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Technical Note

A Hypothesis on Modes of Failure of Rock Samples Tested in Uniaxial Compression

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1. Introduction

A geotechnical specification of the rock mass requires information on the mechanical properties of the intact rock. The mechanical properties of a rock mass are affected by discontinuities such as planes of weakness, mineralogical variations, bedding planes, cracks, flaws, joints, etc. On a macroscopic scale the discontinuities are characterised by distinctive joints and the tensile strength of the rock mass is often considered to be zero. On a laboratory scale, there are microscopic discontinuities like micro-defects, intergranular cracks and micro-flaws that require special detection methods. These microscopic discontinuities affect the behaviour of intact rock samples tested in a laboratory (Szwedzicki and Shamu, 1996).

Often large variations in values of strength of rock samples are attributed to sampling errors, accuracy of sample preparation or testing procedures e.g. platen constrain. Even when samples of identical lithological composition are tested, the existence of microscopic discontinuities results in variation in the value of mechanical properties, especially on the uniaxial compressive strength. Whilst it is widely accepted that discontinuities affect mechanical properties of rock and the existence of microcracks and their effect on sample failure propagation were investigated by numerous authors, (e.g. Farmer and Kemeny, 1992; Peng and Johnson, 1972; Horii and Nemat-Nasser, 1985), current laboratory testing practices and standards do not take into account the effects of these microscopic discontinuities on the mechanical properties of the rock.

Various modes of failure of cylindrical samples have been observed and classified (e.g. Reinhart, 1996; Paul and Gangal, 1996; Fairhurst and Cook, 1996). However, these observations were not considered when interpreting the results of uniaxial compressive strength tests. The relation between the mode of failure and strength parameters has not been investigated. Laboratory testing proved that fractures leading to sample failures are initiated on discontinuities. The location, orientation, size, density and extent of microscopic discontinuities contribute to different modes of failure of the rock sample (Szwedzicki and Shamu, 1999).

It is postulated that a common deficiency in assessment of the strength of the rock is that it does not take into account the mode of failure of the rock sample and rock mass. This could explain a large range of obtained values for relatively simple tests on rock samples.

2. Failure in Uniaxial Compression

Rock samples contain randomly oriented discontinuities. Under increasing uniaxial compression, stress in rock samples redistributes around such cracks. Sample failure is the result of microfracturing, the nucleation of cracks (tensile fractures of the microscopic scale) at points of stress concentration and their propagation along the direction of the maximum principal stress. Rock samples under uniaxial compressive stress, due to localised stress concentrations around microscopic discontinuities, can fail in tension, in shear or in coupling of the tension and shear stresses. Depending on the orientation of the cracks and the stress distribution, the failure is instigated in extension, shear or in coupling of shear and extension. The complete set of relations between the strain and stress components can be written in a matrix form. The matrix is known as the compliance matrix. The architecture of the elastic compliance matrix was illustrated conceptually by Hudson and Harrison (1997) as shown in Fig. 1.

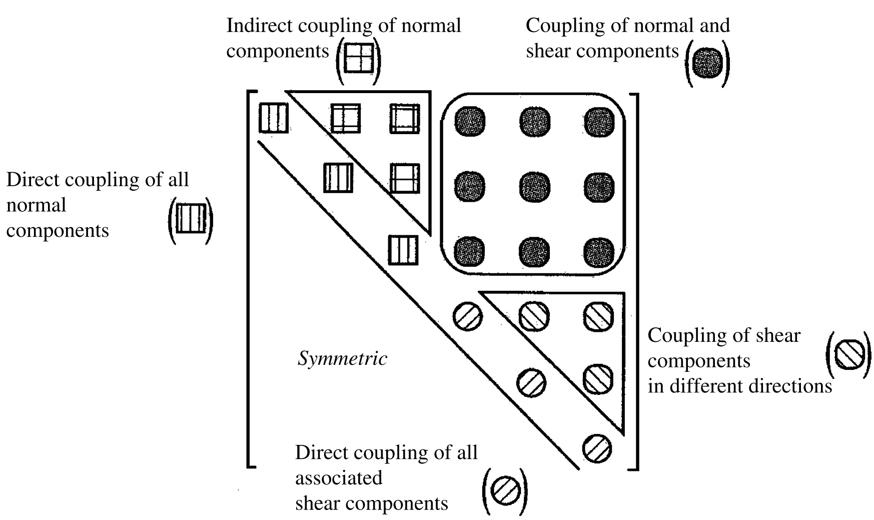

Fig. 1. The architecture of the elastic compliance matrix (Hudson and Harrison, 1997)

Two main categories of brittle fracture for a rock specimen subjected to uniaxial compression – axial cleavage and conjugate shear were identified (e.g. Gramberg, 1989). It was widely postulated that a mode of failure depended upon the degree of the end constraints of the sample offered by the platens of the testing machine and the surface quality of the parallel ends of the sample. Jumikis (1983) stated that the greater the friction between the platens and the specimen, the more likely it was that the sample would fail in shear.

The way the sample fails is reflected by the mode of the sample failure. This means that the mode of failure affects the resultant strength of the sample. Analysis of the mode of failure provides insights into the orientation of principal stress in rock samples. Extension fractures develop at right angle to the minimum principal compressive stress direction and will contain the orientation of the maximum and intermediate principal compressive stress.

The existence of microscopic discontinuities is responsible for "scale effects" i.e. strength reduction with increased sample size. The larger the sample the higher the probability that the discontinuities will effect the strength and that the sample will fail in a shear mode.

3. Matrix of Modes of Failure

The Uniaxial Compressive Strength (UCS) test "allows" a sample to choose the failure path and mode. For hard and brittle cylindrical rock samples five distinct modes of failure were identified by the author: simple extension, multiple extension, multiple fracturing, multiple shear, and simple shear, and are depicted in Fig. 2.

3.1 Simple Extension (Vertical Splitting, Axial Cleavage)

The simple extension mode denotes a failure along a plane parallel to the direction of compression. The simple extension failure doesn't happen frequently and such a failure mode may suggest that the sample was relatively free of microscopic discontinuities.

3.2 Multiple Extension

Where two or more fractures run parallel to the long axis of the sample, with fracture(s) perpendicular to that direction, multiple extension failure takes place.

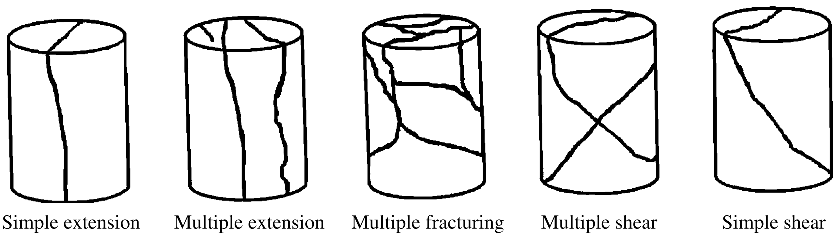

Fig. 2. Modes of sample failure

3.3 Multiple Fracturing

Multiple fracturing involves sample disintegration along a number of planes at various angles. This type of failure of the specimen is often dynamic and violent with a large amount of energy being released. When tensile failure is predominant, most of the disintegration planes are in vertical and perpendicular directions to the loading force. When shear forces are predominant, the sample disintegrates along planes inclined and intersecting the mid height of the sample e.g. hour glassing or cone failure.

3.4 Multiple Shear

When fracturing takes place along two or more planes situated obliquely to the direction of compression, but not being parallel to each other, the mode is called multiple shear. The shear surfaces can be identified by the dust left behind when fracturing occurs.

3.5 Simple Shear

The single shear failure involves one or more major parallel shearing planes (zones) situated at an oblique angle to the direction of maximum compression. The shear planes usually develop across an unconfined part of the sample. Single shear may include shear failure resulting from uneven loading of the sample. This happens when a single shear commences from the top or bottom of the sample and progresses outwards. The maximum testing load for simple shear is often low compared with other failures since the failure plane is often associated with a discontinuity or weak vein material.

It appears that rock samples in the uniaxial compressive test predominantly fail in shear (simple or multiple).

Modes of failure can be classified similarly to the compliance matrix reflecting various stress conditions, Fig. 3. However, it has to be noted that the theory of elasticity does not apply to failure and there is no physical link between the elastic

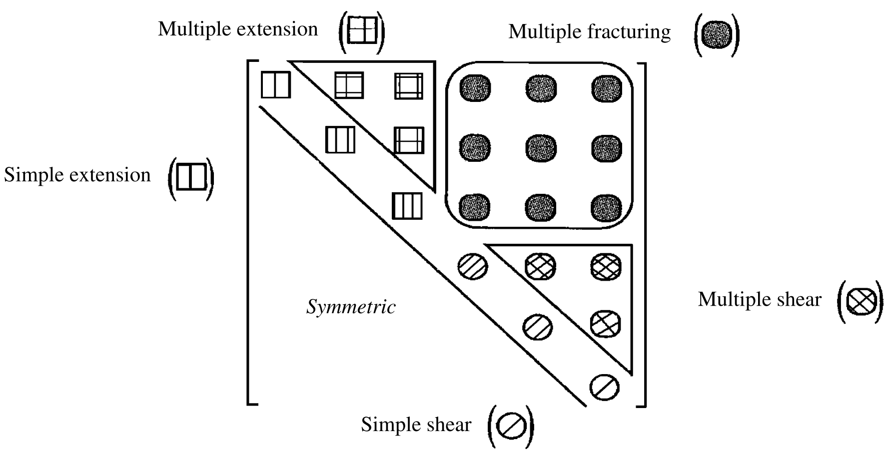

Fig. 3. The architecture of a matrix of failure modes of cylindrical rock samples tested in uniaxial compression

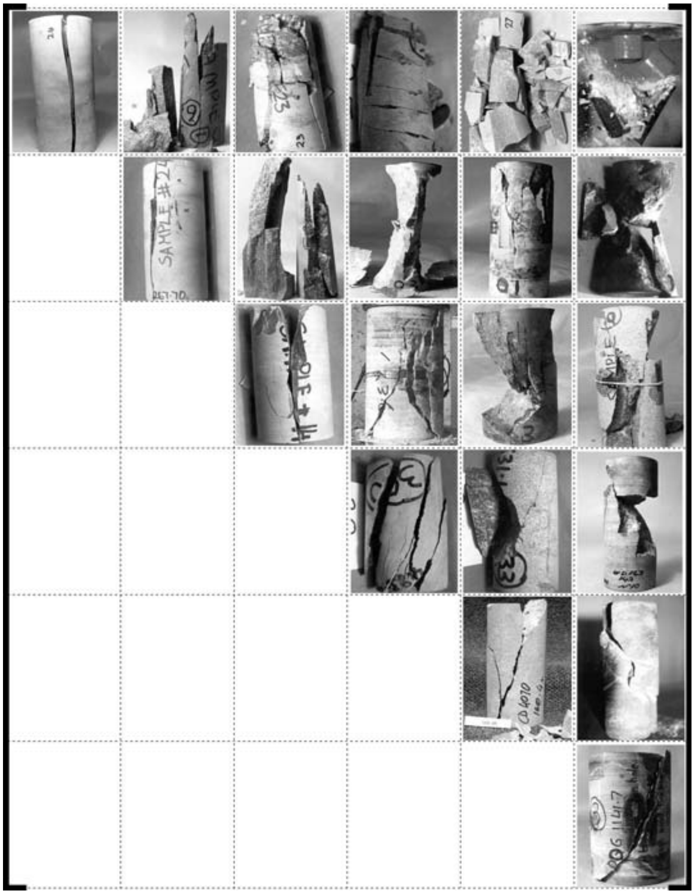

Fig. 4. A matrix form of failure modes of rock samples tested in uniaxial compression

compliance matrix and the matrix of failure modes. It can be argued that the value of compressive strength obtained when the rock failed in shear mode represented properties along the discontinuities, whereas the value obtained when the rock failed in extension mode represented strength of intact rock material.

Examples of cylindrical rock samples that failed in various modes were grouped in the matrix of modes of failure and are presented in Fig. 4.

It should be noted that during testing of rock samples from one geological formation, the mode of failure is usually similar for all samples due to the same type and orientation of defects that contribute to the same mode of failure.

4. Relation Between the Value of the UCS and the Mode of Failure

The results of UCS tests on rock samples are open for misinterpretation. The results of the UCS of rock samples show the coefficient of variation considerably higher than the results of the UCS of man made homogenous materials.

It is hypothesised that the results of tests on rock samples are not strictly comparable because tensile and shear components may vary in magnitude depending on the mode of failure. The reason for this is principally due to discontinuities that affect the modes of failure.

Szwedzicki and Shamu (1999) documented the effect of microscopic discontinuities on the uniaxial compressive strength of cylindrical rock samples. To quantify the effect of the mode of failure under uniaxial compression on the value of strength of samples of different lithologies, a dimensionless parameter was introduced. The parameter was defined as the compressive strength normalised by the value of tensile strength as defined by the Brasilian tensile test. The average value of this ratio was lowest for single shear (6:1), slightly higher for multiple shear (10:1), higher for multiple fracturing (15:1) and the highest for extension failure (20:1).

It is asserted that the variations in values of uniaxial compressive strength of samples from the same lithology depends on the mode of failure. With the same mode of failure, variations may be relatively small. However, when various modes of failure take place on similar samples the variations can often reach extreme values. As an example, four UCS tests on cylindrical contiguous samples of basalt that failed in different modes are presented. The sample that failed in the simple shear mode had a calculated UCS of 62 MPa. The sample which failed in the multiple shear mode had

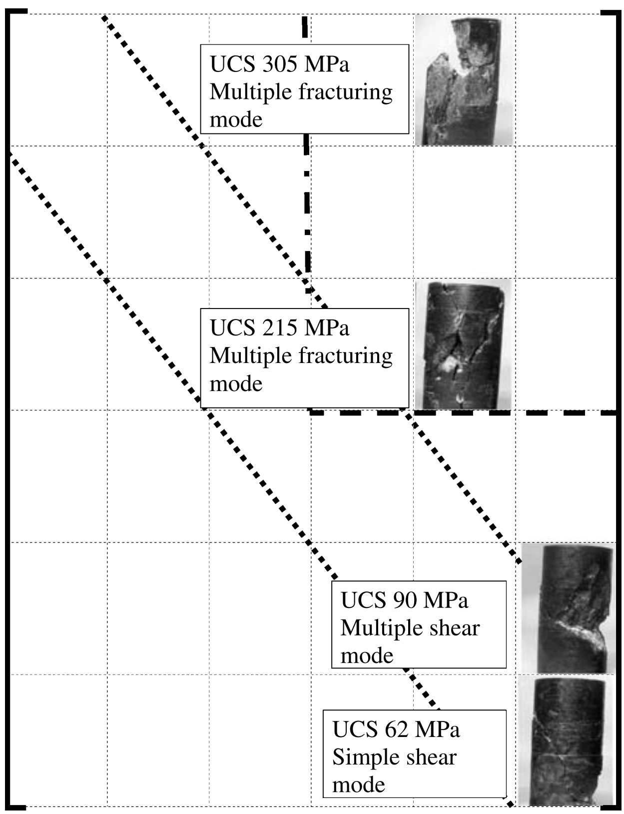

Fig. 5. Examples of values of the UCS of samples of basalt that failed in various modes

the UCS of 90 MPa. Two samples failed in the multiple fracturing mode. One sample that failed predominantly in shear stress had a UCS of 215 MPa and the other that failed predominantly in tensile stress had a UCS of 305 MPa. The value of the UCS and the positions of the samples in the mode matrix are shown in Fig. 5.

5. Conclusions

It appears that different modes of failure are due to the microscopic discontinuities in rock samples rather than variations in sample preparation, test procedure or end-boundary conditions.

It is postulated that analysis of the modes of failure makes it possible to determine whether the rock samples failed in tension, in shear or in coupling of tension and shear.

It is hypothesised that the way the sample fails (i.e. mode of failure) affects the obtained strength of rock samples. The value of the UCS is a function of the mode of failure – the values of the UCS obtained in extension are the highest, whilst the values obtained in shear are the lowest.

Understanding the affect of the mode of failure on strength enables an in-depth interpretation of the results of the Uniaxial Compressive Strength tests.

The hypothesis on the relationship between the modes of failure and strength of rock samples tested in uniaxial compression is presented to induce rock mechanics researchers to further research.

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