Environmental Geotechnics in the U.S. Region: A Brief Overview

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Abstract: The present contribution to the series of Regional Editors themed papers offers a concise yet focused overview of some of the key technical and scientific issues, as well as of current trends and future challenges, related to the broad discipline of Environmental Geotechnics in the U.S. region. Particular attention is devoted to current policy and societal drivers, as well as future professional and research capacity requirements, in critical areas such as innovative recycling and improvement of compost, construction and geologic materials; solid waste management, landfilling and geoenvironmental remediation techniques; and crucial geotechnical engineering aspects of renewable energy production, storage and distribution.

Keywords: ground improvement, bio geotechnics, energy geotechnics, sustainable development.

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Introduction

The United Nations Brundtland Commission (U.N., 1987) defines sustainable development as one "that meets the needs of the present without compromising the ability of the future to meet its own needs." This definition epitomizes the overwhelming theme of ensuring the availability of resources for the well-being of current and future generations. The United Nations Intergovernmental Panel on Climate Change, however, has been issuing increasingly grim warnings about the consequences of a warming planet since the early 1990's. The panel has insisted that without swift and decisive action to limit greenhouse gas emissions from fossil fuels and other sources, the world will almost surely face centuries of climbing temperatures, rising seas, species loss and dwindling agricultural yields. The panel's main conclusions have mirrored those of the American Association for the Advancement of Science, the world's largest scientific society.

Recent findings from the two agencies have prompted increasingly focused efforts by the U.S. government to limit greenhouse gases, most recently with a plan to reduce methane emissions from landfills, agricultural operations and oil and gas production and distribution. The methane strategy is one of several tools embraced by the Climate Action Plan that was recently announced by the executive branch of the U.S. government and seeks to reduce emissions under the Clean Air Act and other statutes (see: www.nytimes.com/2014/04/01/opinion/climate-signals-growing-louder.html). The burden for fulfilling the promise of the plan will fall on the U.S. Environmental Protection Agency (EPA), which is charged with developing regulations to plug methane leaks in pipelines and in oil and gas production systems, reduce emissions from new and existing coal-fired power plants, increase energy efficiency in appliances and buildings, and double renewable energy capacity on public lands by 2020.

The present contribution to the series of Regional Editors themed papers offers a concise overview of some of the key technical and scientific issues, as well as of current trends and future challenges, related to the broad discipline of Environmental Geotechnics in the U.S. region. Particular attention is devoted to current policy and societal drivers, as well as future professional and research capacity requirements, in critical areas such as innovative recycling and improvement of compost, construction and geologic materials; solid waste management, landfilling and geoenvironmental remediation techniques; and crucial geotechnical engineering aspects of renewable energy production, storage and distribution.

Recycling and Improvement of Compost, Construction and Geologic Materials

A major focus of sustainability-related research in the U.S. has been on the reuse of waste materials in various geotechnical applications, particularly in transportation and pavement geotechnics. Biosolids and compost materials, due to their moisture affinity (hydrophilic), low permeability, and fibrous characteristics, are expected to reduce swell and, more importantly, shrinkage behaviors of underlying natural subsoils, thus mitigating pavement shoulder cracking (DeGroot, 1996; Puppala *et al.*, 2007). Recent studies have been undertaken to assess the effectiveness of compost material covers in mitigating expansive soil movements, and to understand the environmental impacts of the surface water runoff emanating from treated shoulders (Puppala *et al.*, 2011). Quality assessments made on runoff samples collected from test plots were related to EPA benchmark limits for discharge into storm sewer systems. While biosolids and compost-amended topsoils were generally found to hold great promise as reusable materials, longer-term environmental monitoring studies are still needed.

On the other hand, natural aggregates obtained from a variety of source rocks have been traditionally used as road base materials. The extraction of these natural aggregates, however, is increasingly constrained by urbanization sprawls, increased extraction costs, and heightened environmental concerns. The use of reclaimed asphalt pavement (RAP) materials in road construction has proven to reduce both the rate of depletion of these natural resources and the amount of construction debris disposed off in urban landfills. RAP base materials have also been reported to yield considerable savings in the overall costs of pavement construction projects. A report released by the EPA in 1993 has estimated in 73 million tons the amount of asphalt pavement material recycled each year, which amounts to approximately 80% of the total asphalt pavement material removed each year in the U.S. (Hoyos *et al.*, 2011; Yuan *et al.*, 2011). Although RAP materials are increasingly becoming a popular alternative to non-bonded materials for base applications, both the unavoidable source-dependent product variability and the deficient strength-stiffness characteristics often limit RAP applications from one state to another (Shen *et al.*, 2007; Xiao *et al.*, 2007; Kim *et al.*, 2009). Most RAP materials, when used as a total substitute for natural aggregates, do not often meet the minimum base material requirements set forth by AASHTO and local state guidelines. These limitations have led to new research efforts aimed at exploring novel, cost-effective stabilization methods, including strength, stiffness and durability tests performed on RAP treated with cement and glass fibers to meet specific guidelines by State Departments of Transportation (Hoyos *et al.*, 2011; Yuan *et al.*, 2011).

As far as geologic materials, the demand for new, sustainable technologies to improve the engineering properties of soils and rock upon and within which infrastructure is developed continues to increase at an unrelenting pace. Regions in metropolitan areas with competent soils have been developed long ago, leaving available only sites with undesirable soil conditions. As a result, the ground improvement industry, which specializes in improving subsurface conditions, has grown rapidly, and currently consists of about 50,000 projects per year worldwide at a total cost of US$7B. Industry development has largely been contractor driven, with new technologies employed at full scale on project sites. This has enabled unique innovations and rapid developments, but it has also relied heavily on cement, energy intensive methods, and synthetic materials (Xanthakos *et al.*, 1994; Karol, 2003). This is not surprising based on the two-fold technology selection criteria that dominate selection for projects: safety and capital cost. The emphasis to date on only safety and cost has led to the use of technologies that have enormous carbon footprints and are far from being considered sustainable practices. The primary challenge for the ground improvement industry is to move towards adoption of a three-fold selection criterion of safety, capital cost, and sustainability. As civil engineers our primary, unwavering responsibility is obviously safety. The relative priorities of capital cost and sustainability are becoming more balanced, particularly as it is now possible to assign "equivalent costs" of a given technology based on their fraction impact on climate change and long term site usability, among other factors (Donnelley, 2009).

There have been considerable efforts over the last decade in developing more sustainable technologies for improving the engineering properties of soil. Modification of existing methods has primarily focused on (partial) substitution of virgin materials (cement) with recycled/waste materials (fly ash, dredge spoils, mine tailings). For example, deep soil mixing, traditionally performed using cement, can be equally effective using a cement-to-fly-ash ratio of 1 to 3. New processes and technologies that have been explored extensively have largely focused on leveraging different bio-geo-chemical processes that exist in natural soil deposits. Though long ignored by geotechnical engineers, soils used in geotechnical construction do contain significant biodiversity, and are far from inert, inactive materials. The processes being explored, for example, range from microbially-induced calcite precipitation (MICP) to solidify sands to bio-film slimes generated to reduce hydraulic conductivity (DeJong *et al.*, 2010). The potential of many of these processes has been explored in the laboratory, and in recent years successful field trials have been reported, as illustrated in Fig. 1 (DeJong *et al.*, 2013).

Moving forward, the modifications to traditional ground improvement methods as well as the new bio-geo-chemical processes being explored require further development, and they must undergo a more comprehensive assessment of their actual contribution to sustainable practices. As a field, the term 'sustainable' has been claimed for new ideas based on qualitative and notional ideas, and not based on rigorous accounting of carbon through, for example, a comparative life cycle analysis.

Solid Waste Management and Polluted Sites

The field of solid waste management remains a major research focus area in environmental geotechnics. Overarching drivers of research include the increasing generation of solid waste worldwide that is associated with the economic recovery of western economies and the growing economy of developing countries, the generation of new waste by-products, and the increased performance requirements of waste management systems. Despite numerous scientific contributions in recent years, major challenges remain and new ones arise. These challenges are in some cases regional; however, examples of major national challenges include:

(1) The realistic assessment of the short-term and long-term performance and longevity of base and cover containment systems and their soil and geosynthetic components. Recent field and laboratory evidence (e.g., Malusis and Shackelford, 2002; Rowe, 2005; Mijares and Khire, 2012; Bradshaw and Benson, 2014) has underlined the complexities associated with the performance of these systems in harsh environments and for extended periods of time.

(2) The regulatory and societal pressures to minimize gas emissions and carbon footprint, and to optimize energy recovery from landfills. These pressures, at their core, challenge the "dry-tomb" philosophy that governs the design and operation of modern landfills and require a re-assessment of the methods by which waste is managed.

(3) The realistic assessment of the complex, coupled processes that occur in the waste mass in bioreactor landfills that impede the optimization of the performance of these facilities as energy recovery facilities. This process involves a comprehensive understanding of the changes in the physical, biochemical, hydraulic and geotechnical characteristics of the waste mass and their interdependencies, that are presently either not addressed, or are addressed in an empirical and conservative manner that is no longer adequate (Barlaz *et al.*, 2010; Wang *et al.*, 2013; Fei *et al.*, 2014; Giri and Reddy, 2014).

(4) The continued changes in waste streams and waste composition. Cultural changes in societies lead to changes in waste generation habits, and new technologies and practices lead to new waste materials that in many cases are disposed of to landfills. Example of the former is the reduction in paper that reaches modern landfills due to increasing recycling rates. Example of the latter is the waste materials generated from various energy sectors including coal and hydrofracking. These changes in practices result in changes in the waste material's compositions that can no longer be handled with empirical rules and design recommendations that were extensively relied upon in the past.

In addition to waste management and engineering challenges, problems of polluted sites continue to persist, with significant ramifications to public health and the environment (Sharma and Reddy, 2004; Reddy, 2014). As of today approximately 1,300 Superfund sites (which represent heavily contaminated sites) and over 500,000 industrial sites exist in the U.S. that are shown to be posing significant immediate threat to public health and the environment; therefore, requiring urgent cleanup. Moreover, improper past disposal and/or storage practices (prior to the passage of environmental regulations such as RCRA and CERCLA) and frequent accidental spills continue to increase the number of contaminated sites at a rate higher than that of the sites being remediated. Contaminated drinking water and air pollution draw immediate attention of general public, government agencies, and environmentalists. However, the consequences of soil and groundwater pollution are generally indirect, slow, and long-lasting, with acute effects on public health and the environment.

The field of contaminated site characterization and remediation has evolved significantly during the past two decades, yet many technical and practical issues remain unresolved (Adams and Reddy, 2012). To address these issues, geoenvironmental professionals are actively engaged in various research programs, and some of the major research issues that are being addressed include: (1) discovery of new and emerging contaminants in subsurface environments; (2) development of innovative non-intrusive and dynamic methods to characterize site contamination; (3) understanding and modeling transient fate and transport of contaminants in heterogeneous and anisotropic subsurface (as multi-phase and multi-species along different exposure pathways); (4) investigating and quantifying toxicity of individual and complex contaminant mixtures and risk assessment methodologies to establish practical remedial goals; (5) developing innovative green and sustainable remediation technologies; and (6) creating adaptive environmental policies, regulations and financial incentives (Reddy, 2014; Basu *et al.*, 2014).

Geotechnics and Renewable Energy

Over the past few years, there has been a strong interest in the geotechnical aspects of renewable energy in the U.S. The research efforts have not only focused on addressing challenges encountered when constructing the infrastructure for systems for geothermal heat exchange, solar thermal energy storage, and support of wind and tidal generation, but also on developing a better understanding of fundamental soil properties and constitutive models. A significant volume of work has been collected in recent years regarding the full-scale response of energy piles, including an evaluation of their thermo-mechanical response (Olgun *et al.*, 2012; McCartney and Murphy, 2012; Murphy *et al.*, 2014; Murphy and McCartney, 2014; Akrouch *et al.*, 2014) and thermal response (Brettman and Amis, 2011; Ozudogru *et al.*, 2012; Murphy *et al.*, 2014; Ozudogru *et al.*, 2014) in actual soil profiles under different conditions. These studies have confirmed that deep foundations are a cost-effective and efficient pathway for heat exchange, without causing major issues in the performance of the foundation system. To complement the field data, the behavior of energy piles has been characterized under carefully-controlled conditions in laboratory tank tests (Kramer and Basu, 2014) and centrifuge tests (McCartney and Rosenberg, 2011; Stewart and McCartney, 2013; Goode *et al.*, 2014; Goode and McCartney, 2014) to evaluate specific issues such as cyclic loading, impacts of head restraint, and impacts of temperature on side shear resistance. Because of the promising outcomes of this research, energy piles have seen widespread integration into new residential and commercial buildings in the U.S. over the past few years, with an example shown in Figure 2(a).

Data from the field and laboratory tests have been used to successfully validate finite element analyses (Ghasemi-Fare and Basu, 2013; Olgun *et al.*, 2014; Wang *et al.*, 2014), which can be used in the future for design guidance. Parameters for these models have been developed using innovative experimental element-scale tests, including tests to evaluate the thermal conductivity of soils under variable saturation and nonisothermal conditions (Smits *et al.*, 2013; Woodward *et al.*, 2013; Likos, 2014) and tests to investigate the effects of different variables on the thermal consolidation of saturated soils such as thermal cycling (Vega and McCartney, 2014) and anisotropy (Coccia and McCartney, 2012). The information from these tests is currently being integrated into defining new constitutive models to consider the nonisothermal response of soils under various saturation conditions.

The lessons learned from the research on energy piles is currently being applied to study new problems involving geothermal heat exchange, such as the storage of heat collected from solar-thermal panels in borehole arrays (Sibbitt *et al.*, 2012; McCartney *et al.*, 2013), as shown in Figure 2(b). The high heat capacity of the subsurface makes it an excellent location for storing heat collected during the daytime in summer months so that it can be used later in the winter. Another new application of geothermal heat exchange involves the improvement of near-surface systems involving unsaturated soils, as heating of unsaturated soils leads to drying and a corresponding increase in shear strength and stiffness (Stewart *et al.*, 2014). This application requires a better understanding of the thermo-hydro-mechanical response of soils, but may permit the use of poorly-draining backfills in retaining walls. Opportunities also exist to directly use heat from sources such as municipal solid waste landfills, which generate heat due to exothermic degradation of organic materials (Coccia *et al.*, 2013), as illustrated in Figure 2(c). Challenges still exist in how to best implement heat exchangers in new and existing landfills, and in assessing the time required for elevated temperatures to occur and the longevity of the heat resource.

The support of renewable energy infrastructure can provide new challenges as well. For example, the foundation system for offshore tidal energy generation systems requires a good understanding of the horizontal cyclic loading of foundations in soft clays (Landon Maynard *et al.*, 2013). A similar understanding is also required to design the foundations for offshore wind turbine (Schneider *et al.*, 2010) and onshore wind foundations (Tinjum and Lang, 2012). It is often also required to perform life-cycle cost analyses on these systems, so recent research has developed frameworks to consider this behavior in design (Rajaei and Tinjum, 2013).

Concluding Remarks

As previously implied in the introduction to this note, the above is not intended to be an exhaustive review of currently critical aspects of *Environmental Geotechnics* in the U.S. Region. The chief intent was to underscore the critical importance of the subject, the future professional and research capacity requirements, and the need for effective governmental policies. Hydraulic fracturing (“fracking”), for instance, deserves special mention as another field where geotechnical engineering can play a major role as the process requires drilling and pumping of geomedium in order to extract the gas from shale layers, as well as simulations and monitoring to ensure safe long-term operation of these facilities. Vast reserves of shale gas have been identified in the U.S., and their removal by various sustainable practices can potentially deliver cheaper energy to the public.

References

Adams JA and Reddy KR (2012) State-of-the-practice of characterization and remediation of contaminated sites. *Geotechnical Special Publication ASCE* **226**: 423-442.

Akrouch GA, Sanchez M and Briaud J-L (2014) Thermo-mechanical behavior of energy piles in high plasticity clays. *Acta Geotechnica* **9(3)**: 399-412.

Barlaz M, Bareither C, Hossain A *et al.* (2010) Performance of North American Bioreactor Landfills II: Chemical and Biological Characteristics. *Journal of Environmental Engineering* **136(8)**: 838-853.

Basu D, Misra A and Puppala AJ (2014) Sustainability and Geotechnical Engineering: Perspectives and Review. *Canadian Geotechnical Journal* **10.1139**/cgj-2013-0120, Published on online: June, 2014.

Bradshaw S and Benson C (2014) Effect of Municipal Solid Waste Leachate on Hydraulic Conductivity and Exchange Complex of Geosynthetic Clay Liners. *Journal of Geotech. and Geoenvironmental Eng.* **140(4):** 04013038.

Brettmann T and Amis T (2011) Thermal conductivity evaluation of a pile group using geothermal energy piles. *Geotechnical Special Publication ASCE* **211**: 499-508.

Coccia CJR and McCartney JS (2012) A Thermo-Hydro-Mechanical True Triaxial Cell for Evaluation of the Impact of Anisotropy on Thermally-Induced Volume Changes in Soils. *ASTM Geotechnical Testing Journal* **35(2)**: 1-11.

Coccia CJR, Gupta R, Morris J and McCartney JS (2013) Municipal Solid Waste Landfills as Geothermal Heat Resources. *Renewable and Sustainable Energy Reviews* **19**: 463-474.

DeGroot D (1996) Workshop on use of compost and recycled content products in highway construction. *Final Report – University of Massachusetts Transportation Center, Amherst, MA*: 83 pp.

DeJong JT, Mortensen B, Martinez M and Nelson DC (2010) Bio-Mediated Soil Improvement. *Ecological Engineering* **36**: 197-210.

DeJong JT, Soga KS, Kavazanjian E *et al.* (2013) Biogeochemical processes and geotechnical applications: Progress, opportunities, and challenges. *Géotechnique* **63(4)**: 287-301.

Donnelley RR (2009) The Scottish soil framework, Edinburgh: The Scottish Government.

Fei X, Zekkos D and Raskin L (2014) An Experimental Setup for Simultaneous Physical, Geotechnical, and Biochemical Characterization of Municipal Solid Waste Undergoing Biodegradation in the Laboratory. *ASTM Geotechnical Testing Journal* **37(1)**: 1-12.

Ghasemi-Fare O and Basu P (2013) A practical heat transfer model for geothermal piles. *Energy and Buildings* **66**: 470-479.

Giri RK and Reddy KR (2014). Slope stability of bioreactor landfills during leachate injection: Effects of heterogeneous and anisotropic municipal solid waste. *Waste Management & Research* **32(3)**: 186-197.

Goode JC III, Zhang M and McCartney JS (2014) Centrifuge Modeling of Energy Foundations in Sand. *Physical Modeling in Geotechnics – Proceedings of the 8th International Conference on Physical Modelling in Geotechnics, Perth, Australia, Jan. 14-17*: 729-736.

Goode JC III and McCartney JS (2014) Evaluation of Head Restraint Effects on Energy Foundations. *Geotechnical Special Publication ASCE* **234**: 2685-2694.

Hoyos LR, Ordonez CA and Puppala AJ (2011) Characterization of cement-fiber-treated reclaimed asphalt pavement aggregates: Preliminary investigation. *Journal of Materials in Civil Engineering ASCE* **23(7)**: 977-989.

Karol RH (2003) *Chemical Grouting and Soil Stabilization*. Marcel Dekker, New York, NY: 558 pp.

Kim Y, Lee HD and Heitzman M (2009) Dynamic modulus and repeated load tests of cold in-place recycling mixtures using foamed asphalt. *Journal of Materials in Civil Engineering ASCE* **21(6)**: 279-285.

Kramer AC and Basu P (2014) Performance of a model geothermal pile in sand. *Physical Modeling in Geotechnics – Proceedings of the 8th International Conference on Physical Modelling in Geotechnics, Perth, Australia, Jan. 14-17*: 771-778.

Landon Maynard M, Schneider JA, McEntee J and Newberg E (2013) Suction caissons for cross-flow tidal power system. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **166(2)**: 99-110.

Likos W (2014) Modeling thermal conductivity dryout curves from soil-water characteristic curves. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* **140(5)**: 04013056.

Malusis MA and Shackelford CD (2002) Coupling effects during steady-state solute diffusion through a semipermeable clay membrane. *Environmental Science and Technology ACS* **36(6)**: 1312-1319.

McCartney JS, Ge S, Reed A, Lu N and Smits K (2013). Soil-borehole thermal energy storage systems for district heating. *European Geothermal Congress, Pisa, June 3-7*: 10 pp.

McCartney JS and Murphy KD (2012) Strain distributions in full-scale energy foundations. *DFI Journal* **6(2)**: 28-36.

McCartney JS and Rosenberg JE (2011) Impact of heat exchange on the axial capacity of thermo-active foundations. *Geotechnical Special Publication ASCE* **211**: 488-498.

Mijares R and Khire M (2012) Field Data and Numerical Modeling of Water Balance of Lysimeter vs. Actual Earthen Cap. *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, **138(8)**: 889-897.

Murphy KD and McCartney JS (2014). Seasonal Response of Energy Foundations during Building Operation. *Geotechnical and Geological Engineering* 1-14. **DOI**: 10.1007/s10706-014-9802-3.

Murphy KD, McCartney JS and Henry KH (2014) Thermo-Mechanical Response Tests on Energy Foundations with Different Heat Exchanger Configurations. *Acta Geotechnica* 1-17. **DOI**: 10.1007/s11440-013-0298-4.

Olgun CG, Martin JR, Abdelaziz SL *et al.* (2012) Field testing of energy piles at Virginia Tech. *Proceedings of 37th Annual Conference on Deep Foundations, Houston, TX, USA*.

Olgun CG, Ozudogru TY, Abdelaziz SL and Senol A (2014) Long-term performance of heat exchanger piles. *Acta Geotechnica* 1-17. **DOI**: 10.1007/s11440-014-0334-z.

Ozudogru TY, Olgun CG and Senol A (2014) 3D numerical modeling of vertical geothermal heat exchangers. *Geothermics* **51**: 312-324.

Ozudogru TY, Brettmann T, Olgun CG, Martin J and Senol A (2012) Thermal conductivity testing of energy piles: Field testing and numerical modeling. *ASCE GeoCongress 2012, Oakland, CA, March 25-29, 2012*: 4436-4445.

Puppala AJ, Hoyos LR, Qasim SR and Intharasombat N (2011) Quality of runoff leachate collected from biosolids and dairy-manure compost-amended topsoils. *Journal of Hazardous, Toxic, and Radioactive Waste ASCE* **15(2)**: 80-88.

Puppala AJ, Pokala S, Intharasombat N and Williammee R (2007) Effects of organic matter on physical, strength and volume change properties of compost amended expansive clay. *Journal of Geotech. Geoenviron. Eng. ASCE* **133(11)**: 1449-1461.

Rajaei M and Tinjum JM (2013) Life Cycle Assessment of Energy Balance and Emissions of a Wind Energy Plant. *Journal of Geotechnical and Geological Engineering* **31(6)**: 1663-1670.

Reddy KR (2014) Evolution of geoenvironmental engineering. *Environmental Geotechnics* **1(3)**: 136-141.

Rowe RK (2005) Long term performance of contaminant barrier systems. *45th Rankine Lecture, Géotechnique* **55(9)**: 631-678.

Schneider JA, Landon Maynard M and Senders M (2010) Geotechnical engineering for offshore wind turbine foundations. *Sea Technology* **51(9)**: 29-33.

Sharma HD and Reddy KR (2004) *Geoenvironmental Engineering: Site Remediation, Waste Containment, and Emerging Waste Management Technologies*. John Wiley & Sons, Inc., Hoboken, New Jersey, 2004: 992 pp. (ISBN: 0-471-21599-6).

Shen J, Amirkhanian S and Miller JA (2007) Effects of rejuvenating agents on Superpave mixtures containing reclaimed asphalt pavement. *Journal of Materials in Civil Engineering ASCE* **19(5)**: 376-384.

Sibbitt B, McClenahan D, Djebbara R, Thornton J *et al.* (2012) The performance of a high solar fraction seasonal storage district heating system – Five years of operation. *Energy Procedia* **30**: 856-865.

Smits KM, Sakaki T, Howington SE, Peters JF and Illangasekare TH (2013) Temperature dependence of thermal properties of sands over a wide range of temperatures [30-70^{o}C]. *Vadose Zone Journal* **DOI**:10.2136/vzj2012.0033.

Stewart MA and McCartney JS (2013) Centrifuge modeling of energy foundations under cyclic heating and cooling. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* **DOI**: 10.1061/(ASCE)GT.1943-5606.0001061.

Stewart MA, Coccia CJR and McCartney JS (2014) Issues in the Implementation of Sustainable Heat Exchange Technologies in Reinforced, Unsaturated Soil Structures. *Geotechnical Special Publication ASCE* **234**: 4066-4075.

Tinjum JM and Lang P (2012) Wind Geotechnics. *ASCE Geo-Strata* **16(1)**: 18-26.

United Nations (1987). *Report of the World Commission on Environment and Development: Our Common Future*: http://www.un-documents.net /wced-ocf.htm. (Accessed: June, 2010).

Vega A and McCartney JS (2014) Cyclic Heating Effects on Thermal Volume Change of Silt. *Environmental Geotechnics*: 1-12. http://dx.doi.org/10.1680/envgeo.13.00022.

Wang X, Nagpure AS, DeCarolis JF and Barlaz MA (2013) Using Observed Data To Improve Estimated Methane Collection from Select U.S. Landfills. *Environ. Sci. Technol. 2013* **47**: 3251-3257.

Wang W, Regueiro RA and McCartney JS (2014) Coupled Axisymmetric Thermo-poro-mechanical Finite Element Analysis of an Energy Foundation Centrifuge Experiment in Partially Saturated Silt. *Geotechnical Special Publication ASCE* **234**: 2675-2684.

Woodward NR, Tinjum JM and Wu R (2013) Water migration impacts on thermal resistivity testing procedures. *ASTM Geotechnical Testing Journal* **36(6)**: 948-955.

Xanthakos PP, Abramson LW and Bruce DA (1994) *Ground Control and Improvement*. John Wiley and Sons, New York, NY, 910 pp.

Xiao F, Amirkhanian S and Juang CH (2007) Rutting resistance of rubberized asphalt concrete pavements containing reclaimed asphalt pavement mixtures. *Journal of Materials in Civil Engineering ASCE* **19(6)**: 475-483.

Yuan D, Nazarian S, Hoyos LR and Puppala AJ (2011) Evaluation and mix design of cement-treated base materials with high content of reclaimed asphalt pavement. *Journal of the Transportation Research Board* **TRR No. 2212**: 110-119.

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Fig. 1. Images from experimental results from upscaling of biocementation technology using microbially induced calcite precipitation (MICP)

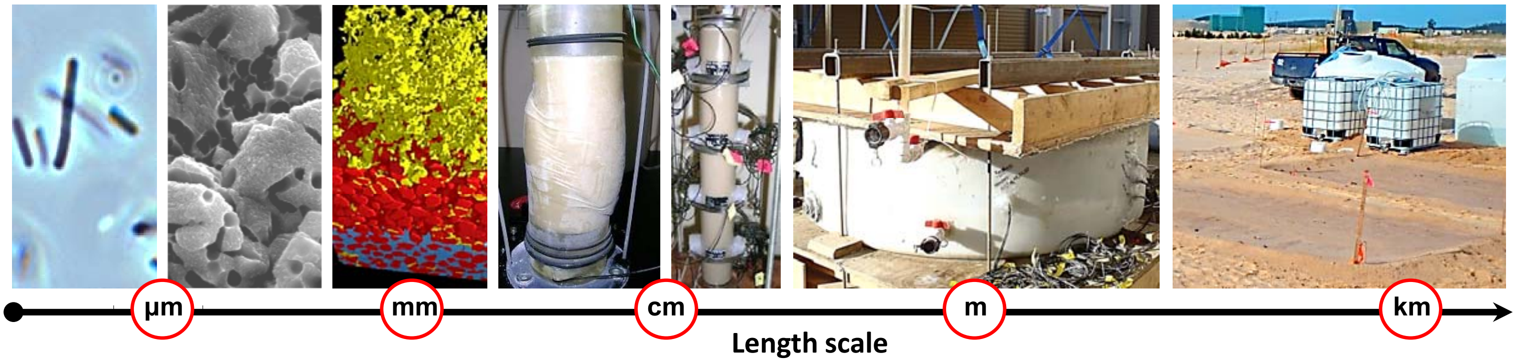
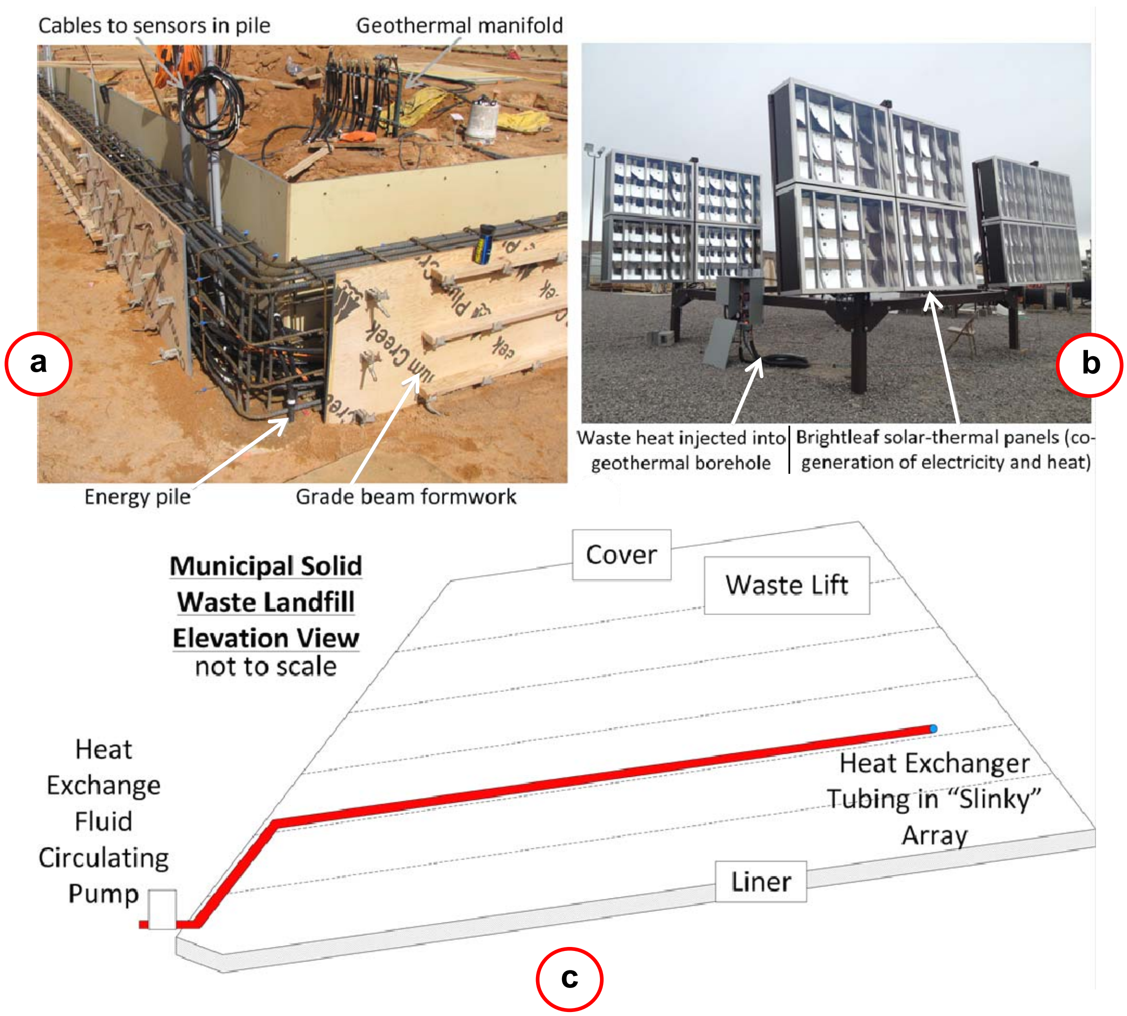


Fig. 2. Applications of geothermal heat exchange systems in Energy Geotechnics: (a) Energy piles integrated into a new building foundation system; (b) Solar thermal panels coupled with geothermal heat exchangers; (c) Heat exchangers integrated into municipal solid waste landfills



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