Environmental geotechnics in the US region: a brief overview

Laureano R. Hoyos PhD
EG Associate Regional Editor; Professor, Department of Civil Engineering, University of Texas, Arlington, TX

Anand J. Puppala PhD
EG Editorial Board Member; Professor, Department of Civil Engineering, University of Texas, Arlington, TX

Krishna R. Reddy PhD
EG Editorial Board Member; Professor, Department of Civil and Materials Engineering, University of Illinois, Chicago, IL

Dimitrios Zekkos PhD
EG Editorial Board Member; Associate Professor, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI

Introduction
The United Nations Brundtland Commission (United Nations, 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 epitomises the overwhelming theme of ensuring the availability of resources for the well-being of current and future generations. Since the early 1990s, however, the United Nations Intergovernmental Panel on Climate Change has been issuing increasingly grim warnings about the possible consequences of a warming planet. The panel has insisted that without prompt and decisive action to limit greenhouse gas emissions, particularly from fossil fuels, the world will almost surely face centuries of climbing temperatures, rising seas, species loss and dwindling agricultural yields. The main conclusions of the intergovernmental panel 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 US government to limit greenhouse gases, most recently with a plan to reduce methane emissions from landfills, agricultural operations and oil and gas production, storage 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 US government, which seeks to reduce emissions under the Clean Air Act and other statutes (New York Times Editorial Board, 2014). The main burden for fulfilling the promise of the plan falls on the US 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 year 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 US 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 United States has been on the reuse of waste materials in various...
geotechnical applications, particularly in transportation and pavement geotechnics. Biosolids and compost materials, owing to their moisture affinity (hydrophilic), low permeability and fibrous characteristics, are expected to reduce swell and, more importantly, shrinkage behaviours 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 traditionally been used as road base materials. The extraction of these natural aggregates, however, is increasingly constrained by urbanisation sprawl, 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 of 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 at 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 United States (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 (Kim et al., 2009; Shen et al., 2007; Xiao et al., 2007). Most RAP materials, when used as a total substitute for natural aggregates, do not often meet the minimum base material requirements set forth by the American Association of State Highway and Transportation Officials (AASHTO) and local state guidelines. These limitations have led to new research efforts aimed at exploring novel, cost-effective stabilisation methods, including strength, stiffness and durability tests performed on RAP treated with cement and glass fibres to meet specific guidelines by State Departments of Transportation (Hoyos et al., 2011; Yuan et al., 2011).

With regard to 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 specialises in improving subsurface conditions, has grown rapidly and currently consists of about 50,000 projects per year worldwide at a total cost of US$7 billion. 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 (Karol, 2003; Xanthakos et al., 1994). 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. The primary, unwavering responsibility of civil engineers 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 focused primarily 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 one to three. New processes and technologies that have been explored extensively have focused largely on leveraging different bio-geo-chemical processes that exist in natural soil deposits. Although 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 microbiologically induced calcite precipitation 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 Figure 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 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 the following:

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., Bradshaw and Benson, 2014; Malulus and Shackelford, 2002; Mijares and Khire, 2012; Rowe, 2005) 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 minimise gas emissions and carbon footprint and to optimise 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 reassessment 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 optimisation 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, which either are presently not addressed or are addressed in an empirical and conservative manner that is no longer adequate (Barlaz et al., 2010; Fei et al., 2014; Giri and Reddy, 2014; Wang et al., 2013).

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. An example of the former is the reduction in paper that reaches modern landfills due to increasing recycling rates. An 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 on 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 (Reddy, 2014; Sharma and Reddy, 2004). As of today, approximately 1300 Superfund sites (which represent heavily contaminated sites) and over 500 000 industrial sites exist in the United States 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 the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (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 the 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 characterisation 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) the discovery of new and emerging contaminants in subsurface environments, (2) development of innovative non-intrusive and dynamic methods to characterise site contamination, (3) understanding and modelling 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 (Basu et al., 2015; Reddy, 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 United States. The research efforts have focused not only 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 (Akrouch et al., 2014; McCartney and Murphy, 2012; Murphy and McCartney, 2015; Murphy et al., 2015; Olgun et al., 2012) and thermal response (Brettman and Amis, 2011; Murphy et al., 2015; Ozudogru et al., 2012, 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 behaviour of energy piles has been characterised under carefully controlled conditions in laboratory tank tests (Kramer and Basu, 2014) and centrifuge tests (Goode and McCartney, 2014; Goode et al., 2014; McCartney and Rosenberg, 2011; Stewart 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 United States 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 non-isothermal conditions (Likos, 2014; Smits et al., 2013; Woodward et al., 2013) and

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**Figure 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
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 non-isothermal 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 (McCarty et al., 2013; Sibbitt et al., 2012), as shown in Figure 2(b). The high heat capacity of the subsurface makes it an excellent location for storing heat collected during the day to use 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 behaviour 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 US 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, also known as ‘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 United States, and their removal by various sustainable practices can potentially deliver cheaper energy to the public. Recently, possible evidence of detrimental seismic effects of this technique on existing infrastructure has prompted geotechnical earthquake engineers and researchers, chiefly through the US Geological Survey, to assess a more definitive connection. Likewise, the field of submarine pollution, and the most adopted environmental strategies for its cost-effective mitigation, is as crucial an issue in the US region: Several Superfund sites have represented submarine pollution areas where the remediation strategies developed to date have been everything but obvious solutions.

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