Sustainability Analysis of Improvement of Contaminated Clayey Soil Using Lime Piles Technique

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Abstract

This study aims to use the concept of sustainability and provide guidance to geotechnical engineers to contribute towards greater sustainability in geotechnical design and construction. The methodology of the sustainability framework aims to support indicators and tools used in the sustainability concept in geotechnical engineering. In addition, available indicators will be used to analyze the role of natural resources, social impacts, environmental and economic aspects. In order to demonstrate the sustainability assessment approach, a case study is evaluated using the methodology of sustainability framework by using Multi-Criteria Analysis (MCA). The assessment is studied for raft footing and deep foundations (driven and bored piles A foundation treatment of 15×15 m and 0.45 m thickness to carry a high static load or to carry cyclic loading is analyzed. The results indicate the calculations of sustainability indices from the multicriteria analysis show that the option of raft footing than deep foundation if raft provides adequate allowable load by improving the soil using lime piles technique is sustainable.

1. Introduction

Sustainability analysis of geotechnical processes is essential to understand interlinked issues of natural resources consumption, environmental, and socioeconomically aspects. In addition, geotechnical engineering has an enormous role in developing the sustainability of civil engineering projects because of its precedence stages in the construction process (Jefferis 2008; Misra and Basu, 2011; Basu et al. 2015). The application of sustainability in geotechnical engineering is one of the new approaches that often encourages the efficient use of resources. Design and construction associated with geotechnical engineering consume plenty of resources (such as concrete, steel, land use) and energy and change the landscape that has a significant influence both in the short term and long term. The good use of natural resources with low cost and appropriate control with reducing waste and harmful emissions to achieve sustainability needs to play a significant role in engineering design. Sustainability translates into minimum consumption of energy and resources in the design and construction and reuses the existing geotechnical facilities as much as possible to reduce waste (Graedel 1994; Harbottle et al. 2008). In fact, geotechnical engineering has enormous potential to improve the sustainability of civil engineering projects, as it is the first step in the design and construction process (Holt 2011). Figure 1 illustrates the three pillars of sustainability as environmental constraints include environmental, social, and economic.

Holt (2011) studied the sustainable assessment of geotechnical projects and identified the concept of sustainable development that requires fundamental changes in the main principles of consumption, technology, and deciding for sustainable construction. Most geotechnical projects suffer from the absence of project assessment methodologies that truly integrate the three pillars of social, economic, and environmental sustainability. Misra and Basu (2011) linked sustainability development with geotechnical engineering. Various aspects of geotechnical sustainability are presented with particular emphasis on sustainability evaluation tools and the introduction of a sustainability assessment framework in geotechnical engineering. Spaulding et al. (2008) presented three case studies comparing soil improvement techniques as an alternative to pile foundations to minimize the environmental impacts. In the first case study, the comparison is between the use of dynamic compaction and soil replacement method. The second case study includes the comparison between the use of stone columns under raft footing rather than driven piles. Finally, the third case study involved a comparison between bentonite-cement cut-off wall methods instead of the soil-bentonite cut-off wall.

The use of a single aspect in sustainability assessment may be insufficient as a universal tool to assess the sustainability of geotechnical projects. There is no comprehensive framework in geotechnical engineering, and also, there are some assessment tools developed recently which have a limited role as a complete application (Jefferson et al. 207). Soil improvement perfectly contributes to developing sustainability by improving the mechanical properties of soil by appropriate means without causing environmental and economic damage and excessive consumption of natural resources. Biological and biodegradation methods are used to improve the mechanical properties and remove the effect of contaminant by soil bacteria with nutrient additions to degrade the fuel oil composition and reduce carbon dioxide emissions (DeJong et al. 2006; Whiffin et al. 2007). Alternative ground improvement techniques have provided a better economy and reduced carbon footprint due to low energy materials such as fly ash, lime, and cement (Misra and Basu 2011). Egan and Slocombe (2010) presented the comparison between the using stone column as soil improvement technique and the conventional deep foundations. The comparison concluded that the use of ground improvement is a more sustainable option than deep foundation.

Reuse and rehabilitation of geotechnical structures is a conventional practice in almost all projects under renewal and rehabilitation. This concept recently has been included in the redevelopment of projects (Butcher et al. 2006). The sustainability assessment of natural resources, environmental, and socio-economical practices concluded that the cost of removing the old foundation is more than that of building a new pile by four times, the removal of soil can cause several damages in the adjacent structures, in addition to the environmental impact due to disturbance and harmful emissions. Several case studies demonstrate the benefits of reuse of foundation have been documented (Butcher et al. 2006; Anderson et al. 2006; Misra and Basu 2011).

2. Sustainability Pillars And Indicators

2.1 Sustainability Pillars

Lozano (2008) presented a practical method to transform from an unsustainable state to more sustainable means to achieve sustainable development. Sustainability analysis needs to contribute to improving the social and economic aspects. Sustainable Geotechnical Evaluation Model (S.G.E.M.) is a qualitative system developed to achieve sustainability in geotechnical projects depending on the natural resources, environmental, socio-economical aspects. This system depends on the color code to contrast the different alternative materials used in slope stabilization. Therefore, the main aspects of sustainability in geotechnical engineering are used (Jiménez 2004):

1. Natural recourse aspects,
2. Environmental aspects,
3. Social aspects,
4. Economic aspects.

2.2 Sustainability Indicators

During the last three decades, many researchers have made attempts to develop indicators of sustainable development, assess progress, and clarify relevant concepts and standards (Rey-Valette et al. 2007). The main function of sustainability indicators is to assist the decision-makers in understanding the steps needed to achieve sustainability. It must be recognized that there are several limits to sustainability indicators, and this is the point of scientific disagreement in the current discussions on sustainable assessment (Munda 2005). Controversy and conflict may arise during the selection of sustainability indicators, which is a major difficulty in subjectivity intervention. Subjectivity intervention may involve two areas the selection and evaluation of indicator results (Farsari and Prastacos 2002). The sustainability indicators are used in this study derived from the most important aspects of sustainability and included the most important indicators used in geotechnical designs. They are as follows:

1) Natural resources aspect that includes:

a. Materials
b. Land use
c. Embodied energy

2) Environment aspect that includes:

a. Land use
b. CO_2 emission and SO_2 acidification
c. Energy use
d. Human health

3) Social aspect that includes:

a. Health and wellbeing
b. Amenity (it means that non-annoyance for society and non-damage to adjacent structures).

4) Economic aspect that includes:

a. Financial return (benefit).

2.3 Sustainability of Soil Decontamination

The large development of industries, raising the level of living, and the urbanization of

small towns lead to soil contamination consideration as an important issue. The industrial waste, which may be solid, liquid or gases held in containers. Nonhazardous industrial wastes do not meet US Environment Protection Agency legislation's (2006) definition of hazardous waste and are not municipal waste. Industrial waste may be toxic, ignitable, corrosive or reactive. If improperly managed, this waste can pose dangerous to human health and environmental consequences and that may affect negatively the geotechnical properties of soil. The main industrial waste generated from thermal power plants is coal ash, residues oil and acidic wastewater. Soil contamination increased in the last years and has negative impacts on the geotechnical soil properties in Iraq. Soil decontamination techniques adopting sustainability concepts are preferred to use environment friendly materials and reduce using of natural resources.

Soil decontamination is considered as sustainable devolvement, and by using Multi-Criteria Analysis (MCA) a comprehensive study to understand the effects of environmental remediation (Harbottle et al. 2008). The use of MCA in decision-making and consideration as a designed system is to arrive at alternatives choices and make decisions. Furthermore, assessments and decision-making can be made more realistic, highly accurate and credible with MCA (Wrisberg et al. 2002). The methodology takes into consideration four basic criteria (Misra 2010):

1. Future benefits are more than remediation costs.
2. Site remediation impacts are less than the effects of leaving the untreated land.
3. The environmental effects of remediation processes are small and measurable.
4. The schedule in which environmental effects take place is part of the decision-making process.

In the present study, soil decontamination and improvement of intact soil are described as a major aspect and pivotal, MCA will include several indicators that will be taken into the following considerations to reduce the environmental and economic impacts and are as follows:

1. Use an environmentally friendly material to treat contaminated soil rather than other alternative means.
2. Reuse an existing foundation to reduce waste and costs. In addition, the cost of removing an existing foundation is more than the costs involved in constructing new piles by four times (Misra 2010).
3. Use of contaminated site rather than of leaving it and using an alternate site.
4. Deep ground improvement contributes to sustainable development instead of using a deep foundation, to reduce the environmental and economic effects.
5. The use of low-energy material like lime leads to a reduction of carbon footprint.

3. Sustainability Framework

The main objective of the sustainability framework in geotechnical applications is to enable designers to achieve sustainability, cover many aspects of sustainability assessment during decision making, and submit more sustainable projects. In this study, the methodology of the sustainability framework aims to support indicators and tools used in the sustainability concept in geotechnical engineering. In addition, available indicators will be used for the most important aspects of sustainability, including natural resources, social impacts, environmental, and economic aspects. In addition, the framework will be implemented within the life cycle assessment tool (LCA) to reach sustainable work by adapting the boundary conditions of the case study of this research. The presented sustainability framework aims to apply sustainability concepts for the different cases studied in this study. This framework is designed on a step-by-step basis during the process of sustainability assessment. The proposed framework consists of seven steps are designed to identify and achieve the specific goals as shown in Fig. 2.

1. Perception the sustainable design of geotechnical project, which means the briefing understanding, values and requirements for a sustainable project.
2. Preparation for assessment which involved determination of the boundary conditions; collection of the required data;
3. Assessment of the case study that represents the project.
4. Interpretation of sustainable design results based on the calculations of indicators related to the pillars of sustainability;
5. Evaluation of sustainable design that relate to the identification of weaknesses in improved design that resulted in a non-achievement of the sustainability principle in the geotechnical engineering project.

The steps of sustainability methodology in geotechnical design are:

3.1. Understanding the sustainable projects

The first step involves understanding the project objectives, values, and design requirements. The sustainability program of the geotechnical project is extensive with several issues such as energy efficiency, resource management, contamination control, and decisions of social and economic (Boyko et al. 2006).

3.2. Preparation data and boundary for assessment

This step is depended on the following requirements:

1. Determine the boundary condition that includes the boundaries will identify the sustainability aspects to be calculated in the assessment.
2. Collecting data for each indicator before starting the project evaluation.
3. Lifecycle analysis should be identified using methodological support and evaluation tool indicators at an early stage of the design process.

3.3. Assessment of the case study

This step has been maintained in evaluating the sustainability of the case study as it has intense evaluation stages and is well used for evaluation (Holt et al. 2010). The six main stages in this step are:

1. Understanding issues;
2. Identifying stakeholders;
3. Reviewing indicators
4. Data compilation
5. Workshops and
6. Conducting an assessment.

3.4. Interpretation of results

Identifying sustainability areas and develop appropriate design options for sustainable work. Determine the most proper means to reach a sustainable design by selecting the relevant indicators related to the pillars of sustainability and the weight of each pillar to obtain sustainable design.

3.5. Evaluation of sustainable design

Reassess any areas that concern raised during the reassessment and re-repetition of steps 3 and 4 as necessary according to the level of expected improvement of the sustainable project.

4. Applications Of Sustainability

In order to clarify the sustainability assessment approach, a case study was evaluated using the methodology as described in the previous sections. This section explains the work of the evaluation system in practical application and supports designers in distinguishing the strengths and weaknesses in the design, improvement, and development of the sustainability of geotechnical projects. Based on the effect of the scale and dimensional analysis, the small scale model can be converted to a prototype model. In this section, the sustainability assessment will be studied with prototype dimensions, which include the case is to study the sustainability assessment of raft footing constructed on oil decontaminated soil and deep foundations (driven and bored piles). In order to study the sustainability methodology in evaluating the environmental, economic, and social aspects of the physical model and the potential of improving and developing the sustainability of the design, this project evaluated by using this scenario a traditional geotechnical approach was used. This case consists of a building has a foundation of dimensions 15×15 m and 0.45 m thickness constructed on silty clay soil and contaminated by residues oil contaminant. Three types of foundations are suggested to carry the building load as illustrated in Fig. 3. These types, scenarios are suggested to enhance the role of sustainability in geotechnical engineering and select the best design contribution to sustainable development. The design includes three scenarios given in Table 1.

Table 1
Scenarios of case study.

Scenario	Dimensions	No. of piles	Area of foundation
Raft footing with lime piles	0.45 m thickness	0	$225\ m^2$
Driven piles	0.3 dia.×14.3 m length with pile cap of 0.45 m thickness	16	
Bored piles	0.4 dia.×14.3 m length with pile cap of 0.45 m thickness	16	

Dimensional analysis in its simplest form proposes to reduce an engineering parameter to its fundamental Mass-Length-Time “measures of nature” while developing scale factors for each of the three quantities. Rocha (1957) was the first to describe scale modeling for problems in soil mechanics systematically. Also, Rocha (1957) differentiated between total stress and effective stress conditions, deriving separate similitude relations for each case. To account for the different stress levels presented in a 1-g scale model from the prototype. Rocha proposed that the soil constitutive behavior be scaled, and therefore assumed that both the stress and strain held a linear relationship between the model and prototype.

Kana et al. (1986) described the application of the Buckingham Pi theorem to the problem of scale modeling the dynamic interaction of a pile in clay and suggested the following non-dimensional equation:

$$\frac{\mathbf{y}}{\mathbf{D_P}} = \left(\frac{\mathbf{E_P I_P}}{\mathbf{E_s D_P^4}}, \frac{\mathbf{M_c}}{\mathbf{D_P M_P}}, \frac{\mathbf{F D_P^2}}{\mathbf{E_P I_P}}, \frac{\mathbf{M_P}}{\rho_s \mathbf{D_P^2}}, \frac{\mathbf{M_P D_P^4}\omega^2}{\mathbf{E_P I_P}}, \frac{\omega^2 \mathbf{D_P}}{\mathbf{g}}\right)$$

1

Where

y is a displacement of pile;

D_P is the diameter of pile;

E_p is the modulus of elasticity of piles;

Es is the modulus of elasticity of soil;

I_p is the moment of inertia of pile;

E_s is the modulus of elasticity of soil;

M_P is pile mass per unit length;

ρ_s is soil density;

Mc is pile cap mass;

M is pile mass per unit length;

F is applied load;

ω is the frequency of oscillation; and

g is the acceleration due to gravity.

The scale effect of the model and prototype of the pile and pile cap characteristics are given in Eq. 2 to Eq. 12.

$$\frac{y}{D_P} = \frac{E_P I_P}{E_s D_P^4}$$

2

$$\frac{y}{D_P} = \frac{M_P}{\rho_s D_P^2}$$

3

$$\lambda = \frac{L_M}{L_P} = \frac{D_M}{D_P}$$

4

Where

λ is length scale factor;

L_M is the model length;

L_P is the prototype length;

D_M is the model diameter;

D_P is the prototype diameter.

$$\left(\frac{E_P I_P}{E_s D_P^4}\right)_M = \left(\frac{E_P I_P}{E_s D_P^4}\right)_P$$

5

$$\left(\frac{E_P I_P}{E_s}\right)_M D_P^4 = \left(\frac{E_P I_P}{E_s}\right)_P D_M^4$$

6

$$\lambda^4 = \frac{D_M^4}{D_P^4} = \left(\frac{E_P I_P}{E_s}\right)_M / \left(\frac{E_P I_P}{E_s}\right)_P$$

7

A laboratory model was designed to simulate the behavior of three types of suggested foundations and get information about the behavior of soil under applied load of building. Depending on Young's modulus and moment of inertia, the prototype is converted from steel and aluminum materials to equivalent concrete material, so the full scale changed from steel material for plate and aluminum material for pile shafts into concrete material for the both. E_{soil} = 12 MPa, E_{steel} = 200 GPa, $E_{alumimum}$ = 69 GPa, and $E_{concrete}$ = 24 GPa.

$$\lambda^4 = \left(\frac{D_M}{D_P}\right)^4 = \frac{3.678 \times 10^{-5}}{(EI)_P}$$

8

$$\lambda = \frac{D_M}{D_P} = \frac{0.019}{0.66} = 0.028$$

9

Prototype scale = $\frac{1}{\lambda} = \frac{1}{0.0285} = 35$ (10)

Prototype scale = Model scale/Scale factor.

$$\lambda_2 = \frac{B_{steel}}{B_{concrete}}$$

11

$$\lambda_3 = \frac{B_{aluminum}}{B_{concrete}}$$

12

Where

B_{steel} is the steel plate width;

$B_{concrete}$ is the concrete raft width;

$B_{aluminum}$ is the diameter of aluminum shaft.

a) Raft footing (Pile cap)

The value of $\lambda_2$is 0.316, thus the width of square raft footing is equal to 15 m and thickness of raft is 0.45 m.

b) Pile shafts

The value of λ_3 is 0.58, thus the diameter of the pile shaft is equal to 1.2 m and the length of the pile shaft is 19 m and 16 piles are used below the pile cap with 0.3 m diameter. Figure 3 explains (a) raft footing of building rested on improved soil by lime piles; (b) building foundation plan and superstructure, and (c) piled foundation system. The soil layer properties obtained from experimental works are unit weight is 19.3 kN/m^{3,} and the allowable bearing capacity of soil and used in the design of foundations is 47 kPa.

5. Sustainability Assessment Of The Case Study

This section explains the work of the evaluation system in the practical application using the steps of sustainability methodology in geotechnical design and based on the sustainability aspects and indicators.

5.1 Resource consumption indicators

The embodied energy values are obtained according to the equations and tables listed in previous work such as (Brown and Buranakarn 2003; Chau et al. 2006; Jefferson et al. 2007; Misra 2010; Misra and Basu 2011; Holt 2011). Then, the consumption of embodied energy for each material and scenario was calculated according to the quantities of such materials. Accordingly, the consumption of embodied energy can be changed from one country to another depending on the local conditions such as construction industry, construction techniques, transportation, weather, etc. The resources used in each category are converted to percentages, and weights are applied to emphasize the relative importance of the categories. If the soil is considered a limited resource, and the scientific reports found that steel production has toxic impacts on human health. Therefore, these sources have a weight equal to 0.3 each. The weight per unit of cement and diesel is set to 0.2 each (total weights equal to the unity). The important argument is the weight indices are random values and can be changed based on designer choice or specific site requirements (Misra and Basu 2011). The larger indicator value means a less sustainable alternative. The calculation of the resource consumption impact indicator observed that the raft and driven pile are more sustainable options than the bored pile based on the use of resource indicator as shown in Table 2.

Table 2
Embodied energy use indicators for three types of foundations.

Resource categories	**Embodied energy consumed (MJ)**			**Percent consumption of embodied energy**			**Weight index**	**Resource use indicator**		
	Raft footing	**Driven pile**	**Bored Pile**	**Raft footing**	**Driven pile**	**Bored pile**		**Raft footing**	**Driven pile**	**Bored pile**
Land	67770	35714	60632	41.294	21.761	36.944	0.3	12.39	6.53	11.08
Cement	51941	71834	100293	23.181	32.061	44.759	0.2	4.64	6.41	8.95
Steel	85320	136185	104878	26.141	41.725	32.133	0.3	7.84	12.52	9.64
Diesel	181765	234532	472906	20.441	26.3756	53.183	0.2	4.09	5.28	10.64
Total Score								28.96	30.73	40.31

Recognizing that the design can be further improved, the design has worked on developing a standard alternative design that compares the use of resources and the construction time on site. Therefore, the most appropriate solution and appropriate design that use the least amount of materials and provide higher tolerability consider the time factor necessary to complete the work. The quantities of materials used in the three suggested scenarios of foundations are calculated according to the detailed design of these scenarios. Therefore, the application of sustainability in geotechnical engineering requires highly experienced people in design, decision-makers, and time-consuming. Also, the design process may add additional cost, but more save in project cost can be obtained through selecting the more economical scenario. Table 3 explains comparison among material consumption of raft and piled foundations.

Table 3
Comparison between material consumption of three types of foundations.

Construction operation	Raft footing mass	Driven piles mass	Bored piles mass	Raft footing saving
Excavation base	101.25 m^3	101.25 m^3	101.25 m^3	-
Excavation piles	51.5 m^3 (lime pile)	5 m^3	26.94 m^3	-
Total excavation off site	151.75 m^3	106.25 m^3	128.19 m^3	– (23.56–45.5)
Concrete of raft or pile cap	101.25 m^3	101.25 m^3	101.25 m^3	-
Concrete of piles	-	15.15 m^3	26.94 m^3	-
Total concrete	101.25 m^3	116.40 m^3	128.19 m^3	15.15–26.94 m^3
Total cement use (1m^3 concrete × 297 kg)	30 ton	34.5 tons	38 tons	4.5–8 tons
Steel of raft or pile cap	8.100 tons	8.100 tons	8.100 tons	
Steel of piles	-	1.970 tons	1.347 tons	
Total steel	8.100 tons	10.070 tons	9.447 tons	1.347–1.970 tons
Lime material	63.51 tons	-	-	– (63.51) tons

5.2 Environmental impact assessment indicators (EIA)

EIA depends on global warming, acidification, energy use, land use, and human health. The effect of global warming (climate change) is calculated in terms of potential for carbon dioxide emissions and is determined as the equivalent of carbon dioxide in grams. Carbon dioxide emission from concrete is equivalent to 320 kg/m^3, while carbon dioxide emissions from lime are equivalent to 148 kg/m^3 of lime. Calculation of acidity from acidification of sulfur dioxide that inherently found in building materials used and soil, in particular, is determined as SO_2 equivalent grams. The ecosystem health category includes both land and freshwater toxicity. The total amount of CO_2 emission from the total mass of cement, steel, concrete and diesel required for the raft and piled foundations is calculated according to the design calculations. The total mass of construction materials is multiplied by the emission values for each mass production unit for construction materials which are obtained from several references (HSDB 1991; Tsang et al. 1994; U.S. Life Cycle Inventory Database 2012; Liang et al. 2014; Shen et al. 2015; Ping et al. 2020).

In this study, the weights guide was adopted for each indicator according to the important factor, where the indicator of CO_2 emission is 0.25 for concrete and lime, the pollution due to the use of energy 0.25, the land use indicator is 0.2, the acidification effect is 0.15, and finally, the human health is 0.15 of total weight index. A larger indicator value means the less sustainable option. Calculations of environmental impact indicators for raft and pile foundations are listed in Table 4. The total scores of environmental impact indicators detected that raft footing is more sustainable than driven and bored piles.

5.3 Socio-economic impact indicators

Using the cost-benefit ratio of 0.19, 0.24, and 0.3 for raft footing, bored and driven pile shafts leads, respectively, to convert the contribution percentage of foundation types in the return financial. The financial return is calculated by assuming that the building will be rented for 10 years at 80.00 $ per square meter per year (the typical values of the urban planning), so the net income is (15×15×80 = 18000 $). The estimated cost of raft footing construction is 112 $ per square meter and 60$ per square meter for soil improvement, the cost of the driven pile is 194 $ per square meter, and the construction cost of a bored pile is about 240 $ per square meter.

Table 4
Calculation of environmental impact indicators for three types of foundations.

Environmental categories	**Raft Footing**	**Driven pile**	**Bored pile**	**Percent of contribution in impact categories**			**Weight index**	**Environmental impact indicator**		
				Raft footing	**Driven pile**	**Bored pile**		**Raft footing**	**Driven pile**	**Bored pile**
CO_2 emission (gram equivalent CO_2) from concrete and lime	52898700	37248000	41020800	40.32	28.39	31.27	0.25	10.082	7.10	7.82
Energy use	320765	264468.7	417944	31.97	26.36	41.66	0.25	8.00	6.59	10.41
Land use	67770.6	35714.35	60632.1	41.29	21.76	36.95	0.2	8.26	4.352	7.39
Acidification	43927.8	65546.31	52623.7	27.099	40.44	32.46	0.15	4.06	6.066	4.87
Human health gram equivalent DB	31025.7	176820.7	49503.7	12.055	68.71	19.23	0.15	1.808	10.306	2.88
Total Score								32.20	34.41	33.37
Note: Human health is calculated in toxicity and potential, which equivalent DB (Dichloride Benzene).										

The effect of noise and vibrations resulting from driving the pile into the soil in the adjacent structures leads to severe opposition from the owners of the neighboring buildings. To avoid the consequences of noise and vibration, shareholders must pay more and thus increase the cost. In the absence of noise and vibration data, it can be assumed the contribution of bored pile is about 30%, lime pile and raft footing is about 30%, and driven pile installation contributes about 40% of noise and vibration. The weighted index of socio-economic benefit aspects has been calculated as an average score for the two categories financial return, noise, and vibration indicators with 0.5 each. Table 5 explains the details of the socio-economic impact indicator calculation. The obtained results from these calculations are observed that raft foundation is more financial return than driven and bored piles, so it is more sustainable than other types of foundation in socio-economic impact indicator.

Table 5
Calculation of socio-economic impact indicators for three types of foundations.

Socio-economic Categories	Raft footing	Driven pile	Bored pile	Percent of contribution in impact categories			Weight index	Socio-economic impact indicator		
				Raft Footing	Driven Pile	Bored Pile		Raft footing	Driven pile	Bored pile
Financial Returns (Cost Benefit Ratio)	0.21	0.24	0.30	28	32	40	0.5	14	16	20
Noise and Vibration	30	40	30	30	40	30	0.5	15	20	15
Total Score								29	36	35

5.4 Sustainability aspects analysis

In this study, the Sustainability Index is an indicator of resource consumption, environmental impact, and economic and social benefits. The use of resources, environmental impact, and socio-economic indicators is multiplied by their weight index, and the resulting products are then summed to obtain sustainability scores. In the present study, the consumption of natural resources and environmental impact index has a weighted index of 0.4 each due to their active role in engineering processes and impact on sustainability factors compared to other aspects. In addition, the socio-economic indicator has a weight index of about 0.2. Since the more significant value of sustainability index is noticed to the unsustainable option, the calculations indicate that raft footing design with appropriate load is more sustainable than the piled foundation whenever driven or bored pile shafts of the case study. Table 6 explains the calculation of sustainability index from multicriteria analysis MCA; and the cumulative of resource consumption, environmental and socio-economic Impact for different foundation types.

Table 6
Calculation of sustainability index from the multicriteria analysis.

Sustainability indicators	Score for the different foundation types			Weight index	Score for the different foundation types		
	Raft footing	Driven piles	Bored piles		Raft footing	Driven piles	Bored piles
Resource Consumption	28.96	30.73	40.31	0.4	11.584	12.292	16.12
Environmental Impact	32.20	34.41	33.37	0.4	12.88	13.76	13.35
Socio-economic Impact	28	36.435	35.55	0.2	5.6	7.287	7.11
Total Score					30.064	33.34	36.584

6. Interpretation Of Results

The accumulation of resource consumption and environmental impact on the three foundation types are studied in this case study. The consumption of resources in bored pile shafts (in terms of cement, land, and diesel) is more than driven piles shafts because the bored piles typically require a larger diameter than driven piles to equivalent an allowable load capacity of the driven pile. In addition, driven piles need more reinforcement than bored piles, and then more consumption of embodied energy due to the large use of steel in driven piles compared with bored piles. For the raft footing design, soil improved with lime piles to increase the soil bearing capacity by about 23% and then exceptionally to achieve piled foundation allowable loads. Lime piles consume more land than piles, but their consumption of other natural resources is less than deep foundations.

The embodied energy choice has been used in the life cycle analysis (LCA) of buildings and construction materials (Chau et al. 2006). The resource consumption index is calculated from the resource's indicator impact in terms of the land, cement, steel, and diesel categories as listed in Table 1. Thus, the obtained results from resource consumption indicate that raft footing is considered a sustainable option than piled foundation. From calculation environmental indicator impacts of three types of foundations, the effect of the raft on land use sector is more than piles because of improving process that includes excavation large number of bores; but its impact on other categories of environment indicator is less than piles. Consequently, the total score of raft footing, calculated by environmental indicator impact, is fewer scores than piles; while the bored pile is closed to the raft index. In multicriteria analysis, the evaluation of sustainability depends on the summation of scores of resources consumption, environmental indicators, and the score of finical benefit indicator. The obtained results indicate the sustainable option of raft footing than deep foundation if raft provides adequate allowable load by improving the soil.

7. Conclusions

The conclusion drawn from this study can be summarized as follows:

- Geotechnical engineering has a primary role in sustainable design because it is the first step in project construction and the availability of several design methods, codes of specifications, types of foundation, methods of analysis, and construction management.
- The rigorous design and several scenarios of foundation lead to a sustainable project.
- The proposed sustainability framework is used to evaluate sustainable development based on Multi-Criteria Analysis (MCA) by summing the scores of resources consumption, environmental indicators, and the score of socio-economic indicators. The results showed that the raft footing is better than using a deep foundation.
- Raft footing rested on oil decontaminated soil using lime piles is more sustainable than deep soil improvement and pile foundation.

8. Declarations

Ethical Approval

Not applicable

Consent to Participate

The authors are participated in preparing this manuscript.

Consent to Publish

The authors are agreeing to publish this manuscript.

Authors Contributions

Conceptualization, M.O.B., M.S.A. and S.B.; methodology, M.O.K. and S.B.; validation, M.S.A.; formal analysis, M.O.K. and M.S.A.; experimental investigation, M.S.A; resources, M.O.K; writing original draft preparation, M.S.A. and M.O.K.; writing—review and editing, M.O.K, and S.B.; visualization, M.O.K. and S.B.; supervision, M.O.K.; project administration, M.O.K.; funding acquisition, M.S.A. All authors have read and agreed to the published version of the manuscript.

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Competing Interests

Not applicable

Availability of data and materials

The authors declared that all data and materials are included in the manuscript.

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Conflict of Interest

The authors declared no conflict of interest.

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Figures

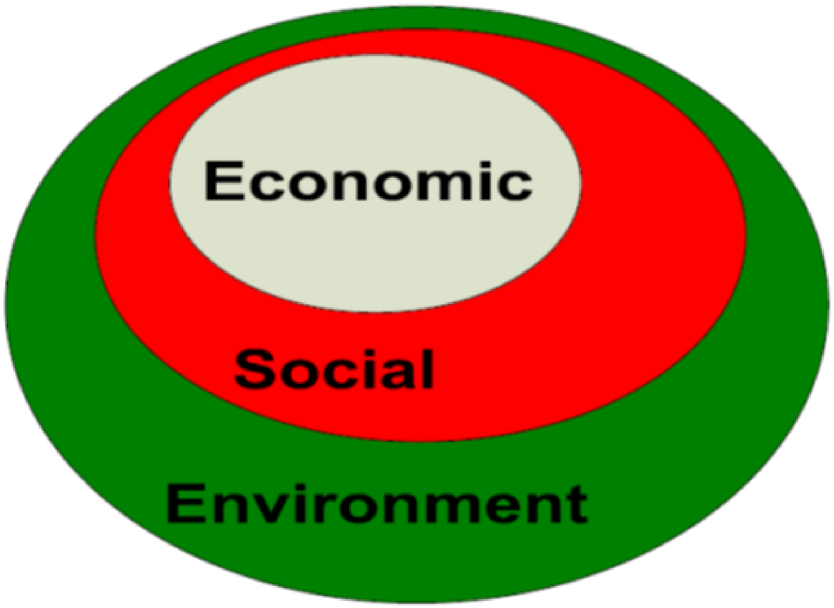

Figure 1

Graphical representation of environmental constraints on the economic and social development (Lozano 2008).

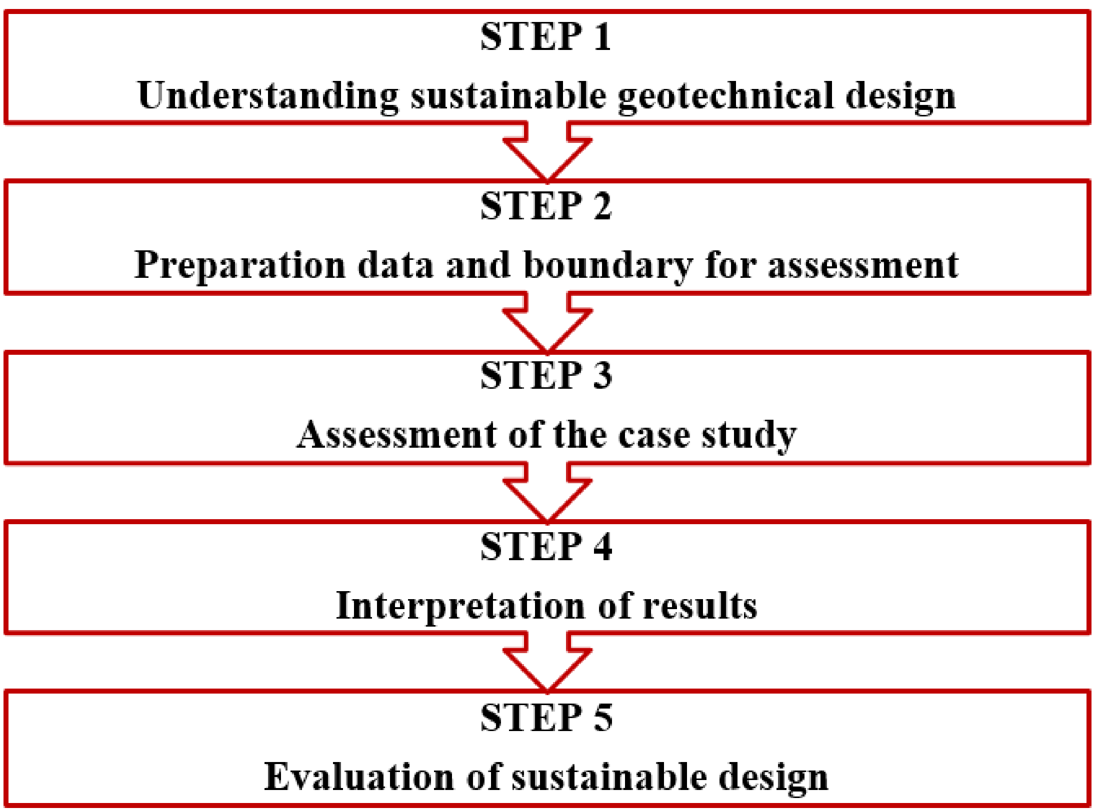

Figure 2

Methodology steps of embedding sustainability in geotechnical design

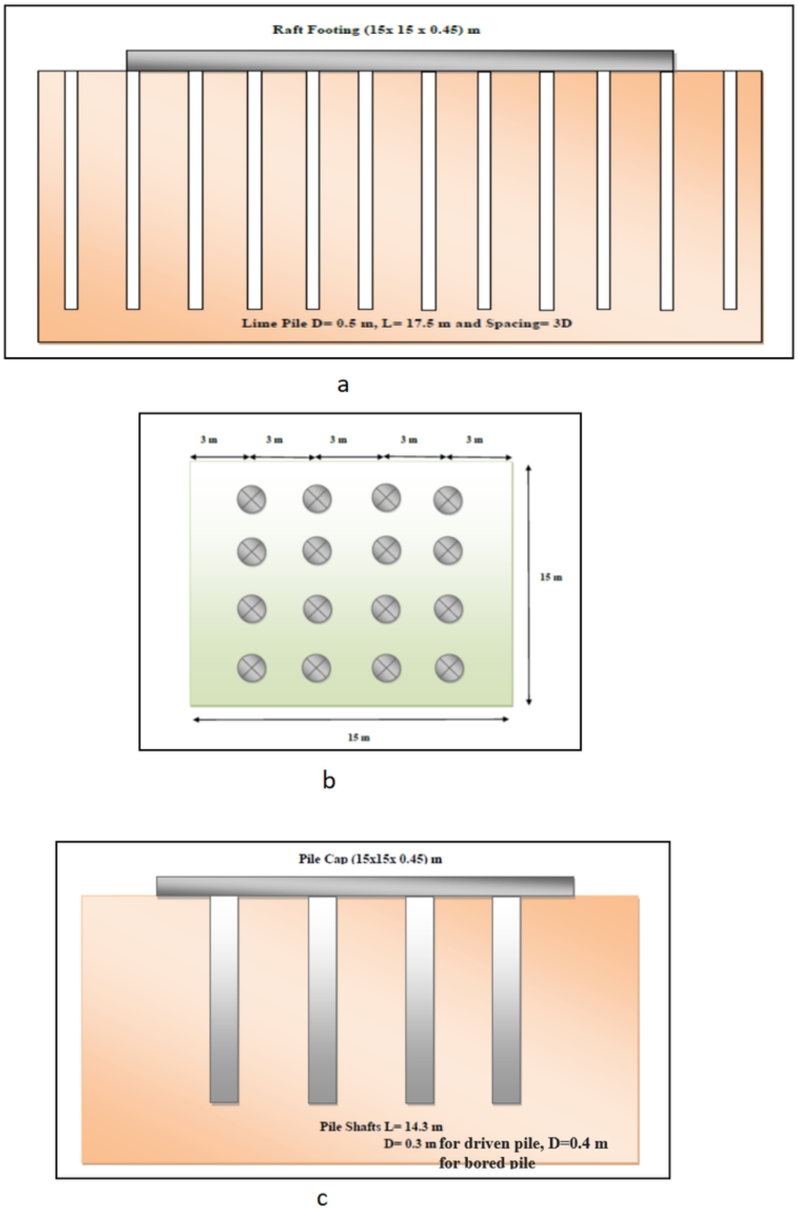

Figure 3

(a) Raft footing of building rested on improved soil by lime piles technique. (b) Plane section of piled foundation system of building. (c) Cross-section of piled foundation system of the building. Plan of building foundation.