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Failure Modes of Rock Mass Models with Non-Persistent Discontinuities

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Abstract: The behavior of rock masses with non-persistent joints is not well known in rock mechanics yet. Despite good knowledge about isolated intact material and persistent joints, the interaction between them creates stress concentrations that invalidate approaches of average behavior adopted by some authors. This paper reports the results of an experimental program of laboratory tests on artificial models of rock masses with non-persistent joints, subjected to biaxial tests. Degree of persistence, spacing and orientation of joint direction with respect to the major load component have been varied in order to investigate their influence on the strength of the model.

INTRODUCTION

The understanding about the behavior of rock masses is fundamental for civil and mining engineering projects. It is directly connected to the assessment of safety and economy matters during the constructive phase.

Much has been discussed about the characteristics of rock masses. Intrinsic aspects like genesis, lithology, petrography, mineralogy and fabric, among others, are surveyed for better classification of the rock. It is known, however, that other factors like the degree of weathering, and the development of discontinuities are also very important for the study of rock masses.

Rock masses, faced as assemblages of intact rock blocks bounded by discontinuities are naturally complex. They require the understanding of the behavior of the intact rock, the discontinuities and the interaction between them. Much effort has been devoted to investigate the mechanical behavior of discontinuities, and some progress about the understanding of some parameters influencing strength, deformability and failure modes has been achieved. Rock masses with persistent discontinuities have been the object of several research works, and that is where most of the progress has occurred. Work related to rock masses with non-persistent joints is scarce.

This paper presents the results of an experimental program with biaxial tests carried out on reduced model of rock masses with non-persistent discontinuities. The results are organized in order to study the influence of each geometrical parameters of the discontinuities, namely, persistence, spacing and orientation, on the failure modes.

PROPERTIES OF DISCONTINUITIES

Discontinuities can be classified according to different aspects which describe and characterize properties, such as geometry and persistence, among others. In this work, the influence of three joint attributes as defined by the ISRM (1983) are investigated:

• Orientation (β): Attitude of the discontinuity, described by strike and dip. In the experimental program, the planes of discontinuities were parallel to the direction of σ_3=0, inclined at angle β with respect to the direction of σ_1. Values of 30°, 45° and 60° were adopted for β.

• Spacing (s): Distance between adjacent discontinuities. It is usually applied to the average or model spacing of a family of discontinuities. Values for S = 2,5 cm and 5,0 cm were adopted.

• Persistence (k): As defined by Franklin & Dusseault (1989), the ratio between the length of the discontinuity and the total length including discontinuity and rock bridge. Persistence k=1 means fully persistent discontinuity. Values for k = 0.588 and 0.740 were adopted.

EXPERIMENTAL PROGRAM

Biaxial tests were carried out on specimens representing reduced models of rock masses with non-persistent joints. The experimental program reproduced tests previously carried out by Muhammad (1992), with some adaptations.

The intact material was modeled by cement mortar, and the joints by the introduction of acetate strips, in the intact material according to procedure previously developed by Bortolucci (1993).

Specimens were 60 cm high 30 cm wide and 10 cm thick. A picture of a failed specimen is shown in Figure 2. More details about the experimental program are presented by Clauver Aguiar (1998).

Among other results, the characterization of four predominant failure modes was established. Table 1 presents a summary the test results which will be discussed further in the following items. In the table, q_u is the unconfined compressive strength of the intact material, σ_r and τ_r are the normal and shear stress on the joint plane at the moment of failure

FAILURE MODE

Stepping

Stepping failure mode is mainly characterized by a failure surface involving isolated stretches of adjacent discontinuities. It is similar to the structure of kinks, as shown in Figure 2.

Failure initiates at the lower right corner and propagates by shear along the discontinuity, and then through intact material forward the upper element of the adjacent joint. Failure progresses at an average to the diagonally opposite corner of the specimen. Tensile failure occurs along the sections of intact material. Figure 3 shown schematically the failure surface.

This failure mode took place in specimens with β=60° and spacing s=5.0 cm, regardless of the value for persistence.

Figure 4 presents the strength envelope for the above mentioned tests, in terms of $p=(\sigma_1+\sigma_2)/2$ and $q=(\sigma_1-\sigma_2)/2$. Strength envelope for both the intact material and discontinuity are also presented as the upper and lower limits for the test results. Values obtained for each specimen are also indicated in the Figure.

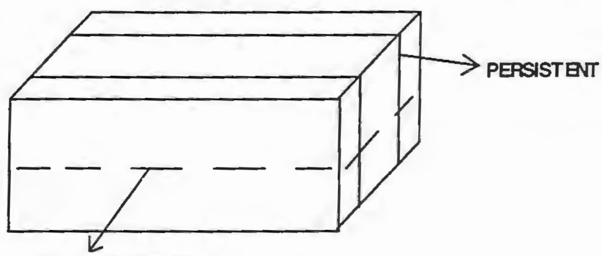

Figure 1 – Block diagram illustrating persistence

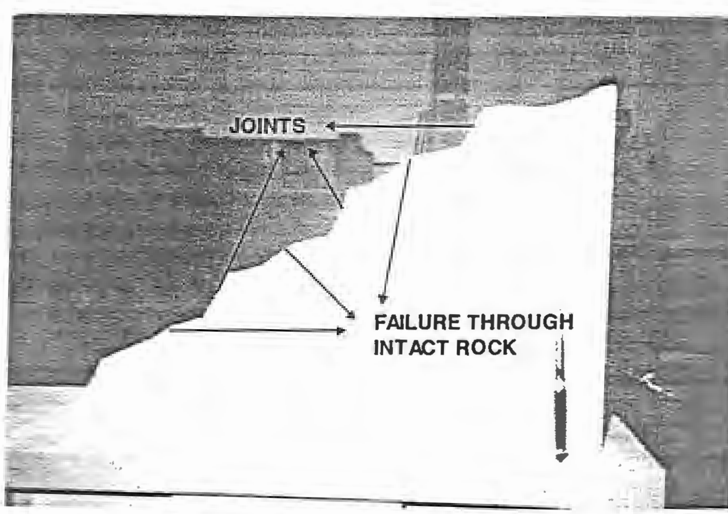

Figure 2 – Geometry of Stepping Failure Mode

Table 1 – Biaxial Test Results

specimen	β°	K	s [cm]	q_u [MPa]	σ_f [MPa]	τ_f [MPa]	Failure Mode
P01	60°	0.588	5.0	9.08	7.45	4.22	Stepping
P01A	60°	0.588	5.0	7.87	6.16	3.46	Multi-Stepping
P02	60°	0.74	5.0	8.32	4.61	2.58	Stepping
P03	60°	0.588	2.5	9.03	5.40	3.02	Multi-Stepping
P04	60°	0.74	2.5	8.59	4.61	2.58	Multi-Stepping
P05	45°	0.588	2.5	9.35	3.31	2.98	Multi-Stepping
P06	45°	0.74	2.5	7.74	3.08	2.70	Multi-Stepping
P07	45°	0.588	5.0	7.59	2.89	2.58	Combined
P07A	45°	0.588	5.0	7.30	2.80	2.50	Combined
P08	45°	0.74	5.0	7.10	3.39	3.09	Combined
P09	30°	0.588	5.0	8.10	2.30	3.17	Along Joint
P10	30°	0.74	5.0	7.51	1.85	2.30	Along Joint
P10A	30°	0.74	5.0	9.61	2.07	2.77	Along Joint

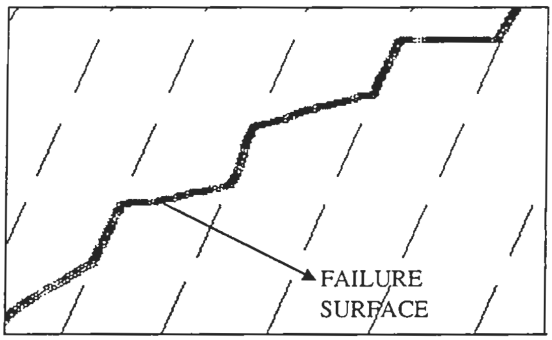

Figure 3 – Scheme of the Stepping Failure Mode

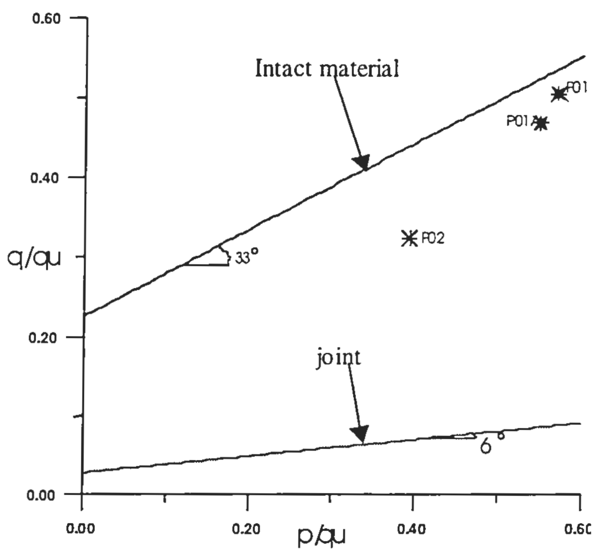

Figure 4 – Strength Envelope for Specimens with Stepping Failure Mode

Multi-Stepping

This failure mode develops by the simultaneous occurrence of several stepping failure surfaces. The pattern of failure propagation is the same described previously. Figure 5 shows schematically this failure mode.

Test data treatment is similar to the stepping failure data. The difference is only due to the number of failure surfaces, but the mechanism is the same.

Specimens with this failure mode have in common the spacing between joints (s=2,5 cm), which seems to be the dominant factor for its occurrence. Strength envelope of tests results with $\beta = 60°$ and multi-stepping failure mode is shown in Figure 6.

Even though most of the tests with this failure mode had $\beta = 60°$, it also occurred for other specimens with β=45°. The strength envelope for these tests is shown in Figure 7.

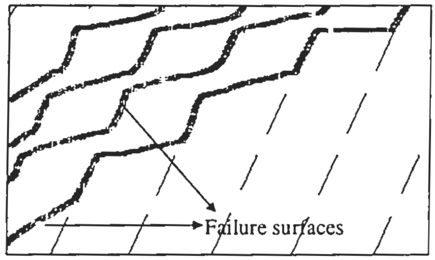

Figure 5 – Scheme of the Multi-Stepping Failure Mode

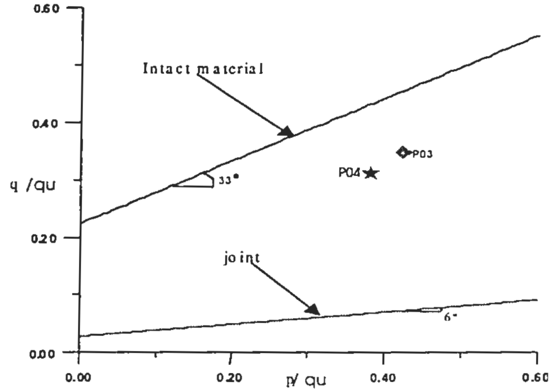

Figure 6 – Strength Envelope for Multi-Stepping Failure Mode, β=60°

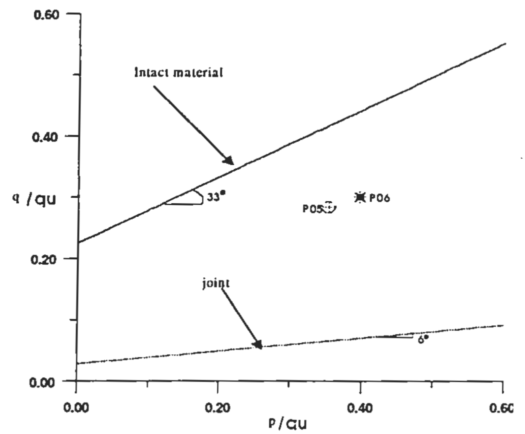

Figure 7 – Strength Envelope for Multi-Stepping Failure Mode, β=45°

Failure Along the Joint

This failure mode is characterized by a failure surface along a single plane, including joints and rock bridges. Failure progresses by shear along both elements. Failure surface therefore coincides with the joint plane. Only one, or more than one parallel failure surfaces may occur, as shown in Figure 8.

The joint attribute that seems to control the occurrence of failure along the joint is also the orientation. Specimens where this failure mode occurred were those with β=30°, regardless of the variation of other attributes. Figure 9 presents the failure envelope for this failure mode.

Combined Failure

Combined failure indicates the occurrence of different failure modes in different regions of the specimen, without the predominance of any one. Figure 10 shows schematically one example of such failure mode.

Specimens with this failure mode had β=45°, *s*=5.0 cm and taking both values of 0.588 and 0.740. The strength envelope for this failure mode is shown in Figure 11.

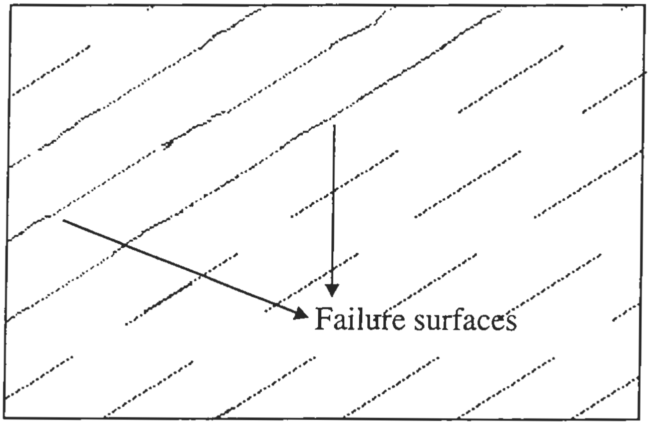

Figure 8 – Scheme of Along-Joint Failure Mode

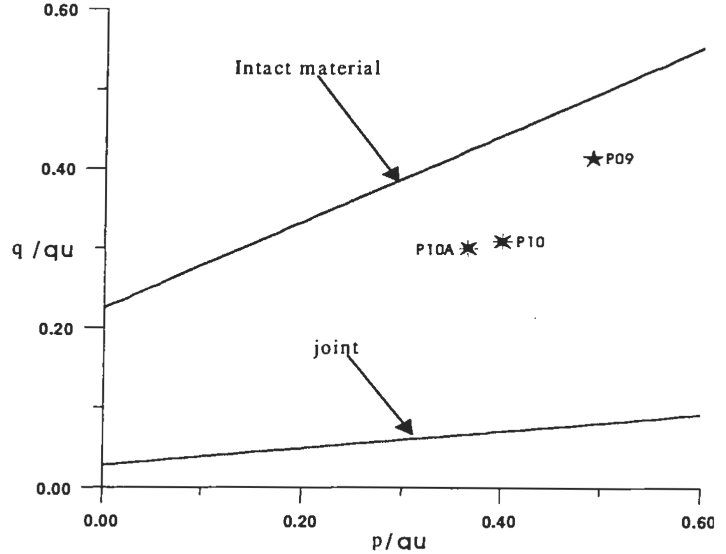

Figure 9 – Strength Envelope for Along-Joint Failure Mode

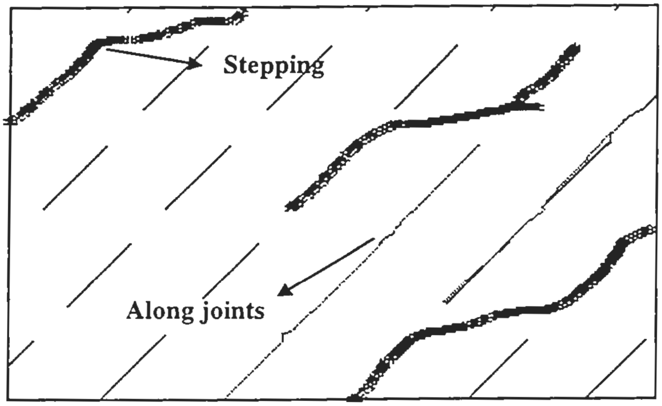

Figure 10 - Typical Scheme of Combined Failure

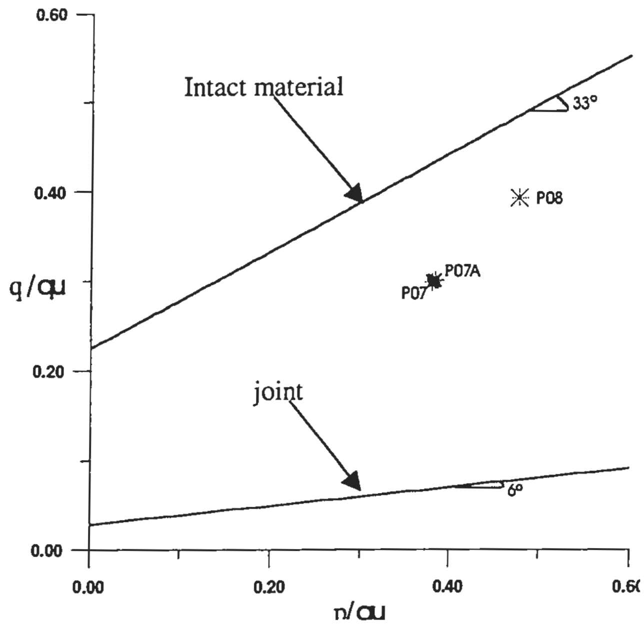

Figure 11 – Strength Envelope for Combined Failure

CONCLUSIONS

The tested models presented four distinct failure modes: stepping, multi-stepping, along joint and combined failure modes. All the modes have peculiar characteristics which allow easy distinction between them.

Stepping failure occurs due to shear along the joints and tensile failure of the intact material. Only specimens with low dip joints (β=60°) had stepping failure, spacing between joints of 5.0 cm and any value for persistence.

Multi-stepping failure mode has similar characteristics of the stepping failure mode, and it is characterized by the occurrence of more than one failure surface. Spacing between joint planes is 2,5 cm in this case. Orientation and persistence seem not to influence the occurrence of this failure mode.

Failure along joint planes occurred for specimens with high dip joints. For β = 30° specimens, shear failure along the joints propagates through the rock bridge with the same orientation. Failure may take place along several distinct planes.

Combined failure occurred for specimens with intermediate dip joints (β=45°), 5,0 cm spacing and any value for persistence. Several failure surfaces occur throughout the specimen, combining the previous failure modes. Shear along the joints, along rock bridges or tensile failure through the intact material may take place simultaneously.

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