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Sustainable Development and Energy Geotechnology– Potential Roles for Geotechnical Engineering

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Abstract

The world is facing unprecedented challenges related to energy resources, global climate change, material use, and waste generation. Failure to address these challenges will inhibit the growth of the developing world and will negatively impact the standard of living and security of future generations in all nations. The solutions to these challenges will require multidisciplinary research across the social and physical sciences and engineering. Although perhaps not always recognized, geotechnical engineering expertise is critical to the solution of many energy and sustainability-related problems. Hence, geotechnical engineers and academicians have opportunity and responsibility to contribute to the solution of these worldwide problems. Research will need to be extended to non-standard issues such as thermal properties of soils; sediment and rock response to extreme conditions and at very long time scales; coupled hydro-chemo-thermo-bio-mechanical processes; positive feedback systems; the development of discontinuities; biological modification of soil properties; spatial variability; and emergent phenomena. Clearly, the challenges facing geotechnical engineering in the future will require a much broader knowledge base than our traditional educational programs provide. The geotechnical engineering curricula, from undergraduate education through continuing professional education, must address the changing needs of a profession that will increasingly be engaged in alternative/renewable energy production; energy efficiency; sustainable design, enhanced and more efficient use of natural resources, waste management, and underground utilization.

Keywords: *sustainability, energy, CO_2 sequestration, education, climate change, research, geothermal, underground storage, hydrate*

1. Introduction

The term "sustainability" and "sustainable development" have been used with increasing frequency by engineers over the past two decades. Engineering schools have started courses and degree programs, and formed centers for sustainable engineering. Sustainable development "meets the needs of the present without compromising the ability of the future to meet its needs" (Brutland Commission - United Nations, 1987). Furthermore, it is "a process of change" in which investments, technology, resource allocation, and institutions transition toward longer-term sustainable activities (Weston, 1994). These observations demand significant engineering research and development. Yet, the scientific literature on sustainability contains little guidance to identify engineering needs; for example, a recent NSF-sponsored workshop "Toward a Science of Sustainability" (Levin and Clark, 2010) did not suggest any specific roles for engineering. However, energy and material use, life cycle analyses, transportation and urban infrastructure are at the core of the transition to a sustainable society.

The development of a sustainable world will require an in depth understanding of global coupled complex adaptive physical, biological, and human systems (Holling, 2001). Understanding these systems' interactions and evolution is needed to address sustainability. However, humanity currently faces inter-related crises that threaten to negatively impact the quality of life in the

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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. Each of these sustainability problems is threatening to significantly disrupt the balance of global physical, biological and human systems. Engineers can make significant contributions by solving these sustainability crises.

In this context, 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; and (2) the degradation of natural systems to the point that may jeopardize their beneficial balancing functions. Included in these observations is 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.

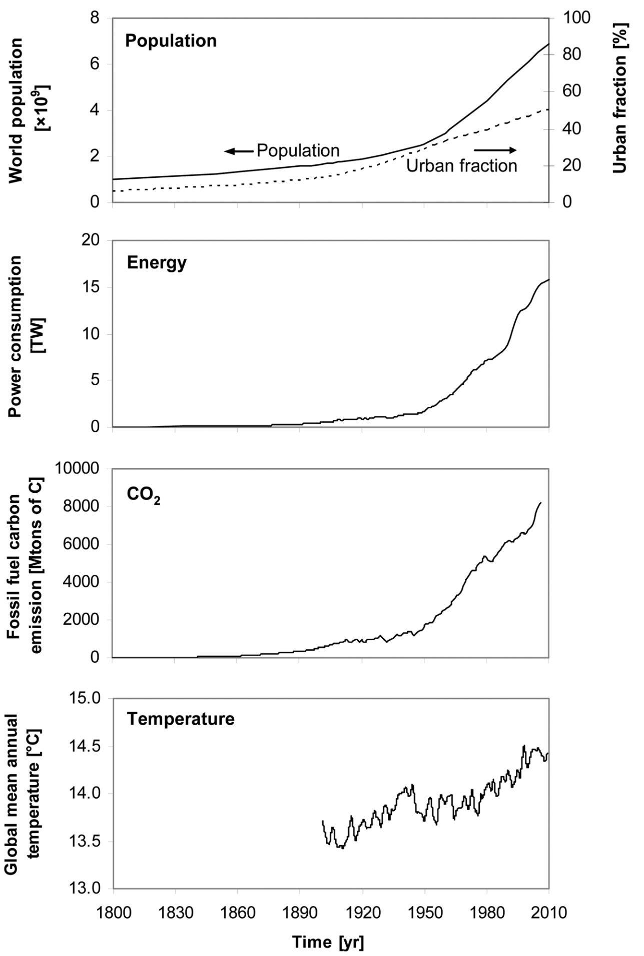

Fig. 1. Population, Power Consumption, Carbon Emissions and Global Mean Annual Temperature Trends for the Last Two Centuries (Data from United Nations-http://esa.un.org/unpp, Agency of Natural Resources and Energy, and Climate Research Unit in University of East Anglia-http://www.cru.uea.ac.uk/cru/.)

The negative impact of the world's use of fossil fuels is central to the discussion of a sustainable future (Fig. 1). In 2007, the world consumed approximately 504 EJ of energy (exojoules; 1EJ = 10^{18} 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, which is less than 25% of the current per capita energy use in the United States (MacKay, 2009). 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.

The effects of current use of fossil fuels, however, are a more immediate problem. 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." Fig. 2 illustrates the goals of zero net increase in CO_2 emissions over 50 years and a 70% reduction in 100 years (Pacala and Socolow, 2004). The reduction in projected emissions from a "do nothing" scenario is captured in "wedges," each of which represents a reduction of 1 Gt/yr after either 50 or 100 years. The challenge is to identify and to implement specific strategies to achieve each wedge reduction.

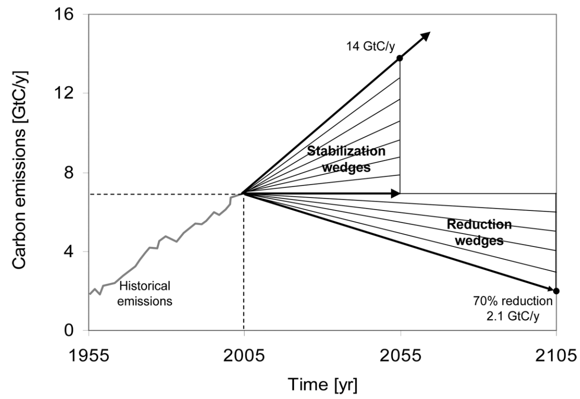

Fig. 2. Carbon Emission Scenario – Stabilization Wedges (After Pacala and Socolow, 2004 and Carbon Mitigation Initiative at Princeton Univ.)

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. The objectives of this paper are to examine the role that Geotechnical Engineering can play in mitigating these 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. While the analysis is inherently limited, we attempt to identify salient issues related to energy geotechnology, the sustainable use of geomaterials, and the potential impact of climate change in geosystems. Then, we explore potential non-standard geotechnical conditions that may arise and propose an in-depth reassessment of the geotechnical curriculum in view of sustainable geoengineering.

2. Energy Geotechnology

Energy and quality of life (infant mortality, education, life expectancy) are intimately related, as shown by the high correlation between the Human Development Index (HDI) and energy consumption per capita (Fig. 3). 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.

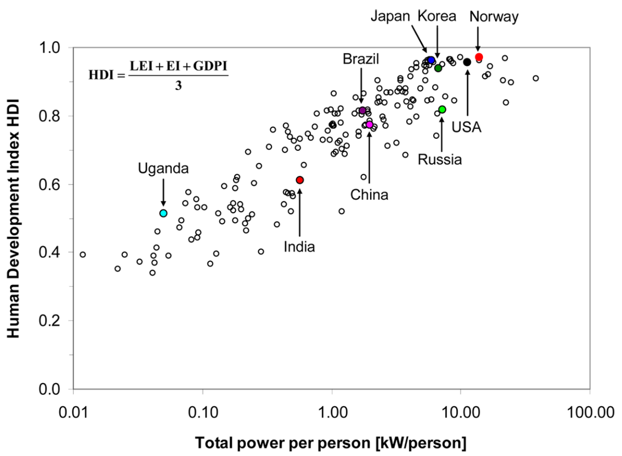

Fig. 3. The Relation Between Human Development Index (HDI) and per Capita Energy Consumption – All Countries (While the human development index is intimately correlated with power consumption, the data show that similar quality of life is attained with vastly different energy consumption levels. Note the human development index HDI is the average of life expectancy index LEI, education index EI, and gross domestic product index GDPI. Data from human development reports in http://hdr.undp.org/en/statistics/data/.)

Based on reported national values, the current global energy consumption rate is ~15 TW ($1\,TW = 10^{12}\,W$). 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 (i.e., 1.5 kW/person - Santamarina, 2006). This situation will exacerbate current issues caused by the dependency on fossil fuels, its environmental consequences, and the international implications due to the mismatch between the geographic distributions of supply and demand of fossil fuels. A sustainable worldwide energy system will require proper long-term national policies within a global approach, strategic pricing that takes into consideration production costs and life-cycle waste processing, reduced population growth rates, and efficiency and conservation with associated changes in cultural patterns.

Geotechnology has historically played an important role in fossil fuel production; for example, in oil production: subsidence, mixed fluid flow, sand production, hydraulic fracture, shale instability, fines migration and clogging. However, there are also many other critical geotechnology roles related to renewable energy and reduction in CO_2 emissions from fossil fuel power plants. The following examples highlight a few salient cases.

2.1 Geothermal Energy

Deep geothermal energy systems extract heat from hot rock formations (temperatures often exceed 350ºC) to produce steam that can be used directly to provide heating or to generate electricity (Fig. 4a). Conventional geothermal technology focuses

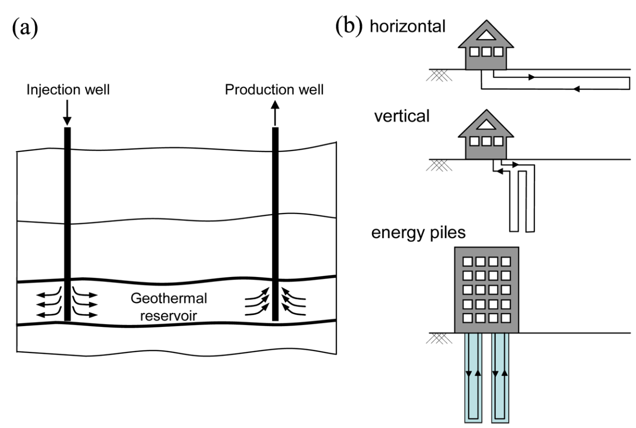

Fig. 4. Geothermal Systems: (a) Deep Geothermal Recovery for Electricity Generation, (b) Distributed Geothermal Storage/ Recovery Systems at Shallow Depth for Residential Purposes

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 (Duchane and Brown, 2002), 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. The extractable thermal energy in the USA alone is estimated to be about 200,000 EJ (Anderson *et al*., 2006), which is over 1400 times the annual consumption of primary energy in the USA, 141 EJ (2007 data in IEA, 2009). Sustainable geothermal systems must satisfy the renewability limits of the resource, i.e., the time scale for the geothermal reservoir recovery (Fig. 5). 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 geomaterials, 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.

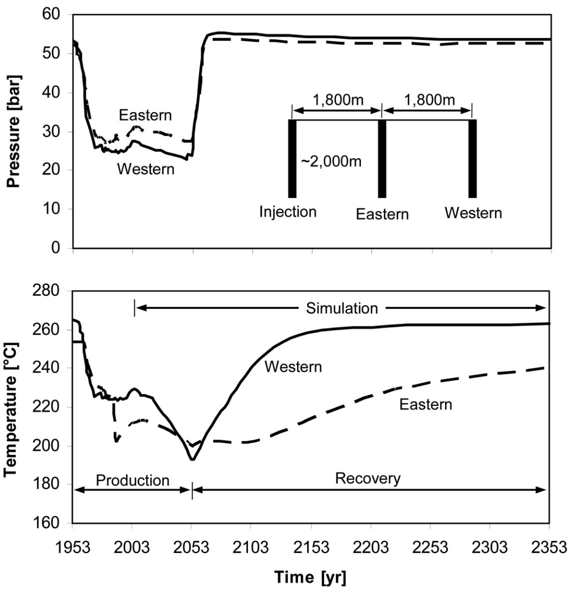

Fig. 5. Pressure and Temperature Recovery in Geothermal Reservoir (Geothermal energy is a resource that can be temporarily depleted. Long recovery times are required afterwards. The data show pressure and temperature evolution at the Wairakei-Tauhara system in two borefields. The values from 1953 to 2003 were measured during operation, and the values from 2004 to 2053 were estimated assuming a constant production level (2003 to 2053) and full recovery (2053 to 2353). Modified from O'Sullivan and Mannington (2005).)

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 (Fig. 4(b)). These systems can have high efficiencies, up to approximately 600%, because as much as 85% of the total energy used may come from the ground (DOE, 2010). 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 (Brandl, 2006). 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 role of geotechnical engineers in the development of geothermal heat pump systems is significant. 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. The design of a geothermal heat pump system for a new construction could be included as part of the standard geotechnical investigation. Testing needed to determine thermal properties would add minimal additional cost when drilling/testing is already required for foundation design. Boreholes used in the site investigation might also be used for the vertical loops of a GHP system, and/or additional boreholes can be drilled during the site investigation. If horizontal loops are preferred, the needed trenching can be utilized as part of the site investigation. Concurrent drilling and trenching during the site investigation would reduce cost and increase the competitiveness and long-term savings of GHP systems.

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.

The issues described above require geotechnical expertise and research. 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.

2.2 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. Although much attention has been focused on advanced rechargeable battery systems, 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 (Fig. 6). There is extensive experience with pumped storage hydroelectric projects; however, there are only a handful of compressed air systems in use today (see Pasten and Santamarina, 2011).

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 (Allen *et al*., 1982a; Allen *et al*., 1982b; Allen *et al*., 1983). The main geotechnical challenges in

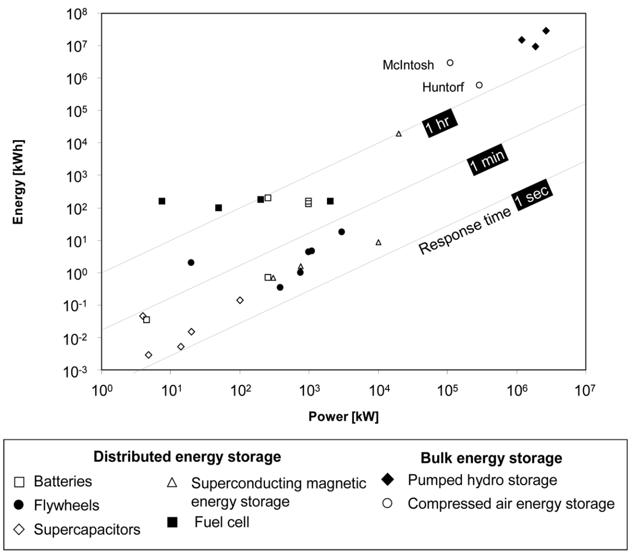

Fig. 6. The Relation between Energy Capacity and Power in Energy Storage Systems (Energy storage systems must satisfy energy capacity and power needs. Geo-storage includes pumped hydro storage PHS, compressed air energy storage CAES, and geothermal storage. Note: PHS and CAES show both high energy capacity and power. Data from Schoenung (2001).)

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, and robust monitoring tools to assess the integrity, evolution and long-term performance of the underground cavern. Research on these topics could make underground compressed air storage a viable option for many of the large-scale wind and solar farms and tidal systems currently under development.

2.3 Radioactive Waste Storage

Nuclear power generation embodies very low CO_2 emissions. To put this alternative into perspective, let us note that:

- Fewer than 500 nuclear power plants have been built and operated around the world since 1951 when electricity was first generated from a nuclear plant.
- Assuming a typical 1 GW plant size, an additional 2400 nuclear power plants would be required to produce the 2.4 TW increase predicted in 25 years under a *status quo* scenario of constant trends in population growth and constant power consumption.
- There is no nuclear waste repository in operation in the world, and waste fuel is kept in pools. While the critical time for waste fuel is ~100 years, the design horizon for waste repositories is 10,000 years in the USA and 1,000,000 years in some European countries.

Leaving aside the practicality of building so many nuclear power plants, and other concerns related to nuclear proliferation and social issues involved, 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.

Various options for long-term radioactive waste geological storage have been considered. The concept relies on 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. Engineered geo-barriers must satisfy challenging criteria: self-healing, thermal stability and clay pyro-metamorphosis, seismic response, biological shield, high heat conduction but low hydraulic conductivity, and radionuclide retention. The extremely long containment time needed for such facilities requires knowledge about long-term coupled thermo-hydro-chemo/radio-bio-mechanical behavior of soils and rock that approach geologic time scales.

2.4 Carbon Storage in Geological Formations

A 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 (Fig. 2). Extensive current research efforts are devoted to the 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. However, the long-term geotechnical implications of CO_2 geological storage are less explored. The principal target formations for CO_2 injection are sketched in Fig. 7 and include: deep saline aquifers (non-usable), petroleum and gas reservoirs (enhances oil production and cap rock acts as seal), low-grade or unminable coal seams (with the potential advantage of methane recovery), deep ocean sediments to form CO_2 hydrate, and CH_4 hydrate-bearing sediments to replace CH_4 with CO_2. Multiple pilot projects are currently underway in the USA and abroad (DOE-NETL, 2008; Torp and Gale, 2004).

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 plugs, subsurface plume tracing and leak detection and monitoring, chemo-hydro-mechanical coupled processes in the reservoir. Anticipated coupling examples range from pressure solution precipitation, changes in permeability, coal swelling, and local deformations, to the development of piping and localized fluid flow, discontinuities and shear localization in contraction (Rutter and Elliott, 1976; Gunter *et al*., 2000; Ceglarska-Stefanska and Zarebska, 2002; Van Bergen *et al*., 2003; Watson *et al*., 2004; Renard *et al*., 2005; Kaszuba *et al*., 2005; Mazumder *et al*., 2006; Andre *et al*., 2007; Shin *et al*., 2009; Jung *et al*., 2010).

2.5 Integrated Assessment of Energy Options

Energy alternatives imply high initial costs, decades for return on investment, different waste streams, and potential implications that extend for hundreds to thousands of years into the future. Trillions of dollars will be spent worldwide on these strategies over the next few decades. It is necessary to carefully evaluate the different energy solutions within a technically rigorous integrated assessment framework.

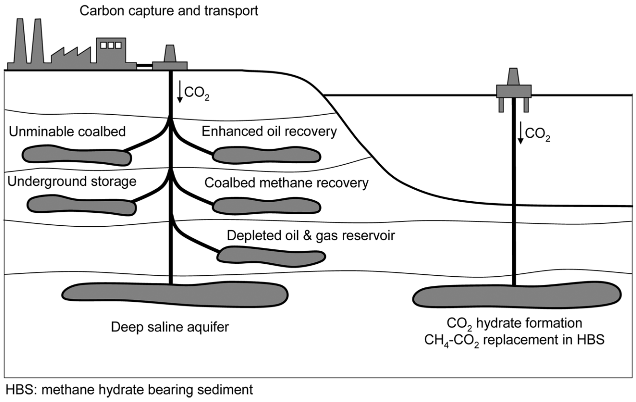

Fig. 7. Carbon Capture and Geological Sequestration (Alternative formation)

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 CO_2 leakage from storage reservoirs, hazard to avian life from windmill blades, and nuclear contamination. Integrated assessment is essentially needed to categorize the Pacala-Socolow (2004) stabilization wedges in terms of cost, risks, and benefits. Geotechnical input related to the risk of CO_2 leakage, seismic risk to nuclear power plants, and the potential for induced seismicity in geothermal projects will be essential for such an analysis.

Integrated assessment often provides unprecedented insight. For example, preliminary results have shown that: (1) carbon capture and storage is justifiable compared to carbon-free wind and nuclear generation only for industries that produce highly concentrated CO_2 emissions, such as cement kilns and coal burning plants, and (2) wind and nuclear generation will have higher return on investment than coal power plants (Tsouris *et al*., 2010).

3. Sustainable Use of Geomaterials: 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. In natural biological systems, waste from one system is the input material for another system. However, human-generated waste is typically not reused within a generation time scale. 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. Geo-related materials such as mine waste, energy-related waste, and dredged sediments are the primary components in the solid waste stream in the United States. The productive reuse of waste materials limits the quantities that must be landfilled or incinerated. For example, in the United States, approximately 46% of municipal solid waste is either recycled, composted, or combusted with energy recovery (Environmental Protection Agency, 2007); approximately 43% of coal combustion products are reused (cement replacement, embankments, agriculture, and aggregate replacement; American Coal Ash Association, 2010); between 50-75% of cement kiln dust is reused internally or commercially (agriculture, pavements, backfill, landfill cover; Environmental Protection Agency, 2010);

and approximately 89% of scrap tires are reused as fuel, ground rubber, or in general construction applications (Rubber Manufacturers Association, 2009). However, the rate of waste generation is staggering, and reuse/recycle is often insufficient or too costly within current pricing schemes. The following paragraphs attempt to capture the magnitude of the problem:

- *Mining.* The mining industry in the United States is the largest in the world, accounts for about 13.4% of total US GDP, consumes approximately 5% of total US energy use, and involves over a billion tons of excavated geomaterials every year, i.e., 4 tons/person/year (Moore Economics, 2009; DOE, 2009). The bulk of the material excavated in mining operations is waste, requires large areas for storage, often leaches hazardous chemicals into the groundwater, and when placed as tailings dams can cause failures, extensive flooding and damage.
- *Coal combustion products*. Fly ash and bottom ash from coal combustion contribute approximately 91 million tons to the US waste stream every year (ACAA, 2008). The increased use of fly ash as a partial substitute for cement in Portland cement concrete has the double benefit of reducing the amount of fly ash that is placed in ponds and landfills, as well as reducing the net amount of carbon released to the atmosphere during cement production.
- *Dredging.* Dredging generates 200 to 300 million tons of materials each year in the US alone. Dredging typically takes place along rivers and ports near urban areas, however, only 30% of the dredged materials is put to any beneficial use.

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 (crushing operations are 1-to-5% efficient as shown in Fig. 8); (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.

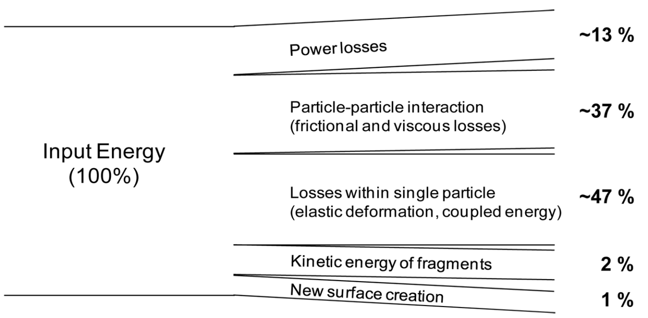

Fig. 8. Rock Crushing and Mineral Grinding Operations have Very Low Energy Efficiency (The data shown corresponds to a ball mill for cement manufacturing. Energy efficiency can be as low as 1%. data from Beke (1964).)

4. From Fossil Fuels to Climate Change: The Effects on Geosystems

Climate change will have significant impact on the built environment. Immediate implications lead to a complex sequence of causally linked phenomena: extreme weather conditions and associated geohazards; global warming; magnification of issues associated with high urban temperature or heat islands (e.g., Phoenix Arizona); melting of permafrost and icecaps; and increase in sea level.

These are not necessarily self-stabilizing processes. 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). Therefore, global-climate feedback could turn the Arctic tundra from a carbon sink to a carbon source (Oechel *et al*., 1993; Zimov *et al*., 2006).

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 geosystems associated with the melting of the permafrost and snow caps (including the evolution of unsaturation and pore pressure generation during gas release); failures of infrastructure; enhanced microbial activity in sediments; evolution of the physical properties of soils as a function of changing weather conditions (including thermal and mechanical); and the consequences of large-scale coupled thermo-chemo-hydro-bio-mechanical processes.

4.1 Sustainable Design Against Multiple Hazards

New environmentally friendly materials, enhanced structural components developed to satisfy sustainability requirements, and unprecedented loading conditions that could result from climate change require the re-evaluation of established performance-based design criteria for resilient, sustainable infrastructure. Currently, the design of resilient infrastructure against multiple hazards is done ad-hoc due to lack of standardized solutions, limited design procedures, and scarcity of case histories for validation.

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; Assessment and re-use of existing foundation elements in view of multiple anticipated hazards; Assessment and retrofitting of waterfront protection systems against rising sea level and the potential increase in the occurrence of tsunamis, hurricanes, and earthquakes.

4.2 Enhanced Use of Underground Space

The development of underground space becomes particularly appealing within the framework of sustainable urban growth and energy conservation (ECTP, 2005). The initial capital cost of tunnels is significantly higher than for surface roads (4-to-6 times) or elevated highways (about 2 times). However, construction costs may be compensated for by the cost of land purchase in urban areas, and the future value of the land when roadways and mass transit are located below ground (e.g., the "big dig" in Boston and the Roslyn-Ballston corridor in Arlington, Virginia). The long-term life-cycle cost may favor underground space (Parker, 2007), particularly when other parameters are taken into consideration as well maintenance costs; life-long energy savings; impact on urban development (right of way, local employment); impact on quality of life (e.g., users' time and cost savings); improved safety and accident reduction; and environmental impact (noise, air quality, greenhouse gases).

Future underground utilization will seek large underground space for multi-purpose space use (shopping mall, stadium, storage, sewage treatment plant; Hudson, 1996), long tunnels of large cross section (convertible road and water drainage tunnel, energy harvesting tunnel; Tan, 2006), or very deep underground space (rescue shelters, nuclear waste disposal; Mörner, 2001).

Geotechnical innovations needed for the efficient and sustainable development of underground space include:

- *Site investigation*: "see ahead" 3D technology and "transparent earth".
- *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. While the geotechnical component is only a part of the total cost, it is important to highlight that the embodied energy in underground excavation with current technology (in the order of 10^8-to-10^9 J/m^3) is much higher than the energy consumption in hand excavation (10^7 J/m^3) and the energy consumed by ants (10^4 J/m^3) (Espinoza and Santamarina, 2010). Therefore, there is plenty of room to improve energy efficiency in underground space construction.
- *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 (Muto *et al*., 1992); flexible lining system to accommodate settlements without losing structural capability or allow water to flow.

5. 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. However, energy geotechnology and sustainability bring new challenges outside the realm of today's geotechnical practice and research. Selected cases are discussed in this section.

5.1 Discontinuities

The development of shear bands has received much attention in the geotechnical community during the last three decades. However, there is increased recognition that positive feedback systems may develop various types of shear and discontinuities (Aydin *et al*., 2006). Discontinuities act as weak zones, change the macroscale mechanical response, limit stability, and define the deformation field. Likewise, the presence of discontinuities can drastically affect fluid transport through sediments, define the "geo-plumbing" of the subsurface, give rise to fluid migration (Selly, 1985; Brown *et al*., 1994), and determine the geological storability of water, oil, gas, compressed air or CO_2. Conversely, engineered discontinuities can be used to enhance resource recovery, e.g., hydrocarbons and geothermal (Economides and Nolte, 2000), or to facilitate waste injection (Keck and Withers, 1994).

5.2 Coupled Processes

Water acidifies when mixed with CO_2, therefore, the geological storage of CO_2 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 (Espinoza *et al*., 2011). Most problems in sustainable geo-engineering involve some form of coupling between chemo-thermo-bio-hydro-mechanical processes (Gens, 2007; Olivella *et al*., 1996). Such complex systems are prone to instabilities and the emergence of unanticipated phenomena. Developments are needed to bracket the range of possibilities through extensive experimental studies complemented with robust numerical tools.

5.3 Biological Phenomena

Biological activity started 2 billion years ago. Microorganisms changed the atmosphere from reducing to oxidizing, and determined the composition of most minerals that form today's soils and rocks. Assuming a nominal bacteria size ~1 μm, the cell count can be as high as 10^{18} cells/m^3 of fluid; in fact, counts in soils vary between 10^{12} and 10^{16} cells per cubic meter of soil. Ongoing research attempts to engineer biological process to alter sediment properties, including skeletal stiffness (bio-cementation); hydraulic conductivity (bio-clogging); water stiffness (bio-gas generation); and bio-remediation of contaminated sites (Mitchell and Santamarina, 2005; Ivanov and Chu, 2008; DeJong *et al*., 2010). Opportunities exist for the use of low embodied energy bio-engineered soils in many geotechnical applications, such as liquefaction mitigation, structural support and excavation retention. 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. There are, however, important challenges in this line of research: minimum pore size to accommodate life, upscaling of laboratory techniques to field conditions, thermodynamic equilibrium and the long-term durability of biological treatments.

5.4 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. Published numerical and experimental results have shown that spatial variability leads to the development of preferential conduction paths and a lower macroscale hydraulic conductivity, enhances the tendency to shear localization (even in contractive media), causes non-homogeneous stress and strain distributions, and results in media with lower stiffness (Jang *et al*., 2011; Kim and Santamarina, 2008). Future developments need to explore new field assessment methods and the development of robust procedures to take spatial variability into consideration during design.

6. Education

The discussion in previous sections shows that energy geotechnology and sustainability invoke scientific principles and engineering concepts that will extend and profoundly change geotechnical engineering analysis and design. In turn, these changes will require renewed engineering curriculum, adapted continuing education programs for practitioners, and increased public awareness and expectations for civil engineering infrastructure. To this end, the following activities and/or initiatives need to be addressed:

- Modify the geotechnical curriculum to cover the fundamental scientific principles involved in geomaterials subjected to hydro-chemo-thermo-bio- and/or mechanical loading.
- Include into the curriculum case-histories of sustainable design with proper Life Cycle Cost Analysis (refer to discussion in the section on Underground Space)
- Training to provide the development of multiple alternative sustainable options as part of decision making and optimization.
- Focus on implementation, accountability, and integration with other disciplines
- Encourage proactive involvement of professional societies such as ASCE in sustainability education.

A new curriculum for the Undergraduate Geotechnical Engineering Course. For the past 60 years, the first undergraduate geotechnical engineering course has focused primarily on <u>soil mechanics</u> to prepare students for subsequent courses that include topics such as foundation engineering, earth retaining structures, slope stability, and seepage analysis. Hence, the emphasis on the mechanical properties of soil, e.g., compressibility and shear strength. A broader understanding of near-surface materials is required for energy geotechnology and sustainable civil infrastructure analysis and design. Topics and case histories could include:

- *mechanical*, i.e., allowable stress and deformation. Case: A tieback system for a deep excavation in a dense urban environment as part of urban development/ redevelopment, borehole instability.
- *hydraulic properties and fluid transport*, i.e, hydraulic conduction and pressure diffusion consolidation. Case: A landfill liner system, gas recovery, CO_2 injection.
- *biological*, i.e., bacteria in soils. Cases: Bioremediation of a contaminated site; biogenic methane production in sediments.
- *chemical,* i.e., mass balance, reaction kinetics, double layer, mineral dissolution, diffusion, reactive transport. Cases: Geological carbon sequestration, nuclear waste storage, salt water intrusion.
- *thermal,* i.e., heat capacity, heat of transformation, conduction and diffusion. Cases: Geothermal heat pump system for residential or commercial development, overheating of buried cables in heat islands.
- *electrical*, i.e., resistivity and permittivity. Cases: Geophysical site investigation and process monitoring in the context of gas production from hydrate bearing sediments
- *optimal use of natural resources*. Cases: Use of waste materials for construction.

The course could be case-based centered and complemented with laboratory measurement of the most relevant properties in each case.

7. Conclusions

In this paper we have examined 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. We showed that -to a large extent- these topics are inherently geotechnical in nature. We need to address them decisively and give the sustainability-related crises the high priority they deserve.

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 geomaterials to extreme conditions, coupled processes, biological phenomena, spatial variability, emergent phenomena, and the role of discontinuities.

The challenges facing geotechnical engineering in the future will require a much broader knowledge base than is currently included in educational programs. 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 geotechnology, enhanced/more efficient use of natural resources, waste management, underground utilization, and alternative/renewable energy.

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