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Environmental Impacts of Drilled Shaft Design in Sand

Mina Lee & Dipanjan Basu
Department of Civil & Environmental Engineering – University of Waterloo, Waterloo, Ontario, Canada

ABSTRACT

A variety of methods are available for design of drilled shafts based on different assumptions and input parameters. Whilst all these design methods ensure safety and/or serviceability of drilled shafts, difference in drilled shaft dimensions ensues for the same design problem if different design methods are used. Consequently, there is a difference in material use depending on the choice of the design method, and this impacts the environment. In this study, life cycle analyses (LCA) are performed to quantify the consumption of resources required to construct drilled shafts designed using different available methods and to estimate the emissions as a consequence of the construction. Different available design methods are selected and compared based on the results of LCA for several different subsurface profiles consisting of sand layers.

RÉSUMÉ

Différentes méthodes sont disponibles pour le dimensionnement des pieux forés sur la base de différentes hypothèses et différents paramètres d'entrée. Bien que toutes ces méthodes de conception assurent la sécurité et/ou la pérennité des pieux, l'utilisation de différentes méthodes pour une même conception peut mener à des différences de dimensionnement. Par conséquent, différents matériaux peuvent être utilisés dépendamment du choix de la méthode de conception utilisée, entraînant ainsi des impacts sur l'environnement. Dans cette étude, des analyses de cycle de vie (ACV) sont réalisées pour quantifier la consommation de ressources nécessaires à la construction des pieux forés en utilisant différentes méthodes de conception, ainsi que pour estimer les émissions toxiques causées par la construction. Différentes méthodes de dimensionnement sont sélectionnées et comparées sur la base des résultats de l'ACV pour différents profils de couches de sable.

1 INTRODUCTION

Drilled shafts or bored piles can be designed in many different ways depending on the practitioners' choice. The available design methods incorporate different design equations based on different input parameters and assumptions. However, all the methods ensure that the design outcome is satisfactory considering either or both the serviceability and ultimate limit states. Hence, selection of a particular design method may not be a significant concern for meeting the technical requirements. However, depending on the design method chosen, the final design dimensions can be different. The design dimensions affect the material use, which controls the quantity of emissions generated in producing the materials for the drilled shaft. Thus, design methods have an impact on the environment and geotechnical engineers should pay attention to this aspect in design.

In this study, a number of drilled shafts are designed considering different soil profiles consisting of sand layers. Resource use and environmental impacts anticipated from using each design method are quantified and evaluated by life cycle analysis. The objective of this study is to examine the effect of various design methods on the environmental impacts and to emphasize the importance of careful decision making regarding the choice of an appropriate design method from the environmental impact point of view in addition to the technical point of view.

2 METHODOLOGY

Comparisons between different design methods are carried out in terms of energy (resource) consumption and emissions. Two major steps are involved in the methodology: performing design calculations for drilled shafts and conducting LCA to measure the environmental impacts for each design.

2.1 Drilled Shaft in Sands

Different design methods presented in eight textbooks or manuals are considered in this study (Budhu, 2008; Canadian Geotechnical Society, 2006; Coduto, 2001; Das, 2011; Federal Highway Administration, 2010; Fleming et al. 2009; Reese et al. 2006; Salgado, 2008). Two methods are proposed in Salgado (2008) for calculating capacity of drilled shaft — one method uses standard penetration test (SPT) results and the other method is based on soil properties such as relative density, angle of friction, and at-rest coefficient of earth pressure. Budhu (2008) and Reese et al. (2006) suggest the same design method.

In order to study the effect of different soil parameters in design, seven different subsurface profiles consisting of sandy soil are considered. Single drilled shafts are designed using all the methods mentioned above for each soil profile. For a given profile, the length of pile shaft is considered fixed to a reasonable value (depending on the soil profile) for all the design methods so that the differences in the design methods result in different diameters. Since a constant axial load is applied to drilled shafts, steel reinforcement in longitudinal direction are required. The quantity of steel reinforcement required for the drilled shafts was decided based on the preliminarily reinforcement requirement as recommended in FHWA (2010). The gross cross section area of steel reinforcement is chosen to be equal to 2.5% of the cross section area of the concrete shaft.

If soil properties or in-situ test results (SPT blow counts) required by the design method is not explicitly provided from the soil profile, the missing data is estimated based on available correlations or empirical equations. For example, the relationship between SPT N value and relative density D_R was determined using an empirical equation based on work by Meyerhof (1957) and Skempton (1986) as recommended in Salgado (2008):

$$N_{60} = \frac{D_R}{100\%}\left(A + BC\frac{\sigma'_v}{p_A}\right) \qquad [1]$$

where N_{60} is the corrected standard blow count, D_R is in percentage, σ'_v is the effective vertical stress, p_A is the reference stress (100 kPa), A, B, and C are correlation coefficients such that $27 \leq A \leq 46$, and $B \approx 27$. The coefficient C is given by

$$C = \frac{1 + 2K_0}{1 + 2K_{0,NC}} \qquad [2]$$

in which K_0 is the coefficient of at-rest earth pressure and $K_{0,NC}$ is the at-rest earth pressure of the soil under normally consolidated condition. The peak friction angle is estimated based on a relationship between peak friction angle and N_{60} proposed by De Mello (1971).

2.1.1 Subsurface Profiles

Seven subsurface profiles consisting of different combinations of sand layers are considered in this study as shown in Figures 1-5. Profile 1 consists of three sand layers with soil unit weight γ = 18, 20, and 22 kN/m^3, and the water table is located 1 m below the ground surface. Profile 2 consists of a homogeneous and completely dry sand layer with relative density (D_R) of 70%. Profile 3 is similar to Profile 2 except the water table is located at the ground surface. Profile 4 consists of dry sand layers, in which the top layer has relative density of 50% and it overlies a bearing layer (D_R = 80%). Profile 5 is the same as Profile 4 except the water table is located 2 m below the ground surface. Profile 6 consists of loose sand layer (D_R = 20%) underlain by a bearing layer (D_R = 80%), and the water table is located at the ground surface. Profile 7 is a four-layer system consisting of dry sands. The critical state friction angle ϕ_c assumed for these profiles vary between 30° and 32°. K_0 varies between 0.4 and 0.45.

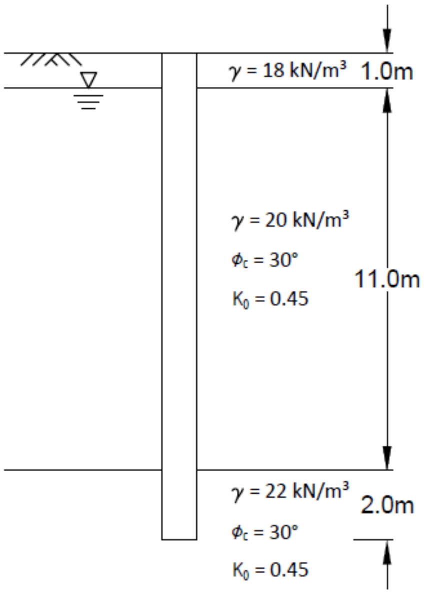

Figure 1. Soil profile 1

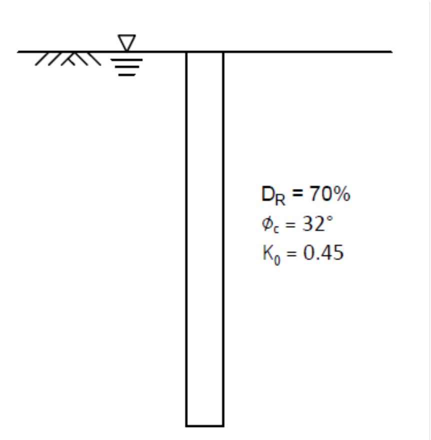

Figure 2. Soil profile 2 (no water table) & profile 3 (with water table)

Drilled shaft embedded in Profile 1 is assumed to have a fixed length of 14 m for all design methods. Similarly, the length of shaft for Profiles 2-6 and Profile 7 are fixed at 10 m and 20 m, respectively. The applied axial load is assumed to be constant at 2000 kN for all profiles except for Profile 7. A higher load of 3500 kN is assumed for Profile 7 to ensure that the design diameter is within a practical range. A factor of safety of 2.5 is applied to all the designs.

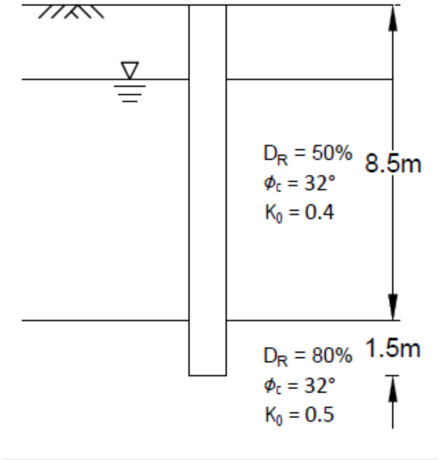

Figure 3. Soil profile 4 (no water table) & profile 5 (with water table)

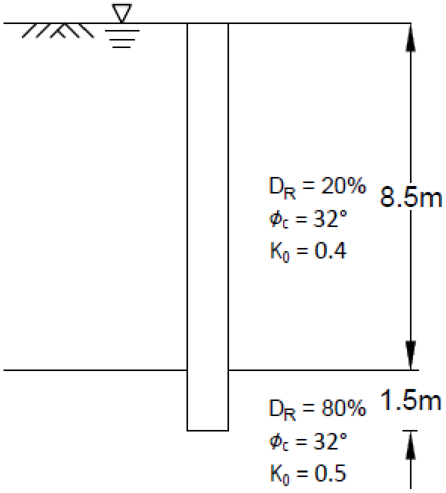

Figure 4. Soil profile 6

2.2 Life Cycle Analysis

Life cycle analysis evaluates inputs and outputs associated with all the stages in the life cycle of a single drilled shaft. Resources and energy are required as inputs for manufacturing drilled shaft, which causes generation of pollutants. These pollutants lead to major environmental impacts like global warming. LCA is usually conducted in two stages, namely, inventory analysis and environmental impact analysis. In this study, LCA is conducted on a "cradle-to-gate" basis, in which the life cycle of a single drilled shaft starts with the extraction of raw materials and continues up to the manufacturing phase as shown in Figure 6. Further stages beyond manufacturing are omitted from the lifecycle, because processes involved in those stages are not likely to significantly affect the results when same type of foundation is compared.

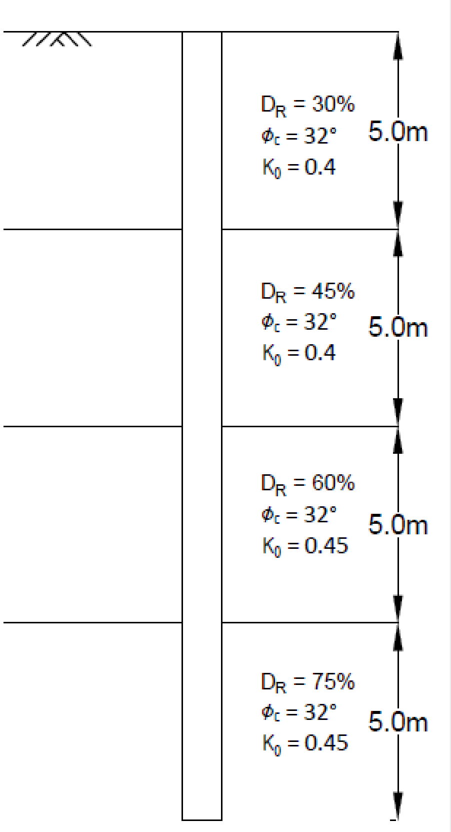

Figure 5. Soil profile 7

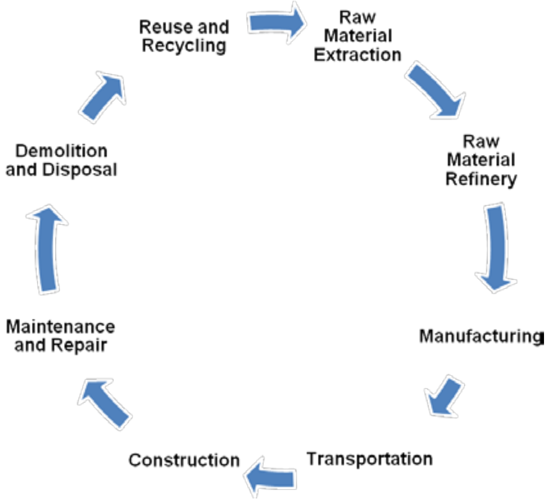

Figure 6. Life cycle system boundary

2.2.1 Inventory Analysis

The inventory analysis quantifies and compiles inputs and outputs for all life cycle processes. In this study, mass of materials (i.e., soil, cement, and steel) and embodied energy are considered as inputs to the processes.

Embodied energy of a material is the total primary energy consumed over its life cycle. In "cradle-to-gate" boundary, embodied energy includes all primary energy consumed from extraction of raw materials until the product leaves the manufacturing factory (Hammond and Jones, 2011). Embodied energy associated with each type of material is computed by multiplying mass of a material and its corresponding embodied energy intensity, obtained from Inventory of Carbon & Energy (ICE) database (Hammond and Jones 2011). The mass of materials are estimated based on the dimensions of drilled shaft obtained from design calculations. Table 1 summarizes the embodied energy intensities used in the inventory analysis.

Table 1. Embodied energy intensity

Material	Embodied Energy Intensity (MJ/kg)
Soil	0.45
Cement (virgin)	4.60
Steel (virgin)	36.40

Embodied energy of concrete is calculated based on the mass of cement because it mostly impacts the environment amongst other mixture materials. Other constituents of concrete, including water, sand, and aggregates, require minimum processing prior to the mixture stage. Hence, it is assumed that the mass of concrete is equivalent to the mass of cement to reflect that environmental impacts of concrete mainly result from the production of cement (Misra, 2010). Summation of embodied energies of each material represents the total embodied energy required to manufacture a single drilled shaft.

The outputs from lifecycle processes include quantity of air emissions such as carbon dioxide, methane, sulfur oxides, nitrogen oxides, etc. National Renewable Energy Laboratory (2012) database provides the list of all air emissions released due to the production of a particular material and their corresponding emission factors. Similar to embodied energy calculations, the mass of air emissions is computed by multiplying mass of a material and its corresponding emission factor. The emission factor specifies the quantity of air emission per unit of the relevant material. For example, it is estimated that 0.374 kg of carbon dioxide is released per kg of manufactured cement (i.e., 0.374 is the emission factor). If the total mass of cement is 4126 kg, then 1543 kg of carbon dioxide is estimated to be emitted to air.

2.2.2 Environmental Impact Analysis

Once the mass of all air emissions are computed, they are characterized in terms of environmental impacts. For example, carbon dioxide (CO_2) and methane (CH_4) are chemical substances affecting global warming. Air emissions are converted into an equivalent measurement to quantify their contribution towards the relevant environmental impacts. For instance, global warming potential (GWP) is measured by mass of CO_2, and the contribution of methane to global warming can be estimated by converting the mass of methane to an equivalent mass of carbon dioxide. As an example, given the mass of methane emitted to air from cement manufacturing is 0.124 kg, and the characterization factor of methane for GWP is 25, then the mass of methane is equivalent to 3.09 kg of carbon dioxide. In other words, contribution of 0.124 kg of methane towards global warming is equivalent to 3.09 kg of CO_2. The conversion or characterization factors are obtained from ReCiPe database provided by Goedkoop et al. (2014). In this study, three categories of environmental impacts are investigated: climate change, ecotoxicity, and human health. Indicators of climate change are global warming potential and acidification potential. Ecosystem health is represented by terrestrial and freshwater toxicity. Lastly, impact to human health is measured by human toxicity. Table 2 summarizes the categories of environmental impacts and their equivalent measurement.

Table 2. Categories of environmental impacts

Environmental Impact	Equivalent Measurement
Global Warming Potential	Kg of CO_2 equivalent
Acidification Potential	Kg of SO_2 equivalent
Human, Terrestrial, and Freshwater Toxicity	Kg of 1,4-DB equivalent

3 RESULTS

The results of design calculations and LCA are summarized in this section. Due to limited space, results for every soil profile and every design method are not provided, but the basic statistics of the key parameters are reported.

3.1 Design Calculations

The design calculations produce the diameter of shaft, volume of concrete, and volume of steel required for constructing drilled shafts. Diameters obtained from using different design methods are analyzed statistically in terms of their mean, coefficient of variance (COV), and range. Table 3 summarizes the basic statistics of the design diameter for every soil profile.

Table 3. Shaft diameters for all soil profiles

Soil Profiles	Average (m)	Coefficient of Variation	Range (m)
1	0.89	0.47	1.15
2	0.92	0.42	1.09
3	1.05	0.41	1.12
4	0.87	0.45	1.07
5	0.97	0.44	1.16
6	1.11	0.45	1.24
7	0.86	0.44	1.04

For demonstration purpose, the summary of design calculations for soil profile 1 is shown in Table 4.

Information similar to those given in Table 4 for the other soil profiles are not provided due to space limitations.

Table 4. Drilled shaft designs for Profile 1

Design Methods	Diameter (m)	Volume of Concrete (m^3)	Volume of Steel (m^3)
Coduto (2001)	1.12	13.89	0.347
Salgado (2008): In-situ based	0.95	9.97	0.249
Salgado (2008): Property based	1.42	22.10	0.552
Das (2011)	0.40	1.67	0.042
Budhu (2008) and Reese et al. (2006)	1.16	14.84	0.371
Fleming et al. (2009)	0.26	0.76	0.019
CGS (2006)	0.63	4.31	0.108
FHWA (2010)	1.16	14.79	0.370

It is observed from Table 4 that the design diameters obtained from Das (2011) and Fleming et al. (2009) methods are relatively small. A high value of the bearing capacity factor is used in the Fleming et al. (2009) method. Consequently, a relatively high base capacity is obtained which then results in smaller diameter. Das (2011) method uses a variety of empirical equations, thus it is difficult to identify the exact reason why the diameter calculated using this method is small. However, it is found that using the design equations given in Das (2011) results in relatively high base capacity as well, which results in the smaller pile diameter.

3.2 Embodied Energy and Environmental Impacts

Total embodied energy consumed in the life cycle of single drilled shafts designed using all the above-mentioned design methods and soil profiles are shown in Figure 7. It is observed that the total embodied energy ranges from 5036 MJ to 232359 MJ. Table 5 summarizes the basic statistics on total embodied energy for every soil profile.

Each material processing results in the generation of emissions and those emissions contribute towards relevant global environmental impacts. The environmental impact of drilled shafts and contribution of each type of materials towards relevant impacts are shown in Figures 8-17.

Similar to total embodied energy, fluctuations in the environmental impacts are observed, as shown in Figures 8, 10, 12, 14, and 16. Different design methods result in variations in design diameter which causes the fluctuations in the environmental impacts. In Figures 9, 11, 13, 15, and 17, the legend pertaining to concrete represents the environmental impacts from concrete mixture process, and the legend pertaining to cement indicates the impacts from cement production. Contributions of all the material processing, namely, steel, concrete, and cement, to global warming and acidification were found to be almost the same. From Figures 13 and 15, it is observed that manufacturing of concrete hardly impacts ecotoxicity and human health, whereas production of cement affects these factors the most. Freshwater toxicity is mostly affected by the production of steel and cement as shown in Figure 17. Basic statistical analysis of environmental impacts for Profile 1 is summarized in Table 6.

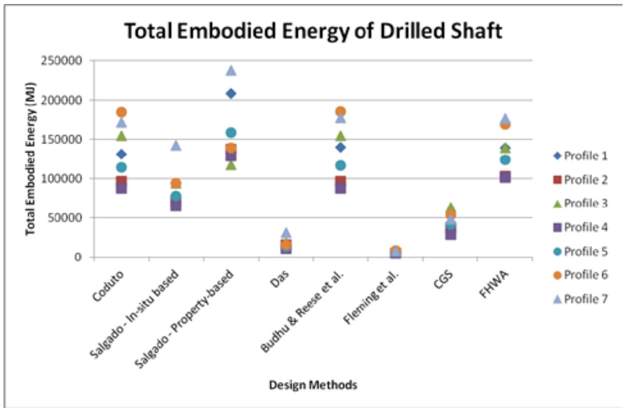

Figure 7. Total embodied energy of drilled shafts

Table 5. Total embodied energy for all soil profiles

Soil Profiles	Average (MJ)	Coefficient of Variation	Range (MJ)
1	97071	0.73	201262
2	70964	0.66	132244
3	93824	0.62	146499
4	64621	0.70	123972
5	81860	0.68	151756
6	106510	0.69	176539
7	124101	0.67	228991

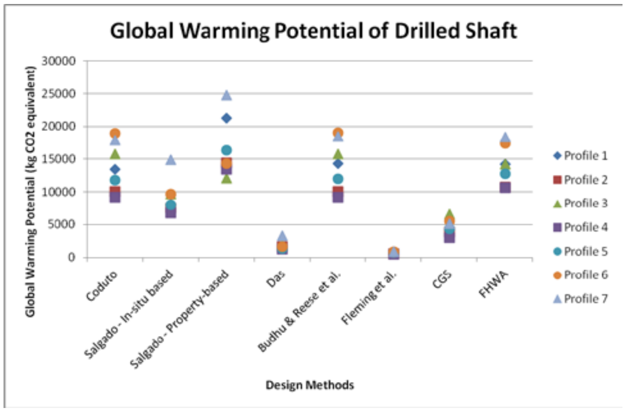

Figure 8. Global warming potential of drilled shafts

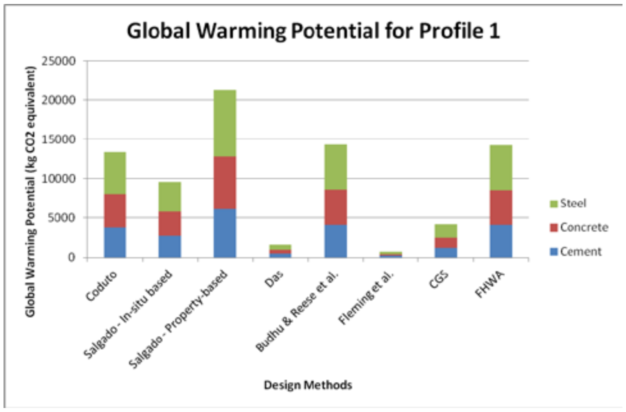

Figure 9. Global warming potential for Profile 1

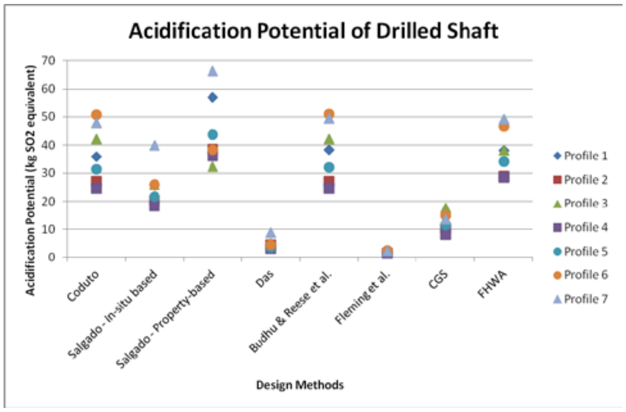

Figure 10. Acidification potential of drilled shafts

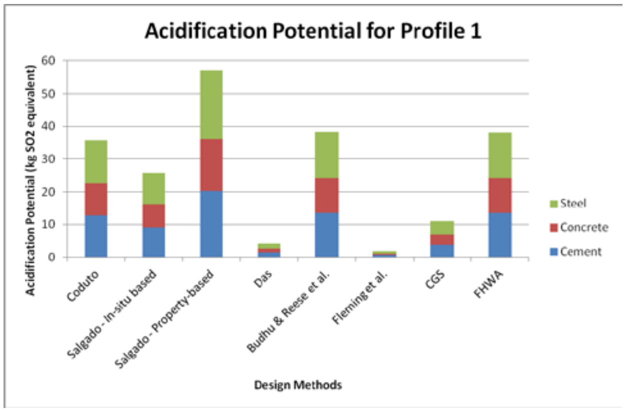

Figure 11. Acidification potential for Profile 1

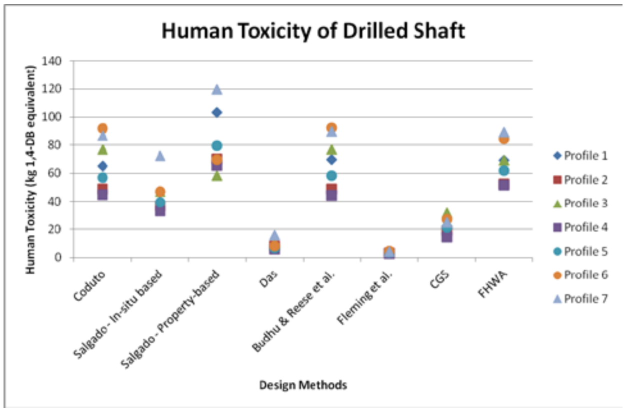

Figure 12. Human toxicity caused by drilled shafts

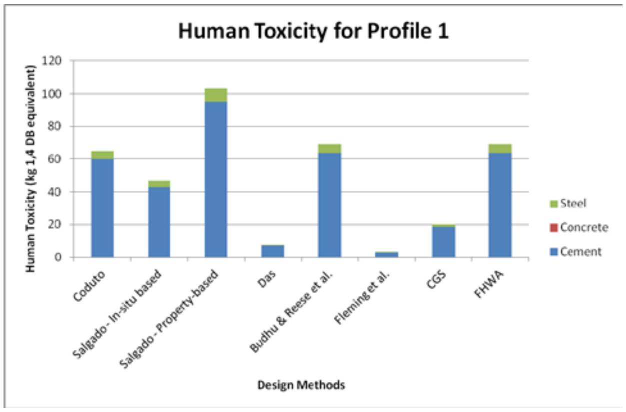

Figure 13. Human toxicity for Profile 1

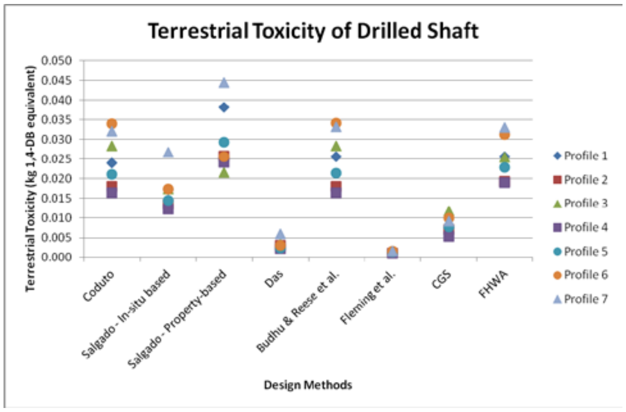

Figure 14. Terrestrial toxicity of drilled shafts

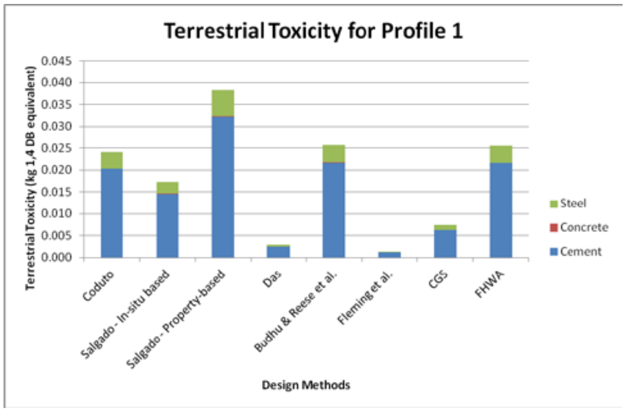

Figure 15. Terrestrial toxicity for Profile 1

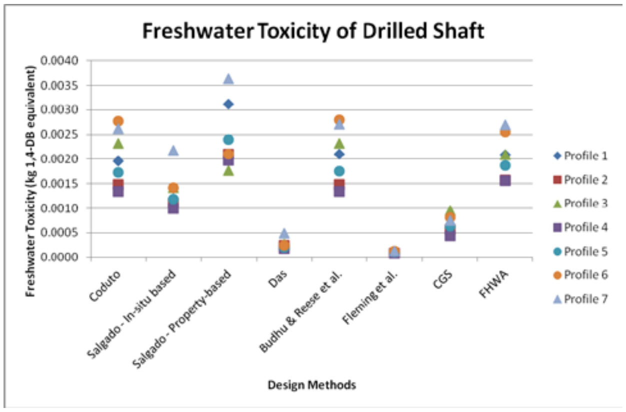

Figure 16. Freshwater toxicity of drilled shafts

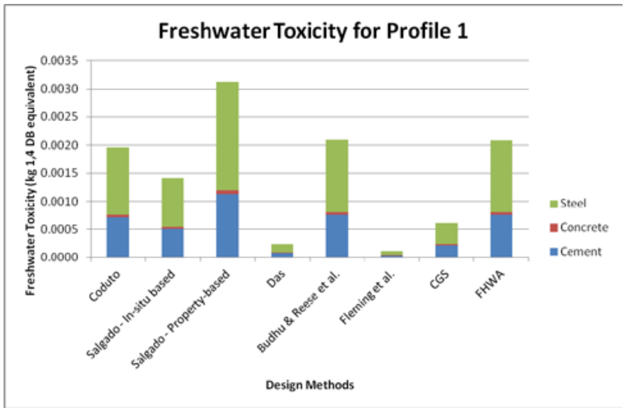

Figure 17. Freshwater toxicity for Profile 1

The effect of each design method on total embodied energy and environmental impacts can be observed from the results of LCA. Table 3 showed that there are variations in the diameter of drilled shaft obtained from the design methods for each soil profile. Consequently, a considerable fluctuation in the total embodied energy is observed, as shown in Figure 7. Similar responses are observed for environment impacts, as shown in Figure 8, 10, 12, 14, and 16. The COV for the design diameter is 44% on the average, while COV for the embodied energy and environmental impacts are both 68% on the average, which is much more than the COV of the pile diameters.

Table 6. Environmental Impacts for Profile 1

Impacts	Average	Coefficient of Variation	Range
Global warming potential (kg of CO_2 equivalent)	9920	0.73	20568
Acidification potential (kg of SO_2 equivalent)	27	0.73	55
Human toxicity (kg of 1,4-DB equivalent)	48	0.73	100
Terrestrial toxicity (kg of 1,4-DB equivalent)	0.018	0.73	0.037
Freshwater toxicity (kg of 1,4-DB equivalent)	0.0015	0.73	0.0030

4 CONCLUSIONS

Environmental impacts of drilled shafts embedded in sands are evaluated by life cycle analysis with a "cradle-to-gate" approach. Categories of impacts examined in this study are global warming, acidification, ecotoxicity, and human toxicity. By analyzing a number of drilled shafts for several soil profiles using different design methods it was observed that the design diameter varies with a coefficient of variation equal to 43%. This variation in design diameter results in considerably larger variation in the consumption of total embodied energy and the environmental impacts over the life cycle of drilled shaft. Although it is difficult to state which design method for drilled shafts is the most appropriate from a technical point of view, practitioners should consider the anticipated environmental impacts from using a particular design method as an additional criteria for decision making.

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