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The Block Failure Likelihood: A Contribution To Rock Engineering in Blocky Rock Masses

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This paper summarizes some results of an applied block theory research conducted at Berkeley over the last three years. The validity of the critical-key-block concept is tested here using block mould statistics sampled from side walls of two tunnels, the raw data of which are shown. The predictive capabilities of the three block-failure-likelihood parameters are tested by correlation with the block mould sample population, and a modification is introduced. A possible method to integrate a block motion criteria in empirical rock mass classification systems is proposed.

INTRODUCTION

Block Theory [1] provides an accurate solution for the removability a block comprised of n planes and a free face composed of m surfaces. It also provides a limit equilibrium analysis for the removable block, its maximum size, and hence the required rock bolt capacity and length. The major drawback of the theory however is its deterministic nature; in order to apply the theory, the attitude of the Joint Pyramid (JP) and free face planes must be known. Commonly the rock engineer does not know in advance exactly which joint attitudes to expect, and which blocks, of all the theoretically removable ones, will form and fail underground. These uncertainties increase as the number of principal joint sets in the rock mass increases, and as the span of attitudes within each joint set expands. As a result, rock engineers typically resort to empirical rock mass classification methods for support dimensioning in discontinuous rock masses.

Recently several efforts have been made in applied block theory research, using field observations and geostatistical methods. Goodman and Hatzor [2] used *block moulds*, found in the wall rock of pilot tunnels, to correlate between observed block failures and the list of theoretically removable blocks, as determined by block theory. They found that the observed block failures correlated with a small subset of the removable block out-come space. This observation has triggered an effort to try and predict the *failure likelihood* of theoretically removable blocks, and to determine the critical-key-blocks of the excavation [3,4]. Further developments include Mauldon's solution for the relative probabilities of joint intersections [5], and Kuszmaul's estimation of key block sizes [6].

The efforts of applied block theory research stem from the need to advance empirical rock mass classification systems. A major drawback of conventional rock mass classification methods [7-11] is their disregard of possible block motion into the newly created space, overlook of the intimate interaction between tunnel azimuth and rock structure, and inability to determine accurately required support dimensions. Block theory provides rigorous analytical tools for these three dimensional problems. In this paper it will be shown how the failure likelihood of removable blocks can be estimated and how the overall tendency of the rock mass to generate block failures may be evaluated, using a block theory based analysis.

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DESIGN APPROACH

Assumptions

The principal assumptions are as follows: 1) Joints surfaces are assumed to be perfectly planar; 2) Joint surfaces are assumed to extend entirely through the volume of interest i.e. no discontinuities will terminate within the region of a key block and no new cracking will ensue prior to block movement; 3) Blocks defined by a system of joint faces are assumed to be rigid i.e. no block deformation or distortion is considered; and 4) The discontinuities and the excavation surfaces are assumed to be *determined* as input parameters.

The Removable Block Out-Come Space

In a discontinuous rock mass with n joint sets, the number of Joint Combinations (N_{jc}) of size k (the number of intersected joints <u>without</u> repetition) is given by $N_{jc} = n!/\{k!(n-k)!\}$. Block theory finds the *removable* joint pyramids from a given free face in each joint combination. If for example we design for a single free face of known attitude, then each joint combination of size k will produce $(k^2-3k+2)/2$ removable blocks of different types [1]. Therefore, the total number of different removable blocks (N_{rb}) from behind the designed free face in a given rock structure is:

$$N_{rb} = N_{jc}\cdot(k^2-3k+2)/2 = \frac{n!(k^2-3k+2)}{[illegible]} \qquad (1)$$

As n increases so does N_{rb}, posing an obstacle to a block theory based design, where an attempt is made to address the stability of all removable blocks in the rock mass.

The Block Mould

The influence of rock structure on the stability of the excavated face was studied in the field by careful examination of cavities within the parent rock that remained following the release of blocks. These cavities, referred to as *block moulds*, reveal all the necessary information about the failed block: The attitude of the boundary joints can be measured; the half space combination (the JP code) and failure mode can be determined by inspection; and the friction angle of the sliding planes can be estimated using the induced wedge test directly on the exposed planes. The block moulds therefore can be viewed as natural experiments, where failure of pre-existing blocks is induced by excavation procedures, primarily blasting and exposure. Field investigations [12] have revealed that for a given free face, cut through a given rock structure, only few removable blocks are represented. This observation is quite striking considering the number of removable blocks in the system (Equation 1). Such blocks are referred to as *critical-key-blocks*.

Approach

Figure 1 shows an example of a block-failure-likelihood histogram for the rock mass of the left abutment of Seminoe Dam, Wyoming, computed on the basis of geological exploration input data of seven joint sets (mean joint set attitude, spacing and friction angle). Inspection of this histogram reveals the critical-key-blocks for that abutment. If the design is aimed at these blocks, in terms of maximum rock bolt length and capacity, then the weakest members of the blocky system can be assumed to be adequately supported. Note that it is not necessary to map block moulds at every project in order to apply this method. In this study block mould data is presented in order to test the validity of the method. The actual analysis however is performed on the basis of independent geological exploration in-put data, concerning the discontinuity orientation, frequency and strength. The out-put is the block-failure-likelihood histogram for all joint combinations and the required rock bolt length and capacity for the critical-key-blocks.

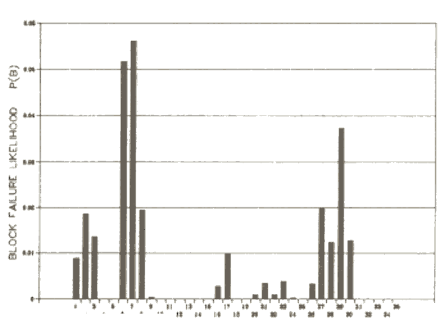

Figure 1: The block failure likelihood histogram, computed for the rock mass at the left abutment of *Seminoe Dam, Wyoming*.

THE FAILURE LIKELIHOOD OF A BLOCK (*P(B)*)

Kinematical Considerations

A block can fail only if it is removable. By application of *Shi's Theorem* [1], the removability test can be performed by inspection, using the stereographic projection; a removable JP is a spherical polygon entirely contained in the space pyramid of the analyzed free face.

Geostatistical Considerations

Removable blocks have different joint intersection probability depending on joint set frequency [2-5] and orientation [5]. A Poisson process model to estimate joint combination probability (P(JC)) has been proposed [2,3,4] assuming negative exponential spacing distribution in the rock mass. Mauldon [5] derived a more general expression, although limited for *tetrahedral* blocks, which also addresses the dependence of the joint combination probability *P(JC)* on joint orientation:

$$P(JC) = (\lambda_i \lambda_j \lambda_k) |\boldsymbol{n}_i \cdot \boldsymbol{n}_j \times \boldsymbol{n}_k| \tag{2}$$

where λ_i are the joint set true frequency found by Terzhagi's correction [13], and n_i are the joint set normals.

Field investigations have shown that the vast majority of block moulds mapped underground represent tetrahedral blocks [12]. Tetrahedral blocks are therefore assumed throughout the analysis.

Mechanical Considerations

A removable block will fail only if found unsafe by limit equilibrium analysis. Block failure modes include opening from all joints (falling or lifting), sliding on one plane or simultaneously on two planes, and toppling. We limit the analysis here for sliding or falling; a discussion of the rotational mode is presented by Mauldon and Goodman [14]. The force required to bring an unsafe block back to limit equilibrium, assuming no joint cohesion, was derived by [1]. This force, the *net sliding force (F^*)* is given by Equations 3a 3b, and 3c, for falling, single face and double face sliding respectively:

$$F^* = |\boldsymbol{r}| \tag{3a}$$

$$F^* = |\hat{\boldsymbol{n}}_i \times \boldsymbol{r}| - |\hat{\boldsymbol{n}}_i \boldsymbol{r}| \tan\phi_i$$

$$F^* = \frac{1}{|\hat{n}_i \times \hat{n}_j|^2} \left(|\boldsymbol{r} \cdot (\hat{n}_i \times \hat{n}_j)| \, |\hat{n}_i \times \hat{n}_j| - |(\boldsymbol{r} \times \hat{n}_j) \cdot (\hat{n}_i \times \hat{n}_j)| \tan\phi_i - |(\boldsymbol{r} \times \hat{n}_i) \cdot (\hat{n}_i \times \hat{n}_j)| \tan\phi_j \right)$$

where **r** is the active resultant, n_i and ϕ_i are joint i normal and friction angle respectively. The *block instability parameter (F)* is given by:

$$F = 2^{(F^*/R)-1} \tag{4}$$

Where R is the magnitude of the active resultant. The block instability parameter F is a mapping of the net sliding force F^* to a range between 0 and 1 where $F=0$ corresponds to a block having no failure mode ($F^*/R \rightarrow -\infty$), $F=½$ corresponds to a state of limit equilibrium ($F^*/R=0$), and $F=1$ corresponds to a falling mode ($F^*/R=1$) as shown in Table 1.

Table 1: The relationship between the normalized sliding force, the state of equilibrium, and the instability parameter.

F^*/R	Failure Mode	Instability Parameter
1.0	Falling	$F = 1$
$0 < F^*/R < 1.0$	Sliding	$½ < F < 1$
0	Limit Equilibrium	$F = ½$
< 0	Safe	$0 < F < ½$
	No mode	$F \rightarrow 0$

The Shape Parameter

Removable blocks vary in yet another aspect, their three dimensional shape, or envelope geometry. Careful study of block mould geometry revealed that the majority of block moulds belong to *open* rather then *closed* removable JPs, where a closed JP is characterized by small interplanar angles and a large apex distance behind the free face [2]. It has been argued that the larger the apex distance, the greater the lateral confinement experienced by closed blocks and therefore their greater stability [2,3,4]. Furthermore, in order for a block to slide out of the rock the sliding vector must be a subset of the JP [1]. Naturally the sliding surface exhibits a degree of roughness which limits the span of the sliding vector. The stabilizing effect of joint roughness becomes less important as the sum of the JP interplanar angles increases (Figure 2). The *Shape Parameter (K)* measures the ratio between the JP spherical triangle area on the stereonet (assuming *tetrahedral* blocks) and the surface area of the projection sphere: $K = \{(A+B+C-\pi)R^2\}/4\pi R^2 = (A+B+C-\pi)/4\pi$, where A,B,C are the JP interplanar angles and R is the radius of the stereographic projection sphere.

The block failure likelihood offered by each joint combination in the rock mass, P(B), can be estimated using the product of the three independent parameters:

$$P(B)=P(JC)\cdot(K)\cdot(F) \tag{5}$$

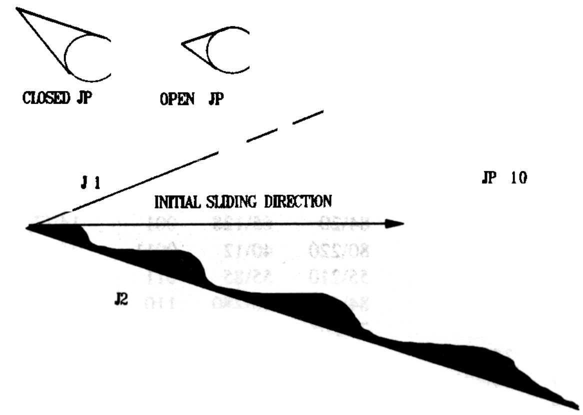

Figure 2: The influence of slip-surface roughness on the free span of the sliding vector.

PREDICTIVE CAPABILITIES OF P(B)

Tables 2 and 3 present block mould data sampled from side walls of two pilot tunnels. Each documented block mould appears with the measured attitudes of the boundary joints, observed JP code, and the correlated global joint combination number. The P(B) values for each removable block were calculated by equation 5, using the given discontinuity data as input. Figures 3 and 4 show the predicted P(B) histograms against the number of correlated block moulds, found in the side walls of the tunnels. The predicted critical-key-blocks are indeed frequently represented, and blocks with very low or nil P(B) values are typically missing in the block mould sample population. The fit however is not perfect, see for example JC(28) and JC(8) in Figures 3 and 4 respectively.

A better insight can be gained by probing into the correlation between each P(B) parameter and observed block moulds. Figure 5 shows the relationship between percent block moulds (of total number found in each tunnel) and the corresponding predicted P(JC) values. A linear regression model $y = ax + b$ shows a correlation coefficient of 0.87. In the realistic model where $y = ax$ the least squares estimate yields a somewhat lower correlation coefficient of 0.82. In both models a positive linear association is observed with good correlation between predicted joint combination probability and mapped joint combination events (block moulds).

The shape and instability parameter are not strict probabilities, and consequently the association is weaker (Figures 6,7). The shape parameter predictions seem erratic, and a non-linear association can be traced. Recall that the mathematical expression of the shape parameter has no theoretical basis; it is only used as a scaling parameter of block geometry. The results shown in Figure 6 indicate that this parameter, if required, must be modified.

The predictions of the instability parameter are more consistent and a positive linear association can be observed, though one outlier (at $F=0.45$) brings the

Table 2: Block mould data from Hanging Lake Tunnel (Free Face=90/330). $J_1=83/358; J_2=74/242; J_3=77/68; J_4=84/175; J_5=32/90; J_6=81/270; J_7=54/297; \lambda_1=1.18; \lambda_2=0.38; \lambda_3=0.25; \lambda_4=0.82; \lambda_5=0.43; \lambda_6=0.49; \lambda_7=0.81; \phi_i=35°$

BLOCK#	J1	J2	J3	CODE	JC{i;j;k}
1	52\300	84\20	65\128	001	14:{7;1;5}
2	58\295	80\220	40\12	0011	24:{7;2;5}
3	55\290	55\210	55\85	011	24:{7;2;5}
4	82\85	84\180	40\280	110	33:{5;4;7}
5	60\315	75\205	35\140	011	24:{7;2;5}
6	35\285	80\190	42\120	011	33:{7;4;5}
7	44\280	75\005	45\105	001	14:{7;1;5}
8	50\96	80\180	65\280	110	33:{5;4;7}
9	53\280	70\10	40\150	001	14:{7;1;5}
10	75\280	80\005	20\190	001	13:{6;1;5}
11	75\290	70\20	20\190	001	13:{6;1;5}
12	85\280	62\18	30\190	001	13:{6;1;5}
13	64\70	75\340	20\280	101	---------
14	50\290	85\20	42\80	001	14:{7;1;5}
15	60\260	88\3	25\80	001	13:{6;1;5}
16	80\270	89\5	17\85	001	13:{6;1;5}
17	60\305	82\10	25\100	001	14:{7;1;5}
18	68\255	83\15	40\120	001	13:{6;1;5}
19	65\265	80\20	24\80	001	13:{6;1;5}
20	78\270	89\40	26\140	001	13:{6;1;5}
21	48\335	88\50	5\160	001	30:{7;3;5}
22	78\290	80\200	40\90	011	33:{7;4;5}
23	70\230	82\177	25\95	011	20:{2;4;5}
24	20\120	65\220	60\315	110	24:{5;2;7}
25	65\250	70\345	20\110	001	3:{2;1;5}
26	80\280	60\350	30\60	001	13:{6;1;5}
27	80\300	80\15	30\60	001	14:{7;1;5}
28	80\300	80\15	30\60	001	14:{7;1;5}
29	65\250	70\15	30\60	001	3:{2;1;5}
30	35\290	85\25	35\95	001	14:{7;1;5}
31	87\310	75\350	25\90	001	14:{7;1;5}
32	75\295	60\18	28\115	001	14:{7;1;5}
33	85\280	65\30	28\115	001	13:{6;1;5}
34	75\260	75\5	28\115	001	13:{6;1;5}
35	88\305	70\35	28\115	001	14:{7;1;5}
36	75\255	70\15	15\125	001	3:{2;1;5}
37	10\120	86\360	45\280	100	14:{5;1;7}
38	35\300	60\160	35\110	011	33:{7;4;5}
39	88\280	70\175	25\280	010	---------
40	88\275	70\10	35\180	001	13:{6;1;5}
41	75\270	80\5	35\130	001	13:{6;1;5}
42	55\290	65\5	40\60	001	14:{7;1;5}
43	42\280	81\345	32\90	001	14:{7;1;5}
44	70\280	85\5	18\150	001	13:{6;1;5}
45	65\230	82\353	30\130	001	3:{2;1;5}
46	55\340	70\270	34\125	001	13:{6;1;5}
47	65\340	80\230	25\120	001	3:{1;2;5}

correlation coefficient down almost to zero. Note however that all moulds represent blocks of a theoretical F value greater then 0.4, where 0.5 is limit equilibrium (Table 1). Block moulds corresponding to removable blocks with theoretical F values smaller then 0.5 can be explained by the influence of blasting vibration on the active resultant. Blasting has not been added to the mechanical calculations. The majority of moulds however correspond to removable blocks having theoretical F value greater then 0.5, namely unsafe blocks which are supposed to slide out of the rock

Table 3: Block mould data from Cumberland Gap Tunnel. (Free Face=90/213). $J_1=38/298; J_2=48/75; J_3=86/94; J_4=83/004; J_5=69/181$ $\lambda_1=1.67; \lambda_2=0.57; \lambda_3=0.37; \lambda_4=0.28; \lambda_5=0.67; \phi_i=30°$

Block#	J1	J2	J3	CODE	JC{i;j;k}
1	37/305	80/280	51/175	100	5:{1;3;5}
2	44/328	82/265	51/175	100	5:{1;3;5}
3	41/345	82/270	62/198	100	5:{1;3;5}
4	43/338	84/262	57/175	100	5:{1;3;5}
5	63/195	50/100	33/290	010	3:{5;2;1}
6	26/345	87/285	81/162	100	5:{1;3;5}
7	89/138	35/60	42/235	010	3:{5;2;1}
8	86/340	64/86	40/267	011	2:{4;2;1}
9	35/312	39/80	53/205	110	-----------
10	52/334	38/50	55/215	110	-----------
11	65/350	60/65	40/180	110	10:{4;3;5}
12	34/352	87/120	karstic enlargement of		
13	45/320	25/138	boundary joints (k=2)		
14	67/165	85/257	30/322	100	5:{5;3;1}
15	74/185	63/87	36/305	010	3:{5;2;1}
16	73/170	64/75	42/290	010	3:{5;2;1}
17	42/360	78/94	55/210	110	5:{1;3;5}
18	70/5	89/260	40/195	110	10:{4;3;5}
19	78/172	41/90	43/285	010	3:{5;2;1}
20	89/20	40/85	40/290	011	2:{4;2;1}
21	85/5	40/85	42/290	011	2:{4;2;1}
22	88/5	62/82	32/295	011	2:{4;2;1}
23	70/165	60/60	43/282	010	3:{5;2;1}
24	78/170	62/75	28/280	010	3:{5;2;1}
25	65/5	70/80	35/220	110	10:{4;3;5}
26	69/5	70/95	50/220	110	10:{4;3;5}
27	84/190	75/110	36/285	010	3:{5;2;1}
28-33	81/190	47/110	47/310	010	3:{5;2;1}
34	66/170	49/90	45/290	010	3:{5;2;1}
35-36	80/7	59/53	35/255	011	2:{4;2;1}
37-38	88/27	59/105	45/300	011	2:{4;2;1}
39-44	73/195	58/72	37/297	010	3:{5;2;1}
45	80/177	45/105	38/308	010	3:{5;2;1}
46-47	84/178	43/85	35/300	010	3:{5;2;1}
48-49	73/185	77/90	36/280	010	3:{5;2;1}
50-53	54/175	53/62	45/300	010	3:{5;2;1}
54	76/190	65/45	45/290	010	3:{5;2;1}
55-57	66/175	58/80	49/312	010	3:{5;2;1}
58	70/180	60/55	34/285	010	3:{5;2;1}
59-60	71/177	52/94	40/295	010	3:{5;2;1}
61-62	80/200	45/95	52/290	010	3:{5;2;1}
63	52/150	42/275	57/5	010	3:{5;2;1}
64	57/155	45/55	34/275	010	3:{5;2;1}
65	54/185	54/285	35/25	010	3:{5;2;1}
66	40/112	43/300	78/30	001	-----------
67	74/178	72/82	43/300	100	-----------
68-70	55/178	48/295	60/38	010	3:{5;1;2}
71	62/180	85/260	48/300	100	5:{5;3;1}
72-73	42/190	46/98	40/325	110	-----------
74	87/350	78/95	37/320	011	4:{4;3;1}
75	70/172	59/320	34/100	010	3:{5;1;2}
76	88/163	70/270	27/278	100	5:{5;3;1
77	52/330	66/45	38/205	110	-----------
78	85/5	38/58	38/305	011	2:{4;2;1}
79-80	80/165	42/82	34/245	010	3:{5;2;1}
81	35/320	80/115	65/212	110	5:{1;3;5}
82	85/360	45/80	40/295	011	2:{4;2;1}
83	76/200	74/95	30/290	110	5:{5;3;1}

84	83/205	63/102	27/285	010	3:{5;2;1}
85	60/200	40/65	28/303	010	3:{5;2;1}
86	58/175	52/290	55/35	010	3:{5;1;2}
87	88/220	37/130	55/300	011	------------
88	65/150	43/43	43/300	010	3:{5;2;1}
89	57/130	75/35	32/290	010	------------
90-92	72/190	57/60	45/280	010	3:{5;2;1}
93-94	57/130	80/52	27/302	110	5:{5;3;1}
95	44/120	52/100	40/270	011	------------
96-97	75/2	45/95	34/295	011	2:{4;2;1}
98	88/28	67/102	36/302	011	2:{4;2;1}
99-100	78/5	70/80	32/275	011	4:{4;3;1}
101	61/192	85/100	32/275	011	------------
102	53/170	80/100	32/275	011	------------
103-105	78/190	80/282	22/295	100	5:{5;-3;1}
106-110	58/178	88/275	34/305	100	5:{5;-3;1}

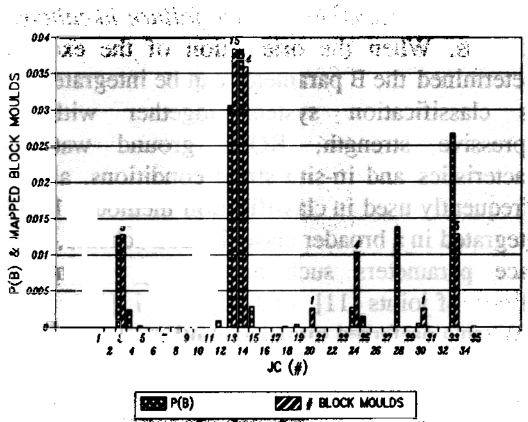

Figure 3: Comparison between the predicted block failure likelihood (P(B)) histogram computed for the rock mass of *Hanging Lake Tunnel, Colorado*, and correlated block moulds (Table 2).

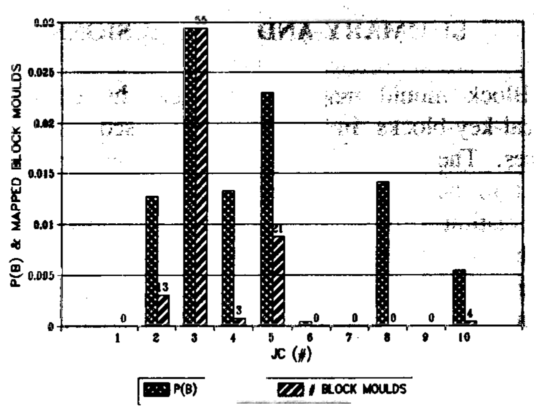

Figure 4: Comparison between the predicted P(B) histogram computed for the rock mass of *Cumberland Gap Tunnel, Kentucky-Tennessee*, and correlated block moulds (Table 3).

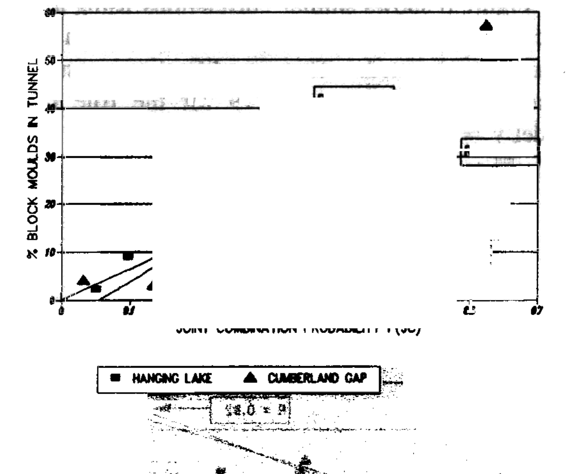

Figure 5: Correl
probability P(JC)
tunnels, using a li
squares estimates

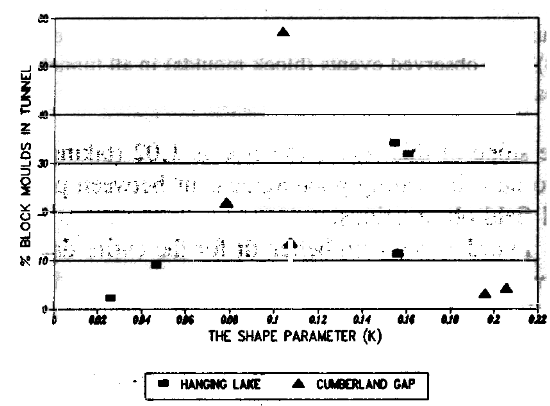

Figure 6: Calculated shape parameter (K) vs. observed events (mapped block moulds).

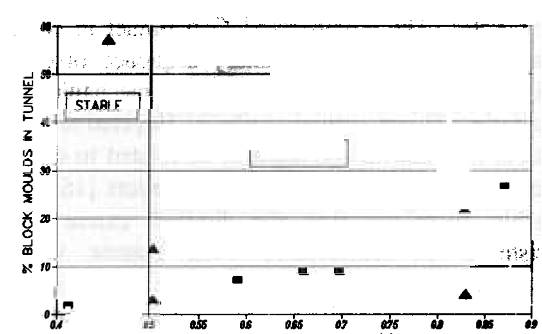

Figure 7: Calculated instability parameter (F) vs. observed events (mapped block moulds).

when exposed by the free face.

Figure 8 shows similar correlations using a modified block failure likelihood equation (P(B)') with the shape parameter omitted. This modification results in a correlation coefficient of 0.79 for the true regression model $y = ax$.

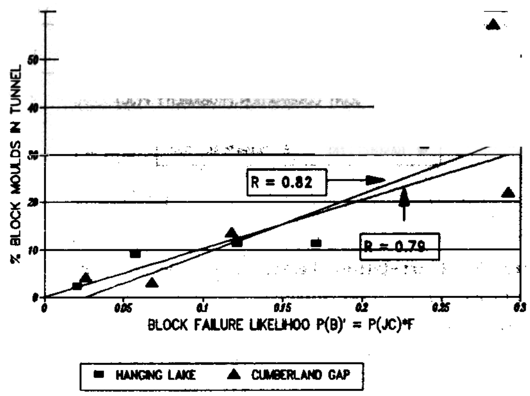

Figure 8: Correlation between modified block failure likelihood P(B)' and observed events (block moulds) in all tunnels, using a linear regression model and least squares estimates.

The slope of this regression line is 1.02 (taking P(B)' in percents), indicating good agreement between predictions and field observations.

In order to obtain better fit for the entire data set (all tunnels) the shape parameter had to be omitted from the block failure likelihood expression. An inspection of Figure 6 reveals that predictions of the shape parameter are better in Hanging Lake tunnel (filled squares), where a positive association between K values and observed block failures can be traced. This is not so in Cumberland Gap (filled triangles), where a *negative* association between the two variables is seen. This result could be related to the different lithologies in the two sites. The Hanging Lake tunnel is excavated through a crystalline rock mass, where the basic block theory assumption of infinite joint planes seems valid. The Cumberland Gap tunnel in contrast is excavated through a sedimentary sequence of carbonate rocks where joints end towards mechanical layer boundaries. This structural attribute of layered sedimentary rocks is well known and seem to be related to differences in mechanical properties of adjacent layers [16, 17]. It is possible therefore that the limited extent of joint persistence in sedimentary rock masses violates a fundamental block theory assumption. As a result, the shape parameter hypothesis regarding closed and open JPs looses its validity because joints never extend far enough to produce maximum key blocks, and the block apex is never at the maximum distance calculated by block theory where infinite joint planes are assumed.

Since the mathematical expression of the shape parameter has no theoretical foundations, and since P(B)' predictions with K omitted do materialize in the field (Figure 8), it seems that the need to incorporate the shape parameter in its present form in P(B) is not justified. Further field work and analysis of block mould statistics in different lithologies could help clarify the relationship between key block shapes and mechanical properties of different rock masses.

P(B) AS A ROCK MASS CLASSIFICATION PARAMETER

The overall tendency of a given rock mass to produce block failures from behind a free face of known attitude can be found using the area of the P(B) histogram:

$$B = \sum_{i=1}^{i=N_{rb}} P(B)_i = \sum_{i=1}^{i=N_{rb}} P(JC)_i \cdot F_i \tag{6}$$

where B is the *cumulative block failure likelihood* of the rock mass. When the orientation of the excavation is predetermined the B parameter can be integrated in a rock mass classification system together with uniaxial compressive strength, RQD, ground water inflow characteristics and in-situ stress conditions, all of which are frequently used in classification methods [10,11]. If B is integrated in a broader classification scheme, then it can replace parameters such as spacing, orientation and condition of joints [11], or J_n, J_r, and J_a [10].

When a preferred tunnel azimuth must be selected, the B parameter can be repeatedly computed for each azimuth interval since P(B) is free face dependent. Thus a spectrum of B values for all tunnel attitudes can be generated in order to select the safest direction. This option does not exist when using conventional classification methods. Theoretical tunnel support spectrums have been computed by Goodman and Shi [15] using support force only and by Mauldon [5] using a combination of the joint intersection probability and support force. Quantitative validation of this new approach however has not been pursued as yet.

SUMMARY AND CONCLUSIONS

Block mould mapping revealed the existence of critical-key-blocks in two different discontinuous rock masses. The failure likelihood of removable blocks is found to be a function of two parameters, the joint combination probability and the removable block instability. It has been found that incorporation of a "shape parameter" in the block failure likelihood expression does not improve predictions. The area of the failure likelihood histogram for all theoretically removable blocks can be used to estimate the tendency of the rock mass to generate block failures, when the free face is fixed. This parameter can be integrated in empirical rock mass classification systems to evaluate the overall rating or quality of the rock mass for engineering purposes.

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