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4 1   **Environmental Geotechnics in the U.S. Region: A Brief Overview**

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9 4   Krishna R. Reddy⁵, and Dimitrios Zekkos⁶
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15 7   **Abstract:** The present contribution to the series of Regional Editors themed papers offers a concise
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17 8   yet focused overview of some of the key technical and scientific issues, as well as of current trends
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19 9   and future challenges, related to the broad discipline of Environmental Geotechnics in the U.S.
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22 10   region. Particular attention is devoted to current policy and societal drivers, as well as future
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24 11   professional and research capacity requirements, in critical areas such as innovative recycling and
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26 12   improvement of compost, construction and geologic materials; solid waste management, landfilling
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28 13   and geoenvironmental remediation techniques; and crucial geotechnical engineering aspects of
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30 14   renewable energy production, storage and distribution.
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36 16   **Keywords:** ground improvement, bio geotechnics, energy geotechnics, sustainable development.
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18 Introduction

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

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

40   The present contribution to the series of Regional Editors themed papers offers a concise
41 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

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4 66 construction has proven to reduce both the rate of depletion of these natural resources and the amount
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6 67 of construction debris disposed off in urban landfills. RAP base materials have also been reported to
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8 68 yield considerable savings in the overall costs of pavement construction projects. A report released
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10 69 by the EPA in 1993 has estimated in 73 million tons the amount of asphalt pavement material
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12 70 recycled each year, which amounts to approximately 80% of the total asphalt pavement material
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14 71 removed each year in the U.S. (Hoyos *et al.*, 2011; Yuan *et al.*, 2011). Although RAP materials
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16 72 are increasingly becoming a popular alternative to non-bonded materials for base applications,
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18 73 both the unavoidable source-dependent product variability and the deficient strength-stiffness
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20 74 characteristics often limit RAP applications from one state to another (Shen *et al.*, 2007; Xiao *et*
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22 75 *al.*, 2007; Kim *et al.*, 2009). Most RAP materials, when used as a total substitute for natural
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24 76 aggregates, do not often meet the minimum base material requirements set forth by AASHTO
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26 77 and local state guidelines. These limitations have led to new research efforts aimed at exploring
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28 78 novel, cost-effective stabilization methods, including strength, stiffness and durability tests
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30 79 performed on RAP treated with cement and glass fibers to meet specific guidelines by State
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32 80 Departments of Transportation (Hoyos *et al.*, 2011; Yuan *et al.*, 2011).

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34 81 As far as geologic materials, the demand for new, sustainable technologies to improve the
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36 82 engineering properties of soils and rock upon and within which infrastructure is developed
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38 83 continues to increase at an unrelenting pace. Regions in metropolitan areas with competent soils
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40 84 have been developed long ago, leaving available only sites with undesirable soil conditions. As a
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42 85 result, the ground improvement industry, which specializes in improving subsurface conditions,
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44 86 has grown rapidly, and currently consists of about 50,000 projects per year worldwide at a total
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46 87 cost of US\$7B. Industry development has largely been contractor driven, with new technologies
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48 88 employed at full scale on project sites. This has enabled unique innovations and rapid
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50 89 developments, but it has also relied heavily on cement, energy intensive methods, and synthetic
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4 90 materials (Xanthakos *et al.*, 1994; Karol, 2003). This is not surprising based on the two-fold
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6 91 technology selection criteria that dominate selection for projects: safety and capital cost. The
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8 92 emphasis to date on only safety and cost has led to the use of technologies that have enormous
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10 93 carbon footprints and are far from being considered sustainable practices. The primary challenge
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12 94 for the ground improvement industry is to move towards adoption of a three-fold selection
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14 95 criterion of safety, capital cost, and sustainability. As civil engineers our primary, unwavering
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16 96 responsibility is obviously safety. The relative priorities of capital cost and sustainability are
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18 97 becoming more balanced, particularly as it is now possible to assign “equivalent costs” of a
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20 98 given technology based on their fraction impact on climate change and long term site usability,
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22 99 among other factors (Donnelley, 2009).
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29 100   There have been considerable efforts over the last decade in developing more sustainable
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31 101 technologies for improving the engineering properties of soil. Modification of existing methods
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33 102 has primarily focused on (partial) substitution of virgin materials (cement) with recycled/waste
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35 103 materials (fly ash, dredge spoils, mine tailings). For example, deep soil mixing, traditionally
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37 104 performed using cement, can be equally effective using a cement-to-fly-ash ratio of 1 to 3. New
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39 105 processes and technologies that have been explored extensively have largely focused on
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41 106 leveraging different bio-geo-chemical processes that exist in natural soil deposits. Though long
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43 107 ignored by geotechnical engineers, soils used in geotechnical construction do contain significant
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45 108 biodiversity, and are far from inert, inactive materials. The processes being explored, for
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47 109 example, range from microbially-induced calcite precipitation (MICP) to solidify sands to bio-
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49 110 film slimes generated to reduce hydraulic conductivity (DeJong *et al.*, 2010). The potential of
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51 111 many of these processes has been explored in the laboratory, and in recent years successful field
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53 112 trials have been reported, as illustrated in Fig. 1 (DeJong *et al.*, 2013).
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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

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4 210 during the daytime in summer months so that it can be used later in the winter. Another new
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6 211 application of geothermal heat exchange involves the improvement of near-surface systems involving
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8 212 unsaturated soils, as heating of unsaturated soils leads to drying and a corresponding increase in
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10 213 shear strength and stiffness (Stewart *et al.*, 2014). This application requires a better understanding of
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12 214 the thermo-hydro-mechanical response of soils, but may permit the use of poorly-draining backfills
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14 215 in retaining walls. Opportunities also exist to directly use heat from sources such as municipal solid
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16 216 waste landfills, which generate heat due to exothermic degradation of organic materials (Coccia *et*
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18 217 *al.*, 2013), as illustrated in Figure 2(c). Challenges still exist in how to best implement heat
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20 218 exchangers in new and existing landfills, and in assessing the time required for elevated temperatures
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22 219 to occur and the longevity of the heat resource.
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27 220 The support of renewable energy infrastructure can provide new challenges as well. For
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29 221 example, the foundation system for offshore tidal energy generation systems requires a good
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31 222 understanding of the horizontal cyclic loading of foundations in soft clays (Landon Maynard *et al.*,
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33 223 2013). A similar understanding is also required to design the foundations for offshore wind turbine
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35 224 (Schneider *et al.*, 2010) and onshore wind foundations (Tinjum and Lang, 2012). It is often also
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37 225 required to perform life-cycle cost analyses on these systems, so recent research has developed
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39 226 frameworks to consider this behavior in design (Rajaei and Tinjum, 2013).
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44 227 45 46 228 **Concluding Remarks** 47

48 229 As previously implied in the introduction to this note, the above is not intended to be an exhaustive
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50 230 review of currently critical aspects of *Environmental Geotechnics* in the U.S. Region. The chief
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52 231 intent was to underscore the critical importance of the subject, the future professional and research
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54 232 capacity requirements, and the need for effective governmental policies. Hydraulic fracturing
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56 233 (“fracking”), for instance, deserves special mention as another field where geotechnical engineering
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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.

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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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