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Fractured and Jointed Rock Masses

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Application of block theory and the critical key block concept to tunneling: Two case histories

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Abstract

This paper describes a new technique for application of Block Theory [1] in highly discontinuous rock mass environments. The technique is applicable for both tunnel and rock slope engineering. It is based on the empirical observation that several critical key blocks control the entire block failure pattern in a given rock structure and excavation geometry. Using this technique one can predict the most likely blocks to fail during excavation in advance, prior to actual construction, on the basis of readily available geological data.

I. INTRODUCTION

Traditional engineering in discontinuous rock masses has been largely based on empirical rock mass classification methods. The output of such methods has typically been in the form of rock load assessments [2], active span stand up time [3], or overall rock quality grade [4,5,6]. Since these methods have been introduced they have been tested and modified extensively. Through the years, a vast empirical data base has been accumulated and correlations between the various methods have been proposed. Such correlations developed into design charts that provided the estimated support pressures for rocks of different quality and excavations of different geometry. Today such design charts provide the rock engineer with a powerful design tool that has been tested and used for a long period of time and is therefore considered reliable.

The commonly used rock mass classification methods however largely ignore *particular* stability problems that may arise due to the formation of frequently occurring removable blocks behind the excavated free face. Such blocks may control the overall behavior and indeed may result in large failures. The factors that influence the formation of such potentially unsafe zones behind the free face are not necessarily correlated with a so called rock quality grade. Rather, such failures are a consequence of the interaction between the particular rock structure and the excavation geometry. Similar blocks may form when the lithology is changed from weak sedimentary rocks to strong crystalline rocks for example, as long as the overall rock structure and the excavation geometry do not change.

Block Theory [1] provides a mathematical formulation that enables the engineer to relate the rock structure to the excavation geometry. For any number of joint intersections behind an excavation free face, Block Theory determines rigorously which of the existing half space combinations will create a removable block, what will be its mode of failure, and what would be the required support pressure to keep the block in place. Such a powerful tool is handy whenever a well determined problem is at hand and wherever the geometry is clearly defined. When the rock structure becomes more complex and a predicted rock behavior is required, application of the theory is no longer straight forward and a great deal of engineering judgement must be invoked.

In this paper a technique for application of Block Theory in complex rock environments is presented. This technique, described here as *The critical key block concept*, attempts to predict the most likely block failures to be encountered during excavation. It uses a joint set characterization of the rock mass with preferred set orientations, the relative spacing of the joint sets, and the corresponding friction angles. A Block Theory removability analysis is built in the technique, as well as a limit equilibrium analysis that is often used in Block Theory applications. The validity of the critical key block concept has been tested so far in several underground excavation projects as well as rock slope excavations. Preliminary results were reported by Goodman and Hatzor [7] and Hatzor and Goodman [8]. In this paper the validity of the technique is demonstrated by means of an analysis of two case histories. In these cases a full application of the critical key block concept is made on the basis of geological exploration data. The predictions are compared with actual block failures that took place following construction.

II. METHOD OF INVESTIGATION

A. *Analysis*

The input data for the analysis include the orientation, spacing and frictional resistance of the discontinuity sets, and the orientation of the excavation free face. The analysis outputs the following:

a. A list of all the possible *Joint Combinations* within the global structure of the rock mass.

b. A Block Theory *removability* analysis. For each joint combination the removable *Joint Pyramid* (JP) is found, with respect to the analyzed free surface, using *Shi's Theorem* [1]. Some joint combinations are detected as *non hazardous* at this stage of the analysis as their corresponding removable JP has an edge that plots on or near the free face, or has no mode of failure.

c. The *JC probability* **P(JC)**. This figure assigns probabilities for the occurrences of the various JC's in the rock mass; the governing factor is the frequency of the individual joint sets in the rock mass and their orientations.

d. The *JP shape parameter* **[K]**. A parameter that is computed for each removable JP of each JC. This figure assigns numerical values to the different removable JP's according to their respective shapes. It is based on the observation that the JP shape has an effect on the degree of freedom it has to slide out of the rock. The governing factor in this figure is the sum of the internal angles between the JP planes.

e. The *JP instability parameter* **[F]**. This figure utilizes the sliding force F_s that is required to keep the JP in place (see derivation in [1], chapter 9), and is based on a limit equilibrium analysis. The sliding force computation requires the friction angle of the sliding surface/s, the density of the rock mass and the direction and magnitude of the resultant force.

f. The *relative block failure likelihood distribution* **P(B)**. This is the desired parameter of the analysis. It is computed for all JC's with respect to a single excavation free face. The relative block failure likelihood of a single joint combination is the product of its P(JC), [K] and [F] values. When P(B) is computed for all joint combinations a distribution results, the modes (high points) of which define the critical blocks for the free face under consideration. Thus P(B) weighs the overall risk offered by each JC when a free face of known orientation is excavated through the rock mass. P(B) is not a formal probability distribution function with values in the range of 0 to 1. Rather, it is a *relative likelihood* with numerical values ranging here from 0 to 2. The significance of this distribution is in its *relative* rather then its absolute values. Using this distribution one can select the critical blocks for each free face of the excavation in the rock mass of concern. The *design blocks* for each free face are selected from the group of critical blocks.

The analysis assumes that it is meaningful to represent the structure of the rock mass by several prominent joint sets, each of which embraces a cluster of orientations. We model the behavior of the expected opening using combinations of ideal joint sets and ignore the combinations that may arise from the intersection of less common orientations. The correctness of this method depends on the correctness of this assumption; i.e. the analysis is invalid when joints are truly random in the rock mass.

B. *Field Investigation*

In the field two pilot tunnels have been studied. The tunnels were driven through crystalline and sedimentary rocks where the structure played a major role in the failure patterns. In both tunnels a great number of blocks were released from the circumference of the excavation, either during the excavation or at some point later in time. The blocks that failed could be traced on the parent rock wall in the form of *moulds*. These moulds were left behind in the rock after the failed block was removed, leaving a "negative" picture of the failed block. In competent rock masses the boundary joints of the blocks are perfectly preserved within the mould and one can measure their attitudes. Thus by measuring the attitudes of the joints at the boundary of each mould, the geometry of the failed block is revealed. The analysis of each mould that was found include the following:

1. Measurement of the boundary joints and orientation of the free face in the particular location.
2. Block theory removability analysis using the mould joints as input in order to confirm the removable JP, the observed half space combination, and the failure mode.
3. Correlation of each boundary joint in the mould with the global joint sets in order to assign the correct joint combination to the observed block failure.

Once all failed blocks are correlated with the corresponding joint combination, a comparison between the predicted failure likelihood and actual failures for each joint combination is made possible.

III. THE CRITICAL KEY BLOCK METHOD OF ANALYSIS

The critical block method of analysis involves all the steps that were mentioned above. A detailed description of the procedure is given by Hatzor and Goodman [8]. Here only the principal points will be discussed.

A. *The joint combination probability P(JC)*

A Joint Combination (JC) was defined as a subsystem of joint sets that intersect over a small region in space. All combinations of joints do not have the same likelihood of passing through the same small volume; in particular, a joint set that exhibits a close spacing has a greater likelihood of intersecting any given volume, and vice versa. The probability that a joint of a given set intersects a line of length interval [x] is determinable if the probability density function for the spacing of the joints is known. For the *negative exponential* distribution, recommended after examination of field data by Priest and Hudson [9], Hudson and Priest [10] and Wallis and King [11], the probability density function is expressed by:

$$f(x) = \lambda e^{-\lambda x} \qquad (1)$$

where the parameter λ expresses the average frequency of discontinuities per unit length; its inverse is the average spacing between discontinuities. This distribution has one parameter λ; both the mean and standard deviation are equal to $1/\lambda$. If the discontinuity frequency is determined using a scan line survey then a Terzaghi correction [12] for the true frequency must be used.

The discontinuities that intersect a scan-line are analogous to arrivals along a time-line. In this analogy, the scan-line is the time-line, the discontinuities that intersect the scan-line are the arrivals, and the spacing between discontinuities are waiting times. If the distribution of the waiting times between arrivals is negative exponential, and if the waiting times between each arrival are independent of previous arrivals, then the distribution of the number of joints N in a fixed interval of length [x] is Poisson. Accordingly, the probability of encountering N = k joints from set i along an interval of length [x_i] along the scan-line in direction normal to the joint (n_i) is determined by:

$$P[N_i = k] = \frac{e^{-\lambda_i x_i}(\lambda_i x_i)^k}{k!} \qquad k = 0, 1. \quad x > 0 \tag{2}$$

where the only required parameter is the joint set frequency λ_i, a rock mass property that can be obtained from a scan-line survey. In practice we are interested in the case where there is one intersections of joint set i along a very small interval $[x_i]$ namely:

$$P[N_i = 1]_{x_i \to 0} = \lambda_i x_i \tag{3}$$

Similarly we can express the Poisson probability for sets j and k of joint combination {i;j;k}. Assuming these events to be independent, the probability of all three joint sets occurring in the small lengths $\{[x_i],[x_j],[x_k]\}$ is the product of the three independent probabilities :

$$\begin{aligned} &JC : \{N_i = 1\} \cup \{N_j = 1\} \cup \{N_k = 1\} \\ &P(JC) \propto P(\{N_i = 1\}) \cdot P(\{N_j = 1\}) \cdot P(\{N_k = 1\}) \\ &P(JC) \propto \lambda_i x_i \cdot \lambda_j x_j \cdot \lambda_k x_k \end{aligned} \tag{4}$$

Note that equation 4 depends on an assumed spacing distribution, and that it does not incorporate the dependence of the probability on the orientation of the joints in the joint combination. Mauldon [13] derived a more general expression that would fit any joint spacing distribution, which also addresses the inherent dependence of the distribution on the joint orientations:

$$P(JC) = \frac{(\lambda_i x_i)(\lambda_j x_j)(\lambda_k x_k)}{V_{ijk}} \tag{5}$$

where V_{ijk} is the volume of the parallelepiped bounded by the pairs of planes formed by joints {i,j,k} with normals $\{\mathbf{n}_i,\mathbf{n}_j,\mathbf{n}_k\}$, where each pair is separated by intervals $[x_i]$, $[x_j]$, $[x_k]$ respectively. The volume of the parallelepiped is given by:

$$V_{ijk} = \frac{[x_i]\,[x_j]\,[x_k]}{\lfloor \mathbf{n}_i \cdot \mathbf{n}_j \times \mathbf{n}_k \rfloor} \tag{6}$$

where • and **x** indicate dot and cross products respectively, and $\mathbf{n}_i$ indicate a unit vector in the direction of the joint normal. Inserting equation 6 into 5 we get Mauldon's equation:

$$P(JC) = (\lambda_i \lambda_j \lambda_k) \lfloor \mathbf{n}_i \cdot \mathbf{n}_j \times \mathbf{n}_k \rfloor \tag{7}$$

In our analysis we use Mauldon's generalized equation to compute the joint combination probability.

B. *The JP shape parameter [k]*

The JP shape parameter [K] evaluates the likelihood of a removable block to actually release from the excavation pyramid [1] using primarily kinematical considerations. It distinguishes between kinematically free and kinematically constrained sliding vectors of different removable Jps. Thus the shape parameter weighs the degree of hazard offered by each removable JP. We distinguish between *Open* and *Closed* Jps, when we discuss the influence of the JP shape on its stability. An Open JP is characterized by large angles between its planes when measured inside the JP and a small apex distance form the free face, whereas a closed JP is characterized by small angles between the planes and a large apex distance from the free face from which it is removable. Using field observations it was found that the majority of the failed blocks had an open JP. There could be several reasons for this phenomena:

a) Considering a circular tunnel cross section, as the apex distance increases, the joint normals come closer to directions tangential to the free face, resulting in higher lateral stresses on the faces of the block.

b) As the apex distance increases, the area of the side planes also increases and if the joint planes exhibit cohesion, a greater cohesive force resists sliding.

c) As the apex distance increases, the permissible directions for block movement become more constrained, and the strengthening effect of joint roughness becomes pronounced.

A way to quantify the shape of a JP was discovered and discussed by Mauldon [14] in his general solution to the probability that a JP is removable. Here we use similar equations to find the risk offered by a JP that is **known** to be removable (the removability of the JP is already established at this stage of the analysis). Each JP has a particular spherical triangle area which reflects the value of the angles between its planes and thus its shape when only tetrahedral blocks are considered. Therefore, the area of a JP spherical triangle offers a grade for the removable JP degree of hazard , where the greater the spherical triangle area, the greater the risk that the JP will produce actual block failures when cut by the free face. The JP shape parameter [K] can be expressed as the ratio of the JP spherical triangle area to the surface area of the stereographic projection sphere:

$$K = \frac{(A + B + C - \pi)R^2}{4\pi R^2} \tag{8}$$

where A,B,C are the internal angles between the JP boundary planes for a JP with 3 joints , and R is the radius of the stereographic projection sphere.

C. *The JP Instability Parameter [F]*

The JP instability parameter is a mapping of the sliding force required to keep the JP in place into a region from 0 to 2 namely:

$$F = 2^{\lfloor F_s \rfloor} \qquad -\infty \le \lfloor F_s \rfloor \le 1 \tag{9}$$

where F is the JP relative instability parameter and $|F_s|$ is the magnitude of the JP sliding force vector normalized by the block weight. The sliding force is computed using limit equilibrium analysis procedures as discussed by Goodman and Shi [1]. In their analysis a JP with a falling mode has sliding force that is equal to the weight of the block and when normalized by that weight it becomes +1.0, representing the most dangerous case. For this sliding mode F equals 2. A JP at limit equilibrium has a sliding force of 0 and therefore an F value of 1.0. A JP that is safe under the assumed friction

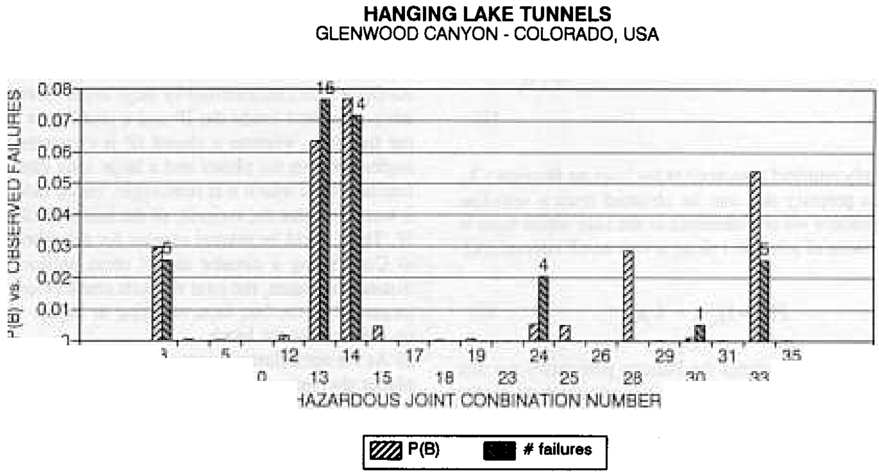

Figure 1: Comparison between predicted block failure likelihood for all hazardous joint combinations and actual blocks (moulds) that were found in the field. Free face orientation is 90/330.

angles on the joints has a negative sliding force vector, meaning that the block must be pulled to be released form the rock. The corresponding F value is smaller then 1 but greater then 0. A JP that has no mode, meaning that the JP will not slide even if a friction angle of zero degrees is assumed, represents an infinitely safe block with an F value of zero.

The F value considers the equilibrium condition of the block. Note that only the net sliding force is used in equation 9. Therefore, Equation 9 allows one to compute the JP instability parameter for all removable Jps on the basis of the joint geometry alone without consideration of actual block size; block size is controlled by the orientation of the free face and the actual block that is formed within the maximum removable block region. Like the JP density and shape parameters, the JP instability parameter can be found on the basis of the exploration data only and it can be used to weigh the risk offered by the different possible removable Jps.

D. *The overall block failure likelihood P(B)*

Using the Joint Combination probability P(JC), the JP shape parameter (K) and the JP instability parameter (F) the overall block failure likelihood can be found for any joint combination in the rock mass. This likelihood compares the relative risk offered by the different joint combinations in the rock mass when a free face of fixed orientation is excavated through it. For every single joint combination the block failure likelihood is given by:

$$P(B) = P(JC)[K][F] \tag{10}$$

where: P(B) = *relative block failure likelihood*
P(JC) = *Joint Combination Probability*
K = *JP shape parameter*
F = *JP instability parameter*

The relative block failure likelihood is computed for all Jcs and thus a distribution of P(B) values for all Jcs is obtained, the modes of which indicate the critical blocks for the excavation free face which is considered. The number of unordered combinations of n joint sets taken k at a time is given by:

$$N_k = \frac{n!}{k!(n-k)!} \tag{11}$$

where the index k is the number of joint sets that comprise a JP. Considering tetrahedral blocks k is equal three, the fourth surface being the free face of the excavation. We have observed in the field that the larger the value of k, the smaller the recurrence of its JP's. JP's with k = 4 proved relatively rare and JP's with k = 5 or more were not observed more than once.

The critical key block analysis process must be repeated for each excavation free face since each determines particular set of removable Jps. From the group of critical blocks the *design blocks* for each excavation face are selected. The geometry of the design blocks and the excavation cross section determine the selected support dimensions.

IV. TWO CASE HISTORIES

A. *Hanging Lake Tunnels: tunneling through crystalline rocks*

These two highway tunnels, driven through the Precambrian basement rocks of Glenwood Canyon, Colorado, were investigated in the field following the completion of the exploratory tunnel excavation and during the construction of the full size opening. The tunnels were excavated through highly discontinuous but very competent crystalline rocks, consisting of migmatite gneiss and quartz diorite intruded in places by granite and pegmatite. The global structure of the rock mass contributes open joints, faults and shears, and foliation planes. Field investigations indicated that the governing mode of failure during or immediately following construction was sliding of blocks along planes of pre-existing structural discontinuities. Only very rarely did blocks fail due

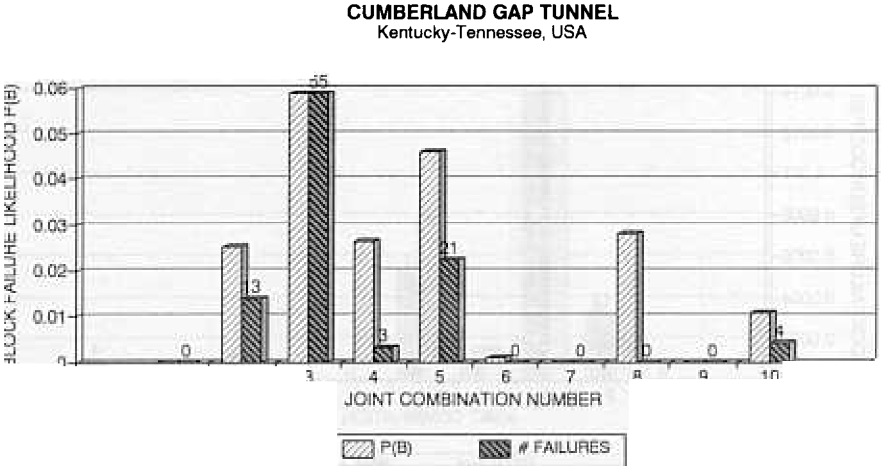

Figure 2: Comparison between predicted block failure likelihood for all joint combinations and actual blocks (moulds) that were found in the field. Free face orientation: 90/213.

Table I: Geological structure of the rock mass in Glenwood Canyon, Colorado, USA

JOINT SET #	DIP	λ (1/ft)	$\Phi°$
1	83/358	1.18	35
2	74/242	0.38	35
3	77/68	0.25	35
4	84/175	0.82	35
5	32/90	0.43	35
6	81/270	0.49	35
7	54/297	0.81	35

to opening of blasting-induced fractures. The rock structure is summarized in Table 1 below. The structural data were obtained using the results of a detailed mapping program of the side walls of the pilot tunnels, performed by geologists and engineers of Woodward-Clyde Consultants. Every tunnel stretch has been mapped in detail and the results of each stretch were summarized on "as built data sheets" that include stereographic projection of all discontinuities in the tunnel stretch, spacing, roughness, filling material and presence of stereographic projection of all discontinuities in the tunnel stretch, spacing, roughness, filling material and presence of ground water. The stereographic projection of all discontinuities were used to select the representative joint set attitudes. The side wall trace maps were used as a scan line to determine the true frequency of each joint set. The joint surface descriptions were used to asses the friction angles.

The critical key block analysis was performed using the structural data in Table 1. Since seven joint sets are present, by Equation 11, 35 joint combinations had to be analyzed, each with three different joints. All removable Jps and their sliding modes were obtained using block theory procedures and the critical blocks were found using the procedure described above.

In the field all moulds of past block failures were documented, the joint surfaces were measured and the block trace photographed. Each case was tested for removability using block theory and all sliding modes were verified.

In each mould the joint orientations were correlated with the global joint sets so that it was possible to correlate the mould with the corresponding ideal joint combination. In each case it was checked whether the removable JP in the ideal joint combination was indeed represented in the mould with the correct half space combination. A comparison between the predicted block failure likelihood distribution for all joint combinations and the actual blocks (moulds) that were found in the field is shown in Figure 1.

B. *Cumberland Gap Tunnel - Tunneling through sedimentary rocks*

In this case the critical block concept was tested in a sedimentary rock environment with distinct bedding planes and several sets of discontinuities. The studied project is located at Cumberland Gap, near the three state intersection: Kentucky-Tennessee-Virginia. Cumberland Mountain lies near the junction of the Valley and Ridge and the Appalachian Plateau provinces within the Appalachian Highlands of the eastern United States. The project site is a fault-bounded block that represents the leading edge of a large scale Permian age thrust fault during which the sedimentary sequence was folded and overthrusted. The lithology in the vicinity of the tunnel ranges from uniform shales and limestones to interbedded sandstone, shales and coals. The structural features in the region include bedding planes, faults, shears and joints. The direction of the bedding plane strike remains consistent throughout the tunnel. The structural attributes of the site are shown in Table 2.
In this case again a detailed study of the exploratory tunnel was conducted using procedures similar to those discussed

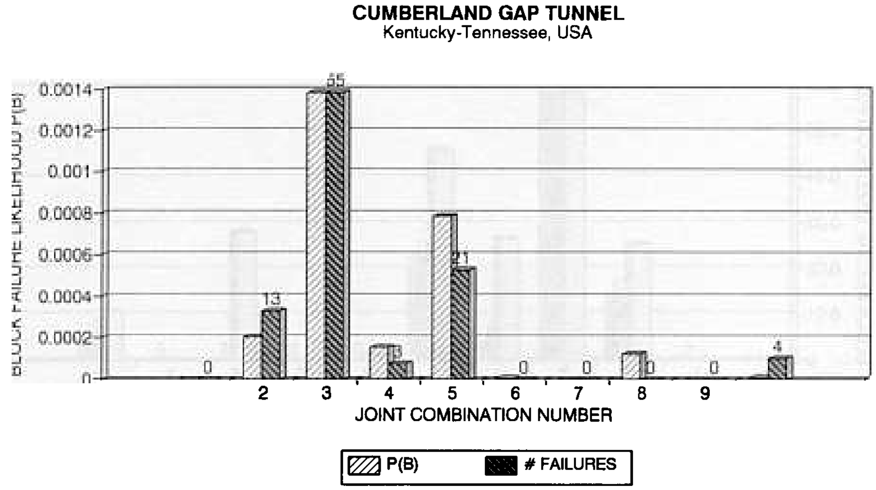

Figure 3: Conditional P(B) distribution calculated for *given* joint frequencies. The λ values were obtained from the number of joints that were found in the field at the boundary of blocks (moulds).

above in the first case history. The site was re-visited when enlargement to the full size opening was under way . All tested moulds however were sampled from the walls of the exploratory tunnel. The critical key block analysis procedure was applied using the given data. The geological exploration was performed by geologists and engineers of Golder Associates and their raw data was used.

The validity of their data was confirmed in the field with respect to the principal joint sets, attitudes, and spacing. Figure 2 presents a comparison between the predicted block failure likelihood for all joint combinations using the data in Table 1, and the number of corresponding blocks (moulds) that were identified in the field.

Table II: Geological structure of the rock mass in Cumberland Gap, Tennessee, USA.

JOINT SET #	DIP	λ (1/ft)	Φ°
1	38/298	1.67	30
2	48/075	0.57	30
3	86/094	0.37	30
4	83/004	0.28	30
5	69/181	0.67	30

DISCUSSION

The two cases that have been presented demonstrate the validity of Block Theory as an analysis tool for failures in blocky rock. A very important result from the field studies is that virtually all documented moulds exhibit the correct joint half-space combination that is rendered *removable* by block theory removability analysis when the mould joints are used as input for such an analysis. This being the case, one can proceed safely to use such frequently occurring moulds in conjunction with block theory to back-calculate the failures and to asses the limit strength of the joints.

Block Theory is proved valuable in yet another aspect; the entire critical key block analysis is based on *Shi's Theorem* [1] which determines the removable half space combination (JP) for each joint combination within the rock mass, for the free face in question. Without this elegant and rigorous tool, the overwhelming number of possible half space combinations in a discontinuous rock mass would render such an analysis impractical.

The most important conclusion that stems from the field investigations however seems to be the fact that there is such an entity as the *critical key block* when a free face is cut through a discontinuous rock mass. This is not surprising. After all, all blocks are formed by an intersection of three or more joints within a small volume in the rock mass. The probability of such an event is therefore related in some way or another to the frequency or spacing of these joints in the rock mass. And so if the rock can be classified into several representative joint sets, each with a preferred orientation, the joint combination probability can be determined, as was shown above.

In addition to the contribution of joint spacings to the failure likelihood, the shape of the JP must be considered. As was explained above, a closed JP with a remote apex is much less likely to be released from the rock even if removable, merely due to the higher confinement it experiences. And finally, the state of equilibrium of the JP has an obvious effect on its failure likelihood. The validity of the block failure likelihood equation can be demonstrated if the joint sets are assigned frequencies according to the real number of joints that were actually found in the field at the boundaries of moulds. This would provide a test because there is no other variable to which the failure likelihood is so sensitive then the frequency of the joint sets in the rock mass. The P(B) values for all joint combinations in the Cumberland Gap case are shown in Figure 3 next to the number of corresponding blocks that were found in the field. The calculation here is performed when we know the "exact" spacing of the joints, and the agreement with the observations is notable.

The last important result from the field investigations is that most observed moulds belong to a three joint JP, namely representing tetrahedral blocks. Four joint JPs were rare and 5 joint JPs were not observed. This again is not surprising. By inspection of equation 4 one can see that the greater the number of joints, the lower the value of P(JC). Physically this means that the probability that four joints will intersect within a small volume in the rock mass is smaller then the probability that three will, and so on. This observation justifies our focus on tetrahedral blocks in the critical key block method of analysis. It also provides support to the current practice to analyze tetrahedral blocks and to ignore blocks with a JP of higher order.

VI. SUMMARY AND CONCLUSION

Using field case histories the validity of Block Theory as an analysis tool for tunneling through discontinuous media is established.

The application of Block Theory in such environments is enhanced with the aid of the critical key block method of analysis. This procedure assumes that not all Joint Pyramids will be represented equally as block failures when tunneling through a discontinuous rock with a fixed structure. The existence of a critical key block has been observed in the field. A method to determine the critical key block is described and its applicability is demonstrated using two case histories in two different geological environments.

Determination of all critical key blocks prior to construction is possible using the procedure outlined above and readily available geological data. When this is done prior to excavation, the support requirements can be assessed realistically in accordance with the geological structure and mechanical strength of the rock, and with the geometry of the opening. Such a procedure can replace rock mass classification schemes if their main object is to arrive at realistic support requirements. It is limited however to competent rock masses where failure patterns are predominantly sliding of blocks into the excavation space. The geological factors that are required include the joint set orientations, the spacing distribution of the joint sets and their strength.

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