Geomechanics Challenges and its Future Direction – Food for Thought*

F. T. Suorineni

Suorineni F. T. (2013), "Geomechanics Challenges and its Future Direction – Food for Thought", *Ghana Mining Journal*, pp. 14 - 20.

Abstract

Geomechanics has proven to be the backbone of safe and cost effective mining practice. However, experience shows it still does not have the appreciation of most mine managements until there is a fatality or costly ore sterilization. The problem can be traced back to the training of mining engineers. The subject is also picked up later in life by other professionals with limited background in geology. The consequences of these limitations are lack of fundamental knowledge in the subject by some who practice it. This lack of understanding has affected the growth and maturity of the subject of rock mechanics, a key component of geomechanics. Today, we are beginning to understand that failure criteria that were inherited from soil mechanics for application to rock are wrong and misleading. Despite these problems, some major achievements have been made towards a better understanding of rock behavior under load. Many more challenges still lie ahead. This paper takes a look at the history of rock mechanics, and therefore geomechanics, its development, required training, present status and what lies ahead in the future. The goal is to provide educators, industry and practicing engineers what it takes to be a good rock engineer and the real benefits of the subject for the good of society.

1 Introduction

Even the definition of geomechanics is confusing. Is there a difference among geotechnology, geotechnical engineering, and geomechanics? Furthermore, is there a difference between engineering geology and geological engineering, areas also closely related to geotechnology, geotechnical engineering and geomechanics?

Historically, geotechnology and geotechnical engineering are courses or branches of civil engineering. Geotechnology often implies the study of soil mechanics. Until the 18th century, no theoretical basis for soil design had been developed, and the discipline was more of an art than a science, relying on past experience. Failure of important structural foundations such as the Leaning Tower of Pisa prompted the development of a more scientific approach to the use of soil mechanics. This initiative was led by Gauthier (1717) with the development of earth pressure theories and soil classification based on unit weight (Muni, 2007). This development was followed by the work of Coulomb (1773) and Mohr (1882). The Mohr-Coulomb failure criterion is well known in both soil and rock mechanics. Other contributors to the science of soil mechanics include Darcy, Rankine, Atterberg and Reynolds.

Advances in soil mechanics and foundation engineering peaked in 1925 with the publication of Erdbaumechanik by Karl Terzaghi (a civil engineer and geologist) who is commonly referred to as the father of soil mechanics and geotechnical engineering. Terzaghi was a mechanical engineer by training. Note now the use of the geotechnical engineering term. It was in 1963 Professor Bjerrum, from Norway, speaking on behalf of A. Casagrande (President of the International Conference on Soil Mechanics) brilliantly explained how rock mechanics should be integrated into soil mechanics as a mere chapter of a wider, more advanced technical science.

The links between rock mechanics, engineering geology, geological engineering and classical geology are intricate and complex. It is not possible to think about rock mechanics without examining and discussing these links.

Geotechnical engineering is soil mechanics and foundation engineering (VanDine, 1987). The principle of effective stress, bearing capacity theory, and the theory of consolidation are all attributed to Terzaghi. Roscoe *et al.* (1958) introduced the theory of critical state soil mechanics that is now the basis for many contemporary advanced constitutive models describing the behavior of soil.

Geomechanics is defined in Wikipedia as the geologic study of the behavior of soil and rock. Note the keywords in the definition as geology, soil and rock. While geotechnology and geotechnical engineering focus on soils, geomechanics combines geology, soil mechanics and rock mechanics. Hence, it is dangerous to be trained in geomechanics without a good background in geology. This is the focus of this paper.

The limitations in the knowledge of soil mechanics practitioners in geology prompted the introduction of the engineering geology profession. In 1951, one of the earliest definitions of "Engineering geologist"

* *Manuscript received February 10, 2012*
Revised version accepted April 7, 2012

was provided by the Executive Committee of the Division on Engineering Geology of the Geological Society of America as a geologist trained in the discipline of engineering geology. Emphasis is the person being a geologist first and then trained by practice in engineering. This background in geology provides the engineering geologist with an understanding of how the earth works, which is crucial in mitigating for earth related hazards. This training also enabled the geologists to effectively communicate with engineers. The need for geologist on engineering works gained worldwide attention in 1928 with the failure of the St. Francis dam in California and the loss of 426 lives. Commenting on the disaster Ransome (1928) wrote “so far as can be ascertained, no geological examination was made of the dam-site before construction began. The plain lesson of the disaster is that engineers, no matter how extensive their experience in building of dams cannot safely dispense with the knowledge of the character and structure of the adjacent rocks, such as only an expert and thorough geological examination can provide.” (Ransome, 1928).

Turning geologists into engineers solved some problems. The limitations of this approach originate from the fact that the so called engineering geologists had difficulties in integrating design principles into their evaluations to appreciate and understand the demands and frustration and the burden of the engineer as being the safe keeper of society. Price (2009) states:

“Engineering geologists” are essentially geologists who deliver basic geological data to engineers, without interpretation.”

Few geologists had sufficient engineering knowledge to understand the requirements of the engineer, and few engineers had more than the most superficial knowledge of geology. It was then thought that to resolve the issue, it is best to train someone simultaneously with engineering and geological principles at the same time. The geological engineering profession was born.

Mathews (1967) describes the geological engineer best, when he stated that the geological engineer is one soundly trained in both geology and engineering fundamentals, and that that is the man, he believes, is best qualified to work closely with the civil engineer responsible for the execution of engineering works.

2 The Geological Engineer

The geological engineering profession is a versatile one (see Fig. 1). The following figure illustrates how versatile the geological engineering profession is. It is my belief that to be able to control or manage the earth, one must understand the earth. By the nature of the training of the geological engineer, he is able to understand the earth through his knowledge in geology and to manage it through his understanding of engineering principles.

Fig. 1 Versatility of the Geological Engineering Profession

3 Soil Mechanics Principles and Theories and how they have misled Rock Mechanics

The Mohr-Coulomb failure criterion is given by Equation (1).

$$\tau = c + \sigma_n \tan\phi \qquad (1)$$

where *t* is the shear strength of the soil, c is the cohesion of the soil. σ_n is the normal stress acting on the shear plane, and *f* is the frictional resistance of the soil.

Anyone who has sat in both a soil mechanics class and a rock mechanics class would have seen this equation at least twice, once in soil mechanics and a second time in the rock mechanics class.

Equation (1) implies that the shear strength of the material is due to the simultaneous mobilization of cohesion and frictional resistance or strength.

What is wrong in applying this criterion, which has its origin in soil mechanics, to rocks?

First, what is the definition of a soil? Second, what is the definition of rock?

Craig (2004) defines soil as any uncemented or weakly cemented accumulation of mineral particles formed by the weathering of rocks, the void space between the particles containing water and/or air. The key words in the definition of soil are “uncemented” and “accumulation of mineral particles”.

By the definition of soil, its shear strength can be mobilized by simultaneous activation of its cohesive and frictional strength. This is because of the fact that the particles are uncemented or weakly cemented, and therefore Equation (1) applies. On the other hand, by definition a rock is a naturally occurring and coherent aggregate of one or more minerals. The key words here are “coherent” and “aggregate”. Friction occurs when two or more surfaces rub against each other as will occur in soils because of their nature. However, in rocks free surfaces rarely exist until fracture occurs through breaking the cohesive bonding in the aggregate of minerals! Thus, the strength of rocks is NOT a simultaneous mobilization of cohesion and friction but successive destruction of cohesion followed by mobilization of the frictional strength due to the presence of free surfaces following the destruction of cohesion. Therefore, while Equation (1) may work for porous and some weakly cemented rocks it will definitely not apply to crystalline rocks (Fig. 2).

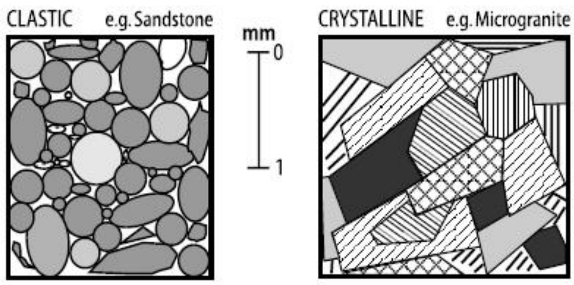


Fig. 2 Porous Rock (left) and Crystalline Rock (right) to which Mohr-Coulomb Failure Criterion may or may not apply

Martin (1993) showed that in massive, hard, brittle strong rock masses maximum friction and maximum cohesion are not mobilized simultaneously as Equation (1) shows, but that by the time friction is fully mobilized a significant portion of the cohesion has been lost (Fig. 3).

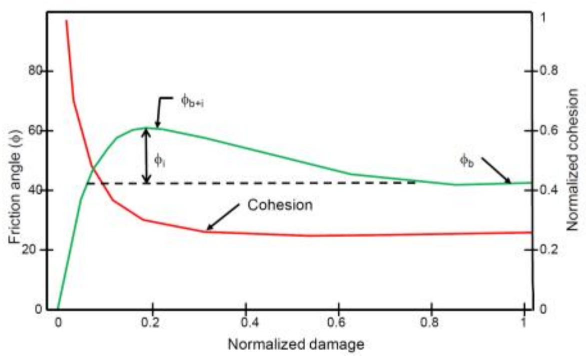


Fig.3 Cohesion Loss-friction Mobilization

$$\sigma_1^{'} - \sigma_3^{'} = \sigma_{ci}\sqrt{\frac{m\sigma_3^{'}}{\sigma_{ci}} + s} \quad (2)$$

$$\sigma_1 - \sigma_3 = \frac{\sigma_{ci}}{3} \quad (3)$$

where σ_1 and σ_3 are the induced major and minor principal stresses, and σ_{ci} is the uniaxial compressive strength of the intact rock.

Equation (3) implies that for massive strong brittle rocks friction plays little role in their failure. Note that Equation (3) was based on tests and observations on granite. Recent work by Suorineni *et al.* (2009) showed that Equation (3) is rock-type dependent, and is restated as follows:

$$\sigma_1 - \sigma_3 = A\sigma_{ci} \quad (4)$$

where A is a rock type dependent parameter.

Note that Equations (3) and (4) implicitly show the importance of understanding geology in engineering. They show that unlike Equations (1) and (2), for crystalline rocks a different failure criterion must be used.

Another demonstration of the importance of geology in rock mechanics and rock engineering is what was not reported at the test site where Equation (3) was developed. At the test site, a tunnel passed through the granite reported, that failed while the tunnel section that passed through a granodiorite did not fail (Fig. 4).

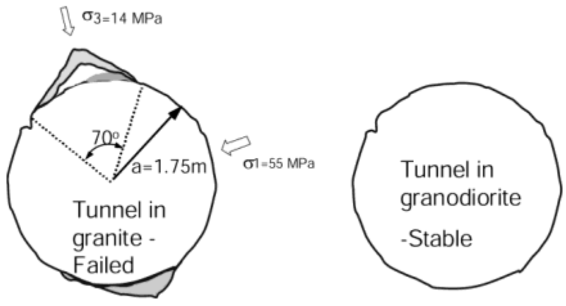


Fig. 4 Comparison of Tunnel Performance in Granite and Granodiorite (after Martin, 1993)

The granite and granodiorite have the same mineralogy, same strength and were under the same *in situ* stress state. The puzzling question at the time was why the granodiorite did not fail. The answer is simple to a rock engineer with good geological background. The granodiorite is fine-grained while the granite is coarse grained!

4 Rock Mechanics and Rock Engineering

“Rock mechanics is the theoretical and applied science of the mechanical behavior of rock; it is that branch of mechanics concerned with the response of rock to the force fields of its physical environment" (Judd, 1964).

Rock mechanics is still a relatively young subject compared to soil mechanics and geology, subjects it is closely intertwined with.

Price (2009) note that the present science of geology owes much of its origin to the civil engineers working in the eighteenth century. These engineers, while constructing the major engineering works associated with the industrial revolution, had the opportunity to view and explore excavations in rocks and soils. Some, intrigued by what they saw, began to speculate on the origin and nature of rocks, and the relationships between similar rocks found in different places. Their ideas and theories, based on the practical application of their subject, formed the groundwork for the development of geology as a science.

Like geology, the great names in rock mechanics are not geological engineers but either civil or mechanical engineers. Terzaghi and Hoek for example are mechanical engineers. They are very successful rock engineers because they learnt and paid particular attention to geology. Neville Cook was a geophysicist.

The same discoverers of geology also discovered rock mechanics as a unique subject. Unfortunately, because the theoretical understanding of engineering was driven by practical engineering problems, the geological knowledge of the engineer, confronted by increasingly difficult engineering challenges, did not progress as rapidly as geology and advanced as a science. Hence, by the end of the nineteenth century the majority of civil engineers knew relatively little about geology, and very few geologists were concerned about, or interested in, its engineering applications.

Today, many engineers continue to rely on inadequate geological knowledge, or over-simplified ground models in their designs. Failures of engineering works such as that of the Austin Dam in Texas in 1900 and the St. Francis Dam in California in 1928 showed that there was often a lack of appreciation of the importance of geological conditions in engineering design.

A review of rock mechanics papers in well renowned international journals demonstrates the ignorance of many so called rock engineers in geology. To most, the assumptions in rock mechanics that rock is a continuous, homogeneous, isotropic, linear, elastic, (CHILE) material are absolutely true. It was a disaster to ask a graduate student in an oral examination in rock mechanics to give the difference between rock and steel. This student had a first degree in civil engineering.

Geologists have their own limitations in engineering. It is frustrating when one asks a mine geologist for a rock type and he says "it is a metasediment"! Basic engineering knowledge should show that engineers need to know the specific type of metasediment. In Equation (1), c depends on the rock type. Knowing the rock type is also useful to an engineer with good understanding of geology. Knowing that the rock type at a planned tunneling route is shale, mudstone or olivine diabase or granite gives a knowledgeable rock engineer the opportunity to forecast the potential problems to be encountered without doing any tests.

4.1 Recognition of the significance of rock mechanics

The importance of rock mechanics in society, unfortunately, is only often recognized after a disaster, just as the subject was developed as a consequence of civil engineering disasters. The most recognized disasters that promoted the development of rock mechanics include:

1. The Malpasset concrete arch dam failure in France in 1959 resulting in a flood that killed about 450 people.
2. Vajont dam disaster in 1963 that killed 2500 people in the Italian town of Longarone.
3. In 1960 a coal mine at Coalbrook in South Africa collapsed with the loss of 432 lives.

   This event was responsible for the initiation of an intensive research program which resulted in major advances in the methods used for designing coal pillars (Salamon and Munro, 1967).
4. On 20th June 1984, a rockburst occurred at the then Falconbridge (now Xstrata) mine in an underhand-cut-and-fill stope killing four miners. Within the same period other large magnitude rockbursts occurred in Creighton Mine, Quirke Mine, Red Lake and Kirkland Lake mines, all in Ontario, Canada.

   As a result of these incidents the Stevenson Commission was established in 1985 to look into emergency preparedness and ground control to ensure that underground workers are safe.

   The Stevenson commission recommended improved rock mechanics programs in Ontario colleges and universities and for the establishment of a research institute in ground control to coordinate ongoing and future research. The Geomechanics Research Centre in Laurentian University was established as a result of these recommendations.

4.2 State-of-the-art of ground control in mines

Rock Mechanics as a science was formerly recognized in 1966 in Liege, Belgium, where the first rock mechanics conference was held.

Unfortunately, experience shows that the geotechnical positions in mines today exist because mines have to demonstrate their commitments to safety under government mining regulations only. Similar to rock mechanics being created and recognized out of disasters, ground control engineers at mines only get spotlights when disasters occur.

Career developments in geotechnical engineering departments in mines are nearly non-existent. There is no pathway from a ground control engineer to rise up to management. This has caused frustration in very competent rock engineers to leave that role and go into production roles where opportunities exist to higher officers. The situation is so painful when you hear management make statements like "you can train a monkey to be a ground control engineer"!

4.3 The future of rock mechanics

The tides are turning. Just as in the 1960s when the role of geology in engineering became relevant amidst calamities in engineering construction works, the role of geology in engineering is again getting recognized. This follows several years of lack of appreciation in the training of engineers in basic geology. The most affected branches of engineering are civil geotechnical engineering and mining engineering. Unfortunately, civil geotechnical engineers dominate the rock mechanics field.

At the 44th United States Rock Mechanics Symposium, which was also the 4th United States-Canada Rock Mechanics Symposium, a pre-conference workshop was organized with invited panelists including Don Banks, William Pariseau, Maurice Dusseault, John Curran, Richard Goodman, and Charles Dowding with Priscilla Nelson as moderator (Fig. 5) to hear their perspectives concerning what has been important for rock mechanics and engineering to achieve in the past 50 years, and to identify what we did and did not achieve (i.e., what has been hard to achieve, what we still have to accomplish). Each panelist identified greatest breakthrough development/achievements of the period. This was a real opportunity for the audience to learn from some of the most prominent rock mechanics educators and practitioners in North America.

Fig. 5 44th US and 4th US-Canada Rock Mechanics Symposium Geomechanics Workshop Participants, Mountain Inn, Park City, Utah, June 2010.

The most common issue and problem identified was the deficiency in the training of rock mechanics engineers today. That deficiency is the absence of sufficient geology in the curriculum of civil and mining engineering programs.

Previous attempts have been to raise this awareness at various international forums. In 2002, at the NARMS in Toronto, one session was devoted to Computational Geophysics and Rock Mechanics, which I chaired. This was a useful session. In recent times, private discussions with colleagues in rock mechanics, the recurring theme has been the lack sufficient knowledge of geology among practicing rock engineers. It is evident that most of the important breakthroughs needed in rock mechanics today cannot happen without deep knowledge in geology.

Today, we are still searching for a robust failure criterion for rocks. The empirical failure criterion by Hoek-Brown (Equation (1)) was known by Hoek himself to be inadequate as stated in his letter to the editor of ISRM. Hoek (1994) wrote:

"In writing Underground Excavations in Rock almost 15 years ago, Professor E.T. Brown and I developed the Hoek-Brown failure criterion to fill a vacuum which we saw in the process of designing underground excavations. Our approach was entirely empirical and we worked from very limited data of rather poor quality. Our empirical criterion and our estimates of the input parameters were offered as a temporary solution to an urgent problem."

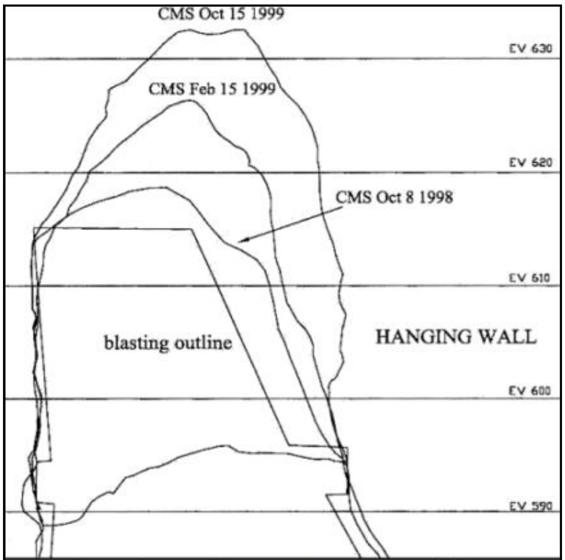
Today's young engineers, unfortunately, are only interested in sitting behind computers generating beautiful pictures without understanding the fundamental knowledge behind the theory, and what those pictures actually mean in practice. Few go to the field. Rock mechanics is in the field. Painfully some criticize what Hoek himself said was a temporary solution to an urgent problem, without offering alternative solutions.

5 Geology as the Pathway for Advances in Mining and Tunneling Technology

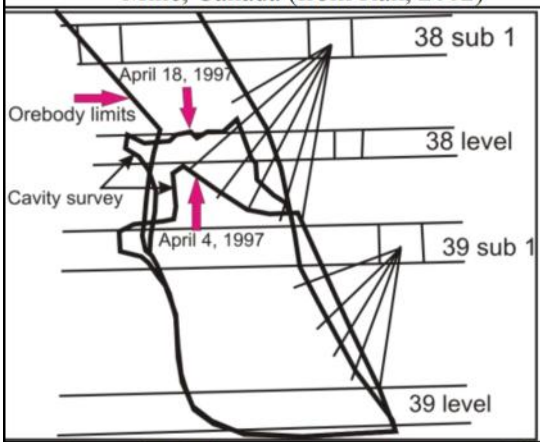
Hoek (1994) made the following observations that are still true today. The problems of measuring the persistence of rock joints, determining the most likely failure mode for a rock mass containing a number of intersecting structural features, or of estimating the in-situ deformation modulus of a rock mass are as formidable as always. Similarly, techniques for measuring in-situ stress, while greatly improved from what they were, still give an amount of scatter which would be unacceptable in almost any other branch of engineering. These problems are all associated with the inherently heterogeneous nature of the rocks with which we have to work and, while the problems are understandable, we have to ask what are we doing to try to improve our understanding of these problems? The answer is "very little".

Today, our underground excavation method in mining and tunneling is shifting from drill-and-blast to mechanical excavation by TBMs. The successful use of TBMs depends greatly on the nature of the ground and our ability to predict what lies ahead of the tunnel face. The question that remains is how we can see through the rock mass. Despite the advances in geophysics, we cannot still answer this question today. To be successful, we need a transparent earth!

It is very well established that time is a critical factor in rock mechanics. In open stope stability for example, we know that time is a critical factor as shown in Fig. 6.



(a) Time effect on stope stability stope stability at Ruttan Mine, Canada (from Ran, 2002)



(b) Timde-dependent open stope stability at AngloGold-Ashanti Obuasi Mine (Suorineni, 1998)

Fig. 6 Time Effects on Mine Excavations (In Suorineni, 2011).

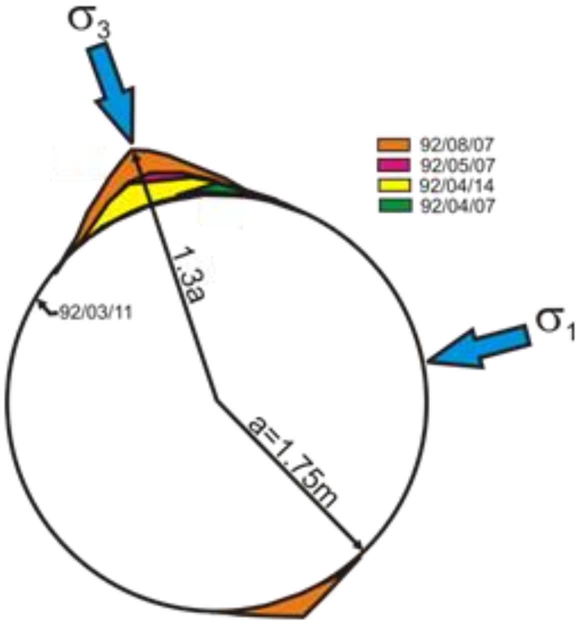


Fig. 7 Time Dependent Stability of a Tunnel in Civil Construction (redrawn from Martin, 1993. In Suorineni, 2011)

The problem of time and excavation stability is also observed in civil tunneling projects as shown in Fig. 7.

It is not clear how we can integrate time into our excavation designs, and it remains a challenge.

There are still no testing standards in rock mechanics such as BS 1377 for soil mechanics. All we have are suggested methods based on principles developed for soil and steel. Direct tensile strength tests for rocks are based on tensile strength testing of metals (Fig. 8). It is not easy to machine a rock as a metal for this test. Consequently, it is rarely used.

Fig. 8 Direct Tensile Strength Testing for Rocks (after Gorski et al., 2007)

Conclusions

Rock mechanics is studied under several disciplines and is a multidisciplinary subject. Geotechnical engineering, engineering geology and geological engineering are all interlinked with rock mechanics as the link. These disciplines are however independent depending on the training of the individuals. It is shown that good rock mechanicists must have a fair knowledge of geology. Today, the geological knowledge of most geotechnical and mining engineers is limited. It is concluded that for technical breakthroughs in rock mechanics, the training of geotechnical and mining engineers should include sufficient geological content, and we do not have to wait to achieve this after another major disaster.

References

Budhu, M. (2007), *Soil Mechanics and Foundations*, John Wiley & Sons, Inc. ISBN 978-0-471-43117 -6.

Mohr, O. (1882), "Über die Darstellung des Spannungszustandes und des Deformation-zustandes eines Körperelementes und über die Anwendung derselben in der Festigkeit-slehre", *Civil-ingenieur*, 28 (1882), pp. 113–115

Craig, F.G. (2004), *Soil Mechanics 7th Edition*, SPON Press, London, 458 pp.

Suorineni, F. T., Chinassane D.R. and Kaiser P.K. (2009), "A procedure for determining rock-type specific brittle Hoek-Brown parameter "s".", *Rock Mech. Rock Eng*.: 42:849–881.

Price, D.G. (2009), *Engineering geology: Principles and practice*, (Ed. de Freitas), Springer-Verlag Berlin Heidelberg, 460 p.

Suorineni, F. T. (1998), *Effects of faults and stress on open stope design*, PhD thesis, University of Waterloo, Waterloo, Ont., Canada, 370 pp.

Suorineni, F. T. (2010), "The stability graph after three decades in use: experiences and the way forward", *Int. J. Min. Reclam. Environ*., 24, (4), 307–339.

Gorski, B., Conlon, B. and Ljunggren, B. (2007), *Forsmark site investigation Determination of the direct and indirect tensile strength on cores from borehole KFM01D*, Svensk Kärnbränslehantering AB Swedish Nuclear Fuel and Waste Management Co., 23 pp.

VanDine, D. F. (1987), "Early History of the Geotechnical Profession in Canada, Proceedings, Canadian Engineering Centennial Convention", Montreal, (R.P. Chapuis and D.W. Devenny, Eds.), Canadian Geotechnical Society, pp. 9-20.

Roscoe, K. H., Schofield, A.N. and Wroth, C.P. (1958), "On the yielding of soils", *Géotechnique* 8: 22-53.

Ransome, F. L. (1928), "Geology of the st. Francis Dam site", *Economic Geology'* volume 23, p. 553 -563.

Coulomb, C.A. (1973), Essai sur une application des règles de maximis et minimis à quelques problèmes de statique, relatifs à l'architecture", Mémoires de mathématiques et de physique présentés à l'Académie royale des sciences par divers savants, et lus sans ses assemblées (Vol. 7, 1776), pp. 343-382.

Mathews, W. H. (1967), Geological engineering at the University of British Columbia. The British Columbia Professional Engineer, pp. 1-9.

Judd, W.R. (ed.) (1964), *Rock stress, rock mechanics and research. In State of Stress in the Earth's Crust*, Elsevier, NY, pp. 5-51.

Salamon, M.D.G. and Munro, A.H. (1967), "A study of the strength of coal pillars", *J. S. Afr. Inst. Min. Metall.*, September 1967. Vol. 68, pp. 55-57.

Hoek, E. (1994), Letter to the editor. ISRM News Journal Vol. 2, No 2, pp. 23-24.

Author

F. T. Suorineni is currently a full Professor and Chair of Mine Geotechnical Engineering in the School of Mining Engineering, Faculty of Engineering, University of New South Wales, Sydney, Australia. He holds a Ph.D. from University of Waterloo, Canada; a M.Sc. from University of Newcastle Upon Tyne, Britain, and B.Sc. from KNUST, Ghana. He serves as a private consultant in mining and geomechanics.