7-1-2011

SUSTAINABILITY IN GEOTECHNICAL ENGINEERING Internal Geotechnical Report 2011-2

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Recommended Citation

Misra, Aditi and Basu, Dipanjan, "SUSTAINABILITY IN GEOTECHNICAL ENGINEERING Internal Geotechnical Report 2011-2" (2011). *Technical Reports*. 1.
https://opencommons.uconn.edu/cee_techreports/1

SUSTAINABILITY IN GEOTECHNICAL ENGINEERING

Internal Geotechnical Report 2011-2

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July 2011

SYNOPSIS

The built environment serves as a dynamic interface through which the human society and the ecosystem interact and influence each other. Understanding this interdependence is key to understanding sustainability as it applies to civil engineering. There is a growing consensus that delivering a sustainable built environment starts with incorporating sustainability thoughts at the planning and design stages of a project. Geotechnical engineering is the most resource intensive of all the civil engineering disciplines and can significantly influence the sustainability of infrastructure development because of its early position in the construction process. In this report, a review is made of the scope geotechnical engineering offers towards sustainable development of civil infrastructure. The philosophies and definitions of sustainability as applicable in geotechnical engineering are discussed and a comprehensive review is done of the research studies performed in geotechnical engineering that contributes to sustainable development. It is revealed from the literature review that there is a need for a quantitative sustainability assessment framework in geotechnical engineering. Consequently, a multicriteria based sustainability assessment framework is introduced that can be used at the planning and design stages of geotechnical projects. This quantitative framework combines life cycle assessment, environmental impact assessment and cost benefit analysis, and can be used to assess the relative sustainability of different design choices in geotechnical engineering.

KEYWORDS: sustainability, pile foundation, life cycle assessment, environmental impact assessment, muticriteria analysis

INTRODUCTION

The civil engineering industry has always remained a means to the goal of anthropocentric development. From road network to residential buildings, dams to nuclear power plants, the civil engineering industry has its footprints on all human efforts to control, modify and dominate nature and natural systems. The built environment serves as a dynamic interface through which the ecosystem and the human society interact and influence each other. For example, a road construction project influences the runoff pattern of an area which, in turn, influences the frequency of flooding in areas downstream of the project — the threat of frequent flooding governs the land prices and development in the downstream area. Thus, the ecosystem and built environment are inextricably linked, and understanding this interdependence is key to understanding sustainability as it applies to civil engineering.

Sustainability in civil engineering is often equated to resource efficiency as civil engineering processes are both resource and fuel intensive. Geotechnical engineering is the most resource intensive discipline within civil engineering. Design and construction related to geotechnical engineering consume vast amount of resources (e.g., concrete, steel and land use) and energy, and change the landscape that persists for centuries. 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 (Jefferis 2008). In fact, geotechnical engineering has a huge potential to improve the sustainability of civil engineering projects due to its early position in the construction process. However, the profession is often dominated by financial motivations (Abreu et al. 2008), and environmental and societal sustainability are traditionally neglected in geotechnical project planning and design. A major problem in introducing sustainability in geotechnical engineering is inadequate knowledge of the effect of a geotechnical process on the ecological balance of the surrounding area (Abreu et al. 2008). At the same time, there is an absence of a reference framework which can help in determining the best geo-engineering solution balancing both economy and ecology. These drawbacks are compounded by the scarcity of geo-sustainability literature and of a proper sustainability assessment framework for geotechnical practice (Abreu et al. 2008).

The purpose of this report is to connect the broader scope of sustainable development with geotechnical engineering, to present a review of the research done on different aspects of geosustainability with particular emphasis on sustainability assessment tools and to introduce a quantitative sustainability assessment framework for geotechnical engineering. First, the fundamental concepts and definitions of sustainability are introduced with an aim to relate sustainability to engineering and, in particular, geotechnical engineering. Subsequently, the recent research studies in geotechnical engineering that contribute to sustainable development are reviewed. A particular emphasis of the review is on assessing the suitability of the available sustainability assessment frameworks in geotechnical engineering. These frameworks, in general, are used to develop indicator systems that help determine whether a geotechnical engineering process is sustainable and whether the geotechnical product contributes to the overall sustainable development of the society. It is found that the available indicator systems in geotechnical engineering are mostly qualitative in nature and do not provide a complete assessment of the different competing alternatives. Therefore, the available process and product sustainability assessment tools are explored with an aim to identify or develop the most complete sustainability assessment framework for geotechnical engineering. Based on the investigation, a multicriteria-based, quantitative sustainability assessment framework is proposed that is appropriate for geotechnical engineering. The framework can provide a complete assessment of a geotechnical project by balancing the social, economical and environmental aspects with the technical and technological aspects.

SUSTAINABILITY: PHILOSOPHIES, DEFINITIONS AND CONNECTION TO GEOTECHNICAL ENGINEERING

Engineering design and construction have traditionally been dominated by a narrow, one-dimensional view of technological efficiency with the implicit assumption that nature is an infinite supplier of resources, perpetually regenerative, with an indefinite capacity to absorb all waste. It was only in the later half of the twentieth century, particularly during the energy crisis of the 1970s, that the negative impacts of over reliance on technological advancement surfaced as a problem to the economic world, and the essential interconnection of society, economics, technology and environment came under scrutiny. The dispute between the one-dimensional view of technological efficiency and the multi-dimensional, systems view of sustainability has been a matter of debate and research across different disciplines. In economics, this debate surfaces as the development of two fundamentally different definitions of sustainability, namely, weak and strong sustainability. Weak sustainability assumes that natural capital is replaceable by human capital or technological development as long as the total capital base remains constant or increases (Arrow 2003), while strong sustainability (Daly 2005) advocates against the decline of natural resources exclusively. In sociology, the debate between the one-dimensional and the systems approach is best explained as the difference in the two philosophies underlying the definitions and concepts of sustainability — resource sufficiency and functional integrity (Thompson 2010). In the resource sufficiency approach, the sustainability of a practice is determined based on how long the practice could be carried on at the present rate of consumption. It supports technological efficiency where the rate of consumption of a resource is measured against the available stock of that resource. The resource sufficiency approach has an anthropocentric view, does not recognize the moral values of non-living entities and does not accept the intrinsic value of biodiversity. In contrast, the functional integrity approach measures the sustainability of a practice based on the threat it creates to the reproducing capacity of a self-regenerating system. Functional integrity supports the "deep ecology" school of thoughts, propagated by Næss (1973), which states that the right of all forms of life to live is a universal right and no particular species has more of this right than any other species. This hypothesis is in support of Leopold's (1949) view of "land ethic", which accepts any practice as right only when it tends to preserve the integrity, stability and beauty of the biotic system. The functional integrity approach thus satisfies intergenerational and distributional justices (Kibert 2008) that foster respect for all species and recognition of the equal right of all life forms on the shared resource of the planet. It considers the scope of regeneration of the entire system and hence is a measure of the sustainability at the systems level.

Practically put, the systems approach to sustainability, as advocated by functional integrity or strong sustainability, is a balance between the three E's — economy, environment and equity (Hempel 2009). Achieving a balance of the three E's, however, is a difficult task involving tradeoffs and optimization because the three E's are often at conflict between themselves (Figure 1). The most common conflict is between the economic growth and the environmental protection, and there is also a conflict between economy and equity, which manifests itself in an unequal distribution of wealth. Sustainability, therefore, presents a compromised solution to any given problem that is acceptable but not the best for all the three E's individually.

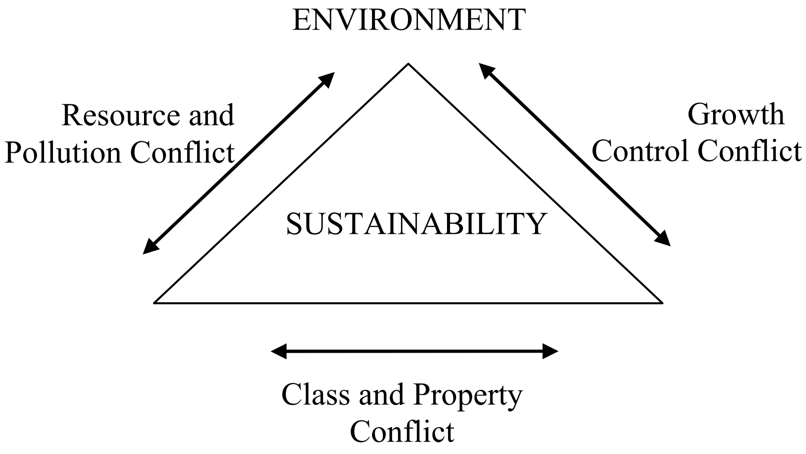


Figure 1. The three aspects and conflicts of sustainable development

It is clear from the above discussion that sustainability is a complex concept and a precise definition of sustainability is difficult to obtain. Brown (1981) described a sustainable society as "… one that is able to satisfy its needs without diminishing the chance of future generations." Later, the Brundtland Commission (1987), formed under the auspice of the United Nations, adapted the ideal of Brown (1981) and defined sustainable development as "development that meets the needs of the present without compromising the ability of the future generations to meet their own needs." The definition by Brundtland Commission is often criticized for being anthropocentric (Curran 1996), for having a negative connotation and for restricting the focus to a limited resource use (Wood 2006). An alternative definition states that sustainability is improving the quality of human life while living within the carrying capacity of the supporting ecosystem (IUCN/UNEP/WWF 1991).

For engineering purposes, sustainability means prudent use of resources at an affordable cost with proper control of harmful emissions (Gradel 1997, Kibert 2008). For geotechnical engineering, sustainability translates to (i) robust design and construction that involves minimal financial burden and inconvenience to the society, (ii) minimal use of resources and energy in planning, design, construction and maintenance of geotechnical facilities, (iii) use of materials and methods that cause minimal negative impact on the ecology and environment and (iv) as much reuse of existing geotechnical facilities as possible to minimize waste. This multi-dimensional objective provides a holistic view and is similar to the functional integrity approach as it does not promote technological efficiency at the cost of ecological injustice or societal inequity. Such a view prevents the use of resources beyond the regeneration capacity of the planet and also checks the production of wastes beyond the assimilation capacity of the earth. This approach automatically favors a closed loop of material use which eventually backs economic and social benefit.

REVIEW OF RESEARCH ON SUSTAINABLE GEOTECHNOLOGY

Establishing a functional integrity approach in geotechnical engineering practice requires rigorous research in several areas of geotechnical engineering — from recycling and reuse of waste materials to sustainable use of underground space — all of which contribute to the sustainable development of civil infrastructure and society. At the same time, there is a strong need to develop rigorous sustainability assessment tools that can evaluate the relative sustainability of competing geotechnical solutions. The salient areas of research related to sustainable geotechnology are outlined in Figure 2, and some of the recent studies are discussed below.

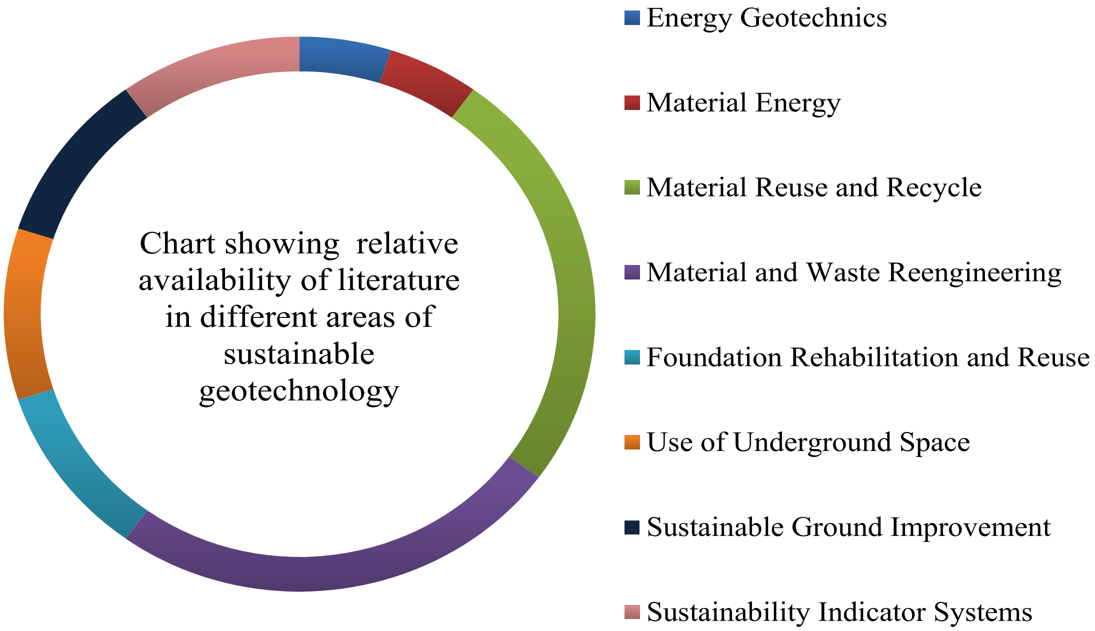


Figure 2. Relative availability of literature in different areas of sustainable geotechnology

As geotechnical engineering uses natural and manufactured raw materials in large quantities, a part of the sustainability related research in geotechnology has focused on introducing new, environment friendly materials and on reuse of waste materials. Use of alternate materials like lignosulfonate, which promotes surface vegetation and natural subsurface fauna, for soil stabilization (Vinod et al. 2010), beneficial use of otherwise hazardous coal and fly ash in geotechnical constructions (Sridharan and Prakash 2010), use of recycled or secondary materials like asphalt pavement and cement-stabilized quarry fines as pavement bases (Saride et al. 2010), use of recycled glass-crushed rock blends for pavement sub-base (Ali et al. 2011), recycling of shredded scrap tires as a light-weight fill material (Voottipruex et al. 2010), and use of pulverized fly ash to improve the thermal properties of energy piles (Patel and Bull 2011) are some of the examples. Bioengineered slope (Storesund et al. 2008, Wu et al. 2008) and use of recycled mixed glass and plastic for segmental retaining wall units (Meegoda 2011) are other examples of alternate construction techniques in geotechnical engineering.

Ground improvement is another area that contributes to sustainable development. Use of solar powered prefabricated vertical drains (Indraratna et al. 2010, Pothiraksanon et al. 2010), and improvement of the mechanical and hydraulic properties of soil using in situ soil bacteria through bio-mineralization and bio-polymerization (Yang et al. 1992, 1994, DeJong et al. 2006, Whiffin et al. 2007) are some examples of green ground improvement techniques. Spaulding et al. (2008) compared, using three case studies, the use of ground improvement techniques as an alternative to conventional deep foundations in an attempt to reduce the environmental impact. In the first case study, the use of dynamic compaction was compared with excavation and engineered fill. In the second case study, controlled modulus columns under slab-on-grade were compared with driven piles. Finally, a cement-bentonite cut-off wall was compared with soil-bentonite cut-off wall. In all the cases, the alternative ground improvement techniques provided better economy and reduced the carbon footprint mostly due to use of low energy materials like fly ash. Egan et al. (2010) also compared the use of ground improvement techniques, particularly, vibro-replacement stone columns, as an alternative to traditional deep foundations and concluded that stone columns are better from the environmental loading standpoint and that further reduction in the loading is possible if recycled materials and aggregates are used in vibro stone columns.

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). The drivers for this change in practice are technological, economic and environmental sustainability. The cost of removal of an old foundation is estimated to be about four times that of constructing a new pile, and the removal disturbs the soil and adjacent structures, and causes voids that need to be backfilled. Several case studies demonstrating the benefits of reuse of foundations have been documented (Anderson et al. 2006, Butcher et al. 2006b, Clarke et al. 2006, Lennon et al. 2006, John and Chow 2006, Tester and Fernie 2006, Katzenbach et al. 2006). A case study of an idealized redevelopment of office building documented by Butcher et al. (2006a) compares the whole life cost (WLC) of the different design options for foundations — design for partial reuse, design for no reuse and design for full reuse. The results showed that the foundations designed for reuse has a much lesser WLC than foundations designed without the reuse option although the initial premium is slightly greater for foundations designed for reuse. Butcher et al. (2006a) also found that the embodied energy consumed in reusing foundations is nearly half of that consumed in installing new foundations. Leung et al. (2011) developed an optimization algorithm for reuse of pile foundations in order to obtain the best configuration of new piles to be used alongside existing piles so that the superstructure loads are safely transferred and, at the same time, material use is minimized.

Another important contribution of geotechnical engineering to sustainable development is utilization of underground space for housing and facilities. Research by Sterling et al. (1985) and Carmody et al. (1983) revealed that underground structures can provide energy efficiency and lessen the burden on limited resources like land while offering protection against human-inflicted and natural calamities. As pointed out by Rogers (2009), utilization of underground space has been adopted by many countries like Hong Kong, Japan, Singapore, Canada, Denmark and Norway for different reasons like severe weather or topography. The Norwegian Tunelling Society provides examples of sustainable use of underground spaces ranging from powerhouses for hydropower projects (Broch 2006) and underground telecommunication centers (Rygh and Bollingmo 2006) to storage of hydrocarbons (Grov 2006) and wastewater treatment plants (Neby et al. 2006, Ronning 2006). Enhanced security, lessened environmental burden, ease of maintenance due to less atmospheric exposure, less interruption to traffic and city life, and better economy have been cited as some of the beneficial effects of use of underground space. In another instance, Jefferson et al. (2009) suggested locating the transportation infrastructure and utility infrastructure of Birmingham Eastside underground in order to reduce the load on land use and to reduce the environmental effects of emissions. Fragaszy et al. (2011) pointed out that underground space can be efficiently used in storing energy, particularly renewable energy like solar, tidal and wind energy, which are characterized by intermittent supplies with seasonal or diurnal fluctuations in production.

Geotechnical 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., pavements and basement walls) can act as heat exchangers (Brandl 2006). The role of geotechnical engineering in promoting geothermal energy includes developing inexpensive and novel methods for drilling and trenching, understanding the thermal properties of soil and backfill materials, understanding the effect of thermal cycles on the behavior of energy piles, developing modeling tools and design methods for thermal load balancing to prevent long term temperature changes in the densely populated areas and understanding the limits of extractable energy for vertical and horizontal ground source heat pumps (Fragaszy et al. 2011). Research is in progress to develop proper characterization, analysis and design of energy related geo-structures like energy piles (Peron et al. 2011, Abdelaziz et al. 2011, Laloui 2011, Wang et al. 2011), wind turbine foundations (Bryne and Houlsby 2003, Musial et al. 2004) and foundations for oil and gas drilling operations (Yu et al. 2011).

It is evident from the above discussion that geotechnical engineering can contribute significantly to solutions of global sustainability problems, and hence, geotechnical processes should themselves be sustainable. In order to determine whether a process is sustainable or not, there has to be a clearly defined framework that evaluates and quantifies the relative sustainability of alternate geotechnical practices. Metrics like global warming potential (Storesund et al. 2008), carbon footprint (Spaulding et al. 2008), embodied carbon dioxide (Chau et al. 2008, Egan et al. 2010) and embodied energy (Chau et al. 2006) have been used in a few studies 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 and economic aspects (Holt et al. 2010). Jefferson et al. (2007) also pointed out that the use of one metric to evaluate the sustainability of a project may not always be sufficient — a holistic sustainability assessment tool in geotechnical engineering, upholding the functional integrity approach, is required. Such a comprehensive framework is lacking in geotechnical engineering although there are some assessment tools that have been developed in the recent past that have limited applicability. These assessment tools are discussed below.

Jimenez (2004) developed a qualitative indicator system called Sustainable Geotechnical Evaluation Model (S.G.E.M.) based on color code for comparing different alternative materials for slope stabilization. The system judges the sustainability of a geotechnical project based on the categories of social, economic, environmental and natural resource use, and on other subcategories like water use, land use and re-usability of materials. Jefferson et al. (2007) proposed a set of 76 generic indicators and 32 technology-specific indicators for ensuring the sustainability of ground improvement methods. The indicator system, known as Environmental Geotechnics Indicators (EGIs), was used at construction sites for ground improvement projects and is based on a point score system ─ 1 for harmful to 5 for significantly improved construction practice. The system was developed by borrowing concepts from the existing sustainability indicators like SPeAR and BREEAM (Jefferson et al. 2007) and by modifying the concepts to suit the particular aspects of ground improvement projects. The EGIs system is designed to cover the entire range of activities over the lifetime of a project but does not consider the economic or social aspects of sustainability.

Holt et al. (2009) developed GeoSPeAR, an indicator system for geotechnical construction, by modifying the Sustainable Project Appraisal Routine (SpeAR) developed by Arup (Figure 3). SPeAR uses a color coded rose diagram to assess a project on the basis of four main criteria ─ social, economic, environmental and natural resources ─ and twenty sub-criteria. It consists of a circle, which is divided into sectors along the circumference based on the criteria and sub-criteria mentioned above. Each sector corresponding to a sub-criterion is further divided radially into seven color coded segments. The performance of a project in a particular sub-criterion is indicated by shading one of the segments with its respective colors. The closer the shaded segment is to the center of the diagram, the more sustainable the project is with respect to that particular sub-criterion. GeoSPeAR replaced some of the indicators of SPeAR like pedestrian and bicycle facility, users' control and housing type by relevant geotechnical indicators like use of existing substructure, use of recycled material and resource efficient design. GeoSPeAR includes an optional provision for life cycle assessment (LCA) of a project to bring transparency to the sustainability indicators like carbon dioxide emissions, noise and vibrations (Holt et al. 2010). GeoSPeAR, however, does not take into account site specific risk elements. Holt et al. (2009) provided a step by step procedure (Table 1) that should be followed in combination with GeoSPeAR to ensure the sustainability of a project, and suggested performing LCA to determine the impacts of a design choice on the resource base and the environment. Laefer (2011) developed a scoring system to augment SPeAR for assessing the sustainability of foundation reuse projects.

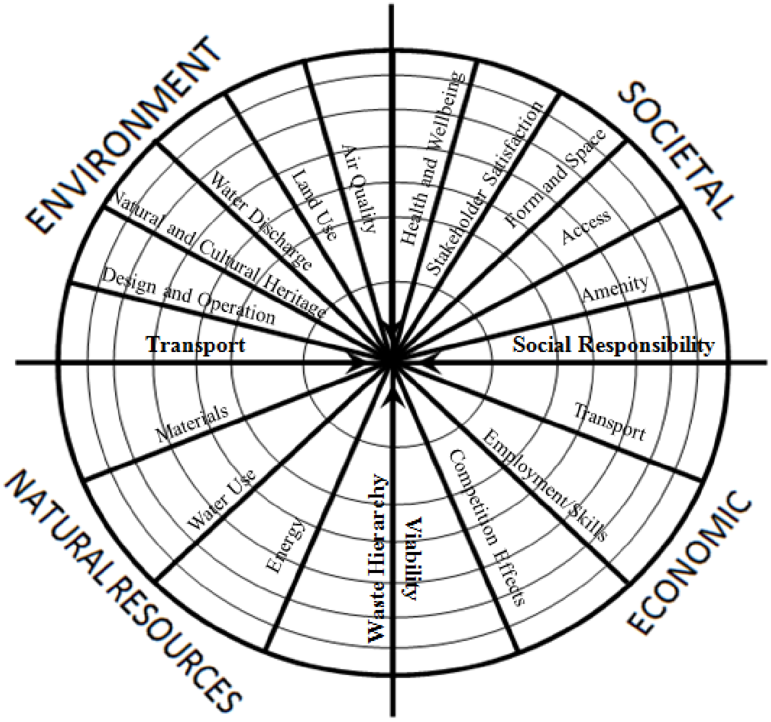


Figure 3. SPeAR template

Table 1. Steps to be followed in assessing sustainability in geotechnical projects

STEP	DETAIL
Pre Assessment	Communication between all parts involved in the process
STEP 1	Setting up boundaries for the assessment
STEP 2	Data collection from the project for different indicators
STEP 3	A baseline assessment using GeoSPeAR
STEP 4	Identifying areas of sustainability concern
STEP 5	Performing LCA to evaluate impact of different design options
STEP 6	Reassessment of improvement for changes in design option
STEP 7	Repetition of Steps 5-6 to arrive at the expected level of improvement

The geotechnical indicator systems described above, albeit useful, are qualitative in nature and limited in scope. A quantitative assessment framework is necessary particularly at the planning and design stages of a geotechnical project (Figure 4). The 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. Unfortunately, such a comprehensive framework does not exist in geotechnical engineering.

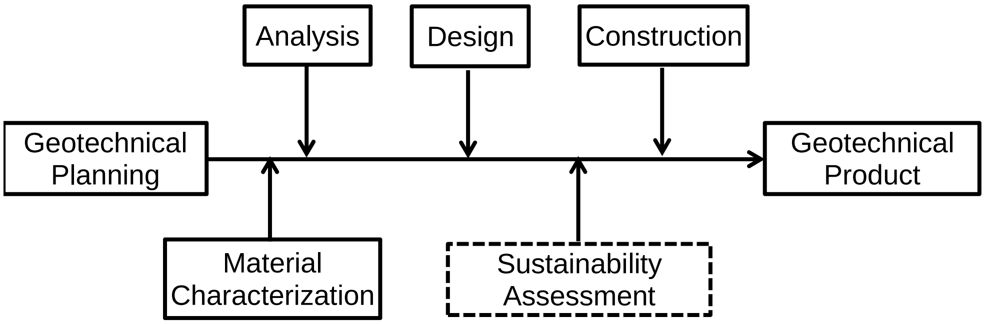
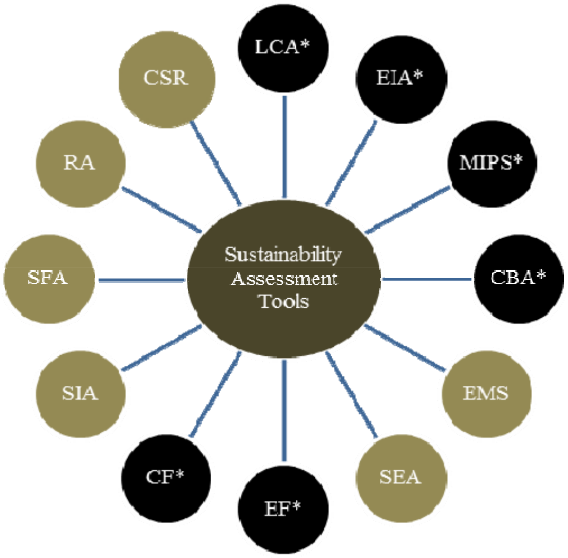


Figure 4. Typical steps in geotechnical projects

SUSTAINABILITY TOOLS APPLICABLE TO GEOTECHNICAL SYSTEMS

The available sustainability assessment tools are investigated in this section to identify the most appropriate tool or set of tools that can be used to develop a comprehensive assessment framework in geotechnical engineering. Quantitative and qualitative assessment tools like Life Cycle Assessment (LCA), Life Cycle Costing

(LCC), Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA) and Cumulative Energy Requirement Analysis (CERA) (Wrisberg et al. 2002, Finnveden and Moberg 2004) have been developed that translate the concepts of sustainable process design into practice. In assessing an engineering process, these tools act as means of reasoning, analysis and communication of the consequences of a choice. Sustainability assessment tools are many and form an evolving aspect of sustainability study. A list of the more frequently used tools is provided in Figure 5 and, in this section, some of these tools are examined for their applicability and appropriateness in geotechnical engineering.



LCA – Life Cycle Assessment
EIA – Environmental Impact Assessment
MIPS – Material Input Per Unit Service
CBA – Cost Benefit Analysis
EMS – Environmental Management System
SEA – Strategic Environmental Assessment
EF – Ecological Footprint
CF – Carbon Footprint
SIA – Social Impact Assessment
SFA – Substance Flow Analysis
RA – Risk Analysis
CSR – Corporate Social Responsibility

*Can be potentially used in geotechnical engineering projects

Figure 5. Salient sustainability assessment tools

As geotechnical engineering is resource intensive, assessment tools that focus on resource accounting for processes can be useful in assessing the sustainability in geotechnical engineering. Available resource accounting tools like Material Intensity Per Unit Service (MIPS) and Cumulative Energy Requirement Analysis (CERA) use either mass or material energy consumption for assessing the sustainability of a process. MIPS uses total mass of materials used in a process to produce one unit of a product or service as the basis of accounting. For calculating MIPS of a product or a service, the resources used in a process are classified as abiotic materials, biotic materials, water, air and soil so that weights can be assigned to these categories depending on their relative importance. CERA, on the other hand, uses material energy as a measure of resource use in a process and is calculated using the embodied energy of the resources. Embodied energy of a material is defined as the sum total of all the energy required to produce that material (Constanza 1980, Brown and Herendeen 1996). It has been used in assessing the sustainability of geotechnical projects (Chau et al. 2006). However, for assessing process sustainability, loss of resource energy that is available to do useful work is often considered a more important parameter than the embodied energy (Bakshi and Hau 2004, Hau 2005). This available energy of a resource to do useful work is termed as exergy. Exergy per unit mass of a material is a measure of the maximum amount of useful (available) energy that can be extracted when the material is brought into equilibrium with its surroundings (Szargut et al. 1988, Ayers 1998, Bastianoni et al. 2005, Dincer and Rosen 2007, Tsatsaronis 2007). As every energy transformation is inevitably associated with a loss of energy to the surrounding atmosphere where it becomes unavailable to perform useful work, a good measure of sustainability of a process is the exergy loss of the process. Hau (2002, 2005), however, criticized both exergy and embodied energy for not considering the ecosystem services that went into making the material. For eco-centric sustainability assessment, Hau (2002, 2005) suggested using emergy as a parameter. Emergy of a resource is the sum total of all the ecosystem services that went into making the resource (Odum 1996). Emergy approach considers the earth as a closed system with three constant energy inputs: solar energy, deep earth heat and tidal energy. For the purpose of emergy calculation, all energy forms are converted to a common base of solar energy with solar emjoules (sej) as the unit.

While mass and energy accounting tools focus on the material input side of a process, they do not provide a complete sustainability assessment as the environmental impact of the processes are not covered. The environmental impact of a geotechnical process can be assessed by using ecological footprints (EF), carbon footprint (CFP) and environmental impact assessment (EIA). Ecological footprints assess the sustainability of a project by the area of productive land required for executing different activities and for assimilating the emissions from such activities. A recent trend is to use carbon footprint, which is an accounting tool that calculates the total emissions from different activities that lead to global climate change. The emissions are calculated in terms of tonnes of carbon dioxide equivalent and provide a measure of the impact of anthropogenic activities on the climate. The environmental impact assessment (EIA) assesses the effects of a particular technological process on the environment at the location of the occurrence of the process (Curran 1996). The most important function of EIA is to compare the ecological effects of alternative technologies pertaining to a particular process. The categories in which impacts are assessed are resource use, human health and ecological consequences (SETAC 1993 and ISO 14040, 2010). The mandatory steps of impact assessment are impact category definition, classification and characterization and are sometimes followed by valuation. In the valuation step, weights are assigned to different categories so that an impact score can be calculated. The salient quantitative weighting approaches are proxy, panel, monetization and distance to target (Lindeijer 1996).

The tools described above focus either on the input side (e.g., MIPS and CERA) or on the output side (e.g., CFP and EIA) of the process. Assessing the sustainability of a process, however, requires a consideration of both the input and output sides, and it is useful to have a single tool that can account for both the sides. One such tool is the Input-Output Analysis (IOA). The input and output sides of a process can be modeled together in IOA, which uses a systems approach to model the flows of products between sectors of an economy. Energy can be added to the model to allow calculation of the embodied energy of any sector. IOA can also be used for assessing the environmental impact by replacing the economic flows by physical flows of materials. While IOA models the interaction between different economic sectors, it does not consider the life cycle wide impacts of a process. Therefore, it may not provide a complete assessment of impacts of geotechnical processes, which start from the stage of extraction of raw materials and, in most cases, continue through the stage of demolition and disposal. A more appropriate tool for geotechnical engineering is life cycle assessment (LCA), which has a life cycle view. LCA sums all the impacts generated by a process/product from the stage of extraction of raw materials to the end of the project or end of the useful life of the product (Finnveden and Moberg 2004, Curran 1996). LCA of a process includes planning, construction, operation and dismantling of the process under study. As standardized by ISO 14040 (2010), LCA consists of four stages: (i) goal definition and scoping, in which the purpose and extent of the study is underlined, (ii) inventory analysis, in which all the inputs to and outputs from the process over its life cycle is accounted for, (iii) impact assessment in which the outputs of the process are related to the impact categories and (iv) interpretation of results where results are analyzed to provide solutions for improvement (ILCD 2010, Curran 1996). An environmental impact assessment (EIA) is generally done at the impact assessment step of LCA while the inventory analysis in LCA can be done either by mass or energy accounting methods. EIA used in conjunction with LCA describes the consequences of the environmental loading estimated at the inventory step of LCA. This helps to translate the quantitative measures of the environmental loading into qualitative terms and to understand the effects of the process.

In addition to incorporating sustainability in material requirement and environmental impact issues, any geotechnical project must also satisfy the financial concern of the stakeholders and maximize the benefits available to the society. This socio-economic aspect of sustainability of a geotechnical project can be addressed through cost benefit analysis (CBA), which is an economic tool for determining whether the benefits of a project or policy outweigh its cost. It aims at expressing all the positive and negative effects of an activity in the common unit of money. CBA views the effect of an activity from a societal point of view, which is different from the traditional economic point of view. The first step in CBA is identification of the benefits and costs of a project. For the chosen benefits and costs, CBA weighs the benefits against the corresponding costs. A project or activity in which the chosen benefits outweigh the costs is considered to be a sustainable choice.

As mentioned earlier, sustainability is a holistic concept that requires balance and trade-offs between conflicting interests. Such a multi-dimensional concept is best assessed by using multicriteria analysis (MCA), which provides an optimization framework that can be used by engineers as a decision making tool. MCA is used in cases where (1) there is no solution available that simultaneously satisfies all the criteria to the fullest extent and (2) the performance of one alternative is better in some cases and worse in others leading to confusion in the choice. MCA is done in two steps. In the first step, the objectives and the tradeoffs between the objectives are identified. In the second step, weights or scores are attached to the different objectives depending on their relative importance. The second step is best explained using a two dimensional evaluation matrix (Table 2) in which a total impact score for each alternative is calculated by summing their weighted scores for different objectives (Ding 2005). The "best" option is then identified from the total score. Weights play an important role in the outcome of an MCA, and hence, considerable judgment should be used in applying the weights to the different objectives. The choice of a weighting method and the values of the weights are influenced by ethical and ideological values of the practitioners. It is important to note that there is presently no consensus on the choice of the weighting methods and on the values of the weights (Finnveden 1999).

Table 2. Multicriteria evaluation matrix

Objective	Weights	Scores for Alternatives			
		I$_1$	I$_2$	…	I$_n$
J$_1$	W_1	S_{11}	S_{12}	…	S_{1n}
J$_2$	W_2	S_{21}	S_{22}	…	S_{2n}
…	…	…	…	…	…
J$_i$	W_i	S_{i1}	S_{i2}	…	S_{in}
Total Impact Score		$\sum_{k=1}^{i} W_k S_{k1}$	$\sum_{k=1}^{i} W_k S_{k2}$	…	$\sum_{k=1}^{i} W_k S_{kn}$

The forgoing discussion suggests that LCA combined with EIA can provide a satisfactory measure of sustainability of geotechnical projects from the viewpoints of resource use and environmental impact. CBA, on the other hand, can capture the social and economic impacts of the project. However, in order to capture these different aspects in a single framework, MCA is required.

PROPOSED QUANTITATIVE ASSESSMENT FRAMEWORK

A MCA framework is introduced in this section for geotechnical engineering with particular application in pile foundations. In this framework, LCA, EIA and CBA are combined to calculate a sustainability index for pile foundations. In the LCA, the input inventory (resource use calculation) is done using energy analysis and the output inventory is used to perform EIA as part of the LCA. A resource use indicator is calculated based on the input inventory (energy analysis) and an environmental impact indicator is calculated from the EIA. Following the LCA, CBA is done based on which a socio-economic indicator is calculated. Finally, a sustainability indicator is calculated in the MCA by combining the resource use, environmental impact and socio-economic indicators. Thus, the overall performance of the geotechnical project is assessed as a combined function of the resource use, the environmental impact and the socio-economic benefit. Figure 6 gives a schematic of the developed framework.

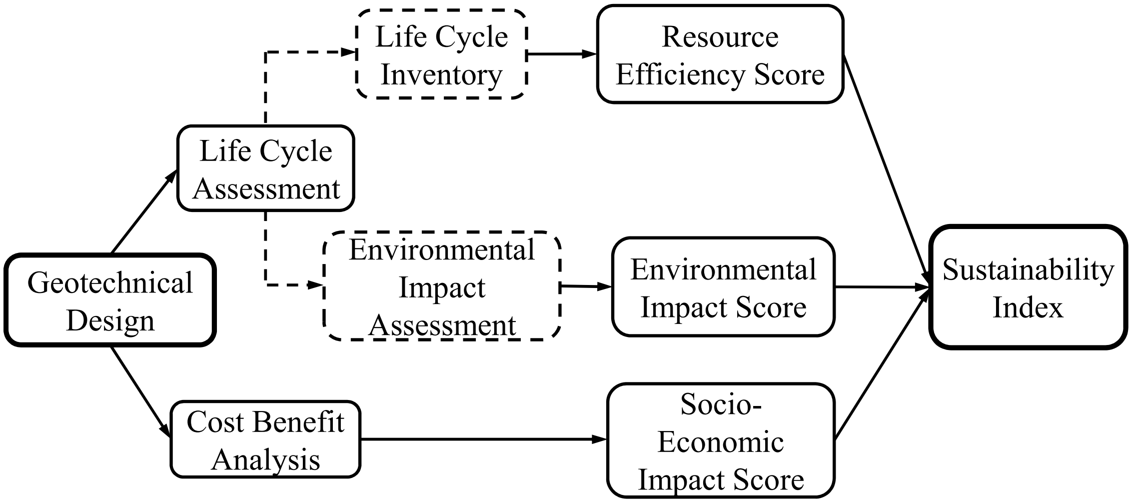
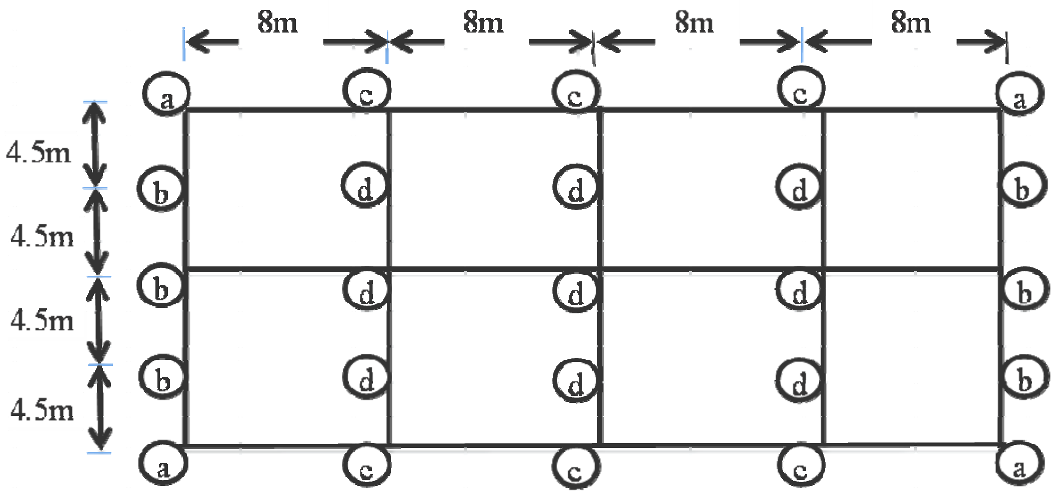


Figure 6. Proposed multicriteria analysis framework

The MCA framework is applied to a hypothetical case study in which a two storied commercial building on a clayey profile is considered. The building is to be constructed on 25 piles placed according to the building plan shown in Figure 7. Drilled shaft and driven concrete piles are considered as alternative options and the goal of the MCA is to determine which of the two pile types is more sustainable. It is assumed that there are no technical and technological constraints in constructing the two types of piles at the site. The piles are designed following the working stress method using a factor of safety of 3 (Salgado 2008). The soil properties used in the calculation are (i) unit weight of clay $\gamma_{sat} = 18$ kN/m^3, (ii) undrained shear strength $s_u = 0.3\sigma'_v$ where σ'_v is the effective vertical stress at any depth z, (iii) overconsolidation ratio (OCR) = 2 and (iv) coefficient of earth pressure at rest $K_0 = 0.4$. The water table is assumed to be at the ground surface. The length of the piles for both the types is kept constant at 12 m (Figure 7). The diameters obtained from the design are given in Table 3.

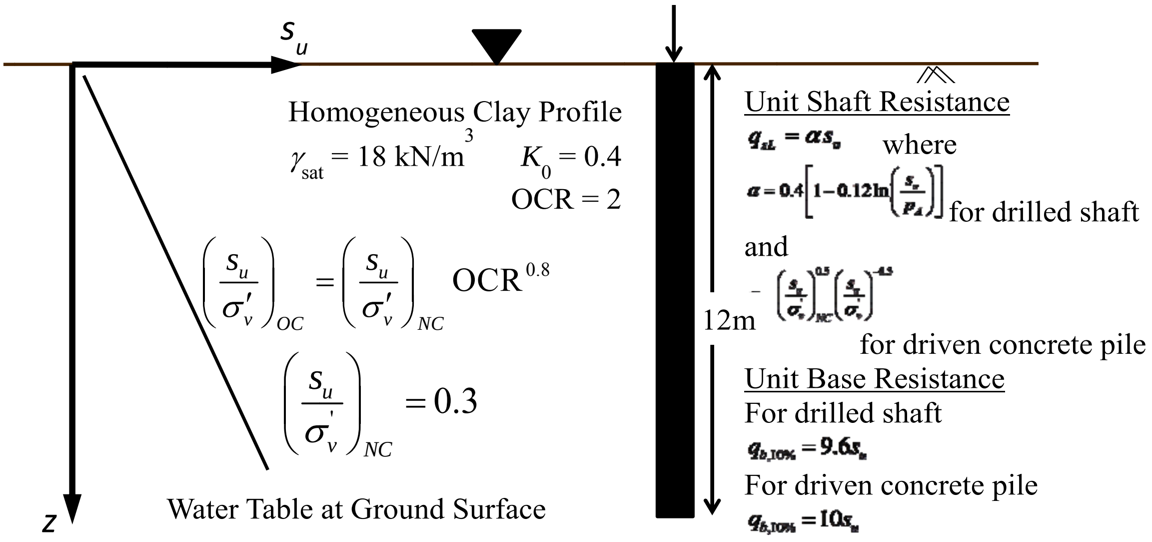
Table 3. Design dimensions and summary of resource consumption and environmental impact of drilled shafts and driven piles

Summary of Resource Consumption from Input Inventory and Environmental Impact from Output Inventory of LCA															
		DRILLED SHAFT							DRIVEN CONCRETE PILE						
			Resource Consumption from Input Inventory			Environmental Impact from Output Inventory				Resource Consumption from Input Inventory			Environmental Impact from Output Inventory		
Working Load		Diameter	Emergy	Exergy	Embodied Energy	Global Warming	Acidification Potential	Human Health	Diameter	Emergy	Exergy	Embodied Energy	Global Warming	Acidification Potential	Human Health
kN	No. of Piles	m	$\times 10^{11}$ (sej)	MJ	MJ	gm Eq CO_2	gm Eq SO_2	gm Eq 1,4 DB	m	$\times 10^{11}$ (sej)	MJ	MJ	gm Eq CO_2	gm Eq SO_2	gm Eq 1,4 DB
415	4	0.59	166198.77	111451.79	117287.13	4624556.32	14030.22	8421.61	0.43	133556.45	66116.03	65124.34	7455259.05	17473.73	46367.82
473	6	0.65	284353.74	180957.17	191329.71	1406202.33	4265.95	2561.31	0.48	245419.52	119882.37	117981.99	1981821.84	4746.75	11591.95
583	6	0.76	355051.67	208746.78	222385.48	11463086.47	34772.62	20884.61	0.57	339551.36	163118.92	160356.57	13369240.27	33219.79	69551.73
765	9	0.92	722247.24	147032.32	416895.24	25312497.19	76778.95	46127.30	0.71	773945.27	366222.58	359655.91	24209601.65	63152.52	104327.59
		TOTAL	1527851.41	648188.07	947897.57	42806342.31	129847.75	77994.83	TOTAL	1492472.59	715339.91	703118.81	47015922.81	118592.78	231839.09



Pile a – Superstructure load 415 kN
Pile b – Superstructure load 473 kN
Pile c – Superstructure load 583 kN
Pile d – Superstructure load 765 kN

(a) Building foundation plan and superstructure load



(b) Soil data and design equations

Figure 7. (a) Building foundation plan and superstructure load and (b) soil data and design equations for hypothetical case study

These designed dimensions of the piles are used in the LCA to determine (i) the quantity of natural resources and processed materials needed for the piles and (ii) the emissions generated to manufacture the required quantity of materials. Figure 8 shows the flow chart for this LCA.

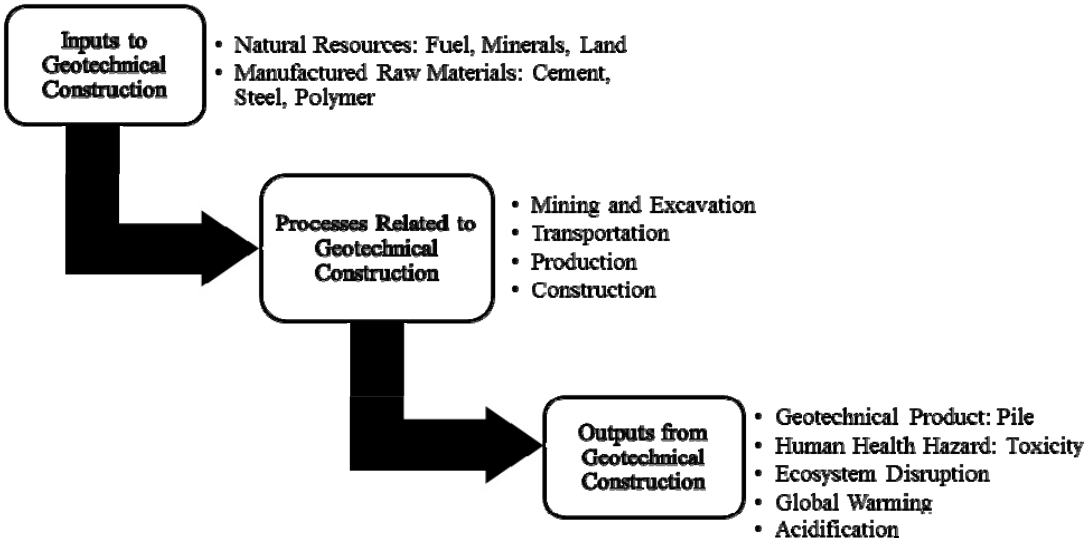


Figure 8. Flow chart showing the inputs, outputs, processes and impact categories in pile construction projects

LCA Step 1: Goal and Scope Definition

The preliminary goals of the life cycle assessment performed in this study is (i) to determine, through life cycle inventory (LCI), the resource consumption and emissions for drilled shafts and driven piles from planning to disposal stages and (ii) to decide, after an environmental impact assessment (EIA) based on the LCI, which of the two aforementioned piles is more environmentally sustainable. The final goal of the LCA is to provide relevant quantitative information that can be used for formulating a sustainability index.

The scope of this study primarily includes identification and quantification of all the major inputs to and outputs from the process of pile construction. Water use, though an important issue, is not considered with the assumptions that (i) it is not a limiting resource for the particular case and (ii) recycled water can be used for the purpose of cement and concrete manufacturing which will reduce the impact. The contributors to energy or resource consumption from the construction and maintenance of the manufacturing plants of cement and steel, electricity consumption of the architect's office and other similar indirect energy consumers are kept out of the scope with the understanding that such contributions are almost the same for all pile types, and hence, do not influence the goal of the study.

LCA Step 2: Life Cycle Inventory

The inputs that are considered in this study are cement, steel and diesel from the manufacturing segment and land from the biosphere. The input inventory of the LCA is done using energy analysis based on embodied energy, exergy and emergy. The resource use calculations, shown in Table 3, are done by first calculating the total mass of land, cement, steel and diesel required for the construction of the piles and then multiplying the mass by the unit emergy, exergy or embodied energy values obtained from different sources. The values of emergy per unit mass of cement and steel are adopted from Brown and Buranakaran (2003) and Pulselli et al. (2007) while the values of unit emergy for land are used from the emergy folios of Odum et al. (2000). The embodied energy values per unit mass are adopted from the ICE Database version 1.6a, prepared by

University of Bath, UK. The exergy per unit mass of cement and steel used in the calculations are based on the values calculated by Szargut et al. (1988). The unit exergy value of land is taken to be the same as that of clay minerals for the clay profile — the values are obtained from Meester et al. (2006). The details of the calculations are given in Misra (2010).

It is assumed that the quantity of cement required to manufacture 1 m^3 of concrete is 297 Kg (Sjunssen 2005). The reinforcement of the driven piles is calculated based on the reinforcement required to support the lifting moment in piles while lifting the piles by head (Tomlinson and Woodward 1994). A nominal reinforcement of 0.5% is assumed for drilled shafts (Salgado 2008).

The outputs considered in the study are the emissions to air and water — particulates, carbon dioxide, carbon monoxide, sulfur dioxide, oxides of nitrogen, methane and ammonia. To calculate the total quantity of the output emissions, the total mass of cement, steel, concrete and diesel required for the piles, as obtained from the design calculations, is multiplied by the emission values per unit mass production of cement, concrete, steel and diesel obtained from the National Renewable Energy Laboratory (NREL), U.S.A database and from Sjunssen (2005). The environmental impact of concrete manufacturing is considered as the sum of (i) the environmental impact of cement manufacturing from extraction of raw materials till it reaches the concrete manufacturing unit and (ii) the environmental impact from the process of concrete manufacturing. The output inventory forms the basis of the EIA performed in the next step of LCA.

LCA Step 3: Environmental Impact Assessment (EIA)

The environmental impact assessment is done based on the categories of global warming, acidification, ecosystem toxicity, and human toxicity (Table 3). The impact in the category of global warming (climate change) is calculated in terms of global warming potential of CO_2 and is determined as gram equivalent CO_2. The impact in the category of acidification is calculated in terms of SO_2 acidification potential and determined as gram equivalent SO_2. The ecosystem health category includes both terrestrial and freshwater toxicity. The terrestrial, freshwater and human toxicities are calculated in terms of toxicity potential of 1, 4 dichlorobenzene (1, 4 DB) and is expressed as gram equivalent of 1, 4 DB. The weights (indexes) used for converting the mass of emissions to their respective gram equivalence in different impact categories are done using the ReCiPe database (2009), which uses the distance to target method of weighting. The midpoint indicators are used as weights (indexes) to avoid the higher degree of uncertainty associated with the end point indicators.

LCA Step 4: Interpretation of Results

Table 3 presents the summary of the cumulative resource consumption and environmental impact for the two pile types considered in the case study. As the drilled shafts typically require a larger diameter than the driven piles, the drilled shafts consume more resources in terms of cement and land than the driven pile. However, the driven piles require more reinforcement compared with the drilled shaft, and hence, emergy, exergy or embodied energy consumed due to the use of steel is greater for driven piles than for drilled shafts.

Resource Use Indicator

The resource use indicator is calculated based on the resources used in the categories of land, cement and steel (Table 4). For the purpose of obtaining the indicator, the embodied energy consumption is chosen to represent the energy use although exergy or emergy could have been chosen as well. The choice of embodied energy is based on the fact that LCA of buildings and related materials have traditionally been done using embodied energy (Chau et al. 2006, Storesund et al. 2008). The resources used in each category are normalized by converting them to percentages, and weights are applied to emphasize the relative importance of the categories. Soil, as land, is a limited resource and steel manufacturing is found to have toxic effects on human health — these two resources are assigned a greater weight of 0.3 each. Cement and diesel are assigned a weight of 0.2 each (the sum of the weights equals unity). It is important to note that the assigned weights are arbitrary and can be changed depending on the choice of the designer or on the requirement of a particular site. The indicator is calculated by summing the product of the percentage contribution of each pile type in a category and the corresponding weight. A greater indicator value implies a less sustainable alternative. Thus, the resource use indicators show that, from a resource-use point of view, driven piles are a more sustainable option than drilled shafts.

Table 4. Calculation of resource use indicator

Calculation of Resource Use Indicator for the Drilled Shaft and Driven Concrete Pile							
	Embodied Energy Consumed (MJ)		Percent Consumption of Embodied Energy			Resource Use Indicator	
Resource Categories	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Weights	Drilled Shaft	Driven Pile
(1)	(2)	(3)	(4)=[(2)/((2)+(3))]×100	(5)=[(3)/((2)+(3))]×100	(6)	(7)=(6)×(4)	(8)=(6)×(5)
Land	116600.23	66756.26	63.59	36.41	0.3	19.08	10.92
Cement	192866.26	110420.27	63.59	36.41	0.2	12.72	7.28
Steel	201689.38	461886.83	30.39	69.61	0.3	9.12	20.88
Diesel	947897.57	64055.45	93.67	6.33	0.2	18.73	1.27
					TOTAL SCORE	59.65	40.35

Environmental Impact Indicator

The categories of impact considered for the purpose of calculating the environmental impact indicator are human health, acidification and climate change. Ecosystem health is neglected as the impact in this category is found to be negligible compared to other impact categories. The impacts in the individual categories are converted to percentage and weights are applied to them. A linear combination of the weights and the corresponding percentage values gives the environmental impact indicator (Table 5). The weights applied are 0.4 for human health, 0.3 for global warming and 0.3 for acidification potential. A greater indicator value implies a less sustainable option. The calculated environmental impact indicator suggests that drilled shafts are a more sustainable option than driven piles from the environmental impact point of view.

Table 5. Calculation of environmental impact indicator

Calculation of Environmental Impact Indicator for Drilled Shaft and Driven Concrete Pile

Impact Categories	Drilled Shaft	Driven Pile	Percent Contribution in Impact Categories		Weights	Environmental Impact Indicator	
			Drilled Shaft	Driven Pile		Drilled Shaft	Driven Pile
(1)	(2)	(3)	(4)=[(2)/((2)+(3))]×100	(5)=[(3)/((2)+(3))]×100	(6)	(7)=(6)×(4)	(8)=(6)×(5)
Global Warming Potential (gram equivalent CO_2)	42806342	47015922.81	47.66	52.34	0.3	14.30	15.70
Acidification Potential (gram equivalent SO_2)	129847.75	118592.78	52.27	47.73	0.3	15.68	14.32
Human Health (gram equivalent 1,4 DB)	77994.83	231839.09	25.17	74.83	0.4	10.07	29.93
					TOTAL SCORE	40.05	59.95

Cost Benefit Analysis

The financial return calculation is done with the assumption that the building will be leased at $24.00 per square feet (a value typical of Connecticut) with a discount rate of 10% per year. This results in a net income of $1350663.00. The cost of construction assumed for drilled shaft is $400.00 per linear foot and for driven concrete pile is $80.00 per linear foot (these values are obtained from a local company at Connecticut). Using these numbers, the cost benefit ratio is calculated as 0.23 and 0.05 for drilled shaft and driven pile, respectively. The cost benefit ratios are then converted to percentage to calculate the contribution of the pile types in the category of financial return.

The loud noise and vibrations produced during pile driving may not be welcomed in the neighborhood. The extent of opposition can be parameterized by a survey in the locality on the willingness to pay more in order to avoid the consequences of noise and vibration. Such a survey ensures social equity by including all the affected people into the process of decision making and may serve as a convincing argument to the financial stakeholders. In the absence of such data, it is assumed that drilled shafts contribute 40% and driven piles contribute 60% in this category.

The socio-economic benefit indicator is calculated as a weighted average of the scores in the above two categories with equal weights of 0.5 assumed for both the categories. Table 6 shows the details of the calculation.

Table 6. Calculation of socio-economic impact indicator

Calculation of Socio-economic Impact Indicator for Drilled Shaft and Driven Pile							
			Percent Contribution in Impact Categories			Socio-economic Impact Indicator	
Impact Categories	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Weights	Drilled Shaft	Driven Pile
(1)	(2)	(3)	(4)=[(3)/((2) +(3))]×100	(5)=[(2)/((2) +(3))]×100	(6)	(7)=(6)×(4)	(8)=(6)×(5)
Financial Returns (Cost Benefit Ratio)	0.230	0.05	82.14	17.86	0.5	41.07	8.93
Noise and Vibration	40.00	60.00	40.00	60.00	0.5	20.00	30.00
TOTAL SCORE						61.07	38.93

Multicriteria Analysis

The sustainability index in this study is a function of the resource (embodied energy) use, environmental impact, and economic and social benefits. Mathematically, the resource use, environmental impact and socio-economic indicators are each multiplied by their respective weights and the resulting products are summed to obtain the sustainability indicator (Table 7). An equal weight of 0.4 is arbitrarily assigned to the resource use and environmental impact indicators, and the socio-economic indicator is assigned a weight of 0.2. As a greater sustainability index indicates a less sustainable alternative, the calculations suggest that, overall, driven concrete piles are a more sustainable option than drilled shafts for the case study considered.

Table 7. Calculation of sustainability index from multicriteria analysis

Objectives	Weights	Score for the Alternative Pile Types	
		Drilled Shaft	Driven Pile
(1)	(2)	(3)	(4)
Resource Consumption	0.40	59.65	40.35
Environmental Impact	0.40	40.05	59.95
Socio-economic Impact	0.2	61.07	38.93
Total Score		52	48

CONCLUDING REMARKS

Sustainability is a multidimensional concept that requires a balance of economic, social and environmental equities (3E's) of development. For engineering processes, this balance can be achieved by ensuring efficiency in resource use and by reducing the environmental impact without ignoring the technical, technological and financial concerns related to the process. Such a holistic approach follows the systems view of sustainability as described by the concept of functional integrity.

Geotechnical engineering warrants a sustainability study as it uses vast amount of resources and releases pollutants to the environment. Recently, efforts are being made to make geotechnical engineering practice more sustainable. Research studies on sustainability-related issues in geotechnical engineering is ongoing in the areas of (i) application of alternative materials, (ii) material reuse and recycling, (iii) development of environmentally friendly ground improvement techniques, (iv) efficient use of underground space, (v) reuse of foundations and (vi) energy geotechnics. Some qualitative guidelines for assessing the sustainability of geotechnical construction sites exist, the most prominent among them being the indicator system GeoSPeAR. However, there is a lack of a clearly defined framework to evaluate and quantify the relative sustainability of alternative practices in geotechnical engineering.

Based on a literature review on available sustainability assessment tools, a multicriteria based sustainability assessment framework for geotechnical engineering is introduced with particular application in pile foundation. The framework essentially has three components: life cycle assessment, environmental impact assessment and cost benefit analysis based on which three indicators — the resource use, environmental impact and socio-economic indicators — are developed. These indicators are then combined using a multicriteria analysis to develop a sustainability index that can be used to assess the competing alternatives in geotechnical engineering practice. The framework is illustrated by applying it to a hypothetical case study involving pile foundation, and the suitability of drilled shaft and driven pile as design alternatives is assessed from the sustainability point of view. The framework can be applied to other geotechnical problems as well.

The developed framework supports the functional integrity approach of sustainability. It accounts for efficiency in resource use both from the environmental and economic points of view and aims to reduce the impact of emissions on the environment.

Thus, it provides a holistic approach to ensure that the three E's of sustainability are balanced in geotechnical projects.

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