The Present and Future of Rock Testing: Highlighting the ISRM Suggested Methods

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1 Introduction

The term "Rock Mechanics" refers to the basic science of mechanics applied to rocks, whilst the term "Rock Engineering" refers to any engineering activity involving rocks (Hudson and Harrison 2000). The application of mechanics on a large scale to a pre-stressed, naturally occurring material is the main factor distinguishing rock mechanics from other engineering disciplines. Although, as early as 1773, Coulomb included results of tests on rocks collected from France in his paper (Coulomb 1776; Heyman 1972), the subject of rock mechanics started in the 1950s from a rock physics base and gradually became a discipline in its own right during the 1960s. Rock mechanics was born as a new discipline in 1962 in Salzburg, Austria, mainly by the efforts of Professor Leopold Müller and he officially endorsed at the first congress of the International Society for Rock Mechanics (ISRM) in 1966.

Since the formation of the ISRM, there have been many developments and technological advances in both rock mechanics and rock engineering. Nevertheless, the subject remains essentially concerned with rock modelling behaviour, whether as a research subject or to support the design of structures to be built on or in rock masses. The models developed depend critically on the input parameters, such as boundary conditions (i.e. in situ stresses), rock material and rock mass properties. As seen from Fig. 1, site investigations and laboratory and field tests provide important inputs for rock modelling and rock engineering design approaches. Therefore, determination of rock properties both in the laboratory and for in situ and monitoring of rock behaviour and rock structures, provides some of the main important areas of interest in rock mechanics and rock engineering, which are commonly applied to engineering for civil, mining and petroleum purposes.

The knowledge of a material's ability to safely sustain a load (or indeed a displacement) before breaking has been of paramount importance to man ever since structures were first built. It is difficult to conceive that the qualitative ranking of softwoods, hardwoods and stone were unknown in the Neolithic time, and the earlier civilizations such as Turanian, Indian, Chinese, Greek, Egyptian and Roman civilizations clearly had an understanding of material strength perhaps purely based on experiences initially.

Mechanical testing of materials has been carried out since about 1500 and testing machines have been in existence since the early 18th century (Timeshenko 1953; Gray 1988). In the 1920s, Josef Stini was probably the first to emphasise the importance of structural discontinuities as related to the engineering behaviour of rock masses. Other notable scientists and engineers from a variety of disciplines, such as von Karman (1911), King (1912), Griggs (1936), Ide (1936), and Terzaghi (1946) worked on the failure of rock materials. In 1921, Griffith proposed his theory of brittle material failure and in 1931 Bucky started using a centrifuge to study the failure of mine models under simulated gravity loading. However, after the formal development of rock mechanics as an engineering discipline in the early 1960s, better understanding of the importance of rock mechanics in engineering practice, increasing demands from rock engineering studies and rapid advances in technology resulted in development of a number of laboratory rock testing methods.

In addition, recognition of the fact that test results from a small specimen of rock cannot be directly applied to solve all rock engineering problems (unlike the case of soils,

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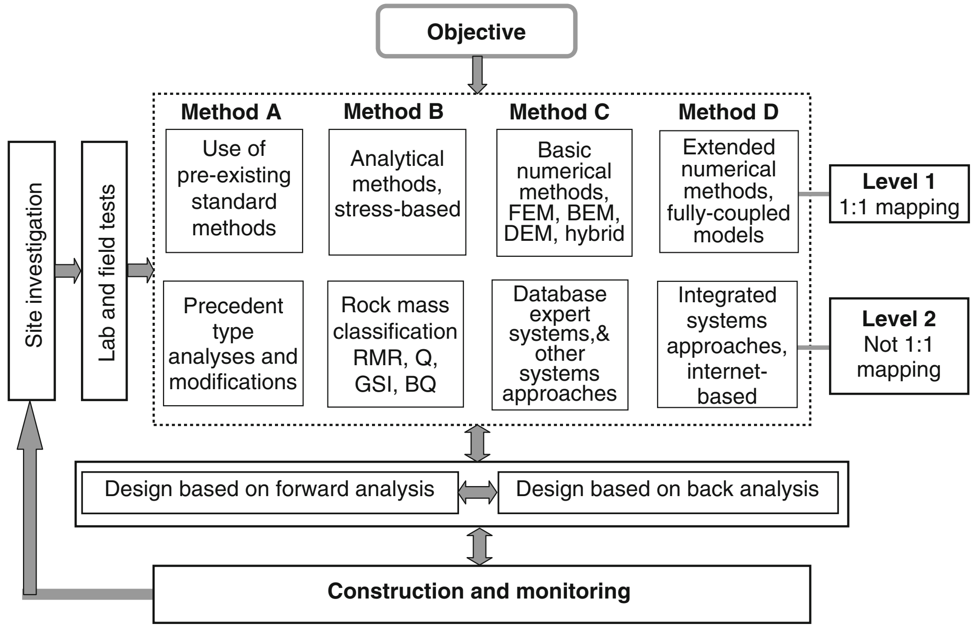

Fig. 1 Flowchart of rock mechanics modelling and rock engineering design approaches (Feng and Hudson 2011)

excepting rockfills), focused attentions on the development of in situ tests and monitoring techniques in rock mechanics. During this period, the efforts by the Commissions established by the ISRM also contributed to the development of experimental methods in rock mechanics and rock engineering by motivating the researchers. Accordingly, since 1974, the ISRM Commission on Testing Methods has spent considerable effort in developing a succession of ISRM Suggested Methods (SMs) for different aspects of rock mechanics through the contribution of a number of Working Groups.

In the first part of this paper, a brief history of both laboratory and in situ rock testing and monitoring techniques, and the main near-future trends associated with experimental methods in rock mechanics are introduced. The emphasis in the second part of the paper is on providing brief information about the tasks of the ISRM Commission on Testing Methods, general principles followed in developing the ISRM SMs, the stages followed in their evaluation and recent progresses related to the ISRM SMs. Because of limitations of space, the references given for the advances listed in the following part of the paper are intended to provide examples of the significant contributions made to the various topics or techniques being discussed and are not intended to be either fully exhaustive or definitive.

2 Historical Background: From the Past to the Present

Interest in materials had began and mechanical testing procedures possibly have been developed thousands of years ago during one of the eras when large-scale wood and stone structures were being built. Mankind has been utilizing rocks in different forms since early times. The earlier uses involve the natural caves and cliffs for accommodation and protecting people against their enemies. They also utilized rocks as excavation tools and creating flames through friction of rock. Although some of them were initially accidental findings, they later improved their knowledge and know what type of rocks can be used. The positive science, which constitutes the basics of rock mechanics and rock engineering of the modern time, is said to have been started following the Renaissance period. However, it is quite arguable who were the pioneers of mechanical laws governing solids and fluids and their testing and monitoring techniques in view of huge engineered structures related to rock built in the lands of Turan, China, India, Middle East (Sumerians, Iranian, Akadian, Urartu etc.), Egypt, Central America, Peru as well as Roman and old Greek lands and some of which were built more than thousands years ago with a high precision of modern days. There are many historical remains related to rocks from various civilizations all over the world such as Sumerians (originally from Central Asia), Turanian, Anatolian, Egyptian, Indian, Chinese, Peruvian, Maya, Aztecs, Iranian, Roman and Greek. Mankind built underground structures in past, and some examples can be still found in the Cappadocia region of Turkey (2000 BC–500 AD) as underground or semi-underground cities, and tombs of pharaohs in Thebes of Egypt (3000–2300 BC), Ajanta and Ellora caves (started to be built in 200 BC) in India and Kızıl Cave and Bezelik excavated in reddish sandstone during 420–589 AD in East Turkistan (Uyguristan), Kandovan underground caves in Azerbaijan. Karez in Turkistan, Qanats in Iran are the well-known irrigation tunnels built in many arid regions of the

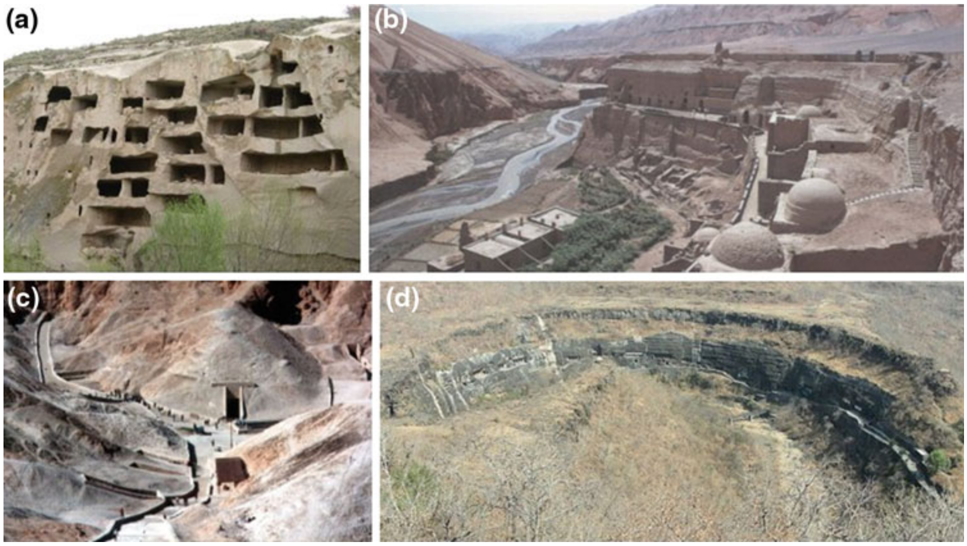

Fig. 2 Examples of man-made historical underground structures: **a** Çat (Cappadocia, Turkey), **b** Bezelik (East Turkistan), **c** Tebes (Egypt), **d** Ajanta Caves (India) (after Aydan 2012a)

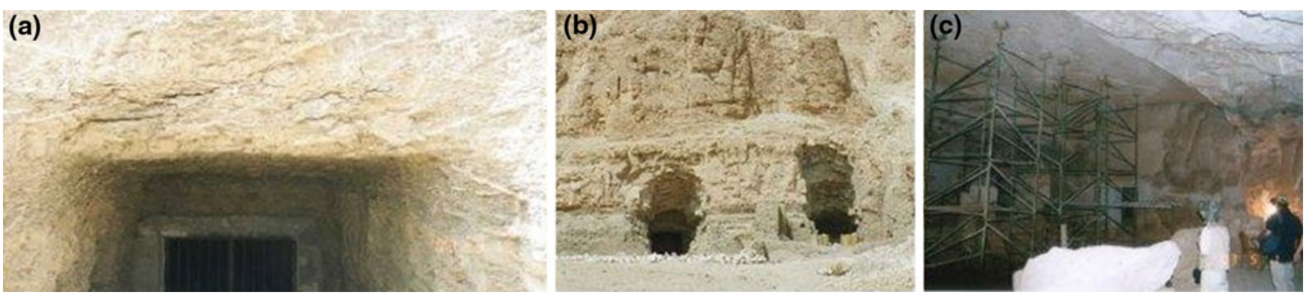

Fig. 3 Progress of opening excavation techniques in old Egypt: **a** shale, **b** roof limestone and sidewall shale, **c** limestone (after Aydan and Genis 2004; Hamada et al. 2004)

world (Fig. 2). Karez network started to be built in 206 BC is about 5,000 km long with 1,100 wells in Turfan in East Turkistan. The excavations were even carried in very hard rocks such as basalts. The underground excavations in the Capadocia region are very extensive and reaching to a depth of 80 m below the ground surface with amazing natural ventilation systems (Aydan and Ulusay 2003).

One can easily notice the progress of understanding short- and long-term characteristics of rocks in the King, Queen and West valleys by the builders of underground Pharaoh tombs in Luxor area in Egypt (Aydan and Genis 2004). They first selected soft shale formation for siting the underground tombs at earlier stages in view of available excavation tools at that time. Since shale easily deteriorates, the tombs should had been suffering from some stability problems in the roof as seen in Fig. 3a. For this reason, they probably had chosen later the limestone as the roof layer while sidewalls and floor was within the shale layer (Fig. 3b). However, the limestone layer just above the shale formation (transition zone) is highly jointed, they should had again experienced the roof stability problems for large span excavations as seen in Fig. 3c. The advance in excavation techniques and tools and better knowledge of rock characteristics with time should had lead the tomb builders to choose the soft-limestone layer for siting the underground tombs. In some underground tombs, the builders seem that they had designed and built the tombs by following the geometry of the soft limestone layer. The orientation of chambers and their dimensions, the number of pillars and their sizes should had been done according to some computations as no randomness is observed in the in situ investigations at all (Aydan and Genis 2004; Hamada et al. 2004). Some underground mining activities existed in Anatolia as early as 3000 BC. The Göltepe tin underground mines near Toros (Taurus) mountains are found to be at least 5000 years old (Kaptan 1992).

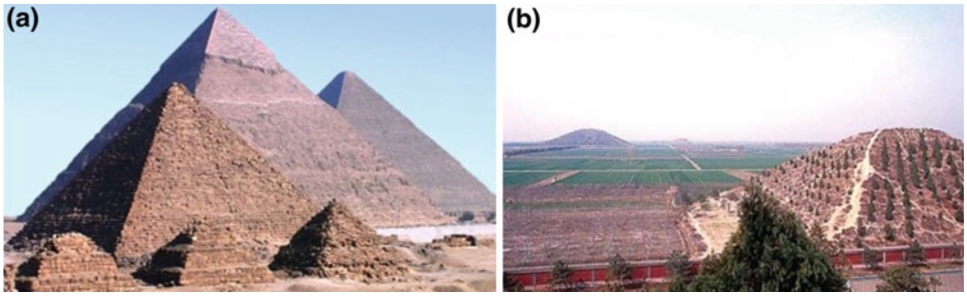

Fig. 4 **a** Pyramids in Giza (Egypt), **b** Turkish pyramids near Xianyang, China (http://www.panoramio.com/photo/)

Fig. 5 Underground quarries in **a** Egypt (Qurna) and Anatolia (**b**. Bazda and, **c**. Kusini) (Kulaksiz and Aydan 2010; Aydan and Kumsar 2005)

Pyramids made of huge rock blocks to achieve both structural stability under both static and dynamic loading conditions for thousands years and those in Egypt are well known worldwide (Fig. 4a). However, some pyramids have been recently unearthed in Peru, Mexico, Bosnia and present China. The pyramids near Xianyang (Fig. 4b) in present China were constructed by Proto-Turks (Proto-Uygurs) about 3000 BC, which makes them oldest pyramids of the world and it confirms the hypothesis that pyramids in Egypt built by people who migrated from Central Asia due to climate change and dried inland seas such as Taklamakan and Gobi Deserts. Besides the good mechanical interlocking of rock blocks, there are caverns within these pyramids. The roof of these caverns consists of beams of hard rock (mainly granite) with blocks in sidewalls put together to form to create inverted V-shape or trapez shape arches (like Sumerian arches). Of course, the beams were dimensioned in a way that they can resist tensile stresses induced by bending due to surcharge loads for thousands years.

As seen in Fig. 5, one can find also some ancient underground quarries in Anatolia and Thebes (Kulaksiz and Aydan 2010, Aydan and Kumsar 2005). Amenophis III Quarry at Qurna of Thebes region of Egypt, limestone mining started probably 3350–3500 years ago. Bazda Quarry at Harran, Urfa region of Turkey probably was opened 4000 years ago by Sumerians (Kulaksiz and Aydan 2010). At Qurna, there are lines and inscriptions, which explain daily progress records and indicator of calculating the payments of excavations workers. The observations are compared with theoretical estimation according to the stability evaluation methods based on bending and arching action of beam with the consideration of rock mass strength evaluations and the results for Qurna and Bazda are consistent with the bending and arching action evaluations of beams.

Aphrodisias is one of the antique cities built by using the marble blocks excavated from the marble quarries nearby. The first school for sculptures and artifacts of marble in history was established in Aphrodisias in Karia, which is one of great Anatolian civilizations (Erim 1986). Quarries are usually bounded by fracture zones such as normal faults (Kumsar et al. 2003). It seems that the quarrymen of Aphrodisias had a good and advanced knowledge of how to utilize the structural discontinuities to their advantage for excavation and extraction of marble blocks as well as to initiate the quarrying operations (Fig. 6). Bedding or schistosity planes are used as the bottom surface of blocks since they can be easily separated from the layer below. This further implies that the quarrymen did also have the knowledge of anisotropy of tensile strength of rocks. It is also interesting to note that Sumerians found that they can increase the strength of clay bricks by straw fibers and firing them and can create open spaces by utilizing inverted V or U shape arches.

These achievements can not be simply intuitive and an experience only and there is no doubt that there are some mechanics and mathematics behind in their achievements,

Fig. 6 Rock column or block extraction techniques in Egypt and Anatolia: **a** slots around the unfinished obellisk in Aswan (Egypt) (Hamada et al. 2004), **b** slots around a marble block in Aphrodisias (Turkey) (Kumsar et al. 2003)

which need further through investigations to understand our ancestors achievements in rock mechanics and rock engineering. All these earlier civilizations have precise unit systems for measuring physical quantities, angles and time, which are the most fundamental elements of testing and monitoring in the past and modern days.

In the general context of material science, the earliest recorded evidence of a written standard, or specification, dates back to the 4th Century BC. However, it should be noted dates may be much earlier in view of achievements of Sumerians. The “Stele of Eleusis” (Fig. 7) is a stone tablet inscribed with the specification of the composition of bronze spigots used for keying together the stone blocks for constructing columns in Greek buildings This stele is important since it clearly implies that (a) the Greeks at that time understood the importance of the relation between the composition of the alloy and its mechanical properties and (b) it is the first reference to the use of turning of a metallic component on a lathe to achieve the desired dimensions (Varoufakis 1940; after Loveday et al. 2004). When the pyramids and temples were constructed, the strength of stone had probably been considered by the Egyptians and Greeks and other civilizations, but no records have been found so far in western sources. Da Vinci (ca. 1500) tested the tensile strength of wire and his note “Testing the Strength of Iron Wires of Various Lengths” is the first recorded mechanical testing. He also studied the strength of columns and the influence of the width and length on the strength of beam.

Fig. 7 4th Century BC Stele of Eleusis (ISO Bulletin 1987)

During the 16th and 17th centuries some experiments on mechanical properties of materials were carried out with simple testing apparatus. Galileo (1638) presented the first serious mathematical treatment of the elastic strength of a material in a structure subjected to bending (Loveday et al. 2004). This is illustrated in the well known drawing that appeared in his ‘Discorsi e Dimostrazioni Matematiche’ published in Leiden (Fig. 8), as discussed by Todhunter and Pearson (1886). Mariotte (1740) extended Galileo’s work and investigated the tensile strength of wood, paper and metal, and of beams with built-in and simply supported ends. During this period, the concept that a simple relation exists between the applied load and elastic (recoverable) deformation of a material was published in 1678 by Hooke. Young (1773-1829) is associated with the measurement of the modulus of elasticity of materials although most modern day research workers would not recognise the description that he used to express the relation between stress and

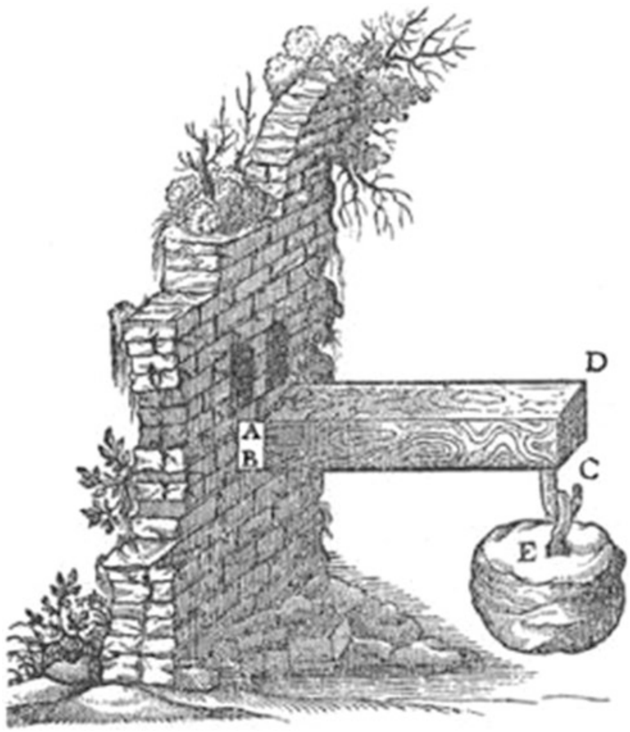

Fig. 8 Galileo's bending test (Galileo 1638)

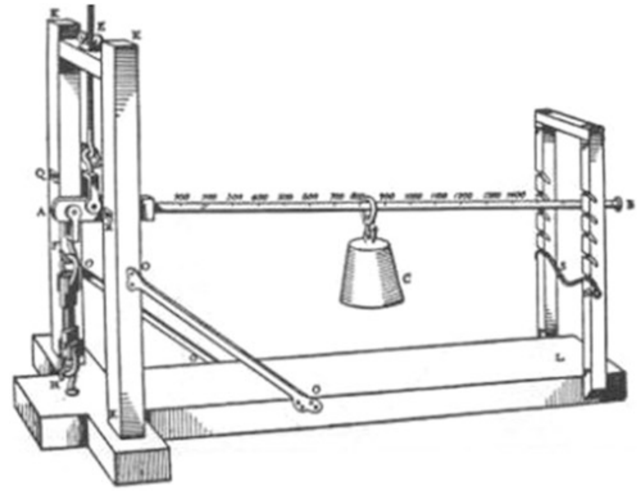

Fig. 9 Petrus van Musschenbroek lever testing machine (after Loveday et al. 2004)

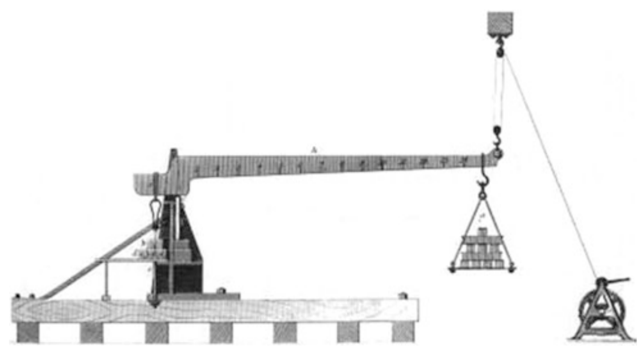

Fig. 10 Fairbain's tensile testing machine used for temperature tensile testing (after Loveday et al. 2004)

strain: "*A modulus of the elasticity of any substance is a column of the same substance capable of producing a pressure on its base which is the weight causing a certain degree of compression as the length of the substance is to the diminution of its length.*" (Loveday et al. 2004). One of the earliest machines used for the systematic measurement of tensile strength was developed by a Dutch physicist von Musschenbroek (1729) at the University of Leiden. In this machine, specimens were held at each end by special gripping devices and load was applied by a system of hooks (Fig. 9). The basic concept of a 'steel-yard' used to apply a load to the sample has subsequently been used in the design of many tensile testing machines.

The first rock mechanics experimental studies were performed by Gauthey, who built a testing machine using the lever system and measured the compressive strength of cubic specimens, in about 1770 for the design of the pillars for the Sainte Genevieve Church in Paris. Gauthey noted that the compressive strength of longer specimens was lower than the cube strength (Hudson et al. 1972). The systematic assessment of the strength of materials at high temperatures using the machine shown in Fig. 10 was an important contribution by Fairbairn (1856). Loads up to 446 kN could be applied to the test pieces by the lever system of this machine (Loveday 1982). David Kirkaldy also made an important contribution to the determination of the strength of materials by designing and building a large horizontal hydraulic testing machine in order to undertake testing to uniform standards (Smith 1982). This machine was used in the first commercial testing laboratory of Kirkcaldy in London and it was capable of testing compression specimens up to 21.5 ft long and 32 in. square and tension specimens up to about 25 ft long (Fig. 11). The real motivation to design and build testing machines was provided in the latter part of the 18th century and early 19th century when stone and cast iron bridges were being build and chain cables were developed for ships (Gibbons 1935). A typical testing machine of the 1880s is shown in Fig. 12.

During the early part of the 20th century, interesting works on the failure of rock materials was conducted by von Karman (1911) and King (1912) in Europe and Griggs (1936) and Handin (1953) in the US, respectively, playing pionering roles in the development of high pressure loading testing machines. In experimental rock mechanics, important developments were performed between 1945 and 1960, based on laboratory large-scaled experimental works by Mogi (1959), the studies on friction of discontinuities by

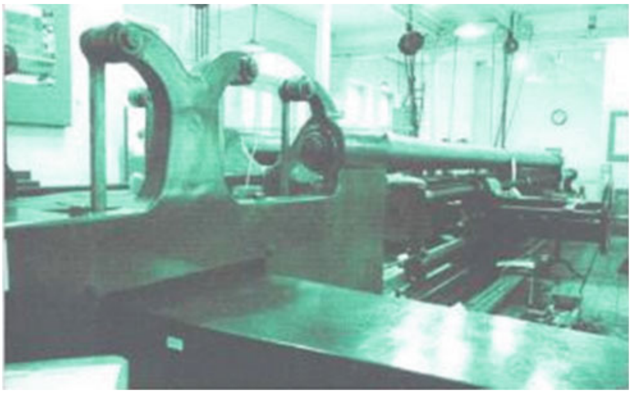

Fig. 11 Kirkcaldy's 300 ton horizontal high hydraulic testing machine in Southwark, London (after Loveday et al. 2004)

Jaeger (1959, 1960) and large-scale triaxial tests performed by Blanks and McHenry (1945), and Golder and Akroyd (1954). In addition, studies by Rocha et al. (1955) and John (1962) motivated a more common use of large scale field shear testing of rock discontinuities in many parts of the world. In the absence of modern fracture mechanics theory and scaling laws, Prof. Fernando L.L.B. Carniero from Brasil, had tried to establish a correlation between compressive strength and flexural tensile strength. A challenging engineering problem inspired Carniero to develop a new test method that is known as the Brazilian test (Fairbairn and Ulm 2002). The method was presented in September 1943, at the 5th meeting of the Brazilian Association for Technical Rules (Carniero 1943) (Fig. 13).

Another important advance in rock testing was the development of stiff and servo-controlled testing machines (Fig. 14a). Until 1966, load-displacement measuring was terminated just after the peak strength had been reached, because the rock specimens failed explosively. This explosive failure was thought to be an inherent characteristic of the rock. In 1966, it was recognised that the stiffness of the testing machine (relative to the slope of the post-peak load-displacement curve) determined whether failure of the specimen is stable or unstable. As shown in Fig. 14b, a soft machine causes sudden failure by the violent release of stored strain energy, i.e. by the testing system itself. In their state of the art review, Hudson et al. (1972) indicated that the advantage of developing stiff testing machines was first suggested by Spaeth (1935). Then laboratory tests on machine stiffness and rock failure and the development of such machines were continued by several investigators (i.e. Cook 1965; Bieniawski 1966; Waversik and Fairhurst 1970; Hudson et al. 1971; Martin 1997).

After the establishment of the ISRM Commission on Testing Methods in 1966, a number of laboratory and field testing methods and monitoring techniques to be used in rock engineering were developed and/or improved with the

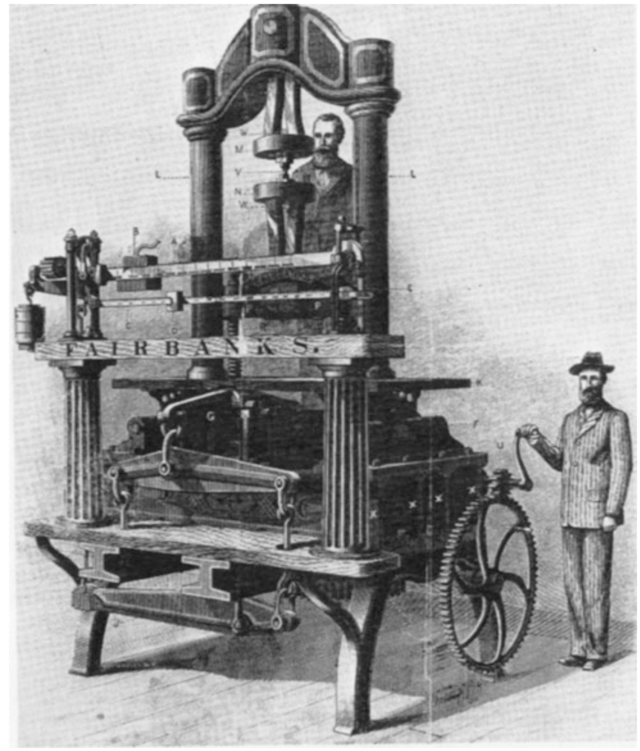

Fig. 12 Testing machine of the 1880s (after Abbott 1884)

Fig. 13 Prof. Carneiro at the laboratory preparing a sample for the Brazilian test (after Fairbairn and Ulm 2002)

efforts of the Commission, its Working Groups and cooperations between other ISRM Commissions (ISRM 1981, 2007), based on the previous experiences and new developments in technology. These methods are given in Sect. 4.5. In this period, in addition to stiff testing machines, the use of computerised methods of test control and automatic test data collection and analysis also became popular and some experimental contributions were made on the determination of shear strength and deformability characteristics, including creep behaviour of discontinuities and

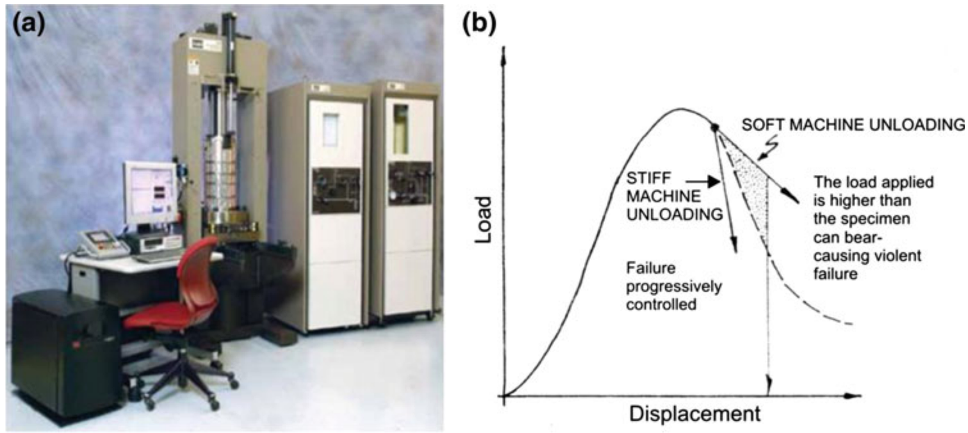

Fig. 14 **a** A stiff and servo-controlled testing system (MTS 2012) **b** comparison of load-displacement curves obtained from stiff and soft machines (arranged from Hudson 1989)

shear zones under desired effective in situ states of stress (Barla et al. 2007).

In the past, particularly depending on the researches on solid materials performed by Inglis (1913) and Griffith (1921), the principles of fracture mechanics have been applied successfully for predicting initiation and propagation of fractures and to design engineering structures in metal and metallic materials. Then the principles of rock fracture mechanics have been adopted from fracture mechanics developed for man-made materials. Rock fracture mechanics dates back to the mid 1960 and its application to rock burst problems and collapses in deep gold mines of South Africa (Bieniawski 1967). Fracture mechanics of rocks have been presented in three text books by Paterson (1978), Atkinson (1987) and Whittaker et al. (1992). It is applied to (i) hydraulic fracture propagation, (ii) rock fragmentation by cutting action and due to blasting, (iii) analysis of rock burst, and (iv) rock slope engineering problems. Mode I (extension and opening) and Mode II (shear and sliding) fracturing are most important in rock mechanics and rock engineering (Stephansson 2001). Mode I fracture mechanics is more frequently studied and the related fracture properties have been standardized, such as the ISRM SM for Determining the Fracture Toughness of Rock (ISRM, 2007). More recently, the experimental procedure for Mode II was also developed and accepted as an ISRM SM (Backers and Stephansson 2012).

Determination of the thermal properties of rock including thermal conductivity, heat capacity, thermal diffusivity etc. has become increasingly important with the widespread interest in building of underground structures such as tunnels, metro stations, repositories for spent nuclear fuel, storage of natural gas and underground energy storage. Furthermore, worldwide investigations related to using geothermal energy require knowledge about the thermal behavior of rock/fluid/stress system.

In addition to laboratory methods for rock mechanics, particularly after the establishment of the ISRM, in situ tests and monitoring of rock structures were considered to also have vital importance in rock engineering applications and they gained an increasing popularity both in research and practice. From the second half of the 20th century to the present, important contributions were made to the development and improvement of the field methods. One of the groups considered in field tests includes the tests used for determining in situ deformability of rock masses, such as plate loading, flat jack and dilatometer tests which have been included in the ISRM SMs (ISRM 1981, 2007).

The other group of field methods commonly applied in rock engineering practice is geophysical techniques. The main emphasis of geophysical surveys in the formative years was for petroleum and mineral exploration. From these surveys, technology continually developed and is developing that allows geophysical techniques to play an important role in modern science. From the 1950s until the present time geophysical methods have enjoyed an increasing role in geotechnical projects, and now are used in an almost routine manner to provide information on site parameters, such as in situ dynamic properties, cathodic protection design values, depth to and condition of rock that in some instances are not obtainable by other methods. Since 1981 a number of geophysical methods were accepted as ISRM SMs (ISRM 1981, 2007) and now are being commonly used in practice. In the last two decades, seismic imaging has an increasing popularity particularly as it relates to rock-burst investigations (Young 1993).

Knowledge of the virgin stress field is very important in many problems dealing with rocks in civil, mining and petroleum engineering as well as in geology, geophysics and seismology. The need for understanding of in situ stresses in rocks has been recognised by engineers and geologists for a long time, and many methods to measure these stresses have been proposed since the early 1930s. One of the earliest measurements of in situ stresses using surface relief methods was reported by Lieurance (1933, 1939) from the US Bureau of Reclamation in Denver. These methods consisted of disturbing the stress equilibrium with some mechanical device and measuring the resulting

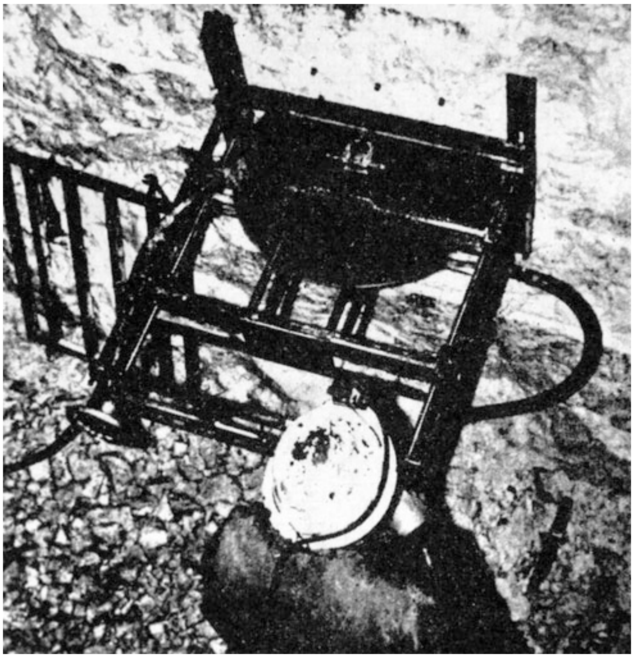

Fig. 15 In situ stress measurement using flat-jack in the 1970s in France (after Hoek 1974)

deformations. Professor Pierre Habib, who was the 4th President of ISRM, was involved in the development and application of the flat jack method (Fig. 15) as early as 1950 (Habib 1950; Mayer et al. 1951; Habib and Marchand 1952), and this method was also used to measure the in situ moduli of rock masses (Habib 1950), as were dynamic methods (Brown and Robertshaw 1953; Evison 1953). After the 1960s a wide range of methods of rock stress measurement had been investigated and developed, and they are reviewed in the books written by Amadei and Stephansson (1997) and most recently by Zang and Stephansson (2010). The stress relief technique, which is also known as the overcoring technique, is based on the assumption that rock behaves elastically. Due to technical and practical difficulties, hydraulic fracturing methods, which can be used at considerable depths, were developed. As observed in the field, the boreholes drilled for in situ stress measurements sometimes starts to fail as the depth increases. For such situations, the borehole breakout method can be useful supplement.

These methods, such as hydraulic fracturing, the CCBO technique, overcoring methods, the flat jack method and other issues considered in situ stress measurements were also accepted as ISRM SMs and published by the ISRM (ISRM 2007; Sugawara and Obara 1999; Hudson et al. 2003; Sjöberg et al. 2003; Haimson and Cornet 2003; Christiansson and Hudson 2003; and most recently Stephansson and Zang 2012). In addition, some in situ stress inference methods using laboratory experiments have also been developed. The acoustic emission (AE) method is one of the well-known methods of this kind. Although some supplementary studies to compare stresses inferred from the AE method applied to oriented samples under uniaxial loading and those of well known in situ stress determination methods (Tuncay and Ulusay 2008) are necessary, it may be a practical tool for engineers in years to come (Tuncay et al. 2002; Lehtonen et al. 2012).

Monitoring of rock deformations, stresses in rock and blast vibrations is important for assessing the stability of rock structures, such as slopes, tunnels, dams, foundations etc. To confirm the validity of the design during/after construction and to assist in answering specific questions concerning a project. Monitoring of performance of excavations in rock had been carried out for many years before the establishment of the ISRM in 1962 and had become an integral part of rock engineering practice through the observational method (Brown, 2011). Early monitoring used mechanical and optical, and then electronical and electro-opical techniques (i.e. Franklin and Denton 1973; Kovari et al. 1979; Dunniclif 1988; Brady and Brown 2004).

In order to achieve successful monitoring, various instruments and systems, such as extensometers, inclinometers and tiltmeters for movement monitoring, hydraulic cells for pressure monitoring and blast vibration monitoring techniques have been developed and were accepted as ISRM SMs (ISRM 1981, 2007). Most recently, the Global Positioning System (GPS) (Fig. 16) has an important potential to contribute through 3D displacement monitoring over an extensive area with high accuracy in real time, and has become an attractive monitoring tool in rock engineering. With the aid of this system; 3D displacements can be measured with millimetre accuracy, and the methods for reducing the influence of tropospheric delays and overhead obstacles have been established, so these measurements will be helpful for rock engineers to understand the unknown mechanisms of complex rock behaviour (Shimizu et al. 2011). In addition, and particularly for open pit mining, laser scanning (LiDAR), radar and satellite imaging techniques and systems are now also used to monitor slope movements (e.g. Hawley et al. 2009; Sakurai et al. 2009; Herrera et al. 2010).

3 Near Future Trends in Rock Testing and Monitoring

Experimental rock mechanics has a very wide scope ranging from laboratory tests to field tests and monitoring of rock structures. There are some issues requiring further investigations and a need for further developments in experimental methods which may lead to new ISRM SMs.

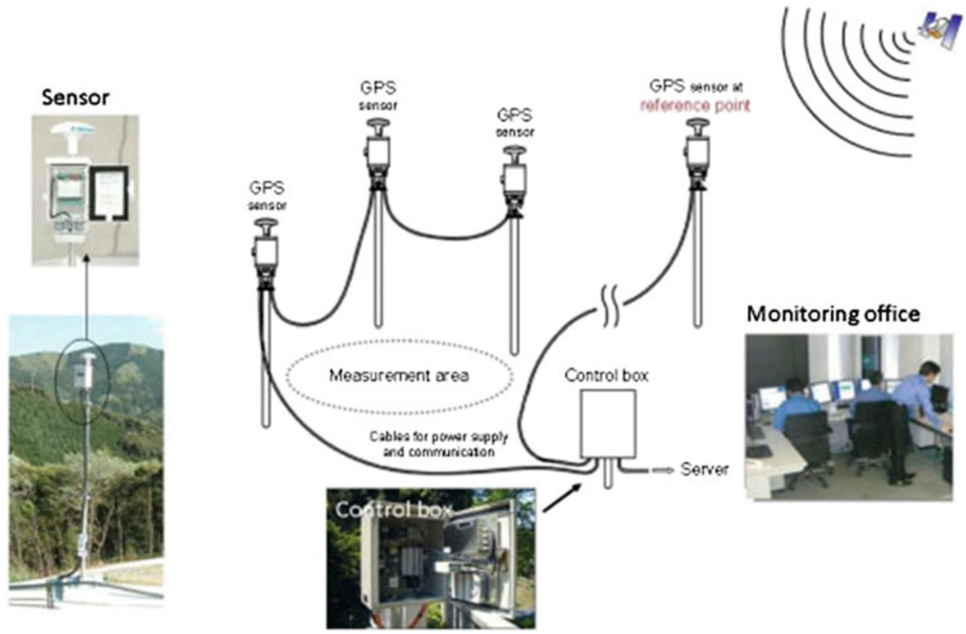

Fig. 16 GPS displacement monitoring system (after Shimizu et al. 2011)

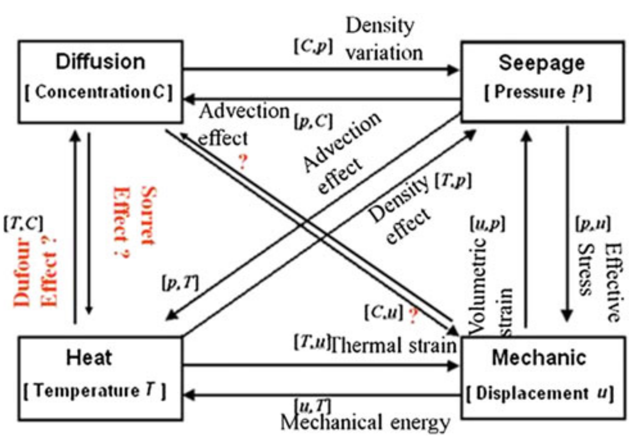

Fig. 17 The concept of the coupling of the governing equations when modelling the high-level nuclear waste disposal problem (slightly modified from Aydan 2008)

A brief summary on these is given in the following paragraphs.

Radioactive nuclear waste disposal and geothermal energy extraction are typical examples of thermo-hydro-mechanical phenomena in geo-engineering. In particular, the nuclear waste disposal issue is one of hot topics in countries utilising nuclear energy and/or having nuclear weaponry. The design time frame ranges from 10,000 to 1,000,000 years. The constitutive law parameters among coupling of diffusion [C], heat flow [T] and seepage [p] are generally unknown and further experimental studies are required to obtain the actual values of Dufour and Soret coefficients for a meaningfull assessment of fully coupled thermo-hydro-diffusion phenomena (Aydan 2008) (Fig. 17).

Due to the additional 4th dimension of time, dynamics has been a more challenging topic to understand and to apply. It remains, at least in the discipline of rock mechanics, a relatively virgin territory, where research and knowledge are limited. Although new dynamic laboratory test methods using Hopkinson bar, which were also accepted by ISRM as SMs (Zhou et al. 2012), have been developed, there are many issues in rock dynamics requiring further investigations; these have been summarised by Zhao (2011) in the most recently published book entitled "Advances in Rock Dynamics and Applications". Among them, as experimental studies, new trends are related to the shear strength of rock joints under dynamic loads (in order to understand the rate effects on shear strength and dilation), and exploration of the mechanical and physical causes of the rate effects on the rock strength and failure pattern etc.

Since stress is a tensorial quantity requiring six independent components, estimation of rock stress is one of the most important and problematic issues in rock engineering due to the considerable variation in the rock stress at all scales (caused inter alia by various types of fracturing). As emphasised by Hudson (2008, 2011) and Bieniawski (2008), although there are some rock stress measurement techniques recommended, the development of a method of rapidly and reliably estimating the six components of the rock stress tensor at a given location is an important need. Also, although the AE method is being used to estimate rock stress, further studies to compare stresses inferred from this method applied suitably on oriented samples under uniaxial loading and those of well-known in situ stress determination methods together with a SM for AE measurement are still urgent needs.

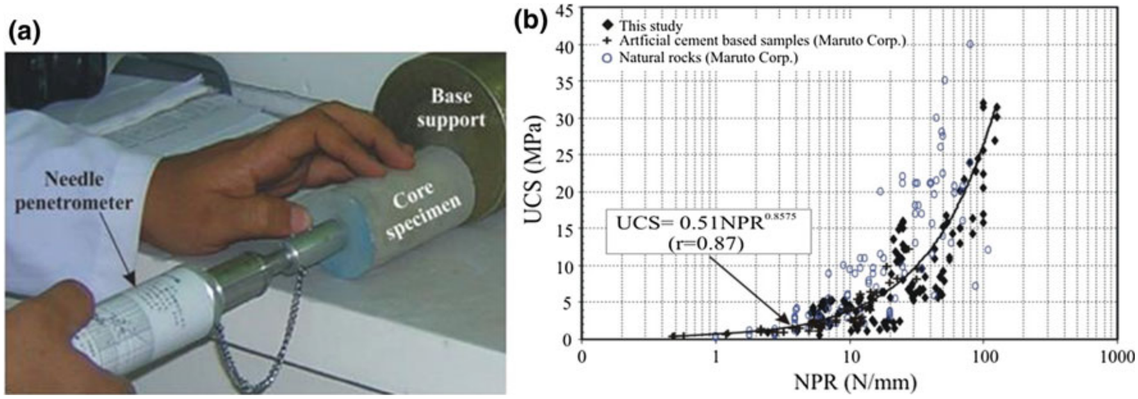

Fig. 18 **a** Needle penetration test, **b** relation between the needle penetration resistance and uniaxial compressive strength (Erguler and Ulusay 2007)

The preparation of smaller samples from weak and soft rocks even for some index tests is also difficult. In addition, sampling from historical sites, monuments and buildings for strength determinations in rock engineering studies is generally discouraged. Also, the degradation of the surrounding rock due to various causes may increase and sampling for laboratory tests becomes difficult. Therefore, the use of non-destructive techniques has been receiving great attention in recent years. To overcome these difficulties, for example, a portable light-weight testing non-destructive device (Fig. 18), called the needle penetrometer, has been developed in Japan and its application in rock engineering has been investigated by several researchers (i.e. Erguler and Ulusay 2007; Aydan et al. 2008; Aydan 2012b; Ngan-Tillard et al. 2012). It has found that the needle penetration resistance determined from this test is a useful index for the estimation of some rock properties (Aydan 2012b). It is a practical test and can be applied both in the laboratory and field. However, this method still needs a standard or a SM. Similarly, rock reinforcement and support elements such as rockbolts, rock anchors and steel ribs may deteriorate or corrode, and concrete linings may crack due to shrinkage, cyclic loading etc. (Aydan 2008). Due to this, developments are still necessary in relation to testing equipments for non-destructive tests.

By considering the increasing interest in TBMs and deep borings, some improvements on the determination of excavability and drillability parameters and the associated preparation of ISRM SMs for them are also some of the near future expectations which may assist considerably in the effort of predicting TBM excavability.

One of the important steps in a rock engineering project is site characterisation of rock exposures, which is required to collect the input data for further analysis, design and numerical modelling. The quality and quantity of the site characterization data play an important role in the subsequent use of the results. Traditional methods are now still used in most of the rock engineering projects, however; they have some drawbacks in terms of capturing enough data for further analysis, which then affects the results for the whole project. The most well-known drawback in traditional methods is that too much personal work is involved in the in situ data acquisition procedure, which is time-consuming, not accurate enough, sometimes difficult, and can be dangerous when reaching the rock faces physically (Feng et al. 2011).

One of the efforts for improving site characterisation data with new techniques is the use of 3D terrestrial laser scanning techniques which have been developed since the late 1990s. These techniques have been used in many engineering fields over the last twenty years and show great promise for characterising rock surfaces. Although any standard or SM for these techniques is not available yet, the studies summarised by Feng et al. (2011) indicate that 3D terrestrial laser scanning techniques have a great potential in rock engineering applications, such as for fracture mapping, identification of rock types, detecting water leakage, monitoring of rock mass deformations, and the associated documentation and visualisation (Fig. 19). Some limits with the current techniques are reported by Feng et al. (2011), such as colour scanning which is limited to having good illumination, difficulties related to processing the large amount of scanning data at high resolution and particularly the lack of software development for application to rock mechanics. The solution of these aspects and the further developments will play an important role in the production of useful SMs on 3D terrestrial laser scanning techniques.

A number of geophysical methods are available to be used in rock engineering. However, newer sophisticated instrumentation with increased measurement sensitivities will permit geophysical techniques to play an increasingly important role in rock engineering. There is need to obtain more rock property information, particularly on the geometry and mechanical properties of rock fractures. More

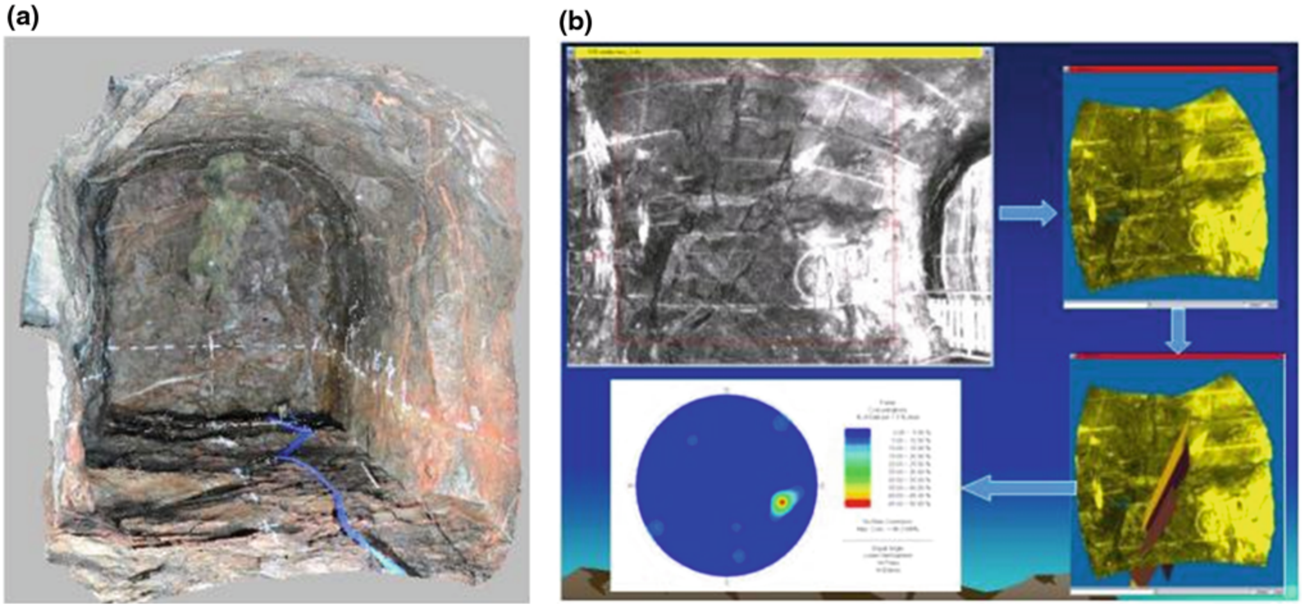

Fig. 19 Some applications of 3D laser scanning techniques: **a** 3D colour model of scanning in a tunnel, **b** semi-automatic fracture mapping (Feng et al. 2011)

emphasis will be given on geophysical methods in site investigation through rapidly developing seismic techniques, especially tomography and associated 3D visualisation methods. As emphasised by the ISRM Commission on Geophysics (Matsuoka, 2011), because CCS is becoming one of the key technologies for the reduction of CO_2 emission in the atmosphere, rock mechanics is expected to contribute to the procedures. Geophysics is also expected to play a central role for monitoring and verifying CO_2 movement in the ground. Although geophysics has been applied already to several CCS fields, there still remain many challenges to be solved in the future. Monitoring geophysics is also developing.

As a result of extracting oil from deeper and more difficult geological settings, the use of rock mechanics in petroleum engineering has become increasingly important since the 1970s (e.g. Roegiers 1999). In terms of rock testing, the factors are mainly the measurement of in situ stresses, particularly shale and sandstone characterisation and petroleum engineering related laboratory tests such as the thermo-hydro-mechanical behaviour of shales (ARMA 2012-Workshop on Petroleum Geomechanics Testing). Boring and testing issues including coring guidelines and best practices, minimising core damage, identifying core damage, sample preparation and handling, "best-practice" testing protocols, index testing, non-standard tests (e.g. creep, high temperature, high pressure, reactive fluids, fractured rock) and the use of analogue materials will be the important developments expected in the near future.

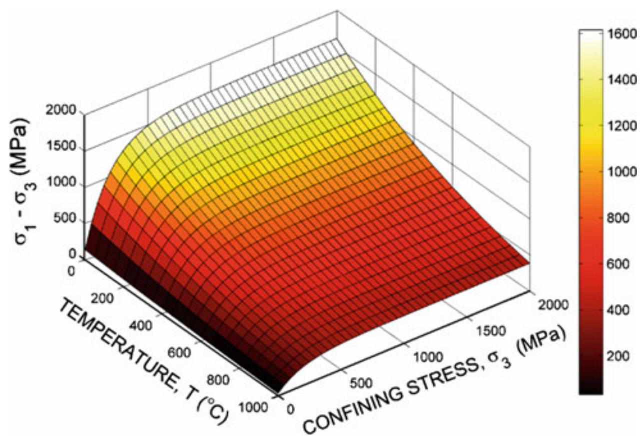

Fig. 20 A three-dimensional representation of Aydan (1995)'s failure criterion for the experimental results of Hirth and Tullis (1994)

In geomechanics, there is almost no yield (failure) criterion incorporating the effect of temperature on the yield (failure) properties of rocks although there has been some experimental researches (e.g. Hirth and Tullis 1994). The criterion proposed by Aydan (1995) is the only criterion known to the author and it was used to study the stress state of the earth. This yield (failure) criterion was applied to experimental results which are shown in Fig. 20. There is a need to focus attention on this issue and to consider the effect of rate dependency and the effect of saturation for some rocks on yield criteria.

Rock spalling is also an important aspect in rock engineering, particularly in underground studies and in the preservation of man-made historical underground openings. As emphasized by the ISRM Commission on Rock Spalling (Diederichs 2008), the focus is mainly on spalling in hard and low porosity rocks. In terms of experimental rock mechanics, the near future primary tasks are providing guidelines for laboratory procedures to detect damage thresholds and suggesting field observations using the televiewer, core discing etc. which can be used during investigations to assess spalling potential. The exact mechanism of spalling in foliated rocks also needs clarification.

One of the important gaps appearing among the ISRM SMs is the methods for determination of the hydraulic properties of intact rocks, discontinuities and rock masses both at laboratory and field scales. Based on current experiences on this issue, the gap may be filled relatively soon. In addition, long-term maintenance and preservation of man-made historical and modern rock structures as well as waste disposal sites become important issues in geo-engineering. Although they are well-known issues, quantitative evaluation methods are still lacking. Important issues are how to evaluate the weathering and degradation rates and effect of variations in water content on rocks with minerals or particles susceptible to water, and to incorporate these in the stability assessments (i.e. Aydan 2003; Aydan et al. 2005; Ulusay and Aydan 2011). Available methods such as slake durability, drying and wetting, freezing and thawing, and swelling tests are insufficient to provide experimental data for constitutive and mechanical modelling. Therefore, the development of new experimental techniques to solve this problem is urgently needed.

Summary tables of the information required for the rock mechanics modelling used to support rock engineering design are given in Feng and Hudson (2011).

4 ISRM Suggested Methods and Recent Advances

4.1 ISRM Commission on Testing Methods

(a) After the formation of the ISRM in 1962 in Salzburg, some Commissions on different aspects of rock mechanics and rock engineering were established by the ISRM. One of these Commission is the Commission on Testing Methods which was established in 1966 at the time of the 1st ISRM Congress as the "Commission on Standardisation of Laboratory and Field Tests". In 1979, its name was changed to "Commission on Testing Methods" at the 4th ISRM Congress held in Switzerland. This commission was chaired by Dr. Don Deere (1966–1972), Prof. Z.T. Bieniawski and Dr. John Franklin (1972–1979), Dr. John Franklin (1979–1987) and Prof. John A. Hudson (1987–2006). Since 2006, the Commission has been chaired by the author of this paper.

(b) The objectives of the ISRM Commission on Testing Methods are
   (i) to generate and publish SMs for testing or measuring properties of rocks and rock masses, as well as for monitoring the performance of rock engineering structures,
   (ii) to raise or upgrade the existing SMs based on recent developments and publish them in book form,
   (iii) to solicit and invite researchers to develop new methods, procedures or equipment for tests, measurements and the monitoring required for rock mechanics and laboratory or field studies, and
   (iv) to encourage collaboration of those who practice in rock mechanics testing. The commission also cooperates with other ISRM Commissions for the development of new SMs as was most recently successfully done with the ISRM Commission on Rock Dynamics.

(c) Since 1974, through the Commission, the ISRM has generated a succession of SMs covering a wide range of subjects. The first collection of the ISRM SMs was edited by Prof. Ted Brown and published by Pergamon Press in 1981. Because this book, affectionally known as the "Yellow Book" (Fig. 21a), is out of print and many new SMs have been produced since then, a book, called the "Blue Book" (Fig. 21b), which includes complete set of SMs from 1974 to 2006, was edited by Professors Resat Ulusay and John A. Hudson and published by the ISRM Turkish National Group (TNG) in 2007. The 'Blue Book' is available from the ISRM Secretariat and ISRM TNG.

4.2 What Is an ISRM SM

The term 'Suggested Method' has been carefully chosen: these are not standards per se; they are explanations of recommended procedures to follow in the various aspects of rock characterisation, testing and monitoring. An "ISRM SM" is a document that has been developed and established

(a) (b)

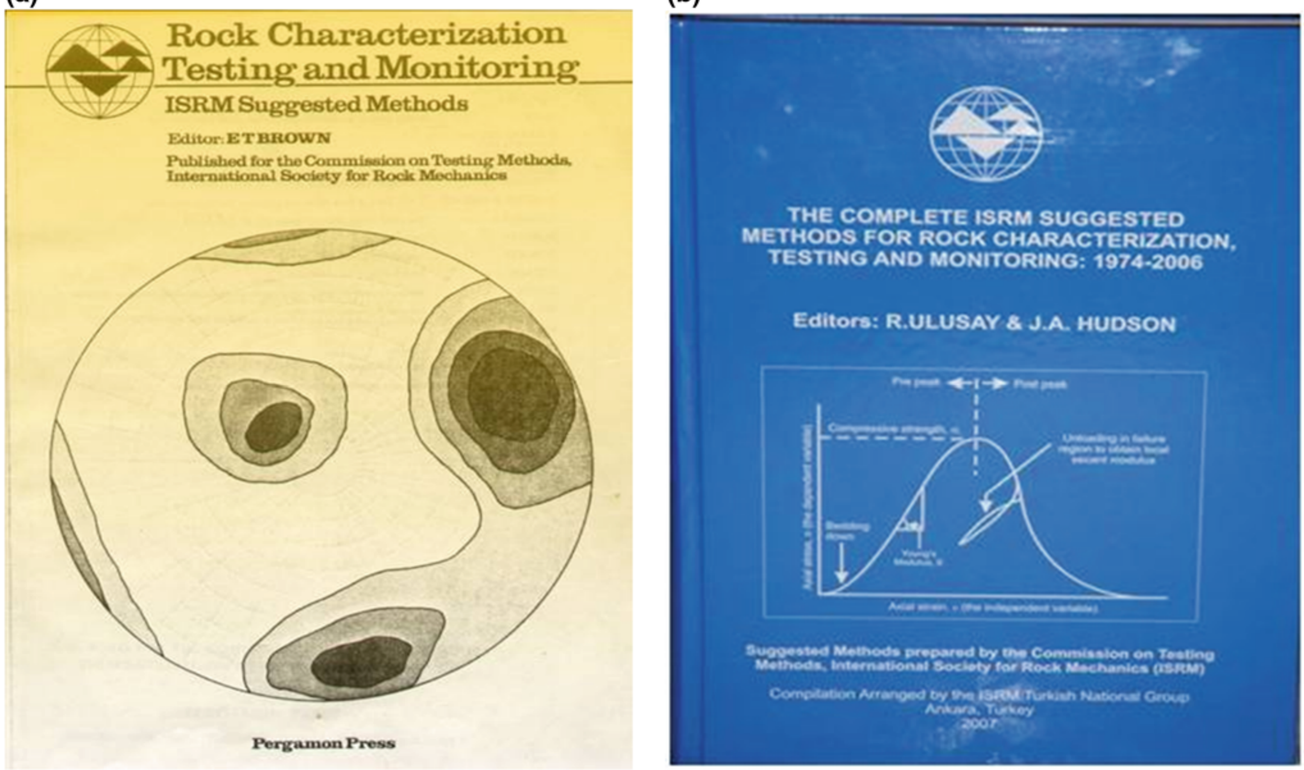

Fig. 21 **a** Yellow Book (ISRM 1981) and **b** Blue Book (ISRM 2007)

within the consensus principles of the ISRM and that meets the approval requirements of the ISRM procedures and regulations. If someone has not been involved with a particular subject before and if this subject is part of a Suggested Method, they will find the guidance to be most helpful. For example, rock stress estimation is not an easy task and anyone involved in measuring rock stresses should not take on the task lightly. The four SMs concerning rock stress estimation cover the understanding of rock stress, overcoring, hydraulic fracturing, and quality assurance. In other words, the two main stress measurement methods of overcoring and hydraulic fracturing are bracketed, firstly by ensuring that the reader is aware of the rock stress pitfalls, and secondly by ensuring that the necessary quality checks have been highlighted. The Suggested Methods can be used as standards on a particular project if required for contractual reasons, but they are intended more as guidance.

The purpose of the ISRM SMs is therefore to offer guidance for rock characterisation procedures, laboratory and field testing and monitoring in rock engineering. These methods provide a definitive procedure for the identification, measurement and evaluation of one or more qualities, characteristics or properties of rocks or rock systems that produce a test result.

4.3 Guideline for Developing ISRM SMs and the Procedure Followed for Their Evaluation

The following guideline is recommended by the ISRM Commission on Testing Methods to the volunteers and invited Working Groups (WG) who intend to develop new or to upgrade the current ISRM SMs.

1. The SM, which will be proposed, must be directly related to rock mechanics and rock engineering. It can be a laboratory or field testing method or a monitoring technique.
2. The proposed method should have been experienced at different laboratories or under different site conditions by different investigators and its results should have acceptable levels of repeatability and reproducibility. Also, the testing device or equipment should be clearly described or commercially available.
3. The effects of the testing device, specimen dimensions, environmental conditions etc. On the rock property, which will be determined or measured, should have been investigated in necessary detail and clearly defined.
4. Before the proposal of the SM is submitted to the ISRM Commission on Testing Methods, some papers and/or

reports on the proposed method should have been published.

5. In addition to the proposal of a new method, methods which can be an alternative to the current ISRM SMs or upgraded versions of the current ISRM SMs may also be recommended.
6. A proposal should be prepared by a WG which is established by a Chairman or Co-chairmen and consist of investigators who are studying the same or similar method from different countries.
7. A proposal for a SM, which will be submitted to the Commission, should include the followings:
   a. Scope (aim of the method and its necessity in rock mechanics and/or rock engineering and technical benefits expected from the method)
   b. Content of the method (testing procedure) and some information on the test device to be used
   c. List of WG members (with their correspondence addresses and e-mails); and
   d. Work plan and date of submission of the draft document to the Commission.

The proposals should be submitted to the President of the Commission by the Chairmen of the WGs. The general content of an ISRM SM is given below:

1. Introduction
2. Scope
3. Apparatus
4. Procedure : (a) Specimen preparation (for laboratory tests), (b) testing
5. Calculations
6. Presentation of results
7. Notes and recommendations (if necessary)
8. Acknowledgements (if necessary)
9. References

The procedure followed by the Commission on Testing Methods and the ISRM for the evaluation and approval of a proposed SM is given in the flow-chart in Fig. 22. Based on this procedure, in case of acceptance of any SM and its approval by the Commission and ISRM Board, respectively, the manuscript is submitted to an international journal on rock mechanics for publication without further review. Until 2012, the SMs approved by the ISRM Board as ISRM SMs were published in the "International Journal of Rock Mechanics & Mining Sciences (IJRMMS)". Since 2012, they are being published in "Rock Mechanics & Rock Engineering (RMRE)".

4.4 How the ISRM SMs Should Be Referenced

Following Dr. Don 's initial work in the late 1960s and early 1970s in establishing the groundwork and priorities for the topics to be covered, the production of the majority of the early SMs was managed by Prof. Z.T. Bieniawski and Dr. J.A. Franklin who arranged WGs to produce successive drafts of each SM. The final versions were then published in the IJRMMS. These earlier SMs did not have authors as such, although the WG members were acknowledged. In 1987, Prof. J.A. Hudson took over the Presidency of the Commission and initiated a system where the documents were produced more in the form of papers, so that the authors would receive full citation recognition of their efforts. Up to now all ISRM SMs have been referenced as ISRM (1981) or with the names of their authors. In order to give full credit to the authors of the SMs and also to indicate that these methods have been approved by the ISRM as ISRM SMs, it is recommended that both the authors of the SMs and the name of the ISRM Book, which includes these SMs, should be referred to in the text as given below (Note that all ISRM SMs published between 1974 and 2006 have been included in the Blue Book (ISRM 2007)). For example, "ISRM SM for Rock Stress Estimation: Part-3", the following referencing style is recommended to be used in the text and figure and table captions, and in the List of References:

Referencing style in the text: "…….(Haimson and Cornet 2003; ISRM 2007)….."

Referencing style in the list of references:

"Haimson, B., Cornet, F.H., 2003. ISRM Suggested Methods for rock stress estimation—Part 3: hydraulic fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF). Int. J. Rock Mech. & Min. Sci., 40, 1011–1020."

"ISRM, 2007. The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974–2006. Suggested Methods Prepared by the Commission on Testing Methods, International Society for Rock Mechanics, R. Ulusay & J.A. Hudson (eds.), Compilation Arranged by the ISRM Turkish National Group, Ankara, Turkey, 628 p."

The old SMs of which the authors are not cited should be referenced as "ISRM (2007)"

4.5 Current ISRM SMs and Most Recent Attempts

From 1974 to the present the ISRM has generated 62 SMs. The SMs are classified into four groups, namely: Site Characterisation, Laboratory Testing, Field Testing and Monitoring. The SMs involving the description of discontinuities and geophysical logging of boreholes are included in the Site Characterisation group. Although some index tests, such as the Point Load Test and Schmidt Hammer Test, can be performed either in the laboratory or in the field using portable laboratory equipment, all index and

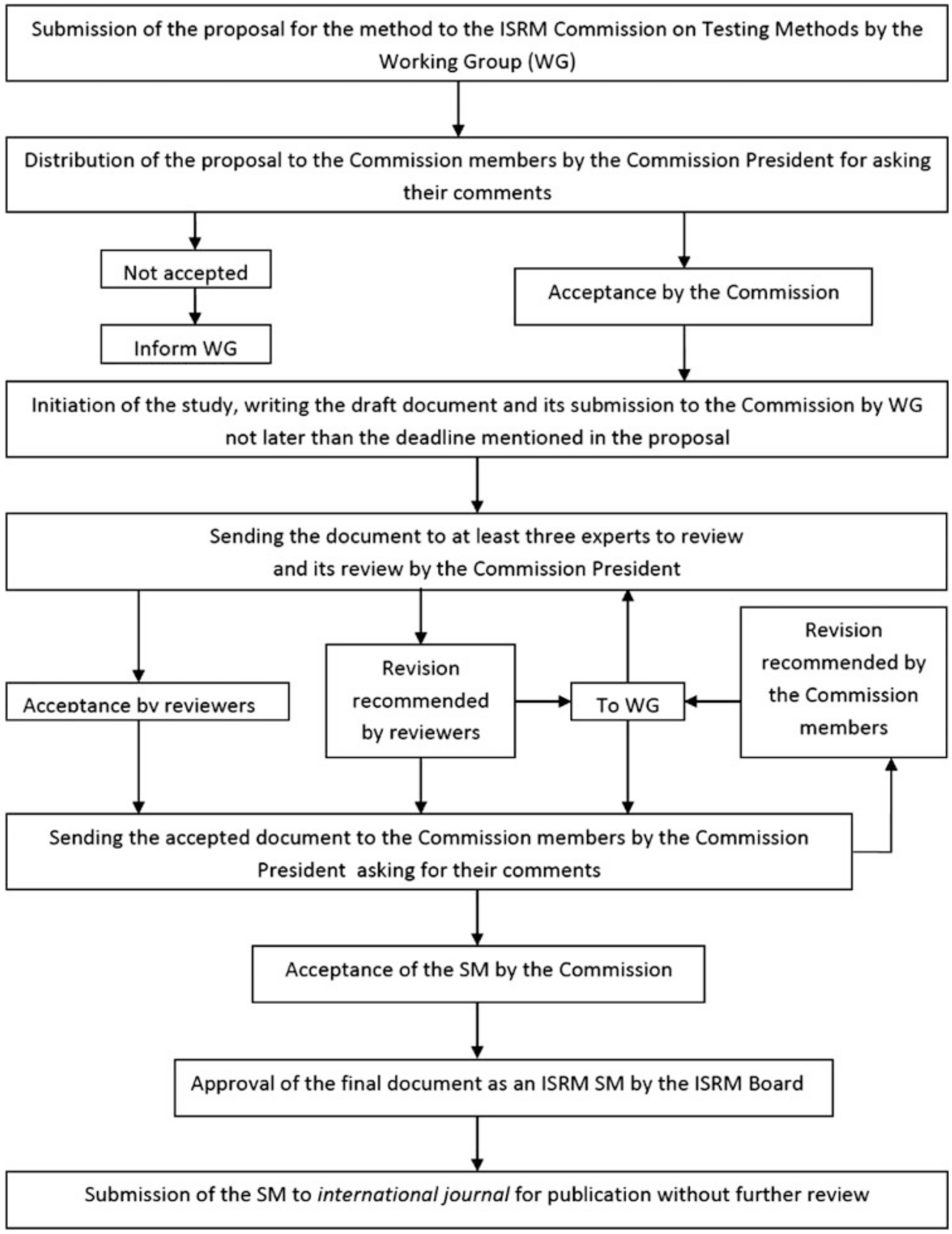

Fig. 22 Flowchart showing the procedure for application, developing and approval of the ISRM SMs

mechanical tests, along with the petrographic description of rocks, are considered in the "Laboratory Testing" group. Note that the 1975 version of the SM for shear strength of rock joints, and 1978 versions of the SMs concerning triaxial compressive strength testing, the measurement of Shore hardness, Schmidt hammer test and sound velocity test were revised in 2014, 1983, 2006, 2009 and 2014, respectively. In the "Field Testing" group, the tests are divided into five sub-groups: Deformability Tests, In situ Stress Measurements, Geophysical Testing, Other Tests, and Bolting and Anchoring Tests. The Monitoring group includes the methods for monitoring of movements, pressures and blast vibrations occurring in rock structures and rock masses. These methods are listed in Table 1 in chronological order. In addition, the ISRM SMs books (Yellow Book, 1981; Blue Book, 2007; Orange Book, 2014), which include these methods, are also mentioned in this table.

Since 2006, twenty one new WGs were established by the ISRM Commission on Testing Methods to develop new and/or revised/upgraded ISRM SMs. Sixteen WGs produced twenty one new and/or upgraded ISRM SMs. These SMs were approved by the ISRM and first published in the journals and then in the ISRM Orange Book. One of these new SMs, entitled "SMs for Determining the Dynamic Strength Parameters and Mode-I Fracture Toughness of Rock Materials" is a product of the ISRM Commission on

Table 1 List of all the ISRM Suggested Methods published between 1974 and 2014 (In chronological order)

SM for Determining Shear Strength[a, b]—1974
SM for Rockbolt Testing[a, b]—1974
SM for Determining Water Content—Porosity—Density—Absorption and Related Properties and Swelling and Slake-Durability Index Properties[a, b]—1977
SM for Monitoring Rock Movements Using Inclinometers and Tiltmeters[a, b]—1977
SM for Determining Sound Velocity[a, b]—1978
SM for Determining Tensile Strength of Rock Materials[a, b]—1978
SM for Determining Hardness and Abrasiveness of Rocks[a, b]—1978
SM for Determining the Strength of Rock Materials in Triaxial Compression[a, b]—1978
SM for Monitoring Rock Movements Using Borehole Extensometers[a, b]—1978
SM for Petrographic Description of Rocks[a, b]—1978
SM for Quantitative Description of Discontinuities in Rock Masses[a, b]—1978
SM for Determining in Situ Deformability of Rock[a, b]—1979
SM for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials[a, b]—1979
SM for Pressure Monitoring Using Hydraulic Cells[a, b]—1980
SM for Geophysical Logging of Boreholes[a, b]—1981
SM for Determining the Strength of Rock Materials in Triaxial Compression: Revised Version[b]—1983
SM for Surface Monitoring of Movements across Discontinuities[b]—1984
SM for Determining Point Load Strength[b]—1985
SM for Rock Anchorage Testing[b]—1985
SM for Deformability Determination Using a Large Flat Jack Technique[b]—1986
SM for Deformability Determination Using a Flexible Dilatometer[b]—1987
SM for Rock Stress Determination[b]—1987
SM for Determining the Fracture Toughness of Rock[b]—1988
SM for Seismic Testing Within and Between Boreholes[b]—1988
SM for Laboratory Testing of Argillaceous Swelling Rocks[b]—1989
SM for Large Scale Sampling and Triaxial Testing of Jointed Rock[b]—1989
SM for Blast Vibration Monitoring[b]—1992
SM for Rapid Field Identification of Swelling and Slaking Rocks[b]—1994
SM for Determining Mode I Fracture Toughness Using Cracked Chevron Notched Brazilian Disc[b]—1995
SM for Deformability Determination Using a Stiff Dilatometer[b]—1996
SM for Determining the Indentation Hardness Index of Rock Materials[b]—1998
SM for Complete Stress-Strain Curve for Intact Rock in Uniaxial Compression[b]—1999
SM for in Situ Stress Measurement Using the Compact Conical-Ended Borehole Overcoring Technique[b]—1999
SM for Laboratory Testing of Swelling Rocks[b]—1999
SM for Determining Block Punch Strength Index[b]—2001
SM for Rock Stress Estimation—Part 1: Strategy for Rock Stress Estimation[b]—2003
SM for Rock Stress Estimation—Part 2: Overcoring Methods[b]—2003
SM for Rock Stress Estimation—Part 3: Hydraulic Fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF)[b]—2003
SM for Rock Stress Estimation—Part 4: Quality Control of Rock Stress Estimation[b]—2003
SM for Land Geophysics in Rock Engineering[b]—2004
SM for Determining the Shore Hardness Value for Rock[b]—2006 (updated version)
SM for Determination of the Schmidt Hammer Rebound Hardness: Revised version[c]—2009
SMs for Determining the Dynamic Strength Parameters and Mode I Fracture Toughness of Rock Materials[c]—2012
SM for the Determination of Mode II Fracture Toughness[c]—2012

(continued)

Table 1 (continued)

SM for Determining Shear Strength[a, b]—1974
SM for Rock Stress Estimation—Part 5: Establishing a Model for the In situ Stress at a Given Site [c]—2012
SMs for Rock Failure Criteria (Six failure criteria)[c]—2012:
a. SM for Mohr-Coulomb Failure Criterion[c]
b. SM for the Hoek-Brown Failure Criterion[c]
c. SM for 3D Hoek-Brown Failure Criterion[c]
d. SM for Drucker-Prager Failure Criterion[c]
e. SM for Lade and Modified Lade 3D Rock Strength Criteria[c]
f. SM for a Failure Criterion for Rocks Based on True Triaxial Testing[c]
SM for for Measuring Rock Mass Displacement Using a Sliding Micrometer[c]—2013
SM for Rock Fractures Observations Using a Borehole Digital Optical Televiewer[c]—2013
SM for Determining the Mode-I Static Fracture Toughness Using Semi-Circular Bend Specimen[c]—2014
SM for Reporting Rock Laboratory Test Data in Electronic Format[c]—2014
SM for Determining Sound Velocity by Ultrasonic Pulse: Upgraded Version[c]—2014
SM for Determining the Creep Characteristics of Rock Materials[c]—2014
SM for Monitoring Rock Displacements Using Global Positioning System[c]—2014
SM for Laboratory Determination of the Shear Strength of Rock Joints: Revised Version[c]—2014
SM for Determining the Abrasivity of Rock by the Cerchar Abrasivity Test[c]—2014
SM for Step-Rate Injection Method for Fracture In-situ Properties (SIMFIP): Using a 3-Components Borehole Deformation[c]—2014
SM for the Needle Penetration Test[c]—2014

[a] Published in ISRM (1981, Yellow Book)
[b] Published in ISRM (2007, Blue Book)
[c] Published in ISRM (2014, Orange Book)

Table 2 The new ISRM SMs under preparation by the WGs established in 2013

1. SM for Determining Thermal Properties of Rock Samples
2. SM for Laboratory Acoustic Emission Monitoring
3. SM for Uniaxial-Strain Compressiblity Testing for Reservoir Geomechanics
4. SM for the Lugeon Test
5. SM for In Situ Microseismicity Monitoring of the Rock Mass Fracturing Process

Rock Dynamics based on the co-operation between that Commission and the ISRM Commission on Testing Methods. The new five WGs, which were established in 2013, are preparing the new SMs given in Table 2. The "SM for Uniaxial-Strain Compressibility Testing for Reservoir Geomechanics" (Table 2), which is under preparation, will be the product of the ISRM Commission on Petroleum Geomechanics based on the co-operation between that Commission and ISRM Commission on Testing Methods.

The Orange Book also includes two supplementary but non-SM documents, such as "3D Laser Scanning Techniques for Application to Rock Mechanics and Rock Engineering" and this paper.

In the near future and based on current experiences and experimental studies, the ISRM Commission on Testing Methods expects the production of new ISRM SMs which will be developed by various WGs and/or based on the co-operation with the commission and other ISRM Commissions. These are listed below.

a. Based on the co-operation between the Commission on Testing Methods and some other ISRM Commissions, the development of new SMs on rock dynamics, petroleum geomechanics (SMs for geomechanical testing of the mudstone cap rock above injection, for block testing with polyaxial stresses and fluid flow-coupling etc.) and rock spalling (such as guidelines for laboratory procedures to detect damage thresholds, suggested field observations to be used during investigations for assessing spalling conditions etc.) are anticipated.
b. SMs for rock mass excavability tests.
c. SMs for 3D laser scanning techniques for application to rock engineering.

d. Although some tests, such as slake durability, freezing and thawing, drying and wetting and swelling tests, are insufficient to provide experimental data for constitutive and mechanical modelling, they are useful for the assessment of rocks during material selection. By considering that ISRM SMs for freezing and thawing, and drying and wetting tests are still not available, the development of SMs for these two tests based on co-operation with the ISRM Commission on Soft Rocks will be useful.

5 Conclusions

Since the establishment of the International Society for Rock Mechanics (ISRM) in the 1960s, there have been important scientific developments and technological advances both in rock mechanics and rock engineering. In particular, modelling of rock behaviour, design methodologies for rock structures and rock testing methods are the main issues in these developments and advances. The models developed depend considerably on the input parameters such as boundary conditions and material and rock mass properties. For this reason, the importance of experimental investigations and the determination of engineering properties of rocks will continue as an integral part of rock mechanics and rock engineering applications in the future.

Developments in the laboratory and in situ testing and monitoring methods in rock dynamics, petroleum geomechanics, new non-destructive testing methods, tests for the determination of the thermo-hydro-mechanical behaviour of rocks, methodologies for detecting rock spalling, and application of 3D laser scanning techniques and GPS methods for rock characterisation and displacement measurements seem to be the most popular areas of interest in terms of experimental rock mechanics. Depending on these developments and future co-operation between the ISRM Commissions, it is expected that valuable contributions through the production of new and upgraded ISRM Suggested Methods will continue with increasing speed.

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