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A Multicriteria Based Quantitative Framework for Assessing Sustainability of Pile Foundations

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A Multicriteria Based Quantitative Framework for Assessing Sustainability of Pile Foundations

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Like everybody, I lived with dreams and, like most of us, my dreams kept waiting for me to find a ‘tomorrow’ to answer their call until suddenly everything changed. On 29 September 2006, I was informed that I have only a very finite ‘tomorrow’ to fulfill my wishes, aspirations and dreams ─ a span of about fifteen years ─ a statistical post treatment survival time for any cancer patient and I had to decide whether to go for my dreams or to just let them go. I chose to fight.

I always wanted to be a researcher and a teacher and this is the first milestone towards achieving that dream. I take this opportunity to remember, acknowledge and thank Dr. Mammen Chandy and his team at the Haematology Department of Christian Medical College, Vellore, India, my parents, my sister and, most importantly, Jia and Jaydip, for their support, the never-say-die spirit they injected in me and for the wonderful gift they gave me ─ my second life. I am forever grateful to them.

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I hope that this thesis will make all my past teachers and the cancer survivors proud. I also hope that this thesis will motivate some more engineers to think about sustainability seriously.

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ABSTRACT

Civil Engineering is the major instrument of anthropocentric development over centuries through ever expanding infrastructure, cities and facilities. Civil engineering processes are both resource and fuel intensive. The building industry alone, during the construction stage, uses about 30-40% of the total resources used in the industrialized countries. 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 most resource intensive although this intensive consumption of energy goes unnoticed mainly because of the indirect nature of the energy used in the form of materials and natural resources (e.g., concrete, steel and land use). Hence, geotechnical engineering warrants a sustainability study to balance the environmental effectiveness, technological feasibility and economic profitability in any civil engineering project.

In this thesis, a quantitative, multi-criteria based sustainability indicator for pile foundations is developed that will aid the design and decision making processes of pile foundation projects. Specifically two types of pile foundations, namely, the driven concrete pile and the drilled shaft, are considered. The impacts these two types of piles create on the environment are investigated from the viewpoints of both resource

consumption and process emissions. A life cycle analysis (LCA), which incorporates environmental impact assessment (EIA), is performed to develop sustainability metrics for pile foundations considering resource use, process emissions and waste generation. Other environmental impacts like change in land use pattern, noise pollution, compaction and vibration have been qualitatively considered in the study. Resources utilized in the process are accounted for by the thermodynamics-based accounting methods of exergy, emergy, and embodied energy. An economic cost-benefit analysis is performed to ensure that the framework is not skewed towards environmental sustainability alone. The performance of the individual pile types in the categories of resource use, environmental impact and cost benefit analysis is quantified as scores in their respective categories, and these scores represent the impact indicators. The impact indicators are then incorporated into a multi-criteria analysis with chosen weights for each category and a sustainability index is obtained. Thus, a new holistic approach to incorporate sustainability in geotechnical design and planning is introduced in this thesis.

CHAPTER 1 SUSTAINABILITY AND GEOTECHNICAL ENGINEERING: OVERVIEW AND SCOPE

1.0 Introduction

This thesis develops a multi-criteria based quantitative framework to assess the sustainability of geotechnical projects at the planning and design stages. 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. As geotechnical engineering is resource intensive, substantial improvement in resource budgeting is possible if sustainability metrics balancing environmental effectiveness, technological feasibility and economic profitability are developed and incorporated at the planning and design stages. However, a quantitative framework for assessing the sustainability of geotechnical practices, particularly at the planning and design stages, does not exist (Jefferis 2008, Bentivegna 1996, Holt 2010, 2009, Kibert 2008, Abreu et al. 2008). The sustainability assessment frameworks available in civil and geotechnical engineering, e.g., SPeAR and GeoSPeAR (Holt 2010), are qualitative and generalist in nature, developed only for the construction stage and often fail to identify site specific risk elements. Thus, there is a distinct need to develop a rigorous and quantifiable sustainability framework for geotechnical design and planning.

Setting up a quantitative framework to help engineers choose a sustainable alternative requires the identification of the measurable aspects of sustainable practices. The discipline of industrial ecology can be showcased as a field that aims at defining the sustainability of industrial processes through quantitative metrics (Kibert 2008). A fundamental objective of industrial ecology is to minimize the environmental impacts of industrial processes through resource, energy and process optimization and through reduction of process emissions. Based on these considerations, parameters have been developed following the principles of thermodynamics to measure the efficiency of different industrial processes. Thus, industrial ecology provides a rigorous framework for sustainable engineering and brings a quantitative dimension to the otherwise philosophical connotation of sustainability.

In this thesis, a quantitative framework is developed for pile foundations that shares the thermodynamic rigor of the approaches used in industrial ecology. The framework provides a tool for the geotechnical engineer to decide which particular type of pile foundation is more sustainable when technological feasibility is not a limiting consideration. Life cycle analysis, a well developed analytical tool that considers the cumulative impact of any process throughout its useful life, is used to assess the environmental sustainability of pile foundations. Resources utilized in the process are accounted for by the thermodynamics based accounting methods of exergy, emergy, and embodied energy. Sustainability indicators are developed to assess the environmental efficiency of pile foundations from the perspectives of resource use for the upstream side of the process and of environmental impact for the downstream side. Subsequently, an economic cost benefit analysis is performed to develop a socio-economic indicator.

Finally, a multicriteria analysis is performed that combines the resource use and environmental impact indicators with the socio-economic indicator to obtain a sustainability index for pile foundations. Thus, a new holistic approach to incorporate sustainability in geotechnical design and planning is introduced.

1.1 Sustainability and Technology: Perspectives

The sustainability revolution has its roots in the environmentalist movements that can be traced back to the age of industrial revolution (Edwards 2005, Meadows et al. 2004). At the initial stages, these movements lacked a systematic and scientific approach, although the effect and importance of nature in nurturing human life did not go unnoticed. The transcendentalist movement of the 1800s looked up to nature as a spiritual teacher that inspired human intuition and imagination (Emerson 1836, Thoreau 1854). The movement was carried forward by Muir who founded the "Sierra Club" in 1892 to "do something for the wilderness and make the mountains glad" (Edwards 2005). Muir first noted the systematic behavior of the natural world and emphasized the need for preserving resources like forests and water bodies. Subsequently, Leopold (1949) and Carson (1962) made the issue of conservation and preservation a mass agenda. Leopold (1949) viewed the natural system to be intrinsically tied to human survival and advocated a preservation approach based on respect for the environment. The vivid narrative of Carson (1962) on the effects of toxins on plants and animals forced all concerned to re-evaluate the carrying capacity of the ecosystem.

The 1972 United Nations Conference on the Human Environment at Stockholm, Sweden was the first concerted effort towards making environmental problems a global concern. It culminated in the formation of the United Nations Environment Programme

(UNEP) whose mission was to "provide leadership and encourage partnerships in caring for the environment by inspiring, informing and enabling nations and people to improve their quality of life without compromising that of future generations". In 1983, the United Nations formed the World Commission on Environment and Development headed by Brundtland to propose long term environmental strategies for achieving sustainable development by the year 2000 and beyond. Immediately after that, in 1984, the Worldwatch Institute published its State of the World annual report which stated that "we are living beyond our means largely by borrowing against the future". In the United Nations Conference on Environment and Development (UNCED), better known as the Earth Summit, held in 1992 at Rio de Janeiro, Brazil, it was decided that environmental problems could no longer be treated in isolation to social or economic problems and adopted an agenda (Agenda 21) of an integrated social-economic-environmental approach for sustainable development. The World Summit on Sustainable Development (WSSD) was held in 2002 at Johannesburg, South Africa to review the outcome of the proposals made in the Earth Summit and to propose plans for their successful implementation.

The relationship of sustainability with technology became relevant after the industrial revolution. The industrial revolution was characterized by unprecedented advances in technology, which promoted economic growth. Technological processes were made efficient with the aim to satisfy a wider consumer base in lesser time and with lower cost. In pursuing this important but narrow view of efficiency, the promoters of the industrial revolution took nature to be an infinite supplier of resources, perpetually regenerative with an indefinite capacity to absorb all waste. Consequently, natural

resources started shrinking at a rapid rate and the effect of human development on nature became noticeable. In fact, Meadows et al. (2004) showed that the industrial development is an exponentially growing process that has a positive feedback for further technological development unless it is restrained by externalities. As shown in Figure 1.1, technological development is bolstered by both monetary capital flow and technological capital investment resulting in a positive feedback loop. For example, one machine manufactures nuts and bolts which are then used to build another machine and this process is backed by monetary capital investment. The negative feedback loop shows the restraints on the technological development that arises due to forces (or "externalities") out of control such as natural depreciation of the technological capital, lack of monetary investment, or unforeseen social or political instability. These restraints were, however, not applied deliberately as part of a policy. In fact, to ensure a sustainable world, environmental impact of such technological development should have been applied as a restraint; but the industrial growth in the twentieth century was perpetually fuelled by the desire to grow economically without any heed to the environmental issues. Technological innovation was promoted as a solution to social and economic problems without regards to the fact that improvement in technology is a necessary condition but not a sufficient condition to eradicate all problems. These technological advances often rely on overuse of resources that negatively impacts the environment and makes future improvements difficult and expensive. For example, technological breakthrough in the construction methodology has made construction speedy and mechanized, and has reduced the hazards at construction sites. Improved construction technologies have also resulted in extension of the infrastructure to remote

areas and in difficult terrains. However, because of the expansion of the infrastructure, the natural land cover has been sacrificed for built-up covers, which has permanently changed the land use pattern and has increased pollution from vehicular emissions. Thus, a significantly reduced natural resource is available to the future generation and, at the same time, the future generation inherits the burden of mitigating the environmental pollution caused by the present generation.

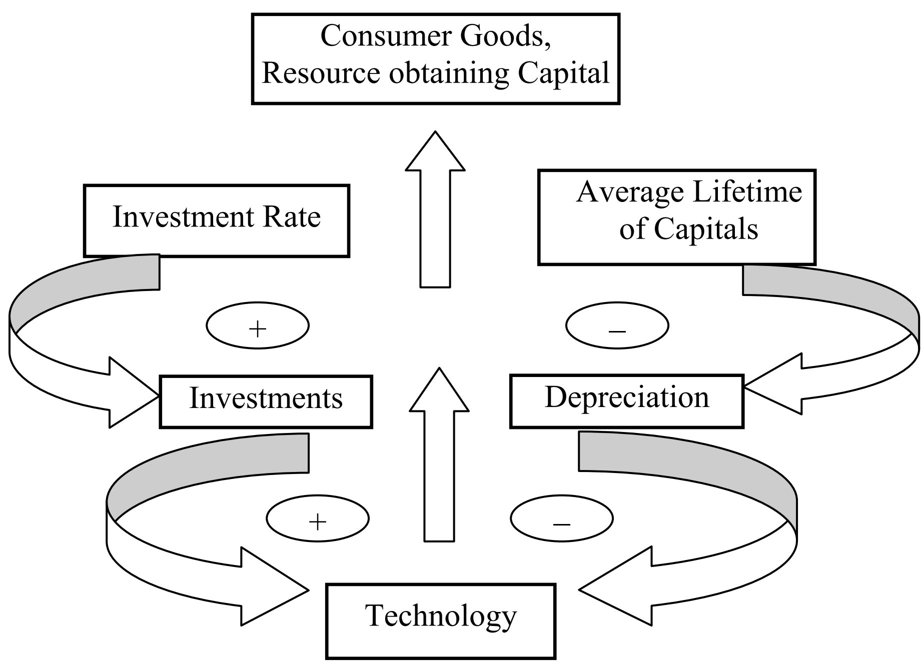

Figure 1.1 Industrial capital feedback loop structure (Meadows et al. 2004)

The technological advancement based on a "one-dimensional" philosophy of economic growth affected both social sustainability and environmental sustainability. Environmentally, it promoted extraction of resources from the planet at a rate greater than

the rate at which nature can replenish it. It favored the production of materials and promotion of species that had explicit economic values at the cost of extinction of other species that apparently had no economic purpose. This had a huge impact on the biodiversity of the planet, which eventually lost a large number of plant and animal species that actually had been balancing the ecosystem with less understood but essential services (Kibert 2008). Socially, the unscrupulous technological stride led to the accumulation of wealth to a privileged few who could afford the increasing cost of resource processing and created an unhealthy gap between the rich and the poor (Meadows et al. 2004). Thus, instead of providing a solution to problems, technology eventually became a promoter of exploitation and inequality (Meadows et al. 2004). It was only in the later half of the twentieth century 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. In fact, the caveats and views opposing the one-dimensional view of technological efficiency were ignored until the first energy crisis of the 1970s. The World Commission on Environment and Development (1987) acknowledged the danger when it stated that the modern technology relies on fuel too much to maintain the cost of resources for industries.

Today, the complex and dynamic relationship between technology and sustainability acts as a constraint, and any innovation is accepted only after studying its short and long term effects on society and environment (Herman 1996). Traditionally, engineering and ecology have been two widely differing disciplines — the professionals of each discipline had very little knowledge of the other. Now, when viewed from a

systems approach, it is apparent that engineering and ecology must work in harmony to initiate a holistic approach toward sustainability. It is important for the engineer to be aware of the ecological tradeoffs that his/ her decision can produce. At the same time, the ecologist should be able to estimate the possible loss of balance in the ecosystem that an engineered solution may cause. This paradigm of green technology or green engineering is rather recent, but interest in this area is growing fast (Kibert 2008).

1.2 Sustainability: Concepts and Definitions

Sustainability, like democracy or faith, cannot be defined precisely. Conceptually, sustainability is a principle that balances the three E's — economy, environment and equity — for a harmonized development (Hempel 2009). However, in a modern society achieving a balance of the three E's can be a difficult task involving tradeoffs and optimization. As shown in Figure 1.2, the three E's are often at conflict between themselves. The most common conflict is between the economic growth and the environmental protection, as described in the previous section, but there is also a conflict between economy and equity, which manifests itself in an unequal distribution of wealth. Conflicts between environment and equity principles occur where, for example, proponents of equity demand affordable housing for everyone which increases built environment and leads to a loss of bio diversity and open space. Sustainability, therefore, presents a compromised solution to any given problem that is acceptable but not the best for all the three E's individually.

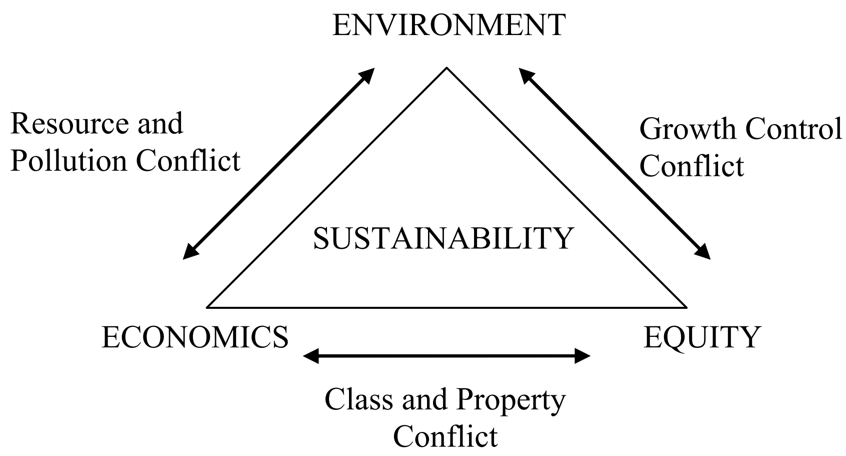

Figure 1.2 Three aspects and conflicts of sustainable development (Hempel 2009)

The balance of the three E's is, in essence, a modern and contextual expression of more general concepts of ethics developed and debated over in the disciplines of philosophy and sociology from the times of Pluto. Concepts and principles of ethics promote a respect for all species and an acceptance of equal right of all life forms on the shared resource of the planet. Common examples of ethical principles are intergenerational and distributional justices (Kibert 2008) which are relevant to any perspective of sustainability, technological or philosophical. In addition to the intergenerational and distributional justices, there are other ethical principles of sustainability that are related to the objective of this research. These are discussed below to form the groundwork before the definitions of sustainability are outlined.

1.2.1 Ethical Concepts underlying Sustainability

Intergenerational Justice

The use of resources by the present generation affects the choices and living standards of the future generation and also the quality of the environment the future generation inherits. The obligation of a generation to its succeeding generation follows a chain rule — the conditions handed down by one generation to the next automatically limits the capacity of the new generation to fulfill their obligations towards their offspring. Intergenerational justice (Kibert 2008) provides the future generation with a resource base that will enable them to fulfill their own needs.

Distributional Equity

Distributional equity (Kibert 2008) addresses the right of everyone to an equal distribution of all available resources (e.g., land, water and fuel) including products and services.

The Precautionary Principle

The Center for Community Action and Environmental Justice (CCAEJ) states the precautionary principle as "when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically." For example, there is a debate over the effect of human generated carbon emissions on the temperature of the planet. However, irrespective of whether human activities actually cause a temperature rise or not, the devastating consequences should be sufficient to deter people from emitting carbon dioxide or methane into the atmosphere (Kibert 2008). This concept has received

negative criticism from different forums as a hindrance to progress — for example, applying precautionary principle forecloses the use of any new drug until all exhaustive experimentation proves that it is beneficial for human and nature.

The Reversibility Principle

The reversibility principle (Kibert 2008) states that decisions taken by the present generation should be such that the effects of the decisions can be undone by the future generation. This principle is related to the precautionary principle in that caution should be employed before taking any decision. However, the reversibility principle is less stringent than the precautionary principle in that it focuses on the reversibility of the action than forgoing any action whose effects are not known or unacceptable.

1.2.2 Definitions of Sustainability

Brown (1981) described a sustainable society as "… one that is able to satisfy its needs without diminishing the chance of future generations." The Brundtland Commission (1987) adapted this ideal 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." However, as noted by Wood (2005), such a definition has a negative connotation and restricts our focus to a limited resource use. He defined sustainability as "improving quality of life consistent with the carrying capacity of the infrastructure."

In order to provide an economic definition of sustainability, Arrow (2003) and other economists of the same school of thoughts interpreted the Brundtland Commission (1987) report within an economic framework and came up with the idea of "genuine

investment". They defined genuine investment as composed of manufactured capital, human capital and natural capital, and contended that the sum totals of these three capitals should remain constant or increase over time for a system to be sustainable. This theory led to the development of two schools of thought — weak sustainability 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, while strong sustainability advocates against the decline of natural resources exclusively. Proponents of strong sustainability like Daly (2005) have criticized the proponents of weak sustainability as trying to replace fish with fishing boats. They assert that providing a fishing boat to every fisherman or improving the fishing technique cannot ensure sustainability as long as there is no measure to ensure quality and quantity of the fish stock.

Thompson (2010) observed that sustainability is always defined in the context of a system boundary. For example, when a soil agronomist considers the sustainability of a farm practice, (s)he usually restricts his/her view to soil chemistry and soil biota, and considers the sustainability of the farmer to be outside the scope of his/her purview. An economist will view the system from a monetary angle and decide on the sustainability of the practice depending on the yield it produces. A sociologist, on the other hand, will be more interested in the sustainability of the entire farmer community in the locality. Thus, defining a system border impacts the decision whether a practice is sustainable or not. Thompson (2010) found that there are two basic approaches in defining and understanding sustainability — the resource sufficiency approach and the functional integrity approach. The resource sufficiency approach is more popular in the

technological field where the rate of consumption of a resource is measured against the available stock of that resource. The sustainability is determined based on how long the practice could be carried on at the present rate of consumption. For example, the rate of extraction of most of the metals is greater than the rate at which nature can regenerate it. Hence, this practice is unsustainable for the society. The functional integrity approach, on the other hand, measures the sustainability of a practice based on the threat it creates to the reproducing capacity of a self-regenerating system. For example, a high murder rate may be sustainable from a resource sufficiency approach as long as the number of people killed is less than the number of lives born. But according to the functional integrity approach, if the threat of murder is sufficient to stagger the birth rate, then it is not sustainable for the society. According to Thompson (2010), the resource sufficiency approach is an extension of the general utilitarian maxim developed 200 years ago by Bentham (1789), which states that practices that maximize the total well being should be chosen. However, the utilitarian school of thought does not recognize the moral values of non-animal entities and does not accept the intrinsic value of biodiversity. The resource sufficiency approach, as a dimension of the utilitarian maxim, has an anthropocentric view, and hence, leaves open debates about whose well-being is being considered and about the definition of well-being. It is in direct contrast to the "deep ecology" school of thoughts propagated by philosopher 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". Land ethic accepts any practice as right only when it tends to preserve the integrity, stability and beauty of the biotic system. This view forms the foundation of the functional

integrity approach which forbids any risk that directly interferes with the integrity of a system. The functional integrity approach considers the scope of regeneration of the entire system and hence is a measure of the sustainability at the systems level.

For technological purposes, the definition of sustainability put forward by Brundtland Commission seems rather vague. It does not specify the need of the future in quantifiable terms, which can be set as a goal or a limiting condition for any anthropogenic process. Hence, for any engineering process, sustainability generally means prudent use of resources and control of harmful emissions (Gradel 1997, Kibert 2008). This two-dimensional view of sustainability is similar to the functional integrity approach described above because it opposes efficiency in resource use that is achieved at the cost of environmental pollution. This 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 benefit. Thus, sustainability from an engineering perspective means efficient use of resources that balances both economy and ecology.

1.3 Sustainability Quantification

As mentioned in the previous section, efficiency of resource use is an important criterion used in judging the sustainability of any engineering process. There are quite a few resource accounting methods ranging from simple mass balance to more rigorous exergy, emergy and embodied energy accounting that give a quantification of the resource efficiency of any engineering process (Hau and Bakshi 2004, Hau 2005, Brown and Herendeen 1996, Gutwoski et al. 2004). Exergy of a resource is its available energy

to do useful work (Dincer and Rosen 2007, Sciubba and Wall 2010, Tsatsaronis 2007). Thus, for any engineering process to be sustainable, exergy loss should be minimized. Emergy is the sum total of the ecosystem services that have been used up to develop a product. Therefore, a sustainable engineering process should target to minimize the emergy of its finished products. Embodied energy of a body is its heat energy. A sustainable process must use materials that are low in embodied energy. Exergy accounting methods are mostly used in industrial manufacturing processes that involve chemical reactions. Emergy is used as an accounting tool in ecological engineering. Embodied energy is mostly used in civil engineering in which physical mass transfer of resources are involved.

Another indicator of sustainability for any technological process is its environmental impact. Technology is related to environmental impact through a conceptual relationship (Erlich and Holdren 1971)

$$I = PAT \tag{1.1}$$

where I is the environmental impact of technology T used by a population P at an affluence level of A. The basic assumption of this relationship is the independence of P, A and T although, in reality, population, affluence and technology are interrelated. The equation can be used not for any specific calculation but for the conceptual understanding of the interrelations of the three E's with technology. Allen et al. (2010) showed that, by keeping the affluence level constant, if the environmental impact of a population is to be offset by technological improvement, that improvement should occur at a rate ten times that of the present rate. At present, technological improvement is assumed to be achievable by increasing resource and energy use efficiency, but Allen et al. (2010)

suggests that, to attain sustainability at a broader scale, changes at the process design level are necessary. Ecology based product design is a step towards that. Ecology based design aims to replicate the synergistic nature of the ecosystem to design processes that generate minimum waste and are harmonious with the natural systems.

It is evident from the above discussion that sustainability quantification of engineering processes should involve both the quantifications of the resources used and of the wastes generated in a process. Thus, an integrated approach involving both the management of the input and output sides of an engineering process is required to ensure a sustainable future.

1.4 Sustainability and Built Environment

The built environment has a complex and direct influence on the biosphere. Constructional activities add to the problems of climate change, ozone depletion, desertification, deforestation, soil erosion, and land, water and air pollution (Kibert 2008). The construction industry uses a large amount of natural resources (e.g., soil, rock, water and mineral ores) as raw material to manufacture components of the built environment (e.g., buildings, bridges and roads) and consumes fuel for operating machineries both at the construction and operation stages of the built environment thus emitting greenhouse gases. In industrialized countries, the building industry alone uses about 30-40% of the total resource usage and the housing sector consumes about 30% of total energy use in the form of utilities and facilities (Pulselli et al. 2007). The construction industry also generates huge amount of wastes because the components of the built environment (e.g., structural and foundation elements) are not designed for reuse or recycling — the facilities built at the expense of so much energy and raw materials are

eventually dumped into landfill sites at the end of their useful life. The construction industry contributes 8% to the GDP of the U.S. and consumes 40% of extracted materials in the U.S. (Kibert 2008). Also, construction and demolition related wastes generated in the U.S. are about 145 million tons with 92% being demolition wastes without any reusable or recyclable value. Hence, resource based energy efficiency is critical in making services delivered by the civil engineering discipline sustainable. With many disciplines like manufacturing and agriculture adopting sustainable practices to ensure a society founded on the principles of justice and equity, the onus is on the creators of the built environment to incorporate sustainable practices in their activities. Green building, sustainable urban planning and sustainable transportation systems are examples of sustainable practices in civil engineering.

Sustainable urban planning and sustainable transportation infrastructure are interlinked in that only a sustainable city planning can ensure sustainability in transportation related issues. Sustainable city planning includes compact and pedestrian friendly infrastructure, a diverse housing facility for diverse population built as a series of related neighborhood and endowed with public amenities. An example of the principles that may guide a sustainable urban development can be found in the Ten Principles of Smart Growth (Farr 2008). Sustainable transportation, in turn, focuses on reducing and replacing fossil fuel consumption through better mass transit systems and on experimenting with alternative pavement designs like porous pavements to prevent the draining of rainwater. Recent sustainable transportation initiatives in the United States include Green Leadership in Transportation Environment Sustainability (GreenLITES) developed by New York State Department of Transportation

<https://www.nysdot.gov/programs/greenlites>, Illinois-Livable and Sustainable Transportation (I-LAST) Version 1.01 developed by the Joint Sustainability Group of the Department of Transportation, the American Council of Engineering Companies - Illinois and the Illinois Road and Transportation Builders Association <https://www.dot.il.gov/green/documents/I-LASTGuidebook.pdf>, and the GreenRoads developed by the University of Washington and CH2M HILL <www.greenroads.us>. The considerations for achieving urban and transportation sustainability are, however, distinctly different from those for geotechnical engineering. Geotechnical engineering, being resource intensive, needs special consideration in terms of resource efficiency and energy consumption. The concepts related to resource use efficiency, a major consideration in sustainable geotechnical design and planning, are somewhat related to green building design and sustainable construction which are briefly discussed below.

1.4.1 Sustainable Construction and Green Building

The aim of sustainable construction has been defined by the Conceil International du Batiment (CIB), an international construction research networking organization as to “create and operate a healthy built environment based on resource efficiency and ecological design” (Kibert 2008). The seven principles of ensuring sustainability in a built environment from its planning to deconstruction stages as per CIB are (1) reduction of resource consumption, (2) reuse of resources, (3) using recyclable resources, (4) protecting nature, (5) eliminating toxins, (6) applying life-cycle costing and (7) focusing on quality. These principles are to be applied for all materials and services both directly and indirectly related to the construction of a facility. Also, it is important to oversee that

the same principles are used over the natural resources — land, water, energy and ecosystems — exploited during construction.

A green building is one that has been created using the principles and methods of sustainable construction. Green building is also called high-performance building. The U.S Office of Energy Efficiency and Renewable Energy (EERE) defines a high-performance building as a building that "uses whole building design to achieve energy, economic, and environmental performance that is substantially better than standard practice." A whole system design connects the different components of a system and tries to solve multiple problems with a single solution (Kibert 2008). For built environment, a whole system design implies a holistic approach by considering the interrelations between site, energy, building materials, natural resource and indoor environment. It links these components to work together thus ensuring resource efficiency and lower environmental impact.

1.4.2 Green Building Movement and LEED Rating System

The Green Building Movement evolved as a response to the effect of built environment on the natural resources and climate changes. The key American organization promoting the movement is the U.S Green Building Council (USGBC) which came up with the building assessment tool called LEED (Kibert 2008, Farr 2008). LEED or Leadership in Energy and Environment is a point based rating system that has helped remove some ambiguity associated with the understanding of sustainability for built environment. LEED was first launched in 1998 as LEED 1.0 and the modified version, LEED 2.0 was published in 2000. LEED 2.1 (2003) was modified to include "New Construction"(NC) to distinguish new construction from other types of

construction like existing building (EB), commercial interior (CI) and homes (H). These systems consider the performance of a building with respect to sustainability on the basis of a few categories and assign points (or weights) to them so that the building sustainability can be quantified based on the total accumulated points. For example, currently LEED-NC provides four categories of certification — (i) platinum, (ii) gold, (iii) silver and (iv) bronze or "certified"— based on a total of 69 points. LEED-NC awards points based on six categories: (1) sustainable sites (14 points), (2) water efficiency (5 points), (3) energy and atmosphere (17 points), (4) materials and resources (13 points), (5) indoor environment quality (15 points) and (6) innovation and design process (5 points). The allocated points represent the weight of the category as conceived by the developers of LEED. These weights are, however, arbitrary — it is arguable whether indoor environment quality is more important than materials and resource or water efficiency. Another drawback of LEED is that, since a building is rated on an overall basis, failure to meet the standards in some categories may be masked by better performances in some other categories. As the built environment is a multi-component system, sustainability concepts and measures should be applied to each component separately. Clearly, LEED is not the most scientific method for sustainability quantification in building construction and design — it lacks the rigor present in the quantitative resource accounting frameworks developed based on thermodynamics (Malin 2003, Zimmerman and Kibert 2007). However, LEED has been somewhat successful in bringing sustainable practices to the building industry.

1.5 Sustainability in Geotechnical Engineering

Geotechnical work involves large amount of natural resources, consumes vast amount of energy and fuel, and involves changes in the landform 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. The most relevant contribution of a geotechnical engineer in making a project sustainable lies in his/her effort to do more with less resource and to experiment with the possible ways of removing (and not just reducing) the adverse effects of geotechnical construction (Jefferis 2008).

According to Abreu et al. (2008), some of the potential areas of research for implementing sustainability in geotechnical engineering are energy efficiency of the materials and methods, reuse, recycle and reengineering of materials and wastes, and control of pollution. In fact, research in several areas of geotechnical engineering is underway that contributes to sustainable development. These areas include the use of recycled and alternative materials, ground improvement, foundation reuse and rehabilitation, efficient use of underground space and energy geotechnics. Some of the recent studies focusing on the sustainability aspects of geotechnical engineering are discussed below.

Vinod et al. (2010) used lignosulfonate instead of traditional admixtures for stabilization of dispersive clay — lignosulfonate is non-toxic, non-corrosive and

environmentally friendly compared with other traditional stabilizers as it promotes surface vegetation and natural subsurface fauna, and helps retain the soil carbon sequestration potential. Jegandan et al. (2010) observed in their research on soil stabilization that by using Portland cement blended binders instead of Portland cement alone reduces the environmental impact. The use of coal and fly ash in geotechnical projects may provide a sustainable reuse of an otherwise environmentally hazardous industrial waste (Sridharan and Prakash 2010) although there is controversy about the impacts of the leachates from coal and fly ash, and further study is needed in the area. Saride et al. (2010) studied the option of using recycled or secondary materials like reclaimed asphalt pavement and cement-stabilized quarry fines as pavement bases in their attempt to ensure sustainable material use in pavement bases. Voottipruex et al. (2010) considered recycling shredded scrap tires as a light-weight fill material for geotechnical projects.

Sustainability in soft ground improvement can be ensured by using prefabricated vertical drains in conjunction with vacuum preloading and by using solar powered prefabricated vertical drains as the use of drains do not introduce chemicals to the ground and is cost effective and energy efficient than several other ground improvement techniques (Indraratna et al. 2010, Pothiraksanon et al. 2010). The use of in situ soil bacteria for ground improvement is another green option — bio-mineralization and bio-polymerization by in situ bacteria can be potentially used for modifying the mechanical and hydraulic properties of soil (Yang et al. 1992, 1994, DeJong et al. 2006, Whiffin et al. 2007).

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. The environmental impact was measured in terms of carbon footprint of the project from both direct and indirect emissions. 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 alternatives of ground improvement provided better economy and reduced carbon footprint mostly due to use of low energy materials like fly ash.

Egan et al. (2010) also studied the use of ground improvement techniques as an alternative to traditional deep foundations. For most of the cases considered in their study, continuous flight auger and driven cast-in-situ piles were replaced by vibro-replacement stone columns, and in one case the piling scheme was replaced by a combination of deep dynamic compaction, vibro-replacement stone columns and driven cast-in-situ piles. Embodied carbon dioxide was used as an environmental metric to judge the sustainability of the options and it was found that using the ground improvement techniques instead of the piles significantly reduced the embodied carbon dioxide of the projects — reductions were typically of the order of 90%. The embodied carbon dioxide approach considers the sum total of carbon dioxide emissions that occur over the entire life cycle of a material from the extraction of raw materials required for the manufacture of the material to the end of its useful life. As pointed out by Egan et al. (2010), the reduction in the embodied carbon dioxide was mainly due to avoiding the use

of concrete and steel, and further reduction is possible if recycled material and aggregates are used for vibro stone columns.

Jefferson et al. (2010), on the other hand, considered the sustainability of the use of primary, secondary and recycled aggregates for vibro stone columns using carbon dioxide emission as the environmental impact parameter. Thomas et al. (2009) had earlier argued that whether the use of recycled aggregate is environmentally more sustainable or not depends on whether the project site is closer to the landfill and demolition sites or to the quarrying and processing units of the primary aggregates. Jefferson et al. (2010) supported the argument of Thomas et al. (2009) and called for a more detailed analysis for a holistic approach towards sustainability by considering all the relevant temporal and spatial aspects like haulage, location and future site restoration. Jefferson et al. (2010), thus, refutes the idea that the use of recycled materials is always, by default, environmentally more sustainable.

Chau et al. (2006) used embodied energy as an environmental impact indicator in their study of four different retaining wall design — (i) a cantilever pressed in steel tubular pile, (ii) a cantilever secant pile wall, (iii) a tied back sheet pile wall with a row of tension piles, and (iv) a tied back sheet pile wall with reinforced concrete mini-pile wall. The design alternatives were studied for a 7 m high railway embankment of granular fill founded on London Clay. For calculating the material energy of the associated materials, Chau et al. (2006) used the embodied energy intensity (EEI) or embodied energy per unit mass values available in public documents published by the University of Sydney, University of Tokyo and National Institute of Environmental Studies, Environmental Protection Agency, Japan. The results showed that, across the designs, propped systems

used less embodied energy than the cantilever systems and that, within the design, the material energy occupies the largest share of energy consumption. Although the quantity of steel used was much less than that of concrete, steel was the dominating contributor for material energy. Chau et al. (2006) attributed this phenomenon to the greater material density and embodied energy values of steel compared with those of concrete. They suggested that the use of recycled steel would decrease the material energy consumption. Chau et al. (2006) concluded from the above study that embodied energy consumption can be used as an environmental impact indicator although other parameters like carbon dioxide emissions also should be studied for a comprehensive analysis.

Chau et al. (2008) extended the earlier study of Chau et al. (2006) by using embodied carbon dioxide as a proxy for assessment of sustainability of geotechnical projects. They compared the environmental impact and energy efficiency of basement wall construction for two commercial buildings in London based on two different site considerations. They found that the difference in energy consumption between the basement wall designed without any consideration to sustainability and the wall designed for sustainability is 250 GJ per meter length of the wall. For a standard perimeter of 200 m, this translates to 50 TJ or 785 annual household equivalents. In the analysis, material energy was found to be the greatest contributor to the overall embodied energy value — the recycled steel walls were more energy efficient than the concrete walls. The environmental impact was translated as units of carbon dioxide emitted and it was shown that emissions due to the construction of the basement wall were equivalent to running a family car for 50,000-75,000 Km. Holt et al. (2010), however, pointed out that expressing the environmental impact in terms of carbon dioxide emissions involves a

number of ad hoc assumptions and generalizations. Moreover, assessing the sustainability of a project based solely on embodied carbon dioxide puts excess emphasis on the environmental aspects and may fail to consider the technical and economic points of view.

A case study assessing the relative impacts of concrete retaining walls and bioengineered slopes through life cycle impact assessment was done by Storesund et al. (2008). Economic Input-Output based Life Cycle analysis (EIO-LCA) was used for life cycle costing while global warming potential (GWP) was used as an indicator for the environmental impact. The study showed a huge reduction of economic expenditure, energy consumption and global warming potential if bioengineered slopes replace concrete retaining walls. Another similar study on bioengineered slope by Wu et al. (2008) showed a reduction in the cost of initial construction of the slope. Both the studies showed the improved performance of soil bioengineering from the environmental sustainability point of view. However, a drawback of bioengineered slopes is its high maintenance cost.

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 the 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 causes voids that need to be backfilled. Several case studies on the reuse of foundations have been documented by Anderson et al. (2006), Butcher et al. (2006b), Clarke et al. (2006), Lennon et al.(2006), John and Chow (2006), Tester and

Fernie (2006) and 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 — (i) design for partial reuse, (ii) design for no reuse and (iii) design for full reuse. The results show that the foundations designed for reuse has a much lesser WLC than foundations designed without reuse option although the initial premium is slightly greater for foundations designed for reuse. From the point of view of environmental impact, Butcher et al. (2006a) found that the embodied energy consumed in reusing foundations is nearly half of that consumed in installing new foundations. However, for reuse, the geometrical compatibility needs to be checked between the load points and the existing structures, and the strength and settlement of the piles with respect to the new structures should be monitored.

Another contribution of geotechnical engineering in sustainable development is in the area of 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). The reasons for choosing underground structures include

security, lessened environmental burden, ease of maintenance due to less atmospheric exposure, less interruption to traffic and city life, and economy. Reasons for constructing underground wastewater treatment plant include reduced infrastructure requirement if the plant is located close to the city center, control of spills and odors, and no visual disturbances. Jefferson et al. (2009) reported on the redevelopment project of Birmingham Eastside with suggestions for locating the transportation infrastructure and utility infrastructure underground in order to reduce the load on land use and to reduce the environmental effects of emissions. Jefferson et al. (2009) concluded that, since sustainability is a developing and complex concept, it is unlikely that all its facets can be incorporated into a decision process at present but, nonetheless, efforts need to be made to make all concerned aware of the available options for improvements in the future.

Geotechnical engineering has a prominent role to play in the alternative energy sectors, e.g., geothermal energy and wind energy. Case studies show that deep foundations can be used as energy storage 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). Use of foundations for harvesting ground energy reduce our dependence on fossil fuel and natural gas for heating and cooling of facilities and do not cause any additional environmental impact. In the case of wind energy, off shore wind turbines provide an answer to the objections raised on onshore wind turbines on account of aesthetic damage (Bryne and Houlsby 2003). Recent research studies have focused on different designs of foundations that can make wind energy projects economic and commercially attractive (Musial et al. 2004).

The above discussion clearly indicates that the importance of incorporating sustainability concepts in geotechnical engineering is being increasingly recognized over the last few years. However, there is a lack of a clearly defined framework to evaluate and quantify the relative sustainability of alternate practices. Indicators and documented strategies like Building Research Establishment Environmental Assessment Method (BREEAM) in United Kingdom <www.breeam.org> or LEED, used in the construction industry, are missing in geotechnical engineering (Lee and Burnett 2008, Abreu et al. 2008). The research studies on developing sustainability indicators for geotechnical engineering are rather limited and are discussed below.

Jimenez (2004) developed a qualitative indicator system based on color code for the purpose of comparison of different alternative materials used for slope stabilization ─ recycled plastic pins, regular soil nails, lime piles, vegetation, and cut and fill ─ and named the indicator system Sustainable Geotechnical Evaluation Model (S.G.E.M.).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. Using this indicator system, Jimenez (2004) showed that, for the particular case study, the use of recycled plastic pins was the most sustainable option.

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, Environmental Geotechnics Indicators (EGIs), was to be used at construction sites for ground improvement projects and was 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 mainly to prevent an early bias on economy in the project.

Holt et al. (2009) developed GeoSPeAR, an indicator system for geotechnical construction, by modifying a sustainability indicator model SpeAR used in building design. SPeAR, acronym for Sustainable Project Appraisal Routine, was developed by Arup and was founded on indicators used in the UN Environmental Programmes and by the U.K. government. SPeAR (Figure 1.3) 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. The major changes made in GeoSPeAR were the modification of the indicator categories and the inclusion of the scope for quantitative assessment like life cycle analysis. 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 analysis 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) have provided a step by step framework (Table 1.1) 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. They further commented that the results of an LCA can prove to be conclusive and decisive when two very similar design options are compared.

At their present forms, S.G.E.M., EGIs and GeoSPeAR are qualitative and fail to provide a rigorous quantitative framework for defining sustainability in geotechnical engineering. Although it is important to have a reference framework like GeoSPeAR to compare the sustainability of a project based on physical parameters, it is more important to have numerical accountability to support the decision process in geotechnical engineering. Indicators for sustainable geotechnical practices should at least include considerations for inputs and outputs to the site (e.g., material and energy for the input side, and material waste, waste water and pollution for the output side), respect for neighbors and local neighborhood, and respect for natural resources on the site and in the environment (Jefferis 2008). Along with the establishment of the indicators, it is important to fix a reference system against which alternatives can be evaluated (Abreu et al. 2008).

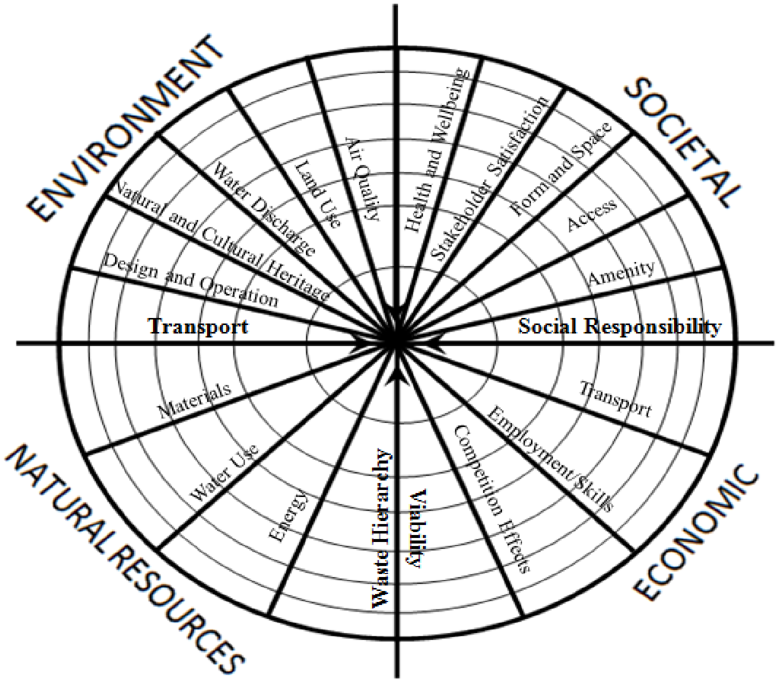

Figure 1.3 SPeAR template (Holt et al. 2009)

Table 1.1 Steps to be followed in assessing sustainability in geotechnical projects (Holt et al. 2009)

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

1.6 Scope and Organization of Thesis

In this thesis, a quantitative framework for assessing sustainability of pile foundations is developed that will aid the design and decision making processes of pile foundation projects. There are different options like drilled shaft, drilled displacement piles, precast concrete piles and steel piles that are available for a pile foundation project. The choice of a particular pile type should not only depend on the technical, technological and economic feasibilities like soil type, loading condition, local economy, availability of pile construction equipment and tradition but also on the environmental impacts of the pile. The decision making tool developed in the thesis is based on the metrics of energy consumption, environmental impact and socio-economic benefits.

The different functional requirements of a sustainable pile foundation design are its (1) technical requirement, (2) economic feasibility, (3) energy or resource efficiency and (4) environmental impact. These functional requirements are dependent on each other. Consequently, the design parameters corresponding to each of the functional requirements need to be optimized so that a sustainable and efficient design ensues. For that purpose, life cycle analysis (LCA), which includes inventory analysis and environmental impact assessment (EIA), is performed along with a cost benefit analysis (CBA). The results are then combined in a multicriteria analysis (MCA) to develop a sustainability index, which can be used as a decision-making tool at the planning and design stages of a pile foundation project.

Two different types of pile, namely, drilled shaft and precast concrete driven pile, installed in homogeneous sand and clay profiles are considered in the thesis. The inventory of resources on the input side of the process is done by the methods of exergy,

emergy and embodied energy, and the environmental impact assessment is done on the output side based on the categories of global warming, human toxicity, ecosystem toxicity and acidification.

The present study assumes a functional integrity approach towards ensuring sustainability in geotechnical projects. It accounts for efficiency in resource use both from the environmental and economic points of view and also considers the impact of emissions on the environment. The study rejects the design approaches that aim to achieve resource efficiency from the economic point of view only and, at the same time, avoids the skew towards achieving lower environmental impact at an impossibly higher premium by including the cost benefit analysis. Efficiency in resource utilization ensures sustainability in inter and intra generational distribution of resources, and lower environmental impact implies a more sustainable environment. Thus, this research provides a holistic approach to ensure that the three E's of sustainability are maintained in geotechnical projects. The developed framework is applicable not only to pile foundations but also to other geotechnical problems in which multiple possible solutions exist. In fact, the sustainability framework can be applied to a variety of infrastructure problems as well.

The thesis is presented in four chapters. In chapter 2, the fundamentals of all the concepts and methods used in the research are described. In Chapter 3, the LCA and CBA of drilled shaft and driven precast concrete pile are done for sand and clay profiles and for different applied loads. Following the LCA and CBA, the MCA for sustainability quantification for pile foundations is done. Finally, in chapter 4, a summary of the research is provided and some future research directions are identified.

CHAPTER 2 FUNDAMENTALS

2.0 Sustainability Assessment Framework in Engineering

Debates on sustainable development or sustainability revolve around the concept of energy 'consumption' (Hau 2005). For example, a statement like 'process A consumes more energy than process B, and hence, process A is not sustainable' is quite frequently found in the literature. The idea that energy can be "consumed" in a process means that energy is irrecoverably used up in the process. There is a connotation of "loss of energy" in the realm of sustainable practices, particularly when people talk of nonrenewable energy (e.g., fossil fuel). However, as we know from the laws of thermodynamics, energy is conserved in a closed system. Energy cannot be created and, more importantly, cannot be destroyed. So, what exactly is the debate on sustainability all about?

The answer to the above question lies in the second law of thermodynamics which states that the natural tendency of any system is to increase its entropy. More practically put, it implies that every energy transformation is inevitably associated with a loss of energy to the surrounding atmosphere where it becomes unavailable to do useful work. So, to measure sustainability of a process, it is important to minimize this loss of available or useful energy, which is alternatively known as exergy. Exergy based framework for quantifying sustainability of industrial processes are well developed based

on the fundamental principles of thermodynamics (Yi et al. 2004, Gutwoski et al. 2003). Another related sustainability quantification framework is emergy algebra (Odum 1986), which is acclaimed for its eco-centric view of process inputs and outputs. Emergy of a resource, expressed in terms of solar energy, is the sum total of all the ecosystem services that went into making the resource. The concept of emergy is also based on rigorous principles of thermodynamics and is closely related to exergy. A widely used sustainability quantification method is the embodied energy analysis which is based on the principle of energy balance. Embodied energy of a material is the sum total of all the energy required to produce that material (Constanza 1980, Brown and Herendeen 1996). Embodied energy calculations accounts for the total energy, both direct (for example, fuel and material) and indirect (for example, transportation and labor), used in making a product.

Exergy, emergy and embodied energy accounting methods are used for modeling the energy flow of a system or a process. They measure the environmental impact of a process based solely on its energy consumption and do not directly relate the emissions from a process to the impact such emissions have on the local or the global environment. Thus, energy analysis can at most be used as an indirect measure of the process emissions because materials with high exergy, emergy or embodied energy content are generally associated with greater process emissions. Hence, energy analysis should be complemented by other studies like environmental impact assessment (EIA) or environmental risk assessment (ERA) that can directly assess the environmental effects of a process.

Beside energy efficiency and environmental impact assessment, any engineering project needs to satisfy the basic criteria of technological and economic feasibilities. In recent times, economic feasibility studies also consider the social benefits of a project by converting such social benefits into monetary values. Such integrated approaches, like cost benefit analysis (CBA), are inherently more sustainable because of the balance they strike between social and economic aspects of a project. Thus, a multi-criteria analysis based on the energy consumption, environmental impact assessment and cost benefit analysis optimizes all the three E's of sustainable development and provides holistic approach to sustainability of engineering processes.

In this chapter, the concepts related to sustainability of engineering processes are outlined and the different analytical tools available for implementing these concepts are discussed. Further, the fundamentals of the different technical elements used in this research are described.

2.1 Concepts, Tools and Elements for Sustainable Engineering Processes

A "concept" in sustainability is an idea about how to achieve sustainability (Wrisberg et al. 2002). Examples of such concepts used in engineering processes are Life Cycle Thinking, Design for the Environment and Eco-efficiency (Kibert 2008) that aim to make a process sustainable. There are standard methods that have been developed to realize such concepts into practice and these methods are actually tools used to ensure or check the application of sustainability concepts in a process. In assessing a process, these tools act as means of reasoning, analysis and communication of the consequences of a choice. Examples of such tools are Life Cycle Analysis (LCA), Life Cycle Management (LCM), Environmental Impact Assessment (EIA), Environmental Risk Assessment

(ERA) and Cumulative Energy Requirement Analysis (CERA) (Wrisberg et al. 2002, Finnveden and Moberg 2004). All such tools are generally supported by elements like energy analysis and mass flow analysis. These elements are, in turn, supported by data (Figure 2.1).

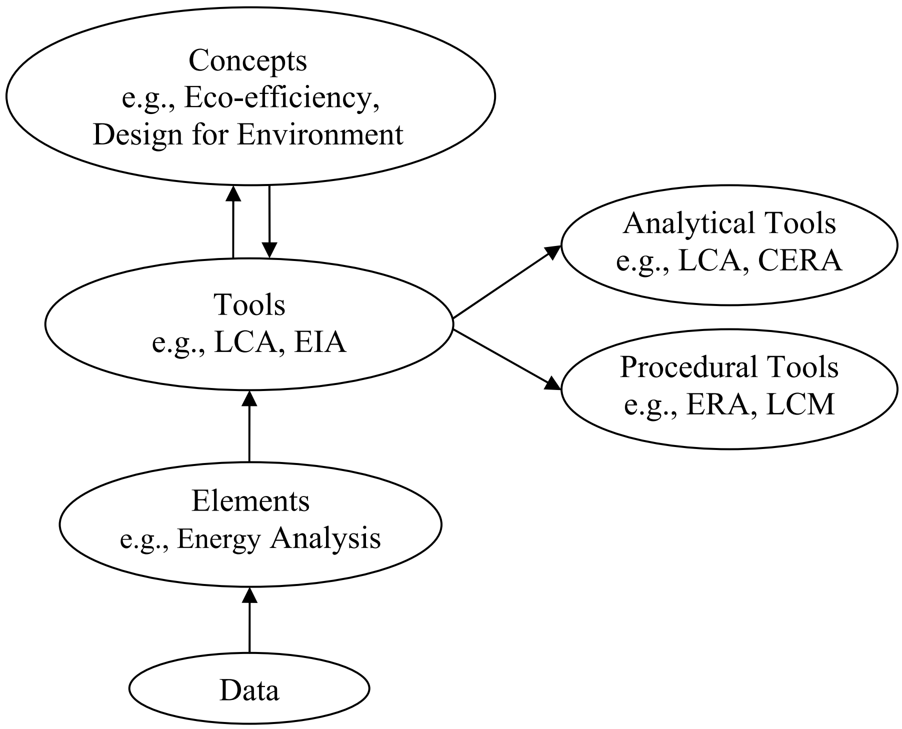

Figure 2.1 Hierarchy in a quantitative sustainability framework

Setting up a quantitative sustainability framework starts with selecting a sustainability concept that is relevant and practically achievable in a project. For example, philosophical concepts like biomimicry are suitable to follow at the architectural design stages while more practical concepts like construction ecology or

eco-efficiency can be set up as a goal for designing technological processes and for construction. At the second stage, after selecting the appropriate concept, an appropriate tool should be chosen that incorporates the elements best suited for assessing the ideals of the chosen concept. For example, the principle of resource efficiency is central to the concept of eco-efficiency and the tools like energy analysis are capable of quantifying the achievement of a process in terms of resource efficiency.

There are a number of tools available for assessing environmental systems. Such tools have been categorized based on their characteristics (Moberg 2006, Finnveden and Moberg 2004) — (i) whether the tools are procedural or analytical, (ii) what impacts they consider, (iii) what the objects of study of the tools are, and (iv) whether they are accounting tools or they consider different alternatives (i.e., change oriented tools). The procedural tools (e.g., Environmental Audit) focus on improving the procedures while the analytical tools (e.g., Life Cycle Analysis) provide information required for optimization of the system that is being studied or for comparing different alternatives (Moberg 2006, Wrisberg et al. 2002). The impacts considered by the tools can be classified as (i) natural resources (e.g., Material Flow Analysis considers only the use natural resources), (ii) natural resources and environmental impact, (e.g., Life Cycle Analysis considers both natural resource use and environmental impact) and (iii) economic aspects including natural resources and environmental impacts (e.g., Life Cycle Costing considers the three aspects of economy, natural resource use and environmental impact). The object of study can be a policy, a region, an organization, a product, a process or a substance. The accounting tools (e.g., Environmental Audit) give information which describes a

particular state while change oriented tools (e.g., Environmental Risk Assessment) describe the consequences of a choice.

Since sustainability concepts are multi-dimensional, a combination of tools is often necessary to perform a complete sustainability assessment of a process (Wrisberg et al. 2002). For example, Saouter and Feijtel (2000) introduced a procedural tool called Integrated Product Assessment as a combination of the procedural tool, environmental risk assessment (ERA), and the analytical tool, life cycle analysis (LCA), to analyze and compare the environmental loading of two detergents. While LCA provided an insight into energy and material use of the process, ERA provided the assurance that none of the impacts of the process crossed the threshold values at the local level.

In this thesis, environmental system analysis is done to aid a decision making process of choosing a more sustainable pile from the two commonly used pile types — drilled shaft and driven pile. The analytical tool LCA has been used to account for the natural resource use and environmental impact of the two pile types. The environmental impact has been assessed by the procedural tool EIA, which, for this particular thesis, forms a part of the LCA. The economic aspect including natural and societal impacts is accounted through the use of the analytical tool cost benefit analysis (CBA). Finally, a multicriteria analysis (MCA) is performed which serves as a final decision aid tool for the choice of a particular type of pile. The MCA, which combines the results of LCA and CBA, optimizes the impacts in the categories of resource use, environmental impact and economic aspect by using weights across these categories, and provides a final score which is easy to compare and interpret. The details of the tools and elements that have been used in this thesis are provided later in this chapter.

2.2 Sustainability Concepts in Engineering

There are certain concepts in sustainability that are particularly relevant to engineering processes. Some of these concepts are introduced in this section.

Life Cycle Thinking

The concept of life cycle thinking (Wrisberg et al. 2002) extends the responsibility of everyone related to a process or product beyond the stage which they are directly related to. For example, while designing a foundation, the designer should consider not only the technical and economic aspects of design and construction but also the reuse and recyclability of the construction materials. This concept is based on a cradle to grave approach (Wrisberg et al. 2002) and encourages the practitioner to consider the environmental implications of his/her decision over the entire span of the process or product.

Life Cycle Management

The concept of life cycle management (Wrisberg et al. 2002, Finnveden and Moberg 2004) is a product oriented approach that aims to improve the environmental effects of a product or process from a life cycle point of view. It is an integrated framework of concepts and techniques to address environmental, economic, technological and social aspects of products and organizations.

Construction Ecology

Construction ecology (Kibert 2008) borrows its concepts and principles from industrial ecology. Construction ecology (i) promotes the ideals of closed loop material cycle integrated with eco-industrial and natural systems, (ii) depends solely on renewable

energy sources and (iii) preserves natural system functions. Built environments that follow these ideals are generally de-constructible easily. Such built environments have components that are easily replaceable and are made of recyclable products.

Design for the Environment

Also known as green design, Design for the Environment (DfE) integrates the environmental considerations into process engineering and is based on the entire life cycle of the product (Wrisberg et al. 2002, Kibert 2008). Application of DfE in building design implies that building components should be designed to enable reuse and recycling.

Biomimicry

Also known as “conscious imitation of nature’s genius” (Benyus 1997), the theory of biomimicry advocates creation of strong, tough and intelligent materials from naturally occurring materials at ambient temperature using solar energy to run a manufacturing process so that there is no generation of waste. For example, natural ceramic seashells are produced in sea using locally available materials and these sea shells, after their useful life, degrade and provide resources for the future. In contrast, manufacture of artificial ceramic tiles needs large amount material transport and a high kiln temperature of about 2700°F. These tiles generally end up in landfills after the end of their useful life (Kibert 2008). The manufacturing process would be more sustainable if biomimicry could be applied.

Biophilia Hypothesis

The biophilia hypothesis was developed by Kellert and Wilson (1993). It emphasizes that human beings have a genetically based need to affiliate with life and life-like processes. For green buildings to be successful, they must relate to natural processes and promote satisfaction and meaning to human life. There are nine values of biophilia that should be considered while designing buildings to make them sustainable: (i) the utilitarian value, (ii) the aesthetic value, (iii) the scientific value, (iv) the symbolic value, (v) the naturalistic value, (vi) the humanistic value, (vii) the dominionistic value, (viii) the moralistic value and (ix) the negativistic value.

Eco-Efficiency

Eco-efficiency was developed by World Business Council on Sustainable Development (WBCSD) in 1992. In order for a process to be eco-efficient, it must adhere to the following principles: (i) reduction of the material requirements of goods and services, (ii) reduction of the energy intensity of goods and services, (iii) reduction of toxic dispersion, (iv) enhancement of material recyclability, (v) maximization of sustainable use of renewable resources, (vi) extension of product durability and (vii) increase of the service intensity of goods and services. WBCSD indicates that businesses can be profitable by implementing eco-efficiency through process optimization, waste recycling, eco-innovation (e.g., use of better technology to make processes resource efficient), new services (e.g., leasing instead of selling), and networks and virtual organizations (e.g., use of shared resource and physical asset). The end products of an eco-efficient process satisfy human needs, enhance the quality of life and reduce the environmental impact. The eco-efficient process aims to reduce the material input

intensity (i.e., how much material is consumed per unit service available from a product) over the life span of the products.

Factor 4

Factor 4 is essentially an economic measure devised by Weizsacker et al. (1992). The basic concept is to produce more using less resource by adopting efficient production technology. Weizsacker et al. (1992) showed with more than fifty case studies on different disciplines of science and technology that, with technological innovation, production can be doubled with only half of the resources presently used. Thus, by doubling the production and halving the resource use, capital wealth can be increased by a factor of four.

Factor 10

Factor 10 is a long term sustainability goal devised for the developed countries by Schmidt-Bleek(1997) of the Wuppertal Institute. This concept arises from the fact that resources are being consumed faster than their regeneration rate and that there is a huge disparity in the consumption pattern spatially over the world. Schmidt-Bleek (1997) found that the developed nations with a population share of 20% consume 80% of the world's resources. Factor 10 states that, over a generation, material use should be brought down by a factor of 10 by increasing the technological efficiency ten times. This is, however, difficult to implement because a shift in the socio-economic view of people is required so that they are able to do more with less (Schmidt-Bleek 1997). Factor 10 also requires technological advancement and policy changes, and focuses only on the input side of the economy. Thus, Factor 10 is unable to produce any short term benefits, which makes it less attractive to the policy makers.

The Natural Step

The Natural Step (TNS) provides a framework to eliminate the effect of materials on human health (Kibert 2008). The "Four Systems Condition" of TNS states that, for a society to be sustainable, (a) nature's function and diversity should not be systematically subjected to increasing concentration of substances extracted from the earth's crust, (b) nature's function and diversity should not be systematically subjected to increasing concentration of substances produced by the society, (c) nature's function and diversity should not be systematically subjected to impoverishment by overharvesting or other forms of ecosystem manipulation, and (d) resources should be used fairly and efficiently in order to meet the basic human needs globally.

The first condition implies that mining and burning of fossil fuel should not occur at a rate that systematically increases the concentration of the metals and pollutants in the ecosphere. It calls for a comprehensive system of recycle and reuse of metals and minerals and a reduction in the dependence on fossil fuel. The second condition restricts the use of synthetic substances that persist in the nature over a long period. The most common example of such materials is the pesticides used to increase agricultural yield. This condition requires people to rely less on synthetic products for economic benefits. The third condition prohibits people from consuming more than what nature can replenish. It asks us to reduce overuse and overexploitation of natural resources for economic benefits. This condition provides a foundation for respect towards other species and their habitats, and protects biodiversity. This condition is essentially an extension of the philosophy of deep ecology (Næss 1949) and land ethic (Leopold 1949) mentioned in chapter 1. The fourth condition lays the basis for equal distribution of

natural resource globally. It is essentially a social equity principle that promotes fair utilization of resources.

Closed Loop

The closed loop concept (Kibert 2008) advocates keeping materials in productive cycle even after the end of their designated use. Products in closed loop should be capable of being easily disassembled and the constituent materials should be recyclable. For example, in designing a structural element in accordance with the concept of the closed loop, steel structural elements appear to be a better choice because of the ease in both construction and de-construction along with its high potential of recyclability.

Cleaner Technology

The concept of cleaner technology (Kibert 2008, Wrisberg et al. 2002) aims at providing human benefits by choosing the alternative that uses less resource and causes less environmental damage than other alternatives that are economically competitive. UNEP defines cleaner technology as "the continuous application of an integrated preventive environmental strategy applied to processes, products and services to increase eco-efficiency and reduce risk to humans and the environment".

2.3 Tools for Ascertaining Process Sustainability

2.3.1 Life Cycle Assessment

Life cycle assessment or analysis (LCA) is the investigation and evaluation of the environmental impacts of a product or a service (Curran 1996). LCA of a product sums all the impacts generated by the product from the stage of extraction of raw materials to the end of the useful life of the product (Figure 2.2). Such an assessment includes an

accounting of the raw material production, manufacturing, distribution, use and disposal including all the intervening transportation steps involved. LCA of a process includes planning, construction, operation and dismantling of the process under study. Product-based LCA is much commonly used than process-based LCA.

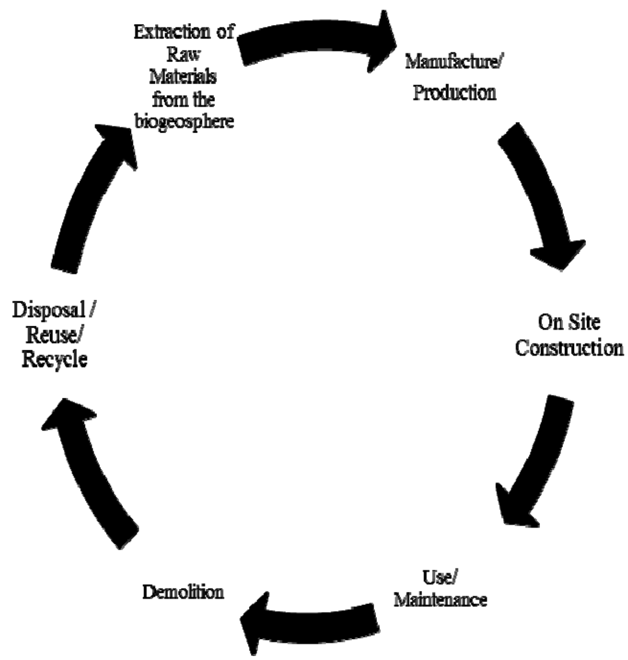

Figure 2.2 Life cycle of building materials

The pioneering studies on life cycles of products and materials were done in the seventies. However, those studies, also referred to as 'net energy analysis', considered only the energy consumption. LCA studies gained momentum as a result of increasing environmental awareness during the 1990s. During this time, quantification of emissions

and impacts of waste disposal were incorporated in the LCA studies. LCA, being a young and evolving tool, there is a lot of controversy and uncertainty regarding the feasibility of the study and regarding the accuracy and reliability of the results (Hau 2005, Curran 1996). Despite this fact, several companies and organizations continue using LCA for product improvement, design of new products, product information, eco-labeling, and exclusion or admission of products from or to the market. LCA is also a part of the ISO 14000 norms and has the promise to play an important role in policy making and in process selection, design and optimization.

Traditional product-based LCA consists of four stages: (i) goal definition and scoping, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation of results (ILCD 2010, Curran 1996). The first step, goal definition and scoping, consists of defining the goals of the analysis, setting up the initial system boundary, and collection and validation of the data. The final step, interpretation of results, includes processing of all the data obtained from the previous steps to present and emphasize the significance of the impacts within a given context.

The inventory analysis consists of two steps: recording and allocation. Recording consists of refinement of the system boundary, collection of relevant information and data based on the refined system boundary, and re-validation of the data. Allocation consists of assigning a fraction of the inputs (e.g., raw material, fuel and services) to the main product and co-products based on some rule.

Impact assessment has the steps of classification, characterization and valuation. Classification consists of assigning the inventory input and output data (e.g., cement, steel and fuel required for pile construction) to the potential environmental stressors (e.g.,

CO_2, NO_x and SO_x) released in the process. Characterization consists of combining the different stressor-impact relationships into impact categories. Valuation consists of assigning different weights to the different impact categories.

2.3.1.1 Inventory Analysis

The inventory analysis step of doing an LCA involves identifying and quantifying all the materials and services on the input side and all the products and the by-products on the output side of the process. The input side is analyzed in this research by energy analysis, which includes exergy analysis, emergy analysis and cumulative energy (embodied energy) requirement analysis (CERA). Energy analysis focuses on the input sides of a process and measures the inputs in physical terms (Finnvaden and Moberg 2004). It provides an indirect measure of the environmental effects as it is generally assumed that products with higher energy (embodied energy, exergy or emergy) have a greater emission potential.

Embodied Energy Analysis

Every material used in construction consumes energy throughout its stages of production, use and disposal. These stages consist of raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and decomposition (Treloar 1998). The energy consumed in production of a material is called the "embodied energy" of the material and is the focus of many research studies on energy consumption and carbon emissions (Treloar 1998). As mentioned in Dixit et al. (2010), Gonzalez and Navarro (2006) suggest that building materials possessing high-embodied energy could possibly result in more carbon dioxide emissions than materials with low embodied energy.

According to Miller (2001), the term “embodied energy” is subject to various interpretations and the published databases on embodied energy intensity are rather unclear (Dixit et al. 2010). Embedded energy has been defined by Crowther (1999) as “the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings.” According to Treloar et al. (2001), “embodied energy (EE) is the energy required to provide a product (both directly and indirectly) through all processes upstream (i.e. traceable backwards from the finished product to extraction of raw materials).” Boustead and Hancock (1979) provided yet another definition according to which embodied energy is “the energy demanded by the construction plus all the necessary upstream processes for materials such as mining, refining, manufacturing, transportation, erection and the like.” A more comprehensive definition was put forward by Ding (2004) based on the studies by Baird (1994), Edwards and Stewart (1994), Howard and Roberts (1995) and Cole and Kernan (1996), according to which the “embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components, and the energy use for various processes during the construction and demolition of the building.”

The explicit and rigorous calculation of indirect energy is the strength of embodied energy analysis. However, there are some drawbacks of the method. For example, embodied energy does not take into account the energy quality which other energy accounting methods like emergy algebra does. Also, the outcome of the calculation depends on the choice of the system boundary which is subjective.

Embodied energy analysis is the most traditional method of energy analysis and the framework of Cumulative Energy Requirement Analysis (CERA) has been developed to standardize the methods of embodied energy analysis (Wrisberg et al. 2002). CERA is an analytical tool that assesses the environmental loading of a product or a process by calculating the total energy consumption of the product or the process. The total primary energy requirement of a product, CERA, is calculated as the sum of all the energies required (i) for the production ($CERA_p$), (ii) during the operational stage ($CERA_u$) and (iii) for the disposal of the product ($CERA_d$) [$CERA = CERA_p + CERA_u + CERA_d$]. The primary energy is defined as the energy content of the carriers that have not been subjected to any conversion (Wrisberg et al. 2002). For example, in a precast pile construction project, the CERA of the construction process is given by the sum of (i) the energy required for production and transportation of the piles to the site ($CERA_p$), (ii) the energy consumed at the site for the installation of the piles ($CERA_u$) and (iii) energy required for dismantling and transporting the piles to the landfill site after the end of their useful life ($CERA_d$). The material energy required at all the three stages can be calculated in the form of embodied energy of the materials (carriers) which is a primary energy form that has not been converted to any other form of energy. Because CERA considers the energy flow in a process by differentiating between the different stages of the process, it helps to detect resource inefficiency of a particular stage. Thus, CERA can be used to increase the energy-use efficiency of all the stages by introducing or increasing closed loop material cycle (i.e., material use, recycle and reuse) in all the stages. At the same time, CERA can be used to have an indirect estimate of the emissions in the

different stages of a process because greater the energy content of a product the greater is the potential for emission in making the product.

Using CERA as the only indicator for the estimation of process efficiency, however, skews the assessment towards energy efficiency alone and can lead to substitution of a higher embodied energy resource with lesser pollution impact by a lower embodied energy resource with greater environmental impact. Hence, CERA is generally followed up by a full scale LCA or at least an environmental impact assessment (EIA) so that an integrated approach towards assessing sustainability is maintained.

Exergy Analysis

Exergy per unit mass of a material is a measure of the maximum amount of useful (available) energythat 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). Exergy per unit mass of a homogeneous system at a defined state 1 is given by

$$b_{state1} = b_{state1,t} + b_{state1,c} + b_{state1,k} + b_{state1,p} + b_{state1,n} + ... \qquad (2.1)$$

where $b_{state1,t}$, $b_{state1,c}$, $b_{state1,k}$, $b_{state1,p}$ and $b_{state1,n}$ are the thermodynamic, chemical, kinetic, potential and nuclear exergy components of the total exergy (Scuibba and Wall 2010). The thermodynamic exergy $b_{state1,t}$ is the energy available due to the differences in the physical properties (such as temperature and pressure) between the system and its surroundings. The chemical exergy $b_{state1,c}$ is the useful energy available due to the conversion of the chemical components of the system, through chemical reactions, to the most stable form of the components in the surroundings. The two terms, $b_{state1,k}$ and $b_{state1,,p}$, are contributions due to the relative velocity and height of the system with

respect to the surroundings. The last term in equation (2.1) is the contribution from the differential in nuclear potential between the system and its surroundings (Scuibba and Wall 2010).

The specific exergy or exergy per unit mass of a material, in the absence of nuclear, magnetic, electrical and interfacial effects, is defined for the material at temperature T and pressure P, relative to its surroundings at temperature T_0 and pressure P_0 as

$$b_{T,P} = h - T_0 s + \sum_i x_i \mu_i + v^2/2 + gz \qquad (2.2)$$

where h is the enthalpy, s is the entropy, μ_i is the chemical potential of component i, x_i is the mole-fraction of component i, v is the relative velocity, z is relative height and g is the acceleration due to gravity. The reference state, denoted by the subscript "0", is assumed to be that of the surroundings with temperature T_0 and pressure P_0. It is assumed that, at the reference state, the chemical, kinetic and potential exergies are zero (i.e., $\mu_{i,0} = 0$, $v_0 = 0$ and $z_0 = 0$ in the surroundings). The term ($h - T_0 s$) is the Gibb's free energy — it is the thermodynamic potential and represents the free energy required to bring the material from its present state to the reference state. The kinetic and potential exergies of a material are the same as the kinetic and the potential energies of the material, respectively, as these two forms of energy are, ideally, fully convertible to work (Meester et al. 2006). The major contribution to the exergy of a material comes from its chemical exergy (Meester et al. 2006). The chemical exergy of a material is calculated based on the exergy of the most stable form of the material available in the atmosphere, seawater or the upper crust of the earth (Szargut et al. 1988). The reference temperature and pressure are generally assumed to be 298.15 K and 1 atmosphere.

Exergy analysis is typically applied at the scale of a process, and does not account for the exergy consumed in earlier processes (Hau 2005). Environmentally conscious decision-making, however, requires the consideration of the entire life cycle of a product or process which makes exergy analysis unsuitable for environmental decision making. In fact, one important criticism of exergy is that it focuses on the output side of a process and is more concerned with emissions and their mitigation than the ecosystem services of the input side of the process. Hence, other exergy-based analyses such as cumulative exergy consumption (CExC), thermo-economics and extended exergy accounting (EEA) have been developed (Hau and Bakshi 2004b, Edgerton 1982) to overcome the limitations of exergy analysis. These methods account for the exergy of all the natural resources consumed in a process and expand the boundary of exergy analysis to include other relevant industrial activities.

The cumulative exergy analysis is used to measure the exergy of all the natural resources used up to produce a product. The cumulative exergy consumption (CExC) of a process is the sum of the exergy of all the natural resources consumed in all steps of the process and its previous processes in the production chain (Hau 2005). CExC is given by

$$\text{CExC}=\sum_{j}^{N} B_j \qquad (2.3)$$

where B_j is the exergy of the j^{th} natural resource stream that enters the production chain and N is the total number of natural resource streams entering the process.

A cumulative exergy consumption analysis is suitable for the purpose of LCA as it considers the life cycle of the product studied (Dewulf et al. 2007). Conceptually, all the processes previous to the process of interest are taken into account in the network.

Emergy Analysis

Emergy, spelled with an 'm', measures both the work of nature and that of human beings in generating services and products. While energy is a measure of the amount of work that can be obtained from a product, emergy is the available energy (and not the total energy) already used up to make that product (Odum 1996). Emergy approach considers the earth as a closed system with three constant energy inputs: solar energy, deep earth heat and tidal energy. It is assumed that other kinds of energy existing on the earth can be derived from these three main sources through energy transformations. To arrive at the emergy of a material, the emergy of all the inputs, resources and services that went into making the material are added up. However, the quality of energy content of one resource is not the same as that of another as they have different work capacities. Hence, for the purpose of comparison, it is necessary to have a common basis which all other forms can be converted to. Commonly, solar energy is used for the purpose. The available solar energy used up directly or indirectly to make a service or a product is defined as the solar emergy (or simply, emergy) and its unit is solar emjoules (sej). Different energy forms are converted to equivalent solar emergy by a transformation coefficient τ, also known as transformity, which is defined as the solar emergy required directly or indirectly to produce one joule of a product or service. Thus, the solar emergy (commonly referred to as emergy) E_m of a product is given by

$$E_m = \sum_i (\tau_i B_i) \quad i = 1, 2, ..., n \tag{2.4}$$

where B_i is the available energy content of the i^{th} independent input material/energy flow to the process and τ_i is the solar transformity of the i^{th} input material/energy flow and n is the total number of material/energy flows. The above equation follows from Bastianoni et al. (2007) and Hau (2002) according to whom the solar transformity of a product is its solar emergy divided by its exergy. Thus, emergy and exergy of a product can be related through

$$E_m = \tau B \tag{2.5}$$

where B is the exergy. As exergy (available energy) decreases with each transformation while the emergy increases, the transformity also increases with each transformation. Note that the transformity is regarded as a measure of energy quality and the transformity of solar energy is defined to be unity.

Emergy and transformity are path dependent properties of a matter or system. Accurate and precise knowledge of these variables will strongly depend on the knowledge of the path of the several processes involved. Odum (2000) calculated the emergy and transformities for many products, services and systems. In the calculations, it was assumed that earth processes are regular meaning that, for the same process in different locations, transformity has approximately the same value (Odum et al. 2000). Although the theory of emergy is conceptually based on thermodynamics, there is resistance in the engineering community to using emergy analysis mainly because of the uncertainties associated with the calculation of transformities (Hau 2005, 2002, Hau and Bakshi 2004a).

2.3.1.2 Environmental Impact Assessment

Environmental impact assessment (EIA) is a procedural tool that is used to assess the effects of a particular technological process on the environment at the location of the occurrence of the process (Curran 1996). The International Association for Impact Assessment (IAIA) defines an environmental impact assessment as "the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made." The most important function of EIA is to compare the ecological effects of alternative technologies pertaining to a particular process. For example, in pile construction, the major environmental impacts are dust and diesel soot (emitted from the construction equipments) which are common to all pile types. But there are also other environmental effects like noise pollution and vibration, which may be specific for a particular pile type. These environmental impacts should be identified for each pile type and taken into account to arrive at a basis of comparison between the different types of piles. EIA provides the tool to perform this comparative study and to choose the pile that has the lowest impact on the ecology.

EIA describes the consequences of the environmental loading determined in the inventory analysis described above. This helps to translate the quantitative measures of the environmental loading into qualitative terms and to understand the effects of the process. In general, there is consensus regarding the major categories of impact assessment as given in SETAC 1993, LCANET 1997 and ISO14040 2010. These categories are resource use, human health and ecological consequences. The mandatory

steps of impact assessment are impact category definition, classification and characterization and are sometimes followed by valuation.

Impact category definition identifies the environmental impacts that are considered relevant and important for the goal and scope of the study. Different set of categories have been defined by different standard procedures. For example, the Nordic guidelines for impact assessment use resource, human health and ecological consequences as impact categories. As a second step of impact assessment, the relative contribution of each input and output is measured, and the contributions of all the inputs and outputs are then respectively aggregated within the different impact categories. The impact potential of certain compounds, e.g., CO_2 and SO_2, are used to characterize the impacts of the inputs and outputs within different impact categories.

The final step of impact assessment, namely valuation, involves assigning weights to different categories so that an impact score can be calculated. The methods employed in assigning weights in this step are controversial and no consensus has been arrived yet as to the choice of a single weighting system. The salient quantitative weighting approaches are proxy, panel, monetization and distance to target (Lindeijer 1996). The proxy approaches use a quantitative measure as representative of the total environmental impact. For example, ecological footprint of a project provides a proxy quantitative measure of the environmental impact of that project (Wu et al. 2006). The panel approach is based on survey, and participants are asked to judge the seriousness across the impact categories empirically or subjectively through questionnaires or interviews. The monetization approach is based on the idea that the importance of a particular category can be measured by the willingness of the people to pay in order to avoid

impacts in that particular category. In the distance to target approach, first, a sustainable emission/pollution standard (target) is defined for each impact category. Then, the weight of a particular category for a project is decided by the gap (distance) between the current emission/pollution level and the standard that has been set. The further a project is from achieving the target for a particular category, the greater the weight is for that category in the project (Seppala and Hamalainen 2001, Wu et al. 2006). The prominent quantitative weighting standards are Eco-indicator99 (Goedkoop and Spriensmaa 1999), Environmental themes (Eriksson et al. 1995) and EPS2000 (Steen 1999). Of these, Eco-indicator99 and Environmental themes are based on the distance to target method while EPS2000 is based on monetization.

The drawback of EIA is the absence of a system boundary. Hence, EIA is local in nature and takes into account only the direct effects (and not the indirect effects) of a process. For example, EIA considers only the emissions from a construction site but not the emissions related to the manufacture of the materials used in the construction process. This limitation, however, can be overcome when EIA is combined with other tools like CERA and inventory analysis.

2.3.2 Cost Benefit Analysis

Cost benefit analysis (CBA) 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. For example, building a recreational facility would traditionally be evaluated by market economy based on the revenue it earns, but CBA accounts for the

apparently intangible benefits the recreational facility provides to the community — e.g., aesthetic value increase of the locality — in monetary terms. The first step in CBA is to identify some of the benefits and costs of a project based on which the CBA will be performed. 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.

2.3.3 Multicriteria Analysis

The functional integrity conceptualization of sustainability provides a holistic approach towards incorporating sustainability in a process. Such an approach often requires balancing of conflicting objectives in an engineering project. Such a balance can be struck by using multicriteria analysis (MCA), which essentially 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. The outcome of MCA is a compromised solution that can be used as a decision aid.

MCA is a two-stage process. In the first stage, the objectives and the tradeoffs between the objectives are identified and, in the second stage, weights or scores are attached to the different objectives depending on their relative importance so that the best option can be identified from the total impact score. This second stage can be expressed as a two dimensional evaluation matrix as shown in Table 2.1.

Table 2.1Multicriteria evaluation matrix

Criteria	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		$\sum_{k=1}^{i} W_k S_{k1}$	$\sum_{k=1}^{i} W_k S_{k2}$	…	$\sum_{k=1}^{i} W_k S_{kn}$

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 criteria. The choice of a weighting method and the values of the weights are influenced by ethical and ideological values of the practitioner. There is presently no consensus on the choice of the weighting methods and on the values of the weights (Finnveden 1997, 1999). Standard methods of deciding weights are available in the literature (Nijkamp et al. 1990, Saaty 1994, Hobbs and Meier 2000) and may involve public participation, ranking or pair-wise comparison.

CHAPTER 3 ASSESSMENT OF SUSTAINABILITY FOR DRILLED SHAFT AND DRIVEN CONCRETE PILE

3.0 Introduction

Like any industrial process that takes in different materials and chemicals as inputs and delivers a finished product as output, pile construction is also a process that uses cement, sand, aggregate and exploits other natural resources like land and water to provide a load transfer interface for the built environment. The process of pile construction generates wastes to land and water and emissions to air and, hence, causes disruption to the functioning of the natural system in and around the construction site. Thus, pile construction warrants an environmental sustainability study to maintain the eco-balance of the region where the construction takes place. Qualitative indicators have been developed to some extent to assess the environmental sustainability of geotechnical construction sites (Jiminez 2004, Jefferson et al. 2006, Holt et al. 2009, 2010). However, when life cycle thinking (Wrisberg et al. 2002) is applied, it can be easily understood that the impact of pile construction is not restricted to the construction site only. Pile construction requires materials that are mined from the earth, transported to facilities to be processed and then again transported to the construction site for use. Moreover, at the end of the useful life span, the de-constructed pile needs to be transported to the landfill site where it engages another limiting resource — land. This entire chain of activities,

upstream and downstream, cumulatively contributes to the effects of pile construction on the environment and needs to be considered for a complete analysis of sustainability of pile foundations.

A life-cycle wide study of the resource and energy used in pile construction provides an assessment of the environmental sustainability of a pile foundation project. Adopting a life cycle view of any process or product also provides an indirect measure of societal sustainability by promoting resource budgeting and by restricting the shift of the environmental burden of a particular phase to areas downstream of that phase (Curran 1993, 1996, ILCD 2010). However, in practice, an environmental sustainability study for any technological project can only be done after the preliminary engineering design has been completed (Holt et al. 2010) and the sustainability study becomes meaningful if it can also successfully address the financial concerns of the stakeholders (Ding 2004). Thus, ensuring sustainability of technical processes should start with choosing process designs that are resource and environment friendly and should include cost benefit analyses that address both the economic sustainability and the societal sustainability by translating any social benefit from the project to financial terms. In fact, the technological design, cost benefit analysis and environmental sustainability study should form an iterative cycle, as shown in Figure 3.1, which helps to maintain the three E approach of sustainability (Hempel 2009) and also satisfies the requirements of functional integrity (Thompson 2010).

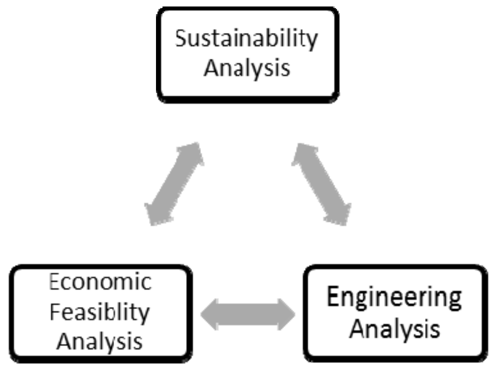

Figure 3.1 Iterative cycle between engineering design, cost benefit analysis and environmental sustainability analysis

In this chapter, a life cycle analysis (LCA) is performed to develop sustainability indicators for pile foundations considering resource use and process emissions. Other environmental impacts like change in land use pattern, noise pollution, compaction and vibration have been qualitatively considered in the study. The sustainability indicators address the shortcomings of the existing generalist standards like LEED by prioritizing the sustainability concerns related to geotechnical engineering. This method comes with the provision that a chosen weight system can be applied to impact or resource categories according to the priority of the impact or resource categories for a particular project — this makes the method versatile and suitable for different possible cases of geotechnical construction. Specifically, two types of pile foundations, namely, the driven concrete pile and the drilled shaft, are considered in the study. The impacts these two types of piles create on the environment are investigated from the viewpoints of both resource consumption and process emissions. Prior to performing the LCA, the two pile types were designed using the working stress method for given structural loads with the

assumption that the piles are installed in homogeneous sand and clay profiles. Subsequent to the LCA, a cost benefit analysis (CBA) is performed which accounts for the socio-economic benefits of the project, and a socio-economic indicator is developed. The results of the LCA and CBA are combined in a multicriteria analysis (MCA) to obtain a sustainability index that judges the performance of the piles in the categories of resource efficiency, environmental impact and socio-economic benefit. The proposed framework is outlined graphically in Figure 3.2.

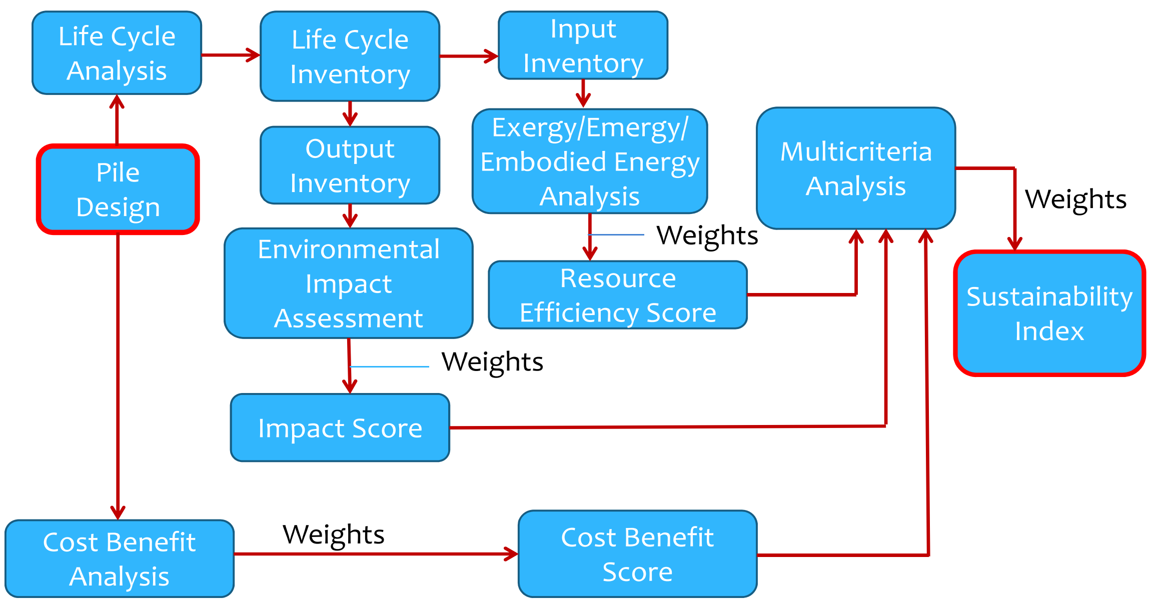

Figure 3.2 Analysis framework

3.1 Pile Foundation: Overview

Pile foundations are long and slender structural elements that typically transfer the superstructure load to deeper and competent soil strata (Tomlinson 1994, Fleming et al. 2008, Salgado 2008). Piles are generally made of steel, concrete, timber, polymers or in combinations of these materials. Pile capacity is the load that the pile can safely transfer to the ground and this capacity depends on the type of pile, the soil condition and the method of pile installation. Depending on the pile installation method, piles can be classified as displacement and non-displacement piles. Non-displacement piles are cast in situ — generally, a cylindrical hole of a desired diameter is drilled in the ground and the hole is filled with concrete and reinforcement. Displacement piles, on the other hand, are driven into the ground by hammering or jacking without any a priori soil removal — the soil in the immediate vicinity of the pile gets displaced as the pile penetrates the ground. Although certain pile types are suitable for certain cases of soil profile and loading condition, in most civil engineering sites, multiple pile types can be used. Hence, the decision on the choice of pile type and the installation method is an important step in foundation design.

Traditionally, the choice of a particular pile type depends on local practice, economics, site and soil conditions, and the range of column loads to be supported by the piles (Salgado 2008). The major advantages of non-displacement piles over displacement piles are (a) economy due to absence of pile cap, (b) no vibration to surrounding structures, (c) less constructional noise, (d) more adaptability to varying subsurface conditions and (e) high axial and lateral load capacity. In contrast, the main advantage of displacement piles over non-displacement piles is that a displacement pile typically

carries greater loads than a corresponding non-displacement pile with the same geometry and material properties. However, displacement piles contain reinforcement much greater than that required for carrying the externally applied load — the additional reinforcement is required for resisting the stresses developed during the hauling and transportation of the piles to the construction site (Tomlinson 1994). At the same time, displacement piles are not reusable and develop lateral stress in the surrounding soil in excess of the in situ lateral stress. It is important to note that, in the decision-making process for the choice of a particular pile type, the environmental impact caused by pile construction is generally not considered unless it is related to some economic benefit. For example, locally available material is used for constructing piles because it reduces transportation cost and boosts local economy and not because it reduces the emissions associated with the transportation or because it can be an environmentally sustainable choice.

The major steps in designing a pile foundation are (a) selection of pile type, (b) selection of pile length depending on the depth of the load bearing strata, and (c) calculation of the pile diameter or cross section depending on the static analysis of pile capacity. For driven piles, these steps are generally followed by the selection of a pile driving system and the minimum driving resistance.

Piles are designed to resist axial and lateral loads without suffering structural damage, excessive settlement or deflection, and bearing capacity failure. In this thesis, only axial capacity of piles is considered. Piles derive their axial load carrying capacity from the frictional resistance developed along the pile shaft due to the relative slip of the shaft with respect to the surrounding soil and from the compressive resistance of the

underlying soil at the base of the pile (Figure 3.3). The ultimate load (Q_{ult}) at the head of the pile can be expressed as the sum of the loads carried by the pile base ($Q_{b,ult}$) and by the pile shaft ($Q_{s,ult}$):

$$Q_{ult} = Q_{b,ult} + Q_{s,ult} \tag{3.1a}$$

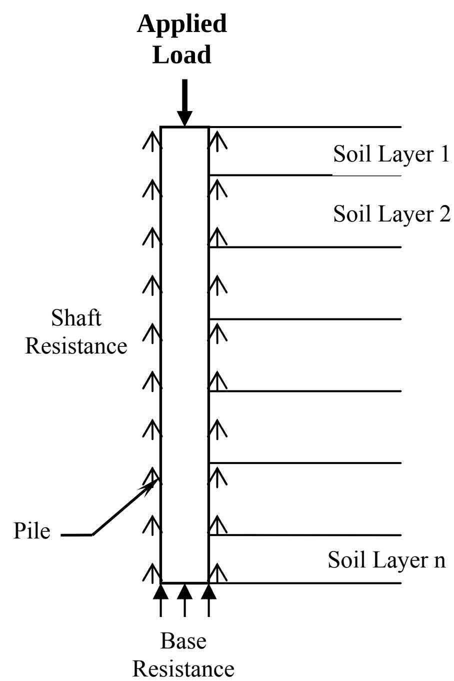

Figure 3.3 Resistances in pile foundation

The ultimate load is generally chosen as the load that causes 10% relative settlement of the pile head (i.e., pile head settlement/pile diameter = 0.1). However, for this amount of settlement, the shaft resistance reaches its limit capacity (Salgado 2008). The ultimate base resistance $Q_{b,ult}$ is given by

$$Q_{b,ult} = q_{b,10\%} A_b \tag{3.1b}$$

where A_b is the cross sectional area of the pile base and $q_{b,10\%}$ is the ultimate unit base resistance corresponding to 10% relative settlement of the pile head. The limit shaft resistance (which is the same as the ultimate resistance $Q_{s,ult}$) is given by

$$Q_{sL} = \sum_{i=1}^{n} q_{sLi} A_{si} \tag{3.1c}$$

where q_{sLi} is the unit limit shaft resistance within any soil layer i that the pile penetrates, A_{si} is the pile shaft area interfacing with the layer i, and n is the total number of soil layers interfacing with the pile shaft. Thus, the ultimate pile capacity is given by

$$Q_{ult} = q_{b,10\%} A_b + \sum_{i=1}^{n} q_{sLi} A_{si} \tag{3.1d}$$

3.2 Design of Drilled Shaft and Driven Concrete Pile

The drilled shaft and driven precast concrete pile, considered in this thesis, are designed based on the working stress method. It is assumed that the piles are installed in homogeneous profiles of sandy and clayey soils. The soil profiles are so chosen that the construction of both types of piles is technically feasible. Both the pile types are assumed to support the same superstructure load. It is also assumed that there are no constraints that limit the availability of raw materials, equipment or technical expertise required for the design and construction of the piles. The equations used for the purpose of designing the piles and the design calculations are provided below.

3.2.1 Equations of Ultimate Unit Base and Limit Unit Shaft Resistances

For drilled shaft in sand, the limit unit shaft resistance is given by (Salgado and Prezzi 2006, Salgado 2008)

$$q_{sL} = K\sigma_v' \tan\phi_c \tag{3.2a}$$

where

$$K = 0.7K_0 \exp\left[\left\{0.0114 - 0.0022\ln\left(\frac{\sigma'_v}{p_A}\right)\right\}D_R\right] \tag{3.2b}$$

in which σ_v' is the vertical effective stress at the depth at which the limit capacity is determined, ϕ_c is the critical state friction angle of the sand, D_R is the relative density of sand expressed as a percentage, K_0 is the coefficient of earth pressure at rest, and p_A is a reference stress (= 100 kPa). The ultimate unit base resistance of drilled shaft in sand is given by (Salgado 2008)

$$q_{b,10\%} = \left[0.23\exp\left(-0.0066D_R\right)\right]q_{bL} \tag{3.2c}$$

where

$$\frac{q_{bL}}{p_A} = 1.64\exp\left[0.1041\phi_c + \left(0.0264 - 0.0002\phi_c\right)D_R\right]\left(\frac{\sigma_h'}{p_A}\right)^{\left(0.841-0.0047D_R\right)} \tag{3.2d}$$

in which σ_h' is the horizontal effective stress at the depth of the pile base.

The limit unit shaft resistance of precast concrete driven pile in sand is given by (Salgado and Prezzi 2006, Salgado 2008)

$$q_{sL} = 0.02\tan\left(0.95\phi_c\right)\left[1.02 - 0.0051D_R\right]q_{bL} \tag{3.3a}$$

where q_{bL} is the limit unit base resistance at the depth at which q_{sL} is calculated. The limit unit base resistance is given by equation (3.2d). The ultimate unit base resistance of concrete driven pile in sand is given by

$$q_{b,10\%} = \left[1.02 - 0.0051 D_R\right] q_{bL} \tag{3.3b}$$

in which the limit unit base resistance q_{bL}, given by equation (3.2d), is calculated at the pile base.

For drilled shaft in clay, the limit unit shaft resistance is given by (Salgado 2006, 2008)

$$q_{sL} = \alpha s_u \tag{3.4a}$$

where s_u is the undrained shear strength of clay at the depth at which the shaft resistance is calculated and the factor α is given by

$$\alpha = 0.4\left[1 - 0.12 \ln\left(\frac{s_u}{p_A}\right)\right] \tag{3.4b}$$

which is strictly valid for 3 ≤ OCR ≤ 5 (OCR is the overconsolidation ratio) and gives a conservative estimate of pile capacity for OCR < 3 (Salgado 2008). The ultimate unit base resistance of drilled shaft in clay is given by (Salgado 2008)

$$q_{b,10\%} = 9.6 s_u \tag{3.4c}$$

The limit unit shaft resistance of precast concrete driven pile in clay is given by equation (3.4a) in which the factor α is given by (Salgado 2006, 2008)

$$\alpha = \left(\frac{s_u}{\sigma_v^{'}}\right)_{NC}^{0.5}\left(\frac{s_u}{\sigma_v^{'}}\right)^{-0.5} \tag{3.5a}$$

in which the subscript NC represents normally consolidated clay. In this thesis, it is assumed that

$$\left(\frac{s_u}{\sigma_v^{'}}\right)_{NC} = \frac{\phi_c}{100} \tag{3.5b}$$

where ϕ_c is the critical state friction angle of clay. The ultimate unit base resistance of driven concrete pile in clay is given by (Salgado 2008)

$$q_{b,10\%} = 10 s_u \tag{3.5c}$$

3.2.2 Design Calculations

In the design calculations done in this chapter, only homogeneous sand and clay profiles are considered. The water table is assumed to be at the ground surface. The working superstructure loads considered are 1000kN, 2000 kN and 5000 kN. Also, the pile length is fixed at 12 m. Thus, for the different piles, the diameter varies depending on the soil profile and the pile capacity.

For the saturated sand layer considered in this chapter, the soil properties are as follows: unit weight of solids G_s = 2.65, relative density D_R = 60%, coefficient of earth pressure at rest K_0 = 0.4, maximum void ratio $e_{\max}$ = 0.9, minimum void ratio $e_{\min}$ = 0.4 and unit weight of water γ_w = 9.81 kN/m^3. This resulted in bulk unit weight of sand γ_{sat} = 19.93 kN/m^3. The design calculations for the shaft and base resistances for the drilled shaft and driven pile in sand for a working load of 2000 kN are shown in Tables 3.1 and 3.2. Based on the design, the drilled shaft diameter obtained is 1.84 m and the driven pile diameter obtained is 0.86 m. A factor of safety of 2.5 is used in the design.

For the saturated clay layer considered in this chapter, the soil properties are as follows: G_s = 2.65, overconsolidation ratio OCR = 1, coefficient of earth pressure at rest K_0 = 0.4, unit weight of water γ_w = 9.81 kN/m^3 and bulk unit weight of clay γ_{sat} = 18kN/m^3. The design calculations for the drilled shaft and driven pile in clay for a working load of 2000kN are shown in Table 3.3. Based on the design, the drilled shaft

diameter is 2.09 m and the driven pile diameter is 1.93 m. A factor of safety of 2.5 is used in the design. Table 3.4 summarizes all the design calculations for this chapter and provides the diameters obtained for the drilled shafts and the driven piles for all the different load cases of 1000 kN, 2000 kN and 5000 kN and for the homogeneous sand and clay profiles.

Table 3.1 Design calculations for drilled shaft in sand for 2000 kN load

Design Calculations for Drilled Shaft in Sand					
Layer No.	Layer Width (m)	Limit Unit Shaft Resistance (q_{sL}) (kPa)	Q_{sL}/d [d = diameter of the pile] (kN/m)	Limit Unit Base Resistance (q_{bL}) (kPa)	Design Calculations
	(1)	(2)	(3) = Π×(1)×(2)	(4)	(5)
1	1	2.40	7.54	—	Load = 2000 kN Factor of Safety = 2.5 $q_{b,ult}$ = $q_{b,10\%}$ = 1309.47 (Refer eqn. 3.2c) $Q_{b,ult}$ = (Π/4)d^2×1309.47 = 1027.94d^2 Q_{sL} = 824.52d Using eqn. 3.1d, d = 1.84 m Volume of concrete = 31.91m^3 Reinforcement = 6 bars of 12m diameter Volume of steel = 0.01m^3
2	1	6.24	19.58	—	
3	1	9.71	30.50	—	
4	1	13.01	40.85	—	
5	1	16.18	50.81	—	
6	1	19.26	60.48	—	
7	1	22.27	69.91	—	
8	1	25.21	79.16	—	
9	1	28.10	88.24	—	
10	1	30.95	97.19	—	
11	1	33.76	106.01	—	
12	1	36.54	114.72	—	
13	0.5	37.91	59.52	—	
TOTAL		281.54	824.52	8459.59	

Table 3.2 Design calculations for driven concrete pile in sand for 2000 kN load

Design Calculations for Driven Pile in Sand					
Layer No.	Layer Width (m)	Limit Unit Shaft Resistance (q_{sL}) (kPa)	Q_{sL}/d [d = diameter of the pile] (kN/m)	Limit Unit Base Resistance (q_{bL}) (kPa)	Design Calculations
	(1)	(2)	(3) = Π×(1)×(2)	(4)	(5)
1	1	1431.57	11.10	34.85	Load = 2000 Kn
2	1	2645.59	20.51	64.41	Factor of Safety = 2.5
3	1	3519.94	27.29	85.70	$q_{b,ult} = q_{b,10\%}$ = 6040.15
4	1	4248.36	32.94	103.43	(Refer eqn. 3.3b)
5	1	4889.14	37.91	119.03	$Q_{b,ult}$ = (Π/4)d^2×845.59
6	1	5469.53	42.41	133.16	= 4741.5d^2
7	1	6004.90	46.56	146.19	Q_{sL} = 571.32d
8	1	6504.98	50.44	158.37	Using eqn. 3.1d,
9	1	6976.41	54.09	169.85	d = 0.86 m
10	1	7423.94	57.56	180.74	
11	1	7851.12	60.87	191.14	Volume of concrete = 7.03m^3
12	1	8260.70	64.05	201.11	Reinforcement = 0.6% of pile
13	0.5	8459.59	65.59	102.98	cross-sectional area
TOTAL		8459.59	571.32	1690.95	Volume of steel = 0.04 m^3

Table 3.3 Design calculations for drilled shaft and precast concrete driven pile in clay for 2000 kN load

Design Calculations for Drilled Shaft and Driven Pile in Clay							
			Drilled Shaft		Driven Pile		
Layer No.	Layer Width (m)	Undrained Shear Stress, s_u (kPa)	Limit Unit Shaft resistance (q_{sL}) (kPa)	Q_{sL}/d [d = diameter of the piles] (kN/m)	Limit Unit Shaft resistance (q_{sL}) (kPa)	Q_{sL}/d [d = diameter of the piles] (kN/m)	Design Calculations
	(1)	(2)	(3)	(4) = Π × (1) × (3)	(5)	(6) = Π × (1) × (5)	Load = 2000 kN Factor of safety = 2.5 For Drilled Shaft:
1	1	4.10	2.27	7.12	2.24	7.04	$q_{b,ult} = q_{b,10\%} = 9.6s_u = 943.49$
2	1	12.29	6.15	19.31	6.73	21.13	$Q_{b,ult} = (\Pi/4)d^2 \times q_{b,ult} = 740.64d^2$
3	1	20.48	9.75	30.61	11.21	35.21	
4	1	28.67	13.19	41.40	15.70	49.30	$Q_{sL} = 848.71d$
5	1	36.86	16.51	51.83	20.19	63.39	Using eqn. 3.1d,
6	1	45.05	19.74	61.99	24.67	77.47	d = 2.09 m
7	1	53.24	22.90	71.92	29.16	91.56	Volume of concrete = 41.06 m^3
8	1	61.43	26.01	81.66	33.64	105.64	Volume of steel = 0.01 m^3
9	1	69.62	29.06	91.24	38.13	119.73	For Driven Pile:
10	1	77.81	32.06	100.67	42.62	133.81	$q_{b,ult} = 10s_u = 982.8$
11	1	86.00	35.02	109.97	47.10	147.90	$Q_{b,ult} = (\Pi/4)d^2 \times q_{b,ult} = 771.82d^2$
12	1	94.19	37.94	119.15	51.59	161.98	
13	0.5	98.28	39.39	61.85	53.83	84.51	$Q_{sL} = 1098.67d$
TOTAL		98.28	289.99	848.71	376.81	1098.67	Using eqn. 3.1d, d = 1.93 m Volume of concrete = 35.14m^3

Table 3.4 Design dimensions of drilled shaft and driven pile for different load cases

Load Case (kN)	Diameter of Piles in Sand (m)		Diameter of Piles in Clay (m)	
	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile
1000.00	1.21	0.57	1.35	1.22
2000.00	1.84	0.86	2.09	1.93
5000.00	3.11	1.46	3.58	3.38
Pile Length = 12 m				

3.3 Life Cycle Analysis of Pile Foundations

3.3.1 STEP 1: Goal and Scope Definition

The preliminary goals of the life cycle assessment performed in this research 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 study based on the LCI, which of the two aforementioned piles is more environmentally sustainable. For the environmental impact study, the results of LCI are classified into different impact categories, namely, human health, ecosystem health, acidification and global warming, and weights are assigned to each category. An impact score is derived which can be used as an indicator of environmental sustainability of a pile type. This analysis can supplement the technological and economic feasibility studies traditionally done in civil engineering projects, thus ensuring a balanced approach towards sustainability. Figure 3.4 shows the flow chart of the different processes involved, inputs and outputs, and the environmental impact categories related to pile construction that are considered in the LCA.

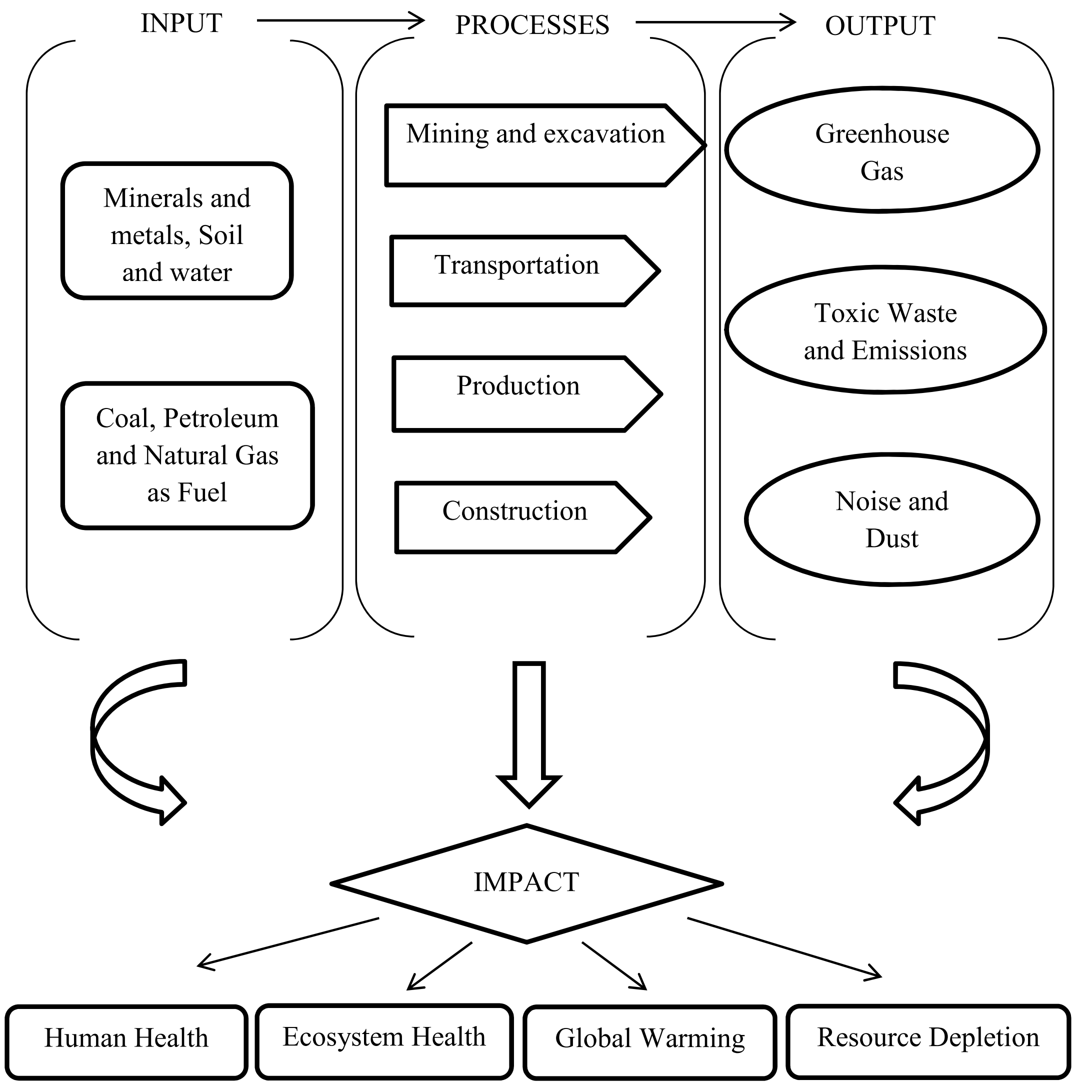

Figure 3.4 Flow chart showing the inputs, outputs, processes and impact categories in pile construction

The final goal of the LCA is to provide relevant quantitative information that can be used for formulating a sustainability index. The sustainability index is assumed to be

a function of economic and social benefits, energy use and environmental impact. The LCA provides the data for the energy use and environmental impact assessment while the CBA provides the data for social and economic benefits. The developed sustainability index is used in this study to compare the sustainability of the two pile types. Thus, the final objective of this study is to quantitatively assess the sustainability of pile foundations.

The scope of this study primarily includes identification and quantification of all the major inputs to and outputs from the process of pile construction. The inputs that are considered in this study are cement and steel from the manufacturing segment and land, water and fuel from the biosphere. The outputs are the constructed piles along with emissions to air and water, and the construction debris to landfill. The goal of this study implies that the scope should also include all inputs upstream and all outputs downstream of the manufacturing of the major inputs, that is, cement and steel. However, the contributors to energy or resource consumption like 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. The effects of the process of construction include permanent change in land use pattern, change in infiltration rate due to soil compaction, damage to soil biota, and noise and dust in the neighborhood. The quantification of these effects is kept out of the scope of the study although a qualitative assessment of such effects is included.

3.3.2 STEP 2: Inventory Analysis

Based on the above stated goal and scope of this LCA, life cycle inventory (LCI) for pile foundation should quantify (i) the inputs and outputs for concrete and steel manufacturing for the manufactured raw material sector and (ii) other inputs and outputs from the natural resource sector. Material inputs to concrete manufacturing consists of cement, sand, aggregate (gravel and macadam) and water. Sand and aggregate are natural resources that are freely available and require minimum processing. Hence, the environmental impact of concrete manufacturing comes mainly from cement and, as such, the cement manufacturing sector is the third largest contributor to greenhouse gas (GHG) emissions in the United States (Ramaswami et al. 2008). For this particular study, the environmental effects of concrete is considered as the sum of (i) environmental impacts 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. 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. All the inputs and outputs for the two different pile types are calculated based on the design calculations given in Section 3.2.2.

Standard LCI methodology accounts for all inputs and outputs in terms of mass flow (e.g., kilogram of input/unit product). One drawback of the method is that the limiting resource on the earth is not mass but energy and, more precisely, available energy that can do useful work. Mass accounting methods neglect the relative consequences of using inputs that have different amounts of available energy. Moreover,

mass accounting does not consider the ecosystem services that went into making the material, and hence, fails to capture the actual effect of material use on the ecosystem. Therefore, in this study, the resource use has been quantified based on exergy, emergy and embodied energy, in addition to mass. The output side of the inventory is calculated in terms of mass, though, because of the nature of the data available.

3.3.2.1 Resource Consumption for Pile Foundations

The calculation for resource consumption is reported in Table 3.5-3.8 and outputs from the processes are reported in Table 3.9-3.14. In the case of cement manufacturing, the resource use for cement with fly ash content greater than 40% is calculated in addition to the calculation of resource use for pure Portland cement. Similarly, for the case of steel manufacturing, the resource consumption of recycled steel is calculated in addition to that of virgin steel. These additional calculations with fly ash and recycled steel is done to show that higher resource efficiency can be achieved if cement mixed with fly ash and recycled steel is used in the construction. However, data regarding the process emissions related to fly ash-cement and recycled steel are not available because of which further calculations for environmental impact assessment are not done for these alternate materials.

Table 3.5 Resource consumption for drilled shaft in sand

RESOURCE CONSUMPTION CALCULATION FOR DRILLED SHAFT IN SAND										
					Emergy		Embodied Energy		Cumulative Exergy	
Sl No.	Materials	Volume (m^3)	Density (Kg/m^3)	Mass (Kg)	Emergy Intensity ($\times 10^{11}$) (sej/Kg)	Total Emergy ($\times 10^{11}$) (sej)	Embodied Energy Intensity (MJ/Kg)	Total Embodied Energy (MJ)	Unit Exergy (MJ/Kg)	Total Exergy (MJ)
		(1)	(2)	(3) = (2) × (1)	(4)	(5) = (3) × (4)	(6)	(7) =(6) × (3)	(8)	(9) = (8) × (3)
1	Soil	31.91		—	—	—	—	—	—	—
(a)	Top soil (3 m)	7.98		16210.93		13617.18				
(b)	Rest	23.93	2031.91	48632.79	28	13617.18	0.45	29179.67	0.02	1478.44
Note: For emergy calculation of soil, only emergy intensity of organic content of soil is considered; Mass of organic content is calculated as 3% of soil mass at top soil and 1% of soil mass below the top soil (Pulselli et al. 2004);										
2	Cement	Calculated as 297Kg/m^3 of concrete;		9414.24	—	—	—	—	—	—
(a)	Virgin			—	19.70	185460.46	4.60	43305.49	5.35	50366.17
(b)	Recycled (Fly ash content >40%)			—	140.00	1317993.14	2.43	22876.60	—	—
3	Steel				—	—	—	—	—	—
(a)	Virgin				41.30	2637.73	36.40	2324.78	41.00	2618.57
(b)	Recycled	0.01	7850.00	63.87	30.90	1973.51	13.10	836.67	—	—
Total emergy / embodied energy / exergy consumption as resources			(i) using virgin materials			215332.56		74809.94		54463.17
			(ii) using recycled materials			1347201.01		52892.93		—

Table 3.6 Resource consumption for driven pile in sand

RESOURCE CONSUMPTION CALCULATION FOR DRIVEN PILE IN SAND										
					Emergy		Embodied Energy		Cumulative Exergy	
Sl No.	Materials	Volume (m^3)	Density (Kg/m^3)	Mass (Kg)	Emergy Intensity ($\times 10^{11}$) (sej/Kg)	Total Emergy ($\times 10^{11}$) (sej)	Embodied Energy Intensity (MJ/Kg)	Total Embodied Energy (MJ)	Unit Exergy (MJ/Kg)	Total Exergy (MJ)
		(1)	(2)	(3) = (2) × (1)	(4)	(5) = (3) × (4)	(6)	(7) =(6) × (3)	(8)	(9) = (8) × (3)
1	Soil	7.03		—	—	—	—	—	—	—
(a)	Top soil (3 m)	1.76		3571.67		9000.62				
(b)	Rest	5.27	2031.91	10715.02	28	27001.85	0.45	6429.01	0.02	325.74
Note: For emergy calculation of soil, only emergy intensity of organic content of soil is considered; Mass of organic content is calculated as 3% of soil mass at top soil and 1% of soil mass below the top soil (Pulselli et al. 2004);										
2	Cement	Calculated as 297Kg/m^3 of concrete;		2088.25	—	—	—	—	—	—
(a)	Virgin			—	19.70	41138.61	4.60	9605.97	5.35	11172.16
(b)	Recycled (Fly ash content >40%)			—	140.00	292355.58	2.43	5074.46	—	—
3	Steel				—	—	—	—	—	—
(a)	Virgin				41.30	13677.22	36.40	12054.50	41.00	13577.87
(b)	Recycled	0.04	7850.00	331.17	30.90	10233.08	13.10	4338.30	—	—
Total emergy / embodied energy / exergy consumption as resources			(i) using virgin materials			90818.29		28089.48		25075.77
			(ii) using recycled materials			338591.12		15841.76		—

Table 3.7 Resource consumption for drilled shaft in clay

RESOURCE CONSUMPTION CALCULATION FOR DRILLED SHAFT IN CLAY										
					Emergy		Embodied Energy		Cumulative Exergy	
Sl No.	Materials	Volume (m^3)	Density (Kg/m^3)	Mass (Kg)	Emergy Intensity ($\times 10^{11}$) (sej/Kg)	Total Emergy ($\times 10^{11}$) (sej)	Embodied Energy Intensity (MJ/Kg)	Total Embodied Energy (MJ)	Unit Exergy (MJ/Kg)	Total Exergy (MJ)
		(1)	(2)	(3) = (2) × (1)	(4)	(5) = (3) × (4)	(6)	(7) =(6) × (3)	(8)	(9) = (8) × (3)
1	Soil	41.06		—	—	—	—	—	—	—
(a)	Top soil (3 m)	10.26		18839.97		15825.58				
(b)	Rest	30.79	1835.46	56519.92	28	15825.58	0.45	33911.95	0.02	1718.21
Note: For emergy calculation of soil, only emergy intensity of organic content of soil is considered; Mass of organic content is calculated as 3% of soil mass at top soil and 1% of soil mass below the top soil (Pulselli et al. 2004);										
2	Cement	Calculated as 297Kg/m^3 of concrete;		12194.16	—	—	—	—	—	—
(a)	Virgin			—	19.70	240224.92	4.60	56093.13	5.35	65238.75
(b)	Recycled (Fly ash content >40%)			—	140.00	1707182.15	2.43	29631.80	—	—
3	Steel				—	—	—	—	—	—
(a)	Virgin				41.30	2637.73	36.40	2324.78	41.00	2618.57
(b)	Recycled	0.01	7850.00	63.87	30.90	1973.51	13.10	836.67	—	—
Total emergy / embodied energy / exergy consumption as resources			(i) using virgin materials		274513.81		92329.86			69575.52
			(ii) using recycled materials		1740806.82		64380.42			—

Table 3.8 Resource consumption for driven pile in clay

RESOURCE CONSUMPTION CALCULATION FOR DRIVEN PILE IN CLAY										
					Emergy		Embodied Energy		Cumulative Exergy	
Sl No.	Materials	Volume (m^3)	Density (Kg/m^3)	Mass (Kg)	Emergy Intensity ($\times 10^{11}$) (sej/Kg)	Total Emergy ($\times 10^{11}$) (sej)	Embodied Energy Intensity (MJ/Kg)	Total Embodied Energy (MJ)	Unit Exergy (MJ/Kg)	Total Exergy (MJ)
		(1)	(2)	(3) = (2) × (1)	(4)	(5) = (3) × (4)	(6)	(7) =(6) × (3)	(8)	(9) = (8) × (3)
1	Soil	35.14		—	—	—	—	—	—	—
(a)	Top soil (3 m)	8.79		16124.68		13544.73				
(b)	Rest	26.36	1835.46	48374.04	28	13544.73	0.45	29024.42	0.02	1470.57
Note: For emergy calculation of soil, only emergy intensity of organic content of soil is considered; Mass of organic content is calculated as 3% of soil mass at top soil and 1% of soil mass below the top soil (Pulselli et al. 2004);										
2	Cement	Calculated as 297Kg/m^3 of concrete;		10436.69	—	—	—	—	—	—
(a)	Virgin			—	19.70	205602.70	4.60	48008.75	5.35	55836.27
(b)	Recycled (Fly ash content >40%)			—	140.00	1461135.94	2.43	25361.15	—	—
3	Steel				—	—	—	—	—	—
(a)	Virgin				41.30	68356.07	36.40	60246.03	41.00	67859.54
(b)	Recycled	0.21	7850.00	1655.11	30.90	51142.92	13.10	21681.95	—	—
Total emergy / embodied energy / exergy consumption as resources			(i) using virgin materials		301048.23		137279.20			125166.38
			(ii) using recycled materials		1539368.32		76067.52			—

Data Source for Resource Consumption Calculation

In the above calculations, the values of unit emergy for cement and steel are adopted from Brown and Buranakaran (2004) and Pulselli et al. (2007) while the values of unit emergy for land is used from the emergy folios of Odum (2000). The embodied energy values per unit mass are adopted from the ICE Database version 1.6a (2009). The exergy values of cement and steel used in the calculations are the same as those used by Berthiume et al. (2004), and are originally 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 quartz for the sand profile and as that of clay minerals for the clay profile, and the values are obtained from Meester et al. (2006).

Assumptions in Resource Consumption Calculation

For a construction site, land use is the total land area affected by construction and for pile foundations it should include the land in between and around the piles. However, for this study, land use is calculated as the volume of soil displaced by the pile volume because (i) the study compares the effects of single piles and not that of a project and (ii) it is assumed that the land use in between and around the piles will be same for both drilled shafts and driven piles as the same working superstructure load is used for the design calculations of both the pile types.

It is assumed that the top 1 m soil has an organic content of 3% and it decreases to 1% at depths greater than 1 m (Pulselli et al. 2007). Thus, the loss of total organic content considered for drilled shaft is calculated based on 3% for the top 1 m and on 1 % for the remaining pile length. Although, for driven pile, soil is not excavated out, it is

assumed that the entire organic content of the soil volume displaced by the pile is lost because the pile penetration process severely disturbs the soil.

It is further assumed that the quantity of cement required to manufacture 1 m^3 of concrete is 297 Kg (Sjunssen 2005). The reinforcement used in the piles is calculated based on the fact that drilled shaft requires nominal reinforcement while driven piles subjected to hammer blows require a greater percentage (Salgado 2008). A minimum reinforcement of 6 bars of 12 mm diameter is assumed for the drilled shaft while a reinforcement of 0.6% of the pile cross sectional area is considered for the driven pile.

The effect of fuel used during pile construction is not considered in the calculation primarily due to lack of data.

3.3.2.2 Output Inventory for Cement, Concrete and Steel used in Pile Construction

The National Renewable Energy Laboratory (NREL) LCA database for emissions to air per kilogram (Kg) of cement and steel manufacturing is used for calculating the process outputs for cement and steel, while the emissions to air per cubic meter (m^3) of concrete manufacturing is adopted from Sjunnesson (2005). The total quantity of cement, steel and concrete required for the piles, as obtained from the design calculations, is multiplied by the emission values per unit production of cement, concrete and steel (as obtained from NREL and Sjunnesson 2005) to calculate the total quantity of the output emissions. Tables 3.9-3.14 show the details of the calculations.

Table 3.9 Output inventory for cement production for piles in sand

Output Inventory for Cement Production					
Agent	Medium	Manufacturing Unit Location Environment	Quantity/ Unit (gm/gm)	Quantity Emitted for Drilled Shaft ($\times 10^3$) (gm)	Quantity Emitted for Driven Pile ($\times 10^3$) (gm)
				(5)	(6)
(1)	(2)	(3)	(4)	(5) and (6) = (4) × 297Kg of cement × volume of concrete used $\times 10^3$	
Particulates, unspecified	air	low population density	0.00235	22.28	4.91
Particulates, > 2.5 µm, and < 10µm	air	low population density	0.00030	2.81	0.62
Carbon dioxide, biogenic	air	low population density	0.37359	3540.91	780.15
Carbon dioxide, fossil	air	low population density	0.55344	5245.54	1155.72
Sulfur dioxide	air	low population density	0.00166	15.76	3.47
Nitrogen oxides	air	low population density	0.00250	23.73	5.23
VOC, volatile organic	air	low population density	0.00005	0.47	0.10
Carbon monoxide	air	low population density	0.00110	10.47	2.31
Methane	air	low population density	0.00003	0.28	0.06
Ammonia	air	low population density	0.00001	0.05	0.01
Hydrogen chloride	air	low population density	0.00006	0.57	0.13

Table 3.10 Output inventory for cement production for piles in clay

Output Inventory for Cement Production					
Agent	Medium	Manufacturing Unit Location Environment	Quantity/ Unit (gm/gm)	Quantity Emitted for Drilled Shaft ($\times 10^3$) (gm)	Quantity Emitted for Driven Pile ($\times 10^3$) (gm)
(1)	(2)	(3)	(4)	(5)	(6)
				(5) and (6) = (4) × 297Kg of cement × volume concrete used × 10^3	
Particulates, unspecified	air	low population density	0.0023503	27.78	23.54
> 2.5 µm, and < 10µm	air	low population density	0.0002963	3.50	2.97
Particulates, < 2.5 µm	air	low population density	0.0000001	0.00	0.00
dioxide, biogenic	air	low population density	0.3735900	4415.09	3741.21
dioxide, fossil	air	low population density	0.5534400	6540.57	5542.26
Sulfur dioxide	air	low population density	0.0016623	19.65	16.65
Nitrogen oxides	air	low population density	0.0025034	29.59	25.07
VOC, volatile	air	low population density	0.0000502	0.59	0.50
Carbon monoxide	air	low population density	0.0011045	13.05	11.06
Methane	air	low population density	0.0000395	0.47	0.40
Ammonia	air	low population density	0.0000048	0.06	0.05
Hydrogen chloride	air	low population density	0.0000649	0.77	0.65

Table 3.11 Output inventory for concrete manufacturing for piles in sand

Output Inventory for Concrete Manufacturing					
Agent	Medium	Manufacturing Unit Location Environment	Quantity/ Unit (gm/m^3)	Quantity Emitted for Drilled Shaft (gm)	Quantity Emitted for Driven Pile (gm)
(1)	(2)	(3)	(4)	(5)	(6)
				(5) and (6) = (4) × volume of concrete used	
Particulates	air	low population density	0.08	2.61	0.58
Carbon dioxide	air	low population density	257.00	8201.56	1807.01
Carbon monoxide	air	low population density	0.59	18.80	4.14
Nitrogen oxides (NOx)	air	low population density	0.49	15.67	3.45
Sulfur dioxides (SO_2)	air	low population density	0.43	13.59	3.00
Methane	air	low population density	1.60	51.06	11.25
Ammonia	air	low population density	0.01	0.22	0.05

Table 3.12 Output inventory for concrete manufacturing for piles in clay

Output Inventory for Concrete Manufacturing					
Agent	Medium	Manufacturing Unit Location Environment	Quantity/ Unit (gm/m^3)	Quantity Emitted for Drilled Shaft (gm)	Quantity Emitted for Driven Pile (gm)
				(5)	(6)
(1)	(2)	(3)	(4)	(5) and (6) = (4) × volume of concrete used	
Particulates	air	low population density	0.082	3.25	2.76
Carbon dioxide	air	low population density	257	10226.37	8665.50
Carbon monoxide	air	low population density	0.589	23.44	19.86
Nitrogen oxides (NOx)	air	low population density	0.491	19.54	16.56
Sulfur dioxides (SO_2)	air	low population density	0.426	16.95	14.36
Methane	air	low population density	1.6	63.67	53.95
Ammonia	air	low population density	0.007	0.28	0.24

Table 3.13 Output inventory for steel manufacturing for piles in sand

Agent	Medium	Quantity of Emission Per Unit (× 10^{-4}) (gm/Kg)	Quantity emitted for Drilled Shaft (gm)	Quantity emitted for Driven Pile (gm)
			(5) and (6)=(4) × weight of steel	
(1)	(2)	(4)	(5)	(6)
Acrolein	air	0.03	0.0002	0.0010
Ammonia	air	10.89	0.0696	0.3607
Antimony	air	0.02	0.0001	0.0005
Arsenic	air	0.11	0.0007	0.0037
Benzene	air	0.04	0.0003	0.0014
Beryllium	air	0.01	0.0001	0.0004
Carbon dioxide, biogenic	air	1373.70	8.77	45.49
Carbon dioxide, fossil	air	19400000.00	123903.14	642465.10
Carbon monoxide, fossil	air	229320.00	1464.61	7594.33
Chlorine	air	0.12	0.0008	0.00
Chromium	air	0.18	0.0011	0.01
Cobalt	air	0.05	0.0003	0.00
Dinitrogen monoxide	air	19.03	0.12	0.63
Ethene, trichloro-	air	0.03	0.0002	0.001
Hydrogen fluoride	air	21.26	0.14	0.70
Lead	air	0.11	0.001	0.004
Manganese	air	0.35	0.002	0.011
Mercury	air	0.06	0.0004	0.0020
Methane	air	7871.90	50.28	260.69
Nickel	air	0.52	0.003	0.017
Nitrogen oxides	air	21102.00	134.77	698.83
Sulfur dioxide	air	7188.30	45.91	238.05
Sulfur oxides	air	29106.00	185.89	963.90

Table 3.14 Output inventory for steel manufacturing for piles in clay

Output Inventory for Steel Manufacturing				
Agent	Medium	Quantity of Emission Per Unit (× 10^{-4}) (gm/Kg)	Quantity emitted for Drilled Shaft (gm)	Quantity emitted for Driven Pile (gm)
			(5) and (6)=(4) × weight of steel	
(1)	(2)	(4)	(5)	(6)
Acrolein	air	0.03	0.0002	0.0050
Ammonia	air	10.89	0.0696	1.8029
Antimony	air	0.02	0.0001	0.0027
Arsenic	air	0.11	0.0007	0.0184
Benzene	air	0.04	0.0003	0.0072
Beryllium	air	0.01	0.0001	0.0021
Carbon dioxide, biogenic	air	1373.70	8.7735	227.3626
Carbon dioxide, fossil	air	19400000.00	123903.1440	3210914.7454
Carbon monoxide, fossil	air	229320.00	1464.6118	37954.9984
Chlorine	air	0.12	0.0008	0.0203
Chromium	air	0.18	0.0011	0.0294
Cobalt	air	0.05	0.0003	0.0077
Dinitrogen monoxide	air	19.03	0.1215	3.1495
Ethene, trichloro-	air	0.03	0.0002	0.0048
Hydrogen fluoride	air	21.26	0.1358	3.5181
Lead	air	0.11	0.0007	0.0184
Manganese	air	0.35	0.0022	0.0573
Mercury	air	0.06	0.0004	0.0099
Methane	air	7871.90	50.2759	1302.8866
Nickel	air	0.52	0.0033	0.0861
Nitrogen oxides	air	21102.00	134.7734	3492.6146
Sulfur dioxide	air	7188.30	45.9099	1189.7432
Sulfur oxides	air	29106.00	185.8930	4817.3652

3.3.3 STEP 3: Impact Assessment

In this chapter, the impact assessment of driven and drilled piles is divided into two categories — the quantifiable impacts and the non-quantifiable impacts. The impact of resource use and emissions to air due to the manufacturing processes of the associated materials has been quantified using existing databases like ReCiPe — these form the quantifiable impacts. The other impacts like change in land use pattern, rate of infiltration and run-off, noise pollution and vibration could not be quantified due to lack of information and has been discussed qualitatively under the category of non-quantifiable impact.

3.3.3.1 Quantifiable Impacts

For this study, the impact categories that are important and relevant are (1) resource use, (2) human health and (3) ecological consequences. Under resource use, there are two sub-categories – material use and land use. The human health category primarily deals with toxicity. The ecological consequences category has three further sub-categories – global warming, acidification and ecosystem health. Tables 3.15-3.20 show the results.

Table 3.15 Impact classification and quantification for cement manufacturing for piles in sand

Environmental Impact of Cement Production											
			Quantity/ Unit	Quantity Emitted for Drilled Shaft	Quantity Emitted for Driven Pile	Global Warming Potential ($\times 10^3$) (gm equivalent CO_2)			Acidification Potential ($\times 10^3$) (gm equivalent SO_2)		
Agent	Medium	Manufacturing Unit Location Environment	(gm/gm)	($\times 10^3$) (gm)	($\times 10^3$) (gm)	Index	For Drilled Shaft	For Driven Pile	Index	For Drilled Shaft	For Driven Pile
				(5)	(6)		(8)	(9)		(11)	(12)
(1)	(2)	(3)	(4)	(5) and (6) = (4) × 297Kg of cement × volume of concrete used $\times 10^3$		(7)	(8) = (5)×(7)	(9) = (6)×(7)	(10)	(11) = (5)×(10)	(12) = (6)×(10)
Particulates, unspecified	air	low population	0.00235	22.28	4.91	—	NA	NA	—	NA	NA
Particulates, > 2.5 µm, and < 10µm	air	low population density	0.00030	2.81	0.62	—	NA	NA	—	NA	NA
Carbon dioxide, biogenic	air	low population density	0.37359	3540.91	780.15	1.00	3540.91	780.15	—	NA	NA
Carbon dioxide, fossil	air	low population density	0.55344	5245.54	1155.72	1.00	5245.54	1155.72	—	NA	NA
Sulfur dioxide	air	low population density	0.00166	15.76	3.47	—	NA	NA	1.00	15.76	3.47
Nitrogen oxides	air	low population	0.00250	23.73	5.23	—	NA	NA	0.52	12.34	2.72
VOC, volatile organic	air	low population density	0.00005	0.47	0.10	—	NA	NA	—	NA	NA
Carbon monoxide	air	low population	0.00110	10.47	2.31	—	NA	NA	—	NA	NA
Methane	air	low population	0.00003	0.28	0.06	25.00	7.11	1.57	—	NA	NA
Ammonia	air	low population	0.00001	0.05	0.01	—	NA	NA	2.23	0.11	0.02
Hydrogen chloride	air	low population	0.00006	0.57	0.13	—	NA	NA	—	NA	NA
TOTAL IMPACT IN CATEGORIES							8793.56	1937.44		28.20	6.21

Table 3.16 Impact classification and quantification for cement manufacturing for piles in clay

Environmental Impact of Cement Production											
Agent	Medium	Manufacturing Unit Location Environment	Quantity/ Unit (gm/gm)	Quantity Emitted for Drilled Shaft ($\times 10^3$) (gm)	Quantity Emitted for Driven Pile ($\times 10^3$) (gm)	Global Warming Potential ($\times 10^3$) (gm equivalent CO_2) Index	For Drilled Shaft	For Driven Pile	Acidification Potential ($\times 10^3$) (gm equivalent SO_2) Index	For Drilled Shaft	For Driven Pile
				(5)	(6)		(8)	(9)		(11)	(12)
(1)	(2)	(3)	(4)	(5) and (6) = (4) × 297Kg of cement × volume of concrete used × 10^3		(7)	(8) = (5)×(7)	(9) = (6)×(7)	(10)	(11) = (5)×(10)	(12) = (6)×(10)
Particulates, unspecified	air	low population density	0.0023503	27.78	23.54	—	NA	NA	—	NA	NA
Particulates, > 2.5 µm, and < 10µm	air	low population density	0.0002963	3.50	2.97	—	NA	NA	—	NA	NA
Particulates, < 2.5 µm	air	low population density	0.0000001	0.00	0.00	—	NA	NA	—	NA	NA
Carbon dioxide, biogenic	air	low population density	0.3735900	4415.09	3741.21	1.00	4415.09	3741.21	—	NA	NA
Carbon dioxide, fossil	air	low population density	0.5534400	6540.57	5542.26	1.00	6540.57	5542.26	—	NA	NA
Sulfur dioxide	air	low population density	0.0016623	19.65	16.65	—	NA	NA	1.00	19.65	16.65
Nitrogen oxides	air	low population density	0.0025034	29.59	25.07	—	NA	NA	0.52	15.38	13.04
VOC, volatile organic compounds	air	low population density	0.0000502	0.59	0.50	—	NA	NA	—	NA	NA
Carbon monoxide	air	low population density	0.0011045	13.05	11.06	—	NA	NA	—	NA	NA
Methane	air	low population density	0.0000395	0.47	0.40	25.00	11.68	9.90	—	NA	NA
Ammonia	air	low population density	0.0000048	0.06	0.05	—	NA	NA	2.23	0.13	0.11
Hydrogen chloride	air	low population density	0.0000649	0.77	0.65	—	NA	NA	—	NA	NA
TOTAL IMPACT IN CATEGORIES							10967.34	9293.37		35.15	29.79

Table 3.17 Impact classification and quantification for concrete manufacturing for piles in sand

Environmental Impact of Concrete Production											
			Quantity/ Unit			Global Warming Potential (gm equivalent CO_2)			Acidification Potential (gm equivalent SO_2)		
Agent	Medium	Manufacturing Unit Location Environment	(gm/m^3)	Quantity Emitted for Drilled Shaft (gm)	Quantity Emitted for Driven Pile (gm)	Index	For Drilled Shaft	For Driven Pile	Index	For Drilled Shaft	For Driven Pile
				(5)	(6)		(8)	(9)		(11)	(12)
(1)	(2)	(3)	(4)	(5) and (6) = (4) × volume of concrete used		(7)	(8) = (5)×(7)	(9) = (6)×(7)	(10)	(11) = (5)×(10)	(12) = (6)×(10)
Particulates	air	low population density	0.08	2.61	0.58	—	NA	NA	—	NA	NA
Carbon dioxide	air	low population density	257.00	8201.56	1807.01	1.00	8201.56	1807.01	—	NA	NA
Carbon monoxide	air	low population density	0.59	18.80	4.14	—	NA	NA	—	NA	NA
Nitrogen oxides (NOx)	air	low population density	0.49	15.67	3.45	—	NA	NA	0.52	8.15	1.7952
Sulfur dioxides (SO_2)	air	low population density	0.43	13.59	3.00	—	NA	NA	1.00	13.59	2.9953
Methane	air	low population density	1.60	51.06	11.25	25.00	1276.51	281.25	—	NA	NA
Ammonia	air	low population density	0.01	0.22	0.05	—	NA	NA	2.23	0.4982	0.1098
TOTAL IMPACT IN CATEGORIES							9478.06	2088.25		22.24	4.900

Table 3.18 Impact classification and quantification for concrete manufacturing for piles in clay

Environmental Impact of Concrete Manufacturing											
			Quantity/ Unit	Quantity Emitted for Drilled Shaft	Quantity Emitted for Driven Pile	Global Warming Potential (gm equivalent CO_2)			Acidification Potential (gm equivalent SO_2)		
Agent	Medium	Manufacturing Unit Location Environment	(gm/m^3)	(gm)	(gm)	Index	For Drilled Shaft	For Driven Pile	Index	For Drilled Shaft	For Driven Pile
				(5)	(6)		(8)	(9)		(11)	(12)
(1)	(2)	(3)	(4)	(5) and (6) = (4) × volume of concrete used		(7)	(8) = (5)×(7)	(9) = (6)×(7)	(10)	(11) = (5)×(10)	(12) = (6)×(10)
Particulates	air	low population density	0.082	3.25	2.76	—	NA	NA	—	NA	NA
Carbon dioxide	air	low population density	257	10226.37	8665.50	1	10226.37	8665.50	—	NA	NA
Carbon monoxide	air	low population density	0.589	23.44	19.86	—	NA	NA	—	NA	NA
Nitrogen oxides (NOx)	air	low population density	0.491	19.54	16.56	—	NA	NA	0.52	10.16	8.61
Sulfur dioxides (SO_2)	air	low population density	0.426	16.95	14.36	—	NA	NA	1.00	16.95	14.36
Methane	air	low population density	1.6	63.67	53.95	25	1591.65	1348.72	—	NA	NA
Ammonia	air	low population density	0.007	0.28	0.24				2.23	0.62	0.53
TOTAL IMPACT IN CATEGORIES							11818.02	10014.21		27.73	23.50

Table 3.19 Impact classification and quantification for steel manufacturing for piles in sand

Environmental Impact for Steel Manufacturing																		
Agent	Medium	Quantity emitted for Drilled Shaft (gm)	Quantity emitted for Driven Pile (gm)	Human Toxicity (gm equivalent 1,4 DB)			Terrestrial Eco-Toxicity (gm equivalent 1,4 DB)			Freshwater Eco-Toxicity (gm equivalent 1,4 DB)			Acidification Potential (gm equivalent SO_2)			Global Warming Potential (gm equivalent CO_2)		
		(5) and (6)=(4) × weight of steel		Index	drilled shaft	driven pile	Index	drilled shaft	driven pile	Index	drilled shaft	driven pile	Index	drilled shaft	driven pile	Index	drilled shaft	driven pile
(1)	(2)	(5)	(6)	(7)	(8) = (7)×(5)	(9) =(7)×(6)	(10)	(11) = (10)×(5)	(12) = (10)×(6)	(13)	(14) = (13)×(5)	(15) = (14)×(6)	(16)	(17) = (16)×(5)	(18) = (16)×(6)	(19)	(20) = (19)×(5)	(21) = (19)×(6)
Acrolein	air	0.0002	0.0010	6154.00	1.2	6.20	1.11	0.0002	0.001	0.49	0.0001	0.0005				—	NA	NA
Ammonia	air	0.0696	0.3607	—	NA	NA	—	NA	NA	—	NA	NA	2.23	0.15514	0.804	—	NA	NA
Antimony	air	0.0001	0.0005	35230.00	3.7	19.24	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Arsenic	air	0.0007	0.0037	649500.00	461.9	2395.06	5.75	0.004	0.021	1.74	0.0012	0.0064	—	NA	NA	—	NA	NA
Benzene	air	0.0003	0.0014	0.36	0.0001	0.001	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Beryllium	air	0.0001	0.0004	17800.00	1.5	7.54	130.00	0.011	0.055	68.19	0.0056	0.0289	—	NA	NA	—	NA	NA
Carbon dioxide, biogenic	air	8.77	45.49	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	1.00	8.77	45.49
Carbon dioxide, fossil	air	123903.14	642465.10	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	1.00	123903.1	642465.1
Carbon monoxide, fossil	air	1464.61	7594.33	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Chlorine	air	0.0008	0.00	209.90	0.2	0.8537	0.44	0.0003	0.002	0.01	0.00001	0.00005	—	NA	NA	—	NA	NA
Chromium	air	0.0011	0.01	0.34	0.0004	0.002005	9.06	0.010	0.053	0.35	0.0004	0.0021	—	NA	NA	—	NA	NA
Cobalt	air	0.0003	0.00	4310.00	1.3	6.67221	23.29	0.007	0.036	12.74	0.0038	0.0197	—	NA	NA	—	NA	NA
Dinitrogen monoxide	air	0.12	0.63	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	298.00	36.22	187.79
Ethene, trichloro-	air	0.0002	0.001	193.70	0.04	0.18530	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Hydrogen fluoride	air	0.14	0.70	266.10	36.1	187.32	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Lead	air	0.001	0.004	23110.00	16.4	84.88	8.79	0.006	0.032	0.17	0.0001	0.0006	—	NA	NA	—	NA	NA
Manganese	air	0.002	0.011	26230.00	58.0	300.72	0.01	0.00002	0.00011	1.96	0.0043	0.0224	—	NA	NA	—	NA	NA
Mercury	air	0.0004	0.0020	1224000	465.4	2413.25	1698	0.646	3.348	11.44	0.0043	0.0226	—	NA	NA	—	NA	NA
Methane	air	50.28	260.69	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	25.00	1256.90	6517.30
Nickel	air	0.003	0.017	680.90	2.3	11.73	80.00	0.266	1.379	32.94	0.1095	0.5677	—	NA	NA	—	NA	NA
Nitrogen oxides	air	134.77	698.83	—	NA	NA	—	NA	NA	—	NA	NA	0.52	70.08	363.39	—	NA	NA
Sulfur dioxide	air	45.91	238.05	—	NA	NA	—	NA	NA	—	NA	NA	1.00	45.91	0.00	—	NA	NA
Sulfur oxides	air	185.89	963.90	—	NA	NA	—	NA	NA	—	NA	NA	1.00	185.89	963.90	—	NA	NA
TOTAL IMPACT IN CATEGORIES					1047.91	5433.66		0.95	4.93		0.13	0.67		302.04	1328.10		125205.03	649215.7

Table 3.20 Impact classification and quantification for steel manufacturing for piles in clay

Environmental Impact for Steel Manufacturing																			
Agent	Medium	Quantity of Emission Per Unit ($\times 10^{-4}$) (gm/Kg)	Quantity emitted for Drilled Shaft (gm)	Quantity emitted for Driven Pile (gm)	Human Toxicity (gm equivalent 1,4 DB)			Terrestrial Eco-Toxicity (gm equivalent 1,4 DB)			Freshwater Eco-Toxicity (gm equivalent 1,4 DB)			Acidification Potential (gm equivalent SO_2)			Global Warming Potential (gm equivalent CO_2)		
			(5) and (6)=(4) × weight of steel		Index	drilled shaft	driven pile	Index	drilled shaft	driven pile	Index	drilled shaft	driven pile	Index	drilled shaft	driven pile	Index	drilled shaft	driven pile
(1)	(2)	(4)	(5)	(6)	(7)	(8) = (7)×(5)	(9) =(7)×(6)	(10)	(11) = (10)×(5)	(12) = (10)×(6)	(13)	(14) = (13)×(5)	(15) = (14)×(6)	(16)	(17) = (16)×(5)	(18) = (16)×(6)	(19)	(20) = (19)×(5)	(21) = (19)×(6)
Acrolein	air	0.03	0.0002	0.0050	6154.00	1.2	30.99	1.11	0.0002	0.006	0.49	0.0001	0.0025				—	NA	NA
Ammonia	air	10.89	0.0696	1.8029	—	NA	NA	—	NA	NA	—	NA	NA	2.23	0.15514	4.020	—	NA	NA
Antimony	air	0.02	0.0001	0.0027	35230.00	3.7	96.17	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Arsenic	air	0.11	0.0007	0.0184	649500.0	461.9	11970.06	5.75	0.004	0.106	1.74	0.0012	0.0320	—	NA	NA	—	NA	NA
Benzene	air	0.04	0.0003	0.0072	0.36	0.0001	0.003	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Beryllium	air	0.01	0.0001	0.0021	17800.00	1.5	37.68	130.00	0.011	0.275	68.19	0.0056	0.1443	—	NA	NA	—	NA	NA
Carbon dioxide, biogenic	air	1373.70	8.7735	227.3626	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	1.00	8.77	227.36
Carbon dioxide, fossil	air	19400000.0	123903.1	3210914.7	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	1.00	123903.1	3210915
Carbon monoxide, fossil	air	229320.00	1464.6118	37954.998	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Chlorine	air	0.12	0.0008	0.0203	209.90	0.2	4.2669	0.44	0.0003	0.009	0.01	0.00001	0.00025	—	NA	NA	—	NA	NA
Chromium	air	0.18	0.0011	0.0294	0.34	0.0004	0.010019	9.06	0.010	0.266	0.35	0.0004	0.0103	—	NA	NA	—	NA	NA
Cobalt	air	0.05	0.0003	0.0077	4310.00	1.3	33.34639	23.29	0.007	0.180	12.74	0.0038	0.0986	—	NA	NA	—	NA	NA
Dinitrogen monoxide	air	19.03	0.1215	3.1495	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	298.00	36.22	938.55
Ethene, trichloro-	air	0.03	0.0002	0.0048	193.70	0.04	0.92607	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Hydrogen fluoride	air	21.26	0.1358	3.5181	266.10	36.1	936.17	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Lead	air	0.11	0.0007	0.0184	23110.00	16.4	424.23	8.79	0.006	0.161	0.17	0.0001	0.0032	—	NA	NA	—	NA	NA
Manganese	air	0.35	0.0022	0.0573	26230.00	58.0	1502.93	0.01	0.00002	0.00053	1.96	0.0043	0.1121	—	NA	NA	—	NA	NA
Mercury	air	0.06	0.0004	0.0099	1224000	465.4	12060.93	1698	0.646	16.732	11.44	0.0043	0.1127	—	NA	NA	—	NA	NA
Methane	air	7871.90	50.2759	1302.8866	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	25.00	1256.90	32572.16
Nickel	air	0.52	0.0033	0.0861	680.90	2.3	58.64	80.00	0.266	6.890	32.94	0.1095	2.8371	—	NA	NA	—	NA	NA
Nitrogen oxides	air	21102.00	134.7734	3492.6146	—	NA	NA	—	NA	NA	—	NA	NA	0.52	70.08	1816.16	—	NA	NA
Sulfur dioxide	air	7188.30	45.9099	1189.7432	—	NA	NA	—	NA	NA	—	NA	NA	1.00	45.91	0.00	—	NA	NA
Sulfur oxides	air	29106.00	185.8930	4817.3652	—	NA	NA	—	NA	NA	—	NA	NA	1.00	185.89	4817.37	—	NA	NA
TOTAL IMPACT IN CATEGORIES						1046.63	27156.36		0.95	24.63		0.13	3.35		302.04	6637.55		125205.0	3244653

Data Source and Assumptions for Impact Assessment

In this particular study, the weights (indexes) are used as per the ReCiPe database (2009). ReCiPe and its predecessor Eco-indicator99 was developed for average European conditions and is based on product life cycle. It uses the impact categories of ecosystem health, human health and resource use to classify the effect of environmental loading. Average European data is used to determine the damage caused by exposure to such effects and then weights (indexes) are used to signify the seriousness of the damage caused. The database is created for two sets of weights, the midpoint and the endpoint indicators. Because environmental impact categories are interlinked, different agents contributing to different primary impact categories like global warming and acidification can also be related to a single secondary impact category like human health. Midpoint indicators relate the agent to its primary impact while endpoint indicators relate to the secondary impact. For this study, midpoint indicators are used as weights (indexes) to avoid the higher degree of uncertainty associated with the end point indicators.

The impact in the category of acidification is calculated in terms of SO_2 acidification potential and determined as gm equivalent SO_2. The category of global warming (climate change) is calculated in terms of global warming potential of CO_2 and is determined as gm equivalent CO_2. The ecosystem health category includes both terrestrial and freshwater toxicity. The categories of terrestrial toxicity, freshwater toxicity and human toxicity is calculated in terms of toxicity potential of 1,4 dichlorobenzene (1,4 DB) and is expressed as gm equivalent of 1,4 DB.

3.3.3.2 Non-quantifiable Impacts

Land Use

Continuous depletion of resource is a rising concern for sustainability. Consequently, resource use optimization has received considerable attention in all standardization. Resources can be sub classified as renewable and non-renewable or as biotic and abiotic. Biotic resources are living and hence regenerative or renewable, while abiotic resources are nonliving like minerals and fossil fuel and mostly non-renewable. Resources are also often classified into deposits, funds and flows. Deposits are resources that cannot regenerate within human life time, e.g., minerals, clays and fossil fuels, while funds are resources that regenerate within human lifetime, e.g., topsoil and groundwater. Flows are resources like rivers and forests that are continuously regenerated.

An important impact of pile construction is the change in land use pattern. Change in land use pattern depletes resource both in terms of abiotic and biotic resources because it interferes with the soil biota and also leads to loss of top soil at the construction site. Characterization of impacts of land use is disputed and is divided into impacts of resource use and impacts on biodiversity. Land transformation leads to a shift in the competitive use of land and changes the quality of land from its original state. The relatively ambiguous concept of quality makes it difficult to characterize this aspect of land use and, as such, there is no characterization method available for this aspect of land use till date.

Land transformation also affects the biodiversity of the area but the relation between these two is complex and data is not sufficiently available to improve the present state of understanding. Characterization methods available at present use the rate of

extinction of species, and the types of species and ecosystems disappearing from the area. Soil plays an important role in cycling of nutrients, regeneration of soil fertility, maintaining micro climate and ground hydrology. All these processes are life supporting and hence any degradation in these processes need to be characterized precisely. However, present day practices only relate to the biological aspect of soil system (e.g., organic content) and the other aspects are ignored. Thus, except for the organic content, the effect of pile construction on land use could not be quantified.

Soil Compaction

Effect on Soil Biota and Biological Processes

Soil compaction alters the physical properties of soil by modifying the soil structure and fabric, density, porosity and pore structure (Beylich et al. 2010, Richard et al. 2001, Paglial et al. 2003, 2004). Compaction results in lower aeration and water infiltration rates and reduced hydraulic conductivity, which affects the growth and sustenance of plants and soil microorganisms, and also the biologically driven processes like respiration rates and macropore formation. Soil compaction also decreases CO_2 efflux and net N-mineralization, and increases C-mineralization (Beylich et al. 2010). Soil compaction negatively impacts the soil fauna as well — the biomass and the population density of the soil animals are reduced and their activity greatly hampered (Langmaack 1999, Beylich et al. 2010). Thus, the major effects of decrease in pore volume due to compaction is a lesser habitable place for soil organisms, lesser access to energy and nutrients, and a reduction in gas exchange between soil and the free atmosphere (Beylich et al. 2010).

According to Oberholzer and Hooper (2006), soil is a nonrenewable resource that provides essential ecosystem services to mankind, and hence, it is important to indicate a threshold value of compaction that does not interfere with the proper functioning of the soil ecological system (Beylich et al. 2010). Based on a literature review, Beylich et al. (2010) arrived at threshold values for some soil parameters which should not be exceeded to maintain the soil ecological balance. Macropore volume should not be less than 5% of the total volume, saturated hydraulic conductivity should not be lower than 0.1 m/day, and the effective bulk unit weight should not exceed 19.62 KN/m^3. Unfortunately, the degree of soil compaction achieved due to pile construction has not been estimated considering the above factors. Thus, further study is necessary so that the effect of compaction caused due to pile construction can be quantified and included as a part of quantitative EIA.

Effect on Infiltration Rate and Runoff

Soil compaction affects infiltration rate resulting in increased run-off volume, greater flooding potential and reduced groundwater recharge. Gregory et al. (2006) measured the change in infiltration rate due to compaction related to construction activity for a site in Florida which was transformed from a forested land to a built-up land, and showed that an overall decrease in infiltration rate from 733 mm/hr to 178 mm/hr occurred due to the use of heavy construction machinery. Construction process also increased the soil bulk unit weight from 13.1 kN/m^3 to 14.6 kN/m^3. Both these changes are significant and should be considered for soil ecosystem health.

General Observations on Non-quantifiable Impacts

From the perspective of non-quantifiable impacts, it is difficult to decide for certain which type of pile is more suitable. In the category of impact on soil biota and on rates of infiltration and runoff, driven piles perform much worse than drilled shafts because the pile driving process disturbs the soil structure considerably. Hence, from the ecosystem perspective, drilled shaft provides a less destructive alternative. However, in the absence of any quantification of the degree of compaction caused by pile driving or soil drilling, it is rather difficult to quantify the effect of soil compaction on the related environmental impacts. In the case of land use, driven pile scores more because of its relatively low volume, and hence, relatively low land area use. However, the construction of driven piles causes vibrations which negatively impact built environment and soil organisms. Unfortunately, sufficient data on the spatial and temporal effect of such vibration on the surrounding structure and on the soil biota is not available. Also, pile driving produces loud noise which causes disturbance in the neighborhood and, if not monitored, may cause serious health effect on the people living in the locality. Therefore, considering vibration and noise, drilled shafts may the more sustainable option.

3.3.4 STEP 4: Interpretation of Results

The impact of drilled shaft and driven pile is separated into categories of (i) impact of resource use and (ii) impact from emissions. This helps to prioritize the site specific conditions as different weights can be assigned to the resource use category and to the emission category (and also across their sub-categories) depending on the requirement of that particular site.

3.3.4.1 Impact of Resource Use

Figures 3.5 and 3.6 show the resource consumptions for driven piles and drilled shafts across the sub-categories of soil, cement and steel. The drilled shafts consume more emergy, embodied energy and exergy across the categories of soil and cement use because of the greater diameters required. Further, the total energy consumption in the form of emergy, embodied energy and exergy is greater for the drilled shafts than for the driven piles (see Tables 3.5-3.8).

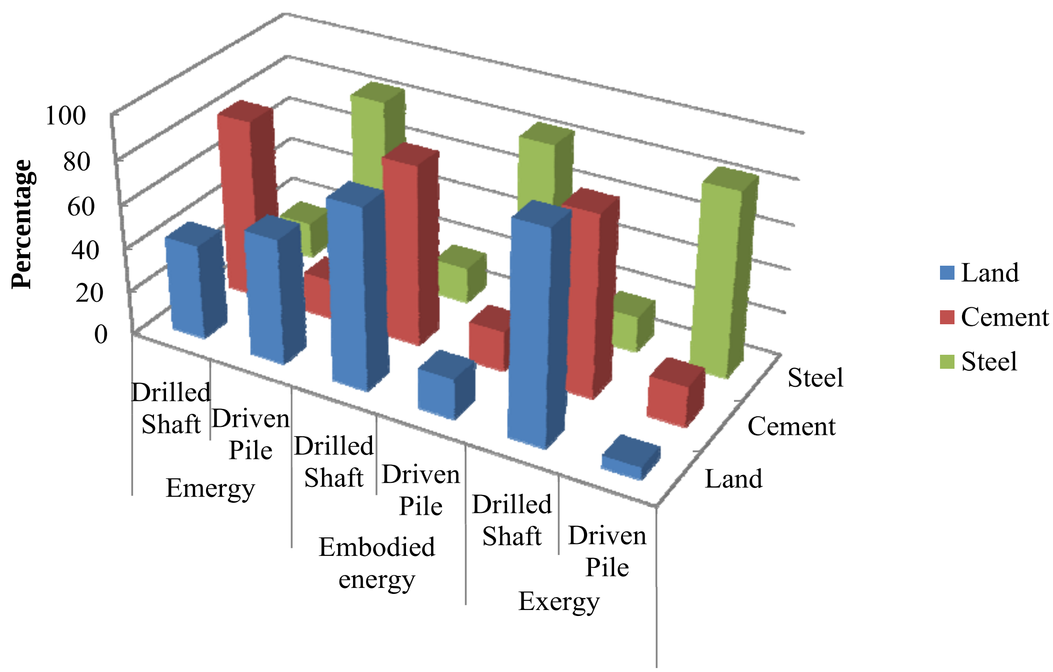

Figure 3.5 Percent consumption of emergy, cumulative exergy and embodied energy for piles in sand across the categories of land, cement and steel

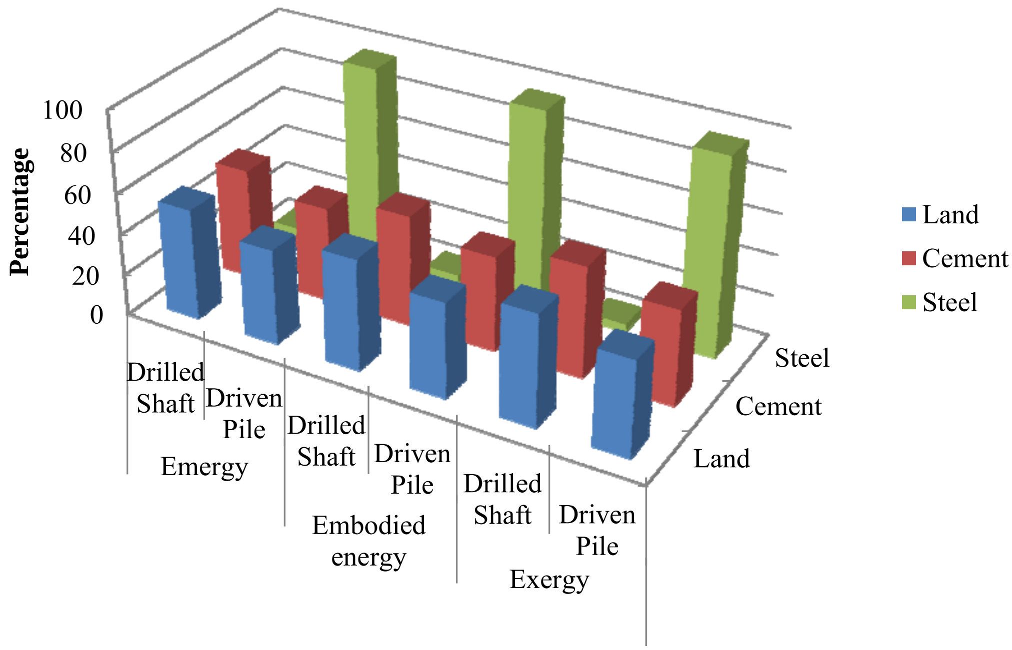

Figure 3.6 Percent consumption of emergy, cumulative exergy and embodied energy for piles in clay across the categories of land, cement and steel.

3.3.4.2 Impact of Emissions

Figures 3.7 and 3.8 show the environmental impact of driven piles and drilled shafts across the sub-categories of acidification, global warming and human toxicity. The effect of emissions on ecosystem health is much less than that of the other categories, and hence, has been kept out of the figures.

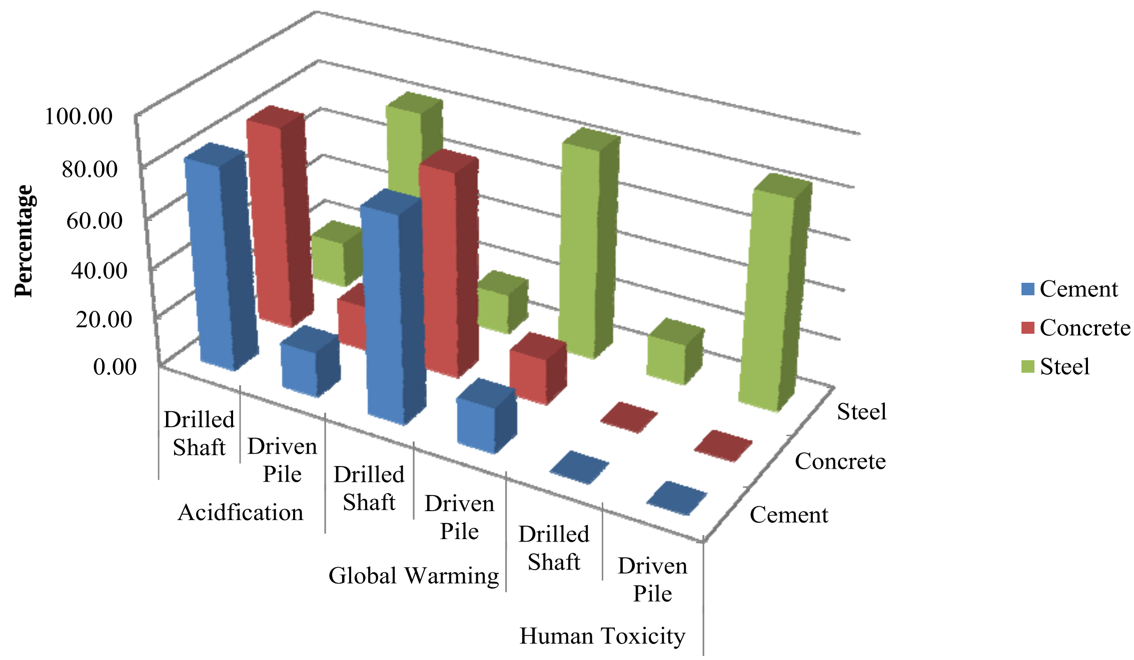

Figure 3.7 Environmental impact on selected categories for piles in sand

The impact of cement and concrete manufacturing is the highest contributor to the global warming potential, and since, drilled shafts generally have a greater volume than driven piles, they have a greater impact on the climate change factors. On the other hand, driven piles use a greater percentage of steel, and hence, contribute significantly to human toxicity because human toxicity is caused due to emissions from steel manufacturing.

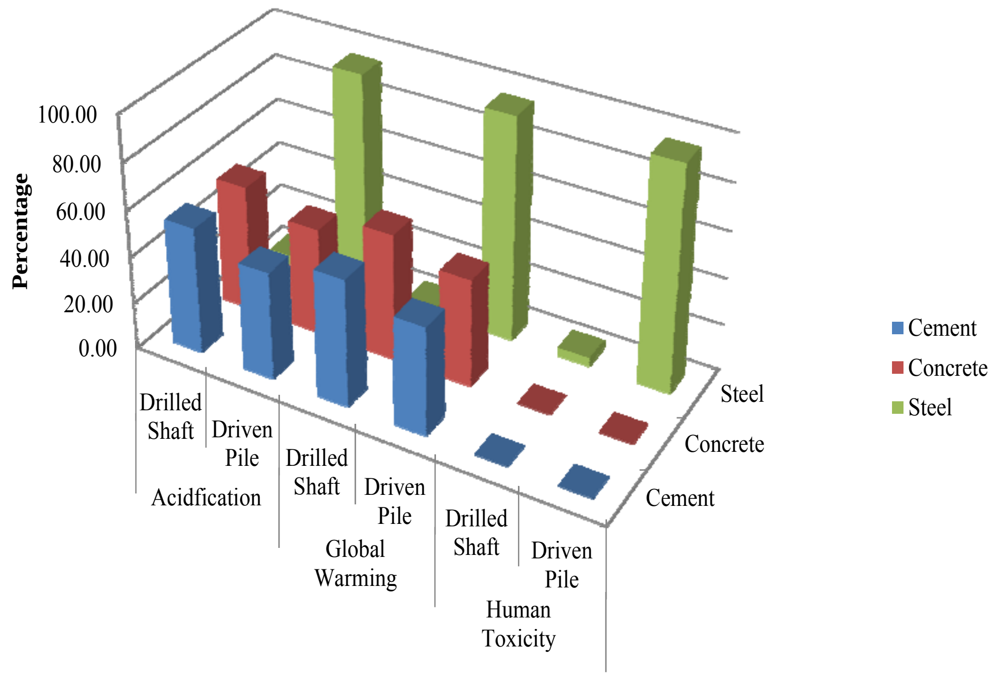

Figure 3.8 Environmental impact on selected categories for piles in clay

3.3.4.3 Calculation of Indicators

Environmental Emission Indicator

The major areas of impact of cement and steel manufacturing considered for the purpose of calculating the impact factor are human health, ecosystem health, acidification and climate change. According to survey conducted at ReCiPe, the human health and the ecosystem health have an equal weight (of about 0.4) and the global climate change has a weight of about 0.2. Whilst human toxicity is of primary importance and should maintain a high weight, the weight of ecosystem health is taken as low as 0.0 (or, in other words, ecosystem health is neglected) in this research because the impact of the emissions on ecosystem toxicity was found to be negligible in the study. On the other hand, cement and concrete manufacturing causes significant impact on the category of global warming.

Hence, the indicator is calculated with weights of 0.4 for human toxicity, 0.3 for global warming and 0.3 for acidification potential. The results show that driven piles have a greater environmental impact in clayey soil due to the use of steel. However, for sandy soil, driven piles provide a more sustainable option for all the load cases considered.

The indicator is calculated by multiplying the percentage of contribution of each pile to the total impact in that category by a chosen weight which represents the importance of that category for the particular project. The results are shown in Tables 3.21 and 3.22.

Resource Use Indicator

For the purpose of obtaining an indicator, the embodied energy consumption has been chosen to represent the energy used mainly because of the current trend of LCA of buildings and related materials. Soil, as land, is a limited resource and hence is assigned a greater weight of 0.4 while both cement and steel are assigned a weight of 0.3 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 results are shown in Tables 3.23 and 3.24.

Table 3.21 Calculation of environmental impact indicator for piles in sand

Environmental Impact Category	Unit	Impact from Drilled Shaft				Impact from Driven Pile				Percentage Imact from Drilled Shaft	Percentage Imact from Driven Pile	Weight	Indicator Value for Each Category for Drilled Shaft	Indicator Value for Each Category for Driven Pile
		Cement	Concrete	Steel	Total	Cement	Concrete	Steel	Total	(9) = [(4)/(4)+(8)] × 100	(10) = [(8)/(4)+(8)] × 100		(12) = (11)×(9)	(13) = (11)×(10)
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)			(11)		
Human Toxicity	gm,1,4 DB Eq	0.00	0.00	1046.63	1047.91	0.00	0.00	5433.66	5433.66	16.15	83.85	0.40	6.46	33.54
Acidification	gm Eq SO_2	28199.30	22.24	302.04	28501.36	6213.01	4.90	1328.09	7546.00	79.08	20.92	0.30	23.72	6.28
Global Warming	gm Eq CO_2	8793556.41	9478	125205	18396823.49	1937440.43	2088.3	649215.68	4674910.25	77.52	22.48	0.30	23.26	6.74
Final Indicator Value													53.44	46.56

Table 3.22 Calculation of environmental impact indicator for piles in clay

Environmental Impact Category	Unit	Impact from Drilled Shaft				Impact from Driven Pile				Percentage Imact from Drilled Shaft	Percentage Imact from Driven Pile	Weight	Indicator Value for Each Category for Drilled Shaft	Indicator Value for Each Category for Driven Pile
		Cement	Concrete	Steel	Total	Cement	Concrete	Steel	Total	(9) = [(4)/(4)+(8)] × 100	(10) = [(8)/(4)+(8)] × 100		(12) =	(13) =
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)			(11)	(11)×(9)	(11)×(10)
Human Toxicity	gm,1,4 DB Eq	0.00	0.00	1046.63	1046.63	0.00	0.00	27156.36	27156.36	3.71	96.29	0.40	1.48	38.52
Acidification	gm Eq SO_2	35154.79	27.73	302.04	35484.56	29789.03	23.50	6637.55	36450.08	49.33	50.67	0.30	14.80	15.20
Global Warming	gm Eq CO_2	10967343.81	11818	125205	11104366.87	9293374.08	10014	3244652.83	12548041.11	46.95	53.05	0.30	14.08	15.92
												Final Indicator value	30.37	69.63

Table 3.23 Calculation of resource use indicator for piles in sand

Resource Category	Resource Consumption						Percentage Resource Consumption						Calculation of Resource Use Indicator		
	Emergy ($\times 10^{11}$) (sej)		Embodied energy (MJ)		Exergy (MJ)		Emergy		Embodied energy		Exergy				
	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Weight	Indicator Value for Each Category for Drilled Shaft	Indicator Value for Each Category for Driven Pile
Land	27234.4	36002.47	29179.7	6429.01	1478.44	81.1571	43.07	56.93	81.95	18.05	94.8	5.204	0.4	32.78	7.22
Cement	185460	41138.61	43305.5	9605.97	50366.2	11096.9	81.85	18.15	81.85	18.15	81.95	18.05	0.3	24.55	5.45
Steel	2637.73	13677.22	2324.78	12054.5	2618.57	13577.9	16.17	83.83	16.17	83.83	16.17	83.83	0.3	4.85	25.15
Final Indicator Value														62.18	37.82

Note : Percentage of consumption is calculated as percentage consumed by each pile type in a particular category ; Total consumption in a category by the pile types together = 100%

Table 3.24 Calculation of resource use indicator for piles in clay

Resource Category	Resource Consumption						Percentage Resource Consumption						Calculation of Resource Use Indicator		
	Emergy ($\times 10^{11}$) (sej)		Embodied energy (MJ)		Exergy (MJ)		Emergy		Embodied energy		Exergy				
	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Weight	Indicator Value for Each Category for Drilled Shaft	Indicator Value for Each Category for Driven Pile
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14) = (13)×(9)	(15) = (13)×(10)
Land	31640.9	27080.64	33900.9	29015	1717.65	1470.09	53.88	46.12	53.88	46.12	53.88	46.12	0.4	21.55	18.45
Cement	240225	205602.7	56093.1	48008.8	65238.7	55836.3	53.88	46.12	53.88	46.12	53.88	46.12	0.3	16.16	13.84
Steel	2637.73	68356.07	2324.78	60246	2618.57	67859.5	3.72	96.28	3.72	96.28	3.72	96.28	0.3	1.11	28.89
Final Indicator Value														38.83	61.17
Note : Percentage of consumption is calculated as percentage consumed by each pile type in a particular category ; Total consumption in a category by the pile types together = 100%															

Indicators as functions of Applied Load

The variation of the resource use and environmental indicators as functions of applied load is shown in Figures 3.9-3.12. For clayey profiles, the drilled shafts have a lower impact than the driven piles from both the resource efficiency and environmental impact points of view. For sandy profiles, the driven piles have a lower impact in both resource use and environmental impact categories.

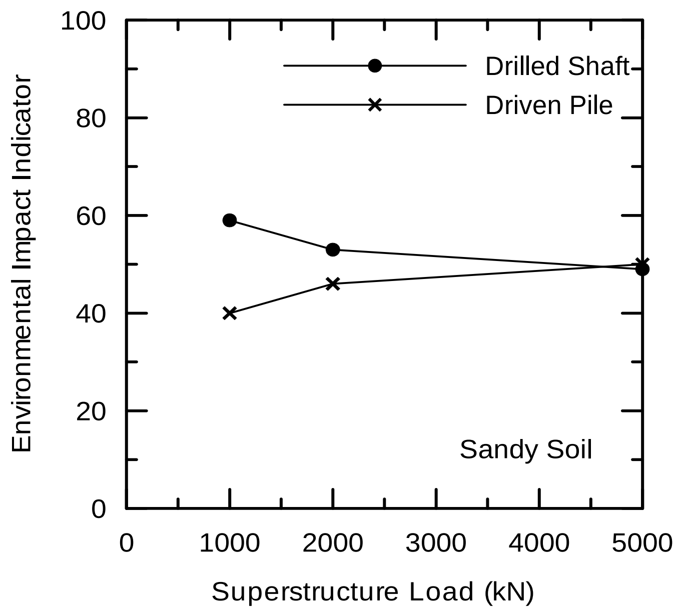

Figure 3.9 Variation of environmental impact indicator for piles in sand

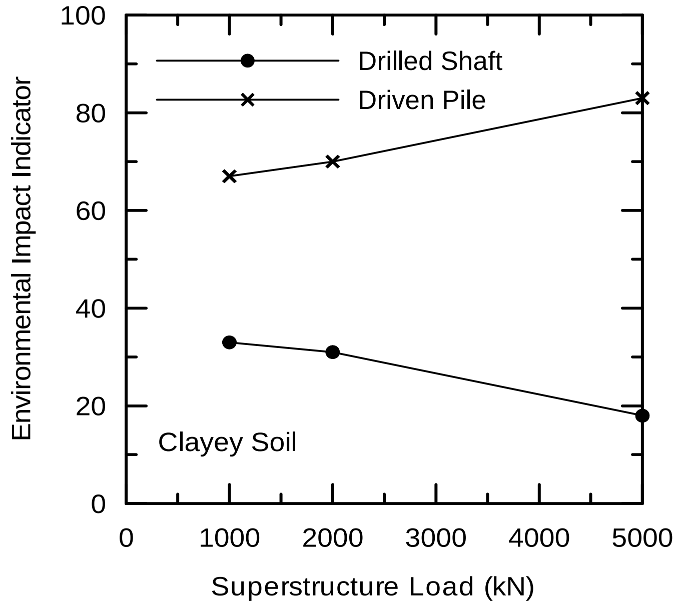

Figure 3.10 Variation of environmental impact indicator for piles in clay

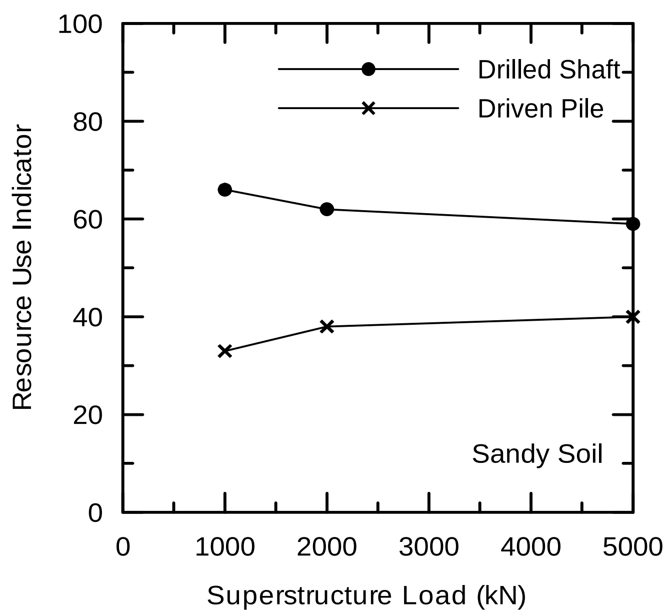

Figure 3.11 Variation of resource use indicator for piles in sand

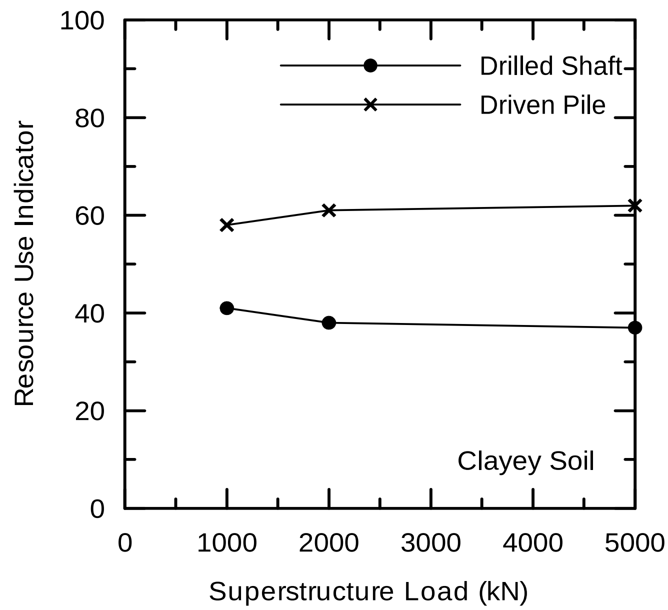

Figure 3.12 Variation of resource use indicator for piles in clay

3.3.5 Concluding Remarks on LCA

The indicators derived from the environmental impact assessment and resource consumption can be used as a stand-alone decision supporting metric for any geotechnical project. From the LCA itself, it can be concluded that, for clayey soils, driven piles are less environmentally sustainable than drilled shafts mainly because of a greater percentage of steel consumption but, for sandy soils, driven piles are more sustainable than drilled shafts. However, as mentioned earlier, to arrive at a balanced sustainability index, both economic and social factors should be considered before a final decision is taken. CBA helps in achieving this by comparing the social benefits of the alternatives available to the public.

3.4 Cost Benefit Analysis of Pile Foundations

As the study presented in this chapter focuses only on single piles, real life financial returns and social benefits cannot be assessed. The average cost of construction of concrete pile is about $16 per meter length of pile (Mukherjee 2010, personal communication). For this research, the pile lengths for driven piles and drilled shafts have been kept constant while the diameters have been varied. As drilled shafts require a greater diameter, it can be generally concluded that they will need a greater length if the same diameter were to be maintained. Hence, for both the soil types chosen for this analysis, drilled shafts require a greater financial investment for the same financial benefit. However, this difference may be negligible for piles in clayey profiles.

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. Since actual analysis of financial return and societal benefits is not done in this research it cannot be concluded for certain that one alternative can score better than the other in this category. Therefore, an equal score is assigned to both the pile types in the category of financial return and social impact.

3.5 Multicriteria Analysis

Process engineering is mostly concerned with optimization, especially with respect to economic objectives. However, it is possible to include environmental criteria to economic optimization. One possible method of doing it is making either the

economic criterion or the environmental criterion as the goal and set the other as the constraint (Sen and Yang, 1998). But, the more effective and balanced way of achieving optimization in engineering processes is to consider all the objectives together in the optimization process (Bauman and Tillman 2001). Thus, a multi-objective optimization analysis is often suitable for achieving sustainability in engineering processes.

A multi-criteria decision analysis framework is developed for pile foundation in order to formulate a sustainability index. The major contributing factors in formulating a sustainability index are the energy use (EU), the environmental impact (EI) and the economic and social benefits (EB). Mathematically, the sustainability index (SI) can be represented as

$$SI = f(EU, EI, EB) \tag{3.6}$$

The energy use and environmental indicators can be obtained from Tables 3.21-3.24 based on the LCA done earlier. The socio-economic part is obtained from the cost benefit analysis. Since resource consumption is of primary concern for geotechnical engineering, a slightly greater weight of 0.4 is assigned to the category, while the environmental impact and socio-economic benefit categories are assigned equal weights of 0.3 each. The calculations for both sand and clay profiles for the superstructure load of 2000 kN are reported in Tables 3.25 and 3.26, in which a higher total score indicates a less sustainable alternative.

Table 3.25 Calculation of sustainability index for drilled shaft and driven pile in sand

Piles Types in Sand	Environmental Impact Criteria			Resource Use Criteria			Socio-Economic Benefit Criteria			Sustainability Index
	Environmental Impact Indicator Value	Weight	Score for Environmental Impact Criteria	Resource Use Indicator Value	Weight	Score for Resource Use Criteria	Socio-Economic Benefit Indicator Value	Weight	Score for Socio-Economic Benefit Criteria	
(1)	(2)	(3)	(4) = (3)×(2)	(5)	(6)	(7) = (5)×(6)	(8)	(9)	(10) = (8)×(9)	(11) = (4)+(7)+(10)
Drilled Shaft	53.44	0.30	16.03	62.18	0.40	24.87	50.00	0.30	15.00	55.91
Driven Pile	46.56	0.30	13.97	37.82	0.40	15.13	50.00	0.30	15.00	44.09

Table 3.26 Calculation of sustainability index for drilled shaft and driven pile in clay

Piles Types in Clay	Environmental Impact Criteria			Resource Use Criteria			Socio-Economic Benefit Criteria			Sustainability Index
	Environmental Impact Indicator Value	Weight	Score for Environmental Impact Criteria	Resource Use Indicator Value	Weight	Score for Resource Use Criteria	Socio-Economic Benefit Indicator Value	Weight	Score for Socio-Economic Benefit Criteria	
(1)	(2)	(3)	(4) = (3)×(2)	(5)	(6)	(7) = (5)×(6)	(8)	(9)	(10) = (8)×(9)	(11) = (4)+(7)+(10)
Drilled Shaft	30.37	0.30	9.11	38.83	0.40	15.53	50.00	0.30	15.00	39.64
Driven Pile	69.63	0.30	20.89	61.17	0.40	24.47	50.00	0.30	15.00	60.36

3.6 Conclusions

The sustainability indexes (SIs) for the dilled shafts in sand, considered in this chapter, are greater than those for the corresponding driven piles. On the other hand, the SIs for the driven piles in clay, considered in this chapter, are greater than those for the corresponding drilled shafts. Hence, for the cases studied in this chapter, driven piles are more sustainable in sandy soils while drilled shafts are better for clayey soils. Thus, whether a particular pile type is more sustainable than another depends on the soil profile in which the pile is constructed. Therefore, rather than depending on local tradition or

local economy, it is more reasonable to do a sustainability analysis of the different available pile types before a final choice is made. The developed framework helps as a decision tool by balancing all the major aspects — economic, environmental, societal and technical — that ensures the equilibrium of the 3 E's of sustainability. The framework provides a holistic approach and fulfills the requirements of the functional integrity conceptualization of sustainability. The framework is not only applicable to pile foundations but also to other relevant geotechnical problems in which multiple solutions exist.

CHAPTER 4 RESEARCH SUMMARY AND FUTURE DIRECTIONS

Geotechnical engineering is resource intensive. The resources used in geotechnical engineering are obtained from the biogeosphere and from the industrial processes. The industrial processes generate toxic emissions to air and cause pollution to land and water. Although the direct environmental impact of geotechnical engineering is limited to resource use and to the pollution and emissions caused at the construction site, the indirect impact of geotechnical construction can affect a wide range of environmental processes including human and ecosystem health.

A review of the relevant literature shows that research studies on sustainability-related issues in geotechnical engineering exist in the following areas: (i) application of alternative materials in geotechnical engineering, (ii) material reuse and recycling in geotechnical engineering, (iii) development of environmentally friendly ground improvement techniques, (iv) efficient use of underground space, (v) reuse of foundations and (vi) energy geotechnics. Limited number of research studies on developing qualitative guidelines for assessing sustainability of geotechnical construction sites also exist — the most prominent among them being the development of the indicator system

GeoSPeAR. However, there is a lack of a clearly defined framework to evaluate and quantify the relative sustainability of alternate practices in geotechnical engineering.

In this thesis, a quantitative framework for assessing sustainability of geotechnical processes is developed and applied to pile foundations. In the developed framework, first, two quantitative indicators are developed, one for resource use and the other for environmental impact. Then, a third indicator is introduced that accounts for the socio-economic benefit of the project. Finally, these three indicators are assigned weights and linearly aggregated to form the sustainability index. The framework can be used at the planning and design stages of a project instead of the construction stage. It is important to have sustainability indicators at the planning and design stages because geotechnical engineers generally have multiple choices regarding the type of solution (e.g., choice between ground improvement and deep foundations or between different types of pile foundations), construction materials (e.g., choice between conventional reinforcement or reinforcement with shredded tires), and the methods of construction they can use for a particular project. The decisions in such cases are generally taken based on local tradition and economy rather than sustainability. The developed framework can help geotechnical engineers to make decisions that promote environmental sustainability along with socio-economic sustainability.

A life cycle thinking approach is considered to account for the cumulative impacts of all the processes upstream and downstream of a geotechnical construction. A life cycle analysis (LCA) is done in which the input side of the inventory analysis is used to judge the sustainability of the project from the resource use point of view. The resources used are categorized and normalized, and weights are applied across the categories to

emphasize the relative importance of the categories. The values obtained by combining the resource use in each category with its respective weight are aggregated, which gives the resource use indicator. It is important to note that, instead of mass flow accounting which is common for LCAs, this research uses energy accounting methods in the LCA. The output inventory of LCA is used to perform the environmental impact assessment (EIA) as part of the LCA. In the EIA, the emissions obtained from the output inventory are classified into relevant impact categories and, again, weights are used to emphasize the relative importance of the categories. A linear combination of the weights and the values in each category gives the environmental impact indicator. Following the LCA, a cost benefit analysis (CBA) is done based on the considerations of financial return and impact of the adverse effects of the geotechnical construction, and weights are assigned to both the considerations. Again, a linear combination is done to obtain the socio-economic indicator. Finally, a multicriteria analysis (MCA) is done to assess the overall performance of the geotechnical project as a function of the resource use, the environmental impact and the socio-economic benefit. In the MCA, weights are applied to the categories of resource use, the environmental impact indicator and the socio-economic indicator, and the scores are aggregated to obtain the final sustainability index.

The framework is used to compare the performance of two commonly used piles, drilled shaft and driven pile, subjected to different superstructure loads. A homogeneous sand profile and a homogeneous clay profile are chosen for the study. The soil profiles are so chosen that the installation of both the pile types in them are technically feasible — this provides the ideal case for judging the usefulness of the developed framework as a decision making tool.

The piles are first designed following the working stress method so that they can safely carry the superstructure loads. The length of the piles is kept constant while the diameters are varied in the design. Then, in the LCA, the designed dimensions of the piles are used 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. These data are then categorized and weighted across, and the resource-use and environmental impact indicators are obtained. The results of the LCA show that, for the piles in sand considered in this thesis, driven piles use resources more efficiently than drilled shafts and, for the piles in clay considered in this thesis, the resource-use efficiency of both types of piles are more or less the same. The analysis further indicates that, from the environmental impact point of view, the driven piles performed better in the sandy profile while the drilled shafts performed better in the clayey profile. After the LCA, the CBA is done. The driven piles are more cost effective but have a greater adverse effect on the neighborhood due to loud noise and vibration. In the absence of real-life data, it is assumed that a linear combination of performance scores and weights in the categories of financial return and social impact will yield the same socio-economic indicator value for both the pile types. In the final step, the MCA is performed that aggregates the performance of the piles in the categories of resource use, environmental impact and economic benefit. The MCA shows that, on an overall basis, the driven piles in the sandy profile are more sustainable while, in the clayey profile, the drilled shafts are more sustainable.

The weights used in the analysis are arbitrarily chosen to stress the fact that the framework can be used to suit site-specific risk elements. For effective use of the

sustainability framework developed in this thesis, the local conditions should be given priority in choosing the weights across the different categories. In the case of a densely populated area, the environmental impact can have a greater weight while, in areas plagued with resource scarcity, resource use should have a greater weight. This is an indication of the flexibility inherent in the framework.

However, the drawback of this flexibility is that the choice of the weights remains at the discretion of the decision maker. This is probably inherent in all decision processes because assigning importance to impact categories depends on the perspective of the decision maker. Further, the impacts considered are almost always interlinked — human health is related to ecosystem health which is, again, related to global warming and acidification. Similarly, environmental impacts are related to socio-economic impacts which are, in turn, tied with resource use. Thus, the choice of weights is often controversial and till date no consensus is available on what an appropriate weighting system might be. One possible way of fixing weights is by surveying. Surveying ensures participation of all concerned and highlights local factors. However, it is often difficult to have enough willing participants in a survey and it has been found out that people generally deters from expressing their opinions publicly.

A mathematical way of ascertaining weights is by optimizing the performance of a system in different categories. The framework presented in this thesis is based on the method of constructing a single aggregate objective function which uses weights suggested by the decision maker to optimize the performances in different categories. As the weights are suggested by the decision maker, these weights reflect the personal biases of the decision maker, and hence, are not always acceptable to all concerned. Also, this

method does not account for the uncertainties associated with the system under assessment.

Based on the above discussion it is clear that an important future research should be on developing an unbiased weighting system based on rigorous optimization techniques that also incorporates the different uncertainties associated with the problem. The weighting system must be flexible enough to incorporate the site-specific risks and must include the opinions of all concerned affected in a project. Another direction of research would be to apply the framework to different geotechnical and infrastructure problems in which multiple solutions are possible.

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