Grand Challenges in Earth Resources Engineering

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Background

A committee of Section 11 –Earth Resources Engineering of the US National Academy of Engineering, was established in 2010, charged with identification of *Grand Challenges in Earth Resources Engineering.* Formation of the committee was stimulated by two (then) recent developments in NAE;

1. ***Renaming of NAE Section 11*** *(in 2006)*
   From Petroleum, Mining and Geological Engineering;
   Engineering applied to the discovery, development and responsible production of nonrenewable earth resources;
   To Earth Resources Engineering;
   Engineering applied to the discovery, development and environmentally responsible production of subsurface earth resources

This change had been made in recognition of the widening scope of engineering activities associated with the subsurface. 'Subsurface earth resources' now included both traditional fossil fuel, mineral and groundwater resources, but recognized also the unique capability of the subsurface to serve to protect the global population and the biosphere from danger and harm. Use of the subsurface to isolate high-level radioactive wastes in geological repositories, recommended by the US National Academy of Sciences in 1957[1] was the first example, but other possible uses have since been identified.

2. ***Publication of the 2008 NAE report 'Grand Challenges in Engineering.'*** *

This report identified 14 challenges (see http://www.engineeringchallenges.org/challenges.aspx) including four that have a direct connection to both extraction and use of Earth resources viz; *sequestering carbon dioxide; providing access to clean water; managing the nitrogen cycle; restoring and renewing the urban infrastructure.*

**NAE President Charles Vest defined a 'Grand Challenge' as one that is "visionary, but do-able with the right influx of work and resources over the next few decades"— a challenge that, if met, would be 'game-changing' and have a "transformative" effect on technology.*[2]

*** The UN defined sustainable development in 1987 as development that "meets the needs of the present generation without compromising the ability of the future generation to meet their needs". Another useful concept developed by John Elkington in 1997 calls for an appropriate balance among economic prosperity, environmental quality and social justice.*

The Section 11 Committee identified the four Challenges described below. As with the original fourteen NAE Challenges, these four do not preclude the identification of other Challenges of comparable importance. The four Challenges in Earth Resources Engineering have not been formally approved by the NAE.

Transparent Earth

Has the potential to do for subsurface engineering what imaging has done for the practice of Medicine.
'Transparent Earth' has broad implications. It includes the ability to

- communicate by voice directly through 1-2km of solid rock.
- 'see' the rock mass two-three diameters of a tunnel boring machine.
- control autonomous mining equipment through the rock.
- observe the consequences of engineering activities on the adjacent rock mass e.g. seismic and aseismic response of rock to 'stimulation' by fluid injection or extraction
- establish, in real time, the detailed structure of the opaque rock mass, over the wide range of scales relevant to subsurface engineering activities. Petroleum research has made major advances in 3D geophysical mapping and well-bore logging techniques, but these can sometimes require days or longer to process and interpret.
- observe ongoing deformation changes at depth, due to motion of Earth's tectonic plates.[3]
- protect surface systems from earthquake- induced deformations.[4]

Any success in this Grand Challenge would transform major aspects of subsurface engineering.

The following example provides an insight into the potential of developments in Transparent Earth technology The international TV audience that watched on July 20, 1969 as astronaut Neil Armstrong stepped onto the surface of the Moon was estimated at ~500 million viewers. The words *"One small step for a man, one giant leap for mankind"* were heard, in real time, around the world. The audience record remained unbroken for over 40 years, until October 13, 2010 when ~ one billion watched as 33 Chilean miners trapped underground for 69 days, were all hoisted to safety. The rescue was an heroic international effort, involving

> "… *.three large, international drilling rig teams, nearly every Chilean government ministry, the expertise of the NASA space agency and more than a dozen multi-national corporations from nearly every continent… Seventeen days after the* [August 5, 2010] *accident, on 22 August, a note written in bold red letters appeared taped to a drill bit when it was pulled to the surface after penetrating an area believed to be accessible to the trapped workers. It read simply "Estamos bien en el refugio, los 33" (English: "We are well in the shelter, the 33 of us")*[5].

Should such an accident occur today, how long would it take to determine whether or not the miners were alive, and would the method of alerting rescuers of the miner's location have changed?

Some efforts to establish voice communication through rock are ongoing, but progress is slow.[6] A vigorous US Bureau of Mines program might perhaps have accelerated advance.

The report, Elsworth D., and C. Fairhurst (2006) *Geo-Science and Geo-Engineering Research at DUSEL includes* considerable discussion of Transparent Earth concepts. (See http://bit.ly/2cNB8tq)

Coupled Processes

The huge resource of geothermal energy and potential of Enhanced Geothermal Systems (EGS)[7] in the US has already been noted (see Figure 10). The high temperatures and pressures encountered at these depths and the need to extract heat by injection of cold fluid and extraction of hot fluid via a network of fractures in the rock result in chemical reactions between the rock and the fluid; cooling of the rock enlarges the fracture apertures, greatly reducing the resistance to flow along these fractures. This tends to enhance the tendency for the fluids to short-circuit between injection and extraction points. Dissolution of chemicals from the rock e.g. at high temperature locations[8] and precipitation at low temperature sites will occur –changing apertures and modifying flow. Understanding such coupled THMC (Thermo-Hydro-Chemical- Mechanical) processes, such as illustrated in Figure 12, will be essential to the design of commercial EGS systems.

Such coupled processes were also operative during the formation of mineral deposits over geological time. Understanding these systems will be a central component of attempts to develop 'minimally invasive' mining systems.

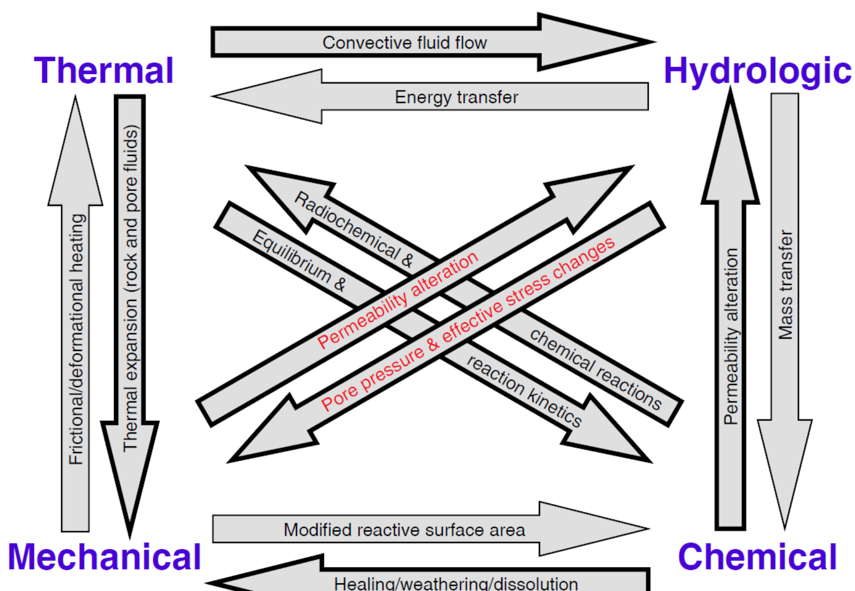

Figure 1. *Coupled Thermo-Hydro –Mechanical- Chemical (THMC) processes in rock.*

Adapted from Figure 1; Yow, J.L, and J.R. Hunt (2002) *Coupled processes in rock mass performance with emphasis on nuclear waste isolation* Int. J. Rock Mech. Min. Sci. Vol. 39 pp. 143–150 [9]

Minimally Invasive Mining Systems

Seeing huge open-pit mines at depths of the order of 1km or more,[10] some extracting ores that contain 1% or less of the desired metal –and hence 99% waste – or an underground gold mine, as in South Africa, approaching 4km deep, extract gold that is of the order of 1 ounce/ton (3 parts/ million) of rock extracted and hauled to the surface - it is tempting to ask whether it might not be less expensive, and perhaps less environmentally damaging, to develop techniques to extract some ores via borehole technology –as is standard in the petroleum industry, and as practiced in solution mining of salt. Extraction using 'environmentally friendly' biological systems is also developing, both via boreholes and in leaching of residual minerals from mine waste piles, [11] This is clearly a major Challenge –and opportunity for interdisciplinary research and development.

Protection of the Environment and the Public.

As indicated by the earlier discussion of "Manufacturing and Minerals", minerals are the essential foundation for much of all manufacturing processes. If the US is to sustain a vigorous manufacturing sector in the future, it will need to have assured supplies of minerals. Also, although efforts to replace fossil fuels are ongoing, reliable sources of these will be required for a considerable number of years. The US is currently heavily dependent on imports for many critical minerals. Where domestic resources exist it is in the interest of the nation to establish whether these can be produced without seriously adverse environmental harm. Where imports are required, the US should be recognized as the international leader in mineral –and fossil fuel technology, in order to retain a significant influence in the global mineral resource arena. Establishing a vigorous R&D program in subsurface engineering is the way to develop and maintain this position.

The subsurface and subsurface engineering can protect the environment in a variety of ways. Some have been mentioned earlier. Development of Enhanced Geothermal Systems; Isolation of long –lived, high-level radioactive waste –and other hazardous waste products - from the biosphere; C_2 sequestration; (Shallow) underground location of nuclear power plants to reduce vulnerability to earthquakes; Three-dimensional Planning of Cities[12]; etc. While it is usual to hear advice to *"take shelter, preferably in the basement, if you have one"* there is little discussion of the fact that extreme weather effects are confined primarily to the ground surface and above. Temperature extremes are rapidly attenuated at depths of a few meters; extreme winds, tornadoes do not penetrate below the surface. Scandinavia has led in discussion and implementation of subsurface development opportunities [13] Discussion of such opportunities in the US can be found in the National Academy Press Report (2013) "*Underground Engineering for Sustainable Urban Development.*" [14]

Endnotes

[1] https://www.nap.edu/catalog/10294/the-disposal-of-radioactive-waste-on-land

[2] News Conference, AAAS Meeting, Boston, Feb.15, 2008\ http://www.engineeringchallenges.org/challenges/15583/newsconf.aspx [Hear Introductory Oral Comments by Charles Vest; 1min 4sec to 1min 15sec]

[3] Considerable progress is being made in scientific observations. See e.g. Nat.Sci. Fdn, Earthscope http://www.earthscope.org/ https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=501035

[4] http://www.americanscientist.org/issues/feature/2015/5/a-protective-cloak-against-earthquakes-and-storms

[5] Extract from Wikipedia https://en.wikipedia.org/wiki/2010_Copiap%C3%B3_mining_accident

[6] https://en.wikipedia.org/wiki/Through-the-earth_mine_communications

[7] Tester, J.F. et al; (2006) "*The Future of Geothermal Energy*" http://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf See Synopsis p.5 (5)

[8] Some chemicals exhibit higher solubility at elevated temperatures; other chemicals exhibit the opposite tendency. A rock mass may consist of both types of chemicals

[9] http://ccrm.berkeley.edu/pdfs_papers/2.09/yow_hunt_int_j.pdf

[10] http://www.mining-technology.com/features/feature-top-ten-deepest-open-pit-mines-world

[11] https://en.wikipedia.org/wiki/Biomining [See also http://www.spaceship-earth.org/REM/BRIERLEY.htm]

[12] https://www.youtube.com/watch?v=jXNyEiw28D0

[13] See Winquist, T and K.E Mellgren (1988) Going Underground, Royal Swedish Academy of Engineering Sciences 177p. Bergman S.M (Ed). (1978) Rockstore 77. Proc. First Inter'l Symp. on Storage in Excavated Rock Caverns, Stockholm, 5-8 Sept. 1977; 3 Vol. Pergamon (Oxford); Bergman S.M. (Ed). (1980) Proc.ISRM Int'l Symp. Rockstore 80 (Stockholm, June 23-27). Subsurface space: environment protection, low cost storage, energy savings. 3 Vol. Pergamon (Oxford)

[14] http://www.nap.edu/catalog/14670/underground-engineering-for-sustainable-urban-development

Biography

Charles Fairhurst, Professor Emeritus, University of Minnesota, Minneapolis, USA; Senior Consultant, Itasca International Inc. Minneapolis, obtained his Ph.D. in Mining Engineering from the University of Sheffield, UK in 1955. He joined the University of Minnesota faculty, School of Mines and Metallurgy in 1956, serving as Head for several years to 1970, when the Mining program was joined with Civil Engineering to form the Department of Civil and Mineral Engineering. He served as Head of the joint Department from 1973-87, and retired in 1997.

He has consulted on rock stability problems for tunnels, dams, mines and excavations throughout the world. He remains active in consulting, with a current emphasis on the mechanics of fracture propagation in naturally fractured rock and the effective stimulation of geothermal reservoirs. He served as President of the International Society for Rock Mechanics from 1991-1995, and has been elected to the U.S. National Academy of Engineering (1991) and the Royal Swedish Academy of Engineering Sciences (1979). He is a Fellow of the American Rock Mechanics Association.

Dr. Fairhurst holds honorary doctorate degrees from the University of Nancy, France; St. Petersburg Mining Academy, Russia; University of Sheffield, England; and University of Minnesota, USA; and is Advisory Professor to Tongji University, Shanghai, China.

In December, 2013, he was inducted as Officier, Légion d'Honneur, France.