Sustainability in Geotechnical Engineering

Viabilité en géotechnique

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ABSTRACT: This paper presents an overview of the different research studies performed in geotechnical engineering related to sustainable development. The philosophies of sustainability as applicable in geotechnical engineering are discussed. A review of the research and case studies performed in geotechnical engineering and how they can impact sustainable development is presented with particular emphasis on foundation engineering and ground improvement.

RÉSUMÉ : Cet article présente une vue d'ensemble des différentes recherches effectuées en géotechnique liée au développement durable. Les philosophies de la durabilité comme applicable en géotechnique sont discutées. Un examen des études de recherche et de cas réalisées en géotechnique et comment ils peuvent influer sur le développement durable est présenté avec un accent particulier sur les travaux de fondation et de l'amélioration du sol.

KEYWORDS: sustainability, waste recycling, life cycle assessment, multicriteria analysis, risk, resilience, carbon footprint.

1 INTRODUCTION

Civil engineering processes are both resource and fuel intensive. According to Dixit et al. (2010), the construction industry accounts for about 40% of the global energy consumption and depletes about two fifth of the sand, gravel and stone reserves every year. Construction activities also add to the problems of climate change, ozone depletion, desertification, deforestation, soil erosion, and land, water and air pollution (Kibert 2008). A geotechnical construction project not only has the above detrimental effects on earth's resources and environment but also changes the land use pattern that persists for centuries and affects the social and ethical values of a community. Thus, geotechnical projects interfere with many social, environmental and economic issues, and improving the sustainability of geotechnical processes is extremely important in achieving overall sustainable development.

This paper attempts to connect the broader scope of sustainable development with geotechnical engineering and presents a review of the research done on different aspects of sustainability in geotechnical engineering with particular emphasis on foundation engineering and ground improvement.

2 SUSTAINABILITY AND GEOTECHNOLOGY

Sustainability of a system is its ability to survive and retain its functionality over time. For an engineered system to be sustainable, it should be efficient, reliable, resilient, and adaptive. Efficiency requires that the resource use, cost and environmental impacts of the engineering system are minimal. Reliability ensures that the system is sufficiently far away from its predictable failure states. A resilient system has the ability to return to its original functioning state within an acceptable period of time when subjected to unpredictable disruptions. An adaptive system is responsive to gradual and natural changes within itself and in its environment, and is flexible to modifications and alterations required to cope with such changes. Together, these characteristics help in deciding whether an engineered system is capable of surviving in a complex and evolving socio-economic environment without losing its own character and function, and without violating the limits of the carrying capacity of the natural systems. Thus, the objective of sustainable engineering is to ensure the integration of an engineered system into the natural and man-made environment without compromising the functionality of either the engineered system or that of the ecosystem and society, and this harmony between the natural and built environments must be maintained at the local, regional and global scales. Therefore, in the engineering domain, sustainability can be looked upon as a dynamic equilibrium between four E's — engineering design, economy, environment and equity, as described in Figure 1.

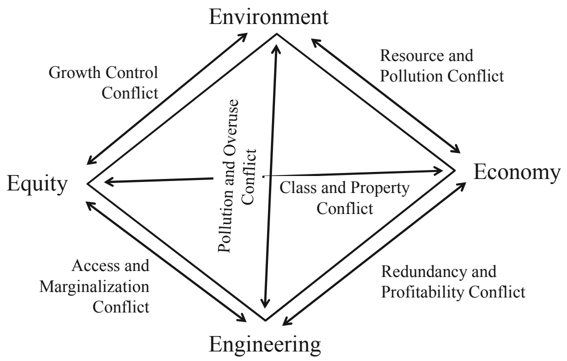

Figure 1. The four E's of sustainability in engineering projects.

In view of the four E's approach of sustainable engineering, the sustainability objectives that may be incorporated in geotechnical projects are: (i) involving all the stakeholders at the planning stage of the project so that a consensus is reached on the sustainability goals of the project (such as reduction in pollution, use of environment friendly alternative materials, etc.), (ii) reliable and resilient design and construction that involves minimal financial burden and inconvenience to all the stakeholders, (iii) minimal use of resources and energy in planning, design, construction and maintenance of geotechnical facilities, (iv) use of materials and methods that cause minimal negative impact on the ecology and environment, and (v) as much reuse of existing geotechnical facilities as possible to minimize waste. This approach aims at reaching a dynamic equilibrium between engineering integrity, economic efficiency, environmental effectiveness, and social acceptability and equity.

In an endeavor to incorporate sustainability in geotechnical design, three new trends have been identified (Iai 2011): (i) geo-structures are now designed for performance rather than for ease of construction, (ii) designs are now more responsive to site specific requirements, and (iii) the designs consider soil-structure interaction rather than just analysis of structural or foundation parts.

3 SUMMARY OF SUSTAINABLE GEOTECHNLOGY RESEARCH

Several research studies have been performed that aim at making geotechnical engineering practice sustainable. The areas in which research has progressed include (1) the use of alternate, environment friendly materials in geotechnical constructions, and reuse of waste materials, (2) innovative and energy efficient ground improvement techniques, (3) bio-slope engineering, (4) efficient use of geosysnthetics, (5) sustainable foundation engineering that includes retrofitting and reuse of foundations, and foundations for energy extraction, (6) use of underground space for beneficial purposes including storage of energy, (7) mining of shallow and deep geothermal energy, (8) preservation of geodiversity, and (9) incorporation of geoethics in practice.

Geohazards mitigation is another important aspect of sustainable geotechnical engineering — related studies include studies on the effects of global climate change and of multi-hazards on geo-structures. In this context, it is important to note that sustainable geotechnical engineering should not only focus on minimization of ecological footprints but also on making geo-structures reliable and resilient so that the effects of hazards, both natural and man-made, can be minimized. The aspect of reliability and resilience is particularly important for critical infrastructures (e.g., lifeline systems like transportation and power supply network without which other systems like cities cannot function) of which geo-structures like dams, embankments, slopes and bridge foundations are important components.

The recent research studies on geosustainability are mostly based on the common notions of sustainability like recycling, reuse and use of alternate materials, technologies and resources. However, whether such new approaches are actually sustainable or not cannot be ascertained without proper assessment using, for example, whole life cost analysis and risk based performance analysis. Therefore, a complete sustainability assessment framework is necessary for geotechnical projects to ascertain the relative merits of different options available for a project.

Any geosustainability assessment framework should have a life cycle view of geotechnical processes and products and should (i) ensure societal sustainability by promoting resource budgeting and restricting the shift of the environmental burden of a particular phase to areas downstream of that phase, (ii) ensure financial health of the stakeholders, and (iii) enforce sound engineering design. As the uncertainties associated with geotechnical systems are often much greater than those with other engineered systems, sustainability framework for geotechnical engineering should include an assessment of the reliability and resilience of the geo-system, and offer flexibility to the user to identify site specific needs.

From the environmental impact point of view, quantitative environmental metrics like global warming potential (Storesund et al. 2008), carbon footprint (Spaulding et al. 2008), embodied carbon dioxide (Egan et al. 2010), embodied energy (Chau et al. 2006) and a combination of embodied energy and emissions (carbon dioxide, methane, nitrous oxide, sulphur oxides and nitrogen oxides) (Inui et al. 2011) have been used to compare competing alternatives in geotechnical engineering. But, assessing the sustainability of a project based solely on metrics like embodied carbon dioxide or global warming potential involves ad hoc assumptions, puts excess emphasis on the environmental aspects and fails to consider a holistic view that must also involve technical, economic and social aspects (Holt et al. 2010, Steedman 2011).

Among the sustainability assessment tools that address the multidimensional character of sustainability, some are qualitative and represent the performance of a project on different sustainability related sectors pictorially (e.g., GeoSPeAR) (Holt 2011). The second category of multidimensional assessment frameworks consist of quantitative and life cycle based tools. Life cycle costing (LCC), life cycle assessment (LCA), multicriteria analysis and combinations of LCC and LCA have been used for this purpose. Assessment frameworks and metrics like Green Airport Pavement Index, BE^{2}ST-in-Highways and Environmental Sustainability Index fall under this category (Pittenger 2011, Lee et al. 2010b, Torres and Gama 2006).

The third approach to sustainability assessment is based on point based rating systems that provide a measure of sustainability of projects based on points scored in the different relevant categories. Rating systems like GreenLites (McVoy et al. 2010), I-LAST (Knuth and Fortman 2010), Greenroads (Muench and Anderson 2009), MTO–Green Pavement Rating System (Chan and Tighe 2010) and Environmental Geotechnics Indicators (Jefferson et al. 2007) fall under this category.

4 SUSTAINABLE GROUND IMPROVEMENT

A major part of the sustainability related research in geotechnical engineering has focused on ground improvement through the introduction of novel, environment friendly materials with particular emphasis on the reuse of waste materials. Puppala et al. (2009) proposed the use of alternate materials for soil stabilization including the use of recycled materials in geotechnical constructions. Other examples include the use of recycled glass-crushed rock blends for pavement sub-base and recycling of shredded scrap tires as a light-weight fill material.

Reuse of old pavements including asphalt and concrete pavements has been on the rise (Gnanendran and Woodburn, 2003). The old pavements are recycled into full and partial depth reclamation bases with cement or other additive treatment. Sometimes these pavements are recycled into aggregate materials which are termed as reclaimed asphalt pavement (RAP) materials. RAP materials have been used as bases with chemical stabilization, and several state DOT agencies in the USA has been using them in the new pavement construction projects. Puppala et al. (2009) performed a series of resilient modulus tests on cement and cement-fiber treated RAP for use as pavement base material. They reported that the structural coefficients increase with an increase in the confining pressure and these values are higher for cement and cement–fiber treated aggregates. The significant increase of structural coefficients with cement-fiber treatment (30%) was attributed to the tensile strength and interlocking properties offered by the fiber content.

Investments made on transportation and processing is reduced when native material after stabilization is used as a base or backfill material. This saves money that might otherwise be spent on fuels for transportation. The old pavement material if cannot be reused has to be landfilled, which increases the costs associated with the landfilling practices. Therefore, the use of old pavement materials as stabilized bases reduces the space used for landfills, which, in turn, reduces the overall carbon footprint of the project by not using aggregates from quarries.

The Integrated Pipeline (IPL) project which involves a long pipe line installation is a joint effort between the Tarrant Regional Water District (TRWD) and Dallas Water Utilities (DWU) that is aimed at bringing additional water supplies to the Dallas/Fort Worth metroplex. As a part of the pipeline layout and construction, large amounts of soil need to be excavated during the pipeline installation. Also, large amounts of material need to be imported for bedding and backfilling of the trenches. Both importing new fill material and exporting excavated trench material for landfilling will have serious implications on the economic and environmental aspects of the construction project.

As a result, a research study was initiated at the University of Texas at Arlington to identify chemical treatment of in-situ soil material that can be reused as either bedding, zone or backfill materials for the pipeline installation. Based on the comprehensive laboratory studies, the soils along the pipeline alignment are identified for potential reuse as backfill, bedding and zone materials after chemical amendment, and more details can be found in Chittoori et al. (2012). The cost and environmental benefits as well as emissions reductions of using in-situ native material versus imported fill materials are also explained.

5 SUSTAINABLE FOUNDATION ENGINEERING

Foundations form an integral part of geotechnical construction, and sustainable design and construction of foundations are very important for overall sustainable development. Sustainable foundation engineering entails robust analysis and design, economical and environment friendly construction that cause minimal disruptions to life and damage to adjacent properties, reuse and retrofitting of existing foundations as much as possible, and use of foundations in harvesting geothermal energy.

Robust design of foundations essentially involves a rigorous analysis (e.g., use of proper constitutive equations and analytical or numerical modeling of appropriate boundary value problems) and choice and execution of an appropriate design methodology (e.g., identification of all possible limit states and moving the design state sufficiently away from the limit states by either using a reliablity based method or by applying load and resistance factor design (LRFD) methodology). The recent trend in geotechnical engineering to incorporate LRFD is encouraging and several research studies have been conducted to rigorously develop resistance factors based on reliability analysis (e.g., Basu and Salgado 2012). Further, the incorporation of random fields to characterize spatial heterogeneity of soil in the probabilistic analysis of foundations and related soil structure interaction problems significantly contributes to sustainable foundation engineering (Haldar and Basu 2011, 2012).

Misra and Basu (2011, 2012) recently developed a multicriteria based sustainability assessment framework for pile foundation projects. The framework considers a life-cycle view of the pile construction process (Figure 2), and combines resource consumption, environmental impact and socio-economic benefits of a pile-foundation project over its entire life span to develop a sustainability index (Figure 3). The use of resources is taken into account based on the embodied energy of the materials used, the impact of the process emissions is assessed using environmental impact assessment and the socio-economic impact of the project is assessed through a cost benefit analysis. Three indicators are derived from the three aspects and are combined through weights to calculate the sustainability index (SI) for the different alternatives available for the project (Figure 3).

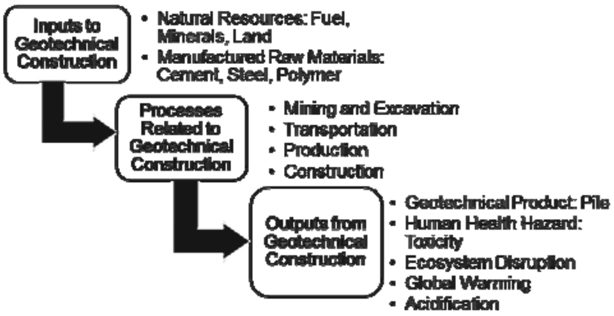

Figure 2. Flow chart showing the inputs, outputs, processes and impact categories in pile construction.

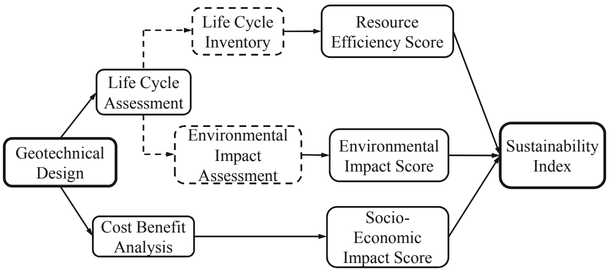

Figure 3. Multicriteria based sustainability assessment framework.

Reuse and retrofitting of foundations is a traditional practice for almost all refurbishment projects, but recently the concept has been extended for redevelopment projects as well (Butcher et al. 2006a). Reuse of foundations is an attractive option because the cost of removal of an old foundation is about four times that of construction of a new pile, disturbance to adjacent structures caused by foundation removal can be avoided, and backfilling of voids created by the removed foundation is not required. At the same time, the embodied energy consumed in reusing foundations is nearly half of that consumed in installing new foundations. Consequently, several case studies demonstrating the benefits of reuse of foundations have been documented (Anderson et al. 2006, Butcher et al. 2006b).

Foundation engineering has a prominent role in the alternative energy sectors like geothermal and wind energy. Case studies show that deep foundations can be used as energy storage and transmitting elements (Quick et al. 2005) while concrete surfaces in contact with the ground (e.g., basement walls) can act as heat exchangers (Brandl 2006). Research is in progress to develop proper characterization, analysis and design of energy related geo-structures like energy piles (Laloui 2011), wind turbine foundations (Doherty et al. 2010) and foundations for oil and gas drilling operations (Yu et al. 2011).

6 CONCLUSIONS

In recent times, a concerted effort is noted within the civil engineering industry in delivering built facilities that are eco-friendly and sustainable. Geotechnical construction, being resource intensive and by virtue of its early position in civil engineering projects, has a great potential to influence the sustainability of such projects. Incorporating sustainability in geotechnical engineering requires an understanding of the ideological conflicts that characterize sustainability and of the approaches that can make engineering processes sustainable. Philosophically, engineering sustainability can be looked upon as the balance between engineering design, economy, social equity and the environment (4 E's).

Sustainability related research studies in geotechnology essentially belong to two categories: those that contribute to global sustainability through the use of alternative materials and innovative engineering and those that develop sustainability assessment frameworks. A summmary of these research studies is provided with emphasis on two particular areas, ground improvement and foundation engineering. The focus of these studies is mostly on the environmental and economic aspects. It is recommended that a more holistic approach considering environmental, social, economic, reliability and resilience aspects (the 4 E's) should be developed for sustainable geotechnical practices.

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