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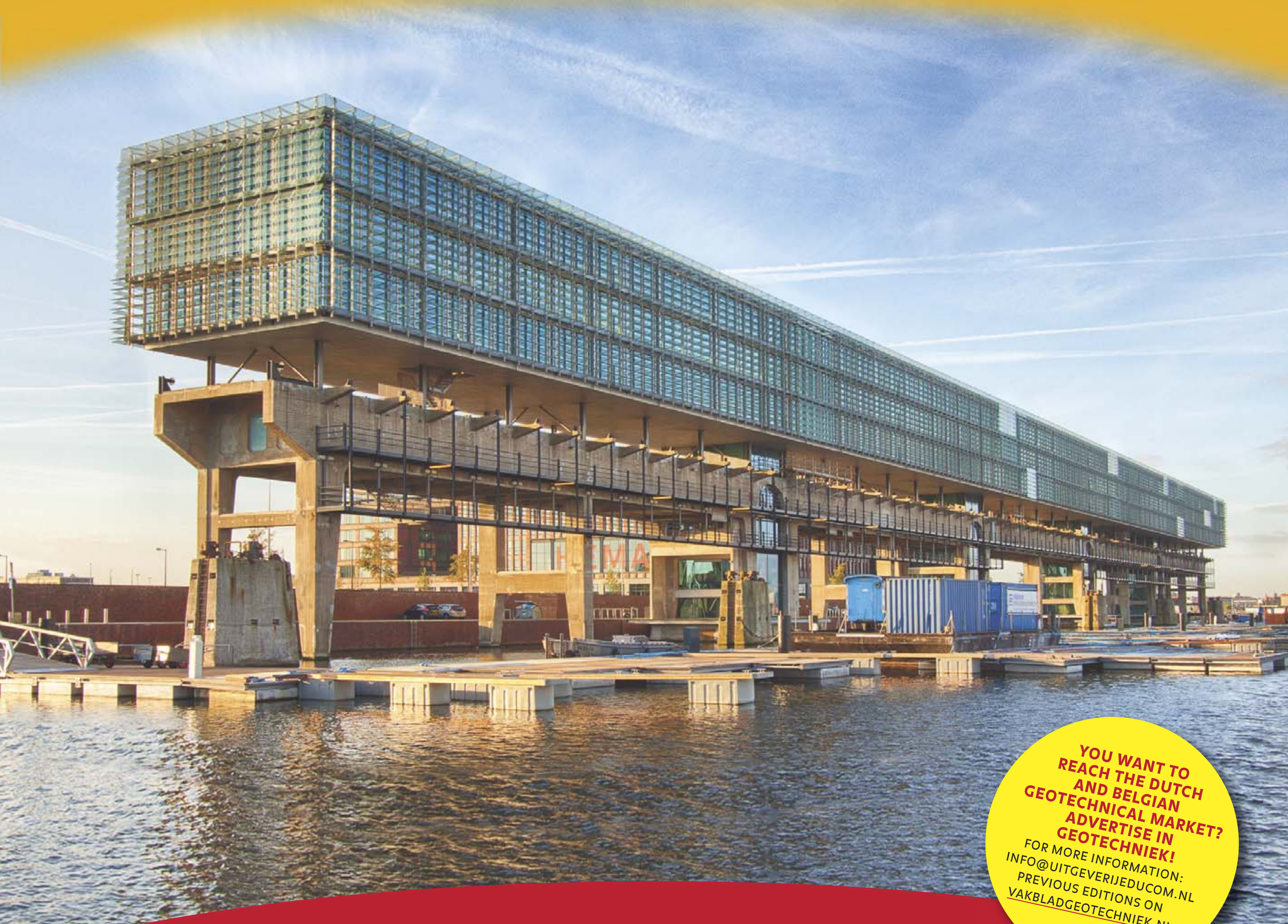

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Dear readers and visitors,

The Construction Industry is contributing significantly to the CO_2 emissions, and so is the Deep Foundation Industry. With sustainability becoming more relevant each and every day, we, as a profession, have a role to play to reduce our emissions. Decarbonization is the first option: more efficient design reducing volumes of concrete or steel, and the use of different materials with lower carbon footprint. However, this should not be viewed as the only option available: the reuse of existing foundations must be considered as well, and even preferred as the most sustainable option.

In March 2023, DFI Europe and the Geotechnical Section of the KIVI organized a very successful 3-day conference to discuss these burning topics in Amsterdam, The Netherlands. This was the occasion to share recent experiences and good practices to raise the level of the industry in this challenging matter. The organizers want to keep the pace and the second conference on this topic was scheduled in May 2024. Following the success of the conferences in 2023 and 2024 we are excited with the 3rd edition of the Conference on Decarbonization and Reuse of Foundations, once again in Amsterdam in the beautiful KIT, in March 2026. The choice of the KIT, as it was highlighted during the first edition, is driven by the fact that in 2017 the KIT launched the SDG (Sustainable Development Goals) House. It is home to more than 50 organizations and acts as a catalyst for sustainability initiatives, as a place to meet and exchange ideas on Sustainability.

In Amsterdam, the issue of the durability of the old timber pile foundations and their reuse is a recurring topic of endless debate, as was discussed already during the editions of 2023 and 2024. This can be because the loads have increased since the structure was first designed, as is the case with the bridges in Amsterdam, or because a new building is constructed to replace a structure that no longer meets the current requirements. This can provide insight for the many other places in the world where this issue is getting momentum, with urban centres being reconstructed and transformed, and the issue is also not limited to just timber piles. How do you address the remaining service life of steel piles that may have been subjected to corrosion? Or how do you assess the bearing capacity of any foundation pile, for which the original design and construction data is no longer available?

The construction industry is making significant strides toward sustainability, and the foundation sector —responsible for the installation of vast amounts of concrete and steel— must be an integral part of these efforts. By rethinking traditional practices and embracing innovative approaches, this sector can play a crucial role in reducing carbon emissions and minimizing the environmental impact of construction.

In this special edition of GEOtechniek, various topics on foundation decarbonization and reuse are explored. The aim is to inspire all involved (developers, architects, designers, structural engineers, and foundation specialists) to actively contribute to a more sustainable built environment.

KIT

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Photography: Bob Doets

FOUNDATION DECARBONIZATION: NOT A PILE PIPE DREAM

Next year the third edition of the International Conference on Foundation Decarbonization and Reuse (www.foundationreuse.com) will be held. During this conference, which will again be hosted by DFI Europe and the Geotechnical Section of the Royal Dutch Society of Engineers, various approaches to reduce the carbon footprint of a foundation will be covered. One option is obviously the continued use of an existing foundation when the old superstructure is replaced by a new one. This may require some out of the box thinking, e.g. how to supplement the existing foundation with new foundation elements or how to design the load-bearing structure of the new superstructure to match the existing foundation lay-out. But there are many other ways to reduce the carbon footprint, which will also more than likely reduce the cost of that foundation.

Building Green is Saving Green

In the northeastern corner of Texas, where I lived until a few years ago, there is a car dealership that has a logo set against a green background. At the end of their commercials, they show their logo as they claim that "seeing green is saving green", implying that buying a vehicle from them will save money (referring to the color of US banknotes). It is a small step to change that slogan to "building green is saving green", as green is also the color associated with sustainability. As Seth Pearlman, the CEO North America and board director at Menard, stated during a webinar I moderated "sustainability really means ... designs using fewer materials and resources to produce". Obviously fewer material and resources equate to lower cost, thus building green is saving green!

One way of obtaining design that requires fewer materials is by applying additional testing. The Adagio Sonate project in The Hague, The Netherlands is a good example to illustrate this. The original design called for 102 screwed pipe piles with a 762-mm diameter and a wall thickness of 12 mm. To demonstrate the feasibility of the design it was decided to install a full-size test pile and also 3 reduced size piles to confirm the pile capacity through Rapid Load Testing. The outcome of the load testing, which took less than 2 working days, allowed the total number of piles to be reduced to 92 piles and the length of each pile to be reduced by some 3 m. The overall pile length reduction decreased the concrete volume by some 280 m3 and the steel weight by some 160 tons, which clearly improved the project's bottom line. But the testing also resulted in a reduction of some 338 tons in CO2 emissions. Taken together the additional load testing resulted in an optimized design that was more sustainable and more cost effective. In other words: building green is saving green.

Two for the Price of One

A completely different approach to get a more sustainable foundation can be characterized by another and more general marketing slogan: two for the price of one. This is really a great way to describe energy foundations.

Geothermal energy, that is energy obtained from the heat generated by the earth, is nothing new: the ancient Romans used it 2000 years ago for space heating. Today it is still used, and according to the International Renewable Energy Agency (IRENA), geothermal energy provided in 2021 electricity generation in more than 30 countries worldwide, reaching a total installed capacity of around 16 gigawatts (GW), with roughly 1/16 of that in Europe. But wherever it is used, it is just a mere fraction (less than 1 %) of the potential geothermal energy.

A common way to capture this source of energy is through geothermal boreholes: vertical holes, generally between 0.125 and 0.2 m in diameter, with a HDPE thermal loop installed after drilling and before filling the hole with grout (usually a water, sand and bentonite mixture). If we assume an 0.2 m diameter borehole that is 100 m deep, the geothermal energy generated could easily be 3500 watts or slightly more than 30 MWh, equivalent to the energy use of approx. 3 homes.

But the same can be achieved in an even more sustainable manner, by installing a thermal loop in a foundation, at little extra cost, to turn a foundation into an energy foundation and to eliminate the need to install a geothermal borehole. This way the foundation gets an additional function: not only is it supporting the superstructure, but it also generates the energy that can be used to cool or heat that superstructure (in other words you buy one function and get the second function not entirely free, but at minimal cost.

Using the geothermal borehole described above as a starting point, the same geothermal energy can be generated by converting four 0.6 m diameter bored piles with a length of 25 m. And converting these four foundation elements will actually cost less than the construction of the geothermal borehole.

While an energy foundation may not be the right solution for every project, each project team should at least consider whether an energy foundation makes sense for their project. It might just be that they can take advantage of the two-for-one opportunity and in doing install increase the use of the geothermal energy.

A Foundation as Carbon Sequestration

The examples above clearly illustrate a more sustainable approach to foundations, examples where through "smart" design the carbon footprint is lowered, simply by reducing the amounts of concrete and/or steel in the design. After all, these materials feature production processes that require a lot of energy and thus the reduction in quantity has a distinct impact on the overall carbon footprint of the project. But in almost all cases, even in many foundation reuse projects, the design still calls for putting "new" steel and concrete in the ground, thus adding to the overall carbon footprint. But there may be yet a "smarter" design and that is the use of timber pile foundations. While obviously the preparation of a timber pile, its transportation to the job site and the installation itself create emissions, they are more than offset by the total amount of carbon absorbed by the tree and thus stored in the pile. This means that timber piles act as a carbon sink and therefore a timber pile foundation is a form of carbon sequestration, the process of capturing and storing atmospheric carbon dioxide. This means that through sequestration the amount of carbon dioxide in the atmosphere is actually reduced.

Although this carbon stored in the pile is re-released into the atmosphere at the end (e.g. due to decomposition of the timber pile), a properly designed timber pile foundation can last centuries, as is well known in The Netherlands. There are many 17th century buildings that are standing on long wooden piles, e.g. the Royal Palace in Amsterdam with some 14,000 piles that were driven some 380 years ago and are still in excellent condition. And the use of timber piles is not something that was only done in the distant past or in Europe. For example, thousands timber piles were used for the foundation of facilities at JFK Airport in New York, and at Dulles International Airport in Northern Virginia. In New Orleans, the Superdome (constructed some 50 years ago) is supported on timber and in Nevada a 300-m long viaduct that is part of highway system is also supported on timber piles.

Obviously when these project were constructed the concept of carbon sequestration was not part of the decision making process, but today, when designing foundations for a sustainable future, it should be. After all every cubic meter of timber is equivalent to 1 ton of CO_2 emissions.

Finally, the use of timber piles is not limited to foundation elements. While not necessarily relevant for a country as flat as The Netherlands, the option to use piles to address slope stability issues must be mentioned and obviously timber piles could be used for that application as well. So whether for slope stabilization or for supporting a superstructure, the use of timber piles is an excellent way to provide a sustainable design.

And Finally: Let's Do Things Differently

After these examples of out-of-the-box thinking to decarbonize foundations, I should say something about foundation reuse, or better the continued use of foundations, as well. When discussing foundation reuse, the aspect that remains largely uncovered is what is required when new foundations are installed to simplify their reuse at some point in the future. For while in the past it was common that buildings would have a lifetime measured in centuries (e.g., during the conference field day last year the attendees visited the Old Church, which was founded in the 13th century), the lifespan of buildings these days is more measured in decades. And that means that our children or grandchildren are likely to replace the structures we have constructed and then have to deal with the aspects associated with foundation reuse. The question is therefore what we can do with new foundations now to simplify the reuse option in the future.

The most obvious answer to that question is to ensure that (the final version of) design and construction records are kept and that as-built documentation is truly as-built. A good example of that are the construction records for the building where the conference is held, the KIT in Amsterdam. More than a century after it was constructed, the design drawings, design calculation and even the pile driving records are all available. Unfortunately that is more the exception than the rule.

While there are other things that can be done as well, I would like to focus here on the first part of that obvious answer, i.e., record keeping. But where? When engineering firms change ownership or go out of business, it is likely that many records are destroyed. When the original owner sells a building, it is likely that design and construction records are not transferred to the new owner. And that means that when at some point in the future the option of foundation reuse is considered to provide a sustainable approach for the new superstructure, it is less likely that foundation reuse is a realistic option. Clearly, all of us in the foundation industry can do our part by addressing this issue of record keeping, and thus by making foundation reuse in the future a more likely option. And come to think of it, this would be a great topic to tackle during one of the panel discussions at the upcoming edition of the conference.

Conclusion

With some out-of-the-box thinking we can definitely reduce the carbon footprint the foundations that are designed and constructed. But I am convinced that we can do more, that there are other approaches to achieve this goal. During the upcoming conference some of them will be presented and as Conference Chair. I hope that this article and this edition of the magazine will encourage you to attend in 2026 and maybe submit a paper describing yet another approach.

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LIFE CYCLE ASSESSMENT OF UNDERGROUND CAR PARKS IN GERMANY – CASE STUDY

Introduction

The most common option to increase parking spaces in urban areas is to build car park facilities above ground, or beneath a building or other spaces, i.e. public gardens,…. Parking structures above grade take up space that can be used for more socially valuable activities, whereas underground facilities increase land value. Although many UCPs have been built in the last decades all over the world with steel sheet piles as permanent walls (see Figure 1), German architects and design engineers are still quite reluctant to consider this proven solution.

A Dutch case study of a two level UCP performed in 2020 by a Dutch engineering firm (Witteveen+Bos, 2020) for ArcelorMittal demonstrated that an UCP built in the region of Amsterdam with permanent sheet pile walls was more cost-effective than alternative solutions such as Cutter Soil Mix wall, secant pile walls and slurry walls (diaphragm walls). A Life Cycle Assessment (LCA) (ArcelorMittal, 2021), which was peer-reviewed by an expert from the Dutch institute TNO (TNO, 2021), established that the permanent steel sheet pile wall had also the lowest carbon footprint. Transposing these findings to other European countries would need correction factors to consider local influences, hence the best option is to perform a detailed analysis for each specific project.

Design and cost analysis of the ucp

ArcelorMittal launched the analysis for the German market with the Berlin branch of the design engineering firm ARUP in 2021. The case study is limited to the region of Berlin, is based on German design standards, such as the EAB (2021), local state-of-the-art execution techniques, local ground conditions and installation costs. The second phase of the study was launched in 2022 and consisted in a more detailed design performed by the German design office GRBV (GRBV, 2023). GRBV provided the detailed cost analysis and the complete data for the LCA.

Design

The new building lies in the center of Berlin, between existing buildings founded on shallow foundations (see figure 2). It has two levels below grade and four above grade, the dimensions are 28 m by 28 m, and the vertical loads transmitted to the retaining wall are 350 kN/m. The service life of the structure is 50 years.

The representative soil strata consist of backfill and soft silty sands in the upper layers, and a more consistent sand layer below (see figure 2). The groundwater level is relatively shallow (1 m below the street level). The excavation pit is more than 7 m deep, and due to the high water pressure, the bottom slab is poured under water, and is fixed with vertical ground anchors to resist the heave forces. This execution method allows the installation of a single temporary support. All the retaining walls need to penetrate the competent sandy soil by at least 2 m. Corrosion rates of steel in the soil were taken as 0.01 mm/year.

The four alternatives are a permanent steel sheet pile wall, a reinforced concrete (RC) wall built inside a temporary steel sheet pile wall, a secant pile wall, and a slurry wall (diaphragm wall). We assume that the temporary sheet piles can be extracted and reused in other projects.

The engineer used the German design software GGU-Retain, which is based on a Limit Equilibrium Method (LEM). The optimised design yielded following solutions

- steel sheet pile wall – permanent: AZ 32-750, steel grade S 355 GP, 14.50 m long;
- steel sheet pile wall – temporary – with a permanent reinforced concrete (RC) wall: AZ 32-750, steel grade S 355 GP, 14.50 m long and a 40 cm thick RC wall;
- secant pile wall: diameter 1.18 m, concrete C 25/30 with reinforcing steel of 100 kg/m^3, 14.50 m long;
- diaphragm wall: thickness 1.00 m, concrete C 25/30 with reinforcing steel of 80 kg/m^3, 16.00 m long.

Notes of the authors: using high strength steel grades (i.e. S 460 GP according to EN 10248-1:2023) might have led to a lighter sheet pile section. Besides, we recommend the use of a Soil Structure Interaction Model (SSIM) for the design of such structures.

Cost analysis

The cost determined by GRBV is shown in Figure 3. It only considers the execution and material costs specific to each alternative, not the costs that are common to all of them. It is representative of the costs in 2023.

Figure 3 shows that the temporary sheet pile wall with a RC wall is the most cost-effective solution, 8 % less costly than the permanent steel sheet pile wall. The permanent sheet pile wall is more cost-effective than the two other concrete based alternatives, the cost difference with the secant pile wall is +18 %, respectively +24 % with the diaphragm wall.

Figure 1 – Permanent steel sheet pile wall of an UCP – Parking Miroir, Brussels, Belgium.

SUMMARY

Underground car parks (UCPs) are one option to increase the number of parking spaces in densely urban areas. Many UCPs are built with permanent steel sheet pile (SSP) retaining walls, but this is rarely the case in Germany. This case study compares four retaining wall alternatives for the execution of a typical two level UCP in the Berlin area. It shows that a permanent SSP wall is more cost-effective than a secant pile wall and a diaphragm wall, and a Life Cycle Assessment shows that the permanent SSP wall has also a lower carbon footprint (difference ≥ 120 %).

Life cycle assessment of the UCP

The LCA is performed according to the standards ISO 14044/40 with reference to the European standard EN 15978, with the software One Click LCA based on the bill of materials (BOM) provided by the design office. The International Standard ISO 21930 (2017) and the European Standard EN 15804 (2013, 2019) set out a common life cycle model for building and construction works. As this LCA is a comparative assessment between different construction materials, to be in line with the legislation and ISO standards, the LCA has been peer-reviewed by a panel of three German independent experts (iPoint, 2024).

The comprehensive LCA considers all the life cycle stages: production (Modules A1-A3), transport (A4) and installation (A5), deconstruction or demolition (C1), transport to waste treatment facility (C2), waste treatment and processing (C3), and potential net benefits or burdens from reuse or recycling of the materials and products (D). Modules B (use phases) are not relevant for this type of retaining walls.

LCA assumptions

We decided to focus on the Global Warming Potential (GWP) expressed in kg CO_2-eq., which can be used as an expression of the carbon footprint of the project. However, the conducted LCA contains all the environmental indicators of an EPD according to the EN 15804+A2.

The LCA covers the whole life cycle (Modules A-C) and includes Module D. All data, including EPDs, are based on the standard EN 15804+A2.
Whenever available, EPDs of individual products, published on a European EPD platform, have been chosen (i.e. in the base scenario, EPDs of steel products representative of EAF steel production manufactured with 100 % scrap and 100 % renewable electricity). Data for transport and installation were taken from either the German database Ökobaudat or from published EPDs. The temporary sheet pile wall is assumed to be used five times before being recycled, with some damages (losses) in between uses. Additional realistic assumptions were made for the transport. Note that the End-of-Life scenario for steel and concrete can be controversial: in this study, we assumed that the steel sheet piles can be recovered and recycled (except for the part of corroded steel), whereas the secant pile wall and diaphragm wall will be left in place.

A life cycle assessment of permanent retaining walls is usually quite simple, but the case with the temporary sheet pile wall turned out to be a challenge.

LCA results – Base scenario

Table 1 shows the GWP of the production of the

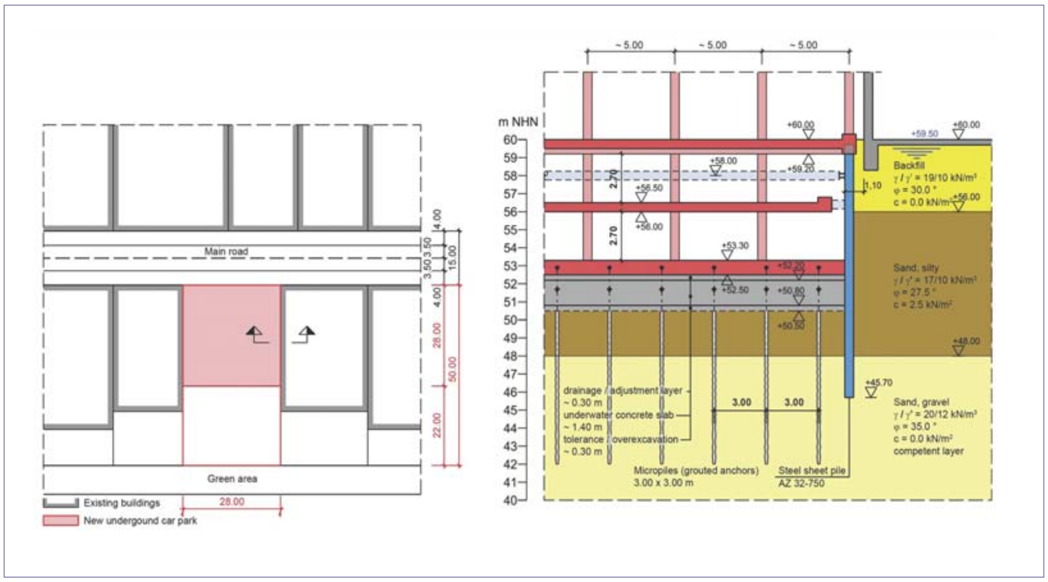

Figure 2 – Case study: layout of the UCP and cross section with typical Berlin conditions.

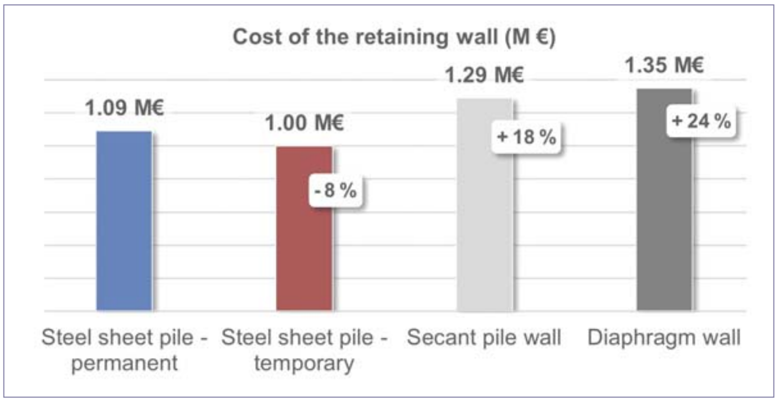

Figure 3 – Cost of the four alternatives to build the retaining walls around the excavation (2023).

	Product	EPD Program operator or LCA database	Year	GWP_{Total} Modules A1-A3	Unit
Steel	Steel sheet piles	EPD International (SE)	2023	409	kg CO_2-eq/t
Steel	Rebars	Ökobaudat (DE)	2022	474	kg CO_2-eq/t
Steel	Steel hollow sections	EPD International (SE)	2023	646	kg CO_2-eq/t
Concrete	C 25/30	Ökobaudat (DE)	2022	201	kg CO_2-eq/m³
Concrete	C 30/37	Ökobaudat (DE)	2022	248	kg CO_2-eq/m³

Table 1 – GWP_{Total} of the main materials – base scenario.

	Product	LCA database	Year	GWP_{Total} Modules A1-A3	Unit
Concrete	C 25/30	Ökobaudat (DE)	2023	165	kg CO_2-eq/m³
Concrete	C 30/37	Ökobaudat (DE)	2023	178	kg CO_2-eq/m³

Table 2 – GWP_{Total} of the main materials – Scenario #2 – Low carbon emissions concrete.

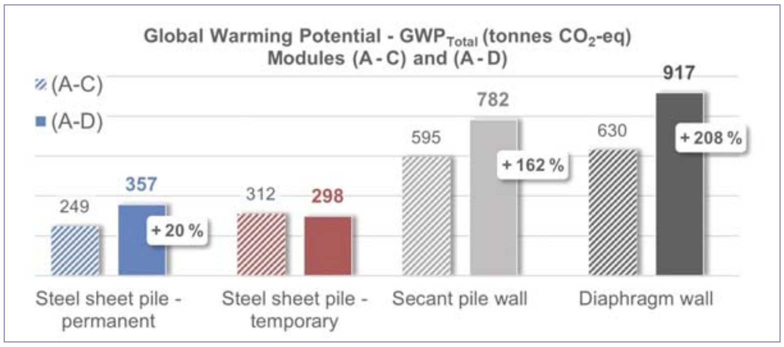

Figure 4 – Scenario #2: GWP$_{Total}$ of the solutions – Modules (A-C) and (A-D).

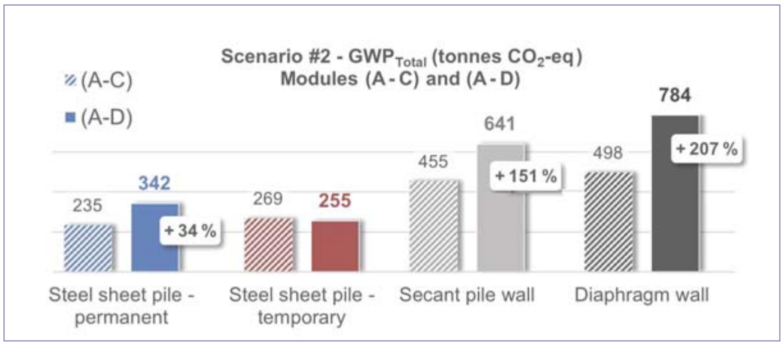

Figure 5 – Scenario #2: GWP$_{Total}$ of the solutions – Modules(A-C) and (A-D).

materials used in the LCA (Modules A1-A3) of the base scenario that have a major effect on the GWP. Following data is taken from *EPDs: EcoSheetPile™* Plus (2021) for the steel sheet piles and *XCarb®* Hollow sections (2023) for the steel tubes. For reinforcing bars and for the "standard" ready-mix concrete, we took the data from Ökobaudat (Ökobaudat, 2022), that represent the country specific situation. At the time of the study there was no EPD available based on EN 15804+A2 for low carbon emission rebars, and the peer-reviewers did not accept to mix data from two different versions of EN 15804. A sensitivity analysis with low carbon emissions concrete was also performed (see scenario #2).

Figure 4 shows the GWP$_{Total}$ of the base scenario. Considering the whole life cycle (Modules A - D), the solution with the temporary steel sheet pile wall and the RC wall has the lowest GWP, followed by the permanent steel sheet pile wall, for which the difference is + 20 %. The two other alternatives have a higher GWP, the difference being + 162 % for the secant pile wall, and + 208 % for the diaphragm wall.

There are two main contributors to the GWP that explain the significant difference in GWP of the secant pile wall and diaphragm wall compared to the sheet pile solutions: the quantities of concrete and the quantities of steel rebars inside the concrete structures.

Note that the transport of products manufactured in Europe has a small contribution to the GWP of a project (i.e. usually less than 10 % of the GWP of a steel product) but it is worth including it in all the LCAs.

Sensitivity analysis – low carbon emissions concrete – scenario #2

For certain applications, cement with GGBS (Ground Granulated Blast-furnace Slag) from the Blast Furnace production route can significantly reduce the environmental impact of concrete. However, the quantities of cements with GGBS are currently limited and will further shrink with the future switch from Blast Furnace steel to alternative less emissions intensive steel production.

The standard concrete was replaced with low carbon emissions concrete datasets from Ökobaudat (see Table 2). Compared to standard concrete, it has a lower GWP$_{Total}$ of around - 30 %, mainly due to the use of CEM II and CEM III cements.

Figure 5 shows the GWP$_{Total}$ of the alternative scenario #2. Low carbon emissions concrete has also a significant impact on the temporary sheet pile wall solution due to the permanent RC wall, but it has only a minor effect on the permanent steel sheet pile wall solution. The conclusions are almost the same as for the base scenario.

Conclusions

The case study focuses on the cost and on the environmental impact of several alternatives to build a two-level underground car park (UCP) below a building in the region of Berlin, Germany. Four alternatives for the retaining walls were designed by a German design office, and a comparative Life Cycle Assessment (LCA) was conducted by ArcelorMittal's experts.

The findings of the cost analysis are that a permanent steel sheet pile wall is more cost-effective than a secant pile wall (difference of 18 %) and a diaphragm wall (difference of 24 %). However, a combination of a temporary steel sheet pile wall with a permanent reinforced concrete (RC) wall inside the temporary excavation is the cheapest solution.

The LCA was peer-reviewed by a panel of independent experts. It focuses on the environmental indicator Global Warming Potential (carbon footprint) and is based mostly on product specific EPDs according to EN 15804+A2. The base scenario of the LCA shows that the solution with the temporary steel sheet pile wall and the RC wall has the lowest carbon footprint, the difference being approximately 20 % compared to the permanent steel sheet pile wall, 162 % compared to the secant pile wall, and 208 % to the diaphragm wall. A sensitivity analysis showed that using low carbon emissions concrete reduces only slightly the gap between the alternatives.

This case study is based on local design conditions, as well as a prevalent price structure representative of the year 2023. The results cannot be simply transposed to other time periods or regions, and the best option is to perform an LCA for each project.

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REUSE - UPCYCLING OLD FOUNDATION TO FIT FOR MODERN PURPOSE

REUSING EXISTING FOUNDATIONS – A SUSTAINABLE APPROACH

Introduction

Across the world, countless buildings no longer meet modern requirements, whether for lay-out, floor load capacity, thermal insulation, or climate control systems. Of those that are not demolished already, some are still in use, while others are simply abandoned, taking up valuable space. These structures, once serving as apartments, warehouses, offices, shipyards, or community centers, now seem destined for future demolition.

However, demolition significantly contributes to construction waste, accounting for over 90% of the industry's total waste. While some materials from demolished buildings can be salvaged and repurposed, a large portion ends up in landfills. The demolition of existing foundations to make room for a new one further exacerbates the problem, given the associated demand for raw materials, transportation, and energy consumption, generating a significant carbon footprint.
In cases where the existing foundation does not fully meet the new building's requirements, a hybrid approach—combining old and new foundation elements—can provide a viable solution. Obviously, reusing foundations presents challenges, but the environmental and economic benefits make it a worthwhile endeavor in sustainable construction.

What can be wrong with an existing foundation?

The primary reason for demolishing an old building is rarely structural failure or material degradation, but rather its inability to meet modern functional and regulatory requirements, marking the end of its economic lifespan. Even in cases of severe damage, such as fire, the foundation often remains intact and structurally sound.

It is therefore important to distinguish between a building's economic and technical lifetime. The technical lifetime refers to how long a structure or foundation can remain functional based on its original design and material properties. The economic lifetime, on the other hand, is determined by the building's ability to serve its intended purpose within evolving societal and regulatory demands. Consequently, economic obsolescence usually occurs well before the end of the technical lifetime.

When a building reaches the end of its economic lifecycle, its foundation is often still structurally sound. This means that in many cases foundations can be reused, possibly in combination with new foundation elements. Only when the material integrity of foundation piles is compromised—such as through significant degradation, corrosion, or other forms of deterioration—does the foundation reach the end of its technical lifetime. Other potential limitations include excessive settlement caused by overloading, additional negative skin friction, or a reduction in soil resistance due to liquefaction. However, when these issues are not present, reusing existing foundations can be a sustainable and cost-effective alternative to complete replacement.

Figure 1 – The Royal Palace on Dam Square in the heart of Amsterdam was originally built on 13,659 timber piles. Over time, its foundation underwent significant restoration to address uneven settlements. During an extensive renovation in 1945, additional piles were installed to stabilize the structure. As a result, the palace now stands on a total of 13,681 piles, effectively extending its technical lifetime.

Proven quality

The key question when considering the incorporation of the existing foundation in a new design is whether it can still support the intended building load. To answer this, it is useful to reflect on the foundation's performance while supporting the previous structure.

Did we ever question the foundation's quality, bearing capacity, or longevity while the original building was in use? Were there any indications that the foundation was underperforming or nearing failure? As engineers, we generally design foundations to be robust and durable, ensuring they provide long-term structural stability.

Many buildings have remained stable and functional for decades due to well-designed and adequately constructed foundations. Only when visible signs of deterioration—such as cracks, differential settlements, or structural distress—begin to emerge do we typically reassess the foundation's condition. Without such warning signs, there is often no technical reason to assume that an existing foundation is unfit for reuse.

SUMMARY

With increasing emphasis on sustainability, the reuse of existing foundations presents a viable alternative to a completely new foundation whenever a new building is constructed at the site. After all, the economic lifetime of buildings is often shorter than the technical lifetime, leaving structurally sound foundations underutilized. However, reusing foundations presents challenges, primarily related to uncertainties in their bearing capacity and remaining service life.

The paper advocates for a shift in the design process: instead of assessing whether an existing foundation meets a predetermined structural layout, designers should first evaluate the foundation's potential and then tailor the superstructure accordingly. By aligning the new with the existing foundation, greater reuse opportunities emerge, ultimately promoting a circular economy in the construction industry.

Foundation Health Assessment

Allnamics has conducted over 1,000 foundation investigations in Amsterdam's historic city center, where many buildings—some nearly 400 years old—were constructed on timber piles. Until recently, foundation health, that is the extent to which a foundation remains fit for its intended purpose, was not a primary concern for potential buyers. Instead, factors such as the building's appearance, architectural style, atmosphere, location, and historical significance were taken into account when deciding whether or not to purchase.

But when the foundation health does need to be assessed, e.g. as per local regulations as is now the case in Amsterdam, the question is what should be minimally known. To answer that question, it is only logical to make a comparison with newly constructed foundations. For those foundations many things are should be known, assuming the foundation was constructed as per the design:

- Soil investigation results
- Piling plan
- Pile specifications (type, length, cross section, installation method, etc.)
- Material specifications (i.e. steel grade, concrete mix)
- Toe level, penetration depth
- Design loads, factored and unfactored
- Calculated or predicted bearing capacity
- Installation records (i.e., blow counts, mortar pressure, boring speed, vibration speed)
- Issues during construction, if any, and how they are solved
- And preferably, drawings as-built versus as designed.

The same information should be required for an existing foundation, and this is what is attempted when examining an existing foundation. Archives are searched for installation logs, piling plans, etc., and using historical records foundation installation methods are reconstructed. However, to judge the suitability of the old foundation for reuse additional information is often demanded, mainly related to the actual bearing capacity of the foundation and its remaining lifetime.

Actual Bearing Capacity

The desire to know the actual bearing capacity of a foundation intended for reuse is to some extent surprising, since this requirement is not common for new foundations. Then engineers rely entirely on design methodologies, soil investigation data, and the application of appropriate safety factors. This is emphasized by the fact that in the Netherlands pile load testing is not a standard requirement for a new foundation: the design standards are trusted which eliminates the need for verifying the actual bearing capacity. For existing foundations, on the other hand, the lack of load test data often leads to the conclusion that its capacity cannot be determined. This raises the question: why is it considered essential to determine the actual bearing capacity of an existing pile when the maximum allowable design load can be calculated for a new foundation. Does the age of the pile —whether 30 years, 30 months, or even 30 days— make a fundamental difference? Obviously in cases where the dimensions are unknown or where significant uncertainties exist regarding its original design and installation parameters, determining the bearing capacity through testing may be preferable to relying solely on assumptions about the pile's properties. But available load test data should not be a mandatory requirement when assessing an existing foundation.

The issue of the remaining lifetime of an existing foundation is completely logical. When construc-

Figure 2 – Pile load tests, like the StatRapid test, can help to eliminate uncertainties in pile performance.

Figure 3 – Change of function causes different, not necessarily higher, loads on the foundations. Investigating the existing foundation should prove that the foundation can resist change in loads.

ting a new building on an existing foundation, it is crucial to ensure that the foundation's technical lifespan remains sufficient. This is the case when it exceeds the economic lifespan of the new superstructure and not necessarily the technical lifetime of that new structure. A foundation remains in use only as long as the superstructure remains economically viable. Once that reaches the end of its economic life, it is likely to be replaced, regardless of the foundation's condition. And the nearly 400-year durability of timber foundations in historic Amsterdam is just one example of a foundation with a technical lifespan that far exceeds the lifespan of the structures it supports.

A complicating factor in all this is that designs are based on a 'design period'. A design period—often set at 50 years—does not necessarily align with either the economic or technical lifetime of a structure. Instead, it primarily influences the applied design loads. In a probabilistic design approach, the likelihood of extreme events—such as a 1-in-1000-year storm or earthquake—occurring during a 50-year design period is greater than in a shorter timeframe, such as 5 or 10 years. However, the design period assigned to the superstructure does not directly determine the actual lifespan of the foundation or its ability to be reused.

Factors and Codes: The Dutch Alpha-p and Its Impact on Existing Foundations

In 2017, Dutch foundation design codes underwent a significant change by reducing the pile toe resistance design factor (Alpha-p) by 30%. Before this change, seven end-bearing piles could support a given load, but from then on, ten piles were required for the same capacity. This adjustment had a substantial impact on existing foundations, as any recalculations based on the updated codes indicated insufficient capacity, making reuse impossible, even when the design loads remained the same and when the existing foundation had shown no signs of failure, excessive settlement, or performance issues. Consequently, the inability to reuse foundations was not based on actual structural concerns but purely due to regulatory changes.

To mitigate this issue, a modification to the code now allows the capacity of existing piles to be calculated using the old Alpha-p values, provided the new design load additional load does not exceed the new additional design load by more than 15%. However, if this threshold is exceeded, the foundation must be reassessed using the reduced toe resistance factors. As a result, most existing foundations cannot be reused for significantly higher loads without supplemental piling, leading to hybrid solutions with new foundation elements supplementing the existing foundation.

However, this modification seems to ignore the logic behind design factors. The design factors are rooted in safety philosophy. Design codes incorporate partial safety factors to address various uncertainties affecting bearing capacity, including variations in soil strength and the impact of construction practices on the final foundation performance. Building inspectors and structural engineers often assume that the full design safety margin must remain intact even after pile installation. However, a portion of this safety margin is deliberately allocated to account for construction-related uncertainties. As a result, when assessing an existing foundation, a lower safety factor should be deemed acceptable, as many uncertainties associated with the initial construction have already been resolved.

Optimizing the Design Process for Reusing Foundations

The approach to reuse foundations has often focused on the inspection and evaluation of the existing foundation. But one of the key challenges for reusing foundations lies in the traditional design process. Typically, an architectural design is developed first, followed by the structural design, and finally, the foundation is designed to support these structures. In most cases, the existing foundation layout will not align with the footprint and structural design of the new superstructure. So instead of forcing an existing foundation to fit within a predetermined design, the process should be reversed: the assessment of the existing foundation should dictate the design possibilities.

Figure 4 – When hidden safety can be mobilized, the existing piles can be additionally loaded. New methodologies, design methods, and resistance factors can result in different outcomes for the bearing capacity of an existing foundation compared to the original.

By shifting the design approach to begin with an evaluation of the foundation assets, architects and structural engineers can develop a plan that integrates and optimizes the potential of the existing foundation, if necessary supplemented by additional foundation elements (hybrid foundation). This strategy significantly increases the feasibility of reuse, resulting in cost savings, reduced material consumption, and a lower carbon footprint while maintaining structural integrity.

Conclusions: Reframing the Approach to Foundation Reuse

A foundation does not need to last forever—it only needs to serve the economic lifetime of the superstructure it supports. However, the technical lifetime of a foundation is often significantly longer than that of the building above it, presenting opportunities for reuse, possibly even more than once.

There is no such thing as a foundation's lifetime. When reusing existing foundations, distinguishing between technical and economic lifetime of the superstructure has to be made and understood. Additionally, this should not be confused with the design period, which primarily influences applied design loads rather than the actual longevity of the foundation.

If foundation reuse is a viable option, all available information should be collected and assessed, recognizing that some level of uncertainty is inevitable—just as with newly constructed foundations. Testing firms can conduct thorough investigations, but a balance must be struck between the cost of data collection, the likelihood of reuse, and the potential savings in material and construction costs.

The same level of information required for designing new foundations should also be applied when evaluating existing ones. Both new and existing foundation elements are not monitored for remaining lifetime, decay, or performance after construction.

The decision to reuse a foundation should be made before the design process begins. The assets already in place must be assessed in advance to determine their feasibility. A well-informed investigation will highlight both the opportunities and limitations of reusing an existing foundation. If this assessment is integrated into the early stages of design, architects and structural engineers can align their plans accordingly. This increases the likelihood of successful reuse—whether entirely or as part of a hybrid foundation—leading to reduced costs, shorter construction timelines, minimized use of raw materials, and ultimately, a lower carbon footprint. ●

Davy Maes
General Manager at Fundex

FUNDEX, A FAMILY BUSINESS SINCE 1953

Funderingstechnieken Verstraeten BV (Fundex) was founded in 1953 and has been an expert in the field of international foundation projects for many years. You can only achieve that status if you continuously innovate and Fundex is unique in that too.

The inventors of the Fundex pile® and the Tubex pile®

FUNDEX® and TUBEX® are two brands of which the Fundex group is 100% owner and they therefore symbolize the innovative power of the company. Davy Maes: "A number of foundation companies around the world are allowed to make Fundex and Tubex piles, as long as the correct drilling points are used and purchased through us. This results in a certain level of quality, necessary to give these pile types the name Fundex or Tubex. We continue to improve our products and are seen in the market as the specialist in the field of vibration-free (deep) foundations for many structures, but also certainly in high-rise buildings."

On the way to a cleaner construction site

The fully electric Fundex CD20E drill was recently put into use. The CD20E is a compact zero-emission foundation machine that produces less noise and fewer emissions. In addition, the CD20E is flexible and versatile and the machine is an excellent alternative in areas with strict environmental standards. Furthermore, a first successful test was carried out with the Fundex F4800E in Leiden. The foundation work was carried out using a zero-emission drilling rig. The F4800E was equipped with a vibration-free drill so that the immediate neighbors were taken into account. "Zero-emission foundation machines will play a decisive role in realizing construction projects," says Davy Maes, general manager at Fundex, the group's specialist in soil-displacing, vibration-free techniques.

At our locations in Oostburg (Zeeland) and Zeebrugge (Belgium) we are also investing in sustainability through the use of solar panels, charging stations and making the vehicle fleet more sustainable.

Reuse through smart engineering

We are happy to assist our clients with innovative solutions. We enjoy collaborating with our customers. Fundex's engineers have successfully demonstrated multiple times that "smart engineering" can be the deciding factor in complex projects. For example, in the Blaak 333 project in Rotterdam, a significant portion of the existing basement and foundation was reused, resulting in substantial savings on project costs and materials.

Davy Maes: "We have been working on making all our light and heavy foundation machines more sustainable for some time now and in the last few years we have seen that we are actually receiving orders for this. Collaboration with the customer, but also the suppliers of batteries, software and specific knowledge of electrification and connections is a must. Less noise causes less nuisance in an inner-city area and results in a completely different experience of construction work in the living environment. We are on the right path in the foundation industry and will certainly be ready to meet the 2030, 2040 and 2050 ESG guidelines! On to a cleaner construction site!"

New! Fundex Services

Fundex Services is part of the Fundex Group. All machines and equipment are housed in this section. Fundex Services also arranges the entire logistics. This of course happens for Fundex's own projects at home and abroad, but it also regularly happens that machines are rented. This can be done with or without a foundation team. Visit our website www.fundex.nl/services. ●

Gerald Verbeek
Allnamics USA, Chair of the Conference on Foundation Decarbonization and Reuse

FOUNDATION DECARBONIZATION AND REUSE – USEFUL SOFTWARE

Next year the International Conference on Foundation Decarbonization and Reuse, which will be organized in March 2026, will feature a new event: a workshop on software tools to help the user to minimize the carbon footprint of foundations and to assess the options to reuse existing foundations. This article can obviously not predict the workshop's outcome, but it can highlight some key requirements to make software a useful tool in that endeavor.

To assist with decarbonization, the key requirement is straightforward: the software should be able to define the foundation with the smallest carbon footprint.. For reuse, however, defining the requirements is not as simple. Obviously, it should recalculate the bearing capacity of the foundation as designed. But should it also generate options to supplement those existing foundations if that bearing capacity is inadequate? Or should it merely detail user-defined options? These questions will be examined in this article.

Carbon Footprint Calculations for Foundations – the DFI/EFFC Carbon Calculator

These days there are dozens of carbon footprint calculators available online. It seems that government agencies, non-profits, trade groups and societies all feel the need to publish their own calculator, each with different levels of detail and focus depending on the entity behind it. Since the focus in this case is deep foundations (or foundations in general, which then also includes ground improvement), it makes only sense that the most appropriate calculator is one developed specifically for foundations. The tool that then comes to mind is the EFFC/DFI Carbon Calculator, which was developed collaboratively by the European Federation of Foundation Contractors (EFFC) and the Deep Foundations Institute (DFI).

When it was developed three main purposes were identified:
– Benchmarking: the tool should be able to compare different designs.
– Assessing Techniques: the tool should provide insight into how different foundation types affect a project's carbon footprint.
– Tracking Performance: the tool should be able to measure a project's performance against initial expectations.

To achieve these goals the Carbon Calculator includes some very important features:
– It utilizes standardized data for reliable benchmarking.
– It provides default values when live data is unavailable.
– It allows a choice of various ground engineering techniques, materials, and transport modes.
– It enables users to model different approaches to the same project.

With these features it allows the user to assess the carbon footprint of one or more foundation designs for a specific project (to evaluate alternatives on their potential emissions) and then to update this value during the construction phase by using actual data, incl. actual quantities.

The calculator also covers all types of greenhouse gas emissions, in other words Scope 1, Scope 2 and Scope 3 emissions. These different types can be described as follows:
– Scope 1 covers the direct emissions from energy sources that a company owns or controls (e.g., burning fuel in company vehicles).
– Scope 2 covers the indirect emissions from purchased energy (e.g., emissions associated with the generation of the electricity used in company buildings).
– Scope 3 covers the indirect emissions from all activities that a company performs (including, but not limited to emissions from employee travel, purchased materials and waste disposal)

However, in order to provide a complete understanding of the emissions associated with a project it is important that a so-called cradle-to-grave analysis is performed. Such an analysis considers the resources used and the environmental impact at each stage of a product's life cycle, as illustrated in figure 3.

The Carbon Calculator only covers the so-called cradle-to-gate perimeter, which contains only the material acquisition & pre-processing phase and the production phase. To some extent this limitation makes perfect sense. As clearly stated in the Carbon Calculator user's manual: the distribution and storage phase has no significance for foundations activities because the foundations are produced on site, and since a foundation is a passive product, it does not consume energy during the use phase[1]. However, the end-of-life phase should be considered. While it is true that the end-of-life of a foundation may happen a long time after its construction, the time to decide what to do with an existing foundation is likely to come a lot sooner. This is because the economic lifetime of the superstructure, the time that a superstructure is fit for purpose, is more than likely a lot shorter that the lifetime of a foundation. Therefore, the aspect of future use of a foundation should be taken into account when assessing the total greenhouse gas emissions associated with a foundation construction project, even if the conclusion is that

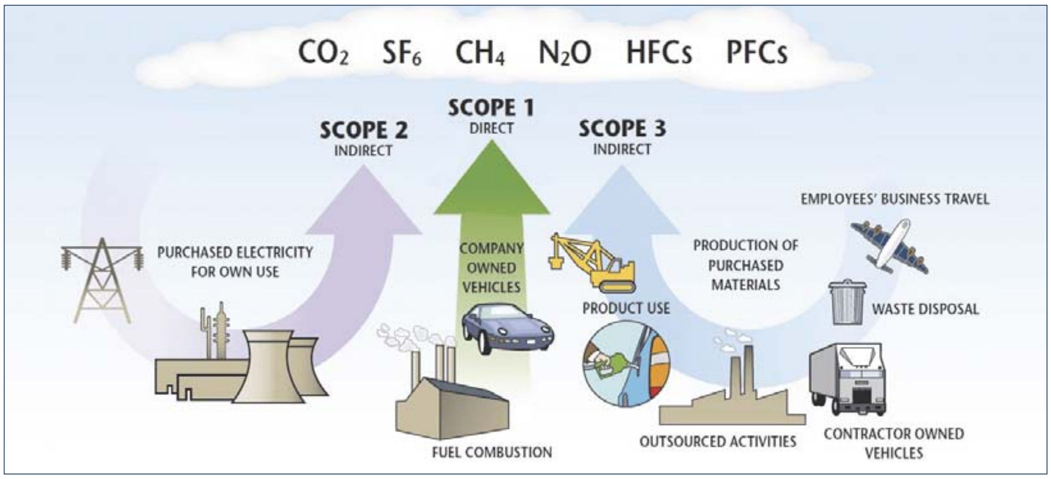

Figure 1 – Scope 1, Scope 2 and Scope 3 emissions.

it can be ignored for a particular project (as the designers of the EFFC/DFI Carbon Calculator assume to be the case in general as stated in the user's manual).

Capacity Calculations for Foundations

The software to calculate the capacity of a foundation seems at first sight rather straightforward. There are numerous software packages that can calculate (in accordance with the applicable standards) the bearing capacity and settlement based on soil properties and foundation geometry, with the ability to input multiple load cases (dead, live, wind) and combine them for comprehensive analysis. Some software can even suggest reinforcement details and optimize foundation dimensions to meet design requirements, although not necessarily to optimize the foundation's carbon footprint. But there is a fundamental issue associated with existing foundations. These days more and more design standards are based on factored design, which tries to cover various uncertainties through resistance factors. This resistance factor is a numerical value less than 1 that is applied to the nominal strength of a structural member to account for uncertainties in material properties, fabrication/construction quality, and other factors that could potentially reduce its actual resistance to loads.

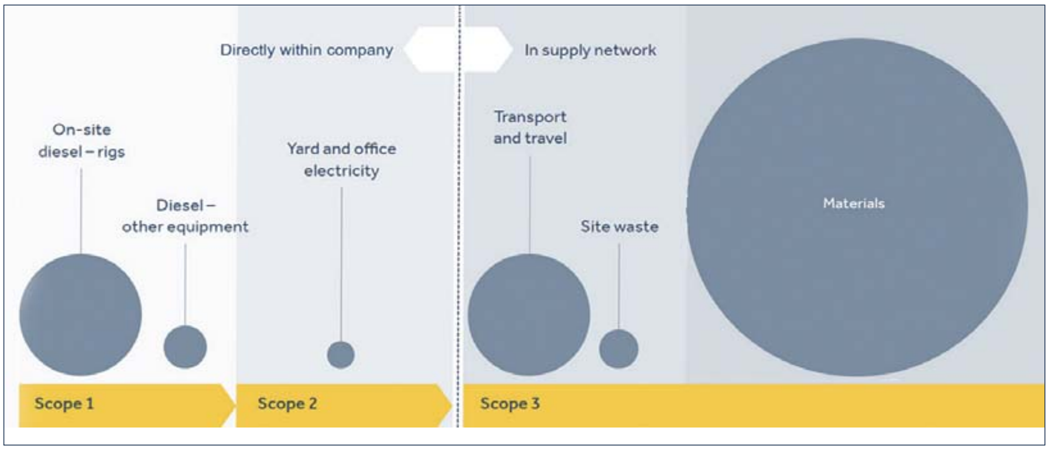

Figure 2 – CPTs also conducted on the water close to the existing pile foundations.

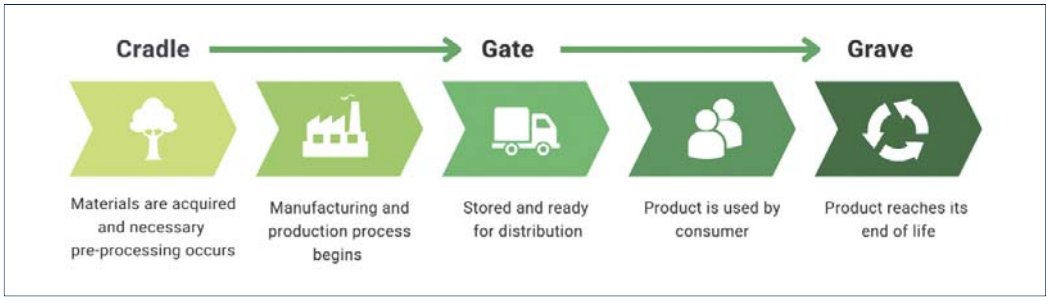

Figure 3 – CPTs also conducted on the water close to the existing pile foundations.

So the question arises, can the same methodology that is used for a new foundation, where the uncertainty in fabrication or construction still exists, be applied to an existing foundation that during its lifetime has demonstrated its performance. This question is at the heart of the slogan used made by the Pile Driving Contractors Association (PDCA) in the United States: a driven pile is a tested pile. After all, the installation of a driven pile provides information on the bearing capacity through the blow count, and that in the eyes of PDCA should justify a higher resistance factor. Obviously the same argument can be made for a pile that is about to be reused, but if that argument is accepted, how is the resistance factor adjusted? For the resistance factor covers a variety of uncertainties, one of which is that related to the fabrication or construction.

Instead of increasing the resistance factor, some would make the argument that a lower resistance factor is much more appropriate for a foundation to be reused. The basis for that argument is really the assumption that a foundation ages: that over time it deteriorates and therefore does not have the capacity it had when it was first installed. While that may be true for certain types of foundations (e.g., steel foundations that are installed in corrosive soils and thus subject to corrosion), it cannot be assumed for all types of foundations. In The Netherlands the durability of timber pile foundations is well known, but an interesting illustration of that durability and the potential for foundation reuse comes from Italy. Over the years methods employed to extend the life of timber piling have evolved. Ancient civilizations used various animal, vegetable, and mineral oils to preserve timber. In Roman times, timbers were smeared with cedar oils and pitch, then charred to extend their service life. Using this approach, Roman roads built on treated piles are still in good condition 1,900 years later. And a building built in Venice, Italy in 900 A.D. was rebuilt around 1900 on the same 1000 year old piles.

Apart from the deterioration issue described in the paragraph above, there is another aspect that needs to be highlighted. The common perception is that a new foundation is flawless, or at least with minimal flaws that can easily be ignored, and that the condition of that new foundation can be confirmed with some basic integrity and load tests. But what if we were to apply the same type of testing to an existing foundation that is applied to a new foundation, should we than not be able to interpret the results in the same way, irrespective of whether the foundation is new or existing? Because if we trust those test results for a new foundation, we should trust them as well when applied on an existing foundation.

The preceding paragraph only raised questions and did not provide any definite answers. And the list of questions becomes even longer when an existing foundation needs to be supplemented by additional foundation elements to meet the requirements for the new superstructure. Should the design software be able suggest alternate approaches to optimize the dimensions of those additional foundation elements (and preferably also the carbon footprint)? Could Artificial Intelligence be applied to define those alternate approaches, or is that still a bridge too far (or better "a foundation too far") and does this still require input from design engineers (with the possibility that this engineering judgement does not generate the optimum solution)?

Conclusion

When it comes to software tools that can be used for foundation decarbonization and reuse, it is easy to state what the requirements are, but not always so easy to get those requirements implemented. While for the calculation of a foundation's carbon footprint the DFI/EFFC Carbon Calculator provides a functional tool, a tool that adequately deals with the reuse of existing foundations may have yet to be developed. Or maybe it is already there, unbeknownst to the geotechnical engineering community at large. The workshop associated with the next edition of the International Conference on Foundation Decarbonization and Reuse may shed some light and this article may just provide the impetus to attend the conference and the workshop. ●

1 It should be noted that in case of geothermal foundations the energy generation during the use phase should be taken into account.


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TOWARDS SUSTAINABLE PORT INFRASTRUCTURE BY PERFORMING FULL-SCALE PILE LOAD TESTS

Introduction

The Port of Rotterdam stands as Europe's largest seaport, stretching over 40 kilometers and handling an impressive annual throughput of 470 million tonnes of goods. It welcomes approximately 30,000 seagoing vessels and 120,000 inland navigation vessels each year. One of the core responsibilities of the Port of Rotterdam Authority is to develop, manage, and operate the port sustainably. In collaboration with partners, the port authority aims to reduce CO_2 emissions from port activities by 50% by 2030, with the ambitious goal of achieving carbon neutrality by 2050. A typical carbon footprint of a deep-sea quay wall in Rotterdam is illustrated in figure 1, where foundation piles (13%), anchors (9%), and the combi wall (26%) are identified as major contributors to the overall emissions.

However, current pile foundation design methods rely heavily on empirical factors and limiting resistances derived from experience with weaker soils. This introduces uncertainties regarding their applicability to the stronger soils and higher load demands encountered in the Maasvlakte port district. Furthermore, many technical studies that detail field tests on piles fail to highlight the associated economic and environmental advantages gained by optimizing pile design methods. Providing clear, quantifiable insights into the added value of such optimizations is essential to persuading stakeholders within the industry to adopt full-scale field testing.

This study aims to demonstrate the technical, economic, and environmental benefits of four full-scale field tests conducted at the Port of Rotterdam. These include: (1) laterally loaded steel tubular flexible dolphins in the Beneluxhaven port basin; (2) axial capacity testing of precast driven concrete foundation piles in the Waalhaven port basin; (3) axial capacity assessment of steel MV pile anchors in the Mississippihaven port basin; and (4) axial bearing capacity testing of three types of foundation piles in the Amaliahaven port basin. The findings from these case studies reveal that, while full-scale field tests involve significant initial costs, they play a crucial role in optimizing construction expenses and reducing the carbon footprint of port infrastructure.

Case 1: Beneluxhaven: laterally loaded flexible dolphins

MOTIVATION

This full-scale test investigated the performance of eight flexible dolphins subjected to failure loads. These steel tubular piles, primarily designed to absorb the energy of berthing vessels through lateral deflection, lacked comprehensive design guidelines for sand-filled tubular configurations. The project aimed to address key aspects, including: (i) Variations in soil behaviour under static versus low-dynamic loading, (ii) the performance of dolphins situated on slopes, (iii) effects of local buckling near wall-thickness transitions and in soil-filled piles, and (iv) Propagation of vibrations in sandy soils during pile installation.

TEST SETUP

The testing program featured the following primary parameters: tube diameter of 914 mm, a pile length of 21.5 m, and soil conditions consisting of moderately dense sand with traces of silt. The embedded pile length was 11 m. To capture data, test piles were instrumented with fibre optic strain sensors and shape accel array inclinometers. Additionally, three piezometers were installed, and pile displacements were monitored using a total station (as described in Roubos et al., 2014; Van der Meer et al., 2015). Deformations during low-dynamic tests were recorded and analysed with a high-speed camera.

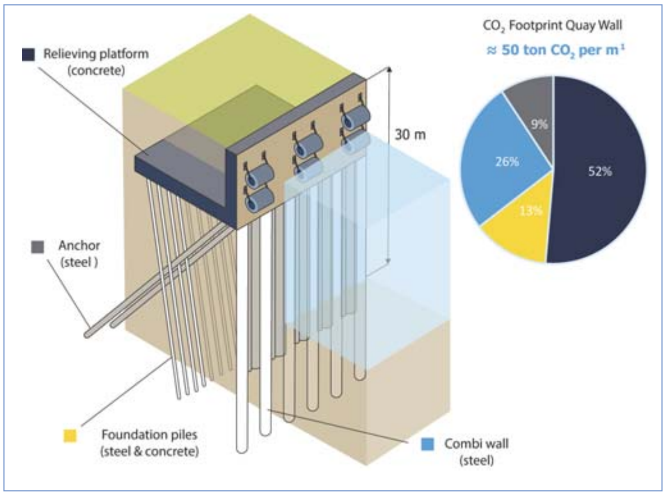

Figure 1 – Typical carbon footprint for a deep-sea quay wall.

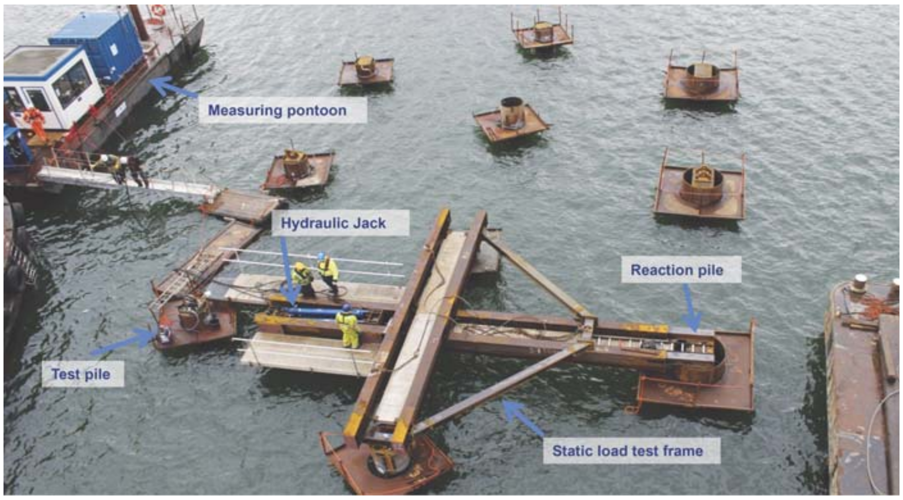

Figure 2 – Overview test setup pile load test Beneluxhaven.

SUMMARY

The Port of Rotterdam Authority aims to develop sustainable and future-proof port infrastructure. They aim to reduce CO_2 emissions of new port infrastructure by 50% before 2030, with the ultimate goal of achieving a net-zero carbon footprint by 2050. A critical factor in meeting these ambitious targets lies in the efficient use of both new and existing materials. However, accurately determining the capacity of port infrastructure poses a challenge, as these structures have demonstrated excellent performance without any observed failures. To better understand the reserve capacity of such infrastructure, full-scale field tests were conducted on flexible dolphins, foundation piles, and anchor piles. This paper highlights the technical, commercial, and environmental outcomes of recent pile load tests carried out in the Port of Rotterdam. The findings reveal significant reductions in CO_2 emissions related to the manufacturing and installation of foundations, alongside minimized installation risks. Additionally, achieving higher reliability with reduced material usage has been made possible. Despite the expenses associated with full-scale testing, this study underscores the importance of verifying the actual capacity of foundation piles to enhance the sustainability of port infrastructure.

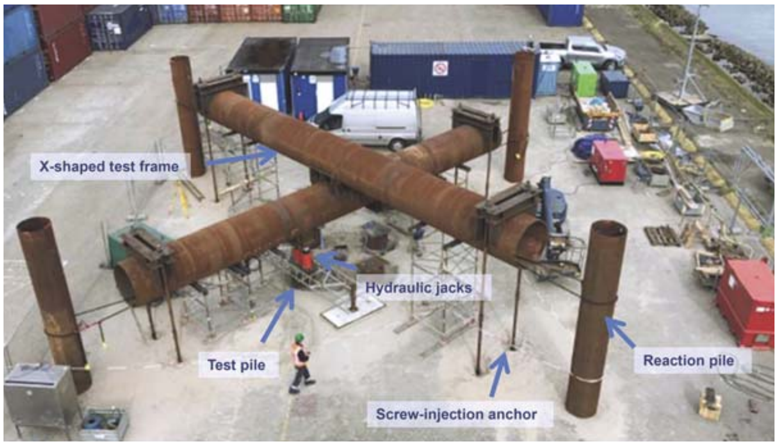

Figure 3 – Overview of test setup plie load test Waalhaven.

Table 1 – Technical, economic and environmental value Beneluxhaven test.

Technical	- New design guidelines for local buckling of sand-filled tubes. - New recommendations for dolphins installed in slopes. - Update of existing method for predicting the propagation of pile-installation induced vibrations.
Economic	- Project 1[a]: direct savings of €4.5m (15% of total costs). - Project 2[b]: direct savings of €0.8m (5% of total costs). - Project 3[c]: direct savings of €1m (30% of total costs). - For future dolphin projects savings up to 10-20% can be expected, approximately €5m per year. - The amount of site investigation around a single pile can be reduced by 75%. For a typical berth this results in savings of about €0.2m. - Optimisation of project planning: 2-3 months shorter.
Environmental	- Project 1[a]: direct CO_2 savings of 200 ton. - Project 2[b]: direct CO_2 savings of 50 ton. - Project 3[c]: no information available

[a] Realisation 50 flexible dolphins for inland barges and VLCC tankers.
[b] Realisation new jetty for Aframax tankers.
[c] UXO site investigation Botlek port basin.

Static and low-dynamic tests were conducted during the study. Static tests were performed using two hydraulic jacks with a stroke of 2.5 m and push/pull capacities of 2 x 400 kN and 2 x 1000 kN. These jacks were mounted on a custom frame supported by three reaction piles while applying loads to the test pile (figure 2). Low-dynamic tests employed a system of cables, pulleys, and a crane positioned on a floating pontoon (Roubos et al., 2014). The total cost of this extensive test program was approximately €0.75 million.

RESULTS

The Beneluxhaven tests provided groundbreaking insights into the performance of flexible dolphins. Table 1 summarizes the technical, economic, and environmental findings. Key outcomes indicated that optimizing designs by selecting smaller pile diameters, thicker walls, and reinforcing the area near the harbour bottom improves material efficiency and mitigates risks of local buckling. These design refinements support safer, cost-effective, and more sustainable solutions by reducing material usage. Additionally, the propagation of vibrations in the soil during pile installation was measured, offering crucial data to optimize site investigations. This is particularly important for minimizing risks associated with unexploded ordnances (UXOs) in the area.

Case 2 Waalhaven: axial bearing capacity of precast concrete piles

MOTIVATION

In 2017, the Dutch national standardization institute (NEN) updated the Dutch National Annex of Eurocode 7 (NEN-EN 1997-1, 2017), recommending a 30% reduction in pile base factors used or designing axial static resistance. These lower factors significantly impact the dimensions of pile foundations and increase associated installation risks, as longer piles would be required. To address this challenge, four precast concrete piles were tested as part of a quay wall project in Waalhaven. The study investigated two key aspects: (1) the effect of "pile aging" on pile capacity and (α_t) the applicability of the current constant pile factors that relate Cone Penetration Test (CPT) resistance to pile base and shaft capacity, as specified in the Dutch National Annex.

TEST SETUP

Four precast driven concrete foundation piles, each measuring 450 mm x 450 mm with a length of 36 m, were subjected to geotechnical failure during testing. The piles were instrumented with two types of optical fibers—Fibre Bragg Grating (FBG) and Brillouin scattering (BOFDA)—along their entire length. These sensors enabled detailed measurements of shaft friction and base resistance. Because the optical fibers were installed

Table 2 – Technical, economic and environmental value Waalhaven test.

Value	*Example*
Technical	Update existing pile factors of NEN-EN 1997-1 for the Waalhaven quay-wall project (pile base factor α_p and pile shaft factor α_s).
Economic	Project 1a: direct savings of €0.55m (25% of the costs per foundation pile, and 5% of the total project costs).
Environmental	Project 1[a]: 25% less foundation piles.

[a] Realisation 450m quay wall in the Waalhaven port basin.

during the casting process, unique insights into residual stresses within the piles were obtained after hardening and installation. The test utilized an X-shaped steel test frame, built with two Ø1420 mm steel tubes and capable of handling a maximum load of 9,000 kN. The frame was secured with eight 45-meter-long screw injection anchors, ensuring stability during testing (Matic et al., 2019). The total cost of the test program amounted to approximately €0.45 million.

RESULTS

The test revealed that considerable residual loads developed during pile installation, significantly influencing the distribution of axial loads within the piles. When these residual loads were disregarded, the base reduction factors (α_p) for resistance aligned closely with those recommended by the Dutch National Annex. However, accounting for residual loads allowed for an increase in base reduction factors by as much as 40%. Additionally, incorporating friction fatigue effects into shaft capacity predictions resulted in far more accurate assessments compared to current recommendations in the NEN design code (Gavin et al., 2021). The results further indicated that aging effects were more pronounced near the lower portion of the piles. Geotechnical failure of the precast driven piles occurred under an approximate load of 6,500 kN. Although the study provided valuable technical insights, the results are challenging to generalize for other quay wall projects, as the piles were driven approximately 1 meter into dense sand layers. Table 2 summarizes the technical, economic, and environmental contributions of this test.

Figure 4 – Overview of test setup pile load test Mississippihaven.

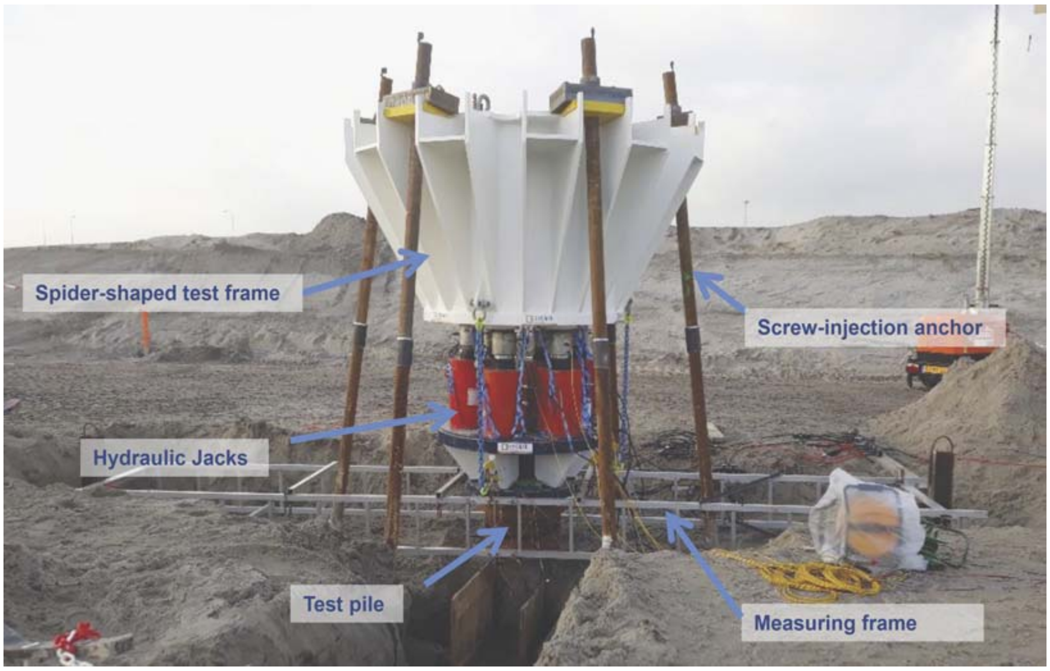

Figure 5 – Overview of test setup pile load test Amaliahaven.

Case 3 Mississippihaven: axially loaded MV pile anchors

MOTIVATION

MV pile anchors consist of an H-shaped steel beam driven into the ground, while grout is injected through two pipes into reservoirs at the pile tip. This grout layer enhances pile driveability and significantly increases shaft friction upon hardening. Given the potential variability in MV pile quality due to production processes, approximately 2% of MV anchors are typically tested. However, most prior tests were conducted on production anchors and not extended to geotechnical failure. As a result, the precise relationship between shear resistance and cone penetration resistance (α_t), as well as the potential upper limit for shaft friction, remains unclear (e.g., the current design method assumes a limiting value of 250 kPa).

Furthermore, as the soil-retaining height of deep-sea quay walls increases with vessel draft, the corresponding length of MV piles also rises, posing higher installation risks—particularly in dense sand layers with elevated cone penetration resistance (q_c) values. To address these challenges, the Port of Rotterdam Authority conducted a series of six full-scale tests on MV pile anchors, pushing them to geotechnical failure to better understand their actual capacity.

TEST SETUP

Each test pile was instrumented with fiber optic sensors along its full length to measure strain. Steps were also taken to debond the pile from the surrounding soil within the active wedge zone of the quay wall. The applied test loads were capped at 95% of the steel beam's yield strength, equivalent to approximately 10,750 kN. To facilitate the tests, a custom steel reaction frame was developed, which transferred axial tensile loads from the test pile to two reaction piles (Putteman et al., 2019). The center-to-center distance between the test pile and reaction piles was approximately 6.5 meters. A set of four hydraulic jacks was used to generate the tensile load.

RESULTS

The testing revealed a maximum measured shaft friction of approximately 600 kPa, suggesting no physical justification for limiting shaft friction to

Table 3 – Technical, economic and environmental value Mississippihaven test.

Value	*Example*
Technical	- Update existing CPT-based design method (shaft friction factor α_t and limiting value). - High correlation between installation parameters and bearing capacity. - New mobilisation curves for shaft friction.
Economic	- Project 1*: direct savings of €4.5m (capacity of existing MV anchors was 10% higher). - For future deep-sea quay walls savings of €1m per km seem possible.
Environmental	- Project 1*: 1 kton CO_2. - For future deep-sea quay walls savings of 0.5 kton CO_2 per km seem possible.

*Deepening 1.6 km deep-sea quay wall in Maasvlakte port basin. The costs and CO_2 reduction are based on installing additional screw-injection anchors.

Table 4 – Technical, economic and environmental value Amaliahaven test.

Value	*Example*
Technical	- Update existing CPT-based design method (pile base factor α_p, pile shaft factor α_s, and limiting value). - New design method to determine bearing capacity on the basis of the q_c-averaging technique was developed.
Economic	- Project 1[a]: direct savings of €11m (30% cost reduction per foundation pile; 3.3% of total project costs) - Project 2[b]: direct savings of €4.5m. - For future deep-sea quay walls savings of about €4m per km seem possible.
Environmental	- Project 1[a]: direct savings of 8 kton CO_2. - Project 2[b]: direct savings 3 kton CO_2. - For future deep-sea quay walls savings of about 3.3 kton CO_2 seem possible per km.

[a] Realisation of 3 km deep-sea quay wall in the Maasvlakte 2 port district.
[b] Deepening 1.6 km deep-sea quay wall in Maasvlakte 1 port basin.
The costs and CO_2 reduction are based on installing additional precast concrete piles.

Table 5 – Financial and environmental savings for all four cases

Case	*n*	*Costs*	*Realised savings*		*Future savings**	
	[-]	*[m€]*	*[m€]*	*[kton CO_2]*	*[m€]*	*[kton CO_2]*
1	8	0.75	6.10	0.25	6.00	0.30
2	4	0.45	0.55	0.75	n/a	n/a
3	6	0.75	4.50	1.00	3.00	1.50
4	11	2.50	15.50	11.00	12.50	10.00
Total	29	4.45	26.65	13.00	21.50	11.80

*Annual savings based on the realisation of 3km deep-sea quay wall, fifty flexible dolphins and two jetties per year.

250 kPa as outlined in the current design method. Moreover, a shaft resistance to cone penetration resistance ratio (α_t) of 1.2% was identified (Westerbeke, 2021), aligning with the design methodology in use for screw-injection anchors (CUR 166, 2012). A new mobilization curve for the shaft friction of MV piles was also developed, closely resembling curves for axially loaded screw-injection foundation piles. Furthermore, the study highlighted a strong correlation between pile installation data—such as energy per hammer blow and grout volume—and bearing capacity, offering promising directions for future research. These insights could pave the way for developing methods to verify the in-situ capacity of MV piles. As an immediate application of the results, the findings were instrumental in deepening an existing deep-sea quay wall by an additional two meters of nautical depth. Table 3 summarizes the technical, economic, and environmental contributions of this test.

Case 4 Amaliahaven: axial bearing capacity foundation piles

MOTIVATION

Building on insights gained from the Waalhaven test (Case 3), this study focused on evaluating the axial bearing capacity of foundation piles. Unlike the Waalhaven test setup, the test piles in Amaliahaven were installed deeper into the dense sand layer to achieve the following objectives: (i) enhance pile design by deriving project-specific pile class factors, and (ii) update the national pile class factors and assess whether limiting cone penetration resistance (q_c) values are necessary for estimating base and shaft resistance. To accomplish these goals, three different pile types were tested as part of a broader program involving a total of eleven piles. The tests included three driven precast concrete piles, four screw injection piles, and four driven cast-in-situ (vibro) piles. An overarching motivation for the Port of Rotterdam Authority was to optimize the design of a large-scale deep-sea quay-wall project that required the installation of 2,600 foundation piles.

TEST SETUP

Axial load testing was carried out using a spider-shaped reaction frame anchored by screw-injection anchors. The system had a maximum test capacity of 25,000 kN. Each pile was equipped with sensors to record strain along its entire length, while settlement at the pile head and pile installation data were also monitored. The loading system comprised six automatically controlled hydraulic jacks, each with a capacity of 5,000 kN. To ensure accurate load measurement, six calibrated load cells (dynamometers) were installed on top of each jack. The displacement of the pile head was measured relative to a stable reference frame. The total cost of the testing program was approximately €2.5 million.

RESULTS

The test results confirmed that residual stresses from pile installation play a critical role in determining pile class factors for displacement piles [10]. No evidence was found to support the necessity of limiting q_c values for any of the tested pile types. Additionally, the driven precast and in-situ cast concrete piles demonstrated higher axial bearing capacities compared to those predicted by the NEN-EN 1997-1 (2017) design method. However, segregation issues were observed in the driven cast-in-situ piles, complicating the distinction between base and shaft resistance in the dense sand layers. Despite this limitation, the shallower soil layers provided valuable insights into the response of shaft resistance, particularly regarding friction fatigue. In contrast, the screw injection foundation piles exhibited significant softening effects, leading to the development of new mobilization curves for these pile types. The Amaliahaven test also marked a significant milestone as the first set of results accepted into the Dutch national pile load test database. The findings from this study are summarized in Table 4, showcasing the technical, economic, and environmental value of the tests.

Conclusion

The technical findings from the case studies have provided several new insights into soil behaviour, including: (i) the distinctions between static and dynamic loading; (ii) the impact of soil aging on performance; (iii) the relationship between cone penetration resistance and bearing capacity; and (iv) the influence of pile driving-induced vibrations in sandy soils. Collectively, these studies demonstrate that current design methods, while safe, tend to be overly conservative.

Despite the considerable costs associated with conducting full-scale field tests, the results, summarized in Table 5, highlight substantial material savings and optimized design potential for port infrastructure. Furthermore, the insights gained from these tests contribute not only to improving material efficiency but also to mitigating installation risks. This underscores the critical value of full-scale testing as a strategy for advancing sustainable and cost-effective engineering solutions in port development.

In addition to delivering a solid return on investment, the project directly saved approximately 13 kton of CO_2 emissions, with an estimated ongoing annual reduction of 10 kton. To put this into perspective, 1 ton of CO_2 is roughly equivalent to 6,000 kilometres driven in a diesel car and has a monetary value of approximately €100. This translates into significant annual savings of around €1 million. The authors strongly advocate for not only publishing the technical findings of full-scale field tests but also highlighting their economic and environmental benefits. Doing so will enhance funding opportunities and support for future large-scale testing initiatives, which are essential to bridging the gap between theoretical models and practical applications.

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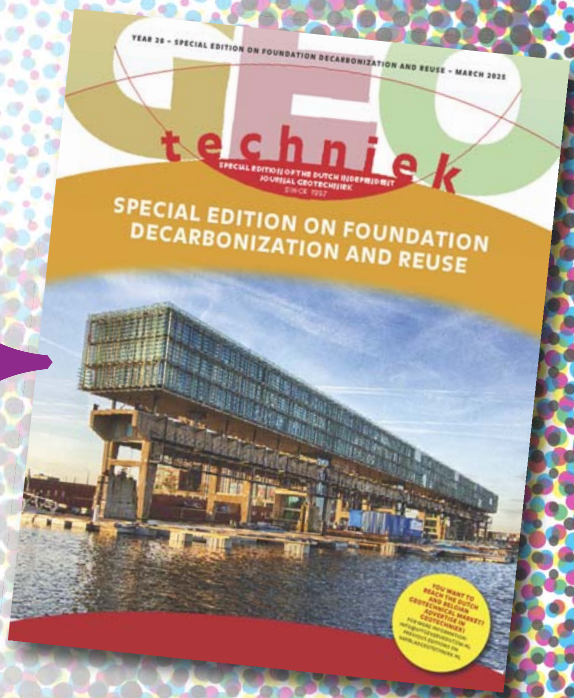

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