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Subsurface Engineering – A Path Forward!

Introduction

The series of articles presented in the January 2017 issue of HFJ were stimulated by reflections on the contrast between advances in different sectors of science and technology, especially in the United States, in the sixty years since the First US Rock Mechanics Symposium in April 1956. Coincidentally, the period July 1, 1957-December 31, 1958 marked the beginning of the International Geophysical Year (IGY) .

The most dramatic development of the IGY occurred on October 4, 1957, when the Soviet Union launched Sputnik1 into Earth orbit[1] This evidence that the USSR was ahead of the US in rocket systems prompted President John F Kennedy, on his election in 1961, to accelerate the US rocket development program. On May 25 1962, he announced to Congress that "*this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth.*" [2] [See also Rice University speech[3]] This launched NASA's Apollo program. On July 20, 1969, Armstrong set foot on the moon.[4] He and his fellow Apollo 11 astronauts Michael Collins and Buzz Aldrin returned safely to Earth four days later. "*In 2009, NASA ….presented an estimate of the Apollo program costs in 2005 dollars as roughly $170 billion.*" - or $212 billion in 2017. And this was just the start to the developments and expenditures by the US and other countries involved in outer space research The continuing achievements in space exploration and technological developments in global communication, computer power, medicine, etc. have been incredible, - certainly to anyone living in the 1960's. There is wide agreement that these expenditures have been worthwhile.

As can be seen from several of the articles in this and the January issue of HFJ progress, advances in Earth –based geophysics and related rock mechanics and Earth Resources Engineering have not been as spectacular - both in the US and internationally.

Consider, for example, the case of Earthquake Predict*ion* –certainly one of the most sought after goals of geophysical research. .

In 1975, renowned US Geophysicist, Dr Frank Press, writing in Scientific American[5], summarized his paper '***Earthquake Prediction***'; as follows "*Recent technical advances have brought this long-sought goal within reach. With adequate funding several countries, including the U.S., could achieve reliable long-term and short-term forecasts in a decade.*"

Fast forward 40 years! A headline story in the Los Angeles Times[6] on May 4, 2016 reported

San Andreas fault 'locked, loaded and ready to roll' with big earthquake, expert says

The expert was Professor Tom Jordan, NAS, Chairman of SCEC (Southern California Earthquake Center), also an internationally renowned earthquake scientist, speaking at the National Earthquake Center in Long Beach. Dr. Jordan did not indicate ***when*** the quake would occur, but complimented the civil authorities for recognizing that it will occur and taking appropriate precautionary measures. Other seismologists agree with Dr. Jordan's opinion, suggesting that a major earthquake is likely 'within the next several years'.

Thus, some four decades after Dr Press's paper, we are still unable to predict the timing of a major earthquake.

Is this because of a failure to provide the pre-requisite of '*adequate funding*' mentioned by Dr. Press, or is it also because the mechanics of earthquakes is more complex than anticipated?

Certainly, this problem has not attracted the funding that researchers feel is needed -but research on the mechanics of earthquake fault zones over the past decade or so reveals a system of interacting mechanisms considerably more complex that usually assumed in current models of how faults slip during an earthquake.[7]

More generally, it is now being recognized that characterizing the mechanical response of teh sub-surface to engineering is a formidable task, enough to 'stretch' the best minds in applied mathematics and engineering. As noted by Professor Chorin in his Foreword to the book *Scaling* (Barenblatt 2003)

"We are at the beginning of the age of multiscale science and multiscale computation, with a growing need to understand not only phenomena on each of many scales but also the interaction between phenomena at very different scales. …."

A recent example of such a study is discussed briefly in the Appendix to this paper.

The complexity of problems of rock engineering is recognized by Earth scientists and engineers.

Quoting from the writer's paper 'Earth Resources Engineering' in the January issue of HFJ

"*Earthquakes indicate that the subsurface is a 'restless' environment. Rockbursts in deep mines, and seismicity induced by hydraulic fracturing, are smaller scale 'man –made' reminders of this fact. Subject to successive epochs of tectonic and gravitational forces over hundreds of millions and as much as a few billions of years, these heterogeneous assemblies of rock have been deformed and fractured, introducing a variety of planar discontinuities at various times and orientations in space, over a huge range of scales from microscopic grains to tectonic plates.*

The forces imposed on the rock are transmitted in part through the solid structure and in part also by the fluid in the pore spaces within the rock. Some rocks will continue to deform and readjust slowly over millions of years, while other rock types in close proximity will remain elastic and unchanging. A rock mass is a far more complex and uncertain material than any fabricated material used in other branches of engineering.
In some respects, engineering in a rock mass is comparable to the practice of Medicine –one is dealing with an animate, living system. Understanding the mechanical response of such material to sub-surface engineering activities –and developing practical insights on how to conduct those activities safely, and develop resources economically, is a "Grand Challenge" – comparable to any of those already defined by the NAE"

It is for this reason that engineers dealing with design in rock, and especially with the application of numerical models in design, ask that application of the models be subject to critical examination by geoscientists and geoengineers with a variety of professional backgrounds.
As has been noted …*the most powerful computer in the world isn't nearly as intuitive as the one we're born with.*[8]

Another approach to examination of complex problems is that mentioned in the recent short article "*Can Artificial Intelligence Predict Earthquakes?" by Annie Sneed* in the Computing Section of Scientific American, February 15 2017 [9] It is another example of how technologies, in this case the advent of powerful computers and the resulting ability to handle 'Big Data' may have value in application to pressing global problems on Planet Earth.

One might also suggest the use of such technology to the study of hydraulic fracture generation and associated interpretation of microseismic signals.

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Although the US is now arguably in the 'post-industrial' Era, [10] there is still a large portion of the world- and population – that remains in the pre-Industrial Era. What can the new technologies have to offer to help develop such regions and their associated resources for the general benefit of all? The example of how orbiting satellites are changing the technology of mineral exploration from the time, not too long ago, of the grizzled lonely explorer and his donkey, is just one of many.

Reading the recent article *Mining on the Moon* [Peacock (2015)] [11] suggests that such a discussion may not be a 'one-way exchange.' Thus, although much of the current exploration of the Moon has been restricted to surface observations, it is probable, if for no other reason than to provide protection against intense radiation of the surface, that excavation of the Moon's subsurface will be required.

Can excavation technologies developed in mining and civil engineering on Earth – empirically over many years – be applied on other planets? How much will they be affected by the change in gravity, both with respect to sub-surface stresses and the use of machinery; how different are the seismic characteristics of 'quakes' on other planets? Explosives, a dense and lightweight energy source, would seem to be attractive technology for use in excavation on the Moon and other planets, but are there significant differences that should be recognized?

Analytical and numerical models of subsurface technologies on Earth are now well developed - based on comparison between predicted and actual performance over many years. How will such structures be designed on other planets? It is a relatively simple exercise to change gravity, etc. in a model, and examine the consequences. It is a far more daunting task to attempt to arrive at suitable designs by direct testing.

Understanding gained of the fundamental rock mechanics of the Earth's subsurface can be a valuable aid to exploration and development of other planets.

The rapid increase in world population over the next several decades will place heavy demands on many subsurface resources that are essential to a high quality of life; perhaps it is time to draw international attention to the associated challenges.

The idea for the First International Geophysical Year originated over a dinner discussion[12] between a group of geophysicists, all interested in the physics of Earth's atmosphere.

"Someone suggested that, ***with all the new tools now available,*** *such as rockets, radar, and computers, perhaps it was time for a coordinated, worldwide study of Earth's systems. That evening, these scientists planted the seeds of what would eventually be called the International Geophysical Year (IGY*). [Emphasis added]*"* [13]

Although a sound proposal from a distinguished group, it is sure that they did not anticipate the developments that would result from their suggestion.

Perhaps it is time, once again, ***with all the new tools now available,*** **to** stimulate a dialog on how the tools and developments in Outer Space can be applied to the benefit of Inner Space.

Certainly, albeit on a smaller scale, discussion of such a national program in the US is very much needed. One step towards this goal, Engineering Research Centers at US universities, is discussed below.

Engineering Research Centers in Earth Resources Engineering

The term 'Earth Resources Engineering' is used here in the sense defined by the US National Academy of Engineering

"Engineering applied to the discovery, development and environmentally responsible production of subsurface earth resources"[14]

Earth Resources Engineering was introduced to replace the term 'Petroleum, Mining and Geological engineering', used since the foundation of NAE in 1964, emphasizing resource extraction activities. The change was stimulated by the decision to use underground geological repositories in rock for isolation of high-level radioactive waste.

Petroleum companies have a long and distinguished reputation in Engineering Research and Development, and have made many notable contributions to subsurface science in general. Research in Geological Engineering -related primarily to water resources –has been pursued by the US Geological Survey for many years. Rock Mechanics, a part of Geological Engineering, is an important concern in all branches of Earth Resources Engineering. Mining Engineering, so far as it relates to mineral extraction, is susceptible to classical laboratory –scale research. Many mining companies and equipment suppliers conduct research in various aspects of mineral extraction –comminution; chemical extraction processes; etc. Similarly, mining equipment manufacturers have active R&D groups, but very few US mining companies engage in any R&D 'in house.' The US Bureau of Mines was a mainstay of US mining R&D,(especially related to Health and Safety), and support of research at universities - until closed by the US Congress in 1995[15] This also weakened graduate research at US universities.[16] Civil Engineering is also involved in aspects of Subsurface Earth Resources Engineering e.g. for tunnels, dam foundations on rock; rock slope stability;… but, with a few exceptions, US universities are far less involved in research on these topics than counterpart Civil Engineering groups in Europe and Asia.

By contrast, the United States has been a world leader in many technologies stimulated by the US space program; advances in high speed computers, etc. University engineering departments in disciplines related to these technologies are among the world leaders.

Given the developing global importance of Earth Resources as the world population increases, competition for available resources intensifies, etc. it is critically important that this weakness in Earth Resources Engineering disciplines in the US be addressed without delay. To this end, it is recommended that the US government establish a program of interdisciplinary Engineering Research Centers dedicated to Earth Resources Engineering without delay.

Interdisciplinary Engineering Research Centers at US universities were introduced under the auspices of the National Science Foundation in the 1980's and continue today. The following extract from a review completed in 2007 (Lai et al: 2007)[17] describes the purpose of these NSF Centers
Recent concern over threats to the scientific and technical competitiveness of the United States in the global marketplace is reminiscent of the political and economic climate in the mid-1980s that led to the inception of the National Science Foundation (NSF) Engineering Research Centers (ERC) program. The original intent of the NSF ERC program was to integrate engineering practice and training toward the creation of a then-new engineer focused on applied, cross-disciplinary, and systems-level research who was, above all else, industry relevant. The thinking then was that future industrial successes were to depend on a different type of engineer than in the past. The thinking now is much the same, as evidenced by calls for the "engineer of 2020" to help the United States retain its global leadership status in technology and innovation. [Lal et al; (2007)]

As the NSF ERC program enters its third-decade, it is once again focusing on the remaking of university-based engineering research and education to meet the demands of the current more broadly-based global economy. The program has recently taken steps in this direction with its "Gen 3" program solicitation (NSF 07-521), emphasizing numerous center characteristics aimed at strengthening U.S. competitiveness in a global economy by focusing on developing the next generation of engineers who will be adaptive and creative innovators. Gen 3 centers are intended to emphasize:

- Supporting transformational research from fundamentals through to innovation in collaboration with small firms[18]
- International partnerships in research and education
- Developing engineering education programs designed to create innovative, entrepreneurial engineers not process-focused "commodity engineers"
- Technology development aimed at swift market introduction

Although this model of Engineering Research Centers has many attributes that are relevant to Centers in Subsurface Earth Resource Engineering (SERE), it is necessary to define a separate program, not necessarily affiliated with the National Science Foundation, specific to the needs of Earth Resource Engineering. There is a major need to 'make up for lost ground internationally.'

The writer believes that multi- year commitment by the US and global industry to participate on a 50:50 (Industry: Government) matching funds basis is essential to the success of the SERE Centers. With essentially no industrial R&D groups in either mining or civil engineering to serve as a link, it is critical that industry work in close collaboration with university researchers, to ensure that the latter are well aware of industry needs.

For purposes of discussion, the writer recommends a goal of ten such SERE Centers be established at US graduate research universities. Each Center would be funded at $5 million per year for an initial period of five years, with an option for extension for a further five years. Assuming that 'industry' (both US and global) provides 50% of the funding, this would require a Federal commitment of $25 million per year for an initial period of ten years. This would definitely ensure that the US would be a leading and valued partner in Earth Resources Engineering world –wide. It would also certainly provide the US with a more secure future with respect to supply of raw materials essential to national security. Compared to other national expenditures discussed earlier, it is small –but could have a major beneficial impact to the nation.

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In closing, the writer would like to thank his colleague, Dr Ali Daneshy, for his generous gesture in dedicating two Issues of his journal HFJ to a discussion of some of the technological challenges of rock mechanics, and of Earth Resources Engineering in general.

It is our hope that national - and international - policy decision makers may be persuaded to take action to address these challenges.

Appendix

Consideration of Leak-Off in Hydraulic Fracturing.

The following comments are included here as an illustration of the type of 'multi-scale computation' alluded to in the comment by Professor Chorin quoted in the paper above.

In the discussion of hydraulic fracturing by the writer in the paper *Newton in the Underworld* (see HFJ Vol. 4-1 Jan 2016) pp.25-26) it was noted that classical models of fracturing (e.g. PKN (Perkins, Kern and Nordgren) and KGD (Kristianovic, Geertsma, de Klerk) do not consider the important practical factor of leak-off of fluid from the crack into the rock formation. Detournay and co-workers at the University of Minnesota have conducted research on hydraulic fracturing over the past two decades in order to improve on such models, and have devoted considerable effort to developing a fundamental understanding of the processes involved in propagation of fractures in rock driven by pressurization of fluid in the fracture, and taking into account the important factor of 'leak-off' of fluid into the rock, as illustrated for a 'penny –shaped' crack in **Figure A1**.

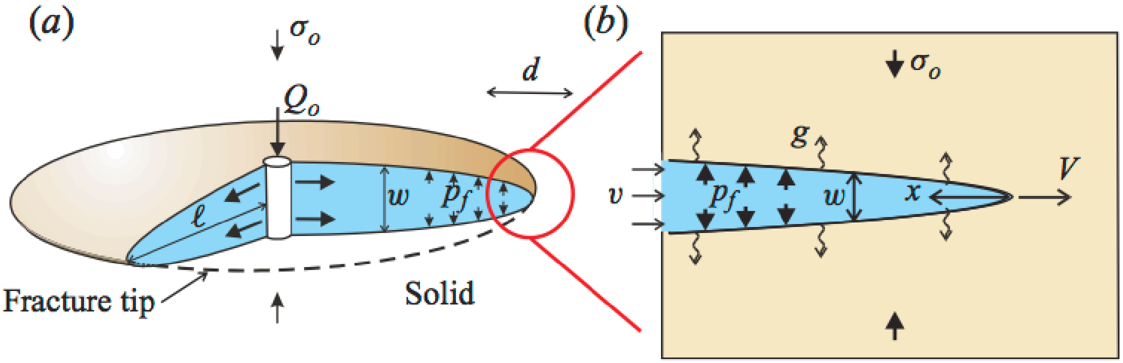

Figure A1. *Radial Flow Model of a Propagating 'Penny Shaped' Hydraulic Fracture with Leak-Off.*

Results for the penny –shaped crack example are presented in terms of dimensional parameters in Figure A2

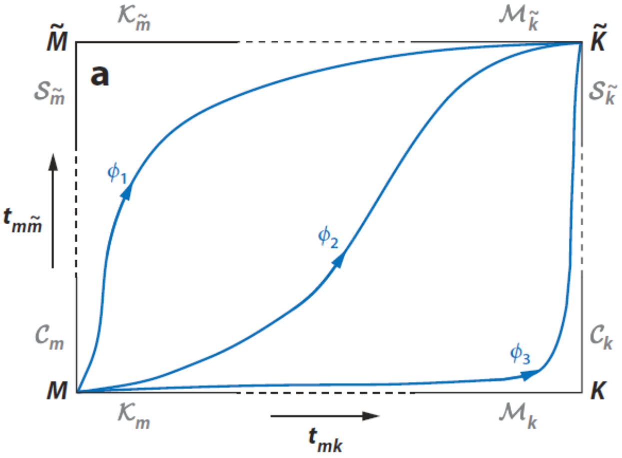

Figure A2*. Parameter Space for a Zero Lag Penny –Shaped Crack Propagating in Permeable Rock.*

The vertical boundary M$\tilde{\text{M}}$ represents the limiting case of fractures of zero toughness; K$\tilde{\text{K}}$ represents the limiting case for fractures of very high toughness; the horizontal base line MK represents the limiting case of fractures with zero leak-off; the upper horizontal line represents the limiting case of very high leak off. For small φ (i.e. for a small-timescale ratio, $t_{mk}/t_{m\dot{m}}$)* such as φ_3 , the trajectory tends to "be attracted by" the *K*-vertex and, conversely by the ˜*M* -vertex for large *φ*, such as φ_1 in the diagram. The trajectory φ_2 illustrates where times t_{mk} and $t_{m\tilde{m}}$ have comparable values [* $t_{m\dot{m}}$ and t_{mk} are dimensionless time parameters.]

A full discussion of **Figure A2** and the analysis underlying this representation is presented in the paper Detournay E. (2016) This paper also presents results for plane strain cases (e.g. similar to PKN and KGD) with leak –off.

Clearly, it is not possible to comprehend the full significance of Figure A1 from the explanation presented here. The intention is simply to draw attention to the importance of such general (dimensionless) analyses in advancing practice. Introduction of important practical parameters (in this case leak-off) complicates the analysis, but provides valuable insights. As with the classical closed form analyses e.g. Kirsch (1898), Inglis (1913) the solutions apply to problems on all scales –an important concern in rock mechanics. They also serve a very important role in verifying numerical codes. Establishing that such a code yields the same answers for the same assumptions as the closed form analyses, provides assurance that the codes provide valid results when applied to specific practical situations outside the bounds of the closed form results.

As noted earlier, hydraulic fracturing is being applied to an increasing variety of practical situations e.g. extraction of geothermal energy from hot rock; borehole mining, etc. These add further variables –e.g. thermal and chemical effects not considered in hydraulic fracturing analyses to date. Insights into how these factors are likely to affect the practical application of hydraulic fracturing can come most effectively from research, sustained over many years by teams of applied mechanicians, and colleagues from other scientific disciplines. Without such teams, practical answers to field problems will not be available when needed.

Endnotes

[1] https://en.wikipedia.org/wiki/Sputnik_1

[2] https://history.nasa.gov/moondec.html

[3] https://er.jsc.nasa.gov/seh/ricetalk.htm

[4] https://www.nasa.gov/mission_pages/apollo/apollo11.html

[5] *Earthquake Predictio**n**- Frank Press. Scientific American.*. May 1975.Volume 232 Number 5 pp.14-23

[6] http://www.latimes.com/local/lanow/la-me-ln-san-andreas-fault-earthquake-20160504-story.html

[7] See e.g. the ISRM video lecture by Professor Jean Salem *Metaphysics Couplings and Stability of Fault Zones,* 2015 http://www.isrm.net/gca/?id=1229

[8] President Obama, announcing the BRAIN Initiative April 2 2013. https://obamawhitehouse.archives.gov/the-press-office/2013/04/02/remarks-president-brain-initiative-and-american-innovation

[9] https://www.scientificamerican.com/article/can-artificial-intelligence-predict-earthquakes/

[10] https://en.wikipedia.org/wiki/Post-industrial_society

[11] Peacock D.A. (2017) *Mining on the Moon; Yes, it's really going to happen.* Mining Engineering Jan. 2017, pp. 25-33 SME (Denver)

[12] The dinner was at the home of Dr. J. Van Allen and his family in Silver Spring, Maryland. [*Opening Space Research, Dreams, Technology and Scientific Discov*ery George H.Ludwig (2011) AGU ISBN 13: 978-0-87590-733-8 doi:10.1029/062SP See Chapter 3, The International Geophysical Year]

See also http://onlinelibrary.wiley.com/doi/10.1029/2011EO400009/abstract

[13] http://celebrating200years.noaa.gov/magazine/igy/welcome.html

[14] The writer would prefer the term …… 'environmentally responsible ***use*** of……' to recognize the increasing number of non-extractive applications, where advantage is taken of the unique ability of the *in situ* rock mass to isolate toxic and hazardous waste products from the biosphere for many thousands of years – plus a number of other technologies e.g. Compressed Air Energy Storage.

[15] https://en.wikipedia.org/wiki/United_States_Bureau_of_Mines

[16] https://www.smenet.org/docs/public/USMiningSchools-SME.pdf

[17] Bhavya Lal et al; (2007) *Designing the Next Generation of NSF Engineering Research Centers: Insights from Worldwide Practice* Science and Technology Policy Institute 1899 Pennsylvania Avenue NW, Suite 520 Washington DC 20006, November 2007] https://nsf.gov/pubs/2015/nsf15589/nsf15589.htm)

[18] The term *transformative* research was recently defined by the National Science Board as: Research driven by ideas that have the potential to radically change our understanding of an important existing scientific or engineering concept or leading to the creation of a new paradigm or field of science or engineering. Such research also is characterized by its challenge to current understanding or its pathways to new frontiers. U.S. National Science Board, NSB-07-32, May 7, 2007