Grand Challenges in Earth Resources Engineering

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NAE Grand Challenges,

as determined by a committee of the National Academy of Engineering (NAE) - 2008.

“All are associated with four broad realms of human concern: Sustainability, Vulnerability, Health and the Joy of Living”.

Make solar energy economical
Provide energy from fusion
Develop carbon sequestration methods
Manage the nitrogen cycle
Provide access to clean water
Restore and improve urban infrastructure

Advance health informatics
Engineer better medicines
Reverse-engineer the brain
Prevent nuclear terror
Secure cyberspace
Enhance virtual reality
Advance personalized learning
Engineer the tools of scientific discovery


A ‘Grand Challenge’ is 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’- have a “transformative” effect on technology.

NAE President Charles Vest, Press Conference, AAAS, February 15, 2008
NAE Section 11,
Earth Resources Engineering. (est. 2006*)

“Engineering applied to the discovery, development and environmentally responsible production of subsurface earth resources.”

Committee appointed in October 2009 to define the leading (five or so)

Grand Challenges in Earth Resource Engineering.

*formerly “Mining, Geological and Petroleum Engineering.”

The name was changed in 2006 to recognize the broadening spectrum of subsurface engineering activities.
Earth Resources Engineering

“Engineering applied to the discovery, development and environmentally responsible production of subsurface earth resources.”

Earth Resource activities are all relatively shallow in the lithosphere; [i.e. solid earth’s crust; ~40 km-300 km thick.]

Deepest borehole is 12 km. Deepest mine is 4 km.
Rock temperature increases approx. 25°C/km depth
Vertical rock pressure $\sigma_v$ increases $\sim 27$MPa/km.
Horizontal pressure $\sigma_h \sim (0.5-3) \sigma_v$
Earthquakes vary from $\sim 20$ km to 700 km in focal depth.
Rising Demands on Earth Resources

- Rapid Population Growth
- Rising expectations worldwide.
- Expansion of BRIC nations (Brazil, Russia, India, China.)
- Rising worldwide demand for earth resources - minerals, groundwater.
- Isolation potential of solid rock cover
- Global warming; reduce carbon footprint
- Move to metropolitan areas. demands on surface space; 3D urban design.

World Energy supply over next several decades.

60% delivered through a borehole (Oil and Gas)
90% from Subsurface (Coal 23% Uranium 7%)

Geothermal - subsurface: Waste isolation - subsurface
Scale!

Earth Resource Engineering problems involve an exceptionally wide range of scales, both Spatial and Temporal.
Inter-atomic spacing, $10^{-9}$ m

Plate tectonics $10^6$ m

**Length Scale - Range $10^{15}$**

Tectonic deformation

\[ n \approx 16 \]

(\approx 100 \text{ million years})

Blasting; \( n \approx -3 \)

(mILLISECONDS)

Zero Strength ? \( \sigma_t = 0 \)

Threshold Strength ? \( \sigma_t \approx 0.5\sigma_c \)

Time Scale - Range \( 10^{19} \)

All rocks are not created equal!
**Grand Challenges in Earth Resource Engineering**

**Overarching challenge**

- to supply society with its energy, minerals and groundwater while protecting people and the environment.

**Specific Challenges**

- Transparent Earth
- Subsurface Processes
- Minimally Invasive Extraction
- Protecting People and the Environment.
We should attempt to map the upper 10 km of the earth’s crust (with particular emphasis on the upper 500m) in more than just descriptive terms. (Member comment)

Very Large Scale  ~ 1000 km
Add depth to EarthScope (www.earthscope.net)

Large Scale  ~ km
3D Seismic + Well logs

Very Small Scale  mm
CAT scan of petroleum shale sample to determine porosity structure and kerogen distribution

Transparent Earth.

to do for Earth Resource Engineering
what imaging etc, is doing for Medicine.
( wide range of length scales.)
Coupled Processes in the Subsurface.

Controlling influence on most aspects of subsurface science and engineering - from earthquakes to occurrence of mineral deposits.

Fluid (water-gas—chemically reactive) flowing at depth through hot rock under pressure
Zeuzier Arch Dam (Switzerland)

Coupled Hydro-Mechanical Effects — Large Scale (Zeuzier Reservoir)

Adapted from Biederman (1982)
Minimally invasive extraction
Extend beyond petroleum

Schematic of Directional Drilling from off-shore oil platforms.

The red borehole is guided remotely to stay within the center of a narrow (ca 4m) producing horizon for several kilometers.
Directional Drilling in Radioactive Waste Repository Exploration. Bure, France
Wall Street  New York   1918

Typical chaotic development of subsurface of major cities in past century. This greatly increases construction costs and forces future uses of underground space to deeper and deeper levels.

Taisei (Japan) concept,  1990

Use of underground space to create new commercial space linked to transportation and utility infrastructures while freeing up precious surface space. In 2004, Japan created a public zone for deep underground space beneath major cities to ease the administrative burden of developing major underground infrastructure linkages.

Improved Urban Infrastructure
Much of Earth Resource Engineering has relied on Empirical Rules because of the complexity of the processes and the inadequacy of closed form continuum solutions.

Computers are changing this.
Extract from Radio Interview of Prof. Leopold Müller:
May 24, 1962. Salzburg
(after registering ISRM as an International Society)

Reporter:
Zum Begriff der Sicherheit. Sind denn die Festigkeiten der Gesteine bekannt?
With respect to safety.

Do we know the strength of rock?

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.“ 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 ISRM
an ‘International Research Institute for Rock’.

ISRM was founded because
“We do not know the strength of a rock mass.”
Advances in Computing Power now allow Strength of Rock Mass to be computed.

Field Verification of Predictive Numerical Models is now the Challenge!
Newton (ca 1687)

Molecular Model of Body Structure

Infinitesimal Calculus

Continuum Hypothesis

Continuum Mechanics

Computer (1970-)

Discontinuum Mechanics (Discrete Element Mechanics; DEM)

Rock

Empiricism

Rock
Fracture representation – 3D Discrete Fracture Network (DFN)

Intact rock representation (including brittle fracture)

Synthetic Rock Mass

Bonded-particle assembly intersected with fractures (Smooth Joint Model – SRM)
PFC2D v. FLAC Model

Particle Velocity Vectors

Approximate FLAC Failure Surface
Bench C2
West Wall Slope at Chuquicamata

note offsets

Reversed plot from PFC model
Size–Strength Effects in Three Jointed Rocks—as indicated by 3D Discrete Element Numerical Model. (for three orientations of the applied axial stress.)

Cundall et al (2008)

Developing a Mechanics-Based Framework for Rock Mass Strength Estimation. Reliability of estimates can be assessed.
(e.g. Monte Carlo simulation –Latin hypercube sampling)
US Geothermal Resource

“We estimate extractable portion to exceed 200,000 EJ or about 2,000 times the annual consumption of primary energy in the United States in 2005.”

EJ = Exajoule (10^{18} Joules)


“At this point, the main constraint is creating sufficient connectivity within the injection and production well system in the stimulated region of the EGS reservoir to allow for high per-well production rates without reducing reservoir life by rapid cooling.”

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.)
While string theorists and cosmologists struggle to understand the dark matter in outer space, there are industrial physicists who are tackling problems related to another kind of dark matter found in inner space.

Dr. Brian Clark, Physicist, Schlumberger

**DEEP SCIENCE**

*As the miner’s headlamp casts light on subterranean darkness, research in deep underground laboratories illuminates many of the most compelling questions in 21st century science...*

**DUSEL  Deep Underground Science and Engineering Laboratory (Lead, S. Dakota)**

**A Major Opportunity for US Rock Mechanics!**
Need to integrate DUSEL into World Network of URL’s

Need Experimental Verification of Models in Different Rock Types (especially sedimentary)

- Mining, Petroleum and Civil Engineering use rock mechanics in professional practice, but the field now extends beyond these disciplines. Considerable input from basic sciences is needed.

- Consider new discipline – “Earth Resources Engineering” – of which Rock Mechanics is a discrete component

- There is a need for several Centers of Excellence in Rock Mechanics at US universities.

- These Centers should be federally funded, but linked intimately to field operations - to allow testing of theoretical predictions and acquisition of field-scale rock properties. DUSEL!
A half century ago, this nation made a commitment to lead the world in scientific and technological innovation; to invest in education, in research, in engineering; to set a goal of reaching space and engaging every citizen in that historic mission. That was the high water mark of America's investment in research and development.

And since then our investments have steadily declined as a share of our national income. As a result, other countries are now beginning to pull ahead in the pursuit of this generation's great discoveries.

I believe it is not in our character, the American character, to follow. It's our character to lead. And it is time for us to lead once again.

“Chronic underinvestment in federal R&D in these subsurface [engineering and geosciences] disciplines has eroded the nation’s capacity to educate and train the next generation workforce necessary for industry, academia, and government.

As a result, the U.S. faces the prospect of ceding its historic leadership role in these disciplines, and thereby undermining its resource security”.

(U.S. Dep’t of Energy, 2009)
Much of Earth Resource development and engineering in the future will occur beyond US boundaries.

US has a strong heritage in rock mechanics, plus world leading universities and institutions.

Applications may be outside US, but we can have a lead role in science and engineering principles of rock mechanics.

We can and should be a leading force in rock mechanics in the future.

It is time to start.

DUSEL is a key element!
The Great Train Robbery  (England 1963).

BBC Interviewer.

“So, who do you think is behind the criminals?”

Inspector - New Scotland Yard.

“Oh, we are – considerably!”

Beyond the Fringe (YouTube)

Thank you for listening!