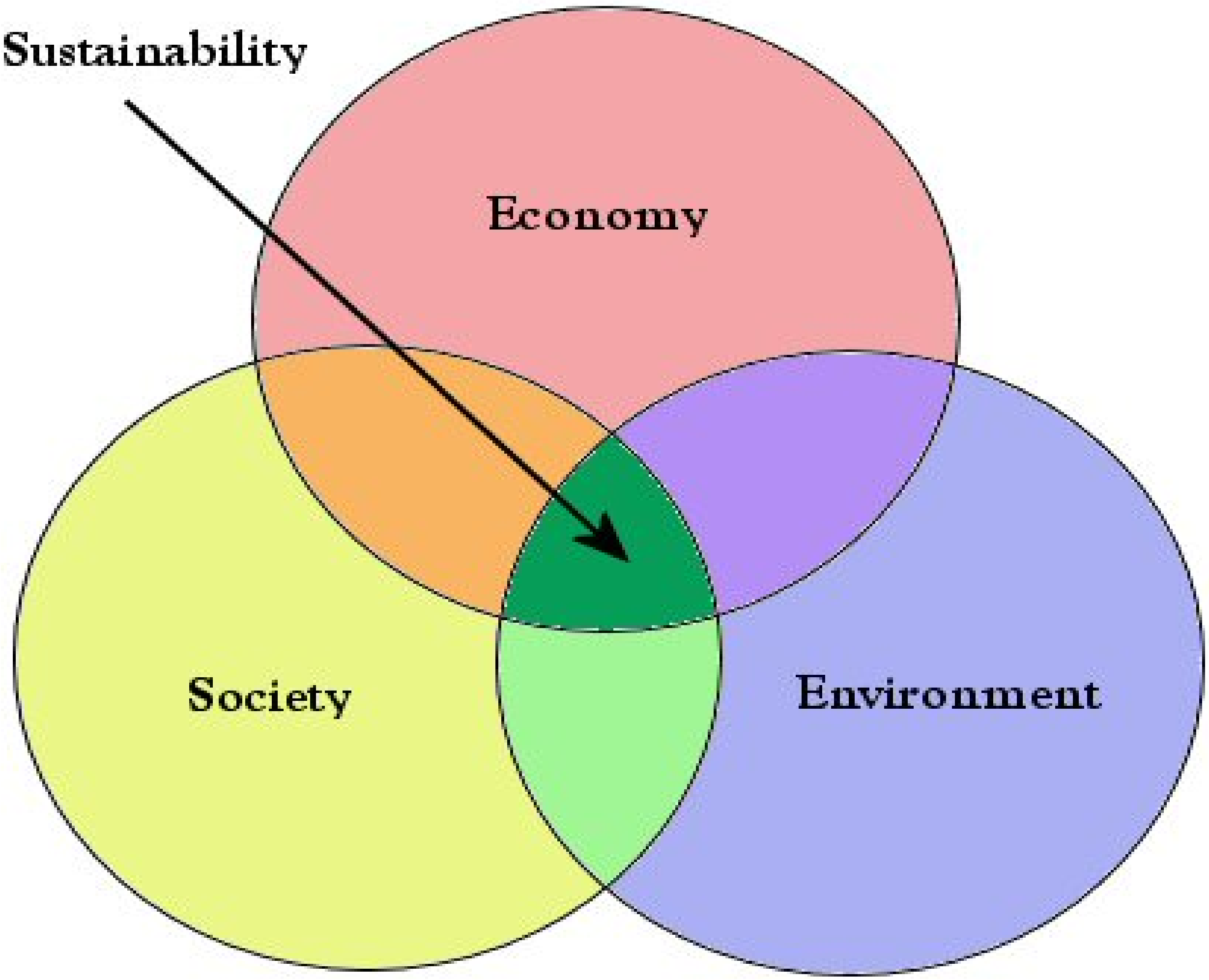
A PRESENTATION ON

SUSTAINABLE DEVELOPMENT AND ENERGY GEEOTECHNOLOGY: POTENTIAL ROLE FOR GEOTECHNICAL ENGINEERING

Lecture 38

Acknowledgments: Miss. Pinom Ering



R.J Fragazy, J.C Jantamarina, A.Amekudzi, D.Assimaki, R. bachus, S.E.Burns, M.Cha , G.C.Cho , D.D cortes, S.Dai, D.N.Espinoza, L.Garrow,H.Huang, J.Jang,J.WW.Jung

OBJECTIVES

- To examine the role that Geotechnical Engineering can play in mitigating the sustainability crises (in particular those related to energy use).
- To help establish research priorities, and to offer suggestions to engineers in practice to help them become more involved in sustainability.
- To identify salient issues related to energy geo-technology, the sustainable use of geo-materials, and the potential impact of climate change in geo-systems.
- To explore potential non-standard geotechnical conditions that may arise and propose an in-depth reassessment of the geotechnical curriculum in view of sustainable geo-engineering.

INTRODUCTION

- Sustainable development “meets the needs of the present without compromising the ability of the future to meet its needs”.
- The development of a sustainable world will require an in-depth understanding of global coupled complex adaptive physical ,biological, and human systems.
- However, humanity currently faces inter-related crises that threaten to negatively impact the quality of life in the developed world, and the ability of developing nations to improve their standard of living.
- These crises include increased energy demands, dependency on fossil fuels, the accelerating use of natural geo-resources, degradation of natural ecosystems, and global climate change.
- These problems threaten to significantly disrupt the balance of global physical, biological and human systems.
- Engineers can make significant contributions by solving these sustainability crises.

http//www.googleimage.com/energy crisis photos/

- Immediate threats to sustainability refer to

(1) the use of natural resources at a rate that will limit the ability of future generations to obtain/utilize resources such as materials, fuels, water, and air

(2) the degradation of natural systems to the point that may jeopardize their beneficial balancing functions.

(3) the global climate change crisis which links anthropogenic effects to the stability of the earth's climate, resulting in significant and potentially catastrophic warming of the earth's atmosphere and oceans, and the concomitant rise in sea levels.

- In 2007, the world consumed approximately 504 EJ of energy (exojoules;1EJ =1018 J), equivalent to 12 Gtoe (gigatons of oil equivalent),81% of which was derived from fossil fuels (IEA, 2009).
- This reliance on fossil fuels is not sustainable in the long term.
- Despite large reserves of coal, oil shales, and possibly methane hydrates, fossil fuels are ultimately exhaustible.
- For example, the world's resources of coal (1600 Gt) would provide 2.5 kW/person for the next 100 years, Oil and natural gas are similarly limited.
- Considering that the world has only been using fossil fuels for approximately 200 years, and current predictions of reserves, the age of fossil fuel will be very short.

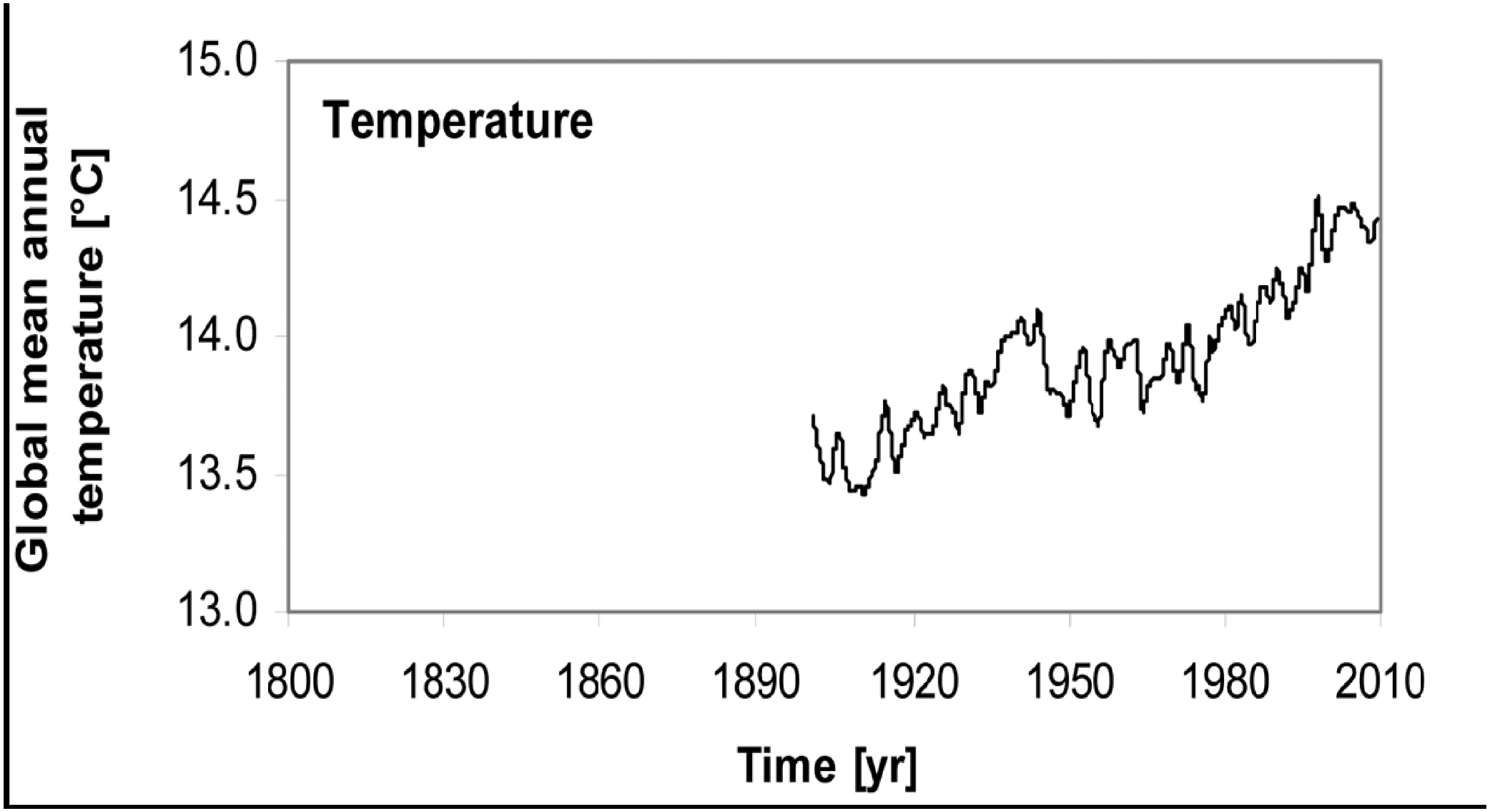


FIG: Global mean annual temperature

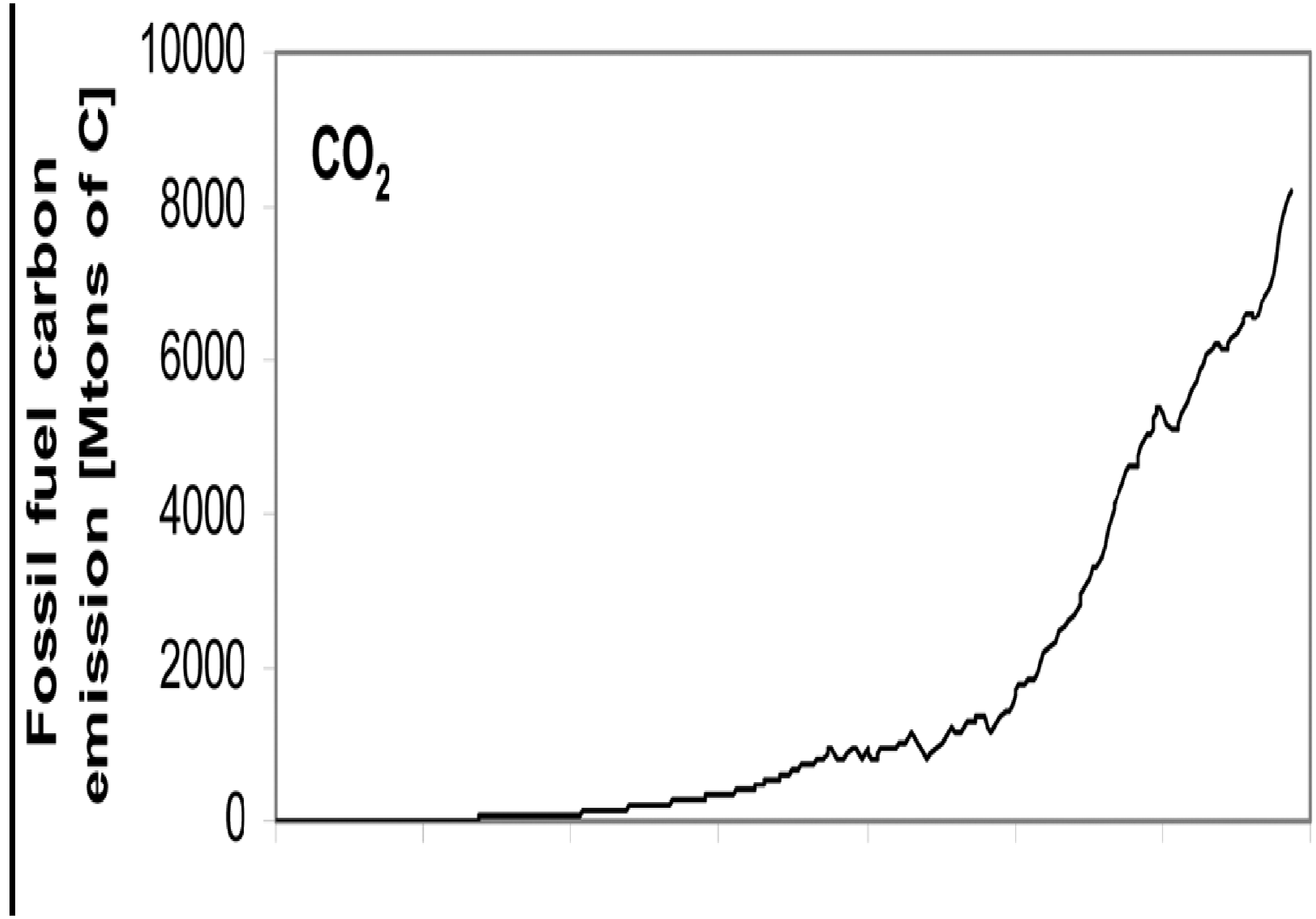


Fig: Carbon emission for last two decades

- The tie between fossil fuel use and global warming through increased CO_2 is well recognized by climate modelers (Chu, 2009).
- The current concentration of CO_2 in the atmosphere is approximately 380 ppm. Research suggests that a CO_2 concentration of 550 ppm could trigger severe climate effects(IPCC, 2000).
- It is estimated that 550 ppm will be reached by the year 2050, unless decisive action is taken by the international community.
- Efforts to control global temperature changes to a level considered acceptable will require curbing CO_2 emissions so the concentration in the atmosphere remains below 380-to-450 ppm.
- To achieve any of these goals requires the reduction in projected CO_2 emissions to the atmosphere by many gigatons(Gt) over the next several decades, sometimes referred to as the"gigaton problem."

- Most of the strategies proposed to date, such as improved gas mileage for vehicles or improved power plant efficiency, do not explicitly involve geotechnical engineering.
- However, a brief analysis of underlying processes readily demonstrates that geotechnical engineering is intimately involved in contributing solutions to the gigaton problem.

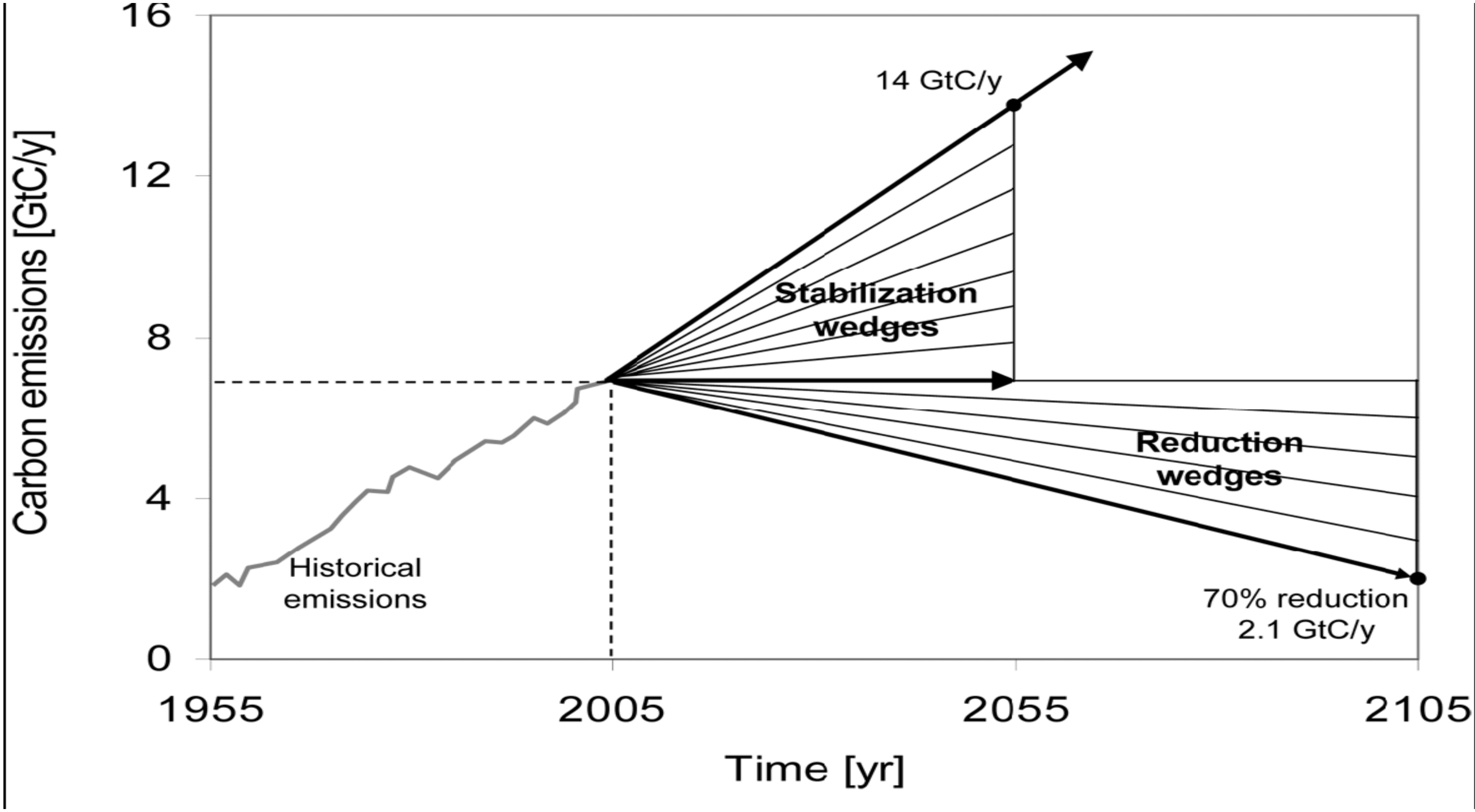


Fig: Carbon Emission Scenario Stabilization Wedges (After Pacala and Socolow, 2004 and Carbon Mitigation Initiative at Princeton Univ.)

ENERGY GEOTECHNOLOGY

- The main sources of energy worldwide are petroleum (34%), coal (26.5%), natural gas (20.9%), combustable renewables and waste (9.8%), nuclear power (5.9%), and hydroelectric (2.2%) and other, mainly wind and solar (0.7%) (2007 data in International Energy Agency,2009).
- Therefore, 81% of all the energy consumed worldwide is obtained from fossil fuels, primarily because of their low cost under present pricing conditions.
- Fossil fuel burning is accompanied by the emission of carbon dioxide, which gradually accumulates in the atmosphere, leading to anthropogenic-driven climate change.

- The current global energy consumption rate is ~15 TW (1TW=1012W).
- There will be a pronounced increase in energy demand in the next 25 years associated with economic development and population growth worldwide:

  (1) 17% increase if consumption and population growth continue at current rates -the business-as-usual option-,

  (2) 66% increase if consumption in the underdeveloped world increases to levels required to attain proper quality of life.

GEOTHERMAL ENERGY

- Deep geothermal energy systems extract heat from hot rock formations (temperatures often exceed 350^{o}C) to produce steam that can be used directly to provide heating or to generate electricity
- Conventional geothermal technology focuses on energy production from rare near surface hot-spots that are sources of steam or hot water.
- However, the vast majority of the world's accessible geothermal energy is found in hot dry rock and the reservoir must be engineered for energy production (i.e., enhanced geothermal systems EGS),typically by hydraulically fracturing the formation to increase hydraulic conductivity and surface area for heat exchange.
- The use of geothermal energy is an appealing strategy for the reduction of CO_2 emissions. Except for the construction of the power plant itself, CO_2 emissions from geothermal power plants are virtually nil.

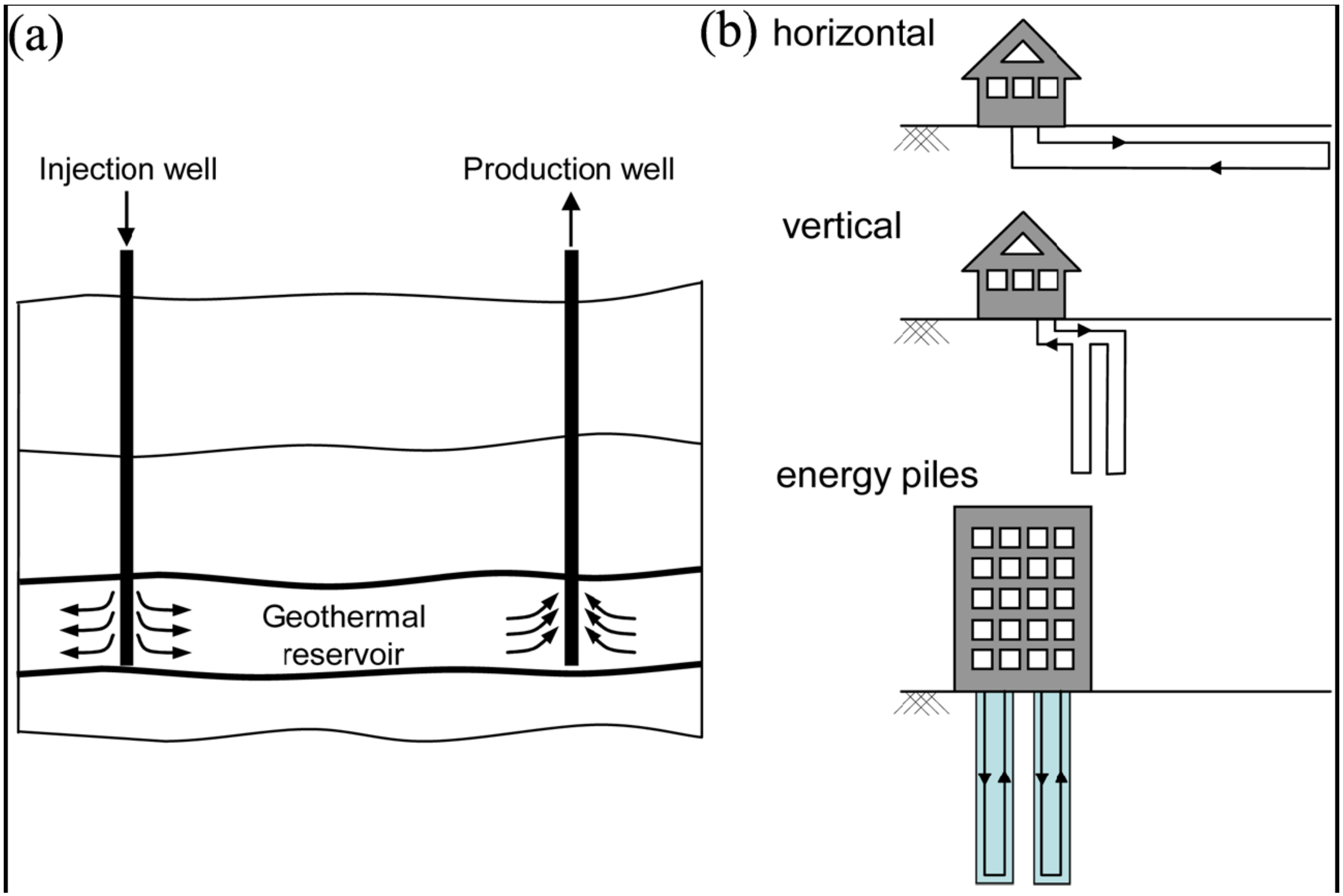


fig: Geothermal Systems: (a) Deep Geothermal Recovery for Electricity Generation, (b) Distributed Geothermal Storage/ Recovery Systems at Shallow Depth for Residential Purposes

- Sustainable geothermal systems must satisfy the renewability limits of the resource, i.e., the time scale for the geothermal reservoir recovery
- Early depletion (fast recovery in the beginning of operation) enhances early return on investment, but it disregards the long-term performance of the reservoir.
- Optimal design and sustainable operation of geothermal systems can potentially delay or prevent depletion, but require: knowledge of the thermal properties of geo-materials, efficient subsurface characterization technology, assessment of ground water flow conditions, ability to analyze hydro-thermo-chemo-mechanical coupled processes to predict short term performance and long-term changes in the reservoir.

- Development of enhanced geothermal systems also requires advances in drilling technology (including high temperature rock drilling for deep systems), controlled hydraulic fracturing in hot rock, and analysis of induced seismicity. Without advances in these areas, geothermal power production will be significantly limited.
- Shallow Geothermal Heat Pumps (GHP) used in homes and commercial buildings utilize the “thermal capacitance” of the ground to transfer heat from the structure to the ground in the summer, and from the ground to the structure in the winter.
- Heat is transported via a fluid flowing through long PVC pipes buried either in horizontal or vertical loops .
- These systems can have high efficiencies, because as much as 85% of the total energy used may come from the ground .

- Geothermal heat pumps often require 100 m deep boreholes or trenching 1-5 m deep for single family home systems, or can incorporate the loops within deep foundations for high-rise buildings, i.e., energy piles .
- The use of GHP systems for residential Heating, Ventilation, and Air Conditioning (HVAC) systems is growing rapidly in Europe, and energy piles are becoming more common in commercial structures. The installation of these systems requires trenching and/or drilling, or the use of deep foundations.
- Efficient design requires the thermal properties of soil and any backfill material used in boreholes, and detailed information of the groundwater regime.
- The main difference in cost between a geothermal heat pump and competing HVAC systems is the initial drilling or trenching cost, thus geotechnical engineers can make these systems more competitive.

- Energy piles have the additional constraint of being utilized for support. Cyclic heating and cooling of the piles may affect the skin resistance of the pile and potentially cause settlement.
- The long-term efficiency of GHP systems, including energy piles, is significantly influenced by the balance between cooling and heating loads. With balanced loads, these systems produce little to no yearly change in ground temperatures that would cause a long-term loss in efficiency.
- When loads are not balanced, ground temperatures gradually increase (cooling load dominates) or decrease (heating load dominates).
- In addition to reducing the efficiency of the GHP system, temperature changes can extend beyond property lines.

- This could be a concern in urban areas where ground temperature changes from one GHP system could affect neighboring systems and structures.
- Research is needed to develop inexpensive methods of evaluating the thermal properties of the ground, to develop modeling tools and design methods for load balancing to prevent long-term temperature changes (in commercial and densely populated urban areas), to understand the effects of thermal cycling on the behavior of energy piles, and to understand the limits of extractable energy for horizontal and vertical systems.

USE OF UNDERGROUND SPACE FOR ENERGY STORAGE

- Solar, tidal and wind energy are inherently intermittent with continual fluctuations in electricity production. Therefore, large-scale energy storage systems are needed to efficiently use generated renewable power.
- Geo-mechanical systems such as pumped storage, hydroelectricity and compressed air offer the means of storing large amounts of out-off peak energy to supply peak demand.
- Salt caverns formed by solution mining, underground rock caverns created by excavating rock formations such as abandoned limestone or coal mines, and porous rock formations can be used for compressed air storage.
- The main geotechnical challenges in the development of compressed air storage are related to: the response of the host rock to large amplitude cycles in pore fluid pressure (e.g., stiffness, strength, strains), thermal fluctuations associated to gas compression and decompression, moisture changes and mineral solubility, evolution and long-term performance of the underground cavern.

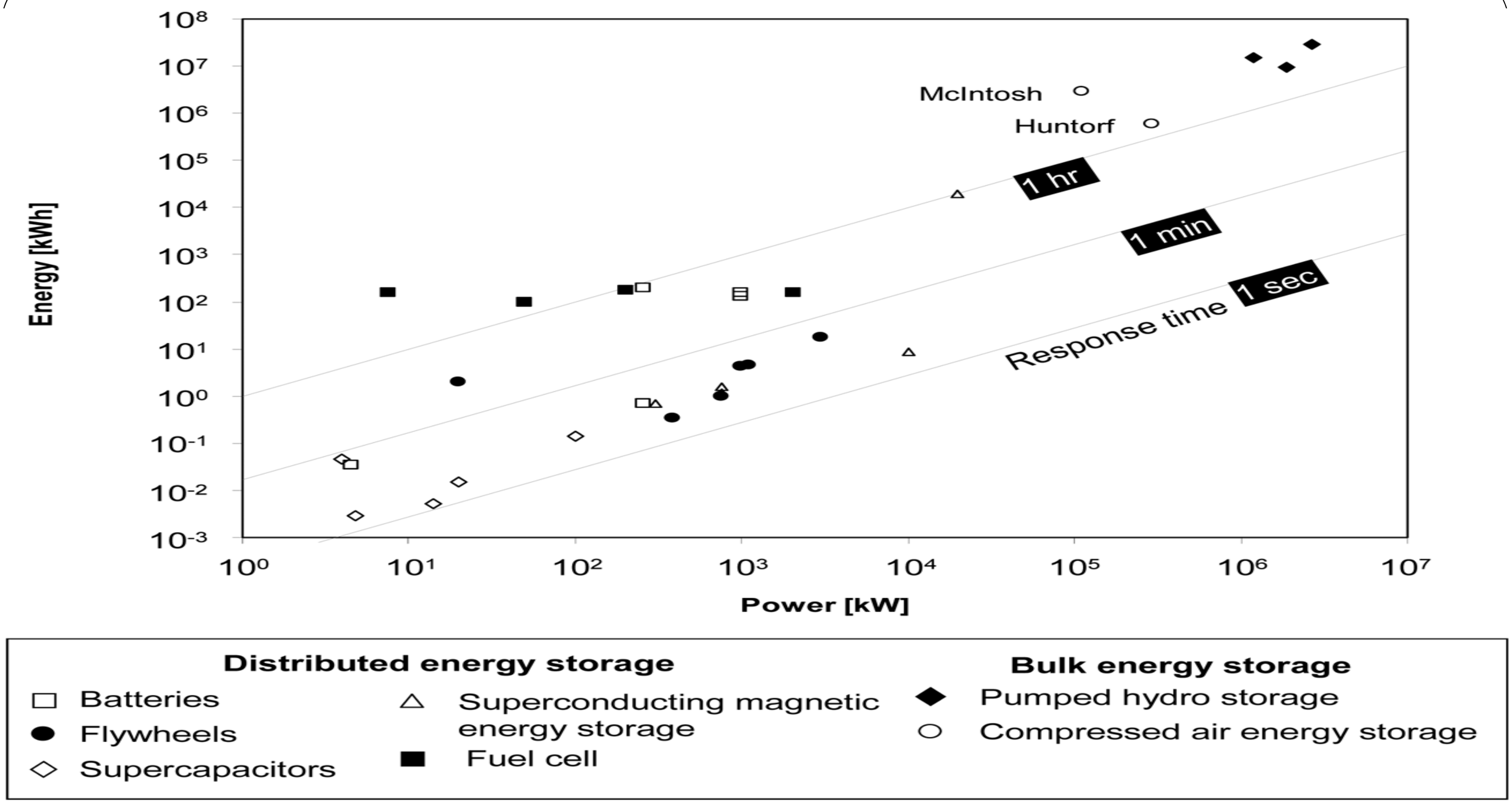


Fig: The Relation between Energy Capacity and Power in Energy Storage Systems (Energy storage systems must satisfy energy capacity and power needs. Geo-storage includes pumped hydro storage PHS, compressed air energy storage CAES, and geothermal storage. Note: PHS and CAES show both high energy capacity and power

RADIOACTIVE SOLID WASTE

- Nuclear power generation embodies very low CO_2 emissions.
- The use of nuclear reactors will demand the development of long-term radioactive waste repositories.
- Geotechnical engineering issues related to nuclear energy are critical at all stages: mining (excavation and handling of tailings), foundation of nuclear plants (static and seismic design, heat absorption for new generation systems, design for decommissioning), spent fuel pools (design for decommissioning, geophysical monitoring and leak detection, bio-remediation), and waste repositories.
- A series of natural and engineered barriers to contain waste that will be carefully prepared, packaged and placed in excavated tunnels.
- Potential geological formations include salt, hard rock, or clay to minimize the amount of radioactive material that may eventually be transported away from a repository and reach the human environment.

CARBON STORAGE IN GEOLOGICAL FORMATIONS

- Significant reduction in CO_2 emissions could be realized by implementing Carbon Capture and Storage (CCS) technologies with the potential to reduce a gigaton of emitted CO_2 per year.
- Development of efficient carbon capture technology to remove CO_2 from plumes emitted by coal-burning power plants and kilns used in Portland cement production.
- Robust technology is available to inject CO_2 into the ground.
- However, significant geotechnical uncertainties remain related to geological storage, including: identification and characterization of suitable formations, continuity and long-term stability of sealing layers, long-term performance of grouts and well plug.

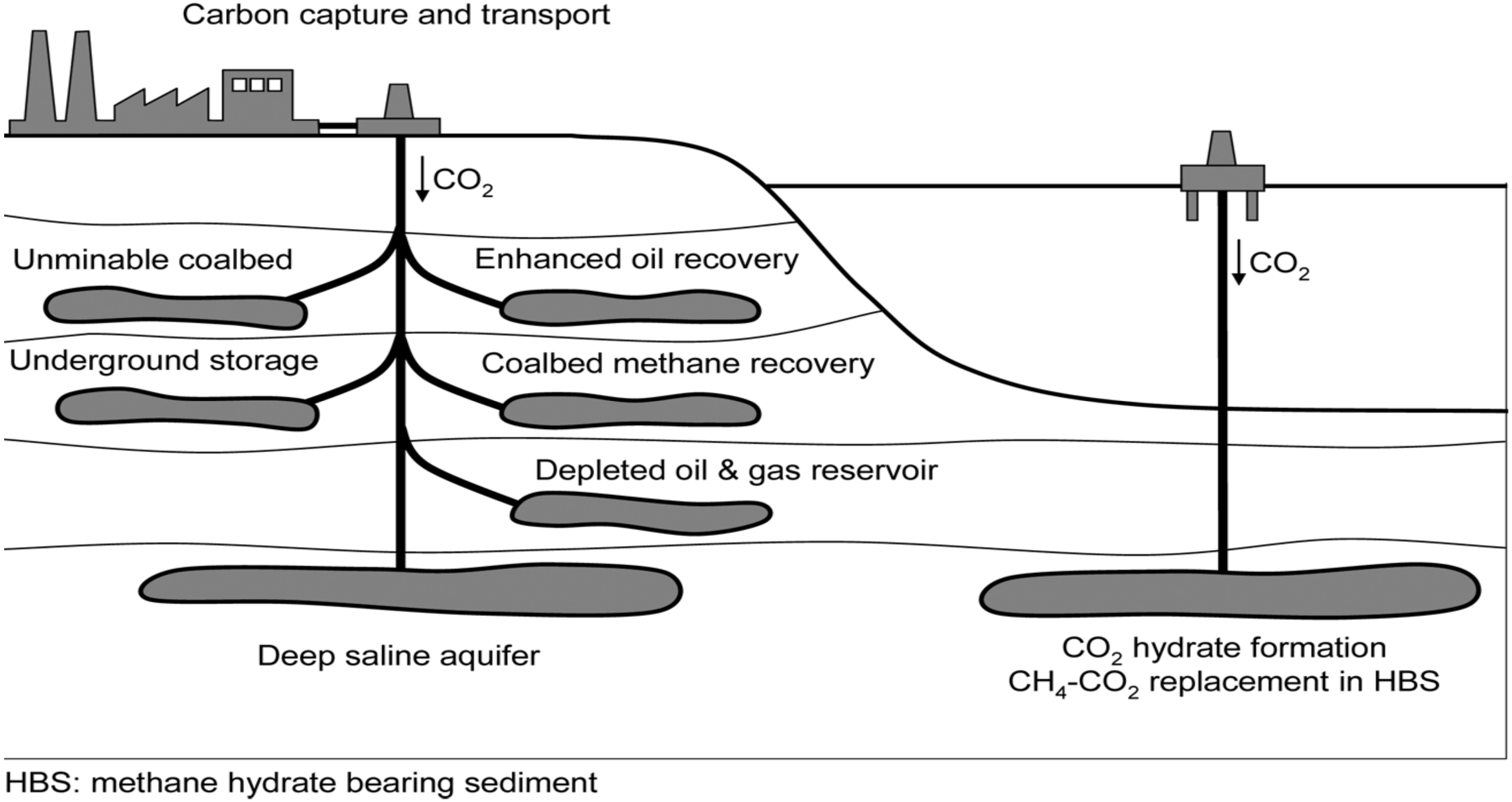


Fig: Carbon Capture and Geological Sequestration (Alternative formation)

INTEGRATED ASSESSMENT OF ENERGY OPTIONS

- It is necessary to carefully evaluate the different energy solutions within a technically rigorous integrated assessment framework.
- Consider for example, the various alternatives of reducing CO_2 emissions, including carbon sequestration, nuclear generation, and renewables such as wind and solar.
- An integrated assessment would compare alternative options, including the life cycle cost of a unit of CO_2 emissions reduction, the revenue stream of electricity produced, and the risks associated with each method ,such as CO2 leakage from storage reservoirs, hazard to avian life from windmill blades, and nuclear contamination.

SUSTAINABLE USE OF GEO-MATERIALS: WASTE GENERATION AND REUSE

- All human activities generate waste, i.e., the loss of natural resources and embodied energy and the unnecessary emission of embodied CO_2.
- Sustainable waste generation requires that the rate of waste generation does not exceed our ability to either reuse or dispose of it.
- In addition, waste generation should not lead to the depletion of materials.
- Waste is categorized as solid waste, hazardous waste, radioactive waste, and medical waste.
- The productive reuse of waste materials limits the quantities that must be land filled or incinerated.

- Geotechnical engineering plays a key role in

  (1) increasing: the efficient use of natural resources, recycling, the more comprehensive use of virgin materials, and energy efficiency

  (2) reducing: volume extraction and waste;

  (3) engineering waste reuse for long term performance and chemical stability;

  (4) developing engineered waste containment facilities (surface and sub-surface) for increasingly unsuitable environments and under increasingly more demanding performance/monitoring requirements.

FROM FOSSIL FUELS TO CLIMATE CHANGE: THE EFFECTS ON GEOSYSTEMS

- Climate change has significant impact on the built environment
- Immediate implications lead to a complex sequence of causally linked phenomena: extreme weather conditions and associated geo-hazards; global warming; magnification of issues associated with high urban temperature or heat islands, melting of permafrost and icecaps; and increase in sea level.
- For example, permafrost is the most vulnerable carbon pool of the earth, and its melting will lead to the release of large amounts of biogenic methane (a potent greenhouse gas).
- Geotechnical consequences of climate change could include: flooding and erosion control for coastal areas and along river margins; engineering hydrogeology to prevent salt-water intrusion and the contamination of fresh water reservoirs; instability of geo-systems associated with the melting of the permafrost and snow caps (including the evolution of unsaturation and pore pressure generation during gas release.

SUSTAINABLE DESIGN AGAINST MULTIPLE HAZARDS

- Geotechnical engineering plays a critical role in the development of a sustainable built environment.
- Research examples include: Dynamic and long-term static soil-pile interaction effects for energy piles; Time varying soil properties over repeated cycles of ground temperature changes and implications on the response of the foundation to extreme loading; Dynamic soil-structure interaction effects for wind turbine foundations, subjected simultaneously to earthquake loading and the dynamic cyclic loading from the superstructure.

ENHANCED USE OF UNDERGROUND SPACE

- The development of underground space becomes particularly appealing within the framework of sustainable urban growth and energy conservation .
- The long-term life-cycle cost may favor underground space particularly when other parameters are taken into consideration as well maintenance costs; life-long energy savings; impact on urban development.
- Future underground utilization will seek large underground space for multi-purpose space use (shopping mall, stadium,storage, sewage treatment plant) long tunnels of large cross section.
- Geotechnical innovations needed for the efficient and sustainable development of underground space include:

- Site investigation

- Excavation: Self-adaptive excavation tools with minimal operator intervention for a wide range of ground conditions; fast, yet low noise/vibration excavation methods; energy efficient excavation.
- Use of excavated materials: Near-site use of excavated materials to make optimal use of natural resources with minimal transportation cost.
- Support system: Low cost short-term tunnel support; self-diagnostic liner segments; self-healing materials flexible lining system to accommodate settlements without losing structural capability or allow water to flow.

NON-STANDARD GEOTECHNICAL ISSUES IN ENERGY GEOTECHNOLOGY

- Various areas of specialization in geotechnical engineering are closely related to technical needs in energy and sustainability; consider for example: frozen ground in hydrate bearing sediments, thermal properties in geothermal energy, unsaturated soils in gas and oil recovery.
- Discontinuities: Discontinuities act as weak zones, change the macro-scale mechanical response, limit stability, and define the deformation field.
- The presence of discontinuities can drastically affect fluid transport through sediments, define the “geo-plumbing” of the subsurface, give rise to fluid migration and determine the geological storability of water, oil, gas, compressed air or CO2.

- Coupled processes : Water acidifies when mixed with CO_2, therefore, the geological storage of CO2 must take into consideration the consequences of mineral dissolution.
- Shear fractures in contraction following mineral dissolution and internal piping discontinuities are examples of chemo-mechanical and hydro-mechanical couplings.
- Most problems in sustainable geo-engineering involve some form of coupling between chemo-thermo-bio-hydro-mechanical processes.
- Such complex systems are prone to instabilities and the emergence of unanticipated phenomena

- Biological phenomena : Microorganisms changed the atmosphere from reducing to oxidizing, and determined the composition of most minerals that form today’s soils and rocks.
- To engineer, biological process alter sediment properties, including skeletal stiffness (bio-cementation);hydraulic conductivity (bio-clogging); water stiffness (bio-gas generation); and bio-remediation of contaminated sites.
- Significant reductions in energy and material use might result if, for example, reinforced concrete foundations can be reduced in size by increasing the strength and stiffness of foundation soils by biological activity.
- Spatial variability : Many sustainability-related geotechnical problems are large-scale.

- Consequently, their analysis must recognize the inherent spatial variability and scale-dependence in the subsurface, its anisotropy and associated emergent phenomena.
- Future developments need to explore new field assessment methods and the development of robust procedures to take spatial variability into consideration during design.

CONCLUSION

- The role of Geotechnical engineering in mitigating global crises related to sustainability, with a focus on energy, global climate change, use of natural resources, and solid waste generation/management.
- The geotechnical engineering profession needs to meet these challenges acting now in a coordinated and determined manner, from individual engineers to professional societies, fully aware of the significant role we can play in the development of a sustainable, energy viable society.
- Scientific and engineering research needs immediately follow from this brief review. Research will need to include non-standard issues such as the response of geo-materials to extreme conditions, couple processes, biological phenomena, spatial variability, emergent phenomena, and the role of discontinuities.

- The geotechnical engineering curriculum, from undergraduate education through continuing professional education, must address the changing needs of a profession that will increasingly be engaged in sustainable design, energy geo-technology, enhanced/more efficient use of natural resources, waste management, underground utilization, and alternative/renewable energy.

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