CHEMICAL ENGINEERING TRANSACTIONS
VOL. 62, 2017
A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Fei Song, Haibo Wang, Fang He

ISBN 978-88-95608- 60-0; **ISSN** 2283-9216
DOI: 10.3303/CET1762079

Blastability Classification of Fractured Rock Mass Based on Weighted Clustering Analysis

Tiejun Tao[a], Ping Huang[b*], Jianmin Zhou[a], Hongbing Yu[a], Jie Li[a]

[a]Guizhou Xinlian Blasting Enginneering Group CO., Ltd, Guiyang 550002, China
[b]College of Environment and Resources, Fuzhou University, Fuzhou 350116, China
pinghuang@fzu.edu.cn

This paper classifies the blastability of fractured rock mass based on the solid coefficient, rock impedance, unit explosive consumption and mean fracture spacing. Specifically, an evaluation model was established according to the principle of clustering analysis, and applied to classify the rock mass blastability of an actual project. According to the field acoustic test, the average longitudinal wave velocity of the layered rock mass is 2,667m/s, and that of the intact rock mass is 3,346m/s. Through the evaluation of blastability, it is concluded that the layered rock mass has a high blastability while the intact rock mass has a medium blastability. The findings lay an important theoretical basis for blasting parameters optimization and field blasting test.

1. Introduction

In blasting engineering, the accurate and quantitative description of rock mass blastability is fundamental to the rational design of blasting parameters. However, there is not yet a unified method for blastability assessment, owing to the complexity of blasting. The existing evaluation approaches adopt different computing methods and a variety of indices (Fan et al., 2007; Xue et al., 2010).

Thanks to the abundance of engineering practices, much research has been done on the classification of rock blastability at home and abroad. For example, the rock mass blastability can be classified based on solid coefficient, fissure parameters, acoustic impedance, unit explosive consumption, etc (Zhang, 1998; Bond, 1960). The American Rock Mechanics Association suggested that rock blastability should be determined by the rock explosive method (Ge, 1995). The Japanese Society for Rock Mechanics (Feng, 1994; Qu, 2009) recommended the classification based on elastic wave velocity, considering fracture spacing, cracking coefficient, shear strength and other factors. In light of the engineering practice in China, Ge Shugao (1995) improved the hartz classification method with the addition of mean fracture spacing, acoustic impedance, uniaxial compressive strength and bulk density. Inspired by artificial network network, Feng Xiating (1994) established the nonlinear relationship between the blasting index and the funnel volume, mass rate, mean pass rate, reject rate and wave impedance. Qu Shijie et al. (2009) analysed the blasting properties of rock mass by weighted clustering, and considered the static tensile/compressive strength, integrity and density of the rock mass as the key to the blasting of hard rock mass. With the aid of fuzzy mathematics, Liu (2008) graded the blastability of the rock mass in Wusteel Chengchao Mine.

Facing the numerous influencing factors, scholars have developed a plurality of grading methods and thresholds for rock mass blastability (Ren et al., 2014). The blastability grades are usually determined by the field measured index value and the specified threshold value (Azimi et al., 2010; Latham and Lu, 1999). Of course, the samples must be diversified to ensure the representativeness of the results. Based on clustering analysis, this paper attempts to classify the blastability of fractured rock mass by the solid coefficient, rock impedance, unit explosive consumption and mean fracture spacing. Specifically, an evaluation model was established according to the principle of clustering analysis, and applied to classify the rock mass blastability of an actual project. The research lays the theoretical basis for blasting parameters optimization and field blasting operations.

Please cite this article as: Tiejun Tao, Ping Huang, Jianmin Zhou, Hongbing Yu, Jie Li, 2017, Blastability classification of fractured rock mass based on weighted clustering analysis, Chemical Engineering Transactions, 62, 469-474 DOI:10.3303/CET1762079

2. Blastability Analysis Model for Fractured Rock Mass

2.1 Index selection

The blastability of rock mass is affected by various factors. It is impossible to make a comprehensive analysis of the blastability based on a single factor. The indices must be easy to obtain by experiment or field test, and reflect different aspects of the rock mass.

(1) Solid coefficient

Blasting is closely related to the strength of the rock mass, which is determined by the uniaxial compressive strength. There is a certain correlation between compressive strength, tensile strength and shear strength of the rock mass. To a certain extent, the correlation can be expressed by the solid coefficient.

(2) Rock impedance

The acoustic velocity is a good indicator of the geological structure of the rock mass. The rock mass usually contains various structures. The elastic wave is scattered by the structural closures and openings, shear deformation and surface filling, resulting in the loss of wave energy, reduction in wave amplitude and decline in wave velocity. The wave velocity also varies with the surface structure and development of the rock. When the rock mass is broken, the elastic wave slows down; when the rock mass is large or the filling material is soft, the elastic wave also decelerates, leading to the decline in blasting frequency.

(3) Unit explosive consumption

With the same test conditions and explosives, the explosive consumption per cubic meter of rock mass demonstrates its blastability. The consumption is positively proportional to the difficulty in rock blasting.

(4) Mean fracture spacing

From the macroscopic perspective, the fracture development directly bears on the blastability of the rock mass. The number of cracks is negatively correlated with the fracture spacing and the difficulty in rock blasting.

The classification indices of rock mass blastability are listed in Table 1.

Table 1: Classification indices of rock mass blastability

Typical categories	Platts' coefficient (f)	Rock impedance ($\times 10^6$) K kg/m^3·m/s	Unit explosive consumption q/kg·m^{-3}	Mean interval of rock mass fracture d/m	Classification level
Ⅰ	≤8	≤5	≤0.35	≤0.1	explosive
Ⅱ	10 or so	6.5 or so	0.4 or so	0.3 or so	medium explosive
Ⅲ	14 or so	10 or so	0.55 or so	0.75 or so	hard to explode
Ⅳ	17 or so	13.5 or so	0.78 or so	1.25 or so	difficult to explode
Ⅴ	≥18	≥15	≥0.9	≥1.5	extremely difficult to explode

2.2 Clustering analysis

The clustering analysis classifies samples based on the degree of similarity between things. Here, the basic idea of Q clustering is adopted to classify rock mass blastability. The principle of Q clustering analysis is introduced below (Gao, 2014):

Suppose there are several samples, each of which has m indices, then the sample matrix is:

$$X = \begin{vmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m1} & \cdots & x_{mn} \end{vmatrix}$$

Since the indices are of different dimensions and magnitudes, the raw data should be normalized into dimensionless data in the range of (0, 1). The processed data are given in the formula below:

$$x'_{ij} = \frac{x_{ij} - x_{i\min}}{x_{i\max} - x_{i\min}} \qquad i = 1,2,\cdots,m; \quad j = 1,2,\cdots,n \tag{1}$$

Where x_{min} and x_{max} are the minimum and maximum values of the first *i* indices, respectively.

The relationship of the samples can be measured by the distance coefficient D_{ij}:

$$D_{ij} = \left[\left(x'_{1i} - x'_{1j}\right)^2 + \left(x'_{2i} - x'_{2j}\right)^2 + \cdots + \left(x'_{mi} - x'_{mj}\right)^2\right]^{1/2} \quad 1 \le i, j \le n \tag{2}$$

The value D_{ij} is negatively correlated to the similarity between samples *i* and *j*.

2.3 Weighted clustering analysis

According to the Q clustering principle, all the indices are treated with equal importance. However, the four indices of the rock mass obviously have different impacts on rock mass classification. Hence, the spacing coefficient D_{ij} should be adjusted as follows.

Let $a_i (i = 1,2,3,4; \sum_{i=1}^{4} a_i = 1)$ be the weight of four indices. The distance coefficient D_{ij} can be rewritten as:

$$D_{ij} = \left\{\left[a_1\left(x'_{1i} - x'_{1j}\right)^2\right] + \left[a_2\left(x'_{2i} - x'_{2j}\right)^2\right] + \cdots + \left[a_4\left(x'_{4i} - x'_{4j}\right)^2\right]\right\}^{1/2} \tag{3}$$

Where $i=1,2,3,4,5$; *j* is the sample to be classified.

Based on the experience of blasting engineering and analysis of blasting mechanism, the distribution and features of structure plane and cohesion between rock particles weigh heavily in the classification of rock mass. Therefore, it is necessary to find the average weights of solid coefficient, rock impedance, unit explosive consumption and mean fracture spacing: $a_1=0.3$, $a_2=0.15$, $a_3=0.2$, $a_4=0.35$.

After normalization, five typical examples of grading standards can be obtained, and the matrix is as follows:

For any instance, as long as the target value $X_i=[x_1\ x_2\ x_3\ x_4]^T$ is known, its category can be determined by the corresponding distance factor $D_{ij}(i=1,2,3,4,5)$ of the standard sample. The minimum D_{ij} means that the sample belongs to the i-th category.

3. Index Acquisition

3.1 Field acoustic test

(1) Test devices

The field test was performed on a RS-ST01D cross-hole acoustic detector (Wuhan Yanhai Engineering Technology Co., Ltd.). In addition to real-time display of the measured waveform, the RS-ST01D ultrasonic system can automatically interpret the acoustic parameters in the continuous data acquisition process, determine the direction, speed and distance of transducer movement based on the depth of the pulley, and generate an intuitive depth in light of these parameters. Moreover, the waveforms and acoustic parameters are automatically stored for each pre-set distance.

(2) Field rock conditions and hole distribution

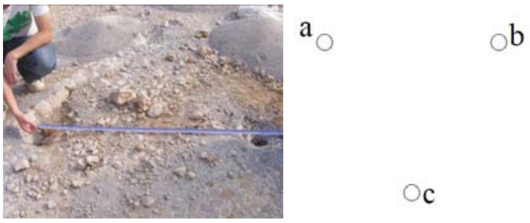
The test site is mainly covered by dense and hard limestones with undeveloped fractures. The area has a good stability. The rock mass takes up about 1/9 of the entire mountain, and the bedrock is dominated by hard rock. Two typical venues were selected for the field test, aiming to obtain the accurate acoustic signal of the site. In one venue, the rock is layered and has developed joints; in the other venue, the rock is relatively intact.

Layered rock mass:

The layered rock mass is moderately weathered and has well-developed joints. The tile angle is about 60°~70°. The average thickness of the layers stands at 20cm. A few joint layers are covered with mud (Figure 1). Several triangular test holes were drilled on the rock (Figure 2) at a spacing of 1m. The line connecting Hole A and Hole B (Line A-B) is parallel to the rock formation, while the line connecting Hole A and Hole C (Line A-C) and the line connecting Hole B and Hole C (Line B-C) intersect with the strike of the rock at an angle of 60°.

(a) (b)

Figure 1: Geological conditions of layered rock mass



(a) Fabric holes diagram (b) Site 1 holes hint

Figure 2: Test holes in layered rock mass

Intact rock mass:

The relatively intact rock mass has a good integrity and undeveloped joints. According to the geological conditions in Figure 3, there are mud layers in this rock mass. The test holes are square and arranged at a spacing of 1m (Figure 4).

(a) (b)

Figure 3: Geological conditions of intact rock mass

(a) field test (b) Site 2 holes hint diagram

Figure 4: Test holes in intact rock mass

Field test:

In the test, a 90mm-diameter, 5m-deep hole was taken as the coupling agent. The transmitting and receiving probes were placed at the two ends of the hole, respectively, and the emission was adjusted to the same level. The acoustic wave velocity was slowly raised by the depth counting pulley. The test diagram is shown in Figure 5. During the test, the probes were slowly lifted for emission and reception, and kept at the same level. The sampling interval was set to 20cm.

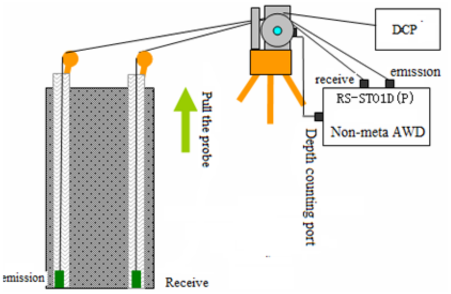
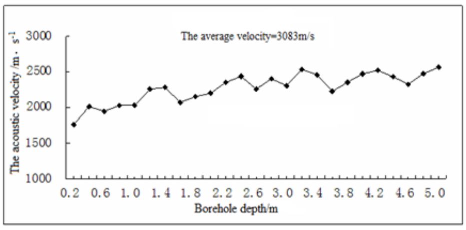


Figure 5: schematic diagram of field test Note: Non-meta AWD is short for non-metal acoustic wave detector

(3) Test Results

Layered rock mass:

The Line A-B, Line B-C and Line A-C were tested. As mentioned before, Line A-B is parallel to the rock formation, while Line B-C and Line A-C intersect with the strike of the rock at an angle of 60°. The test results are illustrated in Figures 6, 7 and 8, respectively.



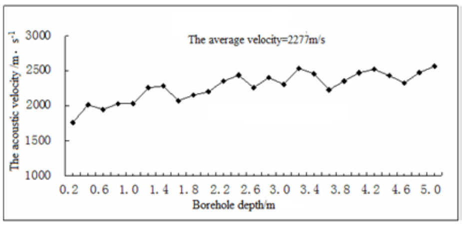


Figure 6: Acoustic velocity curve of Line A-B Figure 7: Acoustic velocity curve of Line B-C

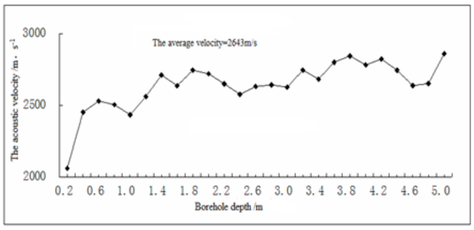


Figure 8: Acoustic velocity curve of Line A-C

From the above test results, it can be seen that the longitudinal wave velocity fell between 2,277m/s and 3,083m/s. Specifically, Line A-B boasts the fastest velocity, followed in descending order by Line A-C and Line B-C. The overall wave velocity is small, which signifies relatively developed rock fracture and the quick attenuation of acoustic wave.

Intact rock mass:

The Line A-B, Line B-C, Line C-D and Line A-D were tested. The test results are given in Figures 9, 10, 11 and 12, respectively.

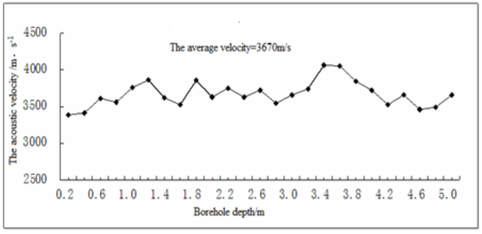


Figure 9: Acoustic velocity curve of Line A-B

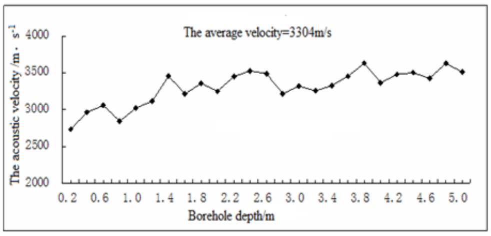


Figure 10: Acoustic velocity curve of Line B-C

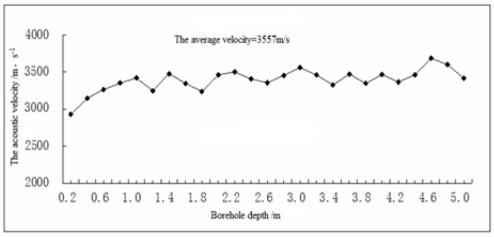


Figure 11: Acoustic velocity curve of Line C-D

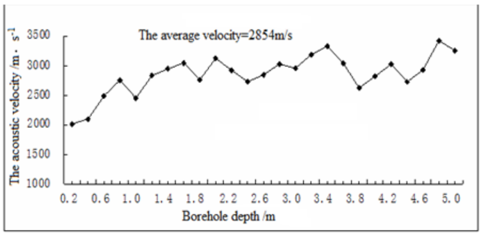


Figure 12: Acoustic velocity curve of Line A-D

As shown in the above figures, the longitudinal wave velocity fell between 3,075m/s and 3,868m/s. The average velocity peaked on Line A-B and Line C-D. The relatively homogenous amplitude testifies the intactness of the rock mass.

(4) Rock impedance

The longitudinal wave velocity averaged at $V_{p1} = \frac{3083+2643+2277}{3} = 2667m/s$. Similarly, the average P-wave velocity is 3,346m/s.

Through the calculation of rock impedance, the author obtained the mechanical parameters of the intact rock mass. The test results show that the limestone density is 2,650kg/m^3. According to the impedance formula *z=ρ×c,* the wave impedance of layered rock mass is 7.06×106kg/m^3·m/s, and that of the intact rock mass is 8.87×106kg/m^3·m/s.

3.2 Other indices

Based on the experience of multiple blasting, the unit explosive consumption q=0.28kg/m^3; if the rock is relatively intact, q=0.43kg/m^3. According to the field test, the average fracture spacing d is 0.2m and 0.7m for the layered and intact rock masses, respectively. The solid coefficient f of limestone is 8.

4. Classification of Rock Mass Blastability

From the test results, the four indices of layered rock mass are: $f=8$, $K=7.06\times10^6 \mathrm{kg/m^3 \cdot m/s}$, $q=0.28\mathrm{kg/m^3}$ and $d=0.2\mathrm{m}$. Besides, the normalized index matrix of the standard samples is X_j=[0 0.206 0 0.071] (no processing is required if the unit explosive consumption is lower than the lower limit of 0.35kg/m^3). Through the calculation of weighted distance coefficient, the distance coefficient matrix was obtained as: *D_{ij}=[0.040 0.068 0.241 0.419 0.500].*

It can be seen that the layered rock mass has a high blastability. Similarly, the four indices of the intact rock mass are: f=8, K=8.87×106kg/m^3·m/s, q=0.43kg/m^3 and d=0.7m. Besides, the normalized index matrix of the standard samples is X_j=[0 0.387 0.145 0.429] (no processing is required if the unit explosive consumption is lower than the lower limit of 0.35kg/m^3). Through the calculation of weighted distance coefficient, the distance coefficient matrix was obtained as: *D_{ij}=[0.164 0.123 0.186 0.336 0.409].*

Hence, the intact rock mass has a medium blastability.

5. Conclusion

This paper classifies the blastability of fractured rock mass based on the solid coefficient, rock impedance, unit explosive consumption and mean fracture spacing. Specifically, an evaluation model was established according to the principle of clustering analysis, and applied to classify the rock mass blastability of an actual project through an acoustic wave test. The main conclusions are as follows:

(1) The average longitudinal wave velocity was 2,667m/s and 3,346m/s for the layered rock mass and the intact rock mass, respectively. The velocity difference shows that the existence of fracture has intensified wave attenuation and velocity decline.

(2) There is anisotropy in the propagation of acoustic waves in the rock mass. The wave moves faster parallel to the structural plane than along the plane, and the wave vertical to the plane propagate at the slowest speed.

(3) Through the evaluation of blastability, it is concluded that the layered rock mass has a high blastability while the intact rock mass has a medium blastability.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (51604082) and Guizhou Province Science and Technology Project (Guizhou scientific cooperation platform personnel [2017]5643).

Reference

Azimi Y., Osanloo M., Aakbarpour-Shirazi M., Bazzazi A.A., 2010, Prediction of the blastability designation of rock masses using fuzzy sets, International Journal of Rock Mechanics & Mining Sciences, 47(7), 1126-1140, DOI: 10.1016/j.ijrmms.2010.06.016

Bond F.C., 1960, Three Principles of Comminution, Engineering geology, 12, 205-223.

Fan L.H., Qu S., Shang L., 2007, Rock Mass Blastability Classification with Fuzzy Diagnosis, Express Information of Mining Industry, 2, 15-17.

Fang K.T., 1982, Cluster Analysis, Beijing: geological publishing.

Feng X.T., 1994, A study on neural network on rock blastability, explosion and shook waves, 14(4): 5-13.

Gao C., 2014, Rock-mass Blastability Classification of Baluba Copper Mine Based on Weighted Clustering Analysis, Copper Engineering, 2, 28-31.

Ge S.G., 1995, Estimation of rock Blastibility and Determination of Adaptive explosive Consumption, Nonferrous Metals, 47(2), 10-15.

Latham J.P., Lu P., 1999, Development of an assessment system for the blastability of rock masses, International Journal of Rock Mechanics & Mining Sciences, 36(1), 41-55.

Li S., Zhang Y., Zhu H., 2015, Blasting classification of rock mass based on clustering analysis of comprehensive weight, Engineering Blasting, 21(3), 18-22.

Li T., Li k., Ding X., 2011, Study of Rock Blastability Evaluation and an Example of Engineering Application, Mining Research and Development, 31(4), 107-109.

Liu W.J., 2008, Blasting Fuzzy Evaluation of Stope Blasting with Sublevel Caving in Chengchao-Iron Mine, BLASTING, 25(4), 32-35.

Qu S., Mao S., Lv W., Xin M., 2006, A method for rock-mass blastability classifcation based on weighted clustering analysis, Journal of University of Science & Technology Beijing, 28(4), 324-329.

Qu S.J., 2009, Rock Mass Blastability Classification and its Application in Shuichang Open Pit Mine, Metal Mine, 11, 25-28.

Ren Z., Xiao S., Li K., Ding X., 2014, Classification of rock mass blastability based on set pair analysis, Electronic Journal of Geotechnical Engineering, 19, 9697-9710.

Xue J.G., Zhou J., Shi X.Z., 2010, Assessment of classification for rock mass blastability based on entropy coefficient of attribute recognition model, Journal of Central South University (Science and Technology), 1, 251-256.

Zhang Q., 1998, Advance in study on rock blastability classification, engineering blasting, 4(3), 75-80.