A sustainable approach to foundation design

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ABSTRACT
Civil Engineering is the major instrument of anthropocentric development over centuries through ever expanding infrastructures, cities and facilities. Over the last two decades, a growing awareness is noted towards making such growth sustainable as well. Geotechnical engineering is the most resource intensive sector of civil engineering and, by virtue of its early position in civil engineering projects, has a huge potential to improve the sustainability aspects of a project. Although many facets of geosustainability are being studied recently, quantitative indicators for assessing the sustainability of geotechnical practices, particularly at the planning and design stages, do not exist. In this paper, two quantitative indicators, the resource use indicator and the environmental impact indicator, are introduced that can help geotechnical engineers in assessing the comparative sustainability of different foundation alternatives for a particular project. A life cycle thinking approach is adopted in developing the indicators to account for the cumulative impacts of all the processes upstream and downstream of foundation construction. The numeric indicators are derived from a life cycle analysis (LCA) for two different pile foundation alternatives — the drilled shafts and driven piles. The inventory analysis of the LCA is used to judge the sustainability of the pile foundations from the resource-use point of view and the output inventory of the LCA is used to perform the environmental impact assessment (EIA). The resources used and the impact of emissions 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 to obtain the resource use indicator and a similar calculation for the environmental impact categories gives the environmental impact indicator. These indicators can serve as decision aiding tool by providing a quantitative assessment of the sustainability of drilled shafts and driven piles on the basis of resource use and environmental impact.

RÉSUMÉ
Génie civil est l'instrument majeur de développement au cours des siècles grâce à anthropocentrique toujours en expansion des infrastructures, des villes et des installations. Au cours des deux dernières décennies, une prise de conscience est noté à rendre une telle croissance durable ainsi. Géotechnique est le secteur le plus de ressources du génie civil et, en vertu de sa position au début de projets de génie civil, a un énorme potentiel pour améliorer les aspects de durabilité d'un projet. Bien que de nombreuses facettes de geosustainability sont étudiés récemment, les indicateurs quantitatifs pour évaluer la durabilité des pratiques géotechniques, notamment au stade de la planification et la conception, n'existent pas. Dans ce papier, deux indicateurs quantitatifs, l'indicateur de l'utilisation des ressources et l'indicateur d'impact environnemental, sont introduites qui peuvent aider les ingénieurs en géotechnique pour évaluer la durabilité comparative des alternatives différentes bases pour un projet particulier. Une approche la pensée cycle de vie est adoptée dans l'élaboration des indicateurs pour rendre compte des effets cumulatifs de tous les processus en amont et en aval de la construction des fondations. Les indicateurs numériques sont dérivées d'une analyse du cycle de vie (ACV) pour deux différentes alternatives fondation sur pieux forés — les arbres et les pieux enfoncés. L'analyse de l'inventaire de l'ACV est utilisé pour juger de la viabilité de l'fondations sur pieux à partir du point d'utilisation des ressources de vue et de l'inventaire de sortie de l'ACV est utilisé pour effectuer l'évaluation d'impact environnemental (EIE). Les ressources utilisées et l'impact des émissions sont classées et normalisées, et les poids sont appliqués dans toutes les catégories de souligner l'importance relative de ces catégories. Les valeurs obtenues en combinant l'utilisation des ressources dans chaque catégorie avec son poids respectifs sont agrégés pour obtenir l'indicateur d'utilisation des ressources et un calcul semblable pour les catégories d'impact environnemental donne l'indicateur d'impact environnemental. Ces indicateurs peuvent servir d'outil aide à la décision en fournissant une évaluation quantitative de la durabilité des puits forés et des pieux enfoncés sur la base de l'utilisation des ressources et l'impact environnemental.

1.0 INTRODUCTION

Civil Engineering has been the major instrument of anthropocentric development over centuries through ever expanding infrastructures, 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 (Pulselli et al. 2007). Resources used in civil engineering processes include both natural and manufactured raw materials. Natural raw materials are limited commodities and manufactured raw materials can be directly linked to process emissions and pollutions. Hence, resource efficiency as a decision making metric is slowly gaining momentum in the civil engineering industry, particularly in the construction sector (Jefferis 2008).

Geotechnical engineering is most resource intensive of all civil engineering disciplines although this intensive consumption of energy and natural resources 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). 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).

Sustainability in geotechnical engineering is often equated to resource efficiency parameterized by the embodied energy or embodied CO_2 of the materials used in a project (Chau et al. 2008). Storesund et al. (2008) used Global warming Potential (GWP), a function of emitted CO_2, as a parameter. But Holt et al. (2010) pointed out that expressing the environmental impact in terms of carbon dioxide emissions involves a number of ad hoc assumptions and generalizations. Moreover, assessing sustainability as a function of CO_2 emissions only often suppresses other serious impacts like toxicity to human and ecosystem health. The available indicator systems for geotechnical practices include Sustainable Geotechnical Evaluation Method (S.G.E.M) (Jiminez 2004), Environmental Geotechnical Indicator System (EGIs) (Jefferson et al. 2006) and GeoSPeAR (Holt et al. 2009, 2010). Both S.G.E.M and GeoSPeAR evaluate the effect of a geotechnical construction project on four sectors of efficiency: economic, environmental, social and technical. These broad sectors are then subdivided into subsectors that are of relevance to the project. EGIs are mainly used to evaluate the sustainability of ground improvement projects. These systems provide a qualitative guideline at the construction stage of geotechnical projects. Although these guidelines serve well at the construction stage, there is little or no help available in the decision-making process during the planning and design stages of geotechnical engineering.

In this paper, two quantitative indicators, the resource use indicator and the environmental impact indicator, are introduced that can be used for assessing the environmental sustainability of foundations. The indicators are developed through a life cycle assessment (LCA) of foundations. The LCA incorporates environmental impact assessment (EIA). The resource accounting in the LCA is done by energy accounting methods — the thermodynamically rigorous concepts of exergy, emergy and embodied energy are used for the purpose. The environmental impact assessment (EIA) determines the impact of the output of the geotechnical process on the ecosystem in the categories like human and ecosystem health, global warming and acidification. In order to quantitatively compare process efficiency, two indicators are introduced: the resource-use indicator and the environmental-impact indicator. These indicators are calculated as the sum of the weighted scores of the processes across chosen categories of resource use and environmental impact. In both the categories, the lower the value of the indicator is, the more environmentally sustainable the process is. The indicators are calculated for two particular pile types, the drilled shaft and the driven reinforced concrete pile, in order to quantitatively compare their environmental sustainability.

2.0 Sustainability and Pile Foundations

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 and 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. However, when life cycle thinking 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. 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. Adopting a life cycle view of a process 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 1996).

In recent times, there is a growing consensus that sustainability of a project can be best ensured by incorporating sustainability assessment at the planning and design stage of a project. As shown in Figure 1, a pile foundation project typically starts with project planning. The planning stage is generally followed up by site characterization, analysis, design and, finally, construction. In general, a feasibility study is conducted at the planning stage of the project and the choice of a particular pile type is made based on the technical, technological and economic feasibilities like soil type, loading condition, local economy, availability of construction equipment and tradition. The environmental impacts of the project are traditionally neglected mainly because of the indirect nature of the impacts and because of an apparent “dilution” of the impacts over the entire life span of the project. Therefore, a life cycle based sustainability study is needed before a foundation type is chosen to ensure the environmental and societal sustainability of the project along with financial feasibility. As shown in Figure 1, this can be best affected by a sustainability study after a preliminary design has been done and data has been collected on the technological feasibility of the different alternatives. The sustainability study at this stage helps the practicing engineer in the decision process and ensures choice of a process design that is resource and environment friendly. The indicators introduced in this paper provides a quantitative basis for assessing the sustainability of different foundation alternatives at the decision making stage of a project.

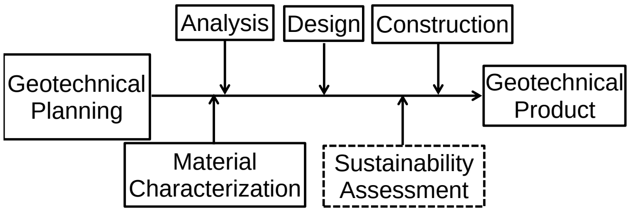


Figure 1. Typical steps in a geotechnical process

The resource-use indicator and the environmental-impact indicator introduced in this paper are best explained with the help of a practical example. For the illustrative case 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 sustainability study as a decision aid for choosing one pile type over another. A homogeneous sand profile and a homogeneous clay profile are assumed for the study. Three working load cases of 415kN, 563kN and 765kN are considered with a factor of safety equal to 3. The length of the piles is kept constant at 12 m while the diameters are varied in the design.

For the saturated sand layer considered in this study, the soil properties are (i) unit weight of solids G_s = 2.65, (ii) relative density D_R = 60%, (iii) coefficient of earth pressure at rest K_0 = 0.4, (iv) maximum void ratio $e_{\max}$ = 0.9, (v) minimum void ratio $e_{\min}$ = 0.4 and (vi) unit weight of water γ_w = 9.81 kN/m^3. The resulting bulk unit weight of sand γ_{sat} = 19.93 kN/m^3. For the saturated clay layer considered in this study, the soil properties are (i) G_s = 2.65, (ii) overconsolidation ratio OCR = 2, (iii) coefficient of earth pressure at rest K_0 = 0.4, (iv) unit weight of water γ_w = 9.81 kN/m^3 and (v) bulk unit weight of clay γ_{sat} = 18kN/m^3. The water table is assumed to be at the ground surface for both the sand and clay profiles (Figure 2).

The piles are first designed following the working stress method (Salgado 2008) so that they can safely carry the superstructure loads. The reinforcement for driven piles are calculated as required for supporting the moments for lifting the piles by head (Tomlinson and Woodward 2005). The reinforcement for the drilled shafts are calculated as 0.5% of the gross area of the piles. Table 1 summarizes the pile diameters as obtained from the design calculations for the different load cases and soil profiles. The designed dimensions of the piles are then used in the life cycle assessment (LCA) to determine (i) the quantity of natural resources and processed materials needed for the piles and (ii) the emissions generated to manufacture the required quantity of materials.

2.1 Life Cycle Assessment of Drilled Shaft and Driven Concrete Pile

The LCA done in this paper consists of four steps, (i) goal and scope definition, in which the purpose and extent of the study is underlined, (ii) life cycle inventory (LCI) analysis, in which all the inputs to and outputs from the process over the life span of the process is accounted for, (iii) environmental impact assessment (EIA) in which the outputs of the process are related to the impact categories and (iv) interpretation of the results wherein the information obtained from the earlier steps are used to form a conclusive understanding of the process performance. Figure 3 shows the flow chart for this LCA.

Table 1. Design dimensions of drilled shaft and driven pile for different superstructure load cases

Working Load (kN)	Diameter of Piles in Sand (m)		Diameter of Piles in Clay (m)	
	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile
415.00	0.34	0.14	0.59	0.43
563.00	0.42	0.18	0.74	0.55
765.00	0.52	0.22	0.92	0.71
Pile Length = 12 m				

2.1.1 Goal and Scope Definition

The preliminary goals of the life cycle assessment performed in this research are (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.

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.

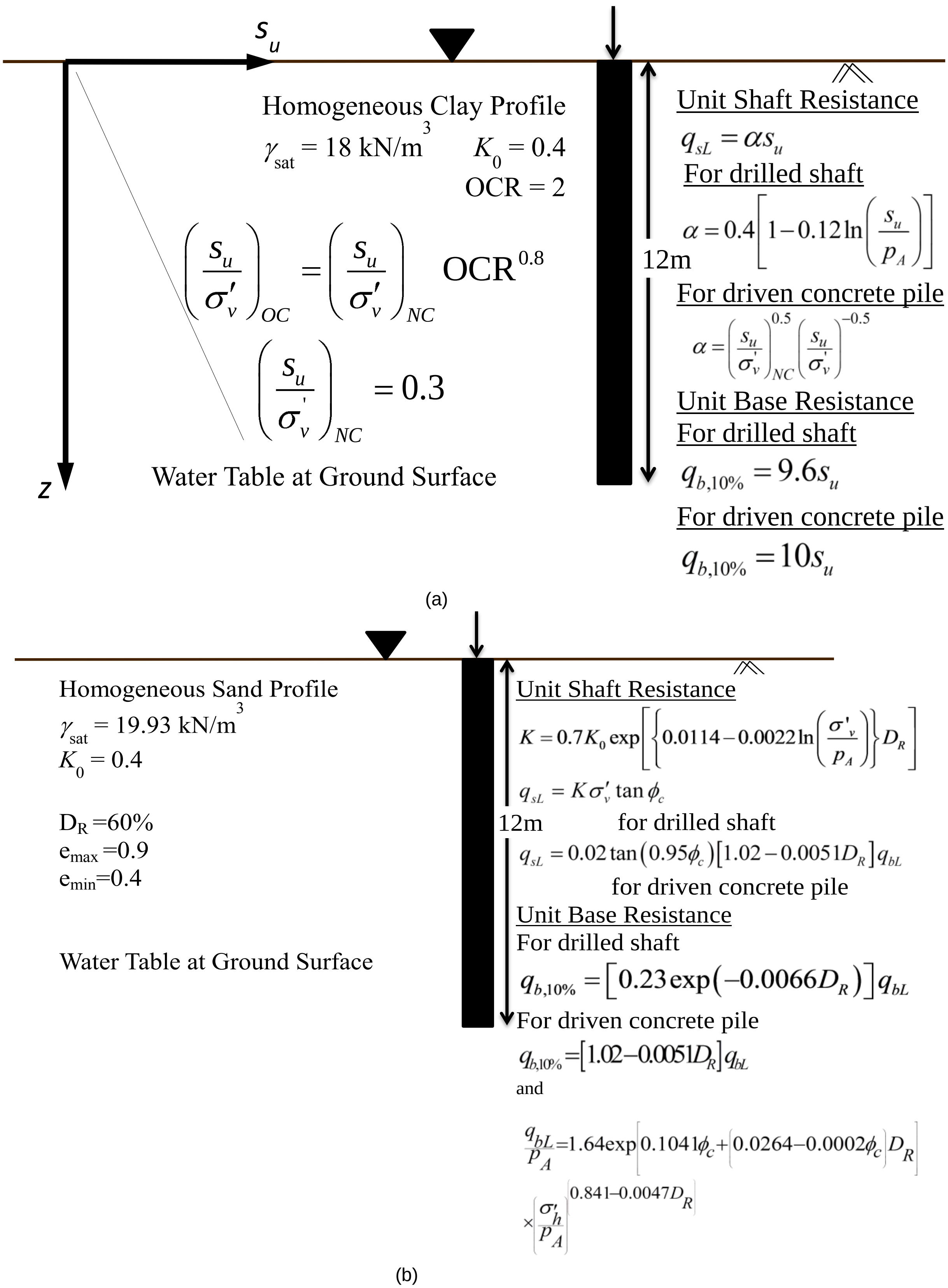


Figure 2. Soil Data and design equations for (a) homogeneous clay and (b) homogeneous sand layers

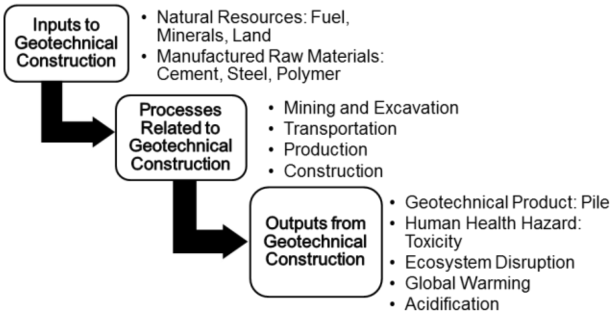


Figure 3. Flow chart showing the inputs, outputs, processes and impact categories in pile construction

2.1.2 Life Cycle Inventory

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.

(i) Input Inventory

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.

Standard LCI methodology accounts for all inputs and outputs in terms of mass flow (e.g., kilogram of input per 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. At the same time, 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.

Exergy of a resource is its available energy to do useful work (Sciubba and Wall 2010). 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 (Odum 1996). Therefore, a sustainable engineering process should target to minimize the emergy of its finished products. Embodied energy of a material is the sum total of all the energy that has been used to produce the material from the stage of extraction of raw materials till its disposal (Herendeen 1996). A sustainable process must use materials that are low in embodied energy. The summary of resource consumption for the two pile types in the categories of land, cement, steel and fuel (diesel) for the load case of 563kN are provided in Tables 2A and 2B.

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 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 — the values are obtained from Meester et al. (2006).

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 fuel use is calculated based on data provided by a local contractor.

(ii) Output Inventory

The output side of the inventory is calculated in terms of mass because the databases available for performing the environmental impact assessment are all available In terms of mass. The total quantity of cement, steel, concrete and fuel required for the piles, as obtained from the design calculations, is multiplied by the emission values per unit production of cement, concrete, steel and diesel obtained from the National Renewable Energy Laboratory (NREL) database and from Sjunnesson (2005) to calculate the total quantity of the output emissions.

2.1.3 Environmental Impact Assessment (EIA)

The environmental impact assessment is done based on the categories of global warming, human toxicity, ecosystem toxicity and acidification. The impact in each category is calculated by first aggregating the emission quantities under different impact categories and then by multiplying the aggregates with corresponding weights. The weights are used to signify the relative importance of the impact categories and they determine the proportion of an emission to be attributed to a particular category. In this particular study, the weights (indexes) are used as per the ReCiPe database (2009) which uses the distance to target method. In the distance to target method, 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). The midpoint indicators are used as weights (indexes) in this study to avoid the higher degree of uncertainty associated with the end point indicators.

Table 2A. Summary of resource consumption for piles in clay for working load 563 kN

Resource Category	Resource Consumption for Piles in Clay					
	Emergy ($\times 10^{11}$) (sej)		Embodied energy (MJ)		Exergy (MJ)	
	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile
Land	10093.43	5350.11	10814.39	5732.27	547.93	290.43
Cement	76606.77	40606.12	17887.88	9481.63	20804.38	11027.55
Diesel	21224.34	75945.37	18706.20	39661.57	21070.17	44673.74
Steel	58274.23	11654.85	69878.67	10248.87	69029.32	10124.30

Table 2B. Summary of resource consumption for piles in sand for working Load 563 kN

Resource Category	Resource Consumption for Piles in Sand					
	Emergy ($\times 10^{11}$) (sej)		Embodied energy (MJ)		Exergy(MJ)	
	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile
Land	155.04	902.49	166.11	966.95	8.42	48.99
Cement	1062.92	6187.41	248.19	1444.78	288.66	1680.34
Steel	7635.03	2893.07	6729.18	1510.87	7579.57	1701.80
Diesel	2913.71	14568.56	2562.22	17469.67	2531.07	17257.33

The impact in the category of acidification is calculated in terms of SO_2 acidification potential and determined as gm equivalent SO_2. The impact in the category of global warming (climate change) is calculated in terms of global warming potential of CO_2 and is determined as 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. Tables 3A-3D summarize the contribution of the two types of pile in the different impact categories based on the emissions of the process for the load case of 563kN.

Table 3A. Summary of environmental impact for drilled shaft in clay for working load 563 kN

Environmental Impact Category	Unit	Impact from Drilled Shaft in Clay				
		Cement	Concrete	Steel	Diesel	Total
		(1)	(2)	(3)	(4)	(5)
Human Toxicity	gm,1,4 DB Eq	0.00	0.00	13235.35	0.00	13235.35
Acidification	gm Eq SO_2	18182.8	14.34	3819.52	21.11	22037.75
Global Warming	gm Eq CO_2	5670044.11	6111.4	1583310	5384	7264849

Table 3B. Summary of environmental impact for driven concrete pile in clay for working load 563 kN

Environmental Impact Category	Unit	Impact from Driven Pile in Clay				
		Cement	Concrete	Steel	Diesel	Total
		(1)	(2)	(3)	(4)	(5)
Human Toxicity	gm,1,4 DB Eq	0.00	0.00	46367.82	0.00	46367.82
Acidification	gm Eq SO_2	10201.78	8.05	11333.20	3.10	21546.12
Global Warming	gm Eq CO_2	3181281	3428.92	5540045.70	789.25	8725544.4

Table 3C. Summary of environmental impact for drilled shaft in sand for working load 563 kN

Environmental Impact Category	Unit	Impact from Drilled Shaft in Sand				
		Cement	Concrete	Steel	Diesel	Total
		(1)	(2)	(3)	(4)	(5)
Human Toxicity	gm,1,4 DB Eq	0.00	0.00	4261.01	0.00	4261.01
Acidification	gm Eq SO_2	5853.8	4.62	1229.66	21.11	7109.18
Global Warming	gm Eq CO_2	1825424.23	1967.5	509734	5384	2342510

Table 3D. Summary of environmental impact for driven concrete pile in sand for working load 563 kN

Environmental Impact Category	Unit	Impact from Driven Pile in Sand				
		Cement	Concrete	Steel	Diesel	Total
		(1)	(2)	(3)	(4)	(5)
Human Toxicity	gm,1,4 DB Eq	0.00	0.00	10303.96	0.00	10303.96
Acidification	gm Eq SO_2	1030.79	0.81	2518.49	3.10	3553.19
Global Warming	gm Eq CO_2	321438	346.46	1231121.27	789.25	1553694.9

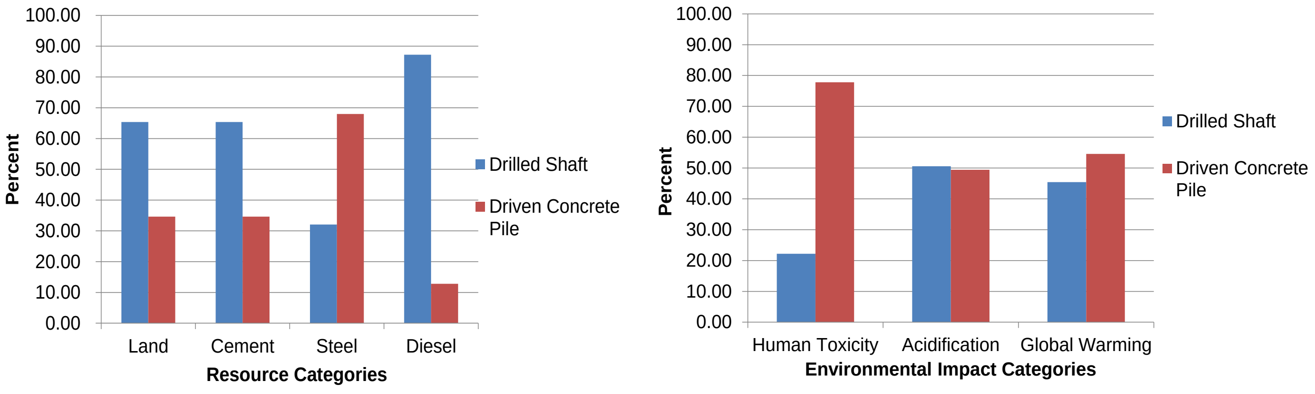
2.1.4 Interpretation of Results

Figures 4(a) and 4(b) show the resource consumptions in terms of embodied energy and the environmental impact for the designed drilled shafts and driven concrete piles in clay across the chosen categories. As the drilled shafts require a larger diameter than the driven piles for the load cases and soil profile considered, the drilled shafts consume more resources in terms of cement, concrete and land than the driven pile. However, driven piles require more reinforcement compared to the drilled shaft and hence, embodied energy consumed as function of steel use, is greater for driven piles than drilled shafts.

Figures 5(a) and 5(b) show the resource consumption and the environmental impact of the piles in sand. In both the cases 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.

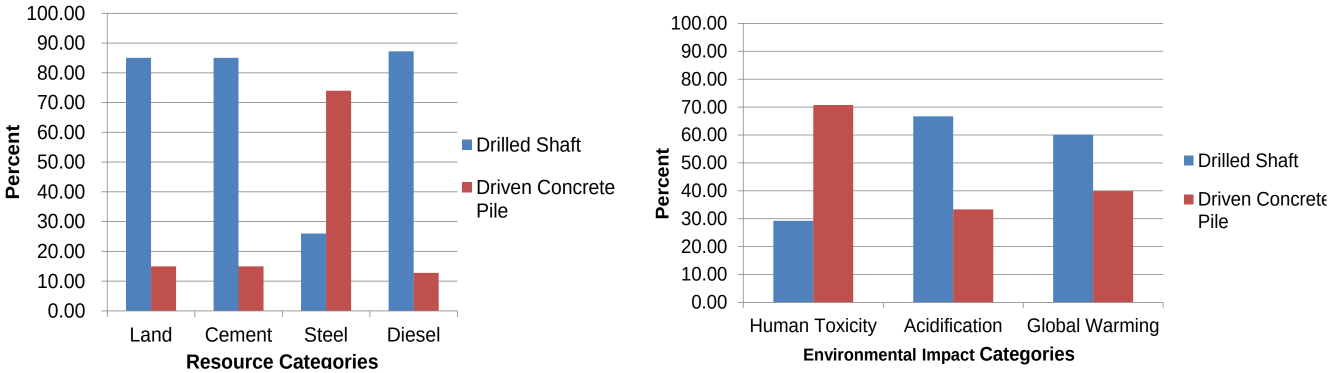
Resource Use Indicator

For the purpose of obtaining the indicator, the embodied energy consumption is chosen to represent the energy use although exergy or emergy could have been chosen. The choice of embodied energy is based on the fact that LCA of buildings and related materials have traditionally been done using embodied energy (Chau et al. 2006, Storesund et al. 2008).The resources used in each category are normalized by converting them to percentages, and weights are applied to emphasize the relative importance of the categories. Soil, as land, is a limited resource and steel manufacturing is found to have toxic effects on human health — these two resources are assigned a greater weight of 0.3 each. Cement and diesel are assigned a weight of 0.2 each (the sum of the weights equals unity). It is important to note that the assigned weights are arbitrary and can be changed depending on the choice of the designer or on the requirement of a particular site. The indicator is calculated by summing the product of the percentage contribution of each pile type in a category and the corresponding weight. The details of the calculations are given in Misra (2010). A greater indicator value implies a less sustainable alternative. Figures 6(a) and 6(b) show the resource use indicator values for the different load cases. From a resource-use point of view, driven piles are more sustainable than drilled shafts.



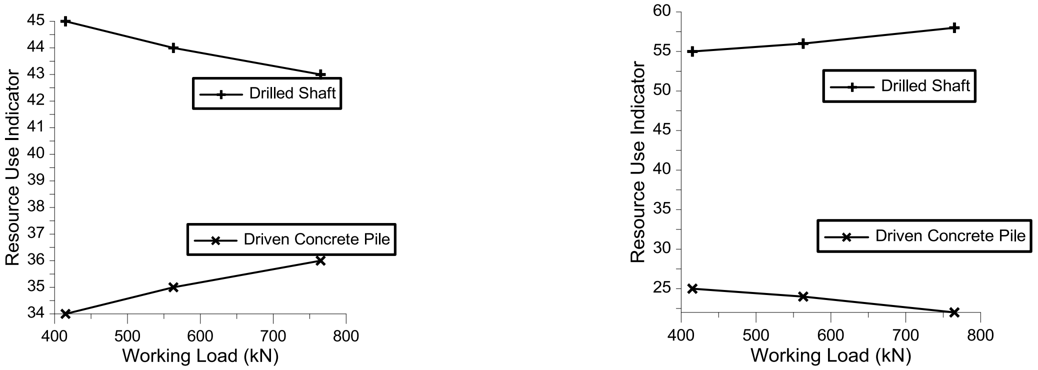
(a) (b)

Figure 4. (a) Percent consumption of embodied energy and (b) percent environmental impact contribution in selected categories for piles in clay



(a) (b)

Figure 5. (a) Percent consumption of embodied energy and (b) percent environmental impact contribution in selected categories for piles in sand

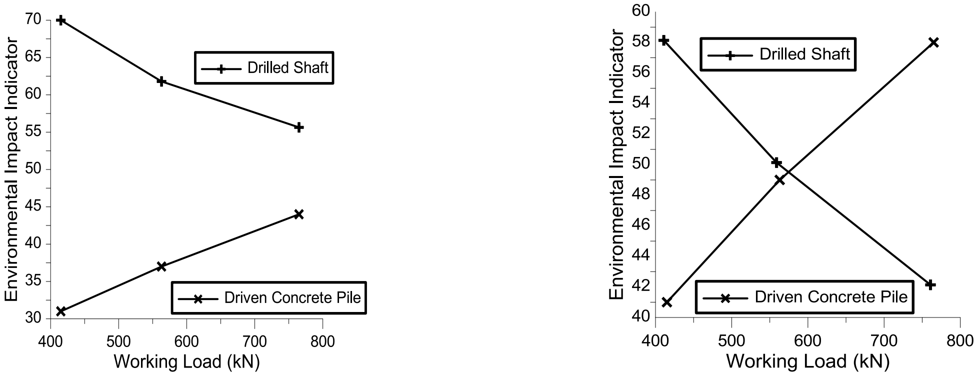


(a) (b)

Figure 6. Working load cases versus resource use indicators for (a) piles in clay and (b) piles in sand

Environmental Impact Indicator

The categories of impact considered for the purpose of calculating the environmental impact indicator are human health, acidification and climate change. Ecosystem health is neglected as the impact in this category is found to be negligible compared to other impact categories. The impacts in the individual categories are converted to percentage and weights are applied to them. A linear combination of the weights and the corresponding percentage values gives the environmental impact indicator. The weights applied are 0.4 for human health, 0.3 for global warming and 0.3 for acidification potential. A greater indicator value implies a less sustainable option. Figure 7(a) and (b) show the environmental impact indicator values for the different load cases considered. The calculated environmental impact indicator suggests that driven piles are more sustainable than drilled shafts from the environmental impact point of view although at a greater load, for piles in sand, the drilled shaft becomes more environment friendly option than driven pile.



(a) (b)

Figure 7. Working load versus environmental impact indicator values (a) for piles in clay and (b) for piles in sand

3.0 Conclusions

Geotechnical engineering is resource intensive. The resources used in geotechnical engineering are obtained from the biogeosphere and from 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.

In this paper, a life cycle analyses of two commonly used types of piles, drilled shaft and driven concrete pile, were performed to assess and compare the environmental sustainability aspects of the piles. The comparative LCA was carried out over three different load cases and the performance of the piles was assessed based on two quantitative indicators – the resource use indicator and the environmental impact indicator. The indicators help to translate the results of the LCA into numeric measures that can account for the relative importance of the resources used and the environmental impacts generated. It is found that, for the particular case study considered, driven piles provide a more sustainable option than drilled shafts although at a greater applied load drilled shafts have lesser environmental impact than driven piles in sand. Since the indicator system balances the resource use with the environmental impact, it provides a holistic approach to assessing sustainability of foundation alternatives at the planning and design stages of a project. Thus, the developed indicators provide a decision aiding tool in choosing one pile type over the other considering environmental sustainability, particularly when technical and technological feasibility is not a limiting factor for choosing an alternative.

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