Life cycle assessment and life cycle cost analysis for geotechnical engineering: review and research gaps

I Samuelsson, S Larsson and J Spross
Division of Soil and Rock Mechanics, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden
E-mail: idasam@kth.se

Abstract. Geotechnical engineering work contributes to the total environmental impact and monetary cost occurring from the construction sector. Decisions made regarding geotechnical engineering aspects have a profound effect on the environmental impact and the monetary cost of the structure during its life cycle. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) are established methods for assessing the environmental impacts and monetary cost from construction works. This paper presents the results from a literature review of 56 published papers regarding the current situation of the use of LCA and LCCA methods in geotechnical engineering. It is found that only limited research has been published in applying LCA and LCCA to geotechnical engineering structures. Further research should focus on developing a framework using LCA and LCCA for geotechnical engineering structures and also identify and fill data gaps in computer software databases. This would help geotechnical engineers in their daily work to reduce the environmental impact and monetary costs throughout the life cycles of the designed structures.

1. Introduction
Decisions that are made during geotechnical design contribute to the total environmental impact from construction and infrastructure activities and to their total monetary cost. Different structures have different impact during their life cycles and their impact is rarely distributed evenly over the life cycle stages. However, geotechnical engineers have the possibility to reduce the environmental impact and monetary cost throughout the structures’ life cycles and implement sustainability as an important factor when making decisions.

IPCC [1], who assess the science related to climate change, state that the warming from anthropogenic emission will cause long-term changes in the global climate system such as sea-level rise, heavy precipitation in several regions, impacts on biodiversity and ecosystems including species loss and extinction and risk for human health. Other impact categories than climate can be taken under consideration depending on the type of construction work, such as land-use, water-use, eutrophication, acidification, ozone-layer depletion, etc. To fight such negative environmental impact, many countries have decided on environmental goals. On an international level, the United Nations has decided on 17 sustainable development goals [2], which all member countries should try to reach by the year 2030. In Sweden, the national parliament has decided that Sweden shall aim to be climate neutral and have zero net greenhouse gas emissions (GHG) by the year 2045 and by 2030 the GHG emission should be reduced...
by 50% compared to 2015. The initiative Fossil Free Sweden encourages the business sector to draw up their own roadmaps on how to be fossil-free and there are 13 roadmaps so far (end of 2019). One of those roadmaps concerns the building and construction sector and states that we should go from value chain to value cycle. A circular economy and a life cycle thinking should be implemented [3].

Geotechnical engineers may not be that familiar with making environmental impact assessments in their daily work. Typically, the size of the investment cost is by far the most important factor when deciding if a construction project is being realized or not. But investment cost is only one part of the total monetary cost related to geotechnical engineering. Decisions made in a geotechnical engineering project affect the environmental impact and monetary cost during the structure’s entire life cycle. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) are established methods for assessing such environmental impacts and monetary cost from construction works. The results can be used to make decisions to reduce the environmental impact and monetary cost in geotechnical engineering projects. However, limited research has been published in applying LCA and LCCA to geotechnical engineering. For example, Jefferis [4] found that there were a lack of specific guidelines on how to implement sustainability in geotechnical engineering.

This paper presents the results from a literature review regarding the current situation of the use of LCA, LCCA and other sustainability methods in geotechnical engineering. The research gaps and the main areas are identified and discussed with respect to where further research would be beneficial and critical for a successful integration of LCA and LCCA with geotechnical engineering design.

2. LCA, LCC and other sustainability assessment methods

2.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a method to assess the environmental aspects and potential environmental impact throughout a product's life cycle, according to its definition in ISO 14040:2006 [5]. An LCA is a collection and evaluation of the input parameters, output parameters and the potential environmental impacts caused by the selected studied subject [6]. LCA is one of many environmental assessment techniques. When performing an LCA, the standards ISO 14040:2006 [5] and ISO 14044:2006 [6] can be applied. The outcome is a sustainability assessment, but it does not include all aspects of the term sustainability, as this also includes the economic and social impact of a product. The result from an LCA is often presented as how much impact the subject’s life cycle has to different impact categories, such as global warming, land-use, water-use, acidification, eutrophication, among others.

The life cycle in an LCA includes raw material acquisition, production, use, end of life treatment, recycling, and final disposal, as defined by the European Committee for Standardization [7] in table 1. Each stage is one part of a product’s life cycle and many processes can be included in each stage. An LCA with only the steps A1-A3 performed is called a cradle-to-gate LCA. If at least step A1-C4 is performed, the LCA is called cradle-to-grave. Which stages that are included and excluded should be declared in the presentation of the performed LCA to increase clarity. When performing an LCA an Environmental Product Declaration (EPD) can be used. It is a declaration that quantifies environmental data of a product, to make comparison between products with the same function easier. An EPD consist often of the steps A1-A3 shown in table 1.
Table 1. Life cycle stages in an LCA according to the European Committee for standardization [7].

| Product | Construction process | Use | End of life | Benefits and loads beyond the system boundary |
|---------|----------------------|-----|-------------|---------------------------------------------|
| A1: Raw material supply | | B1 Use | C1 De-construction | D Re-use - Recycling-potential |
| A2 Transport | A4 Transport | B2 Maintenance | C2 Transport |
| A3 Manufacturing | A5 Construction-installation process | B3 Repair | C3 Waste processing |
| | | B4 Replacement | |
| | | B5 Refurbishment | C4 Disposal |
| | | B6 Operational energy use | |
| | | B7 Operational water use | |

An LCA consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation according to ISO 14044:2006 [6]. They are described below.

2.1.1 Goal and scope definition. The scope includes the system boundary (i.e. what processes should be included in the studied system) and the level of detail. They depend on the intended use of the result from the LCA and they also depend on the studied subject. The scope of an LCA depends on the goal of the conducted LCA and it can differ considerably from case to case. In this phase, a functional unit is chosen, for example a 10 m sheet pile wall, which makes it easier to compare the result from LCAs performed for different design alternatives.

2.1.2 Inventory analysis. The life cycle inventory analysis (LCI) is an inventory of input/output data of the system being studied within the system boundary. It includes the collection of the data necessary to meet the goal of the study. In the inventory phase, case-specific data can be used. When there is no case-specific data or when performing an LCA not that detailed, input data from general databases such as Ecoinvent can be used. These databases are often accessible in the LCA software and generic data in different regions or countries can be chosen. An LCA can be made with various tools and there are softwares that are specialized on LCA that can be used.

2.1.3 Impact assessment. The life cycle impact assessment (LCIA) has the purpose to provide information to help assess the life cycle inventory result of the analyzed system of a subject. Here the different outputs from the LCI are multiplied by a factor, depending on the output unit, to assign the output to an impact category such as global warming, land-use, water-use, acidification, or eutrophication. This step is called characterization. For the characterization, there are defined LCI methods available in software. The quantified impact can be compared to a reference value, which is called normalization. The quantified impacts can be assigned a significance value, different for each impact category, to calculate one single outcome. This is called weighting [5]. The significance value can be chosen based on economic, political or social factors along with other factors.

2.1.4 Interpretation. The interpretation phase includes the results of an LCI or an LCIA, or both, summarized and discussed. This leads to conclusions, recommendations and decision-making regarding the goal and scope definition. Multicriteria analysis (MCA) can be used in this step to get one weighted outcome instead of one result from each impact category. Performing a sensitivity analysis is recommended to see if one or several uncertain inputs are affecting the result significantly. If so, a more comprehensive inventory analysis may be needed.

2.2. Life Cycle Cost Analysis (LCCA)
Life Cycle Cost Analysis (LCCA) is a method to assess the monetary costs throughout a subject’s life cycle. LCCA is used to reduce the monetary costs early and during the design process. It can be used on a system level in early stages when the whole construction is studied (for example on a road section, or when comparing different alternatives in detail such as a construction part). LCCA is not as standardized
as LCA and what is included can differ between different countries and different project. The following analysis procedure is used in Sweden in all large road and railway project built by the Swedish Transport Administration. LCCA is then used to minimize costs during design, procurement, construction and use. Risks and uncertainties can be included in the analysis, according to the Swedish Transport Administration’s supplement appendix for consultancy assignments [8].

According to the Swedish Transport Administration [9], an LCCA should describe the investment costs and future costs such as operations, maintenance and potential external costs. The life cycle cost (LCC) is the net sum of all costs for the product during investment (planning, design, construction etc.), operation, maintenance (including replacement) and external costs (stop costs etc.) and is calculated by:

\[
LCC = C_{INV} + C_{OP} + C_{MAIN} + C_{EXT}
\]

(1)

where \(C_{INV}\) is the costs in the investment stage, \(C_{OP}\) is the costs during operation, \(C_{MAIN}\) is the costs during maintenance and \(C_{EXT}\) is external costs. End of life costs are included if the studied subject has an end of life stage. Investment cash inflow and outflow should be discounted forward and the future cash inflow and outflow should be discounted to the cost status at the chosen baseline year. Doing this is defined as calculating its present value (PV) [8]. Net Present Value (NPV) is the sum of all PVs and can be calculated by:

\[
NPV(i, N) = \sum_{t=1}^{N} \frac{R_t}{(1 + i)^t}
\]

(2)

where \(t\) is the time of the cash flow, \(i\) is the discount rate and \(R_t\) is the net cash flow (cash inflow – cash outflow) at time \(t\). Other ways to calculate NPV are possible.

2.3. Other sustainability assessment methods

LCA and LCCA are sustainability assessment tools. They assess the environmental impact and the monetary cost of a product. There are also other tools that assess sustainability. What they have in common is to assess sustainability. Sustainability includes the economic, the environmental and the social part of a product or service. Sustainable development was defined by Brundtland et al. [10] as a societal development that “meets the needs of the present without compromising the ability of future generations to meet their own needs”. There are a vast variety of sustainability assessment methods available. In the following, two methods are introduced that have been used in geotechnical engineering.

GeoSPeAR is a method developed by Holt et al. [11]. It is presented as a colour-coded rose diagram that assesses the studied subject based on four main criteria: environmental, economic, societal and natural resources. Each criterion has many subcriteria and the most sustainable choices are the ones with the result closest to the centre of the diagram.

Embodied energy (EE) and gas emissions can be assessed, the process of which is a part of an LCA. Embodied energy is the sum of all the energy required during the life cycle of a product. Gas emissions can for example be the airborne emissions CO\(_2\), CH\(_4\), N\(_2\)O, SO\(_X\) and NO\(_X\). Inui et al. [12] has assessed these gas emissions for four design alternatives for an embankment retaining wall system and compared the results. The most common emission to assess is CO\(_2\). Shillaber et al. [13] and Shillaber et al. [14] developed a streamlined energy and emissions assessment model (SEEAM) used for quantifying embodied energy and CO\(_2\) emissions for ground improvement.
3. Status of current research

3.1. Statistical overview

Published conference papers and journal papers on the topics LCA and LCCA in geotechnical engineering have been reviewed using Google Scholar. The search resulted in a variety of journal and conference papers within the scope. Papers that discuss other sustainability assessment tools than LCA and LCCA were also included. 56 papers were found (by the end of 2019), out of which 29 were about LCA and LCCA. The major trends from the found papers and some examples of the content are presented in this section.

It is clear that this is a rather new research area. Before the year 2010, only 9 papers had been published, the oldest one being from 1987 (namely ref. [15]). 28 of all papers (50%) are categorized journal papers and 28 papers (50%) are conference papers and books. If only LCA and LCCA papers are included, 17 papers (58%) are journal papers and 12 papers (42%) are conference papers and books. We have also categorized the papers as either executed assessments or development papers. The executed assessment papers describe a completed LCA, LCCA or other sustainability assessment for some specific purpose. The development papers discuss different sustainability concepts on a more general level. Most papers are executed assessments, 34 papers (61%) of all 56 papers and 24 papers (83%) of the 29 papers considering only LCA and LCCA, the rest are development papers. Figure 1 and 2 show the percent of executed assessments/development papers along with the type of paper of the total number of papers.

![Figure 1. Distribution of paper types and if they are executed assessments or development papers. All 56 papers.](image1)

![Figure 2. Distribution of paper types and if they are executed assessments or development papers. Only the 29 papers with LCA and LCCA.](image2)

34 papers (61%) have an author that has published more than one paper in this research area and these authors can be divided into 8 author groups. Most published papers are the group of Prof. Puppala and Ass. Prof. Basu, who have 13 papers published, which is in fact 23% of the total number of papers. The authors of all found papers are mostly from universities in the US, Canada, UK and Spain but there are papers from all over the world such as Japan, Korea, India, France, Italy, Germany and Sweden.

The applied assessment method of the published papers varies. We have mainly studied LCA and LCCA in geotechnical engineering, but other sustainability assessment methods are also included in the result. The distribution of LCA, LCCA and other sustainability methods are shown in figure 3 and 4 where their percent of the total number of papers and if they are executed assessments or development papers are presented. The number of papers is presented in table 2. If only LCA and LCCA are included, most papers, 17 papers (59%), are about LCA, and 5 papers (17%) are about LCCA, while 7 papers (24%) contain both LCA and LCCA.

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Figure 3. Distribution of paper content (LCA/LCCA/other sustainability method) and if they are executed assessments or development papers. Including all 56 papers.

Figure 4. Distribution of paper content (LCA/LCCA) and if they are executed assessments or development papers. Including 29 papers with only LCA and LCCA.

Table 2. Distribution of paper content (LCA/LCCA/other sustainability method) and whether they are executed assessments or development papers. [Number of papers]

| Method          | Paper type | Geotechnical engineering | Geotechnical investigation | Retaining wall/slope support | Ground improvement | Piles | Fuel | Cement |
|-----------------|------------|--------------------------|----------------------------|-------------------------------|--------------------|-------|------|--------|
| LCCA            | Exec.      | 1                        |                            | 2                             | 1                  |       |      |        |
| LCCA            | Dev.       | 1                        |                            | 1                             |                    |       |      |        |
| LCA             | Exec.      | 1                        |                            | 6                             | 3                  | 1     | 1    | 1      |
| LCA             | Dev.       | 2                        |                            | 2                             |                    |       |      |        |
| LCA+LCCA        | Exec.      | 2                        | 1                          | 3                             | 2                  | 2     |      |        |
| Other Sus. Methods | Exec.  | 2                          | 1                          | 3                             | 2                  | 2     |      |        |
| Other Sus. Methods | Dev. | 15                        |                            |                               |                    | 1     |      |        |

Three main topics can be seen that cover 49 papers (88%) of the papers: geotechnical engineering in general, retaining walls/slope support, and ground improvement. For the papers only concerning LCA and LCCA, these three topics make 26 papers (90%) of the total of 29 papers. Other topics found are geotechnical investigation, piles, fuels in geotechnical engineering and cement types. The distribution among the various topics is shown in figure 5 and 6 where their percent of the total number of papers is presented.
3.2. Review of important research contributions
The major trends were presented in the previous section. In the present section some specific papers are highlighted that were found to have important research contributions or be representative examples of the major trends.

3.2.1 Geotechnical engineering category. In this category, which includes papers about geotechnical engineering in general, most papers are development papers. These papers may also cover sustainability methods for geotechnical engineering other than LCA and LCCA or be reviews of current research. Basu et al. [16] reviewed sustainability in geotechnical engineering, discussing the importance of resilience and system recovery along with different assessment methods such as GeoSPeAR, LCA and LCC. A sustainability index is presented that is a combined index of the design based on resource efficiency and the environmental impact resulted from an LCA and socioeconomic impact.

Kendall et al. [17] reviewed life cycle based environmental assessments of geotechnical systems to find critical gaps for future research. Their review covered 16 publications, out of which 5 were journal papers, 9 were conference papers and 2 were master theses. The review is not comprehensive, but resulted in recommendations about future research needs, such as the need to address the lack of reported impact categories and lack of a standard LCA framework. It states that the availability and quality of region-specific data causes a barrier for future research as well as challenges in evaluating different soil profiles and design alternatives.

Raymond et al. [18] reviewed impact categories and environmental indicators in the LCIA step. Some impact categories, such as energy and global warming, are more often used than others. Land-use and soil-related impacts are not that commonly assessed and indicators for those impact categories are not as developed as for energy and global warming.

3.2.2 Ground improvement category. In this category, Praticò et al. [19] used LCCA and developed a model to select stabilizer and stabilization technique for subgrade soil for low-volume roads with the lowest life cycle cost. An added investment cost of stabilization of subgrade soil to the construction cost in the treated sections minimized the cost for long-term maintenance.

3.2.3 Retaining wall/slope support category. In this category, Zastrow et al. [20] compared 30 cost-optimized earth-retaining walls using LCA. The Ecoinvent database was used for the input data. The amount of concrete and steel, and whether the steel was recycled, had an impact on the resulted environmental impact. Das et al. [21] focused on sustainability and resilience aspects for slope stabilization. Their sustainability assessment included, among other things, LCA and socio-economic impact. These elements were multiplied by a weight factor based on their relative importance. Using multi-criteria analysis, these weighted indicators put a resilience and sustainability index to each stabilization method. The method with the lowest index should be implemented. Using their presented framework, several assessment methods can be combined to one comparable index.

3.2.4 Remaining categories. In the remaining categories, the research is not that extensive and fewer papers have been published than in the other categories. In the category Cement related to ground improvement, Chang et al. [22] compared cost and environmental impact when using biopolymers instead of traditional Portland cement for ground improvement.
4. Research gaps and further research

4.1. Research gaps
This study is a review of published papers regarding LCA and LCCA for geotechnical engineering. We find that not all geotechnical areas or LCA/LCCA stages are covered in the published research. Some interesting notions and research gaps are presented in the following:

- First of all, only 29 papers were found. This is a rather new research area and more research can clearly be done in all parts.

- There is more research done about LCA than LCCA, which is interesting because the concern for environmental impact is rather new, compared to the monetary cost that is a part of LCCA.

- Some of the executed LCA and LCCA studies do not cover the entire life cycle. Instead only the first stages are included and not the use and end of life stages. These are also the stages where most input data are missing. One reason may be that the concept of life cycle thinking might be new to the infrastructure sector.

- The selection of environmental impact categories assessed in the performed LCAs is limited. To get a full picture of the environmental impact, more categories can be included.

- The topics of the papers are mainly focused on ground improvement and retaining wall/slope support. Piles and foundation, lightweight material, excavation and fill, among other topics, are not analyzed fully or not at all. These are common methods in geotechnical engineering, so research and performing LCA and LCCA regarding these methods should be focused on to broaden the knowledge.

- To link LCA and LCCA to each other, cost-benefit analysis (CBA) or cost-effectiveness analysis (CEA) can be done. CBA is where the evaluated value of an action is compared to its monetary cost and CEA is where the outcomes (effects) are compared to its monetary cost. There is a great potential in developing this aspect of life cycle considerations to minimize environmental impact.

4.2. Further research
For successful integration of LCA and LCCA to geotechnical engineering, a standardized framework would be beneficial for the geotechnical engineer in starting using this in their daily work. This framework could provide a guideline on how every step should be done, what options there are and where to find more information if needed. The framework should contain standard functional units for different geotechnical areas to make it possible to compare the result from different LCAs, and it should detail how sensitivity analyses can be performed.

Additional work should be done by the geotechnical industry in making region-specific data available in an open database. Today some companies have their own databases. There are however a limited number of open databases with data for the infrastructure sector. These databases are typically limited, so more data are needed for geotechnical engineering. Such specific databases are key to make the LCA result more accurate and the LCA easier to perform. Easy-to-use software could be developed to make it easier for the geotechnical engineer to get the LCA and LCCA done as efficiently as possible.

Involving the geotechnical engineer in the LCA and LCCA work is crucial for the implementation of LCA and LCCA to gain ground. The knowledge about LCA and LCCA should not stay among the specialists on LCA and LCCA that may not know so much about geotechnical engineering.
5. Concluding remarks
This paper has reviewed published journal and conference papers on sustainability, LCA and LCCA in geotechnical engineering. 52% of those papers discuss LCA and LCCA. This is a growing research area, but still, a general framework for how to do an LCA or an LCCA for geotechnical engineering is missing. Notably, most published LCAs and LCCAs are about ground improvement and retaining wall/slope support. More published LCA and LCCA studies need to be carried out regarding other geotechnical topics to expand overall knowledge. Available region-specific data in open databases are needed to make the inventory phase and the execution of full LCAs and LCCAs easier. This would help the geotechnical engineer to make decisions in their daily work that lead to less environmental impact and less monetary cost throughout a studied subject’s entire life cycle.

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