Quantitative Assessment of Life Cycle Sustainability (QUALICS): Application to Engineering Projects

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Abstract. Civil engineering development has advanced dramatically over the years. The unsustainable use of resources in various activities involved in the engineering projects release undesirable amounts of emissions and other waste streams into the environment causing negative environmental impacts including global warming, resource depletion, eutrophication, acidification among many others. In the past decade or so, considerable efforts have been made to incorporate sustainable practices into the design and construction of infrastructure projects with an aim to minimize the net negative environmental, economic and social impacts of the project. Over the past few years, several researchers have developed project specific tools to aid the practitioners to assess and compare the sustainability of the potential design alternatives in a project. In most cases, these tools focused mainly on the environmental impacts with a minimal (often a qualitative approach) or even no regard to the broader economic and social impacts of the alternative design options in a project. For the true sustainability assessment, it is imperative that the assessment methodology incorporates a quantitative and life cycle approach for the decision-making on the most sustainable design alternative in a project. In this regard, a framework "Quantitative Assessment of Life Cycle Sustainability (QUALICS)" is developed to quantify the overall sustainability of a project/ activity and facilitate the decision-making process. The QUALICS framework is not just limited to civil engineering projects but can be used in projects of any engineering domain. The main aim of this paper is to describe the QUALICS framework and demonstrate its application to assess the overall sustainability of design alternatives in a project.

Keywords: Sustainability, Climate change, Decision-making, Environmental sustainability, Economic sustainability, Geotechnical engineering, Geoenvironmental engineering, Life cycle assessment, Social sustainability.

1 Introduction

Civil engineering has been an integral part of human life since the beginning of civilization. The advancements in civil engineering over the years have led to the development of infrastructure of countries. The buildings are growing taller, foundations are moving deeper, roads are getting wider, and bridges are getting longer. With all these advancements, the amount of raw material consumption, energy usage, waste generation and harmful emissions have increased exponentially. Geotechnical infrastructures, which are a part of civil engineering infrastructures, such as foundations, underground storage tanks, retaining walls, levees, and embankments involve significant amounts of natural resource consumption, energy usage, waste generation, and harmful emissions. In conventional engineering practice, the design and construction of infrastructure projects is mainly driven by cost and functionality of the technical design with no regard to broader environmental, economic and social impacts associated with various stages of the projects [1]. Recently, American Society of Civil Engineers (ASCE) developed a policy, ASCE Policy 418 promoting sustainability in engineering projects by compelling planners and designers to consider life cycle stages, from raw material acquisition to demolition and material disposal and reuse, in the planning and design process and educating stakeholders about net environmental, economic, and social benefits of a project [2].

In the recent years, life cycle approach in the engineering design has gained wide prominence. Life cycle assessment (LCA) is one of the tools that involves evaluation of the environmental impacts of each life cycle stages of a project from material acquisition to waste disposal [3]. However, LCA focuses on assessing only the environmental impacts associated with each life cycle stage. Sustainability is not just related to environmental implications; it covers economic as well as social aspects of a project through its entire life cycle, generally referred to as triple-bottom line sustainability. The environmental impacts are generally assessed in terms of energy usage, ozone depletion, global warming, fossil fuel depletion, eutrophication, land use. There are various tools developed to quantify these environmental impacts. On the other hand, economic impacts are quantified in terms of direct costs (e.g. cost of materials, equipment, labor) and indirect costs (e.g. social cost of carbon emission) associated with the project. One of the common methods used to assess direct costs and benefits associated with a project is life cycle cost analysis (LCCA) [2]. A detailed discussion on the economic sustainability assessment and the available tools is presented in Reddy et al. [4]. Social sustainability assessment is a challenging task as there are no defined metrics or tool to quantify the social impacts of a project. However, for a triple-bottom line sustainability assessment, social sustainability is equally important as environmental and economic sustainability. One of the semi-quantitative tools to assess social sustainability is social sustainability evaluation matrix (SSEM) developed by Reddy et al. [5].

Overall sustainability is achieved by the holistic integration of the environmental awareness, economic equity, and socially viable aspects into engineering designs. Although, there are several tools available to assess the environmental, economic and social sustainability individually, there is no tool that integrates the three pillars of sustainability and quantifies the overall sustainability by normalizing the multivariate impacts into a common scale which can be used to compare the sustainability of design alternatives in a project.

QUALICS is a new framework that integrates the three pillars of sustainability by using two multi-criteria decision analysis tools: Integrated Value Model for Sustainable Assessment (MIVES) and Analytic Hierarchy Process (AHP). This paper presents the fundamentals of the QUALICS framework along with its applications to geotechnical and geoenvironmental engineering projects. Two case studies demonstrating the applicability of the QUALICS framework to arrive at the most sustainable option among various alternatives in typical geoenvironmental and geotechnical projects are presented in this paper.

2 Quantitative Assessment of Life Cycle Sustainability (QUALICS) Framework

QUALICS is a framework to quantify the overall sustainability of a project. The framework combines two multi-criteria decision methods, MIVES and AHP [6]. The schematic of overall methodology of the framework is shown in Fig. 1. The framework can be applied for sustainability assessment of any kind of engineering projects/product/activities.

2.1 Steps in QUALICS framework

An engineering problem can have more than one suitable solution. For example, an earth retaining structure could be a cantilever wall made of reinforced concrete or a mechanically stabilized earth wall, both which can be designed to perform the same function. In order to choose the most sustainable solution among the two options, it is important to quantitatively assess the broader environmental, economic and social implications across all the life cycle stages involved in the execution of the project. Therefore, the first step of the QUALICS framework is the selection of potential design alternatives, which can perform the same function, for a project. This step involves complete technical design of each of the alternatives based on the project and site requirements and activities.

Second step of the framework is to define the qualitative and quantitative variables that closely represent the major environmental, economic and social implications of all the design alternatives. The variables are divided into several categories including requirements, criteria and indicators. The variables under requirement level/category are essentially environmental, economic and social domains. Similarly, each requirement is further subdivided into set of variables categorized as criteria. Furthermore, each criterion is divided into another set of variables categorized as indicators. The variables are project specific and hence may vary from one project to another. The requirement level variables form the basis of the triple-bottom line sustainability assessment which include environmental, economic and social aspects. The criteria level variables include the variables which are the subset of the requirement levels. The environmental criteria include air, water usage and impacts, energy usage, land and ecosystems. Similarly, economic criteria include direct and indirect costs, and social criteria include socio-individual, socio-community, socio-economic and socio-environmental aspects. The variables at indicator level are the ones that represent the impacts that lead to broader impacts at the higher level (e.g. the requirement level).

In the QUALICS framework, the environmental indicators are derived from the impact categories of some of the well-established environmental impact assessment tools such as LCA, Spreadsheets for Environmental Footprint Analysis (SEFA) and SiteWise [6]. The economic indicators include direct costs associated with materials, labor, equipment, transportation and waste disposal as well as the indirect costs such as social cost of carbon emissions. The social indicators may vary depending on the project and the design alternative being assessed. An example of set of variables under requirement, criteria and indicator levels are shown in Table 1.

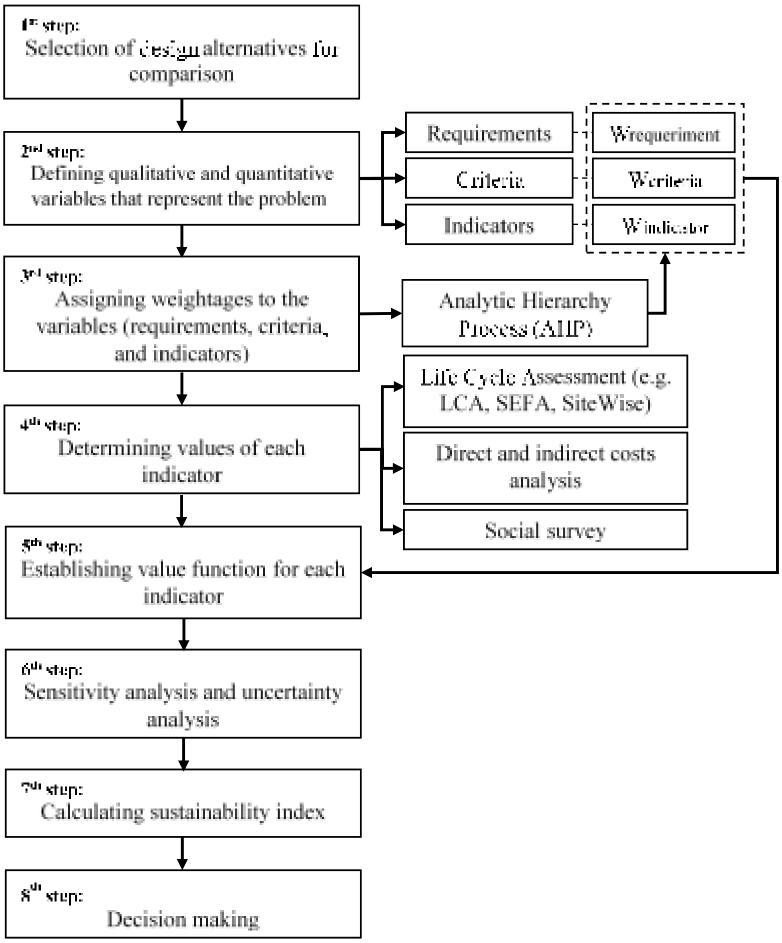

Fig. 1. Schematic of the QUALICS framework

Table 1. An example of requirements, criteria and indicators and their corresponding weightages used in QUALICS framework.

Requirement	$W_{requirement}$ (%)	Criterion	$W_{criteria}$ (%)	Indicator	$W_{indicator}$ (%)
Environmental	33.33	Air	25	Ozone depletion (kg CFC-11 eq)	15
				Greenhouse gas emissions/Global warming (kg CO_2 eq)	20
				Smog Formation (kg O_3 eq)	15
				Human health - Cancer (CTUcancer)	20
				Human health - Noncancer (CTUnoncancer)	15
				Human health - Particulate (PM2.5eq)	15
		Water usage and impacts	25	Acidification potential	50
				Eutrophication potential	50
		Energy	25	Fossil fuel depletion	100
		Land & Ecosystems	25	Ecotoxicity	100
Economic	33.33	Direct Costs	50	Materials (USD)	50
				Operations (USD)	50
		Indirect Costs	50	Social cost of CO_2 (USD)	100
Social	33.33	Socio-Individual	25	Overall health and happiness	20
				Income generating activities	20
				Contaminant exposure (trespassers, workers)	20
				Accident risk-injury	20
				Effect on recreational activities	20
		Socio-Community	25	Appropriateness of future land use with respect to the community environment	17
				Enhancement of commercial/income-generating land uses	17
				Enhancement of recreational facilities	17
				Degree of "grass-roots" community outreach and involvement	17
				Time for completion of project and access to public	17
				Degree of improvement in aesthetic value	17
		Socio-Economic	25	Economic impacts of project on community	20
				Accidental risk and damage to property	20
				Effect on tourism	20
				Disruption of businesses and local economy during construction / remediation	20
				Employment opportunities during construction / remediation	20
		Socio-Environmental	25	Degree of consumption of natural resources	20
				Degree to which proposed project will affect other media (i.e., emissions/air pollution resulting from	20
				Effects of anthropogenic contaminants at "chronic" concentrations	20
				Degree of protection afforded to remediation workers by proposed remediation	20
				Effects of anthropogenic contaminants at "acute" concentrations	20

The third step of the framework involves assigning weightages to the variables of each category. The AHP process is followed to arrive at the weightages of the variables. AHP, a method proposed by Saaty [7], is used to make judgments in an orderly fashion and to identify the priorities among different criteria. The AHP method comprises of various steps which include defining the problem, structuring the problem in terms of hierarchy from requirement to indicator level. A pairwise comparison matrix is established to compare the relative importance of one variable against another, e.g. relative importance of environmental aspect against economic aspect for the given project/design alternative. The pairwise comparison establishes the priorities of the variables which is then used to derive the weightages. A simple example of the weightages assigned to each variable is shown in Table 1. The expert knowledge and judgments are used to make comparisons and establish weightages. Detailed explanation on AHP methodology with respect to QUALICS framework can be found in Trentin et al. [6].

The fourth step in the framework is to determine the quantitative values of the variables at the indicator level. The values of environmental indicators are determined using environmental impact assessment tools such as the LCA which considers the life cycle stages from material acquisition to the waste disposal. The values of economic variables can be determined by considering the direct and indirect costs associated with the activity. The direct costs involve the cost of materials, labor, machinery, transportation and waste disposal. The indirect cost involves social cost of carbon emissions. The social impacts are quantified with the help of surveys. The social impact indicators are chosen based on the expert judgment. The survey respondents are chosen based on their experience, knowledge and expertise in the relevant field. The survey results are compiled to arrive at the final scores for each social impact indicator.

The fifth step of the framework is to establish value function for each indicator. The value function normalizes each indicator value in a scale of 0 to 1 with 0 being a value of minimum satisfaction and 1 being highest satisfaction. Value function allows comparison of variables with different units of measure. There could be various forms of value function varying from linear to S-shaped [5]. The mathematical expression of the value function used in this study is shown in Eq. 1.

$$V_{ind} = \frac{\ln(\frac{x}{x_{max}})}{\ln(\frac{x_{min}}{x_{max}})} \tag{1}$$

The sixth step involves sensitivity analysis of the parameters influencing the overall sustainability of the project. It is important to identify the factors which are outweighing the other parameters in the impact assessment. For example, if the negative impacts are predominantly due to transportation across all the impact categories, then the sensitivity analysis can be performed by varying the transportation distance.

The seventh step in the framework is determination of sustainability index. Sustainability index is calculated following the MIVES methodology [7]. In the MIVES methodology, the values of the indicators (V_{ind}) derived from the value function is multiplied with their respective weightages (W_{ind}). The sum total of the products of indicator value and its weightage gives the value for the variables under criterion category (V_{cr}) (Eq. 2). Each criterion value is multiplied by its respective weightage (W_{cr}) and summed to get the value of variables under requirement level (V_{req}) (Eq. 3). The final value (V_{final}) also called the sustainability index is derived from the sum of the products of requirement value and its respective weightage (W_{req}) (Eq. 4).

$$V_{cr} = \sum_{1}^{n} V_{ind} \times W_{ind} \tag{2}$$

$$V_{req} = \sum_{1}^{m} V_{cr} \times W_{cr} \tag{3}$$

$$V_{final} = \sum_{1}^{k} V_{req} \times W_{req} \tag{4}$$

where, n, m and k are the number of variables under each category (indicator, criterion and requirement, respectively).

The eighth and the final step in the framework is decision making. The decision-making process involves comparison of the sustainability index values of each option. The alternative obtaining highest sustainability index value is considered the most sustainable option. The overall sustainability of a project is sometimes subjected to the stakeholders' relative preference of environmental, social and economic aspects. For example, in some projects social aspects are more important than the environmental and economic aspects. In such case, social requirement is given more weightage during sustainability assessment. A detailed description of the QUALICS framework is presented in Trentin et al. [6].

3 Case Studies

This section describes the use of the QUALICS framework in assessing the sustainability of different design alternatives in geotechnical or geoenvironmental projects. The applicability of the framework is demonstrated using two case studies. A brief overview of the project and site description, potential design alternatives/strategies, the technical design, and the results from the sustainability assessment using QUALICS framework are discussed under each case study.

3.1 Case study 1: Contaminated site remediation

The site under study is an 87.52-acre land historically used for agricultural purposes since 1874 which was later transformed to electrical power generating facility in 1969. A total of 16 peaker units were installed at the site. The site discontinued electricity generation in 2004. The peaker plant operated for 35 years (1969–2004), during which five documented spills occurred. These spills included fuel oil, lubricating oil, diesel fuel, and mineral oil. The geology of the site is mostly clay deposits with some concrete and fill from previous site activity. The saturated hydraulic conductivity of the project site soils ranges between 1.26×10^{-5} m/s and 3.17×10^{-6} m/s. The well borings showed that the groundwater table is between 3 and 12 feet below ground level. During the initial site investigation involving 96 soil borings and 6 groundwater monitoring wells, the site was tested for benzene, toluene, ethylbenzene and xylene (BTEX) compounds, Polychlorinated biphenyl (PCBs), ethylene glycol, Volatile organic compounds (VOCs), Semi-volatile organic compounds (SVOCs), pesticides, and priority pollutant metals. The test results showed that among 13 locations where samples were taken, 7 locations had been detected to contain hazardous compounds. All seven locations were contaminated with BTEX, PAHs, PCBs, and metals.

A conceptual site model was developed to identify all potential sources of contamination, contaminated media, exposure pathways, and receptors. The exposure pathways included incidental ingestion, inhalation of particulates, and dermal contact. The potential receptors were identified to be residents and construction workers. The baseline risk assessment for carcinogenic and non-carcinogenic risk for the identified contaminants of concern was conducted and the preliminary remediation goals for the site were established. Based on the baseline risk assessment, seven hot spots of approximately 100 ft. × 100 ft. were identified for remediation. Feasibility evaluation of different remediation technologies was conducted and three potential remediation technologies namely electrokinetic remediation (EKR), excavation and disposal, and phytoremediation were identified. The preliminary design and implementation considerations of the three potential remedial options is presented in Trentin et al. [6]. The three remedial options were further assessed for their relative sustainability using the QUALICS framework using the data derived from the preliminary design of the three remediation technologies.

The environmental impacts of each remedial option were assessed by performing LCA as per the International Organization for Standardization (ISO) standards using SimaPro version 8.5. The details on the scope (system boundary) of the LCA, the life cycle inventory and the impact assessment method used for the LCA in this case study are provided in Trentin et al. [6]. The functional unit considered for sustainability assessment of the three potential remedial alternatives was 100 ft. x 100 ft. x 4 ft. of contaminated soil (one out of the seven hotspots). Fig. 2 shows the results of the life cycle environmental impact assessment of each life cycle stage considered in the EKR option.

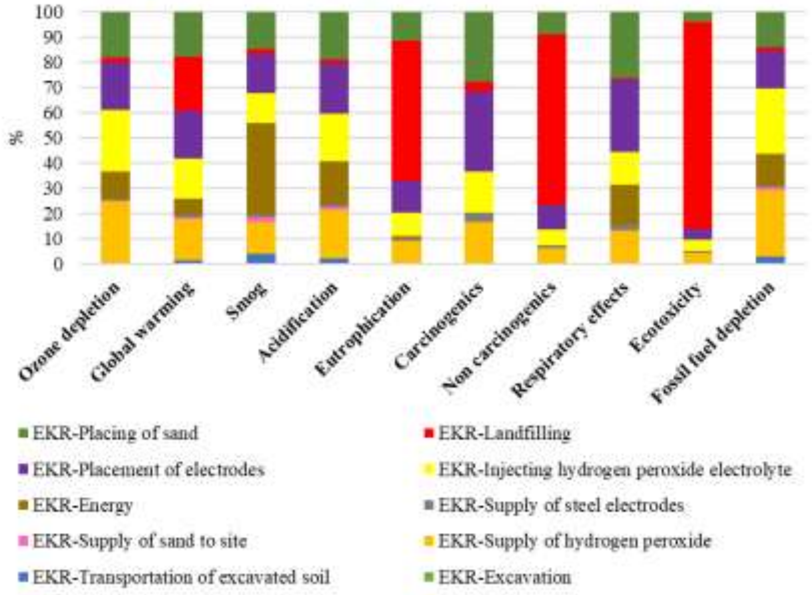

Fig. 2. Environmental impact assessment of each component of the EKR option using TRACI 2.1 V1.01 / US 2008 method

The economic impacts were also determined by calculating the direct costs (e.g., cost of materials, equipment, labor, transportation) and the indirect costs (e.g., cost of environmental emissions and impacts) at each life cycle stage. The total direct and indirect costs was determined to be $1,301,151, $1,011,319 and $498,883, for EKR, excavation/disposal and phytoremediation, respectively. Finally, the social sustainability assessment was performed based on the survey conducted using the Social Sustainability Evaluation Matrix developed by Reddy et al. [5]. The results from these analyses were compiled and used in the value function analysis involving MIVES and AHP method in the QUALICS framework and the sustainability indices for each remedial alternative considering equal weightages to environmental, economic and social aspects were found to be 0.49, 0.32 and 0.69 for EKR, excavation/disposal and phytoremediation options, respectively (Fig. 3a). A sensitivity analysis with respect to EKR was also performed to evaluate the influence of energy source, distance traveled, materials used for the electrodes and the cost of materials. In addition, the weightages of environmental, social, and economic requirements were also varied to identify the sensitivity of stakeholder preferences on the resulting sustainability indices (Fig. 3).

The results from the sustainability assessment showed that the phytoremediation option was the most sustainable option with the least environmental and economic impacts. However, the social sustainability of the EKR option was found to be the highest among the three alternatives. It was further concluded that phytoremediation was found to be the most sustainable option irrespective of the stakeholder preferences (Fig. 3).

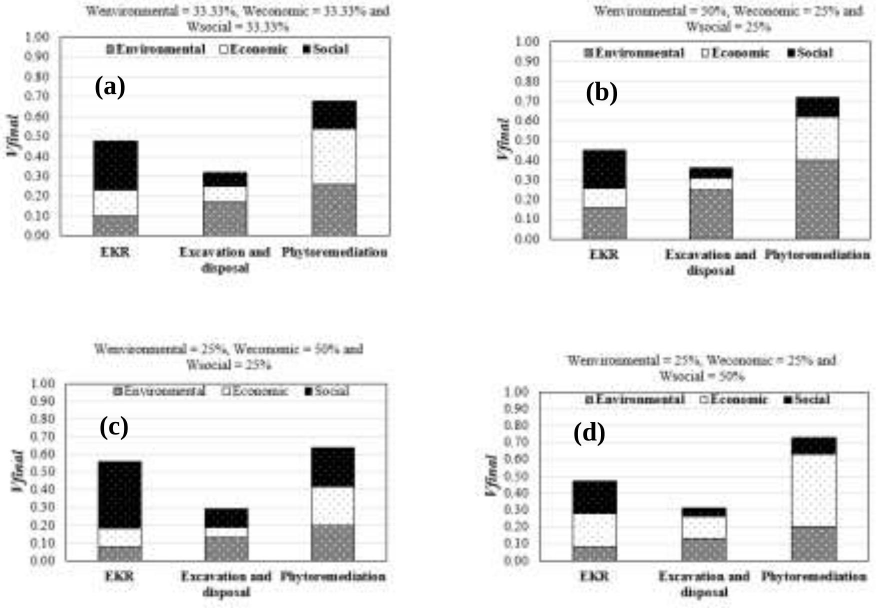

Fig. 3. Sustainability indices based on different stakeholder preferences

3.2 Case study 2: Deep foundation system

This project involved the sustainability assessment of construction of a deep foundation system for a site in Chicago, Illinois, USA. The two deep foundation systems assessed for their overall sustainability with regard to the design and construction were drilled shafts (caissons) and pile foundation. The scope of the assessment was limited only to the raw material acquisition, material manufacturing, transportation and construction stages only. The impacts from the disposal of the construction waste generated were not included. The generalized subsurface soil profile at the site is shown in Kumar et al. [9]. The functional unit for the sustainability assessment of the two deep foundation systems was assumed to be five columns with each column carrying a load of 4448 kN (~1000 kips). Thus, the assessment compared the design and construction of five pile groups (i.e., 5×14=70 steel piles) and five caissons to support the five columns. The depth of both foundation systems required was 16.8 m (~55 ft.), which is the depth at which the base of the foundation was sufficiently within the hard clay.

The geotechnical engineering properties of soil layers including the shear strength (angle of internal friction (ϕ) for sands, and undrained shear strength (c) of clays), and the unit weight of the soil layers (γ) required for the technical design of the pile groups and caissons were determined based on the available site boring logs and laboratory/field testing [9]. Using these properties and the principles for design of pile foundations and caissons, the design of pile group and caisson were finalized. A detailed description of the technical design, the quantities and the unit cost of materials used, and the fuel consumption of the equipment used for the construction of each of the two designs is provided in Kumar et al. [9].

A life cycle assessment (LCA) of the two design alternatives was performed using SimaPro software v8.5. The US life cycle inventory (LCI) database available in the software was used for the materials used in the construction of the two designs. The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), a midpoint life cycle impact assessment (LCIA) method developed by USEPA was used for the environmental impact assessment. The economic sustainability was assessed by evaluating the direct costs (e.g. cost of materials, equipment and machinery, labor and fuel) and indirect costs (e.g. social cost of carbon) associated with the design and implementation of the foundation system. The indirect costs were essentially based on an estimate of the monetized damages caused by an incremental increase in the carbon dioxide (CO_2) emissions in a given year [10, 11]. Based on SSEM approach, the functional and social impacts of each deep foundation system were assessed by conducting an online survey among professionals and academicians familiar with the two deep foundation systems. Questions for the survey were structured to evaluate the social impact of each of the deep foundation alternative on aspects at the functional, individual, community, economic and environmental levels. The indicators used for the social impact assessment are listed in Kumar et al. [9].

The sustainability index was calculated for each design alternative using the QUALICS framework as explained earlier. The results from the LCA showed that for the given functional unit and based on the site’s geologic conditions pile foundations had significantly higher environmental impacts under all the impact categories in the TRACI impact assessment method (Fig. 4). Furthermore, it was found that the steel used in the manufacturing of the pipe piles was a major contributor to most of the environmental impacts in all the impact categories. Likewise, the direct costs associated with material, labor, equipment and fuel consumption along with the indirect cost from the predicted damages caused from CO_2 emissions (social cost of carbon) showed that pile foundation was an unsustainable choice due to its high cost ($ 330,282) compared to the total cost of caissons ($ 30,972). The social impacts assessed based on a survey conducted among the experts also showed pile foundation to be a socially unsustainable choice. Using the values from the individual assessments, the sustainability index was evaluated for the pile foundation and caissons were found to be 0.15 and 0.83, respectively.

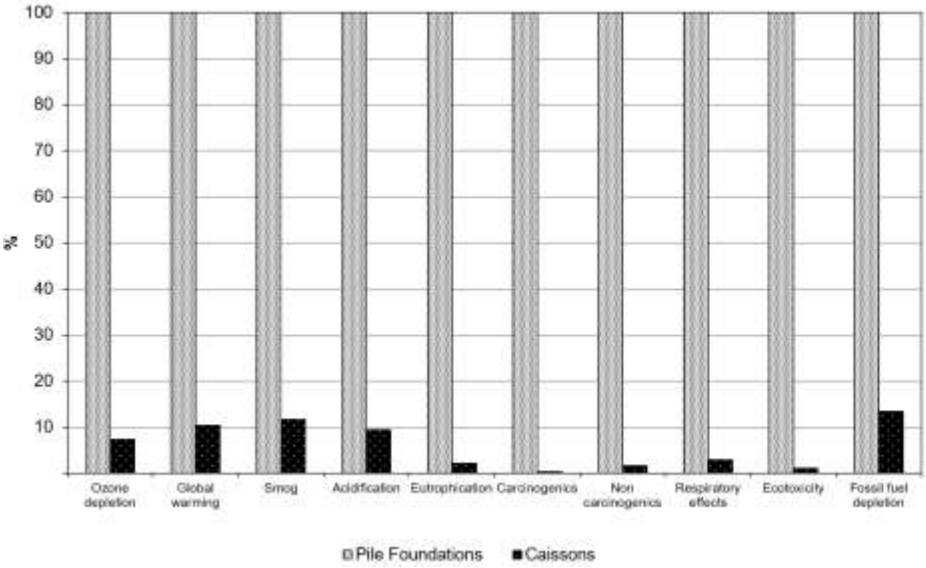

Fig. 4. Relative environmental impacts of piles and caissons determined from the LCA

In conclusion, the authors suggested that the results from the analysis are site specific and may vary based on loading, geologic constraints as well as the weightages derived from the AHP for the analysis. However, such analysis involving the quantitative and holistic assessment of the net environmental, economic and social impacts from the project's activities will result in decisions made on a rational and sound basis.

4 Summary and Challenges

Civil, infrastructure, and environmental engineering projects, including the geotechnical and geoenvironmental projects, are major contributors to the growing problem of global climate change due to the extensive use of energy and resources in the projects that lead to significant emissions and release of waste streams to the environment. Currently, there are well established procedures in practice, at least in the U.S., to design and construct infrastructure in a technically sound basis. Similarly, significant advancements have been made to lay a strong technical framework to identify the hazard, characterize and remediate the contamination at the site, to a level that doesn't pose risk to human health and the environment using a suitable remediation technology. However, in the context of the global challenges faced by the world (e.g., exploding population and global climate change), the concept of sustainability and sustainable development is gaining wide prominence. Project activities in geotechnical and geoenvironmental projects utilize enormous amounts of energy and resources during the entire project life cycle. In this regard, quantifying the broader or secondary impacts from these project activities becomes important to identify the most effective and sustainable remedial option and consequently aid in contributing to the global sustainable development.

Recognizing the need and the importance of sustainable practices in infrastructure and environmental engineering projects many federal agencies, international organizations, and other academic researchers alike have proposed numerous qualitative and quantitative tools to identify a sustainable option among the different available potential design alternatives. However, these tools do not account for the broader economic and social impacts with a life cycle perspective. In addition, most tools focus on either of the three essential pillars of sustainability (environment, economy and society) with more inclination towards environmental impacts. Realizing this gap, a new quantitative assessment of life cycle sustainability (QUALICS) framework is proposed to aid in quantifying the secondary impacts and identify the most sustainable design alternative in an engineering project. The QUALICS framework utilizes the MIVES and AHP, multi-criteria decision-making methods, to quantify the sustainability of different remedial options based on relative importance and relevance of the different criteria and indicators representative of the unique potential impacts envisioned to be arising for the project activities at the site. The method relies considerably on the knowledge and judgmental capacity of the experts and brings reality and complexity of the system in the sustainability assessment.

The applicability of the QUALICS framework is demonstrated using two case studies encompassing typical projects in geotechnical and geoenvironmental engineering. The QUALICS framework is used to identify the most sustainable design alternative/ option to be implemented at the site. In addition, sensitivity analysis performed in the case studies discussed show that the results on the sustainability index may vary based on the stakeholder’s preferences (favoring one sustainability pillar over the other). The future research in this regard should focus on strengthening the economic aspects by involving the indirect costs and benefits that are otherwise unaccounted in most of the tools. Further, the tool used for social sustainability assessment in the QUALICS framework is still wanting. Therefore, a well-structured social sustainability assessment tool that can cater to assess the social sustainability in a rational manner (such as the life cycle assessment methodology) for any project has to be developed.

References

1. Damians, I. P., Bathurst, R. J., Adroguer, E. G., Josa, A., Lloret, A.: Sustainability assessment of earth-retaining wall structures. Environmental Geotechnics, 5(4), 187-203 (2016).
2. Reddy, K. R., Kumar, G.: Addressing sustainable technologies in geotechnical and geoenvironmental engineering. In Geotechnics for Natural and Engineered Sustainable Technologies (pp. 1-26). Springer, Singapore (2018).
3. Reddy, K. R., Kumar, G.: Green and sustainable remediation of polluted sites: new concept, assessment tools, and challenges. ce/papers, Special Issue: XVI DECGE 2018 Proceedings of the 16th Danube - European Conference on Geotechnical Engineering, 2(2-3), 83-92 (2018).

4. Reddy, K. R., Kumar, G., and Chetri, K. J.: Green and sustainable site remediation: incorporating broader economic impacts. In The 17th African Regional Conference on Soil Mechanics and Geotechnical Engineering. (2019).
5. Reddy, K. R., Sadasivam, B. Y., Adams, J. A: Social sustainability evaluation matrix (SSEM) to quantify social aspects of sustainable remediation. In ICSI 2014: Creating Infrastructure for a Sustainable World, 831-841 (2014).
6. da S Trentin, A. W., Reddy, K. R., Kumar, G., Chetri, J. K., Thomé, A.: Quantitative Assessment of Life Cycle Sustainability (QUALICS): Framework and its application to assess electrokinetic remediation. Chemosphere, 230, 92-106 (2019).
7. Saaty, T. L.: Decision making with the analytic hierarchy process. International Journal of Services Sciences, 1(1), 83-98(2008).
8. Lombera, J. T. S. J., Aprea, I. G.: A system approach to the environmental analysis of industrial buildings. Building and Environment, 45(3), 673-683 (2010).
9. Kumar, G., Chetri, J. K., Reddy, K. R.: Sustainability assessment of deep foundations: case study. In 44th Annual Conference on Deep Foundations, Deep Foundations Institute.
10. Raymond, A.J., Pinkse, M.A., Kendall, A., DeJong, J.T.: Life-cycle assessment of ground improvement alternatives for the Treasure Island, California, redevelopment. In Geotechnical Frontiers, 345-354 (2017). Reston, VA: American Society of Civil Engineers.
11. USEPA (United States Environmental Protection Agency): The social cost of carbon: estimating the benefits of reducing greenhouse gas emissions. Available at: https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html (accessed on August 26, 2019).