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First steps in the development of standardised processes for life cycle assessments of geotechnical works

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First steps in the development of standardised processes for life cycle assessments of geotechnical works

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Abstract. Despite geotechnical works contributing considerably to the environmental impact of buildings and infrastructure, the application of life cycle assessments (LCAs) in geotechnical engineering still needs to be developed and matured. This paper presents a scenario analysis of an excavation in a typical Norwegian geology. For three excavation depths, different design solutions were derived varying the length of the supporting wall and the amount of soil stabilisation within the excavation. The cradle-to-site impacts of the different solutions were then evaluated through a LCA. Global warming and acidification potentials were compared for the different design choices in parallel with an estimate of the respective solution's costs and different functional units were considered. The study shows that, for excavations in the chosen setting, most emissions are caused at product stage and the environmental impact related to the excavated volume or to the additional floor space created underground increases with excavation depth. It emphasises that different impact categories need to be considered to get a full picture of environmental impact. Simple to use LCA tools can provide a direct comparison of different potential solutions. Shifting the focus from minimising cost to minimising environmental impact will likely lead to different design decisions for geotechnical works.

1. Introduction

Geotechnical works are resource intensive and contribute significantly to the environmental impact of buildings and infrastructure. In Norway, a 45% reduction of greenhouse gas emissions by 2030 compared to 2005 levels is intended, with a reduction of 40% required by law [1]. It has been recognized that the construction industry has an important role in the reduction of greenhouse gas emissions, and, for example, the municipality of Oslo has set a target for construction sites to be fossil free by 2030 leading to investments in electric construction machinery across the industry. The consultancy company Asplan Viak has developed an LCA tool (VegLCA) for the Norwegian Public Roads Administration to quantify environmental impacts of Norwegian road and railway projects including geotechnical works [2]. VegLCA is frequently used in practice. Yet, outside of the Norwegian Public Roads Administration the assessment of greenhouse gas emissions and other impact factors is not common practice for geotechnical works and will rarely – if ever – be considered in the design phase. Usually engineering designs of geotechnical works are optimized for safety and, potentially, cost. Considering the above-mentioned targets, it is, however, expected that the focus will shift to environmental performance, in particular greenhouse gas emissions. Consequently, the development and harmonization of assessment tools is more topical than ever.

To make LCAs for geotechnical works feasible and useful, Song et al. [3] emphasised a need for harmonisation of LCA parameters such as functional units, system boundaries and uncertainty analyses and for the establishment of comprehensive life cycle inventory (LCI) databases. Kendall et al. [4] pointed out challenges including data quality and availability as well as comparability between different case studies. The environmental impact of foundations and substructures tends to be neglected in element-based building assessments such as BREEAM because of the dependency of design choices on local conditions and requirements [5]. This is equally the case for excavation works. In Norway, the currently proposed revision of the technical building regulations (TEK17) includes a requirement to account for greenhouse gas emissions for new buildings [7]. Yet, the original proposal that went through consultation in autumn 2021, explicitly excluded groundworks with the argument that the developer does not have control over the ground conditions [8]. In Sweden, a climate declaration has to be prepared for all new buildings and it is suggested that this should include earthworks, even if the methodology how to do so has not been established yet and needs further investigation [9]. In order to collectively work towards a global reduction of environmental impacts from the construction industry, it is essential that resource demanding processes, such as geotechnical groundworks, are included in LCAs. It should also be a goal to harmonize these assessments across countries.

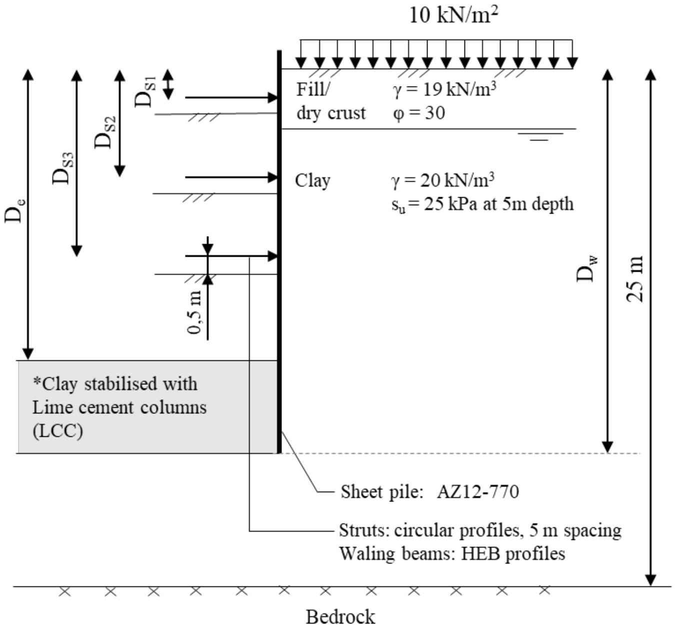
From the design perspective, these discussions are relevant if knowledge about the environmental performance of different, equally feasible solutions would change the decision about which type of, for example, foundation or stability measure will be used in a specific situation. Seol et al. [10] used LCAs to compare different construction methods for urban excavations in Korea. They concluded that consideration of the environmental impact in design would influence the choice of method. However, their study did not report the considered positions in the inventory or data used for the LCA analysis in detail. The current paper presents a scenario analysis for a simplified excavation in a typical Norwegian setting, comparing different design solutions using VegLCA and experience values for cost estimates. The different solutions are related to several different possible functional units. It is further discussed how these environmental impact considerations could be integrated into geotechnical designs and if specific decisions might change if more knowledge and straight forward estimates of environmental performance would be available to the engineer.

2. Methodology: Scenario analysis

To compare the cost and environmental impact of different design solutions, a simple scenario of a 16 m wide excavation in typical Norwegian conditions was analysed and LCAs were performed for different design solutions. The excavations were modelled in Plaxis 2D to obtain dimensions of the support measures which fulfil the considered design requirements (see below). The basic setup is shown in Figure 1. The geology is dominated by a soft clay underlaying 2 m of dry crust. The clay is modelled in two layers to account for higher shear strength in the top layer. The bedrock/firm layer is assumed to be in 25 m depth and the ground water table in 2 m depth. All solutions use sheet pile walls, which is common for this kind of excavation. Three excavation depths of 6, 9, and 12 m were considered. The soft clays in Norway will usually be stabilised for excavation and/or static purposes using lime cement columns (LCC). This is because non-stabilised clays can be difficult to excavate and rips of LCC in front of a sheet pile wall can serve as an internal support of the excavation. For each excavation depth, one solution was derived without considering LCC for static purposes and one with LCC rips in front of the sheet pile wall covering 30% of the excavation area.

The sheet pile wall was supported at depths of 1, 3.5, 6, and 8.5 m for the cases without LCCs and at depths of 1, 4.5 and 8 m for cases with LCC, generally using one support level less if LCCs were considered for static purposes. A typical excavation sequence was followed, excavating to 0.5 m below each support level and then activating the support before excavating to the next level.

As main design requirement, a factor of safety (FoS) of 1.4 was adopted. For real cases, this requirement might vary based on different codes and conditions. Apart from the FoS, a second design requirement was set for the horizontal deformations of the sheet pile wall to stay within a range of maximal 0.5% of the excavation depth. Cases where this was strongly exceeded were discarded as unrealistic design choices.



Case	1	2	3	4	5	6
D_e [m]	6	6	9	9	12	12
D_{S1} [m]	1	1	1	1	1	1
D_{S2} [m]	3.5	-	3.5	4.5	3.5	4.5
D_{S3} [m]	-	-	6	-	6	8
D_{S4} [m]	-	-	-	-	8.5	-
LCC* considered in calculation?	no	yes	no	yes	no	yes

Figure 1. Excavation scenario and list of cases. The excavation depth, D_e, the length of the retaining wall, D_w, and the number and stiffness of struts are varied depending on the case. The soil inside of the sheet pile wall is only stabilised for some of the cases.

2.1. *Life Cycle Assessment*

To assess the impact of the different scenarios, the life cycle assessment tool VegLCA, version v5.01, was used. The tool builds on the standard specifications for roads in Norway [11]. The main focus of VegLCA is the global warming potential. Other environmental impact indicators such as acidification, eutrophication, photochemical smog and energy can also be evaluated. VegLCA considers the product stage (A1-A3), the construction process stages (A4-A5), the replacement (B4) and refurbishment (B5) stage. Further detail about VegLCA can be found elsewhere [e.g., 2].

This work used the so-called "late phase tool" of VegLCA which was developed for detailed planning phases of infrastructure projects identifying the main processes relevant to the calculated cases that cover geotechnical works typical for deep excavations. The default emission factors, electricity mix and transport distances specified in VegLCA were used.

To estimate the material use for the derived design solutions, an amount of lime-cement of 60 kg/m^3 stabilized soil was considered below the final excavation level where LCC are required for the design (30% coverage). Above the final excavation level, it was assumed that the binder content can be reduced to 30 kg/m^3. For those cases where the LCCs was not considered for statical purposes, a coverage of 20% of the excavated volume with LCCs and a binder content of 30 kg/m^3 were considered. These are experience values that would be used in an early design stage. The following sections describe the system boundaries and functional unit for the LCAs.

2.1.1. System boundaries. For excavations, most processes are finished once the construction is completed. The used materials such as steel or concrete often remain in the ground. Whilst a sheet pile wall can in theory be removed to be reused, in Norway this is not usually done as the vibrations would disturb the clay and trigger unwanted settlements. However, the function of the excavation becomes redundant once the structure within it is built and the space between the structure and the excavation walls is backfilled. As such the system here is looked at until the excavation pit is fully established which can be called "cradle-to-site" including process stages A1-A5 [3]. This includes the excavation and transport of excavated material to landfill or a location where it can be reused. Song et al. [3] suggested a system boundary for geotechnical works in building construction that includes permanent elements of the building as well as temporary works that are necessary for the establishment of the building pit but do not serve any function once the building is established. In the current study, only the latter, the excavation, is considered (Figure 2).

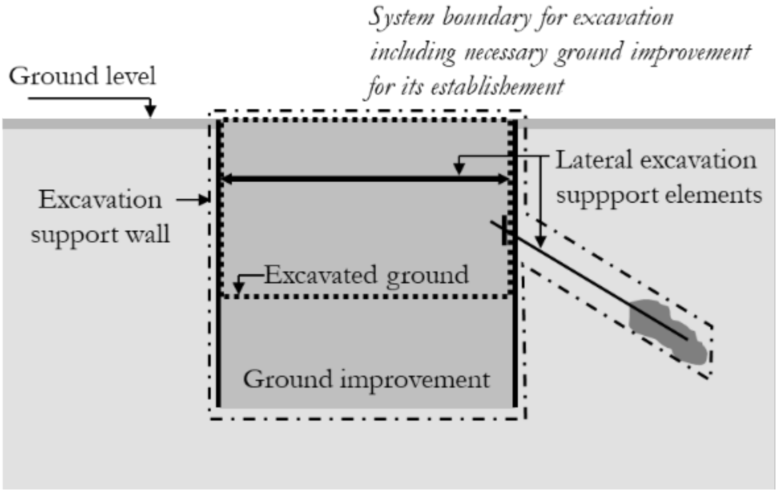


Figure 2. System boundary for geotechnical works as suggested in the current study, based on Song et al. (2020)

2.1.2. Functional unit. The functional unit (FU) represents the function of the system studied and provides a reference measure to which the inputs and outputs of the system are then related. For the current study, the preliminary functional unit was chosen as "establishment of 1 m running length of an excavation of depth D_e and width W_e in typical Norwegian ground conditions". This is similar to the FU used by Damians et al. [5], who also used a FU of 1 m running length to compare different retaining structures. A FU of 1 m running length may be representative for linear infrastructure cases, which are typically modelled using 2D calculations assuming plane strain assumptions. However, different professions might use different FUs. For example, developers frequently adopt the floor space as FU for new building projects [3]. For comparability of cases a more general FU would likely be required. This is explored here by putting the LCA results also in relation to additionally created floor space. Here, only the floor space created underground is considered. The potential of establishing a new FU, relating to the excavated volume, is also discussed.

3. Results

Only the 6 m deep excavation could be designed without lime cement stabilisation. For deeper excavations, stabilisation is required to control wall deformations. Hence, the cases 3 and 5 had to be neglected due to unrealistic wall displacements. As such, only Cases 1, 2, 4 and 6 (Figure 1) were assessed in an LCA. Four main processes were quantified and representative processes chosen in VegLCA. Table 1 lists the processes, the resulting input values and a cost estimate based on experience values. Table 2 lists the quantities of CO_2eq and SO_2eq computed in VegLCA for the four scenarios using internal struts. As specific positions for struts and waling beams are missing in VegLCA, the general position "delivery of steel materials" with the option "reused construction steel" was used. In Table 2, the product and construction stages are summed up, so the table contains stages A1-A5. However, it should be noted that the processes for sheet pile wall and steel delivery in VegLCA focus only on the material production and delivery to construction site (A1-A4). Any emissions from installation of the sheet pile wall are not reported (A5 and direct emissions on construction site).

For the cost estimate, experience values were used that would normally be used for early-stage cost estimates. A steel price of 12 NOK/kg for sheet pile walls, struts, and waling beams was adopted.

Table 1. Derived amounts of materials and cost estimate for four scenarios. The cost estimate is based on experience values

Main process	unit	Case 1	Case 2	Case 4	Case 6
Sheet pile wall*	[m^2]	20	18	24	34
Lime cement stabilisation	[kg]	576	1728	2160	3168
Excavated masses	[m^3]	96	96	144	192
Steel for struts and walers**	[kg]	869	302	1189	2202
Cost estimate	[TNOK]	70	60	104	162
Cost per excavated volume	[NOK/m^3]	730	620	723	1126

* AZ12-770

** Circular profiles for struts, HEB profiles for waling beams

Table 2. Global warming potential and acidification potential of four scenarios with internal struts considering four main processes. The listed emission cover stages A1-A5.

Main process	Case 1		Case 2		Case 4		Case 6	
	kg CO_2eq	kg SO_2eq	kg CO_2eq	kg SO_2eq	kg CO_2eq	kg SO_2eq	kg CO_2eq	kg SO_2eq
Sheet pile wall	1559	4.4	1403	3.9	1871	5.2	2650	7.4
Lime cement stabilisation	563	510	1690	1529	2113	1911	3099	2803
Excavated masses	101	0.3	101	0.3	152	0.4	202	0.5
Steel for struts and walers	1309	4.7	454	1.6	1790	6.4	3315	11.8
Total emission	3532	519	3649	1535	5926	1923	9266	2823
Total emission per m^3 excavated volume	37	5	38	16	41	13	48	15
Total emission per m^2 underground floor space*	110	16	114	48	123	40	145	44

* Assuming 1 floor underground for each 3 m of excavation, not accounting for walls.

Overall, the derived impacts of excavating masses were small compared to the impact of material use (Table 2). The costs per m^3 were similar for depths up to 9 m but significantly higher for a 12 m deep excavation. The global warming potential per m^3 increased by 17% for case 6 compared to case 4. The acidification potential per m^3 remained at a similar scale for all cases using LCC to stabilise the excavation.

Table 1 shows that for the 6 m deep excavations (i.e., cases 1 and 2), the cost for the solution using LCC for statical purposes (i.e., case 2) is estimated to be lower than for the solution where LCCs are not used for statical purposes. This is because an extra support layer is necessary if the LCCs are not considered in the statical model. This difference will increase with increasing steel prices. However, as shown in Table 2, the global warming potential for both cases is similar whereas the acidification potential is much larger for the second case. This is due to LCC stabilisation being the only process that also shows a significant acidification potential. The results for eutrophication potential (kg $PO_4^{3-}eq$) and photochemical ozone creation potential (kg C_2H_4eq) are not presented here in detail due to space constraints but show a similar picture as the acidification potential.

Figure 3 illustrates how much the four main processes contribute to the global warming potential of the cases analysed. It shows that for cases 3 and 4, the distribution is similar and that for cases 1, 3, and 4 the removeable steel elements contribute more than 30% to the global warming potential. This is relevant insofar, as these elements are here only considered up to the point of construction but will be removed and likely reused.

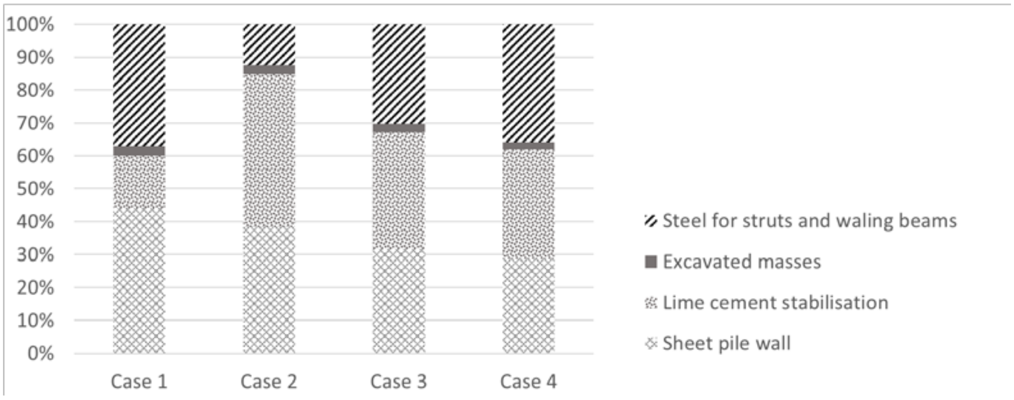


Figure 3. Percentual contribution of the four main processes to the global warming potential of the four cases analysed.

4. Discussion

The analysed scenarios show relatively low emissions caused by the excavation of masses (construction stage) compared to the product stage, suggesting that most emissions caused by earthworks happens at the product stage. These emissions can be reduced on the product level, for example by using recycled steel, or less harmful binders in the soil stabilization process [12]. On the process level, reuse of excavated masses and recovery of the sheet piles could be considered. However, as mentioned before, in the Norwegian soil conditions the sheet piles are usually left in the ground as their removal might cause unwanted settlements in the surroundings. The current paper looked at the potential of emission reduction through design, by choosing the construction method least harmful.

It stands out that lime cement stabilisation contributes significantly not only to the global warming potential but also to other impact categories. Thus, optimising designs to use as little LCC as possible would be desirable. Reducing the analysis to only global warming potential might lead to a false judgement with regards to the environmental performance of a design solution. The presented results thus show the importance of considering multiple impact categories when calculating the environmental impact of geotechnical works. These considerations should also include further development of land-use and soil related impact categories that might be particularly affected by geotechnical works [13].

In geotechnics, engineers will often decide for specific design solutions out of experience. They would also opt for a "robust" design. For example, if a shorter sheet pile would suffice but it's only a few meters to bedrock, engineers would usually choose to extend it to the bedrock. Also, local geological and hydro-geological conditions will influence a design decision. For example, for static purposes anchors could be considered and might be preferred with regard to the spatial organisation of the excavation pit (struts mean a hindrance for excavating the ground). However, in the typical Norwegian conditions, anchors to bedrock also mean a risk for leakage of groundwater from the rock into the excavation. This can lower the ground water table in the bedrock and subsequently in the overlaying clay and lead to settlements of the surroundings over a longer period of time [14].

In addition to the above, contractors often have a certain set of technologies they are familiar with that they might prefer, and additional stabilisation might be required to create safe routes for driving or spaces to place machinery. In an early design stage, which is what is discussed here, there are often uncertainties about the local ground conditions that tend to be captured within the design and are not completely cleared when construction starts. Through continuous monitoring during construction (observational method), temporary elements such as struts can be reduced, but the permanent elements that remain in the ground will be designed so that they cover all possible cases. Simplifications in the designs done here, such as a fixed spacing of struts or the use of a single HEB profile as waling beam would likely not be done for a real design situation, where constructability plays an important role. Overall, design decisions are influenced by a large range of factors that cannot be captured in an LCA.

As might have been expected, the data illustrates that in general less deep excavations will cause less harm and – in a soft clay – an optimization with regard to excavation depth will always be positive. It is also important to remark here that an increase in floor space by building additional floors underground will likely increase the emissions per floor space if earthworks are accounted for. An omission of earthworks in LCA will not capture this effect. A FU relating the environmental impacts of geotechnical works to floor space or excavated volume will enable a meaningful exchange between different experts involved in the project planning and provide a basis for comparison of excavation in different settings and for different purposes.

Apart from defining functional units for geotechnical engineering works, it needs to be evaluated which processes and life cycle stages need to be included in an LCA to appropriately capture the environmental impact from urban excavations. The level of detail of an LCA needs to be inherently connected to the level of detail of the design as the design and construction move along and information about environmental impacts needs to be available at the right point in time and at the right level of detail to adequately inform design decisions. For early design, an LCA tool such as VegLCA that has pre-selected processes (based mostly on EcoInvent) and is simple to use compared to full LCA software programs can provide a direct comparison of different potential solutions. This might shift decisions from cost-optimized to, for example, carbon-optimized solutions. Each decision about an individual project will be influenced by a range of aspects, including project cost and LCA results. How these decisions are taken will depend on the specific setting and likely change with growing environmental awareness. Further and ongoing research is required to understand and optimize these processes.

Including analysis of environmental impact into geotechnical design can facilitate the identification of processes with high impacts on one or several of the environmental indicators that are included in the analysis. These high-impact-processes can be analyzed further to uncover the origin of the impact to the environment. If a hot-spot with a high environmental impact is a material, substitution with alternative materials can be considered. If it is the installation or transportation alternative design solutions can be developed. A targeted and systematic analysis of the environmental impact of the geotechnical design every time the level of detail increases will ensure that the high-impact hot-spots are optimized at each design level. This will also entail a reduction of overall impacts at the local scale.

5. Conclusions

To further the development and understanding of LCAs for geotechnical works, this paper presented a scenario analysis for excavations in typical Norwegian ground conditions. Four cases were analysed varying excavation depth and support elements. For each of the cases, the material use was derived, and cost estimated similar to how would be done at an early design stage. The global warming and acidification potentials were obtained for each case through a simplified LCA analysis using VegLCA for only the four main processes identified.

The data showed that, for the chosen setting, most emissions caused by an excavation are caused at product stage. The global warming potential per m^3 increased with excavation depth whilst the acidification potential per m^3 remained at a similar scale for all cases using LCC to stabilise the excavation. Agreeing on a FU such as the excavated volume or to the additional floor space created underground will enable standardized reporting and facilitate comparative studies between different settings and projects. In that, not only global warming potential should be considered as major environmental impacts might be omitted.

The first choice of construction method when designing an excavation is often based on experience rather than on a comparative analysis of different possibilities. In addition, unforeseen site conditions, availability of materials, or operational requirements mean that what is built can differ considerably from what is planned in an early design stage. However, simple to use LCA tools can provide a direct comparison of different potential solutions and promote continuous learning about the environmental impact of geotechnical works. This will not only change design considerations within the geotechnical profession but also the conversation between different disciplines involved in a project and ultimately further a shift towards more environmentally friendly project design.

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