Rock Mechanics and Engineering

Editor: Xia-Ting Feng

Volume 1: Principles

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Foreword

Although engineering activities involving rock have been underway for millennia, we can mark the beginning of the modern era from the year 1962 when the International Society for Rock Mechanics (ISRM) was formally established in Salzburg, Austria. Since that time, both rock engineering itself and the associated rock mechanics research have increased in activity by leaps and bounds, so much so that it is difficult for an engineer or researcher to be aware of all the emerging developments, especially since the information is widely spread in reports, magazines, journals, books and the internet. It is appropriate, if not essential, therefore that periodically an easily accessible structured survey should be made of the currently available knowledge. Thus, we are most grateful to Professor Xia-Ting Feng and his team, and to the Taylor & Francis Group, for preparing this extensive 2017 "Rock Mechanics and Engineering" compendium outlining the state of the art—and which is a publication fitting well within the Taylor & Francis portfolio of ground engineering related titles.

There has previously only been one similar such survey, "Comprehensive Rock Engineering", which was also published as a five-volume set but by Pergamon Press in 1993. Given the exponential increase in rock engineering related activities and research since that year, we must also congratulate Professor Feng and the publisher on the production of this current five-volume survey. Volumes 1 and 2 are concerned with principles plus laboratory and field testing, i.e., understanding the subject and obtaining the key rock property information. Volume 3 covers analysis, modelling and design, i.e., the procedures by which one can predict the rock behaviour in engineering practice. Then, Volume 4 describes engineering procedures and Volume 5 presents a variety of case examples, both these volumes illustrating 'how things are done'. Hence, the volumes with their constituent chapters run through essentially the complete spectrum of rock mechanics and rock engineering knowledge and associated activities.

In looking through the contents of this compendium, I am particularly pleased that Professor Feng has placed emphasis on the strength of rock, modelling rock failure, field testing and Underground Research Laboratories (URLs), numerical modelling methods—which have revolutionised the approach to rock engineering design—and the progression of excavation, support and monitoring, together with supporting case histories. These subjects, enhanced by the other contributions, are the essence of our subject of rock mechanics and rock engineering. To read through the chapters is not only to understand the subject but also to comprehend the state of current knowledge.

I have worked with Professor Feng on a variety of rock mechanics and rock engineering projects and am delighted to say that his efforts in initiating, developing and seeing through the preparation of this encyclopaedic contribution once again demonstrate his flair for providing significant assistance to the rock mechanics and engineering subject and community. Each of the authors of the contributory chapters is also thanked: they are the virtuosos who have taken time out to write up their expertise within the structured framework of the "Rock Mechanics and Engineering" volumes. There is no doubt that this compendium not only will be of great assistance to all those working in the subject area, whether in research or practice, but it also marks just how far the subject has developed in the 50+ years since 1962 and especially in the 20+ years since the last such survey.

John A. Hudson, Emeritus Professor, Imperial College London, UK
President of the International Society for Rock Mechanics (ISRM) 2007–2011

Introduction

The five-volume book "Comprehensive Rock Engineering" (Editor-in-Chief, Professor John A. Hudson) which was published in 1993 had an important influence on the development of rock mechanics and rock engineering. Indeed the significant and extensive achievements in rock mechanics and engineering during the last 20 years now justify a second compilation. Thus, we are happy to publish 'ROCK MECHANICS AND ENGINEERING', a highly prestigious, multi-volume work, with the editorial advice of Professor John A. Hudson. This new compilation offers an extremely wide-ranging and comprehensive overview of the state-of-the-art in rock mechanics and rock engineering. Intended for an audience of geological, civil, mining and structural engineers, it is composed of reviewed, dedicated contributions by key authors worldwide. The aim has been to make this a leading publication in the field, one which will deserve a place in the library of every engineer involved with rock mechanics and engineering.

We have sought the best contributions from experts in the field to make these five volumes a success, and I really appreciate their hard work and contributions to this project. Also I am extremely grateful to staff at CRC Press / Balkema, Taylor and Francis Group, in particular Mr. Alistair Bright, for his excellent work and kind help. I would like to thank Prof. John A. Hudson for his great help in initiating this publication. I would also thank Dr. Yan Guo for her tireless work on this project.

Editor
Xia-Ting Feng
President of the International Society for Rock Mechanics (ISRM) 2011–2015
July 4, 2016

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Discontinuities

Chapter 1

Characterization and modeling of the shear strength, stiffness and hydraulic behavior of rock joints for engineering purposes

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Keywords: joint characterization, roughness, wall-strength, peak strength, shear stiffness, normal stiffness, physical and hydraulic apertures (Quantification of parameters: JRC, JCS, ϕ_r, K_s, K_n, E and e).

1 INTRODUCTION

The term 'characterization' will be used to describe methods of collection and interpretation of the physical attributes of the joints and other discontinuities, in other words those which control their mechanical and hydraulic properties, and the behavior of jointed rock as an engineering medium. Rock discontinuities vary widely in terms of their origin (joints, bedding, foliation, faults/shears, etc.) and associated physical characteristics. They can be very undulating, rough or extremely planar and smooth, tightly interlocked or open, filled with soft, soil-type inclusions or healed with hard materials. Therefore, when loaded in compression or shear, they exhibit large differences in the normal and shear deformability and strength, resulting in surface separation and therefore permeability. Such variability calls for innovative, objective and practical methods of joint characterization for engineering purposes. The output must be quantitative and meaningful and the cost kept at reasonable levels. The practical methods to be described will be biased in the direction of quantifying the non-linear shear, deformation and permeability behavior of joints, based on the Barton-Bandis (BB) rock engineering modeling concepts. The term 'modeling' will be used to introduce the basic stress-displacement-dilation behavior of joints in shear, and the basic stress-closure behavior when joints are compressed by increased normal stress. These are the basic elements of the (non-linear) behavior, which are used when modeling the two- or three-dimensional behavior of a jointed rock mass. They are the basic BB (Barton-Bandis) components of any UDEC-BB distinct element numerical model (used commercially and for research since 1985). The BB approach can also be used to determine improved MC (Mohr-Coulomb) strength components for a 3DEC-MC three-dimensional distinct element numerical model. In other words for acquiring input at the appropriate levels of effective stress, prior to BB introduction into 3DEC, believed to be a project underway. Due to space limitations, constant stiffness BB behavior of rock joints is given elsewhere.

2 BASIC GEOMETRIC INPUT FOR ROCK MASS REPRESENTATION IN MODELS

ISRM has recommended the following key attributes for the characterization of rock discontinuities:

(a) *Physical attributes affecting the engineering properties of discontinuities:*
   1) Roughness
   2) Strength of rock at the discontinuity surfaces
   3) Angles of basic and residual friction
   4) Aperture of discontinuities
   5) Infilling material

(b) *Geometrical attributes defining the spatial configuration of discontinuities:*
   1) Joint orientations (dip & dip direction)
   2) Spacing
   3) Number of sets
   4) Block shape and size
   5) Joint continuity

In this chapter we will be addressing the characterization and quantification of the first 'smaller-scale' set *(a)* of *Physical attributes* in detail, and the effect each of them can have on the physical behavior of the joints. We can use photographs to introduce *(b) Geometrical Attributes* without going into further detail about these larger-scale structural-geology attributes of rock masses, which determine modeled geometries with UDEC-MC, UDEC-BB and 3DEC-MC. (MC Mohr-Coulomb, BB Barton-Bandis).

Figure 1 Characteristics of joint sets as observed in a Finnish open pit and at the portal of an old unsupported road tunnel in Norway (100 years prior to Q-system tunnel support guidance). We see variable orientation (dip and dip direction), variable spacing within each set, variable numbers of joint sets (two to three), variable block shape and size, and variable joint continuity (e.g. 1–10m and discontinuous).

In order to arrive at a credible final output, namely the mechanical properties of discontinuities, the 'characterization' of the physical and geometrical attributes must adopt integrated approaches by combining *observations, measurements* and *judgment*.

Observations will cater for the intrinsic heterogeneity and variability and thus contribute to reducing 'sampling bias'. *Measurement* of the physical and geometrical attributes requires credible techniques that can be applied in the field and/ or in the laboratory in a standardized manner. Several techniques are available including index tests, laboratory tests and in situ tests. *Index tests* are simple, empirical methods, amenable to standardization and easily executable for measuring fundamental 'indices', such as friction, rock strength, roughness, etc. *Laboratory tests* (*e.g.* direct shear, uniaxial compression) are useful for confirmation of engineering properties predicted by index testing, notably when special types of discontinuities are involved (*e.g.* infilled or intensely pre-sheared). *In situ tests* may also be used for deriving parameters at representative geometrical scales and to study behavioral trends of particular critical discontinuity types, such as major weak features (*e.g.* fault zone materials).

Geometrical and other factors such as continuity, block size, history of displacements, etc. need to be taken into account when interpreting the characterization data in order to derive engineering properties. It is at that stage of characterization that expert *engineering judgment* acquires a special role.

3 CHARACTERIZATION AND QUANTIFICATION OF JOINT PROPERTIES

A convenient assembly of the recommended index tests needed for applying the Barton-Bandis BB model is shown in Figure 2. These tests, including the direct shear tests, were used by Barton & Choubey (1977) in their comprehensive research and developments using 130 joint samples collected from road cuttings near Oslo, Norway. The sketches were developed in the form of colored 'over-heads' for lecture courses, and bought together in one figure in Barton (1999).

Fortunately for the more rapid development of the BB model, Bandis (1980) used the same methods for characterization and description of his numerous joint replicas (used in his scale-effect studies) and for his natural joint samples (used for his normal stiffness studies). The suggested parameters from Barton (1973): JRC, JCS and ϕ_b were expanded to include the potentially lower ϕ_r for weathered joints because of the sometimes slightly weathered joints tested by Barton & Choubey (1977). Following Bandis' 1980 Ph.D. studies, the combined techniques for modeling both shear and normal loading were published in Bandis *et al.* (1981) (mostly concerning shear behavior and scale effects) and in Bandis *et al.* (1983) (most concerning normal stiffness behavior). In Figure 2 histograms can be seen for (suggested) presentation of variability within each index test. For example JRC is given with subscripts JRC_0 and JRC_n. These represent nominal 100mm long or larger-scale values, which might be obtained by the a/L method of Barton (1981). This is also shown in Figure 2, and expanded upon later in this chapter.

Since direct shear tests may be performed as part of the site characterization studies, some short notes are provided, which may or may not perfectly conform with suggested methods. However they are the result of collectively performing many hundreds of direct shear tests on rock joints, rock joint replicas, or rougher tension fractures.

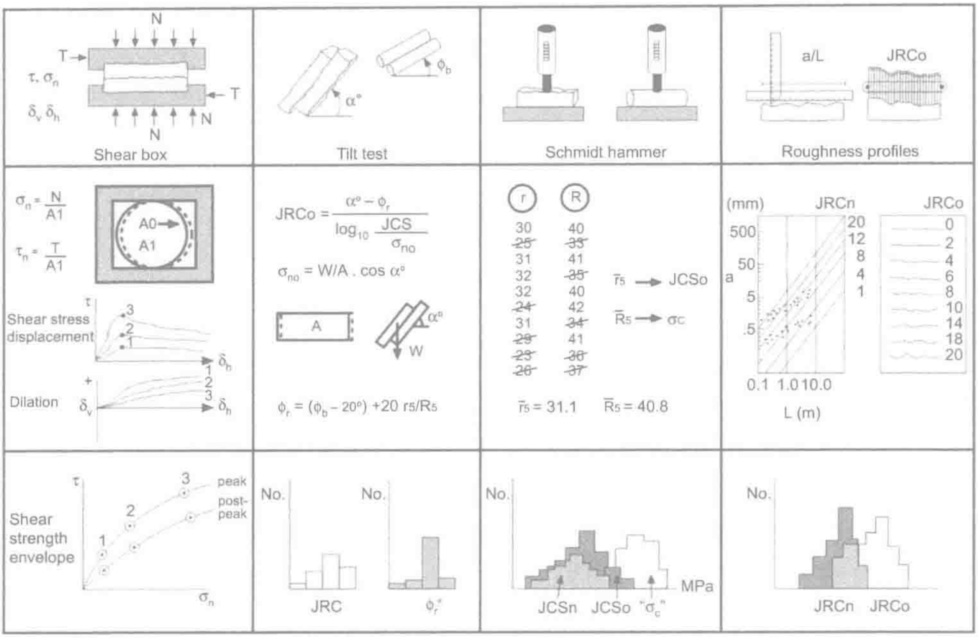

Figure 2 Four columns of diagrams showing 1. direct shear tests principles (Note: apply shear force T 'in-line' to avoid creating a moment), 2. tilt test principles, 3. Schmidt hammer test principles, and 4. roughness recording principles. Each of these simple methods are described in the following paragraphs.

1. *Direct shear tests:* The joint samples may consist of (cored) nearly circular or elliptical, or (sawn) square or rectangular samples, *i.e.* prepared from core, or from sawn blocks recovered from adits or from freshly excavated rock slopes. A strong recommendation is to recover sufficient numbers of representative samples of each joint set of interest, so that multiple testing of the same sample is avoided. The latter tends to 'rotate' the shear strength envelope, when tests at low stress are succeeded by tests at higher stress. An (even more) artificial 'cohesion' intercept is thereby obtained. (See discussion in Barton, 2014). Shear stress-displacement curves and dilation-displacement curves are plotted, and may look similar to the sketches in panel 1.2. The third Panel 1.3 shows 'peak' and ultimate' strength envelopes which will tend to be curved if joints have significant roughness and/or if a significant range of normal stress is applied, such as 0.5 to 5MPa, or 1 to 10MPa. Note that residual strength envelopes are highly unlikely to be reached with just a few millimeters of joint shearing ($\approx 1\% \times L$ may be needed to reach peak, or 1mm in the case of a 100mm long sample. This 1% reduces when testing longer samples). A method of estimating an approximate residual strength based on Schmidt-hammer tests is shown in Figure 2 (combine Panel 3.2 with Panel 2.2). It will be found that $\phi_r < \phi_b$, usually by several degrees if joint weathering ($r < R$) is significant.
2. *Tilt tests:* It is believed that Barton & Choubey (1977) were the first to apply tilt tests in a 'scientific' way to determine specific 'designer-friendly' joint strength properties, since they showed how both ϕ_b and JRC could be obtained from tilt tests. Because a

sound empirical non-linear shear strength criterion is used (Panel 2.2), the tilt test result from gravity shear-and-normal loading at a failure stress as low as 0,001MPa can be extrapolated by three to four orders of magnitude higher normal stress. We will of course reproduce the 'standard set' of 100mm JRC profiles very soon, but in the meantime emphasize that many who concentrate (in the last decades) on the exclusive use of 3D-laser profiling of roughness, may be missing some important details of shear behavior by never performing (3D) tilt tests and 'always' criticizing 2D roughness profiles. (The latter were always intended just as a rough guide, and some 400 could have been selected to represent the typical (direct shear tested) JRC values of Barton & Choubey (1977), since 3 × 130 tilt tests were performed and 3 × 130 2D profiles were recorded. (The representative JRC values were however selected from among the single DST tests on the same 130 joint samples). Panel 2.1 represents the tilt test principle for testing the natural joints for back-calculating JRC, shown in Panel 2.2. Panel 2.1 also shows tilt tests on core sticks (these could be sawn blocks). The way in which the basic friction angle ϕ_b is utilized is shown in the last equation in Panel 2.2. In the case of using artificially 'prepared' surfaces for ϕ_b it is important to avoid using 'polished' samples due to slow drilling or slow diamond sawing. Brief sand-blasting should be performed to expose the mineralogy, without adding roughness. If ridges are present across either type of sample then grinding away of the ridges followed by sand-blasting should be sufficient. Values of ϕ_b tend mostly to be in the range 25° to 35°, and most frequently 28° to 32°. However if a single rock type like chalk or limestone is of interest, values may be consistently close to the upper values. Please be aware that 'so-called ϕ_b values' obtained by subtracting dilation angles from peak shear strength may be (dangerously) over-estimated (by as much as 10°), due to neglect of the asperity failure component a_s (which is of similar magnitude to the dilation angle). This will be illustrated later.

3. *Schmidt-hammer tests (for JCS).* Panel 3.1 illustrates, in diagrammatic format, the use of Schmidt-hammer rebounds (respectively r or R) when measuring on natural joint surfaces, and when measuring on artificially 'prepared' surfaces (core-sticks or sawn blocks). In each case, a flat concrete laboratory floor and clamping to a steel 'V-block' base is advised, so that the impact and rebound are not affected by unwanted 'rocking' or other movements. However, to be on the safe side and in order not to have even the effect of crushing a loose mineral grain, the mean of the top 50% of measurements is found to be superior to the normally recommended mean values. This simple technique is shown in Panel 3.2. Artificially low vales are thereby removed as unwanted 'noise', and the remaining 50% tend to be more uniform and therefore more representative. So finally, the mean values of r_5 and R_5 are used to represent, respectively, the ***JCS (joint wall compressive strength)*** and an approximate measure of UCS (unconfined compression strength). Of course more direct measurement of the latter is usually a part of the site investigation.
4. *Roughness measurement (for JRC).* Panel 4.1 of Figure 2 illustrates the two principal methods for recording joint roughness, and estimating JRC. Panel 4.2 shows in symbolic format, the a/L method and the JRC-profile matching method. A nearly full-scale set of roughness profiles of characteristic 100mm length, with associated JRC_0 estimates, from nearly smooth-planar JRC = 0 to 2, up to extremely rough, undulating JRC = 18 to 20, is reproduced on the next page for ready reference. However tilt testing where possible, or amplitude/length (= a/L) measurements are