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What is the Strength of a Rock Mass?

progress in answering Müller's (implicit) question

Vienna-Leopold-Müller Lecture

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1.0 Abstract

In founding the ISRM in 1962, Professor Leopold Müller identified inability to determine the strength of a rock mass as the most important obstacle to progress in rock mechanics. After first paying tribute to the exceptional contributions of Austrian scientists and engineers to geomechanics, the Lecture describes the introduction of discontinuum modelling and the Discrete Element Method in rock mechanics. A few examples of significant problems addressed by Itasca's DEM codes are described. The Lecture concludes with a brief outline of the most recent development, the Synthetic Rock Mass (SRM) model, that is a major advance towards solving *Müller's problem*, viz. determination of the strength of a rock mass. References to key articles are provided so that readers can study additional details of the SRM.

1.1 Introduction.

It is both a privilege and an honour to be invited to present the First Vienna-Leopold-Müller Lecture. Professor Müller was an inspiration and friend to me, especially during the period 1958 -1970, formative years for the "art and science" of rock mechanics. I was privileged to be invited by Dr Muller, during his visit to the US to attend the Third US Symposium on Rock Mechanics, Golden, Colorado, in 1958, to join the "Salzburger Kreis" (Salzburg Circle), a predominantly Austrian group formed to discuss critical issues of rock mechanics and rock engineering. The decision to establish the International Society for Rock Mechanics in May 1962 was an outgrowth of these discussions. Many of the first group of ISRM members came from the Salzburg Kreis. Figure 1 shows the official ISRM list of the first twenty members. I was privileged to be included.

Much of the literature on engineering geology rock mechanics, especially as it related to the challenge of determining the in-situ behaviour of rock, had been published in the journal *Geologie und Bauwesen*, started and edited by Professor Josef Stini from 1929. Professor Müller took over as editor on the death of Professor Stini in 1958. In 1963, Professor Müller kindly invited me to assist him in extending the international reach of the journal, renamed '*Rock Mechanics and Engineering Geology*' (Figure 1). Currently known as '*Rock Mechanics and Rock Engineering*', the journal is now established as one of the most renowned international journals in rock mechanics and rock engineering.

The enormous debt of the international geomechanics and geotechnical engineering community to Austria is demonstrated by Figure 2. It is truly remarkable that the founders of the disciplines of Engineering Geology (Stini), Soil Mechanics (Terzaghi)¹, and Rock Mechanics (Muller) – each now represented by an International Society,² were all from Austria. The challenges of developing roads,

¹ Although the founder of the discipline of soil mechanics, Terzaghi influenced rock mechanics in the USA in his early years there. (see Appendix 2)

² International Association for Engineering Geology and the Environment (IAEG) [founded 1964]; International Society International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) [founded 1936];

railway tunnels, dams and other civil works through the mountainous Alpine terrain - and, earlier still, mines³ - provided the stimulus. (Tentschert, 2000).

International Society for Rock Mechanics

Early Members

- 1 - Prof. Leopold Müller, Austria
- 2 - Mr. F. Pacher, Austria
- 3 - Prof. L. V. Rabcewicz, Austria
- 4 - Mr. C. Lorber, Austria
- 5 - Prof. F. Kahler, Austria
- 6 - Dr. W. Zanoskar, Austria
- 7 - Mr. W. Finger, Austria
- 8 - Dr. A. Fuchs, Austria
- 9 - Prof. F. K. Müller, Austria
- 10 - Mr. P. Reska, Austria
- 11 - Dr. K. Waschek, Austria
- 12 - Prof. G.B. Fettweis, Austria
- 13 - Dr. Georg Beurle, Austria
- 14 - Neue, Reformbaugesellschaft MbH, Austria
(Supporting Member)
- 15 - Dr. Alois Kieser, Austria
- 16 - Prof. H. Seelmeier, Austria
- 17 - Dr. Adolf Bretterklieber, Austria
- 18 - Mr. W. Wessiak, Austria
- 19 - Prof. A. Watznauer, East Germany
- 20 - Prof. Charles Fairhurst, USA

Journal

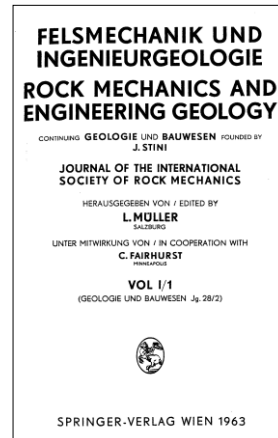


Figure 1. Early members of the ISRM.

(The German structural geologist, Prof. H. Cloos is credited with introducing the term 'geomechanics'.)

Professor Müller officially registered the International Society for Rock Mechanics in Salzburg on May 24, 1962. He and his colleague, Dr. Franz Pacher, were interviewed later the same day on a Salzburg radio station. The transcript of the interview is now part of the official records of the ISRM, on file at the ISRM Secretariat in Lisbon.⁴ A copy of the original German version of the interview, together with an English translation, is shown as Appendix 1 to this paper. In the interview, the reporter asks

International Society for Rock Mechanics (ISRM) [founded 1962]. Co-ordination between the three Societies is maintained through the recently established Federation of International Geo-engineering Societies (FIGS).

³ The Celts mined salt in Hallstatt, Austria around 1000 BC. The oldest salt mine in the world, salt is still being extracted, now by solution mining. There is a fascinating Celtic Mine Museum.

⁴ I am grateful to Senora Maria de Lourdes Eusebio and Dr. Luis Lamas of ISRM for providing me with a copy of this interview

For a billion years the patient earth amassed documents and inscribed them with signs and pictures which lay unnoticed and unused. Today, at last, they are waking up, because man has come to rouse them. Stones have begun to speak, because an ear is there to hear them.

Hans Cloos. Conversations with the Earth , 4 (1885-1951)

"Geomechanics"



Prof. F. Stini.
Engineering Geology
(1883- 1958)
Geologie und Bauwesen 1929



Prof. Leopold Müller.
Rock Mechanics.
(1908-1988)



Prof. Karl von Terzaghi.
Soil Mechanics
(1883- 1963)

Figure 2. "Great things are done when men and mountains meet." (William Blake)

"Do we know the strength of rock?"

Müller replied: *"For rock (specimens) tested in the laboratory, yes.*

For a rock mass, no.

This is what we need to determine.

This is why we need an International Society for Rock Mechanics."⁵

This succinct statement defines what Müller considered to be the central question in rock mechanics:

"What is the strength of a rock mass?"

It seems appropriate, almost 50 years after Prof. Müller first defined this as the main challenge in rock mechanics, to consider how far we have come in answering the question.

Most of the material presented in my Lecture is derived from the work of colleagues at Itasca. Of course, there have been significant contributions from colleagues in other groups. I hope that my presentation will stimulate them to publish, thereby helping develop a more robust response to Müller's challenge.

⁵ Translated literally "Internationale Versuchsanstalt für Fels" is 'International Research Institute for Rock' but Professor Müller is clearly referring to "The International Society for Rock Mechanics" (Der Internationalen Gesellschaft für Felsmechanik) that he had just established.

2.0 Discontinuum Mechanics.

In his Opening Address at the First ISRM Congress in Lisbon, then ISRM President Müller stated

“Many experts agree with me that discontinuity and anisotropy are the most characteristic properties of the material rock and that the properties of jointed media depend much more upon the fabrics bond of the unit rock block system than upon the rock material. Therefore any theoretical investigation of that material has to go its own ways, in the same way as the construction material of soils years ago suggested to soil mechanics its own methods, which differ greatly from the way of thinking of technical mechanics”.

The dominant influence of “discontinuity and anisotropy” and associated scale effect is, of course a significant difference between rock mechanics and soil mechanics, alluded to in Müller’s comment.

Two years later, Trollope (1968) noted

“In the field of geomechanics, granular media and block-jointed rock masses are obvious examples where the concept of the ideal physical continuum –one in which no gaps are formed - cannot be expected to apply....The clastic [i.e. discontinuum] model offers an alternative approach. Indeed it is this writer’s view that only with clastic models or some further development thereof can the problem of predicting the complete load-deformation of solids be tackled optimistically.”

In 1971, Peter Cundall, then a student of Prof E. Hoek at Imperial College, London presented the paper “A Computer Model for Simulating Progressive Large Scale Movements in Blocky Rock Systems” at the ISRM Symposium in Nancy, France. This introduced ‘discontinuum analysis’ to rock mechanics. Joining the University of Minnesota in 1972, and Itasca in 1981, Cundall and his colleagues have continued to develop the ‘discrete element method’ for modelling of jointed rock to the present time. Combined with (i) major and continuing advances in computational power and (ii) field testing of the modelling approach, determination of the strength and full constitutive behaviour to collapse –of a rock mass is now a realistic possibility.

2.1 Empirical Rules and Classification Systems.

Lack of an adequate theoretical foundation on which to base design procedures leads inevitably to the development of empirical rules to help inform design. This is the case where the mechanical behaviour of the material is as complex as rock in situ. An important limitation of empirical rules (one that is not always respected) is that they should not be relied upon outside the boundaries within which the data used to develop the rule has been gathered. With many rock engineering projects moving beyond the bounds of experience it is imperative that we now develop a more rational framework for design. Given the better theoretical framework that is becoming available, it is important to re-examine these rules. They do have value in that they are based on observations and data from field-scale projects, and can serve to validate the basis for the theoretical predictions.

Some examples of recent developments and applications with respect to determination of the mechanical behaviour of rock in situ are presented below.

2.2 Maximum Earthquake at Proposed Yucca Mountain Repository, Nevada, USA.

Estimation of the maximum ground motion during an earthquake to which a proposed high level nuclear waste repository could be subjected during the one million year (statutory) lifetime of the repository is required as part of the determination of the suitability of the site. Since records of ground motions during earthquakes are available typically for the order of 100 years or less, estimates of possible motions over the much longer times required have been made on the basis of statistical extrapolation of existing records. Under US regulations any ground motion with a probability of occurrence less than 1 in 10,000 over 1000 years (i.e. 1×10^{-8} per year) is considered to be negligible.

Initial estimates were developed on the basis of opinions of a selected group of geophysical experts in 'strong motion' earthquake events. With no such events recorded directly at Yucca Mountain, estimates were made on the basis of statistical extrapolation of records at a variety of locations world-wide. Results of this procedure are shown as the 'unbounded hazard' curve in Figure 3, expressed in terms of peak particle velocity (ppv) of the shear wave arriving at the site. It is seen that the predicted motions for the lowest probability events are extremely high. It was acknowledged by the experts that these motions appeared to be unrealistically high - and perhaps not physically possible - but, without further constraints on the geophysical data, the statistical extrapolations appeared to be appropriate.

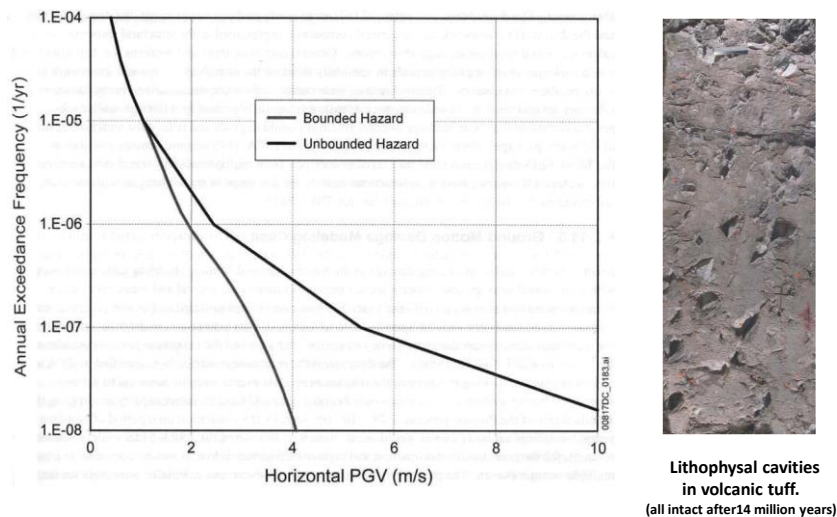
Geomechanics evidence was introduced to assist in constraining the geophysical estimates. It was noted that the shear strengths of the bedded tuff formations in the vicinity of the repository are low and will decrease as the surface is approached, since the normal pressure acting across the layers (the 'overburden stress') will also decrease.

A two-dimensional discrete element model (UDEC) was constructed (Figure 5) of the Prow Pass volcanic tuff unit to simulate the response of this unit to dynamic loading in shear. Different distributions of intact bridges (blue in Figure 5) were considered along joint systems observed in the tuff.

The results of a typical simulation are shown in Figure 6. It is seen that the unit deforms inelastically i.e. dissipating energy as it is deformed by the incoming earthquake shear wave train.

Also, it was observed in the tunnels underground at Yucca Mountain that several of the tuff layers contain an abundance of lithophysae - essentially gas bubbles developed during volcanic deposition of the tuff, that were 'frozen' into the formation as the lava cooled some 14 million years ago.

The lithophysae range in linear dimension from a few centimetres to half a meter or more. A section of the rock showing lithophysae is shown in Figure 3. Examination of the lithophysae revealed that they are intact, with no indication of any damage. Analysis (Lin, Board et al. 2007) indicates that the lithophysae cannot sustain a ppv in shear of more than 2m/s (and probably less) without damage. This indicates that the lithophysal units have not experienced a ppv in shear of more than 2m/s in 14 million years.



Unbounded hazard—statistical extrapolation of earthquake data (~75 years) to one million years.
Bounded hazard— shear wave ppv limited due to limited strength of the rock mass.

Figure 3. Predicted peak particle velocity (ppv) at Yucca Mountain, USA.

Taken together, the UDEC demonstrations and the existence of the intact lithophysae provide sufficient evidence to bound (conservatively) the peak particle velocity to 4m/s at a probability of 1×10^{-8} per year, as shown by the 'bounded hazard' curve in Figure 3. This is a much more realistic upper bound.

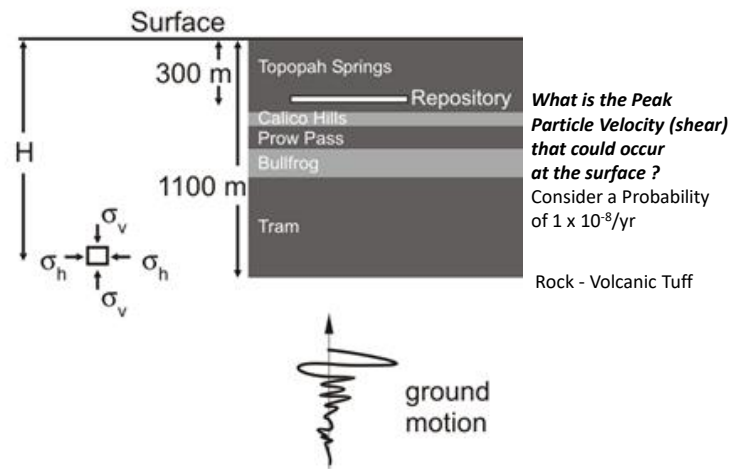
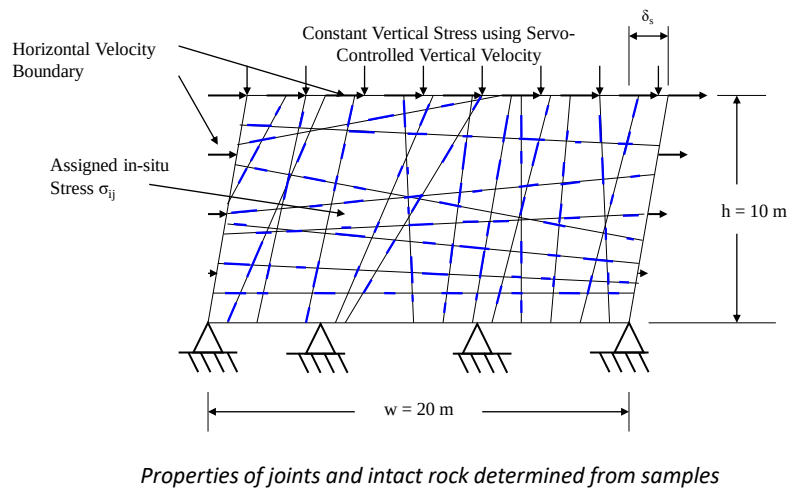


Figure 4. Factors affecting earthquake potential at Yucca Mountain.



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Figure 5. Conceptual UDEC model of field-scale direct shear test.

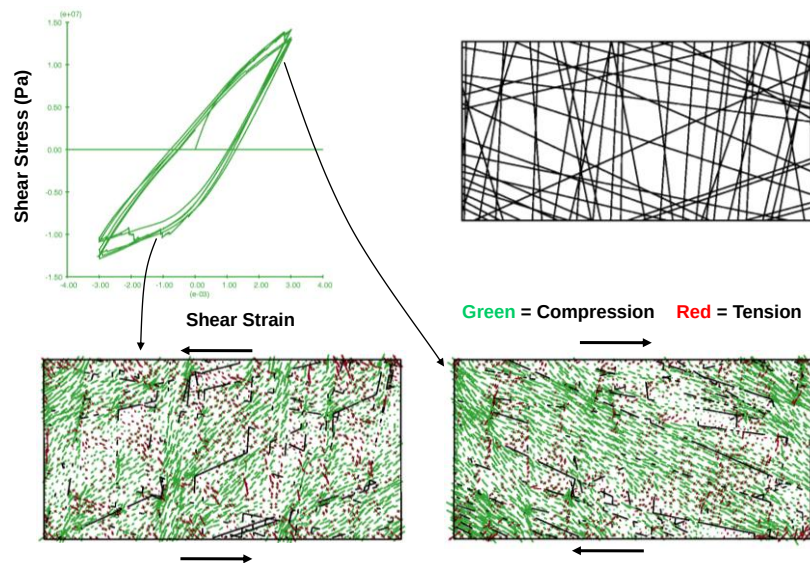


Figure 6. Results from a simulated UDEC cyclic shear test on the Prow Pass Unit of Yucca Mountain - for a maximum shear strain of 0.3%.

3.0. The Synthetic Rock Model (SRM).

The procedure for simulating rock bridges between non-persistent joints in the UDEC modelling procedure in the previous example (see Figure 5) assumes that the joints and bridges are co-linear and that the bridges will fail as the joints. Geological field evidence indicates that this 'single line of failure' is usually not observed.

The Synthetic Rock Mass (SRM) model, developed recently, follows a different approach which, among other advantages, allows disintegration of rock bridges to develop in a 'more natural' manner (Cundall 2008; Pierce et al. 2009a; 2009b).

The rock mass is assumed to be composed of two principal components, viz (1) intact rock and; (2). a system of joints (see Figure 7). It is assumed that the constitutive behavior of the intact rock can be determined from standard laboratory tests in which the 'complete stress-strain response' is observed.

The intact rock is represented in the model by an assembly of circular discs [in 2D analyses] or spheres [3D analyses] bonded at the contacts. These discs/spheres interact through contact stiffness, exhibit strength through contact bonds and particle friction, and develop damage through fracture of bonds. The deformability and strength of the intact rock are defined by calibration of the bond properties such that the overall deformation behavior of the model matches that of the laboratory specimens. Full details of the particle-particle interaction logic are provided in the codes PFC2D, and PFC3D. Latest versions 4.0 (Itasca 2008) (Itasca 2008).

The joints are introduced into the intact rock model through the Smooth Joint Model (SJM) which allows slip and opening on joint planes, avoiding the "bumpy-road" effect when model joints in PFC were required to pass around particle contacts.

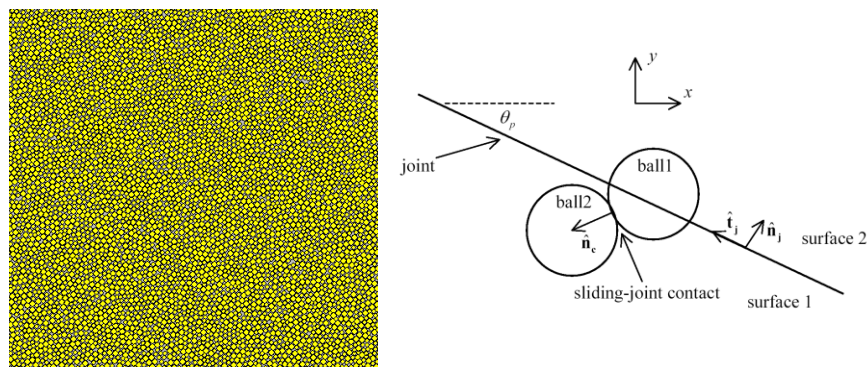
Systems of joints are determined from field observations of joint orientations, from which a Discrete Fracture Network (DFN) is constructed. The DFN provides a statistical representation of the system of joints in the rock mass. Joints can be non-pervasive and non-collinear, with bridges of intact rock between large scale discontinuities. These discontinuities are 'imposed' on the intact rock system to form the SRM. Joint mechanical properties are determined from laboratory measurements.

Figure 8 illustrates an SRM model developed to represent a very large rock mass (km scale) to examine the predicted deformational response of the rock as a large open pit is progressively excavated. It is seen that this model includes a very large number of discontinuities⁶.

With the model thus defined, the pit was 'excavated' [on the computer] progressively, down to the final profile.

Figure 9 (c) illustrates the additional detail - of discontinuous slip along joints above the basal slip circle surface indicated in the FLAC continuum analysis.

Figure 10 shows an enlarged detail of a bench from the model, indicating joint slip – and a photograph of similar behaviour on an actual slope. Such discontinuous deformation mechanisms are often critical to the stability of rock slopes, indicating the value of the discontinuum models.



Intact rock + **Smooth Joint Model applied to elements of fracture network.**

Properties derived from laboratory tests Fracture systems determined in field observations

Figure 7. Components of the Synthetic Rock Mass (SRM) model.

⁶ With this much detail, the excavation analysis was restricted to two dimensions.

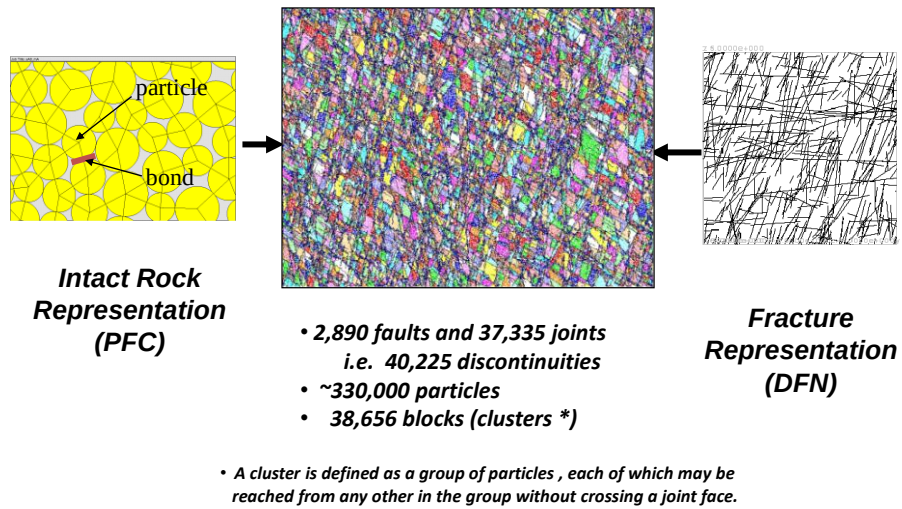


Figure 8 Application of the SRM to modelling of a large open-pit slope; development of the model.

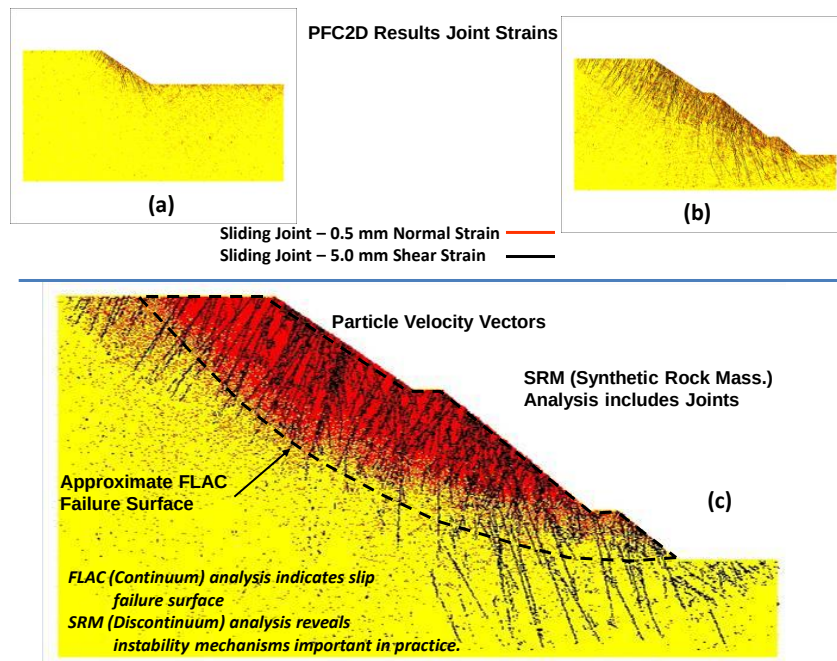


Figure 9. Excerpts from observed SRM results: (a),(b) two stages in excavation of the model pit slope; c) comparison of the discontinuum (SRM) and continuum (FLAC) analyses.

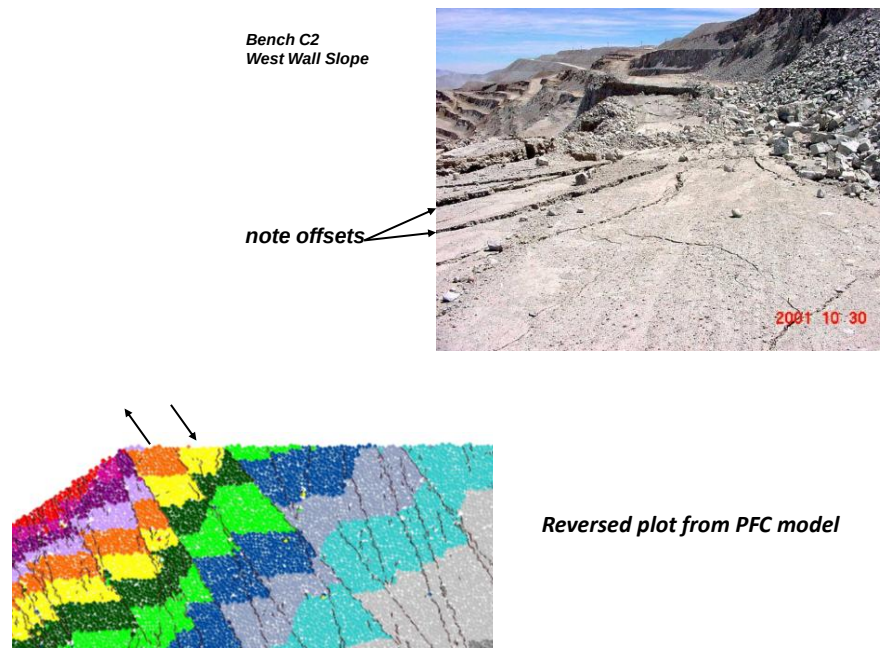


Figure 10. Comparison of model predictions with observed behavior.

3.1 Example of Use of the SRM in Evaluating an Empirical Model – GSI.

The Geological Strength Index (GSI) is an established procedure for estimating the strength of a rock mass based on an estimate of the average joint spacing and on the condition of the surfaces. In an attempt to be more quantitative Cai et al.(2004) replaced joint spacing by block volume on the vertical axis (Figure 11) and the surface quality by a Joint Condition Factor (J_c) on the horizontal axis.

Figure 11(b) shows how the strength is estimated to decrease with decrease in block size relative to the scale of the problem (here a tunnel of 5 m diameter).

Cundall et al (2008) have used the SRM to estimate the strength of three rock types, Carbonatite, Micaceous Pyroxenite and Dolerite, associated with a caving project in Australia. The following extract from this 2008 publication indicates the essential difference between the SRM and empirical approaches i.e. the strength - size is determination is based primarily on measured properties rather than qualitative judgment.

Due to the large joint sizes ..., a large generation volume equal to a cube of edge-length 100 m was employed for the Carbonatite and Micaceous Pyroxenite. A smaller cube of edge length 50 m was used for the Dolerite, which had greater fracture frequency.

The microproperties controlling strength and stiffness of the bonded particle assembly (representing intact rock) were obtained via calibration to measured intact rock properties using the standard procedures outlined by Potyondy and Cundall (2004). The target intact rock properties (unconfined compressive strength (UCS), Young's modulus and Poisson's ratio) were established by scaling the properties obtained from standard uniaxial-compression tests on core samples to what might be expected for an average-sized rock block within each lithology, estimated from the mean joint spacing. ... target and calibrated values for UCS, Young's modulus and Poisson's ratio [were

determined] for the three rock types (Carbonatite, Dolerite and ...All calibrations were performed with PFC3D.... [Cundall et al.2008]

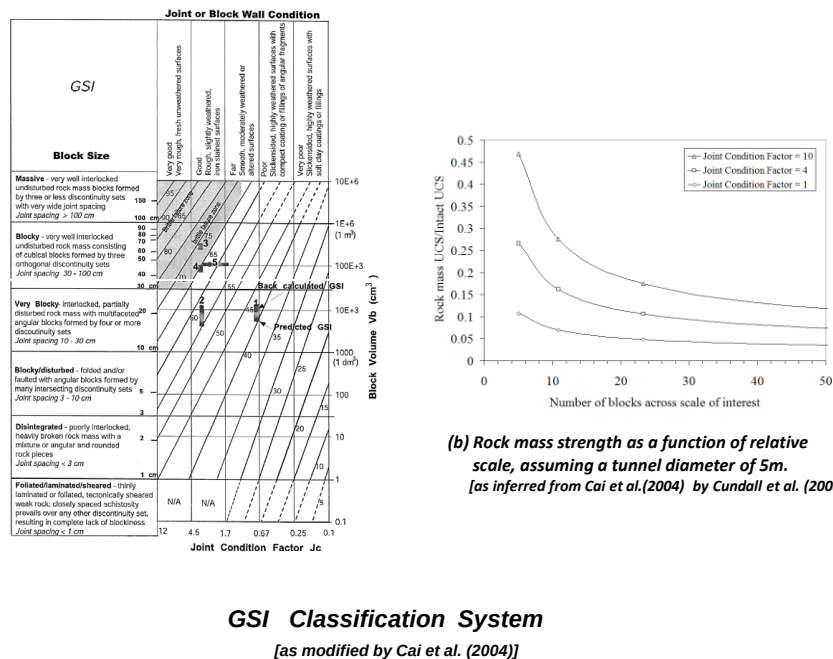


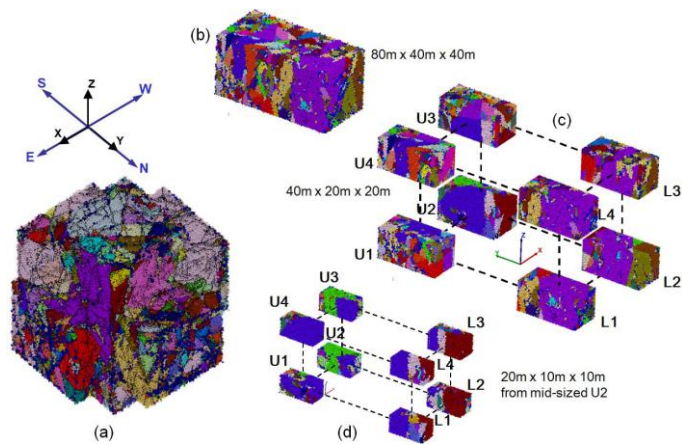
Figure 11. GSI Empirical System for Estimation of the Strength of a Rock Mass

Based on the intact rock properties and a DFN for each rock type, an SRM was developed for each. Generic 80m cubes were then produced for each rock mass.

....The next step involved carving three 80 m x 40 m x 40 m parallelepiped samples from the centre of the generic 80 m cube in the three axial directions (half this size for the Dolerite samples). After that, each of these three large samples was divided into eight medium-sized samples. Finally, one of the medium-sized samples in each of the axial directions was subdivided into eight small parallelepiped samples. In this manner, a total of 51 specimens of 2:1 aspect ratio were generated for each lithology: 24 small-sized specimens (8 in each axial direction); 24 medium-sized specimens (8 in each axial direction); and 3 large-sized samples (1 in each axial direction). The 51 specimens then were submitted to numerical simulations of direct tension, UCS and triaxial compression (5 MPa confinement). (Cundall et al. (2008)

The process of progressively subdividing specimens is illustrated in Figure 12.

It is seen that the decrease in strength (Figure 13) is qualitatively similar to the GSI trend estimated qualitatively [Figure 11(b)]. The important difference is that the SRM approach is based on a clear quantitative model of the rock mass and computational procedure. This is considered to be a significant improvement.



3D Numerical Modeling of Size Effect in Jointed Rock. Cundall et al. (2008)

Figure 12. Determination of Size Effect in a SRM model.

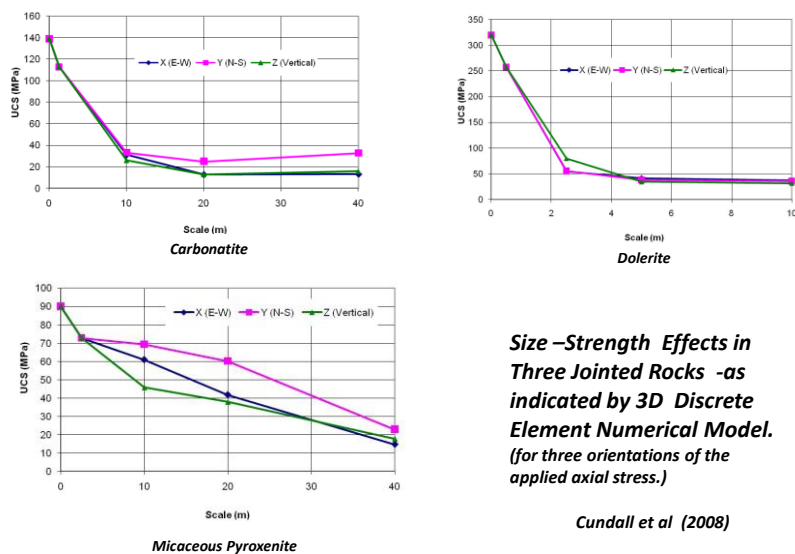


Figure 13. SRM Model results of the Effect of Size on Strength.

Fracture Network Engineering – An example of further SRM development.

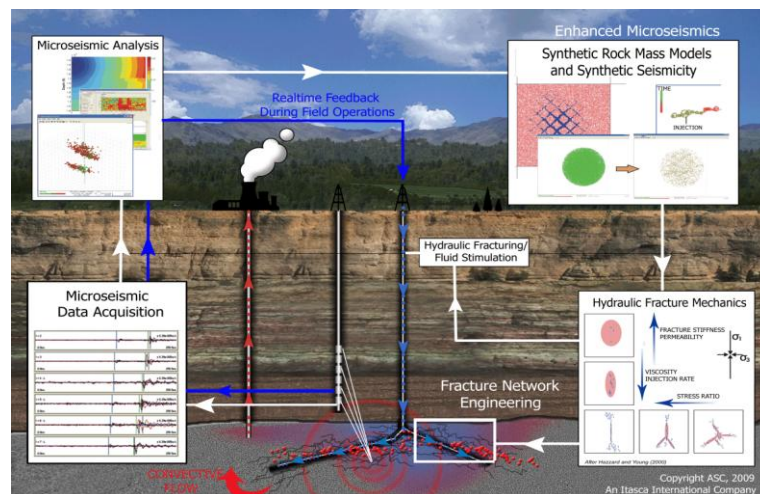
An important attribute of the explicit finite difference calculational procedure followed in all Itasca codes is that they are fully dynamic, so that processes associated with such events as micro-cracking and wave propagation can be modeled readily (e.g as in the discussion earlier of seismic wave propagation at Yucca Mountain)

The current emphasis on development of alternative energy sources suggests further applications of the SRM model, as illustrated by the following example, proposed with respect to monitoring and engineering of controlled fracture growth in order to develop flow networks for effective extraction of heat from geothermal reservoirs.

Work to date in conjunction with Applied Seismology Consultants (ASC)⁷, has allowed microseismic waveforms predicted by a PFC model of a rock mass to be compared with those observed in the field during rock fracturing.

The system shown in Figure 14 suggests that with the SRM procedure, it should soon be possible to monitor fracture development in situ and, via rapid feedback, modify the fracture stimulation procedure so as to control fracture growth. Development of this concept is being pursued.

Stones have begun to speak, because an ear is there to hear them.
Cloos, Conversations with the Earth (1954), 4
Microseismicity –predicted and observed.



Fracture Network Engineering. Synthetic Rock Mass and Synthetic Seismicity Models are compared with observed microseismic signals for real time control of fracture network development. (Enhanced Geothermal Systems.)

Figure 14. Fracture Network Engineering- an application of combined SRM and Synthetic Seismicity models to ‘engineer’ (i.e. predict, observe, correct and control) fracture development in situ.

⁷ ASC is now an integral part of Itasca.

4.0 Conclusions.

- Advances in computer power and discontinuum modeling have allowed development of tools for making more reliable assessments of the strength and general constitutive behavior of a rock mass. Such assessments provide a more rational framework for rock engineering design than current empirical rules.
- An important attribute of the SRM procedure is that it allows easy replication of results using ranges of input parameters in order to provide an estimate of the overall uncertainty –or reliability –of design predictions
- The critical next step to advance of rock mechanics and rock engineering is to obtain reliable field-scale data to verify and improve numerical predictions. Urgent attention should be given to developing cost-effective ways to obtain such data.
- Underground laboratories such as DUSEL (and other URLs) serve a major role in field validation of theoretical development, but will be most effective when linked to observations in conjunction with rock engineering projects.
- As rock mechanics turns its focus to field scale, close interaction with Engineering Geology is essential for optimum advance.
- The major roles of discontinuum mechanics and numerical modelling should not overshadow the rich heritage and essential complementary roles of classical closed form and continuum analysis in rock mechanics.
- As ISRM enters its second half-century it can best acknowledge the vision of its founder, Professor Leopold Muller by pursuing vigorously the focus on understanding the “mechanical behaviour of the rock mass”.

5.0 Acknowledgments.

This Lecture has drawn heavily on the work of colleagues at Itasca Consulting Group Inc. and its partner Applied Seismology Consultants. This assistance is gratefully acknowledged.

My daughter Anne Charlet and Dr. Alfred Zettler kindly prepared the English translation of Prof. Müller's radio interview. Frau Christine Cerny, Secretary to Prof. Poisel has been very patient and understanding during preparation of this manuscript.

It was also an honour to be allowed to present this Lecture as part of the celebration of the 60th birthday of my long-time colleague and friend Prof. Rainer Poisel. Herzlichen Glückwunsch zum Geburtstag, Rainer!

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Appendix 1.

Radio interview by Prof. Leopold Müller, Salzburg, May 24, 1962, on the occasion of officially registering ISRM as an International Society.

(a) Original German Text:

Hinweis: Kursiv gedruckte Wörter wurden in den aufgenommen Text hinzugefügt, um die Sätze für die Übersetzung ins Englisch ausfüllen. . .

N.B. Words in italics have been added to the original transcript of the interview, and incorporated into the English translation.

Rundfunk Interview, gesendet am 24.5.1962, 19:40. 1. Program

- Reporter: « Internationale Gesellschaft für Felsmechanik » - Was ist Felsmechanik?
- Pacher: Die Wissenschaft vom mechanischen Verhalten des zerklüfteten Gesteins gegenüber Kräften, Beanspruchungen und aufgezwungenen Formänderungen.
- Reporter: Welche praktischen Auswirkungen und Aufgaben hat die Felsmechanik?
- Pacher: Auf der Grundlage einer theoretisch richtigen und praxisnahen Felsmechanik lassen sich Fundierungen von Seilbahnstützen und Staumauern in Fels mit größerer Sicherheit berechnen; aber auch die Verkleidung von Tunneln, größeren unterirdischen Hohlräumen usw. lässt sich rechnerisch erfassen, so dass sie in der wirtschaftlichsten Weise und vor allen ohne Gefahr durchgeführt werden können.
- Reporter: Das ist also etwas ganz Neues? Dann möchte ich fast vermuten, dass Malpasset der Anlass war?
- Müller: Nicht so neu. In Salzburg gibt es schon seit 1951 die „Internationale Arbeitsgemeinschaft für Geomechanik“ mit den gleichen Aufgaben. Vor 4 Jahren wurde in Berlin das „Internationale Büro für Gebirgsmechanik“ der Deutschen Akademie der Wissenschaften“ gegründet, bei welchem wir auch vertreten sind. Die Welt (z.B. Kongresse) hat von uns wenig Notiz genommen. Die « Internationale Gesellschaft für Felsmechanik » soll nun eine breitere Basis darstellen.
- Reporter: Was ist denn Bodenmechanik und was ist Geomechanik?
- Müller: Bodenmechanik befasst sich mit Lockermassen, Sand, Ton, usw. Geomechanik ist Mechanik der festen Erdkruste, umfasst auch die Entstehung der Gebirge und *die* Erklärung der *gebirgsbildenden* Vorgänge, soweit sie mechanisch zu verstehen sind.
- Reporter: Kann man denn solche Dinge berechnen?
- Pacher: *Ein* Beispiel ist die Fundierung einer Staumauer wie Malpasset. Die Kräfte sind bekannt, der Fels kommt unter zusätzliche Spannungen und der Vergleich mit den Festigkeiten zeigt, ob er ihnen gewachsen ist.
- Reporter: Zum Begriff der Sicherheit. **Sind denn die Festigkeiten der Gesteine bekannt?**
- Müller: **Für das Gestein, getestet in Labors, ja. Für das Gebirge nein. Diese Festigkeit muss geprüft werden. Daher brauchen wir eine „Internationale Versuchsanstalt für Fels.“**
- Reporter: Was sind die Ziele der Gesellschaft?
- Müller: *Foren*, Tagungen und das Kolloquium im Oktober. Ferner Publikationen und Forschungsvorhaben. Einheitliche Auffassungen, Bezeichnungen und Normen.

Reporter: Warum gerade in Salzburg?

Müller: Alle Baugrundwissenschaften sind von Österreich ausgegangen, Terzaghi – Stini – Geomechanik. Die Österreicher wissen gar nicht, dass sie auf diesen entscheidenden Gebieten führend sind und dass die ganze Welt dies anerkennt. In der Bodenmechanik wurde die Führung abgegeben, Terzaghi ging in die USA.

Hoffentlich gibt man uns die Mittel, führend zu bleiben, wie z.B. unsere Erfolge in Japan. Ob das so bleibt, hängt nicht von uns alleine ab, sondern auch davon, ob der Staat und das Land für diese speziell österreichische Wissenschaft und für die Wissenschaft überhaupt etwas tun.

(b) English Translation

Radio Interview. Broadcast on 24.5.1962, 19: 40 Prog.1	
Reporter:	"International Society for Rock Mechanics." What is Rock Mechanics?
Pacher:	The scientific discipline that studies the response of jointed rock when subjected to forces.
Reporter:	What are the practical results and problems of Rock Mechanics?
Pacher:	Based on fundamental theoretical and practical Rock Mechanics, we are able to design foundations for cable-car pillars and arch dams in rock with a higher factor of safety. Tunnel linings, large underground excavations, etc. can also be calculated mathematically so that we can design economically and, above all, we can develop designs that are safe.
Reporter:	Is this something new? Can we say that it has been stimulated by Malpasset?
Müller:	Not so new. In Salzburg, the "International Working Group on Geomechanics" has been working on these problems since 1951. Four years ago, the International Bureau for Rock Mechanics was founded as a part of the Germany Academy of Sciences; we are part of this group. So far, the world has taken little notice of us. But the "International Society for Rock Mechanics" will provide a wider sphere.
Reporter:	So what is Soil Mechanics and what is Geomechanics?
Müller:	Soil mechanics is concerned with softer, porous materials such as sand, clay etc. Geomechanics deals with the mechanics of the earth's solid crust, incorporating also mountain-building and understanding of the associated mechanical processes.
Reporter:	Can we calculate such things?
Pacher:	Consider the Malpasset Dam foundation, for example. The forces are known, the rock is subjected to additional stresses and comparison of these with the strength shows whether or not the rock strength is adequate.
Reporter:	With respect to safety. Do we know the strength of rock?
Müller:	For rock (specimens) tested in the laboratory, yes. For a rock mass, no. This is what we need to determine. This is why we need an 'International Research Institute for Rock'.

Reporter:	What are the aims of such an organization?
Müller:	Forums –meetings and the Colloquium that we hold every October. These will lead to publications, research activities, uniform concepts, denominations and standards will be developed.
Reporter:	Why in Salzburg?
Müller:	All of the basic knowledge for construction in soil and rock has been developed in Austria- Terzaghi, Stini; Geomechanics. Austrians do not appreciate that we are definitely the leaders in this field, and recognized as such world-wide. We gave up this lead in soil mechanics when Terzaghi went to the USA. We hope that we will be given the means to maintain our lead. We have succeeded in Japan. Whether that continues is not up to us alone, but depends also on whether the country and the state decide to do something for this Austrian scientific expertise, and indeed for Science in general.

Appendix 2.

Terzaghi Rock Load Approach to Tunnel Support Design.

When Dr. Terzaghi established the formal discipline of Soil Mechanics in 1936, after arriving in the United States, he did initially apply some of his ideas to rock - in particular to the problem of design of tunnel supports. (Proctor and White, 1948).

The Rock Load concept introduced by Terzaghi was widely adopted by tunnel support designers in the US, including the US Army Corps of Engineers. Terzaghi deduced the mechanics of loading on the basis of limit equilibrium analysis for soils, a series of laboratory trap-door experiments on sand and observations of the intensity of crushing of wooden blocking placed between the support and the rock. The load-deformation response of the blocks had been calibrated in laboratory tests.

The required support load was determined by the height D and width B of the column of failed ground above the excavation. D and B were functions of the rock type and condition.

The important fact to note is that the load was considered to be constant, independent of the deformation of the support (Figure A2-1). Subsequent revisions were made to reduce the computed loads, which were found to be higher than observed in practice, but the 'constant load' concept remained. The rock load and other approaches to support load calculation are discussed in more detail by Fairhurst and Carranza-Torres (2002). [See also <http://www.itascacg.com/about/ff.php>]

Terzaghi's analysis was a limit equilibrium analysis of shallow tunnels. As noted above, the load was assumed to be independent of the support deformation. It was usual that structural engineers designed tunnel supports for a fixed (dead) load. The geotechnical engineer's role was to provide the value of this load to the support designer.

In 1970, the author was asked to re-examine the mechanics of tunnel support loading by the US Army Corps of Engineers. The Ph.D. thesis by Daemen (1975) examined a number of published procedures, drawing particularly on publications by Fenner (1938), Labasse (1949-54) Talobre (1957) Pacher (1964) and Rabcewicz (1964-65) of the Convergence-Confinement Method were carried out for a variety of practical situations.

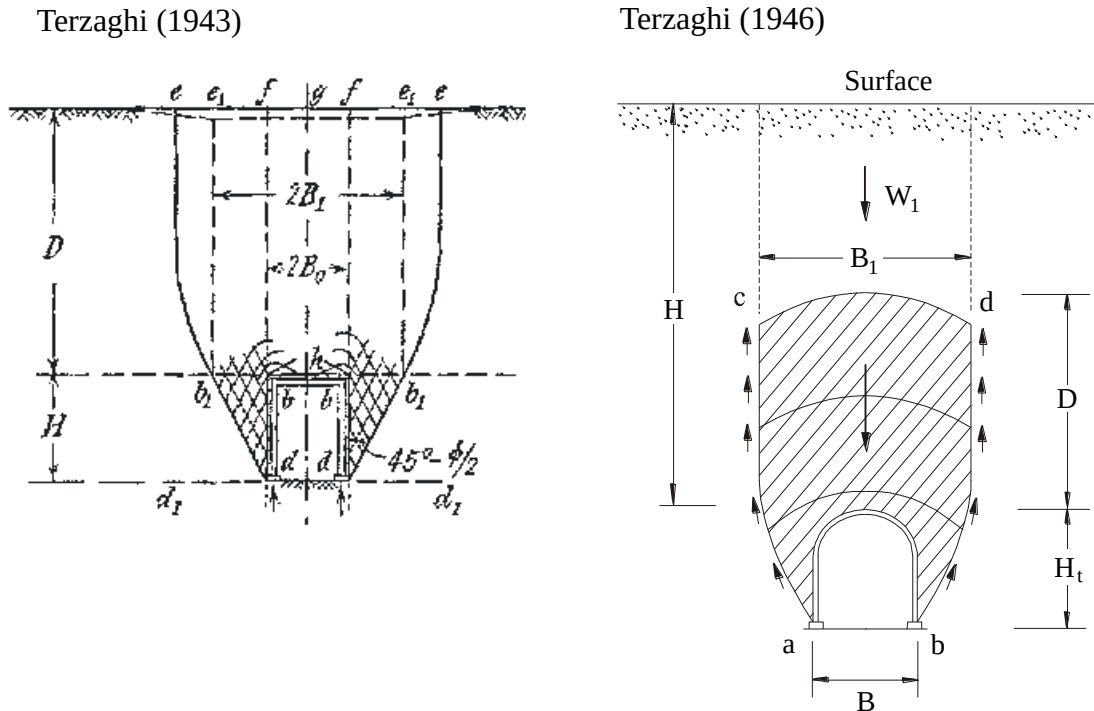
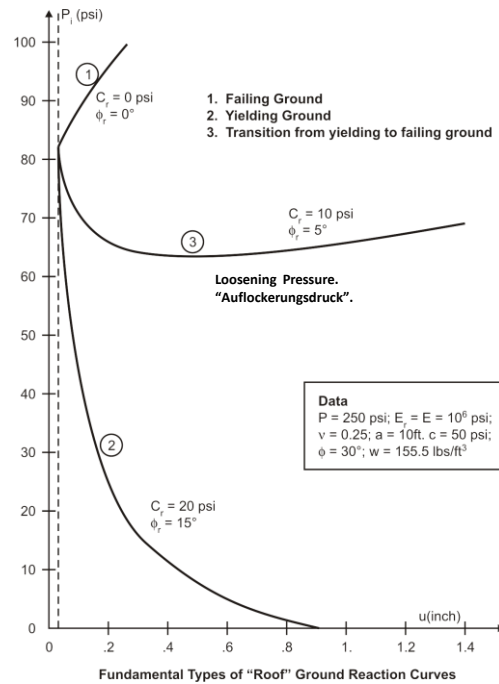


Figure A2-1. Terzaghi Rock Load Concept.

A design report was prepared later, based on the thesis, and intended to replace the Terzaghi approach. It was not adopted, since it was considered to be too theoretical for practical design. Interestingly, Daemen's thesis includes an analysis of the 'rock loosening pressure' phase of tunnel deformation presented by Pacher (1964) –The thesis demonstrates that this load increase with deformation has a sound theoretical basis and is quite possible under certain conditions.(Figure A2-2) Existence of such 'rock loosening' became a topic of heated discussion with respect to the New Austrian Tunnelling Method in the literature several years ago.

This example helps to illustrate the need for a separate field of rock mechanics, as alluded to by Müller, in the last sentence of the quote above viz. *"any theoretical investigation of that material [rock] has to go its own ways, in the same way as the construction material of soils years ago suggested to soil mechanics its own methods, which differ greatly from the way of thinking of technical mechanics"*.



Finally, and possibly most realistic or common, when a gradual strength loss occurs (or a fairly steep one but only well beyond the peak strength) the support pressure required in the roof can decline during the initial stage of nonelastic deformation but will increase beyond the point where the combined effects of strength loss and increased broken rock weight preponderate (curve 3). This is the shape of the ground reaction originally suggested by Pacher (1964) in his discussion of the influence of "genuine rock pressure" and of "loosening pressure" upon support requirements. Daemen, 1975

Figure A2-2. Rock Loosening –after Daemen (1975)