COST AND CARBON IMPLICATIONS OF DIFFERENT FOUNDATION SOLUTIONS - DESK STUDY OF FOUNDATION DESIGN FOR A BRIDGE AND A BUILDING IN NORWAY

von der Tann, L., Norwegian Geotechnical Institute, Oslo, Norway, loretta.von.der.tann@ngi.no
Baardvik, G., Norwegian Geotechnical Institute, Oslo, Norway, gunvor.baardvik@ngi.no
Mortenson, P.-A., Norwegian Geotechnical Institute, Oslo, Norway, per.anders.mortensen@ngi.no
Monsås, E., Norwegian Geotechnical Institute, Oslo, Norway, egil.monsas@ngi.no
Feizi, S., Norwegian Geotechnical Institute, Oslo, Norway, siamak.feizi@ngi.no

ABSTRACT

The choice of method and materials for pile foundations in Norway often builds on the experience of the involved parties and a preference of solutions with fewer, high-capacity piles compared to more, low-capacity piles. In many cases the foundations do not get optimized with regard to resource use and cost. Timber piles, which had a long tradition in the country, are now rarely used. In urban environments, where marine clays are the dominant geological surface formation, shallow building foundations on stabilized ground could be considered. Yet, piled solutions to bedrock are usually chosen due to the concerns related to settlements induced by other building projects.

To investigate whether the current practice could be improved, a desk study was conducted comparing cost and carbon emissions for four different foundation solutions for a bridge foundation in sand (steel pipe piles, HP steel pile, prefabricated concrete piles and timber/concrete combination piles). For a typical building project in Norway, a direct foundation on stabilized clay was compared to the usually chosen piles to bedrock solution. It is discussed what alternatives might be feasible with respect to practicality, robustness, costs, sustainability and environmental issues. In particular, the acceptable movements in the overlying structure will determine the feasibility of more environmentally friendly solutions.

Keywords: Pile foundations, timber piles, steel piles, concrete piles, LCC, sustainability

INTRODUCTION

The costs of geotechnical works regularly exceed what is first predicted (Clayton, 2001), which has – amongst other reasons – been connected to the available knowledge of site conditions, or the quality and quantity of site investigation (Shrestha and Neupane, 2022; Paraskevopoulou and Boutsis, 2020). Yet, there is an "inclination to deal with [the large uncertainty in the performance of structures] by overdesigning" (Redaelli, 2013). Such conservatism has been described as a general obstacle to sustainable design approaches (Wong, 2020). The current study builds on the hypothesis that (a) apart from general conservatism, in current Norwegian practice, often solutions are suggested that "work", building on the experience of the involved parties, and sometimes on the availability of construction materials, and (b) other solutions are not considered that might be feasible, cheaper or more environmentally friendly. Consequently, even if such an approach enables efficient and reliable design, a chosen solution will often not be optimized with regard to cost and resource use.

For any geotechnical problem it is likely that several solutions are technically feasible. But despite the decision for one solution – here for foundation systems – being part of everyday geotechnical work, there are only few examples in the literature where different foundation solutions were detailed for the same structure or problem so that they could be compared in terms of costs or environmental impact. Giri and Reddy (2014) designed two alternative foundations – a pile and a caisson foundation – for a high rise building in the Chicago area and assessed the sustainability of both solutions using a three pilar approach. A lifecycle assessment for the environmental part showed the caisson alternative as less impactful on all considered impact categories, including global warming. This solution is also significantly less costly.

Kraus and Juhasova Senitkova (2019) assessed four alternatives for shallow foundations for a family house in the Czech Republic. Similar to Giri and Reddy (2014), the variant with the least environmental impact was also cheaper than the other solutions considered. Lee and Basu (2022) developed charts illustrating the global warming potential (GWP) of different solutions for variations of soil parameters, loads, and other parameters to enable quick estimations during foundation design. They did not analyze the costs of the different solutions. Whilst these studies give an indication for the ranking of solutions regarding costs and carbon emissions being linked, and a direction for how a simple set of design charts could be compiled for specific solutions, there remains a large gap for further case studies, discussion about location or country specific practice, and a reflection about habits in the industry that might impede the implementation of more sustainable designs.

On this background, to investigate if current practice could be improved, three alternative pile foundation solutions for a bridge foundation in Norway were calculated and optimized in the current study. Round concrete piles with steel casing (steel pipe piles) were compared to prefabricated, square concrete piles and timber piles. HP piles were also considered; however, this solution was not optimized to the same degree. For all solutions, both, carbon emissions and costs were analyzed. It was of particular interest to enquire if such foundations could be decarbonized by reintroducing timber piles into Norwegian practice. Using wood in construction is claimed to have the potential to reduce global warming potential significantly. Kayo and Noda (2018), for example, estimated that in Japan, by 2050 nearly 5 million tons of CO2eq could be avoided through substitution of non-wooden material with wood in civil engineering applications. In Norway, historically, timber piles have been used widely for foundations. The shift to other materials is likely due to a range of factors such as material development, types of structures to be supported, load capacity and design requirements.

In addition to the bridge foundation, a typical building foundation in clay is presented to discuss the effects of an apparent current preference for pile foundations to bedrock on construction costs and carbon emissions. For urban developments built in clay, usually stabilization of the clay is required for the establishment of the excavation pit. The resulting stabilized clay body could be taken into account for assessing the possibility of a compensated foundation. Yet, it is common to prefer a deep foundation solution with piles to bedrock.

The following sections present the methodology followed, the results for the foundation designs, and the assessment of costs and global warming potential (GWP). The results are discussed looking at different aspects of design, uncertainties in the assessment of GWP and potential knowledge gaps. Recommendations are given for further research and considerations that could be incorporated into engineering practice – in Norway or any other places – right away.

DIMENSIONING OF FOUNDATION SOLUTIONS

To discuss the current practice of foundation design in Norway, a desk study was conducted comparing different solutions for a bridge foundation in sand. In addition, a typical building foundation in clay with piles to bedrock was analyzed and the potential for a shallow foundation taking into account a stabilized clay body installed for the establishment of the excavation pit is discussed. For all solutions, lifecycle assessments (LCAs) were conducted using two different tools.

Case Study – Bridge

As a first case, a typical bridge over a river in Norway with a foundation in sand was analyzed. A recently designed road bridge was taken as a case study and the final load combinations at the foundation level delivered by the bridge engineers were used as input for the calculations. These loads resulted from an iteration of stiffness-parameters between the geotechnical and construction engineers, which would likely have led to slightly different loads for each of the foundation solutions. For simplicity, the loads were kept the same for all proposed solutions.

The geology is dominated by a deep layer of clean to silty sand underlaying a top layer of well graded silt-sand-gravel material. From CPTU and laboratory tests, the sand was characterized as having a density of 20 kN/m^3, a friction angle of 35° and a relative density of 0.5. The average groundwater table is 5.5 m under current terrain and the bottom of the base slab for the planned bridge foundation lies 6 m under current terrain, so it can be assumed that all piles will be continuously underwater. The depth to bedrock is not known, but based on soil investigation data, assumed depths are more than 40 m. In the vicinity of the bridge foundation in question, total soundings did not reach the bedrock. Consequently, end bearing piles were not considered a possibility and friction piles were designed.

The piles were dimensioned following the Norwegian pile guidebook (Den Norske Pelekomité, 2019) that is in accordance with Eurocode 7, design approach 2, and provides local requirements and data about commonly used pile dimensions. For friction piles as dimensioned in the current study, results from undrained core penetration tests (CPTu) can be used to determine the sleeve resistance following the NGI-99 method described by Clausen, Aas and Karlsrud (2005). Four CPTu in the area were available and this number was used for deriving the according correlation parameters. The CPTu closest to the analyzed bridge axis (rather than an average of the four CPTu) was used to establish the pile capacities.

In order to carry out a soil-structure interaction analysis of the pile group, first the pile length required to resist the vertical loads given was estimated by determining the bearing capacity of a single pile in the given ground conditions using the CPT method. Afterwards a pile configuration for the pile group analysis was suggested and analyzed for all load configurations. Pile group calculations were performed in the software GeoSuite 22_02. A different tip resistance was set for each pile type depending on the depth of the respective piles. Both geometry and length of piles were varied to find a solution where the load on the highest loaded pile came as close as possible to 100% of the calculated capacity with pile lengths varied in 1 m steps. The lateral capacity was checked following the dowel theory (Den Norske Pelekomité, 2019). In addition, the drivability of the chosen pile solutions with common equipment was checked using the software GRLWEAP14.

For steel pipe piles, concrete piles and HP piles, common dimensions used in Norway were chosen. For the consideration of timber piles, a solution with solely timber piles was not considered feasible, as the moment capacity of these piles is limited. As such, combination piles were chosen with a 5.5 m long concrete pile on top of each timber pile. This length was calculated as sufficient to reach the calculated lateral pile capacity in the concrete cross section, derived from the dowel theory. The length of the timber piles was limited to 18 m as the longest dimension of piles recently used known to the authors.

Table 1. shows the main dimensions derived for the foundations using the four different pile types. Table 1 lists the material quantities resulting for all four solutions considered. It is important to note that the volumes of concrete and reinforcement in the piles are higher for steel pipe piles than for concrete piles. Because of the larger base slab, the total amount of concrete and reinforcement for the solution with wood piles is also higher than for the concrete pile solution. Consequently, it is expected that the concrete pile solution will have lower costs and emissions than these two solutions.

Case Study – Building

As a case study of a typical building development, a ten-story building in Oslo with two basement floors and a gross floor area of 2280 m^2 was used that was built in 2016. The ground consists of 1-2 m fill materials and a few meters of clayey silt and sand over normally consolidated clay. The depth to bedrock varies between 26 and 38 m. Creep settlements of 2-4mm/year occur in the area due to previous fillings and adjacent building developments. Excavation support and piles for the latter can cause water drainage and consequent reduction of pore pressures at bedrock level (Langford et al., 2015). A pile foundation was designed using driven HP-piles to bedrock and without consideration of reuse of existing piles on site. Other kinds of piles were not considered. Many buildings in Oslo experience damages due to differential settlements and often stakeholders act on the side of caution with regard to potential settlements. In total, 126 HP-piles with an average length of 29 m to reach the bedrock were required. For stabilization of the excavation pit, lime cement columns placed in double rows were used to increase passive earth pressure and prevent bottom heave.

Table 1. Dimensions for bridge foundation solutions. SP: steel pipe piles, CP: concrete piles, HP: HP piles, TP: timber/concrete combination piles.

Element	Dimension	Unit	Quantity			
			SP	CP	HP	TP
Base slab	Width (perpendicular to bridge)	m	22.3	18	21	22
	Depth (parallel to bridge)	m	6.1	6	6	8
	Thickness	m	1	1	1	1
Piles	Length	m	18	22	27	5.5 concrete + 18 timber
	Number	-	12	24	28	75
	Distance parallel to bridge	m	4	4	4	1.8
	Distance perpendicular to bridge	m	4	1.45	1.45	1.5
	Diameter/specification	-	Ø813x16	P345MA	HP400x231	Concrete: P270MA Timber: Ø top=300 mm Ø tipp=140 mm

Table 1. Material inventory for bridge foundation solutions. SP: steel pipe piles, CP: concrete piles, HP: HP piles, TP: timber/concrete combination piles.

Main process	Specific process	Unit	Quantity			
			SP	CP	HP	TP
Base slab	Concrete	m^3	136	108	126	176
	Reinforcement	kg	14'941	11'880	13'860	19'360
Piles	Concrete	m^3	103	63	-	30
	Reinforcement	kg	13'637	11'240	-	2903
	Steel	kg	67'932	-	174'636	-
	Timber	m^3	-	-	-	58.1

In a desk study, the feasibility of a compensated foundation on top of the stabilized clay body was assessed. The settlement pressure on the bottom of the base slab was derived as 105 kPa, assuming an even spacing of columns and a 1 m thick base slab. For two basement floors an excavation of 7.7 to 8.7 m is required equaling an unloading of 140 to 160 kPa and a net reduction in vertical pressure at the bottom of the base slab of 35 to 55 kPa. Thanks to increased stiffness, the base slab can be constructed directly on top of this stabilized LCC body. Based on oedometer tests, the reconsolidation settlements underneath the LCC stabilized clay body were expected to be small (between 0.3 and 1.9 cm), but ongoing creep settlements in the area were expected to reach a maximum of 5 cm over 100 years. Due to the large depth to bedrock, consistency in soil layering and load distribution in the foundation system, differential settlements are expected to be small and the overall anticipated settlements were considered acceptable for a compensated foundation. Table 3. shows the material inventory for the building foundation. Both solutions are the same for the amount of lime cement stabilization. The aim of the analysis was to assess how much the foundation piles – here HP-piles – add in terms of environmental impacts.

Table 3. Material inventory for building foundations. LCC: lime cement columns

Main process	Specific process/data	Unit	Quantity LCC only	LCC and HP piles	Assumptions/Details
Base slab	Concrete	m^3	2280	2280	
	Reinforcement	kg	273'600	273'600	120 kg/m^3 concrete
LCC	Binder: Multicem 50/50	kg	1'175'000	1'175'000	100 kg/m^3 stabilized soil
Piles	Steel	kg		682'075	

Life Cycle Assessment

The environmental impact of the different foundation solutions was carried out as a lifecycle assessment (LCA) using the software SimaPro Analyst v. 9.1.1.7 with processes chosen from the Ecoinvent 3.8 database reflecting the global and European market. The GWP was calculated using the ReCiPe midpoint, hierarchical method. As a comparison, an additional analysis was carried out using the excel based tool VegLCA that was developed for the Norwegian Road Administration and contains a range of geotechnical processes. The emission factors reported in VegLCA are specific for the Norwegian market. In the current paper, for both methods only GWP is reported as CO_2-equivalent. Other impact categories are not considered.

Given the location of the bridge and foundation for the current analysis were not fixed, the analysis was performed as a cradle-to-gate analysis, including stages A1 to A3 (raw material supply, transport to manufacturing site, manufacturing of products) of the stages defined in EN 15978:2011 for all materials used. In line with these considerations, the inventory for the different pile foundation solutions includes only materials used and excludes machine hours for installation. Transport of machinery necessary for pile installation is assumed to be similar for all solutions and thus can be excluded, too. Other in-house analyses conducted at NGI showed that the contribution of machine hours for installation is – generally – small. This is also in accordance with Lee and Basu (2022), who calculated emissions for drilled shaft foundations. In their case, the materials accounted for 98% of the total GWP.

The data source for all inventory data is the design calculations conducted as part of this study. The quality of concrete and reinforcement for the base slab were taken from a report by the structural engineers for the real bridge case that also provided the load case for the current study.

Table 2. Processes chosen from the Ecoinvent 3.8 (allocation, cut-off by classification – unit)

Main process	Specific process	Ecoinvent 3 market process	Geography
Base slab	Concrete	Concrete, medium strength	Global
	Reinforcement	Reinforcing steel	Global
Piles	Concrete	Concrete, medium strength	Global
	Reinforcement	Reinforcing steel	Global
	Steel	Steel, low-alloyed, hot rolled	Global
	Timber	Sawnwood, softwood, raw	Global
Soil stabilisation	Cement	Cement, blast furnace slag 36-65%	Europe without CH

Cost Analysis

The costs of the different solutions were assessed using the Norwegian price database "Norsk Prisbok" (Norconsult, 2022) that compiles average prices for a number of construction materials and processes. Where prices were not listed, they were estimated based on experience values from recent projects at

NGI. For the prices, in addition to the material inventory as listed above, the rigging of the machinery and formwork for the base plate were taken into account.

RESULTS

Lifecycle Assessment

The GWP for all analyzed solutions, as calculated in SimaPro as well as in VegLCA, is illustrated in Figure 1. The relative contributions for both methods, put into relation to the solution with the most impact as assessed in the respective method, are illustrated in Figure 3.

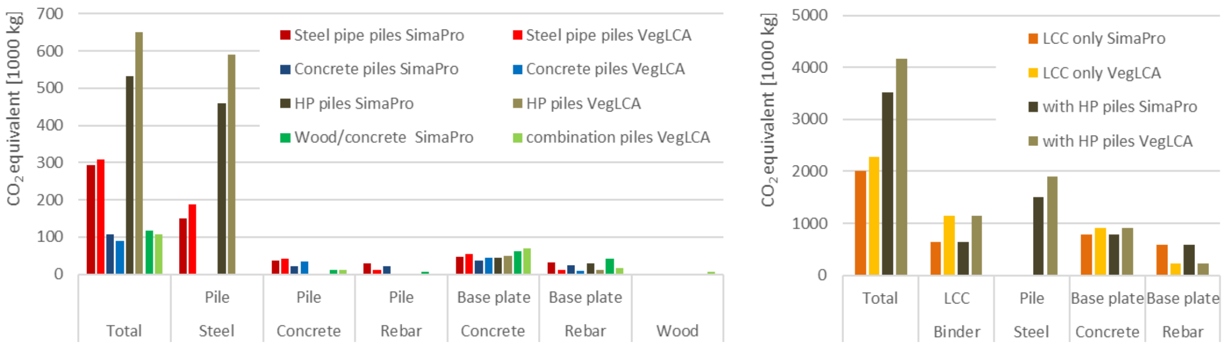

Figure 1. GWP for analysed foundation solutions in kg CO2 equivalent. Right: bridge foundation, left: building foundation. The concrete piles in VegLCA are a pre-defined position including the concrete and the rebar.

The results for the bridge foundations clearly show that the amount of steel is a determining factor for the overall environmental impact, the two solutions with steel elements (steel pipe piles and HP piles) showing a much larger impact than the other solutions. The solution with steel pipe piles compared to the solution with concrete piles uses a larger amount of both concrete and reinforcement in the piles. As such it appears consistent that the emissions for this solution, even discarding the steel pipes, is higher than for the concrete pile solution. The emissions caused by the piles in the combination pile solution are considerably smaller than those by any other solution. Yet, in the overall comparison, the solution would cause more emissions than the concrete pile solution because a larger base plate is required.

For the building foundation, the CO_2 eq was derived as 3'518'438 kg in SimaPro and 4'166'981 kg in VegLCA, respectively. 43% of these emissions (in SimaPro, 45% in VegLCA) were contributed by the HP piles, meaning the piled solution results in more than 40% additional carbon emissions compared to a compensated foundation, had that been considered.

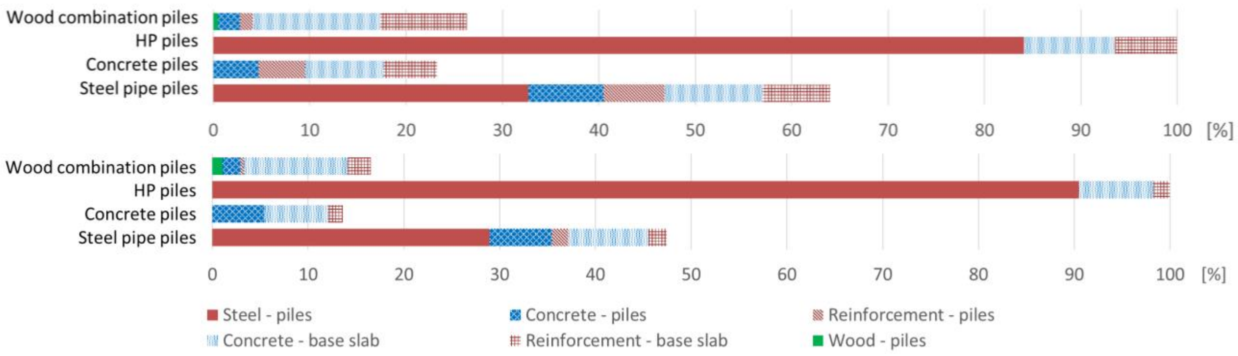

Figure 2. Contribution of different materials to GWP in bridge foundation solutions set in relation to HP piles that have the highest impact. Top: SimaPro; Bottom: VegLCA

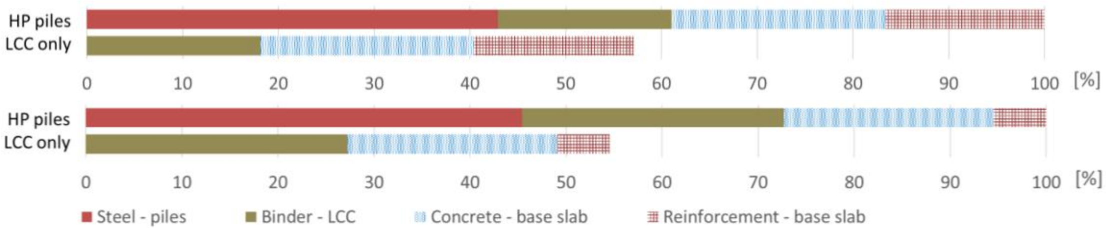

Figure 3. Contribution of different materials to GWP in building foundation solutions set in relation to HP piles that have the highest impact. Top: SimaPro; Bottom: VegLCA

Cost Analysis

The estimated costs of the four bridge foundation solutions are summarized in Table 3. Similar to the LCA results, the steel contributes the most to the costs in both solutions with steel elements. For the concrete and the timber combination piles, the costs for the piles are in a similar range to the costs of the base slab. It is interesting to note that, with regard to overall ranking, the HP pile solution is less costly than the solution with steel pipe piles. As such, looking at only these two options, the more cost-efficient solution is not the same as the one with the least carbon emissions.

For the building, the total costs were estimated to be 30.1 million NOK, of which 39% (11.7 million NOK) were allocated to the delivery and driving of HP-piles. The results for both the building and the bridge foundations are summarized in Figure 4.

Table 3. Costs of the analysed bridge foundation solutions in 1'000 NOK. The concrete piles are pre-defined in VegLCA in one position that includes both, the concrete and the rebar.

Solution	Total	Piles material	Driving of piles	Rigging of pile driving machine	Base slab
Steel pipe piles	6'274	5'148	224	68	834
Concrete piles	1'360	517	120	58	665
HP piles	3'798	2'503	452	68	774
Timber/concrete combination piles	1'930	485	314	58	1'073

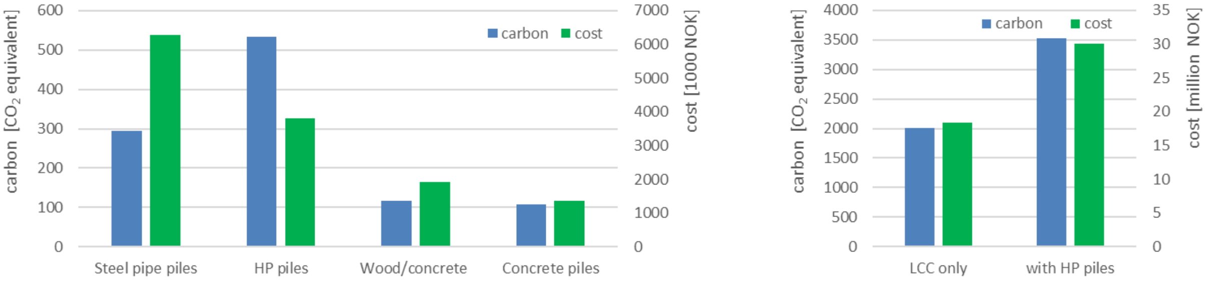

Figure 4. Total cost and carbon emissions for bridge (left) and building foundations (right). Carbon emissions as calculated with SimaPro.

DISCUSSION

Whilst civil and geotechnical calculations become more advanced, it sometimes appears that solutions become more complicated and costly. This might, amongst other reasons, be due to changing requirements during, and limited resources for, the design process. Optimizing pile foundations can be done in many different ways, and this process can produce several alternative solutions. Pile configuration, lengths, number of piles, size of cross-section or area of the slab, and combinations of two or more of these parameters can be varied. The optimization process considering the safety, robustness and sustainability, and at the same time taking into account the cost and practicality, may be very time consuming. In the current study, the dimensioning for the four foundation solutions by using the same soil and load input were conducted by different designers (all co-authors to the paper). Their approaches differed slightly, in particular with regard to the use of approximations and the targeted degree of utilization of the derived pile capacity. In addition, designers would generally act on the side of caution.

Uncertainties in ground conditions, as well as in the use of different calculation factors, can influence the design assumptions considerably. In a survey conducted by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), 46 of 84 respondents (55%) underpredicted the capacity of a pile in sand based on different field data, including CPTs, by up to 83% compared to a measured value from a full-scale field test (Day and Briaud, 2022). In the study reported here, an assumption was made about the resistance derived using the "CPT-method" representing the actual resistance in the field. Usually, when using this method, a check of the pile capacity with trial piling on the first piles (when the work starts) is required.

It appears that in the usual course of design either the client, the contractor, or one of the designers (structural or geotechnical) will, out of experience or due to practical considerations, have a preferred solution which comes in at an early stage in the project and then might not get questioned. For example, for steel pipe piles, the thickness of the pipes might be chosen higher to improve drivability, or a contractor has a certain dimension of piles available in their warehouse from previous projects. Material prices might react to these kinds of circumstances. The cost analysis showed that the ranking of solutions with regard to cost is not necessarily the same as the ranking with regard to emissions. In the current case, this is due to a difference in steel price for HP profiles compared to kg steel as is used for the steel pipes.

Wong (2020) states that the geotechnical profession needs to "develop the ability to compare carbon emission outcomes for different designs" as one of five points to move from "business as usual" to a more holistic/sustainable approach. Simple, excel-based tools such as the VegLCA can be useful to enable designers to conduct first pass assessments of carbon emissions. Yet it remains important to understand the background that goes into the tools and how comparable the reported emissions are when comparing different cases where the data was generated with different tools. Linking CO_2 emissions to BIM could enable a quick comparison of carbon emissions between different elements, solutions and throughout project development (e.g. Obrecht et al., 2020). However, these efforts are subject to the same requirement for understanding of the relevant assumptions and current lack of standardization.

The result of the current study shows that whilst the ranking of the four solutions for the bridge foundation will be the same independent of the method used, the specific values can vary considerably based on the assumptions taken by the analyst or underlying in the chosen methods. In particular, the CO_2-equivalent generated by the steel as calculated in VegLCA is higher than the one calculated in SimaPro. On the other hand, the emissions from the reinforcement production reported through VegLCA are less than those reported through SimaPro. Figure 2 illustrates the scale of the contribution of the steel production in relation to all other materials for the HP piles (84% in SimaPro and 91% in VegLCA) but also the steel pipe piles (51% in SimaPro and 61% in VegLCA of complete steel pile solution).

With regard to the high contribution of steel to the carbon emissions, it is important to note, that in both methods, virgin steel was considered. The use of recycled steel would have reduced the carbon emissions considerably. For example, the emission factors reported in VegLCA for steel using recycled materials is about half of that for virgin materials. Similarly, the carbon calculator developed by the European Federation of Foundation Contractors provides emission values for steel sheets, steel tubes and rebar derived from combined Ecoinvent processes. Again, for recycled materials, the emission is reduced to 36% for steel sheet, 48% for steel tubes, and 34% for rebar, compared to virgin materials (EFFC, 2014).

As such, the use of recycled materials could reduce the overall emissions of the steel pile solutions by more than 30% and those of the HP pile solution by more than 40%. Yet, the overall ranking of solutions by GWP would not change.

Designers of geotechnical projects often do not know what materials will be used in the end and what percentage will be sourced of recycled materials. If carbon should be considered in design, these requirements need to be specified before the design starts and made available to the designer. Ideally, the client would also specify the database that should be used for reporting/considering carbon emissions.

Another aspect that warrants discussion is that in the LCA of the timber pile solution, biogenic carbon was not taken into account. Biogenic Carbon is carbon stored in biological materials, such as in timber. In construction, the biogenic carbon will be stored in the timber for the lifetime of the building. However, it is likely that following demolition the timber goes to incineration and the carbon is released back into the atmosphere. For that reason, the temporary storage of biogenic carbon is not usually accounted for in LCAs, even if common tools and guidelines allow it as an option (Vogtländer et al.,2014). In particular for timber piles, this topic might be worth consideration as it is unlikely that the piles will be dug out in the future. Two environmental product declarations for timber products in Norway (NEPD-2547-1284-NO and NEPD-3442-2053) report the total carbon emissions including the biogenic carbon as -723 and -712 kg CO_2-equivalent per m^3 timber, respectively. Using these values for the case calculated here would mean a reduction of the carbon emissions by approximately 41'500 kg CO_2-equivalent lowering the overall emissions considerably (20-30'000 kg) below those of the concrete pile solution.

With regard to the building foundation, piles might not be required if the building structure has sufficient flexibility to absorb the expected settlements. This should be considered in particular as piles are usually dimensioned as end bearing and thus need to be of considerable length to reach the bedrock. In addition, the piles themselves have often proven to be a problem for future building projects on the same slot. Half the slot of the building that was used as case study in the current paper did have old HP-piles in the ground. These were not reused but cut below ground level so as to not influence the new foundation. In Norway, for the last 30 - 40 years, there are very few examples of reuse of piles. Where reuse is considered, the main challenge lies in the uncertainty of the pile bearing capacity of the existing piles. This pinpoints a need for gaining more knowledge about the existing foundations and their potential reuse when buildings are demolished, which might imply additional time and, thus, financial resources, for the design stage. In addition, methods should be developed for testing or evaluation of the capacity of existing piles and foundations on site when documentation is limited. For new buildings, as-built details of the foundations should be required to be reported to enable reuse in the future.

SUMMARY AND CONCLUSIONS

This paper presented a desk study comparing four different relevant pile foundation solutions for a bridge in sand as well as discussing the potential for considering compacted foundations on stabilized ground instead of pile foundations in clay in an urban setting. The desk study shows concrete piles as the lowest-carbon option for the bridge pile foundation, and HP piles as the solution with the highest carbon emissions. However, these results do not represent a fixed hierarchy and might be ranked differently in a different setting. For the building foundation for a compensated foundation solution, no additional measures would have been required, and any piling will add to both costs and carbon emissions. In addition, the piling will also constitute a barrier in the ground should a new building be constructed in the same space, as well as potentially for underground infrastructure.

Any assessment of carbon emissions or GWP requires an understanding of the underlying assumptions, calculation processes and inherent uncertainties. Whilst rough estimates can allow relative ranking of different solutions, it appears that there is still a way to go before reliable values can be compared across cases and integrated in design.

ACKNOWLEDGMENTS

The research was funded with the NGI base funding received from the Norwegian Research Council.

REFERENCES

Clausen, C.J.F., Aas, P.M. and Karlsrud, K. 2005. Bearing capacity of driven piles in sand, the NGI approach. In: Proc. Of the ISFOG Conference, Pert, WA, September 2005, 677–681.

Clayton, C.R.I. 2000. Managing geotechnical risk: time for change? Geotechnical Engineering, 149(1) 3-11.

Day PW and Briaud J-L 2022. Are we overdesigning: Results of ISSMGE survey. Proc. 20th ICSMGE, Sydney, Australia, 511-529.

Den Norske Pelekomité, 2019. Peleveiledningen 2005. [Oslo]: Norsk geoteknisk forening.

EFFC (European Federation of Foundation Contractors), 2014. EFFC DFI Carbon Calculator Methodological & User Guide V2.2. Available at: https://www.effc.org/content/uploads/2020/10/EFFC-DFI-methodological-and-user-guide-v2.2.pdf

Giri, R.K., and Reddy, K.R., 2014. LCA and Sustainability Assessment for Selecting Deep Foundation System for High-Rise Buildings, in: ICSI 2014, American Society of Civil Engineers, Long Beach, California, 621–630.

Kayo, C., Noda, R., 2018. Climate Change Mitigation Potential of Wood Use in Civil Engineering in Japan Based on Life-Cycle Assessment. Sustainability 10, 561.

Langford, J. *et al*. 2015. Causes of unexpectedly large settlements induced by deep excavations in soft clay, Proc. XVI ECSMGE Geotechnical Engineering for Infrastructure and Development, 1115–1120.

Lee, M. and Basu, D. 2022. Environmental impacts of drilled shafts in sand, Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 1–14.

Norconsult, 2022, Norsk Prisbok 2022 02. [Online]. Norconsult Informasjonssystemer AS og Bygganalyse AS. Available at: https://www.norskprisbok.no.

Paraskevopoulou, C. and Boutsis, G. 2020. Cost Overruns in Tunnelling Projects: Investigating the Impact of Geological and Geotechnical Uncertainty Using Case Studies, Infrastructures 5(9) 73.

Potrč Obrecht, T. *et al.* 2020. BIM and LCA Integration: A Systematic Literature Review, Sustainability 12(14) 5534.

Shrestha, P.P. and Neupane, K.P. 2020) Identification of Geotechnical-Related Problems Impacting Cost, Schedule, and Claims on Bridge Construction Projects, *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 12(2) 04520005.

Vogtlander, J., van der Velden, N.M., Lugt, P., 2014. Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; Cases on wood and on bamboo. The International Journal of Life Cycle Assessment 19, 13-23.

Wong, P.K. 2020. Working Towards Net Zero Emission – Role of Geo-professionals. Keynote address at the AGS Victorian Symposium 2020.