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Sustainability Metrics for Pile Foundations

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Key words

Sustainability, indicators, pile foundations, life cycle assessment, energy accounting

Abstract: Civil Engineering is the major instrument of anthropocentric development over centuries through ever expanding infrastructures, cities and facilities. Lately, a growing awareness is observed towards making such growth sustainable. Geotechnical engineering, being very resource intensive, warrants an environmental sustainability study, but a quantitative framework for assessing the sustainability of geotechnical practices, particularly at the planning and design stages, does not exist. In this paper, quantitative indicators for assessing the environmental sustainability of pile foundations are developed through life cycle assessment (LCA) of pile foundations. The use of resources is taken into account based on energy-centric methods while the impact of the process emissions is assessed using environmental impact assessment (EIA). The resource use 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 weighted values thus obtained are aggregated across the categories to obtain the resource use and environmental impact indicators for drilled shafts and driven concrete piles carrying equal amount of axial loads. The developed indicators can be used to quantitatively compare the impacts of these two types of piles on the environment considering both resource consumption and process emissions. Thus, a holistic approach towards assessing environmental sustainability of pile foundations is proposed.

Introduction

Civil Engineering has been the major instrument of anthropocentric development over centuries through ever expanding infrastructures, cities and facilities. In recent times, a concerted effort is observed within the civil engineering industry to deliver built facilities that are environment friendly as well as financially viable. 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). By virtue of its early position in the construction cycle, sustainable geotechnical practices can substantially improve the overall sustainability of a project, and hence, improving the sustainability of geotechnical processes is extremely important in achieving overall sustainable development (Jefferis 2008).

Sustainability as a decision metric is slowly gaining popularity within the geotechnical industry and a review of the existing literature reveals a few projects where sustainability has been used as a criterion to choose the best alternative. Chau et al. (2006) used embodied energy as an environmental impact indicator in their study of four different retaining wall designs. Later, Chau et al. (2008) compared the environmental impact and energy efficiency of basement wall construction for two commercial buildings in London in terms of embodied carbon dioxide. 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). Spaulding et al. (2008) compared, using three case studies, the use of ground improvement techniques as an alternative to conventional deep foundations and used carbon footprint as a measure of environmental sustainability. Egan et al. (2010) also studied the use of ground improvement techniques as an alternative to traditional deep foundations using embodied carbon dioxide as an environmental metric. These projects have mainly relied on a single metric, either resource efficiency or environmental impact, which is not sufficient to determine the best engineering solution balancing both economy and ecology.

Some qualitative guidelines are available that use multiple criteria (e.g., social, economic and environmental impacts) for assessing the sustainability of geotechnical construction sites. These include the Sustainable Geotechnical Evaluation Method (S.G.E.M) (Jiminez 2004), the Environmental Geotechnical Indicator System (EGIs) (Jefferson et al. 2007) and GeoSPeAR (Holt et al. 2009, 2010). S.G.E.M. uses a

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color coded indicator system, based on the categories of social, economic, environmental and natural resource use, for the purpose of comparing different alternative materials used in slope stabilization. EGIs consists of 76 generic indicators and 32 technology-specific indicators and was developed for ground improvement projects by borrowing concepts from the existing sustainability indicators like SPeAR and BREEAM (Jefferson et al. 2007). GeoSPeAR is an indicator system for geotechnical construction and was developed by modifying SpeAR (Holt et al. 2010). Although these qualitative indicators serve well at the construction stage of a project, there is a lack of a clearly defined framework to evaluate and quantify the relative sustainability of alternative practices in geotechnical engineering at the planning and design stages of a project (Abreu et al. 2008).

The objective of this paper is to introduce a quantitative framework for assessing the comparative sustainability of different technically feasible options available for a geotechnical project. Life cycle assessment (LCA), in conjunction with environmental impact assessment (EIA), is proposed as a quantitative decision aid tool to incorporate environmental sustainability in geotechnical engineering, particularly, in pile foundation design. Based on the LCA, a resource use indicator and an environmental impact indicator are developed to quantitatively compare the sustainability of competing alternatives. The framework is explained through case studies involving pile foundations in order to determine whether driven concrete piles or drilled shafts are more sustainable for the cases investigated. The purpose of the case studies is to illustrate the utility and effectiveness of the developed framework.

Sustainability Assessment of Geotechnical Projects

A sustainable project balances the social, environmental and economic equity in order to achieve sustainable development. Indiscriminate consumption of natural resources in a project affects the distributional equity of resources, and hence, violates the social equity principle of sustainability. The use of manufactured raw materials in a project disturbs the environmental balance through process emissions and pollutions. A project that focuses only on the financial return and does not consider the social impacts contradicts the economic and social equity principles of sustainability. As geotechnical projects use vast amount of resources and energy, generate considerable amount of waste, involve financial investment of stakeholders and often permanently change the landscape, it is important that they are assessed for sustainability considering resource consumption, environmental impact and socio-economic impact.

In practice, sustainability assessment of geotechnical projects can be done by using life cycle assessment (LCA) that combines resource inventory and environmental impact assessment (EIA) and by using a socio-economic impact assessment tool like cost benefit analysis (CBA). LCA is a quantitative tool that assesses the impacts of a process or a product on the environment over the entire lifespan of the process or the product. In most geotechnical processes, the LCA should follow a "cradle to grave" approach because reuse of materials after decommissioning of a project is generally not considered. In addition, it is better to do the resource accounting in the LCA by energy accounting methods instead of mass accounting because available energy to do work is the ultimate limiting resource. The environmental impact assessment (EIA) determines the impact of the output of a process on the ecosystem on different categories like human and ecosystem health, global warming and acidification. A combination of LCA and EIA provides a holistic environmental sustainability assessment for geotechnical projects.

Life Cycle Assessment of Pile Foundations

The use of the sustainability framework developed in this study is illustrated by applying it to case studies involving pile foundations. Two commonly used pile foundations – drilled shafts and driven concrete piles – are considered in the case studies in order to determine their comparative sustainability. Assessing the sustainability of pile foundations should start after a preliminary design has been done and after data has been collected on the technological feasibility of the different alternatives.

The pile design in this study follows the working stress method. The ultimate pile capacity is assumed to be that corresponding to a pile head settlement of 10% of the pile diameter. 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 driven concrete piles and drilled shafts 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 design equations used in the case studies are provided in Tables 1 and Table 2. Three working load cases of 250 kN, 300 kN and 400 kN are considered with a factor of safety equal to 2.5. The length of the piles is kept constant at 12 m while the diameters are varied in the design. The dimensions obtained from the design calculations are provided in Table 3.

For the sandy soil 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

Table 1 Design equations for sandy profile (Salgado 2008)

Design Equations for Drilled Shaft in Sand	Design Equations for Driven Concrete Pile in Sand
• Limit Unit Shaft Resistance $q_{sL} = K\sigma'_v\tan\phi_c$ where $K = 0.7K_0\exp\left[\left\{0.0114 - 0.0022\ln\left(\frac{\sigma'_v}{p_A}\right)\right\}D_R\right]$ • Ultimate Unit Base Resistance $q_{b,10\%} = \left[0.23\exp(-0.0066D_R)\right]q_{bL}$ where $\frac{q_{bL}}{p_A} = 1.64\exp\left[0.1041\phi_c + (0.0264 - 0.0002\phi_c)D_R\right] \times \left(\frac{\sigma'_h}{p_A}\right)^{(0.841-0.0047D_R)}$	• Limit Unit Shaft Resistance $q_{sL} = 0.02\tan(0.95\phi_c)\left[1.02 - 0.0051D_R\right]q_{bL}$ where $\frac{q_{bL}}{p_A} = 1.64\exp\left[0.1041\phi_c + (0.0264 - 0.0002\phi_c)D_R\right] \times \left(\frac{\sigma'_h}{p_A}\right)^{(0.841-0.0047D_R)}$ and is calculated at a depth at which q_{SL} is required • Ultimate Unit Base Resistance $q_{b,10\%} = \left[1.02 - 0.0051D_R\right]q_{bL}$
σ_v' is the vertical effective stress at a depth at which the capacity is calculated, σ_h' is the horizontal effective stress at a depth at which the capacity is calculated, 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)	

Table 2 Design equations for clayey profile (Salgado 2008)

Design Equations for Drilled Shaft in Clay	Design Equations for Driven Concrete Pile in Clay
• Limit Unit Shaft Resistance $q_{sL} = \alpha s_u$ where $\alpha = 0.4\left[1 - 0.12\ln\left(\frac{s_u}{p_A}\right)\right]$ • Ultimate Unit Base Resistance $q_{b,10\%} = 9.6s_u$	• Limit Unit Shaft Resistance $q_{sL} = \alpha s_u$ where $\alpha = \left(\frac{s_u}{\sigma'_v}\right)_{NC}^{0.5}\left(\frac{s_u}{\sigma'_v}\right)^{-0.5}$ and $\left(\frac{s_u}{\sigma'_v}\right)_{NC} = 0.3$ • Ultimate Unit Base Resistance $q_{b,10\%} = 10s_u$
s_u is the undrained shear strength of clay, NC represents normally consolidated clay, p_A is a reference stress (= 100 kPa)	

pressure at rest K_0 = 0.4, (iv) maximum void ratio e_{max} = 0.9, (v) minimum void ratio e_{min} = 0.4, (vi) unit weight of water γ_w = 9.81 kN/m^3 and (vii) critical state friction angle ϕ_c = 30°. The resulting bulk unit weight of sand γ_{sat} = 19.93 kN/m^3. For the clayey soil considered in this study, the soil properties are (i) G_s = 2.65, (ii) OCR = 2, (iii) γ_w = 9.81 kN/m^3 and (iv) γ_{sat} = 18 kN/m^3. The water table is assumed to be at the ground surface for both the sand and clay profiles.

The designed pile dimensions are used in the LCA to determine (i) the quantity of natural resources and processed materials needed for the piles and (ii) the emissions generated to manufacture the required quantity of materials. 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 its life cycle 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 results in which the resource use and environmental impact indicators are calculated. Figure 1 shows the flow chart for this LCA.

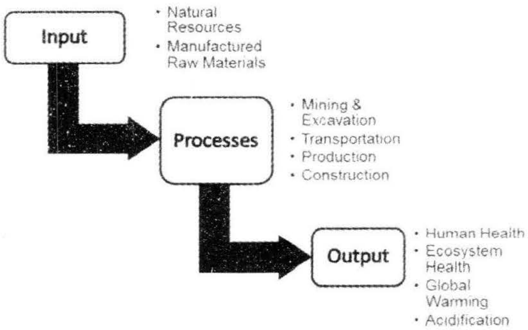


Fig. 1 Flow chart showing the inputs, outputs, processes and impact categories in pile construction

LCA Step 1: Goal and Scope Definition

The goals of the life cycle assessment performed for this case study are (i) to determine, through life cycle inventory (LCI), the resource consumption and emissions for drilled shafts and driven concrete piles over the lifespan of the project and (ii) to decide, after an environmental impact study based on the LCI, which of the two aforementioned piles is more environmentally sustainable.

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 from the biogeosphere. The outputs are the constructed piles along with emissions to air and water. The contributors to energy or resource consumption from the construction and maintenance of the manufacturing plants of cement and steel, electricity consumption of the architect's office and other similar indirect contributors are kept out of the scope with the understanding that such contributions are almost the same for both the pile types, and hence, do not influence the goal of the study.

LCA Step 2: Life Cycle Inventory (LCI)

Input Inventory

Based on the above stated goal and scope of this LCA, life cycle inventory 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. For this particular study, the environmental effects of concrete is considered as the sum of (i) environmental impacts of cement manufacturing from the 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 it is not a limiting resource for the particular case and that 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 pile types are calculated based on the design calculations given in Table 3.

Table 3 Design dimensions of drilled shaft and driven pile for different superstructure loads

Working Load (kN)	Diameter of Piles in Sand (m)		Diameter of Piles in Clay (m)	
	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile
250.00	0.38	0.16	0.68	0.50
300.00	0.51	0.22	0.91	0.70
400.00	0.63	0.27	1.11	0.87
Pile Length = 12 m				

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 is quantified using exergy, emergy and embodied energy in addition to mass. The output side of the inventory is calculated in terms of mass, though, because the data available are all in terms of mass.

Exergy of a resource is its available energy to do useful work (Dincer and Rosen 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 (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 (Brown and Herendeen 1996). A sustainable process should use materials that are low in embodied energy.

The values of unit emergy for cement and steel are adopted from Brown and Buranakaran (2003) and Pulselli et al. (2004) while the values of unit emergy for land are obtained from the emergy folios of Odum et al. (2000). The embodied energy values per unit mass are adopted from the ICE Database version 1.6a prepared by the University of Bath, U.K. (Hammond and Jones 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 sandy profile and as that of clay minerals for the clayey 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. 2004). 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 soil is not excavated out for driven piles, it is assumed in this study that the entire organic content of the soil volume displaced by the driven piles 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 350 Kg. The reinforcement of the driven piles is calculated based on the reinforcement required to support the lifting moments in piles that occur during the lifting of the piles by head (Tomlinson and Woodward 1994). The calculated reinforcements satisfied the minimum required value of 2% of the shaft cross sectional area. A nominal reinforcement of 0.5% of the area of cross section is assumed for drilled shafts (Salgado 2008). Sample calculations for the resource consumption of driven piles in sand for a working load of 400 kN is reported in Table 4.

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 given in terms of mass. The total quantity of cement, diesel, concrete and steel required for the piles, as obtained from the design calculations, is multiplied by the emission values per unit production of cement, concrete and steel, and per unit combustion of diesel, as obtained from the National Renewable Energy Laboratory (NREL), U.S.A database and from Sjunnessen (2005), to obtain the total quantity of the output emissions. As illustrations of the calculations, the output inventory and environmental impact of the outputs are provided in Tables 5-8 for piles in sand for a working load 400 kN.

LCA Step 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 the 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) for this in order 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 gram 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 gram 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 gram equivalent of 1, 4 DB.

Table 4 Resource consumption for driven pile in sand for working load 400 kN

RESOURCE CONSUMPTION CALCULATION FOR DRIVEN PILE IN SAND FOR WORKING LOAD 400 kN										
					Emergy		Embodied Energy		Cumulative Exergy	
SI No.	Materials	Volume (m^3)	Density (Kg/m^3)	Mass (Kg)	Emergy Intensity ($\times10^{11}$) (sej/Kg)	Total Emergy ($\times10^{11}$) (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	0.68		—	—	—	--	—	—	—
(a)	Top soil (3 m)	0.17		344.59		289.45				
(b)	Rest	0.51	2031.91	1033.76	28	289.45	0.45	620.26	0.02	31.43
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										
2	Cement (Portland)	Calculated as 350Kg/m^3 of concrete		201.47	19.70	3968.97	4.60	926.76	5.35	1077.87
3	Steel (Virgin)	0.02	7850.00	184.87	41.30	7635.03	36.40	6729.18	41.00	7579.57
4	Fuel (operation at site)	Average 5 piles a day, 8hrs/day,11gal/hr [Crane+pile driving hammer+welding machine+secondary small crane]		56.62	1.13 Emergy intensity is 1.13×10^5sej/J	2913.71	45.25	2562.22	44.70	2531.07
Total emergy / embodied energy / exergy consumption as resources					15096.62		10838.42		11219.94	

Table 5 Output inventory and environmental impact for cement requirement of piles in sand for working load 400 kN

Output Inventory and Environmental Impact for Cement Requirement for Piles in Sand For Working Load 400 kN									
Agent	Quantity/ Unit (gm/gm)	Quantity Emitted for Drilled Shaft ($\times10^3$) (gm)	Quantity Emitted for Driven Pile ($\times10^3$) (gm)	Global Warming Potential ($\times10^3$) (gm equivalent CO_2) Index	Drilled Shaft	Driven Pile	Acidification Potential ($\times10^3$) (gm equivalent SO_2) Index	Drilled Shaft	Driven Pile
		(3)	(4)		(6)	(7)		(9)	(10)
(1)	(2)	(3) and (4) = (2) × 350Kg of cement × volume of concrete used $\times10^3$		(5)	(6) = (5)×(3)	(7) = (5)×(4)	(8)	(9) = (8)×(3)	(10) = (8)×(4)
Particulates, unspecified	0.00235	2.58	0.47	—	NA	NA	—	NA	NA
Particulates, > 2.5 μm, and < 10μm	0.00030	0.32	0.06	—	NA	NA	—	NA	NA
Carbon dioxide, biogenic	0.37359	409.34	75.27	1.00	409.34	75.27	—	NA	NA
Carbon dioxide, fossil	0.55344	606.41	111.50	1.00	606.41	111.50	—	NA	NA
Sulfur dioxide	0.00166	1.82	0.33	—	NA	NA	1.00	1.82	0.33
Nitrogen oxides	0.00250	2.74	0.50	—	NA	NA	0.52	1.43	0.26
VOC, volatile organic compounds	0.00005	0.05	0.01	—	NA	NA	—	NA	NA
Carbon monoxide	0.00110	1.21	0.22	—	NA	NA	—	NA	NA
Methane	0.00003	0.03	0.01	25.00	0.82	0.15	—	NA	NA
Ammonia	0.00001	0.01	0.00	—	NA	NA	2.23	0.01	0.00
Hydrogen chloride	0.00006	0.07	0.01	—	NA	NA	—	NA	NA
TOTAL IMPACT IN CATEGORIES					1016.57	186.92		3.26	0.60

Table 6 Output Inventory and Environmental Impact for Diesel Combustion for Piles in Sand for Working Load 400 kN

Output Inventory and Environmental Impact for Diesel Combustion for Piles in Sand for Working Load 400 kN									
	Quantity/ Unit	Quantity Emitted for Drilled Shaft (Kg)	Quantity Emitted for Driven Pile (Kg)	Global Warming Potential (Kg equivalent CO_2)			Acidification Potential (Kg equivalent SO_2)		
Agent	(Kg/L)			Index	Drilled Shaft	Driven Pile	Index	Drilled Shaft	Driven Pile
		(3)	(4)		(6)	(7)		(9)	(10)
(1)	(2)	(3) and (4) = (2) ×liters of diesel used		(5)	(6) = (5)×(3)	(7) = (5)×(4)	(8)	(9) = (8)×(3)	(10) = (8)×(4)
Carbon dioxide, fossil	0.27000	122.63	17.9863	1.00	122.63	17.99	NA	—	—
Carbon monoxide, fossil	0.01400	6.36	0.9326	NA	—	—	NA	—	—
Methane, fossil	0.00010	0.05	0.0067	25.00	1.14	0.01	NA	—	—
Nitrogen oxides	0.05000	22.71	3.3308	NA	—	—	0.52	11.81	1.73
Particulates, > 2.5 um, and < 10um	0.00160	0.73	0.1066	NA	—	—	NA	—	—
Sulfur oxides	0.00060	0.27	0.0400	NA	—	—	1.00	0.27	0.04
VOC, volatile organic compounds	0.00140	0.64	0.0933	NA	—	—	NA	—	—
TOTAL IMPACT IN CATEGORIES					123.77	17.99		12.08	1.77

Table 7 Output Inventory and Environmental Impact for Concrete Requirements for Piles in Sand for Working Load 400 kN

Output Inventory and Environmental Impact for Concrete Requirement for Piles in Sand for Working Load 400 kN									
	Quantity/ Unit	Quantity Emitted for Drilled Shaft (gm)	Quantity Emitted for Driven Pile (gm)	Global Warming Potential (gm equivalent CO_2)			Acidification Potential (gm equivalent SO_2)		
Agent	(gm/m^3)			Index	Drilled Shaft	Driven Pile	Index	Drilled Shaft	Driven Pile
		(3)	(4)		(6)	(7)		(9)	(10)
(1)	(2)	(3) and (4) = (2) × volume of concrete used		(5)	(6) = (5)×(3)	(7) = (5)×(3)	(8)	(9) = (8)×(3)	(10) = (8)×(4)
Particulates	0.08	0.30	0.06	—	NA	NA	—	NA	NA
Carbon dioxide	257.00	948.14	174.34	1.00	948.14	174.34	—	NA	NA
Carbon monoxide	0.59	2.17	0.40	—	NA	NA	—	NA	NA
Nitrogen oxides	0.49	1.81	0.33	—	NA	NA	0.52	0.94	0.1732
Sulfur dioxides	0.43	1.57	0.29	—	NA	NA	1.00	1.57	0.2890
Methane	1.60	5.90	1.09	25.00	147.57	27.13	—	NA	NA
Ammonia	0.01	0.03	0.00	—	NA	NA	2.23	0.0576	0.0106
TOTAL IMPACT IN CATEGORIES					1095.71	201.47		2.57	0.473

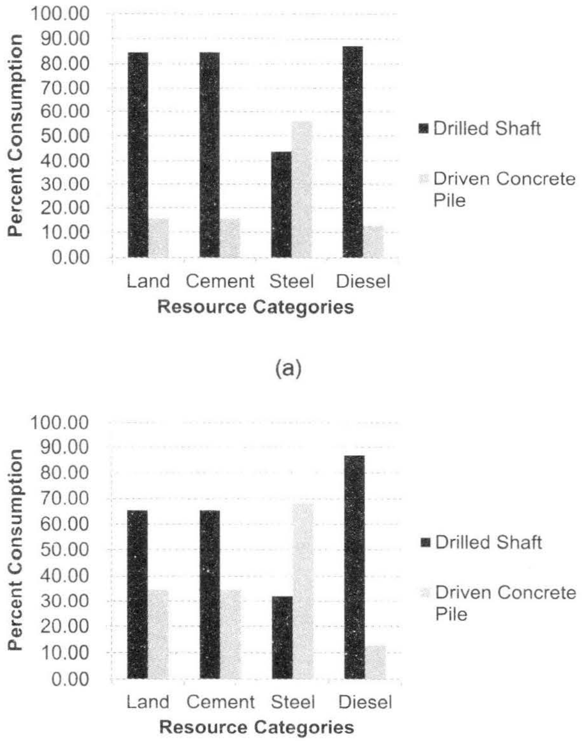
Table 8 Output Inventory and Environmental Impact for Steel Requirements of Piles in Sand for Working Load 400 kN

Output Inventory and Environmental Impact for Steel Requirement for Piles in Sand for Working Load 400 kN																		
Agent	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)		
		(3) and (4)=(2) × 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)	(3)	(4)	(5)	(6) = (5)×(3)	(7) =(5)×(4)	(8)	(9) = (8)×(3)	(10) = (8)×(4)	(11)	(12) = (11)×(3)	(13) = (11)×(4)	(14)	(15) = (14)×(3)	(16) = (14)×(4)	(17)	(18) = (17)×(3)	(19) = (17)×(4)
Acrolein	0.03	0.0004	0.0005	6154.00	2.7	2.94	1.11	0.0005	0.001	0.49	0.0002	0.0002				—	NA	NA
Ammonia	10.89	0.1577	0.1710	—	NA	NA	—	NA	NA	—	NA	NA	2.23	0.35175	0.381	—	NA	NA
Antimony	0.02	0.0002	0.0003	35230.0	8.4	9.12	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Arsenic	0.11	0.0016	0.0017	649500	1047.2	1135.45	5.75	0.009	0.010	1.74	0.0028	0.0030	—	NA	NA	—	NA	NA
Benzene	0.04	0.0006	0.0007	0.36	0.0002	0.000	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Beryllium	0.01	0.0002	0.0002	17800.0	3.3	3.57	130.00	0.024	0.026	68.19	0.0126	0.0137	—	NA	NA	—	NA	NA
Carbon dioxide, biogenic	1373.70	19.8916	21.5671	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	1.00	19.89	21.57
Carbon dioxide, fossil	19400000	280917.69	304580.00	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	1.00	280918	304580
Carbon monoxide, fossil	229320.00	3320.6208	3600.3240	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Chlorine	0.12	0.0018	0.0019	209.90	0.4	0.4047	0.44	0.0008	0.001	0.01	0.00002	0.00002	—	NA	NA	—	NA	NA
Chromium	0.18	0.0026	0.0028	0.34	0.0009	0.00095	9.06	0.023	0.025	0.35	0.0009	0.0010	—	NA	NA	—	NA	NA
Cobalt	0.05	0.0007	0.0007	4310.00	2.9	3.16316	23.29	0.016	0.017	12.74	0.0086	0.0094	—	NA	NA	—	NA	NA
Dinitrogen monoxide	19.03	0.2755	0.2988	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	298.00	82.11	89.03
Ethene, trichloro-	0.03	0.0004	0.0005	193.70	0.08	0.08784	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Hydrogen fluoride	21.26	0.3078	0.3337	266.10	81.9	88.80	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA
Lead	0.11	0.0016	0.0017	23110.0	37.1	40.24	8.79	0.014	0.015	0.17	0.0003	0.0003	—	NA	NA	—	NA	NA
Manganese	0.35	0.0050	0.0054	26230.0	131.5	142.56	0.01	0.00005	0.00005	1.96	0.0098	0.0106	—	NA	NA	—	NA	NA
Mercury	0.06	0.0009	0.0009	1224000	1055.2	1144.07	1698	1.464	1.587	11.44	0.0099	0.0107	—	NA	NA	—	NA	NA
Methane	7871.90	113.9874	123.5888	—	NA	NA	—	NA	NA	—	NA	NA	—	NA	NA	25.00	2849.69	3089.72
Nickel	0.52	0.0075	0.0082	680.90	5.1	5.56	80.00	0.603	0.654	32.94	0.2482	0.2691	—	NA	NA	—	NA	NA
Nitrogen oxides	21102.00	305.5631	331.3014	—	NA	NA	—	NA	NA	—	NA	NA	0.52	158.89	172.28	—	NA	NA
Sulfur dioxide	7188.30	104.0887	112.8563	—	NA	NA	—	NA	NA	—	NA	NA	1.00	104.09	0.00	—	NA	NA
Sulfur oxides	29106.00	421.4634	456.9642	—	NA	NA	—	NA	NA	—	NA	NA	1.00	421.46	456.96	—	NA	NA
TOTAL IMPACT IN CATEGORIES					2372.95	2575.99		2.15	2.34		0.29	0.32		684.80	629.62		283869	307780

Tables 5-8 summarize the contribution of the two types of piles in sand in the different impact categories based on the emissions of the process for the load case of 400kN. Similar calculations were done for piles in clay.

LCA Step 4: Interpretation of Results

Figures 2(a) and (b) show the resource consumptions in terms of embodied energy for driven piles and drilled shafts in sand and clay across the categories of land, cement, diesel and steel. As the drilled shafts require a larger diameter than the driven piles for the load cases and soil profiles considered, the drilled shafts consume more resources in terms of cement and land than the driven piles. However, the driven piles require more reinforcement compared with the drilled shafts, and hence, energy consumed due to the use of steel are greater for driven piles than for drilled shafts.



(a)

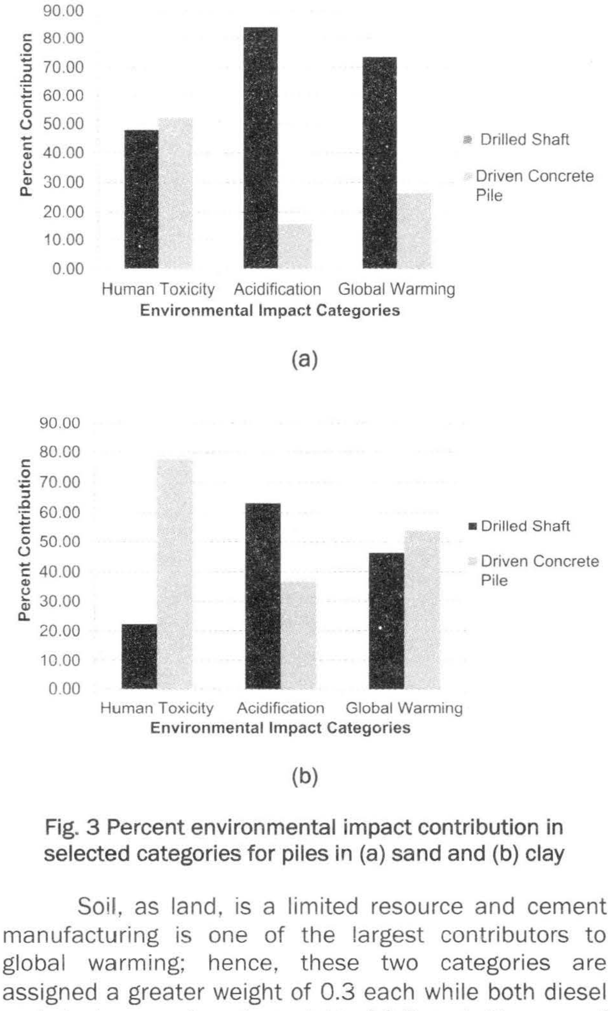
(b)

Fig. 2 Percent consumption of embodied energy for piles in (a) sand and (b) clay across the categories of land, cement, steel and diesel

Figures 3(a) and (b) 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 in the figures.

Resource Use Indicator

The resource use indicator is the sum of the weighted scores of the percentage embodied energy consumption of the two pile types across the chosen categories of land, cement, diesel and steel. For the purpose of obtaining an indicator, the embodied energy consumption was chosen to represent the energy use. The choice of embodied energy was made mainly because LCA of buildings and related materials have traditionally been done using embodied energy.

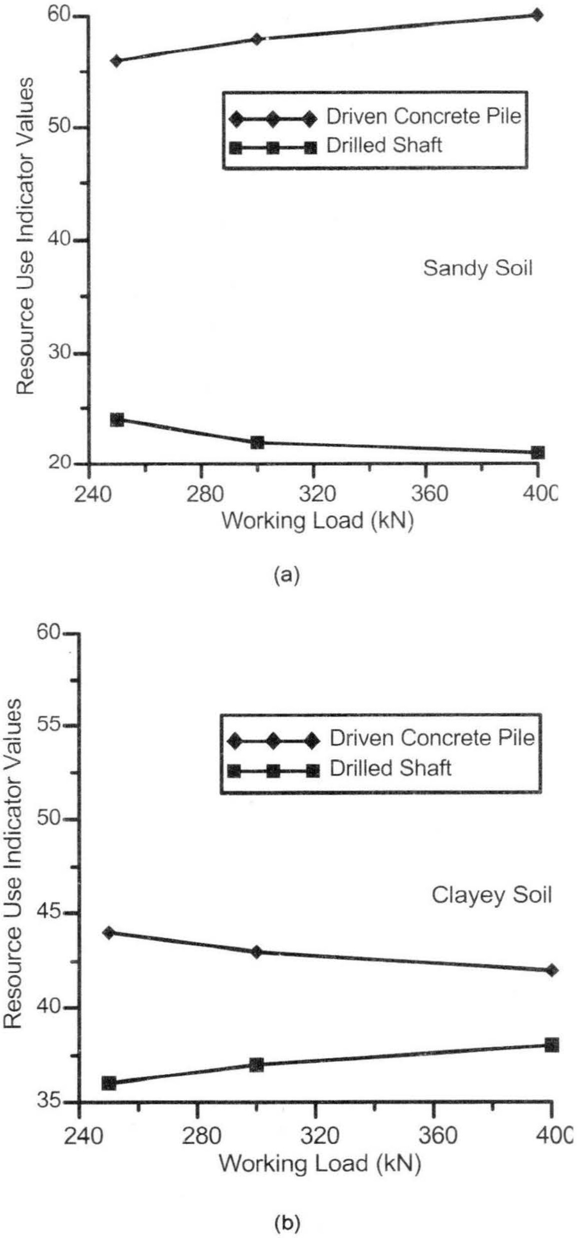


(a)

(b)

Fig. 3 Percent environmental impact contribution in selected categories for piles in (a) sand and (b) clay

Soil, as land, is a limited resource and cement manufacturing is one of the largest contributors to global warming; hence, these two categories are assigned a greater weight of 0.3 each while both diesel and steel 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. Sample calculations for piles in sand are provided in Table 9. Similar calculations were done for piles in clay. The details of the calculations are reported in Misra (2010). The indicators calculated for driven piles and drilled shafts for the different load cases are plotted in Figures 4(a) and (b) for the different superstructure loads. The lower the value of the indicator is, the more sustainable the process is. Thus, from a resource use point of view, driven piles are more sustainable (for the cases considered in this study) although the performance of both the pile types are almost the same for the clayey profile.



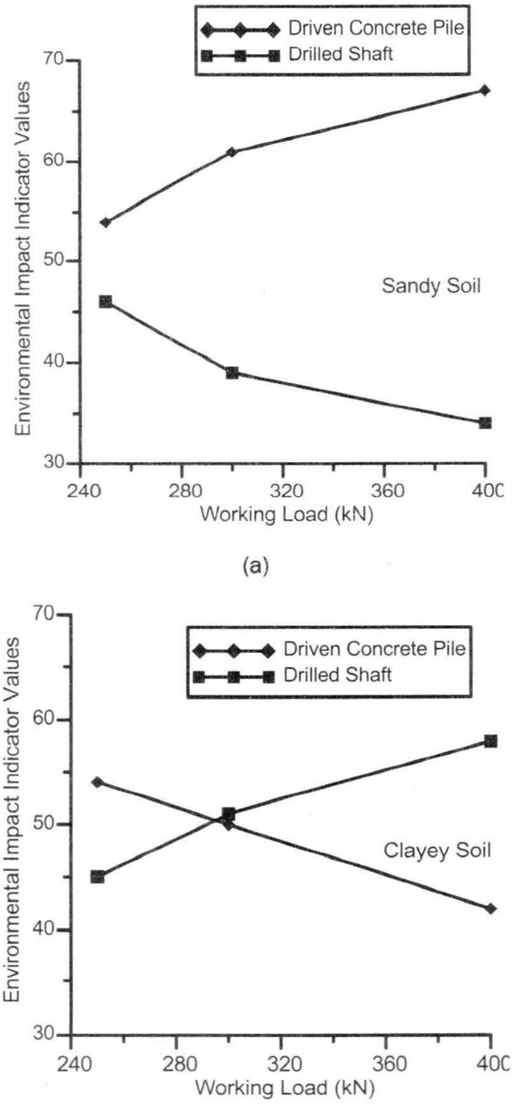
(a)

(b)

Fig. 4 Resource use indicator for piles in (a) sand and (b) clay as a function of superstructure load

Environmental Impact Indicator

The environmental impact indicator is the sum of the weighted scores of the percent contribution of the two pile types in the environmental impact categories of 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 indicator is calculated with weights of 0.4 for human toxicity, 0.3 for global warming and 0.3 for acidification potential. Sample calculations for piles in sand are shown in Table 10. The indicators calculated for driven piles and drilled shafts are plotted in Figures 5(a) and (b) for the different superstructure loads. As a low value of the indicator represents a more sustainable option, the driven piles are better in the sandy profile (for the cases considered in this paper) from an environmental impact point of view. For the clayey profile, the performance of the piles depends on the superstructure load for which they are designed.



(a)

(b)

Fig. 5 Environmental impact indicator for piles in (a) sand and (b) clay as a function of superstructure load

Table 9 Calculation of Resource Use Indicator for Piles in Sand for Working Load 400 kN

Calculation for Resource Use Indicator for Piles in Sand for Working Load 400 kN																
	Resource Consumption						Percent Resource Consumption						Calculation of Resource Use Indicator			
	Emergy ($\times 10^{11}$) (sej)		Embodied Energy (MJ)		Cumulative Exergy (MJ)		Emergy		Embodied Energy		Cumulative Exergy					
Resource Category	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Driven Pile	Drilled Shaft	Weight	Indicator Value in Each Category for Driven Pile	Indicator Value in Each Category for Drilled Shaft
Land	578.91	3148.41	620.26	3373.30	31.43	170.91	15.53	84.47	15.53	84.47	15.53	84.47	0.30	4.66	25.34
Cement	3968.97	21585.41	926.76	5040.25	1077.87	5862.03	15.53	84.47	15.53	84.47	15.53	84.47	0.30	4.66	25.34
Steel	7635.03	10092.76	6729.18	5270.83	7579.57	5936.92	43.07	56.93	56.08	43.92	56.08	43.92	0.20	11.22	8.78
Diesel	2913.71	14568.56	2562.22	17469.67	2531.07	17257.33	16.67	83.33	12.79	87.21	12.79	87.21	0.20	2.56	17.44
Total	15096.62	49395.15	10838.42	31154.04	11219.94	29227.19							Final Indicator Value	20.53	59.47

Table 10 Calculation of Environmental Impact Indicator for Piles in Sand for Working Load 400 kN

Calculation of Environmental Impact Indicator for Piles in Sand for Working Load 400 kN																
		Drilled Shaft					Driven Pile					Percentage Impact from Drilled Shaft	Percentage Impact from Driven Pile	Weight	Indicator Value in Each Category for Drilled Shaft	Indicator Value in Each Category for Driven Pile
Environmental Impact Category	Unit	Cement (1)	Concrete (2)	Steel (3)	Diesel (4)	Total (5)	Cement (6)	Concrete (7)	Steel (8)	Diesel (9)	Total (10)	(11) =[(5)/(5)+(10)] × 100	(12) =[(10)/(5)+(10)] ×100	(13)	(14)= (13) × (11)	(14)=(13) × (12)
Human Toxicity	gm,1,4 DB Eq	0.00	0.00	2372.95	0.00	2372.95	0.00	0.00	2575.99	0.00	2575.99	47.95	52.05	0.40	19.18	20.82
Acidification	gm Eq SO_2	3260.0	2.57	684.80	12081.72	16029.05	599.42	0.47	629.62	1771.99	3001.50	84.23	15.77	0.30	25.27	4.73
Global Warming	gm Eq CO_2	1016574.36	1095.7	283869	123770	1425309	186920	201.47	307780.32	17993.88	512896.1	73.54	26.46	0.30	22.06	7.94
													Final Indicator Value		66.51	33.49

Note that the cost of installation of driven piles is much less than that of drilled shafts. However, the loud noise and vibrations that ensues during the construction of driven piles may not be welcomed in the neighborhood and may cause damage to the existing structures around the construction site. In real life problems, the financial aspects and social impacts including those due to noise and vibrations must also be taken into account while deciding on a particular type of pile.

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. Thus, it is important to perform sustainability assessment of geotechnical projects in order to ensure that the resources used and the pollutions caused are kept at a minimum.

A comparative LCA was carried out for drilled shafts and driven concrete piles in sandy and clayey profiles designed to carry three different loads. The LCA consists of LCI and EIA. Based on the LCA, two indicators, the resource use indicator and the environmental impact indicator, were calculated for the two types of piles. A lower value of the indicators suggests a more sustainable option. The calculated indicators show that, for the piles in sand considered in this study, driven piles use resources more efficiently than drilled shafts and, for the piles in clay, 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 perform better in the sandy profile but, for clayey profile, the performance depends on the design load. Thus, the framework developed in this study provides a decision aiding tool in choosing one pile type over the other considering environmental sustainability, particularly when technical feasibility is not a limiting factor for choosing an alternative.

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