Analysis of Controlling Parameters for Shear behavior of Rock Joints with FLAC3D

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***Abstract*—The research aims at performing analysis to determine the sensitivity of parameters affecting the strength of joints in rock mass. Friction angle, normal stiffness, shear stiffness and shear displacement are the parameters analyzed with respect to shear strength of rock joints. Discontinuities have an important influence on the deformational behavior of rock systems; hence, proper consideration of the physical and mechanical properties of discontinuities is necessary during experimental investigation in order to correctly evaluate the shear behavior. These parameters are utilized to simulate the in-situ stress condition in numerical modeling, which is important for safe and economical design of various engineering constructions. These parameters can be obtained through laboratory testing on natural rock core samples. In the present work, the detailed account of test results of direct shear tests performed on rock joints is presented. Rock samples, containing joint are obtained by core drilling in an underground mine, in Nevada, and are used to perform direct shear strength test. Calibration of numerical model is done on average values obtained from direct shear strength test. Analysis of sensitivity of parameters effecting shear strength of rock is done in FLAC3D shear test environment. A numerical parametric study is done, according to the Mohr-Coulomb constitutive model, and results obtained are plotted to estimate performance of rock joints.**

***Index Terms*—FLAC3D, numerical modeling, rock joints, shear strength**

I. INTRODUCTION

Rock joint shear strength is one of the key properties used in the stability analysis and design of engineering structures in rock mass, e.g. slopes, tunnels and foundations [1]. Joints are the main features encountered in rock and are defined as ruptures of geological origin along which no relative displacement is visible [2]. Since sliding of rock blocks on joints is classified as the principal source of instability in underground excavations, the parameter which has drawn attention for its major importance in this context is the peak shear strength of joints [3]. Various factors affect shear behavior of in-situ rock joints and these factors are utilized to simulate the *in situ* stress condition in numerical modeling, which is important for safe and economical design of various engineering constructions. These concerns require accurate quantification of shear strength of unfilled and in filled joints, proper understanding of the basic mechanics of discontinuity and the principals involved in their shear deformation [4]. Therefore, the choice of an appropriate shear-strength criterion for rock joints, that can be used to engineer structures in rock, depends on a sound understanding of the basic mechanics of shear failure. This requires an understanding of the factors that influence the shear- strength characteristics of a rock mass. In the present paper the detailed account of test results of direct shear tests performed on rock joints is presented. These jointed rock samples are obtained by core drilling in an underground gold mine in Nevada and are used to perform direct shear strength test. Results obtained from tests are used to develop a numerical model and analyze the effect of various parameters on shear strength of rock joints.

Mohr-Coulomb's criterion is used to describe the shear strength of the joints. The rock samples containing joints are used to perform direct shear strength test. Series of direct shear testing are carried out on direct shear testing machine to determine the friction angles (φ), cohesion (c) and stiffness of rock fractures.

The shear box device was used to determine the initial peak and residual shear strength of a test material as a function of stresses normal to shear plane. It consists of setting a test specimen in an encapsulation compound within the shear box device with the joint plane positioned precisely between the upper and lower sample holders. The normal and shear deformations are monitored as normal and shear loads are applied [5].

II. RESEARCH OBJECTIVE

The objective of the study is to perform analysis to determine sensitivity of parameters affecting the strength of joints in rock mass. The study is focused on both direct shear strength laboratory testing method and Numerical Simulation using finite difference computer

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Manuscript received July 31, 2015; revised October 23, 2015.

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doi: 10.18178/ijscer.5.1.62-66

program, Fast Lagrangian Analysis of Continua (FLAC). It is the aim of this work to contribute to this understanding and to encourage readers to further explore the subject of joint shear strength.

III. LABORATORY TESTING

Fig. 1 shows a typical 'Direct Shear Test' apparatus suitable for direct shear testing. The test specimen is mounted inside of the shear box and grouted into the upper and lower halves of the box. The specimen is then subjected to normal and shear stresses. The normal load can be applied through a double acting actuator mounted in an external load frame. A normal load is applied to the material placed in the box through the top plate, and the shear load is applied from the left (or right) side of the upper half box. During a conventional direct shear test, the amount of applied normal stress is kept a constant value while the applied shear force, and normal and shear displacements are recorded for further analyses. Preparation of the samples for testing will follow the relevant ASTM standard D5607-08 as much as practical [6].

Figure 1. Direct shear test apparatus.

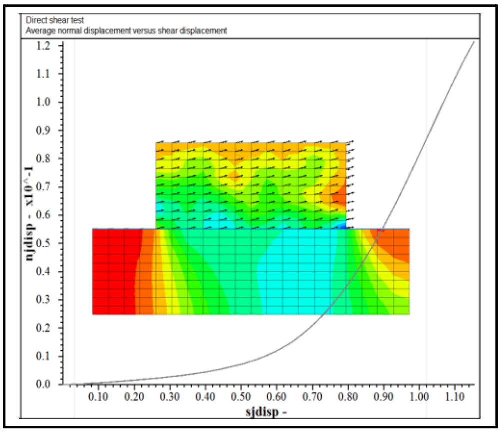

Figure 2. Direct shear test environment in FLAC3D.

In order to obtain the shear strength characteristics (cohesion and internal friction angle) of the rock samples, 12 direct shear tests are performed for identical samples under different normal loads and by plotting the best linear fit through at least three points (pairs of normal stress-peak shear stress) the Mohr-Coulomb failure envelope is obtained. Using this failure envelope, cohesion and friction angle are estimated. Table I shows the results obtained from Mohr-Coulomb failure envelope. Average value of the friction angle and cohesion is calculated and used to calibrate the numerical model developed with FLAC3D. Fig. 2 shows the modeling of shear test environment in FLAC3D. Normal force is acting in vertical direction and shear force is acting horizontally on upper block towards right hand side in the model. The variation of average normal displacement with shear displacement obtained in FLAC3D shear test environment is also shown in Fig. 2.

TABLE I. RESULTS OF DIRECT SHEAR TEST DERIVED FROM MOHR-COLUMN FAILURE ENVELOPE

Sample	Friction angle (°)	Cohesion (psi)
1	35	0
2	20	1.77
3	32	3.74
4	26	8.7
5	33.3	3.48
6	28	14.5
7	28.3	17.4
8	26	9.8
9	27	5.5
10	30	8.2
11	28	7.0
12	27	8.1

TABLE II. PARAMETERS OF ROCK SAMPLES USED IN FLAC 3D ANALYSIS

Parameter	Average value
Friction angle (degree)	28
Cohesion (psi)	7.25
Shear stiffness (lb-f/in)	6.84×10^4
Normal stiffness (lb-f/in)	8.55×10^4

IV. NUMERICAL ANALYSIS

The average values of the data obtained from laboratory experiments are shown in Table II These values are used to calibrate the developed model in FLAC3D using the results of shear test as shown in Fig. 3.

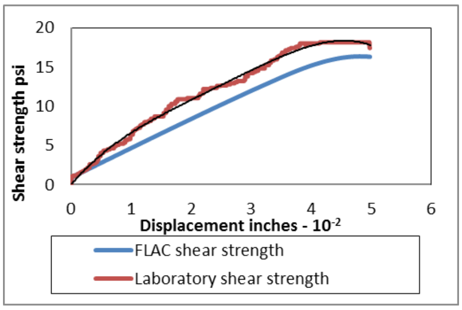

Figure 3. Calibration of FLAC analysis with the results of laboratory direct shear test.

Numerical model calibration is performed with the data obtained by the laboratory test. In the laboratory tests, shear load is applied on jointed core samples at different normal stresses. In the numerical simulations, Joint is modeled with using the interfaces element in FLAC3D, represented with triangular elements (interface elements), each of them are defined by three nodes (interface nodes) [7]. Generally, interface elements are attached to a zone surface face; two triangular interface elements are defined for every quadrilateral zone face [8].

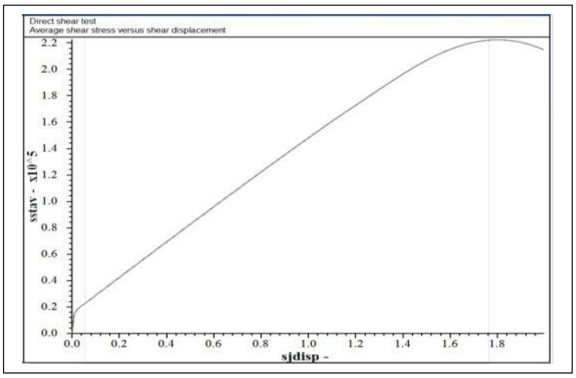

Figure 4. Average shear stress vs. shear displacement in FLAC3D environment.

Variation of the shear stress with the shear displacement, along the joint and the average normal displacement versus shear displacement is plotted as shown in Fig. 4. These plots indicate that joint slip occurs for the prescribed properties and conditions. The loading slope is initially linear, and then becomes non-linear as interface nodes begin to fail and reach a peak shear strength. The joint begins to dilate when the interface nodes begin to fail in shear as shown in Fig. 4. The curve includes two parts: the linear elastic stage and the perfectly plastic stage [9]

The average value of the data obtained from laboratory experiments is used to perform numerical modeling using FLAC3D. Parameter analysis is carried out on different mechanical properties based on these values.

V. RESULTS

Shear tests were simulated for different normal stress conditions in FLAC3D model. Behavior of parameters such as friction angle, normal and shear stiffness of joints is observed for various normal force loading values. Using the results of FLAC3D analysis, the variation of shear strength with various parameters for three different normal stresses are plotted (Fig. 5, Fig. 6 and Fig. 7). Normal stresses used to perform direct shear test in FLAC3D model are 15 psi, 36 psi, and 72 psi.

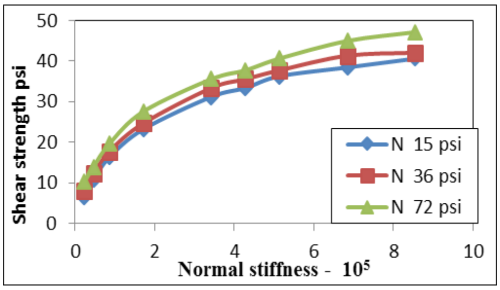

Figure 5. Plot of shear strength vs. normal stiffness

Also, normal stiffness values might be co-related to the filling material. The normal stiffness values for rock joints typically range from roughly 10^3 to 10^4 lb.-f/inch for joints with soft in-filling, to over 10^5 to 10^6 lb-f/inch for tight joints in rocks. Published data on stiffness properties for rock joints are limited; summaries of data can be found in reference literature [10]. Lower values used here resemble the soft filling material condition in rock joints while higher values reflect the hard joint condition. Table III represents correlation between normal stiffness and type of fill material in rock joints.

TABLE III. CO-RELATION BETWEEN NORMAL STIFFNESS AND FILL MATERIAL

S./no.	Normal stiffness (lb-f/inch)	Filling material (property)
1	1000	Very soft
2	100000	Medium soft
3	1000000	High joint condition

A. *Plot Between Shear Strength vs. Normal Stiffness*

In Fig. 5, shear strength is plotted against normal stiffness value for three normal stresses. Normal stress values are referred as N, and the plot in Fig. 5 shows the variation of shear strength with normal stiffness. It shows that at lower values of normal stiffness, shear strength of the model is very sensitive towards this parameter and shows rapid increase as normal stiffness increases.

Furthermore, increase in stiffness reduces the joint dilution, causing the normal stress increases due to the shear displacement.

From the plot obtained in Fig. 5, it can be concluded that the shear strength is sensitive when the filling material behavior changes from very soft, soft to hard nature. There is steep increase in shear strength at lower stiffness increment. Also, shear strength shows less variation when hard joint condition is observed. It shows very less sensitivity at higher values. Normal stiffness value is co-related with type of fill material in rock joints. Table IV shows co-relation between sensitivity of shear strength with the type of filling material.

B. *Plot Between Shear Displacements vs. Normal Stiffness*

In Fig. 6, shear displacement of joint at failure is plotted against normal stiffness. Normal stress values are referred as N. Plot shows that although shear strength is increased with the increment of normal stiffness, the displacement at failure is decreased.

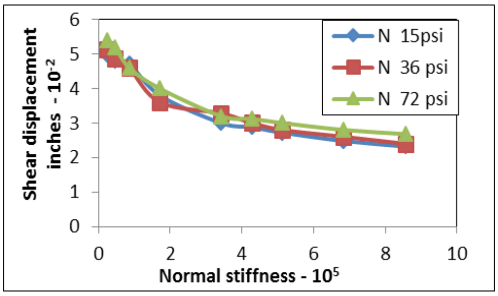

Figure 6. Plot of shear strength vs. friction angle.

Lower values used here resemble the soft filling material condition in rock joints while higher values reflect the hard joint condition. Fig. 6 shows that at lower values of normal stiffness, shear displacement of model is very sensitive towards this parameter and shows rapid decrease as normal stiffness increases. At higher stiffness shear strength shows brittle behavior and joint fails at very less shear displacement as compared to lower stiffness values. Table V shows the co-relation between sensitivity of shear displacement with the type of filling material.

C. Plot Between Shear Strength vs. Friction Angle

In Fig. 7, the influence of normal stress on the friction angle is plotted against shear strength of rock. Normal stress values are referred as N. Plot shows the sensitivity shear behavior of joints towards friction angle range. It shows almost linear behavior between shear strength and friction angle. Although at higher friction angle, strength shows more sensitive behavior towards friction angle as shown in Table VI.

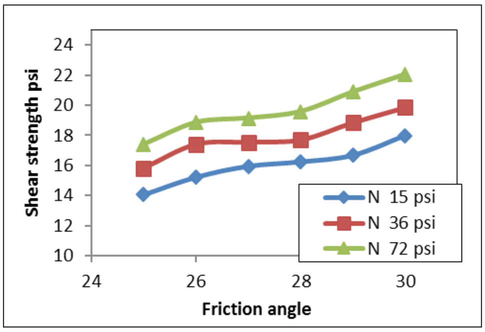

Figure 7. Plot of shear strength vs. friction angle

TABLE IV. SENSITIVITY OF SHEAR BEHAVIOR OF ROCK JOINTS WITH RESPECT TO FILLING MATERIAL

S/no.	Filling material	Sensitivity of shear strength	Shear behavior
1	Very soft	Highly sensitive	Sharp increase
2	Medium soft	Linear relationship	Linear increase
3	Hard joint condition	Very less effect	Constant

TABLE V. SENSITIVITY OF SHEAR DISPLACEMENT OF ROCK JOINTS WITH RESPECT TO FILLING MATERIAL

S/no.	Filling material	Sensitivity of shear strength	Shear displacement
1	Very soft	Highly sensitive	Sharp decrease
2	Medium soft	Linear relationship	Linear decrease
3	Hard joint condition	Very less effect	Constant

TABLE VI. SENSITIVITY OF SHEAR BEHAVIOR OF ROCK JOINTS WITH RESPECT TO FRICTION ANGLE

S/no.	Friction	Sensitivity of shear strength	Shear behavior
1	Low	sensitive	Linear increase
2	Medium	sensitive	Linear increase
3	High	Slightly more sensitive	Linear increase

D. Plot Between Shear Strength vs. Shear Stiffness

Fig. 8 shows the plot between shear strength and shear stiffness of rock joints. The trend line shows the increase in strength of joint as stiffness is increased but is very less sensitive towards the shear stiffness values. In general, shear strength increases with increase in shear stiffness value and does not change for higher values as shown in Table VII. For higher normal stress, shear strength is controlled by normal stress and shows less sensitivity towards shear stiffness.

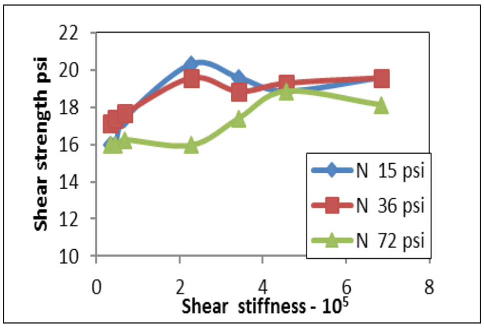

Figure 8. Plot of shear strength vs. shear stiffness

TABLE VII. SENSITIVITY OF SHEAR BEHAVIOR OF ROCK JOINTS WITH RESPECT TO SHEAR STIFFNESS

S/no	Stiffness	Sensitivity of shear strength	Shear behavior
1	Low	Sensitive	Linear increase
2	Medium	Less sensitive	Slight increase
3	High	Very less effect	Constant

VI. DISCUSSIONS

Sensitivity of shear strength to different parameters is analyzed and various co-relations are established from the results obtained from FLAC3D. Results of the numerical model suggest that shear strength and shear displacement before failure is affected by the friction angle and joint stiffness of rock mass.

The conclusions are based on the numerical model and the data obtained from direct shear laboratory test. From the results plotted, it can be concluded that the normal stiffness is the most sensitive parameter of the shear strength. Normal stiffness values are correlated with the filling material in joints. The plot between the normal stiffness and the shear strength of model is very sensitive at lower stiffness values and shows less sensitivity at higher stiffness values.

The plot between normal stiffness and shear displacement at failure is also very sensitive at lower stiffness values and shear displacement shows very less sensitivity at higher stiffness values. Hence, it can be concluded that shear strength and shear displacement values are very sensitive when soft filling materials are present in rock joints.

The plot between friction angle and shear strength shows linear behavior. On the other hand the plot between shear strength and shear stiffness shows less sensitivity at higher stiffness values.

For numerical modeling of rock joints, a discrete element simulation with angular particles (instead of triangular element) is recommended. Angular particles resemble rock grains present in rock formation. Therefore, numerical model simulation will be more realistic.

ACKNOWLEDGMENT

The authors wish to thank Mr. John Leland in University of Nevada, Reno, for his support during the laboratory testing of rock samples for this project.

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