Bench stability in open pit mines : a methodology for jointed rock masses

Hafid Baroudi, D. Hantz, P.D. Asof, Jack-Pierre Piguet

REGIONAL CONFERENCE ON
FRACTURED AND JOINTED ROCK MASSES

Lake Tahoe, California, June 3-5, 1992

BENCH STABILITY IN OPEN PIT MINES : A METHODOLOGY FOR JOINTED ROCK MASSES

BAROUDI H. Ph.D., INERIS, Ecole des Mines, Parc de Saurupt, 54042, Nancy, FRANCE
HANTZ D., Ass. Professor, IRIGM - Université de Grenoble, FRANCE
ASOF M. Ph.D., Min. Dept, Fakultas Teknik Universitas Sriwijaya Palembang, INDONESIA
PIGUET J.P., Professor, Ecole des Mines de Nancy, FRANCE

Abstract

The methods used to design the global angle of open pit mines are not adapted to design the benches. This paper presents a methodology in order to study the stability of the benches. This methodology is based on geometrical modelling of the fractured rock mass wich provide an assemblage of blocks. The block stability is analysed by method based on limit equilibrium. In order to take into account the statistical aspect of the discontinuities, an optimal number of simulations is recommended. Thus, the results can be interpreted statistically. This methodology was applied for 22 benches in 5 different mines, the results obtained are consistent with the observed instabilities.

I. INTRODUCTION

The methods used to determine the overall gradients of the slopes in open pit workings aim to sufficiently eliminate all risk of failure on a scale comparable with the pit walls. For this the slopes must be made shallow gradual and reinforcing measures must generally be applied. Most often these consist of ensuring the drainage of the slopes and in limiting the effects of blasting (reinforcement is generally too costly in the case of very high slopes and deep planes of failure).

When the slopes contain benches and berms it is not possible a priori to eliminate all risks of failure of the same scale as the benches. Indeed, this risk is greater for vetical or almost vertical faces and it would require too detailed a knowledge of the structure of the rock mass, which is not possible at this stage feasability, for a forecast to be perfectly reliable. On the other hand some degree of risk of failure on a scale comparable with the benches may be accepted if the rock falls are halted by horizontal berms or can be prevented by local reinforcement, installed as soon as any excessive risk is identified. For these conditions to be realised, one must be able to predict these failures and their effects and to have methods, preventing them, available.

This paper describes a mean of improving the existing methods for the prediction and prevention of bench failures.

2. TRADITIONAL METHODS OF STUDYING THE STABILITY OF BENCHES

2.1 The traditional method

In order to estimate the stability of benches one generally uses the same methods as those used for the pit walls or the slopes studied in civil engineering

(Hoek and Bray, 1977, Hoek and Londe, 1976). First these methods consist of all of identifying the most unfavourable mechanisms of potential failure, based on the structure of the rock mass and which is more or less known before the excavation (one is normally aware of the general form of the strata and the large tectonic irregularities, the smaller discontinuities being often modelled in the form of sets defined by their average orientation). Safety factors are then calculated for the mechanisms identified, then the gradients of the slopes are determined in such a way that the lower factors are greater than a certain value selected by the geotechnician (as a function, especially, of the situation of the working, the mechanism of the failure, the calculation model used and of the uncertainty affecting the data). The values selected in the case of mining engineering are lower than those selected in civil engineering. In effect, the life of mines is shorter than that of civil engineering structures and the latter are not open to the public, are frequented daily by knowledgeable staff and are regularly inspected.

Although the methods are well suited to the case of the pit walls and intermediate high slopes in the case when one wishes to avoid any risk of failure during the period of exploitation, we considered that they are less well adapted for evaluating the risks relating to failures at the benches scale.

2.2 Limitations of the traditional method

Experience shows on the one hand, that it is practically impossible to avoid any risk of failure with respect to the benches and, on the other hand, that a great number of failures are not dangerous, because the fallen blocks are halted by the horizontal berms separating the benches. Indeed an inquiry (NGOT CONGOLO, 1990) relating to five mining sites and over a cumulative bench length of 3775 metres, made it possible to distinguish between four states of bench stability.

* The stable state is defined by the absence of fallen blocks on the berm situated at the foot of the bench. It represents 26 % of the cumulative length of the benches. (state: very good)

* The second state corresponds to the case where some isolated blocks have fallen on the berm. It represents 33 % of the cumulative length of the benches. (state: good)

* The third state, which represents 19 % of the cumulative length of the benches examined, corresponds to the case where the berm is covered by a large number of blocks. (state: medium)

* The totally unstable state, which represents 22 % of the length observed, is defined by the crumbling of the benches. (state: bad)

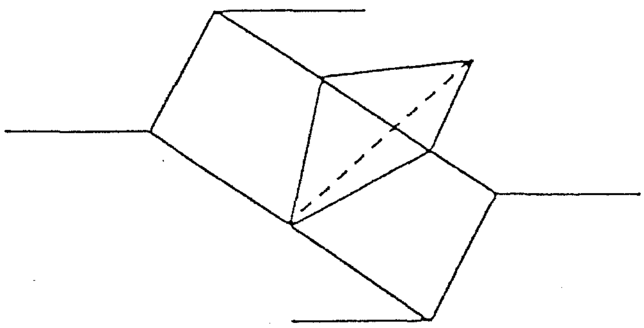
The state of stability thus defined is directly related to the danger of rock collapse which could threaten the personnel moving about at the foot of the pit walls. Note that other parameters recorded, such as the difference between the angle provided for and the observed angle of the benches, or the percentage of pre-cut relief holes that are still visible, seem to be less representative of the danger. As a matter of fact the failures related to these could have occurred during blasting or during the loading of the mined materials and in this case could never have constituted a danger. They correspond to very low safety factors.

The traditional method does not allow one to distinguish in a satisfactory way, between dangerous and safe situations by taking the example of wedge failures - it gives the largest unstable volume that may exist in the case of a single failure (fig 1a) but it does not distinguish between the case in which a large number of failures of such volume will actually occur (fig 1b) and the case in which several failures of smaller volume will occur. To evaluate this danger it is necessary to predict the spatial frequency of the failures and the probable volumes concerned. For that it is necessary to take into consideration the distribution in space of the discontinuities and their persistence.

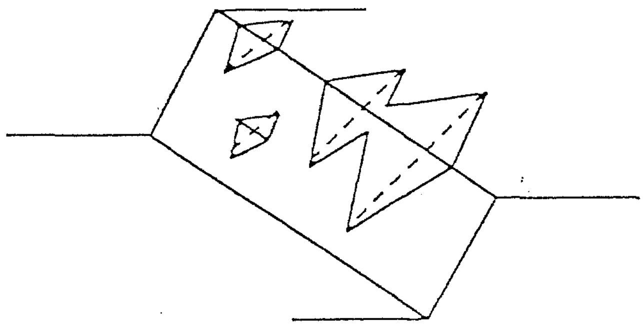
3. PROBABILISTIC APPROACH TO BENCH STABILITY

3.1 Necessity of a probabilistic approach

In order to dimension the pit sides one tries to avoid any possibility of failure by choosing a mean safety coefficient sufficiently high to have a probability of failure negligible or acceptable. One can then explain (or justify) the fact that the probabilistic aspect of the safety coefficient is rarely allowed for in these studies. Another explanation is provided by (Hoek & Londe 1976): " The evaluation of the stability in terms of failure probability in itself presents a problem, most customers refuse to accept that their consulting engineer or their design office recognises that there exists a probability, even a small probability of failure". A certain value of the safety factor (for example 1.3) may be considered



a : Classical method - The greatest wedge



b : Real bench with small and big wedges

Fig.1 : Classical method results and possible aspect of a real bench.

as sufficient, for one is accustomed to that, and experience indicates that stability will be assured, whereas a failure probability of 1 in 1000 or 1 in 100 which undoubtedly means exactly the same thing, will be regarded with mistrust.

If one no longer tries to avoid any possibility of failure, and this is the case when one is demensioning the benches, it becomes necessary to predict the spatial frequency of the failures and the volumes concerned. A deterministic method (using the mean values of the input paramaters) would provide unstable average volumes. Rather than applying a safety factor to these volumes, it seems to us more realistic to make the probabilistic approach and thus to reason in terms of volume having a low probability (chosen in advance) of being exceeded. Furthermore this type of approach should be more easily accepted by the miners in the context of the mine benches for it does not exclude the possibility that certain failures will occur.

3.2 Methodology proposed

Structural study and statistical treatment of discontinuities.

The structural study should lead to the identification of the major dicontinuities at the bench scale, for example, the faults and the stratigraphy as well as the different joints set. For the joints set, the orientation, the extension and the spacing must be defined statistically. A large number of studies (HUDSON and al, 1983) (KABBAJ,1989) have shown that in the majority of jointed rock masses the orientation is in accordance with a LANGEVIN-FISHER statistical law, the extension and the spacing obey exponential and log-normal laws. The quality and the number of data guarantee a good statistical definition.

Geometrical modelling of the bench.

Once the discontinuities are determined and before studying the stability of the bench, a geometric model of the bench is prepared with RESOBLOK (HELLIOT, 1988) a block generator software.

The RESOBLOK software requires, first of all, the definition of a "zone of interest" in which the discontinuities of the rock mass will be simulated. This zone is defined by the height, the length and the width of the bench studied. The discontinuities can then be placed in a deterministic way, in the zone of interest or created by simulation on the basis of statistical laws defining the distribution of orientation and spacing of each set. The extension of the discontinuities is introduced by defining the blocks cut out by the latter. For example, the diaclases of a certain set can affect only the blocks situated between two given stratigraphic joints; in other words "they will stop" on these joints: it is a question of a hierarchic approach in order to simulate the discontinuous rock masses.

Generally it is difficult to estimate the discontinuities extension on the field. Simulation in the geometric model, by a strict method and taking into account the hierarchy between sets of fractures is not easy. Thus, as a first approximation, and in the absence of any clear hierarchy between fractures, the extension may be considered on the scale of the bench.

Fig 2 shows an example of a geometric representation of a bench in an uranium mine. The detailed data for this example are given in (BAROUDI and al, 1990).

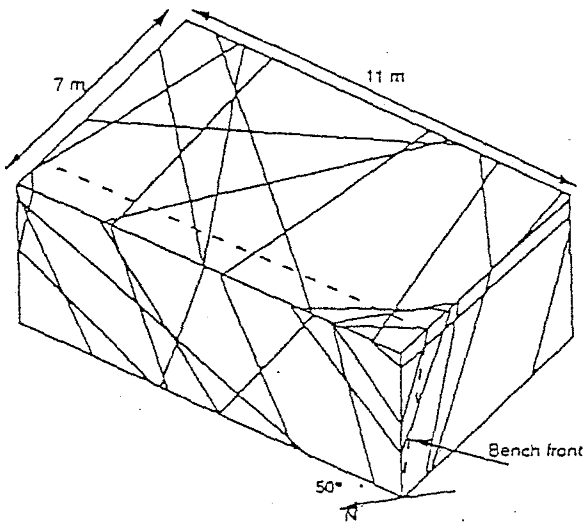


Fig. 2 : Visualisation of the discontinuities network of the bench - simulation n°.1

Geomechanical data and studies of stability.

The geometric modelling of the bench provides a group of blocks for which the stability has to be studied. The BSA software has been written following RESOBLOK, it enables us to analyse the stability of single bloks. The fundamental algorithm is that of WARBURTON (WARBURTON, 1981) and it comprises two stages :

- geometric analysis in order to identify whether the block is displaceable.

- mechanical analysis based on the limiting equilibrium of the block using the Mohr-Coulomb criterion.

In the case of instability, three types of failure can be determined; free fall, plane failure, or wedge failure. The rotation is then analysed in accordance with the algorithm of (LIN and al, 1988).

The properties of the discontinuities necessary for the analysis of stability are the cohesion (c) and the angle of friction (φ). These are generally determined in the laboratory by empirical (BARTON and al, 1990) or experimental methods. If one has local failures on the scale of a given bench one can determine c and φ by back-analysis. This approach was used by (BAROUDI and al, 1990) and (RODE and al, 1990); the values measured in the laboratory and those calculated by back-analysis were of the same order of magnitude. In order to simplify the back-analysis the cohesion of the discontinuities may be assumed to be nil, for the latter are close to the working faces and have thus been subject to the effects of blasting.

Distribution of unstable blocks.

For statistical data on discontinuities it is necessary to apply several simulation processes to the same bench. Each simulation provides a set of blocks for which the stability has to be investigated in accordance with the method previously explained. For each simulation (i), the total volume (v_i) of the unstable blocks is one of the characteristic papameters of the state of stability of the bench. For a number (n) of simulations, the (v_i) constitutes a random variable (v) of mean (m) and standard deviation (σ).

In a large number of cases (HANTZ, 1990) and for a considerable number of simulations (discussed below), (v) follows an exponential law. For example, in the case of the bench shown in fig 2, the distribution of (v) for 50 simulations is represented by fig 3. The validity of the exponential adjustment may be verified by comparing the mean (m) and the standard deviation (σ) which are equal in the case of the exponential law.

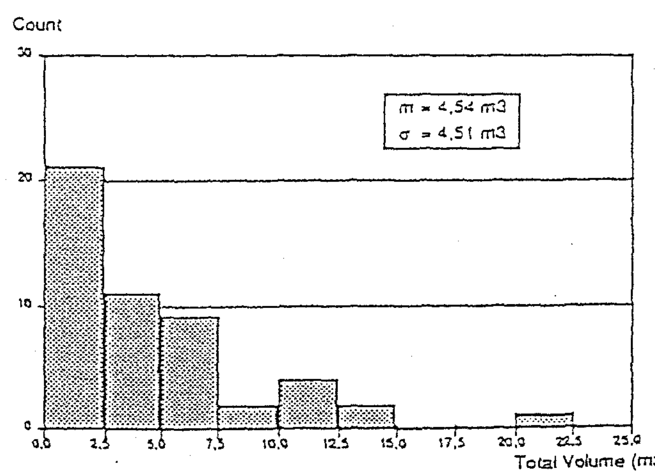


Fig. 3 : Distribution of the total volume of unstable blocks for 50 simulations.

It is demonstrated (ASOF, 1991) - see APPENDIX A - that the error relative to the estimation of (m) on the basis of (n) simulations is 2 / (n + 1), thus for 40 simulations the error is less than 5 %.

Influence of scale.

In reality the length of a bench can exceed 50 m or even 100 m. This raises the question of what representative length of bench should be modelled. This length must be determined by considering two criteria.

* The fracturation must be homogeneous over the length considered. A relatively long bench must be cut into homogeneous sections.

* In the case of a homogeneous section the length (L) to be modelled must be greater than the minimum length (Lmin). The latter is defined such that the mean of the total volumes of the unstable blocks (m) is independent of L.

For example in the case of the bench previously referred to, (Lmin) is estimated to be 8m. Fig 4 shows that above that limit one can put m = 0.4 L.

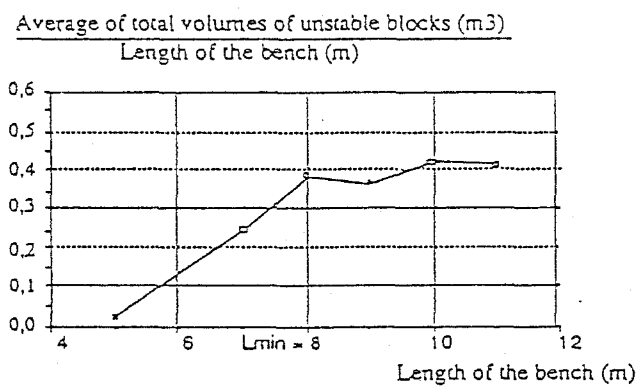


Fig. 4 : Influence of the bench length .

Note that if the actual length of the bench is less than (Lmin) the statistical simulation of the fractures is not valid. That would indicate that the distributions of the sets of fractures are not representative of such a bench dimension. In this case one must introduce all the fractures in a deterministic manner in order to model the geometry of the bench.

4. ANALYSIS OF THE STABILITY OF 22 BENCHES

On five different sites 22 sections of benches were studied in accordance with the preceding method (NGOT, 1990). In order to campare the observations in situ with the results obtained by modelling, two global variables were selected.

* The qualitative variable "State of bench" introduced in chapter 2.2, which characterises the observed state of stability of the bench.

* The variable (m): mean total volume previously discussed. To ensure that (m) was homogeneous throughout the different benches it was reduced to a length of 5 metres.

Fig 5 represents (m) as a function of the "State of the bench". For 22 benches, as a whole there is a good degree of correlation. The deviations from this tendency that were observed could be explained by:

- The subjective character of the variable "State of the bench". Only the extreme states are clearly discriminated ("very good" and "bad"); intermediate states are generally not clearly assessed.

- The geomechanical properties of the fractures could not be determined for all the benches so certain analyses are approximate.

In the case of benches in very good condition HOEK's traditional method often gave "pessimistic" results; greater instabilities than were actually present. By the method proposed the results are more realistic; this could be explained by the fact that one is taking into account the dispersion around the average orientation and the average spacing.

5. CONTRIBUTION OF THE METHODOLOGY PROPOSED FOR THE DIMENSIONING OF THE BENCHES

The methodology proposed may be of help in dimensioning the benches of open-pit mines. The parameters that may be studied are: angle, orientation, height, width of the berm and reinforcement.

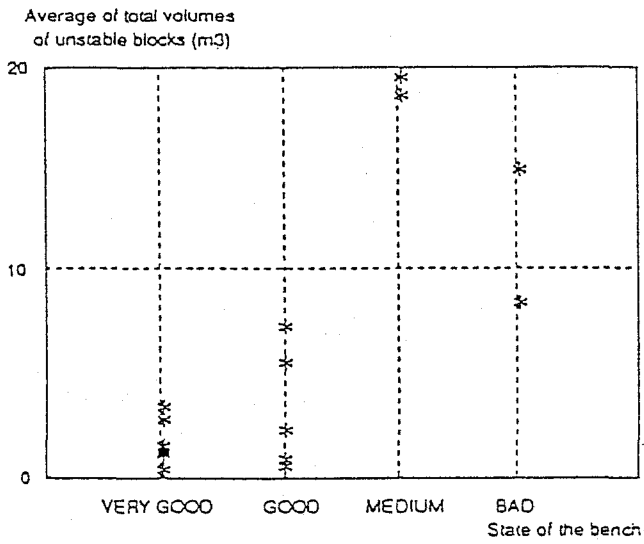


Fig. 5 : Stability analysis of 22 benches.

The angle and the orientation of the bench may be optimised by minimising the volume of the unstable blocks. Fig 6 shows, for the previous bench, that the most unstable state corresponds to an angle of 80°; this result is in effect foreseable without special modelling. The most favourable orientation is 60°, the volume of unstable blocks being smallest for the different angles.

As for the case of the orientation and the angles, different heights may be compared in accordance with the creterion of minimisation of the volume of unstable blocks.

As to the width of the berm, (HANTZ, 1990) proposes a method - too long to be explained in this paper - based on the distribution of the length of heap of fallen blocks and inspired by the method of (MARTIN and al, 1978). This width is determined from the results obtained with RESOBLOK-BSA.

In the case of unstable blocks BSA provides the plan for reinforcement (number and orientation of bolts) in accordance with a method adapted from (SHI and al, 1983). Developments are in progress to make it possible to evaluate a given system of

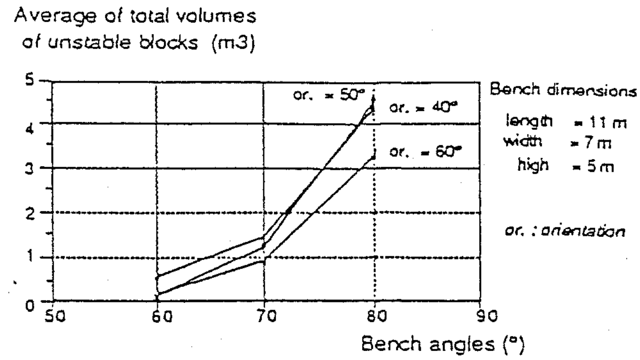


Fig. 6 : Optimisation of orientation and bench angles.

reinforcement. In this case it is a question of determining the distribution of the total volume of unstable blocks in the case of the reinforced bench and thus comparing different systems.

To make the method operational for dimensioning in a given site a stage of validation is necessary. In the absence of quantitative data a comparaison of the condition of the bench and the results of simulations helps us to determine the validity of the approach.

6. CONCLUSION

In this paper a methodology has been propoded for studying the stability of the benches in open-pit mines in fractured rock masses. This methodology is based on geometric modelling of the bench, based on characterisation of the sets of discontinuities. The stability is then considered by analysis at the limiting equilibrium of single blocks. Several simulations are carried out providing a statistical distribution of the volumes of unstable blocks.

This methodology has proved to be better adapted than the traditional methods used at the slope scale. After validation, even a summary validation, the method can help in the dimensioning of the bench and in evaluation of the reinforcement patterns.

BSA may also be adapted to improve the analysis of single blocks, for example to make it possible to amalgamate a limited number of blocks and study the stability of the resulting block. Nevertheless it is essential that the principle of the method should remain simple (few parameters to be introduced) and easy to use.

APPENDIX A

Let m_n the average volume of instable blocks for n simulations:

$$m_n = (v_1 + ..+v_i+......v_n)/n \qquad (1)$$

v_i is the total volume of instable blocks for simulation number i. v_i constitutes a random variable v.

For the $(n+1)^{th}$ simulation, one can write:

$$m_{n+1} = (nm_n + v_{n+1})/(n+1) \qquad (2)$$

For an exponential law of v, with 95% probability, we have :

$$0 < v_i < 3\lambda \qquad (3)$$

Where λ is the parameter of the law estimated by m_n :

$$\lambda = m_n \qquad (4)$$

From (2), (3) and (4) :

$$-1/(n+1) < (m_{n+1} - m_n)/m_n < 2/(n+1) \qquad (5)$$

From (5) :

$$| m_{n+1} - m_n | / m_n < 2/(n+1) \qquad (6)$$

REFERENCES

ASOF M., 1991 - Etude du comportement mécanique des massifs rocheux fracturés en blocs (méthode à l'équilibre limite) : réalisation et applications. Thèse INPL - NANCY, p. 142.

BAROUDI H., PIGUET J.P., ASOF M., CHAMBON C., 1990 - Utilization of the block generator RESOBLOK to complex geologic conditions in an open pit mine. *Mechanics of Jointed and Faulted Rock*, Rossmanith ed., Balkema, Rotterdam, pp. 529 - 535.

BARTON N.R., BANDIS S.C., 1990 - Review of predictive capabilities of JRC-JCS model in ingineering practice. *Rock Joints*, Barton & Stephansson ed., Balkema, Rotterdam, pp. 603 - 610.

HANTZ D., 1990 - Prévision et prévention des chutes de blocs dans les mines à ciel ouvert. *Rapport final CECA* - INERIS - FRANCE.

HELIOT D., 1988 - Generating a blocky rock mass. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* - Vol 25 n°3, pp. 127-138.

HOEK E., BRAY J.W. 1977 - *Rock Slope Engineering* - The Institution of Mining an Metallurgy, London.

HOEK E., LONDE P., 1976 - Travaux de surface au rocher - *Industrie minérale*, mine, n° 1-76.

HUDSON J.A., PRIEST S.D., 1983 - Discontinuity Frequency in Rock Masses - *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* - Vol 20, pp. 73 - 89.

KABBAJ R., 1989 - Traitement statistique de la fracturation - Etude bibliographique. Rapport interne INERIS - NANCY 89 (1) 31.71.1111 N° 5.

LIN D., FAIRHURST C., 1988 - Static analysis of the stability of three-dimensional blocky systems around excavation in rock. *Int. Journal Rock Mechanics* - Vol. 23 n° 3.

MARTIN D.C., PITEAU D.R., 1978 - Select berm width to contain local failures - E/MJ Operating *Handbook of Surface Mining*, Mc Graw-Hill Inc. New-York.

NGOT KONGOLO J.C., 1990 - Stabilité des gradins des exploitations à ciel ouvert. Approche statistique mécanique et probabiliste. Thès INPL - NANCY, p. 161.

RODE N., HOMAND F., HADADOU R., SOUKATCHOFF V., 1990 - Mechanical behaviour of joints in cliffs and open pits. *Rock Joints*, Barton & Stephansson ed., Balkema, Rotterdam, pp. 27 - 33.

SHI G.H., GOODMAN R.E., 1983 - Keyblock bolting, *Rock bolting* - Ed Balkema, pp. 143 - 167.

WARBURTON P.M., 1981 - Vector stability analysis of an arbitrary polyhedral rock block with any number of free faces. *Int. Journal Rock Mechanics* - Vol. 18.