masses is strongly dependent upon the frequency and direction of jointing, most forms of analysis are based upon the assumptions of porous media flow. More sophisticated forms of analysis are available (Ref. 32) but the difficulty of determining relevant hydraulic parameters is such that these techniques have not yet found general acceptance in rock mechanics (Ref. 33). Provided that sufficient allowance is made for changes in water level and for the filling of tension cracks and vertical fissure systems during heavy rains, the author feels that the results of stability calculations based upon the assumption of porous media flow are acceptable for most practical purposes (Ref. 14). In order to carry out these calculations, it is important that some attempt should be made to locate the groundwater surface in the slope and this can be done by observation of the level of face seepage, measurement of the standing water level in adjacent wells and, where necessary, the installation of piezometric devices.

(d) - Influence of External Factors on Slope Stability

External factors such as accelerations imposed by nearby earthquakes or large blasts or the additional loading of the slope by the deposition of a waste dump or the passage of heavy equipment are sometimes blamed for slope failures. Whitman (Ref. 34) suggests that the most important of these factors, namely the accelerations due to a nearby earthquake, will only cause slope failure when the factor of safety is close to unity. Simple calculations of the loads imposed by these external factors confirm that these loads are normally small as compared with the gravitational loads in the rock mass. Exceptions can, however, occur if a fault passing through the site is activated by an earthquake or if liquefaction can occur in a soft saturated layer or tailings dam slope. For most practical rock slope problems, the author feels that it is acceptable to increase the factor of safety from say 1.3 to 1.5 to allow for additional loading in areas which are known to be prone to earthquakes or where it is intended to use very heavy blasting.

One form of damage which is seldom considered in rock slope design is that caused by the actual process of excavating the slope. It is becoming increasingly common to use large blasts in excavating slopes and the damage to the rock faces left by these blasts can have a significant influence on the stability of the slopes. Experienced slope engineers who have compared slopes which were excavated by hand tools and small charges with modern opencast mine slopes feel that a reduction of 5 to 10° in the safe slope angle is caused by blasting damage. The use of pre-split blasting techniques (Ref. 35) can substantially reduce this damage and the author believes that research into this aspect of rock slope design is urgently required.

IV - CONCLUSIONS

How far away are reliable slope design methods? There is no simple answer to this problem since the process of designing a rock slope cannot be compared with the design of a structure such as a bridge or an aircraft which is constructed entirely of man-made materials with known mechanical properties. A rock mass is a complex assembly of elements with widely differing properties in different directions and on

different surfaces. The stability of this mass can be affected by the presence of groundwater and by factors such as the damage caused by blasting during excavation. The most serious problem in rock slope design is the definition of the location, orientation and inclination of structural discontinuities since these discontinuities control the mechanical properties and hence the stability of the rock slope.

In spite of these difficulties, the author feels that significant progress has been made in the development of a practical engineering approach to rock slope design. As the basic mechanisms which control slope behaviour are understood and applied in slope design, some of the malpractices which have grown out of ignorance will begin to disappear. The implementation of simple and inexpensive surface drainage measures to prevent tension cracks from becoming water-filled, the use of pre-split blasting to avoid excessive damage to final slope faces and the re-routing of highways to avoid extremely difficult slope conditions - these are positive steps which can be taken to minimise the risk of major slope failure. Most important is the realisation that rock slopes can and do fail if they are made too high or too steep and several techniques are now available for estimating the limiting heights and angles of slopes under different conditions. Further research will certainly improve the accuracy and reliability of these techniques but such research will only be justified when available techniques have been applied and a need for greater accuracy in slope design has emerged.

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VI - REFERENCES

1. JAEGER, J.C and COOK, N.G.W. Fundamentals of Rock Mechanics. Methuen, London. 1969. 513 p.
2. MOYE, D.G. Rock Mechanics in the investigation and construction of T.1. underground power station, Snowy Mountains, Australia. Engineering Geology Case Histories. Nos 1-5. Geol. Soc. of America. New York. 1964. pp 123-154
3. BLAKE, W. Finite element model is excellent pit design tool. Mining Engg. AIME. Vol 29, No.8 1969.

4. WANG, F.D. and SUN, M.C. Slope stability analysis by the finite element stress analysis and limiting equilibrium method. U.S.Bureau Mines. Rep. Inv.7341 Jan.1970. 16p.
5. STACEY, T.R. Application of the finite element method in the field of rock mechanics with particular reference to slope stability. S.Afr. Mech. Engrnr. Dec. 1969. pp 131-134.
6. GOODMAN, R.E., TAYLOR, R.L. and BREKKE, T.L. A model for the mechanics of jointed rock. J. Soil Mech. and Found. Div. ASCE. Vol.94, No. SM 6, 1968.p 637
7. ROSENGREN, K.J and JAEGER, J.C. The mechanical properties of an interlocking low-porosity aggregate. Geotechnique. Vol.18, 1968. pp 317-326.
8. BROWN, E.T. Strength of models of rock with intermittent joints. J.Soil Mech. Found. Div. ASCE. Vol. 96. No. SM 6, 1970 pp 1935-1949.
9. JOHN, K.W. Engineering methods to determine strength and deformability of regularly jointed rock. Proc. 11 th Rock Mech. Symposium. Berkeley. Calif. 1969.
10. TROLLOPE, D.H. Mechanics of Rock Slopes. Trans. AIME. (Mining) Vol. 222, 1961 . pp 275-281.
11. CUNDALL, P.A. The measurement and analysis of accelerations in rock slopes. Ph.D Thesis. London University. 1971 . 182 p.
12. BARTON, N.R. A model study of the behaviour of steep excavated rock slopes. Ph.D Thesis. London University. 1971. 375 p.
13. SKEMPTON, A.W. and HUTCHINSON, J. Stability of natural slopes and embankment foundations, State of the art report. Proc. 7th Intl. Conf. Soil Mech. Mexico . 1969. Vol 1. pp 291-340
14. HOEK, E. Estimating the stability of excavated slopes in opencast mines. Trans. Inst. Min. Metall London. Vol 79, 1970 pp A 109-A 132. Discussion and author's reply to be published in Trans. IMM, April 1971.
15. JAEGER, J.C. Rock friction and the stability of slopes. 1971 Rankine Lecture to be published in Geotechnique, June 1971.
16. HOEK, E and BOYD, J.M. Stability of slopes in jointed rock. Proc. Symposium on Highway slopes. Univ. Newcastle upon Tyne, 1971 . in press.
17. LONDE, P., VIGIER, G and VORMERINGER, R. Stability of rock slopes - graphical methods. J.Soil Mech. Found. Div. ASCE. Vol 94, No SM 4, 1970 p 1411.
18. JOHN, K.W. Graphical stability analysis of slopes in jointed rock. J. Soil Mech. Found Div. ASCE. Vol. 94, No SM 2, 1968, pp 497-526.
19. WITTKKE, W.W. A numerical method for calculating the stability of loaded and unloaded slopes. (in German). Felsmechanik und Ingenieurgeologie. Vol.30. Suppl. II, 1965. pp 52-79.
20. LONDE, P., VIGIER, G and VORMERINGER, R. Stability of rock slopes, a three-dimensional study. J. Soil Mech. Found. Div. ASCE. Vol 95, No SM 1, 1969.
21. GOODMAN, R.E and TAYLOR, R.L. Methods of analysing rock slopes and abutments - a review of recent developments. Proc. 8th Rock Mech. Symp. Minnesota. 1967. pp 303-320.
22. PENTZ, D.L. Methods of evaluation and analysis of stability of rock slopes. Proc. Symp. Stability for open pit mining. Vancouver 1970. in press.
23. MENCL, V. The influence of the stiffness of a sliding mass on the stability of slopes. Rock Mech. and Engg. Geol. Vol. 4, 1966, pp 127-131.
24. CALDER, P.N., BAUER, A. and MACDOUGALL, A.R. Stereo photography and open pit mine design. Canadian Inst. Min. Metall. Bull. in press.
25. ROCHA, M. An integral sampling technique for site investigation. Proc. 2nd Cong. Intl. Soc. Rock Mech. Belgrade, 1970. Vol 4 . in press.
26. ROSENGREN, K.J. Rock Mechanics of the Black Star open cut, Mount Isa. Ph.D Thesis. Aust. Nat. Univ. 1968.
27. ZEMENEK, J. et al. The Borehole Televiwer - a new logging concept for fracture location and other types of borehole inspection. J. Petrol. Technol. 1969, p.762.
28. JAEGER, J.C. The behaviour of closely jointed rock. Proc. 11th Symp. Rock Mech. Berkeley, Calif. 1969.
29. GOODMAN, R.E. The deformability of joints, in Determination of the in-situ modulus of deformation of rock. Amer. Soc. Testing and Matls. Special Tech. Publ. No 477 . 1970.
30. PATTON, F.D. Multiple modes of shear failure in rock. Proc. 1st Cong. Intl. Soc. Rock Mech. Lisbon, 1966. Vol.1. pp 509-513.
31. HOEK, E and SHARP, J.C. Improving the stability of rock slopes by drainage. Proc. Symp. Planning Open Pit Mines. Johannesburg. 1970, in press.
32. LOUIS, C. A study of groundwater flow in jointed rock and its influence upon the stability of rock masses. Imperial College Rock Mech. Res. Rep. No. 10, Sept. 1969. 90 p.
33. LOUIS, C and MAINI, Y.N. Determination of in situ hydraulic parameters in jointed rock. Proc. 2nd Cong. Intl. Soc. Rock Mech. Belgrade, 1970.
34. WHITMAN, R.V. Influence of earthquakes on stability. Proc. Symp. Stability for Open Pit Mining. Vancouver, Nov. 1970 . in press.
35. STEWART, R.M. and KENNEDY, B.A. The role of slope stability in the economics, design and operation of openpit mines. Proc. Symp. Stability for Open Pit Mining. Vancouver, Nov 1970. in press.