

YEAR 28 - SPECIAL 2ND ANNUAL CONFERENCE ON FOUNDATION DECARBONIZATION AND REUSE - MAY 2024

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SPECIAL 2ND ANNUAL CONFERENCE ON FOUNDATION DECARBONIZATION AND REUSE



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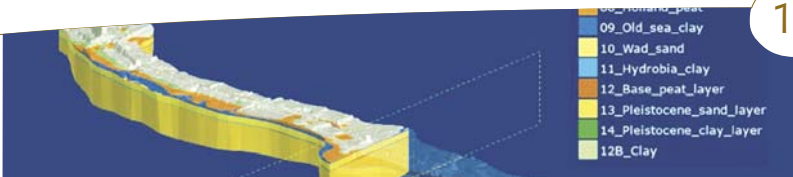
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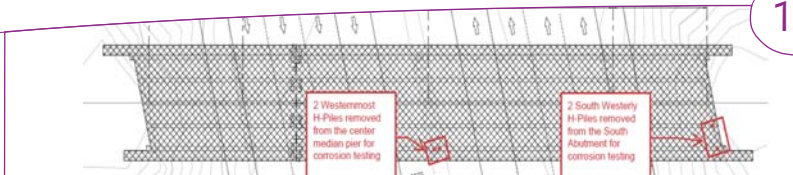
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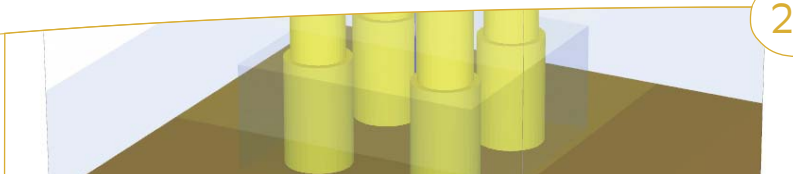
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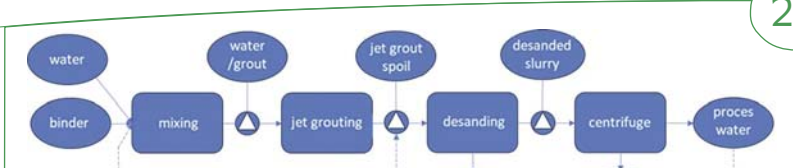
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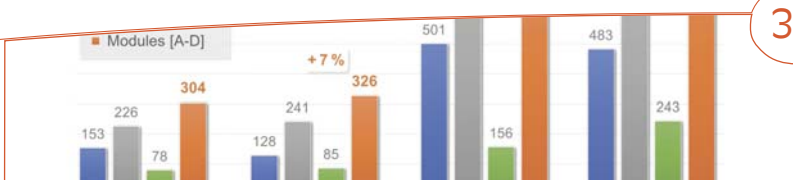
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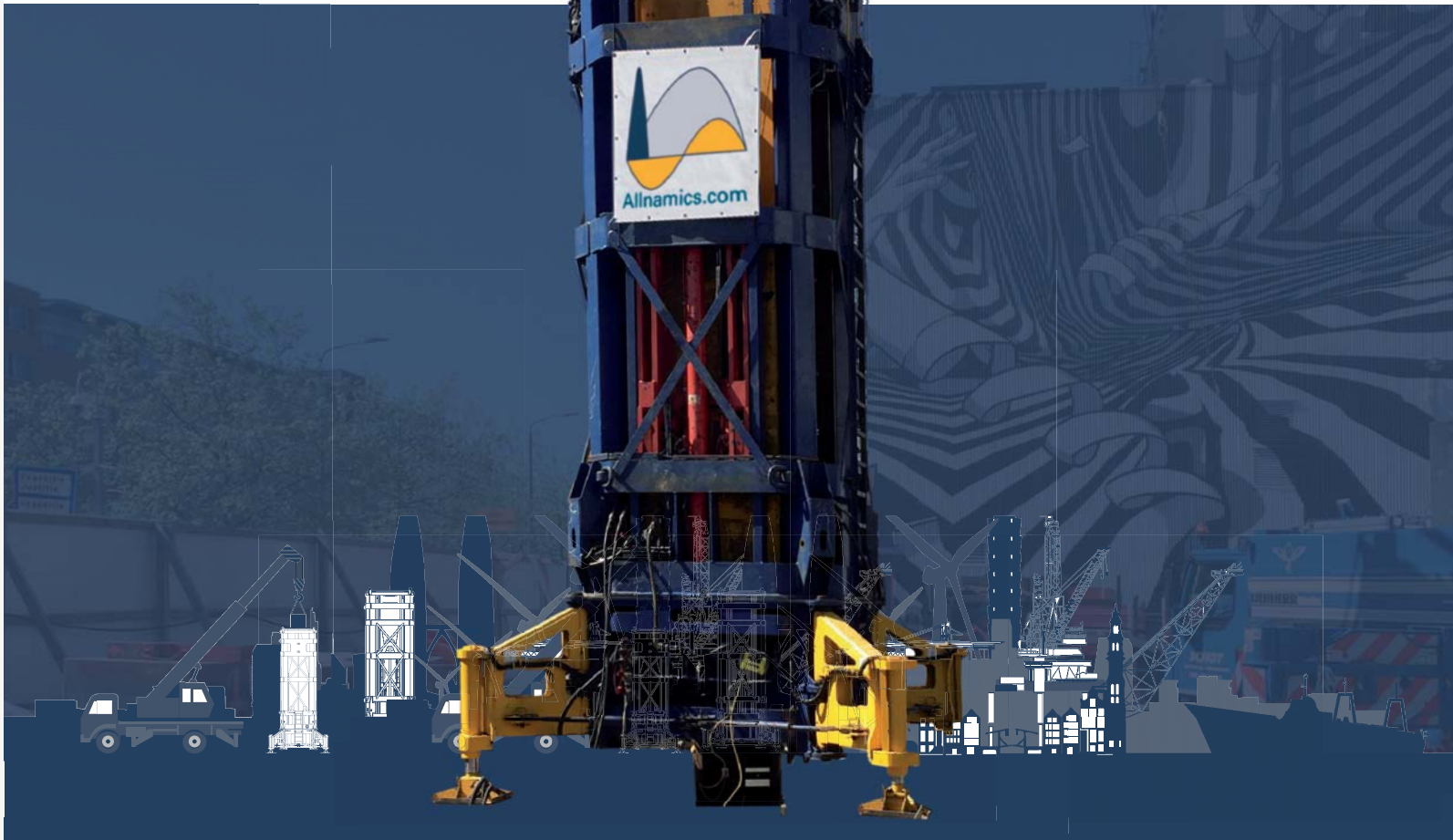
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WELCOME

Dear readers and visitors,

The Construction Industry is contributing significantly to the CO₂ 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 is now scheduled for May 2024, once again in Amsterdam in the beautiful KIT. 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 first edition. 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?

In this second edition of the International Conference all these aspects will be covered in four sessions that will focus on the overall concept of foundation decarbonization and reuse, the assessment of existing foundations, the design aspects associated with this topic, and finally the impact this approach will have on the construction phase. A special focus will be given to contractual and insurance aspects.

The Conference format will be similar to the first one, with some enhancements, to capitalize on our first experience. Each session will be opened by a keynote speaker, after which papers from all around the world will be presented. The session will then close with an extended Q&A session with all the speakers. In addition, a panel discussion will be organized where the owner with his legal representation will discuss with an architect, a structural engineer, and a geotechnical engineer, the options to repurpose an existing structure that involves the reuse of the foundation.



KIT Royal
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FOUNDATION DECARBONIZATION AND REUSE

Design optimization is a concept that every engineer has to deal with. While the design has to meet the functional requirements (that is it has to be strong enough and last long enough to meet the design objectives), any overdesign (that is to make it even stronger and last longer) is not always perceived as something positive. One of the obvious reasons why overdesign is frowned upon is that it increases the cost and the time fabricate or construct the item. Foundation engineers are very familiar with this conundrum. A foundation has to be robust enough that the load-settlement behavior meets the requirements and the foundation also has to last the entire design life of the superstructure, which may be 50 or 75 years or even 100 years. And since the cost of a foundation is sizable part of the overall project cost, any overdesign will not just increase the overall project cost, it may cause the project to become unfeasible.

Apart from the cost consideration, there is another aspect that foundation engineers have to deal with. Most foundations are constructed from concrete and steel, both materials with a high impact on carbon emission. The drive for more sustainability has reinforced the drive for “goldilocks” foundations: not too big, not too small, but just right. Or in other words, foundations that meet the requirements for the least amount of money and with the smallest carbon footprint. It should be noted that those two objectives mostly go hand in hand, and as a result foundation design has always incorporated sustainability, well before this concept became a common theme.

Apart from optimization the foundation size, the material selection also affects the carbon footprint of a foundation. There are numerous examples of ways to decarbonize the foundation in this manner and thus make it even more sustainable. The use of fly ash or metal slag as cementitious material in concrete, the use of recycled concrete aggregate and recycled steel, and the use of timber piles are just a few of the many options engineers have available when it comes to decarbonization. Implementing these approaches definitely reduce the carbon footprint, albeit that it may not reduce the actual foundation construction cost.

When combining foundation size optimization and the use of materials that further decarbonize a foundation, the resulting foundation design fits perfectly in the waste hierarchy as illustrated in figure 1. This concept, which is a key element of the so-called circular economy, ranks options to manage waste materials from most to least preferable based on the environmental impact. This waste hierarchy is a regular feature whenever the sustainability aspects of foundations is discussed, such as at a conference organized by the Deep Foundation Institute (DFI) and the European Federation of Foundation Contractors (EFFC) in Berlin, Germany in May 2022. At this conference there was a workshop on sustainability the day before the conference started, followed by two panel discussions on sustainability during the opening day. However, as is often the case, a very logical option to provide for a more sustainable solution, that is the reuse of an already existing foundation, got little attention.

While still in Berlin, the process began to find a way to address this lack of attention. As part of that process, it became very obvious that the reuse of foundations has drawbacks for all involved in a project:

- For the geotechnical engineer foundation reuse may require the assessment of the condition and capacity of existing foundation elements, with the associated risks;
- For the structural engineer it may mean adapting the design to match the existing foundation layout;
- For the architect it may restrict the design options for the same reason;
- For the (foundation) contractor foundation reuse would seemingly result in a smaller scope of work and thus in a lower contract value;
- For the owner it may mean dealing with requests for additional upfront investigations that may result in overall project savings (which will not be known until much later in the project execution phase) and with members of his project team that feel constrained;
- For the regulatory agency, it could mean giving approval for a concept that it is still relatively new and not really covered by codes and standards.

As a result, the initial response to a proposal to reuse an existing foundation when a new superstructure is constructed at a previously developed site is mostly negative, but this also means that a valuable asset is left in the ground. Moreover, when incorporated into the design of the new superstructure, the foundation reuse would more than likely reduce the overall project cost and definitely reduce the carbon footprint. And to convey this idea more broadly it would make sense to organize a regular event focused on foundation reuse. And so in less than one year after the conference in Berlin, and with the support of the European section of the Deep Foundation Institute and the geotechnical section of the Dutch engineering society KIVI, the first Conference on Foundation Decarbonization and Reuse was held in Amsterdam, The Netherlands, in March of 2023. During the first two days the conference topic was covered in 4 sessions, starting with the overall concept of foundation decarbonization and reuse, followed by the assessment of existing foundations, and the design aspects associated with this topic, and finally the impact this approach will have on

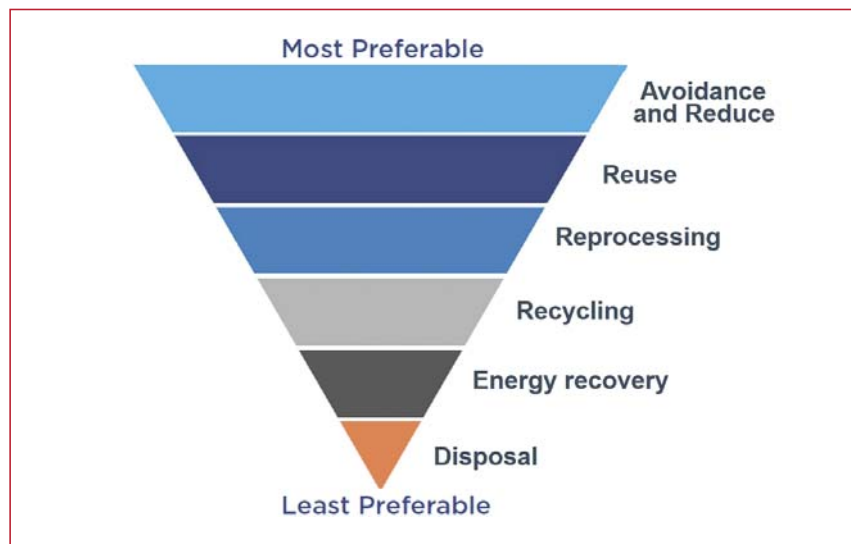


Figure 1 -
 Waste Hierarchy
 Pyramid.

SUMMARY

In late May of this year the second edition of the Conference on Foundation Decarbonization and Reuse will be held in Amsterdam. In this article the conference chair, Gerald Verbeek, describes the reasoning behind this conference

as well as the objectives and goals that the organizers have formulated for this event.



Figure 2 -
Inspection of
an Existing Timber
Pile Foundation.



Figure 3 - Conference Banner.

the construction phase. Each session was opened by a keynote speaker, after which papers from all around the world were presented. The session then closed with an extended Q&A session with all those that had made a presentation in that particular session.

After two days of presentations (which together with the papers themselves can be found on the conference website www.foundationreuse.com), the third day offered the attendees an opportunity to visit several sites and projects in and around Amsterdam where some of the concepts covered in the presentations were actually implemented.

While both the presentations and sites on the third day provided numerous examples of foundation reuse, some of the more memorable observations came from the keynote speakers. The first session was opened by Jan-Jacob van Blijswijk with Shell Moerdijk in The Netherlands, who used as the basis for his presentation a recurring scenario for Shell: whenever a refinery a process unit needs to be replaced by a larger and/or more efficient unit, the current foundation should be re-used for that new process unit if at all possible. The session on the design and engineering aspects associated with foundation reuse was opened by Henry Tayler with Arup in the United Kingdom, who reminded the attendees once that “redevelopment and regeneration of urban areas have left a legacy of old foundations, congested underground space and archaeological artefacts”, which simply require the reuse of those old foundations when new superstructures are constructed. The final session

of the conference was opened by Patrick IJnsen of Van ‘t Hek in The Netherlands, kicking off the discussion on the construction aspects. His presentation clearly stated the dilemma for a construction contractor. As he put it, “reuse of deep foundations can have a positive impact on a client’s budget; however, for the contractor it (only) brings uncertainty:

- What will it cost to make it fit for another service life?
- Can all elements be used or do we need to replace some?
- What time is required for inspection, and what do we find?”

But he then continued by stating that foundation decarbonization and reuse is going to happen. The conclusion that foundation reuse is going to happen gave the organizers the confidence to organize the second edition of the conference in May of this year and to already plan for the third edition in March of 2025. At the time this article is written, the preparations for this year’s conference are still ongoing, and therefore it is too early to describe in detail what will be presented. While the format will be similar to the first one, there will be an additional panel discussion where the owner will discuss with an architect, a structural engineer, and a geotechnical engineer, the options to repurpose an existing structure that involves the reuse of the foundation. This promises to be an interesting discussion, highlighting the hurdles that have to be overcome when foundation reuse is suggested, which may not always be achieved. At the same time, the keynote address for the opening

session, which will be given by Maya Sule of Rijkswaterstaat (the Directorate-General of the Ministry of Infrastructure and Water Management of the Netherlands), will deal with the way towards climate-neutral and circular foundations for infrastructure, which again reinforces Patrick IJnsen’s conclusion last year.

As conference chair it is very rewarding to see that the conference on foundation reuse is more than just another event on the long list of conferences that are held each year. It is the first international conference that deals with a topic that will become more and more common, and that is essential to make construction activities more sustainable. And finally it is also very appropriate that this conference is held in the KIT in Amsterdam. In 2017 the KIT started the SDG house, referring to the sustainable Development Goals defined by the United Nations. The SDH House is home to more than 50 organizations, and acts as a catalyst for sustainability initiatives and as a place to meet, exchange ideas, identify synergies, and build enduring partnerships. And that is exactly what the conference aims to achieve in the area of foundation reuse. By meeting once a year to bring together individuals from all over the world, who are interested in the concept of foundation reuse, to hear presentation on projects where foundation reuse was applied, and to exchange ideas how reservations about this concept can be successfully addressed, this conference may act as a catalyst to make foundation reuse a common component of construction projects at previously developed sites around the world. ●

ALLNAMICS FUNDAMENTAL DECARBONISATION

With a focus on sustainability, the reuse of materials has become increasingly important in the construction industry. For Allnamics, this was the impetus last year to initiate a conference on this topic in the field of foundations. From May 28th to 30th, the '2nd annual Conference on Foundation Decarbonization and reuse' will be held at the KIT in Amsterdam. "We want to raise awareness of the importance of and potential for reuse in this sector," says Remco Offenbergh, managing partner of the company.

Circularity benefits

Although reuse is not a new concept, Van Dorp, also a managing partner, still observes a certain laziness among designers or developers to incorporate the reuse of existing foundations into their plans. "It's easier - even for aspects like safety design - to make a plan for an empty plot and not have to consider anything else." Nevertheless, circular use of footings means significant savings in producing, transporting, and processing new building materials. Reduced construction activities lead to less transportation to and from construction sites, which is beneficial for a busy center like Amsterdam. It also reduces inconvenience for residents. "Fortunately, our advice on reuse is gradually gaining more traction, also because companies are seeing it more applied around them and don't want to miss out."

Conference perspectives

The conference broadly addresses foundations. Allnamics approaches this topic from the perspective of researching, testing, and evaluating them. "Another perspective comes from contractors. They mainly consider the load-bearing capacity of a structure. Their goals are not always easy to achieve, especially in city centers where space to work is often limited. Architects, on the other hand, are responsible for designing something that fits on or with the existing foundation," says Van Dorp. He further mentions the presence of environmental consultancy firms at the KIT. "They often provide numerical support, such as precise calculations of the carbon footprint and what interventions can yield significant results and which ones may not." Offenbergh: "What we missed a bit last year at the first conference were representatives from the regulatory authorities. For this edition, we're paying extra attention to

that, hoping to welcome more delegates from various government bodies. They play an important role in building zoning plans, of course."

Stakeholders

"A building design has a reference period of 25, 50, or 100 years. At the end of such a period, sometimes decisions to demolish and rebuild are made too easily. The structure may not necessarily be fully utilized, and the foundation might still have sufficient capacity or only need partial replacement. It's worthwhile to conduct research into this," explains Offenbergh. In geotechnical engineering, an owner or building owner commissions an architect to make a functional design. A structural engineer is involved for their knowledge of

concrete and steel possibilities. For explicit knowledge of soil mechanics and foundations, a consultancy like Allnamics comes into play. The company assesses both new and existing foundations and tests wooden, steel, and concrete piles. This expertise is also applied offshore, drawing on experiences from offshore oil platforms for the construction of wind farms.

Origin

Allnamics' start involved extensive research in Amsterdam on existing timber pile foundations. These analyses were necessary due to the city's policy of subdividing many properties into multiple dwellings. "To protect future buyers, the municipality requires proof that the foundation will re-



Photo 1 –
Test installation
below bridge deck.



Photo 2 – Bridge deck abutment at street level.

main maintenance-free for at least 25 years,” says Offenberg. Van Dorp adds: “We also conducted many foundation investigations when owners wanted to make significant alterations to their properties. They were obliged to have the existing foundation assessed.” The motivation for splitting dwellings was to increase housing supply, while for major alterations, structural safety was paramount. At that time, environmental concerns were not significant, but now, reusing resources is growing in significance, partly driven by European climate goals.

Recent developments

“In recent years, many buildings on concrete foundations from the ‘60s and ‘70s are being replaced because the superstructures are outdated in terms of environmental performance (isolation, energy consumption, etc.) and functionality”, says Offenberg. “This has led to an increase in inspections of precast concrete piles.” Van Dorp on this matter: “What’s happening on a large scale, is the grinding of used concrete to make new concrete.” He also points out a nuance in renewing foundations, where new piles are increasingly added to existing foundations instead of removing and replacing them entirely. “This reduces the volume of new concrete piles required.”

Case study

Van Dorp recalls, “A few years ago in Amsterdam, there was a project involving wooden piles under a bridge structure over Vijzelstraat. The municipality of Amsterdam is very busy examining and maintaining bridges and quay walls. There were no design drawings available, so they wanted to assess its state and strength.” He describes how the wooden piles under the abutment were exposed, which was quite complex due to working below the water level in an underwater pit. “Once the piles were exposed, kentledge load could finally be applied for testing.”

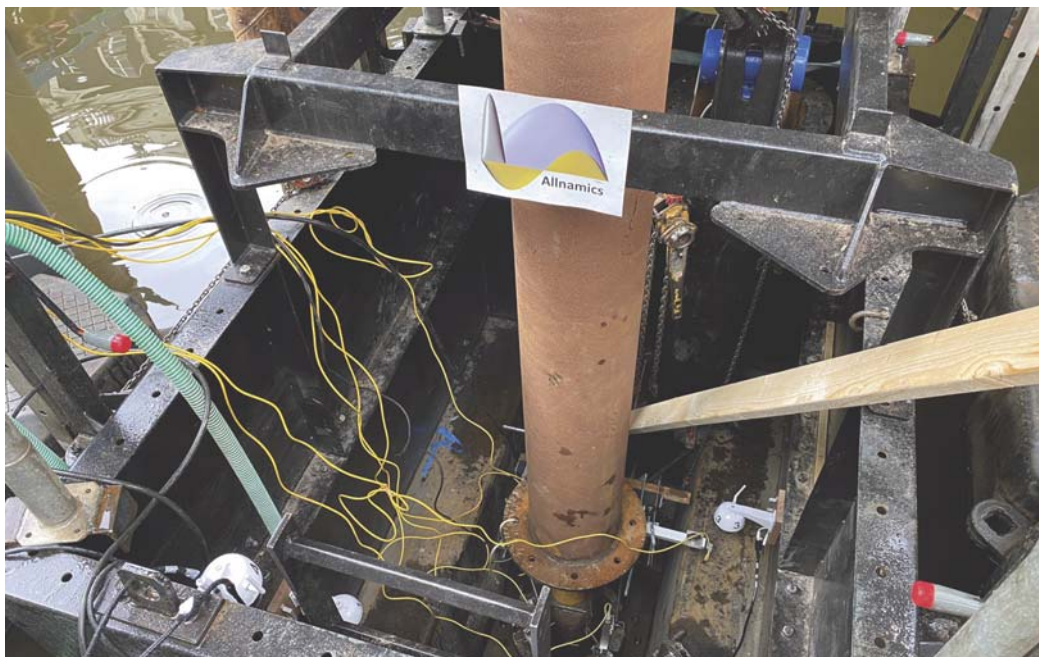


Photo 3 – Inside of dry casing around testpile, with follower to kentledge load on bridge deck.

Testing

The tests involved applying and measuring the load on a part of the foundation using a hydraulic jack, load cell and displacement gauges. The same test is repeated on adjacent piles to reveal any differences. “The protocol states that a certain load must be applied for at least half an hour, after which the load will be increased to the next step”, Van Dorp explains. “In this case the test piles had lost their function because new foundation piles had already been installed in the abutment. This was because over the years the traffic load had increased beyond safe levels for the existing foundation, but it offered a splendid opportunity to test multiple piles in the existing foundation. The results yielded very useful information for assessing state and capacity of other existing foundations in the city.

Silo Tower Leiden

Another project that demonstrated the value of foundation reuse involved a site with a former flour silo in Leiden. “It was an old silo, and silos are heavily loaded structures,” Van Dorp states. “The foundation consisted of wooden piles placed practically shoulder to shoulder. To determine whether the capacity of the existing foundation was completely consumed by the silo or that it still could have accommodated another one, we conducted load testing. Ultimately, the load-bearing capacity proved to be more than sufficient for the total number of apartments realized in the silo tower.” Offenberg: “It’s important to leave existing piles in place as much as possible, as disturbing a foundation is undesirable. And if you do leave them in place anyway, it’s advisable to investigate what the foundation can still withstand and whether it can be partially or entirely re-used”. ●





REVITALIZING INFRASTRUCTURE: GEOTECHNICAL DESIGN AND SUSTAINABLE FOUNDATION REUSE IN THE A9BAHO PROJECT NEAR AMSTERDAM

Project location

The A9BaHo project is an infrastructure project near Amsterdam spanning 11 kilometers where 11 civil structures, dating from the 1960's-1970's, will be renewed and widened to accommodate for the additional traffic lanes. The widening of the A9 between Badhoevedorp and Holendrecht is part of the Schiphol-Amsterdam-Almere (SAA) road expansion. To improve the accessibility of the Randstad, Rijkswaterstaat is expanding the road network between Schiphol, Amsterdam, and Almere. The A9 will be expanded from 3 to 4 lanes per direction between Badhoevedorp and Holendrecht including a reversible lane. FCC Construcción is the main contractor for this project. Fugro has been contracted to conduct the soil investigation & monitoring and make the various geotechnical and geohydrological designs for this project.

One of the goals of the project is to reuse the foundation of as many civil structures as possible. This paper highlights the geotechnical design process of one civil structure, namely "KW004", which will be extended from 37.5 meters to 60 meters wide. The existing foundation is constructed

on prefab concrete piles while the new extension will be constructed on bored soil displacement piles with a permanent casing.

Soil investigation

For the A9BaHo project, an extended soil investigation campaign has been conducted consisting of over 2600 CPT's and 250 boreholes. Additionally, extensive laboratory testing has been done to determine the soil parameters.

The performed soil investigation shows that the area is largely made up of Holocene peat and clay layers. The general soil stratigraphy at the project location is shown in table 1.

A cross-section of the soil stratigraphy located at civil structure KW004 is shown in figure 1. This cross-section is taken from the 3D groundmodel that has been made specifically for this project based on the soil investigation campaign. An overview of the 3D groundmodel is shown in figure 2.

Foundation design

The safety philosophy for the design of piled foundations is described in NEN9997-1 Chapter 7. The

design is based on safety classes and reliability indices. The safety philosophy is further outlined in NEN-EN-1990. New civil structures are designed for a design life cycle of 100 years. In the case of steel tubular piles, corrosion is also taken into account for permanent piles. Existing re-used structures are recalculated for a design life cycle of 30 years.

The reuse of the piled foundation is assessed in accordance with NEN8707. NEN8707 states that, if the average increase in pile loads is lower than 15% in the new situation, the old pile class factors (Pre 2016) may be used for the bearing capacity calculations. If the load increase is higher than 15%, the new pile class factors (2017) should be used.

General principle is that only the piled foundation of KW004 will be re-used. The rest of the structure will be rebuilt. These adjustments, in combination with increased traffic loads, lead to an increase in the pile loads. The plan view of the pile plan and foundation is shown in figure 3. The contour of the existing civil structure, with the existing piles, is highlighted in red. The locations and pile tip level of the existing piles are verified using "Magneto CPT's" which uses a specialized cone to detect the steel reinforcements of the existing piles.

PILE CLASS FACTORS AND PILE LOADS

When the increase in pile loads is smaller than 15% for existing piles foundations, the old pile

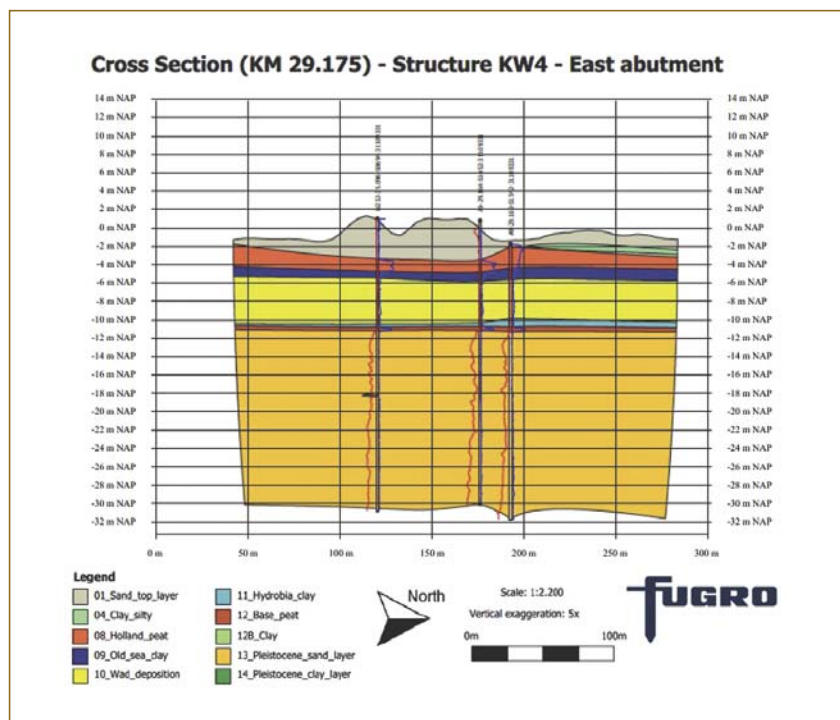


Figure 1 –
Cross-section
of soil stratigraphy
located at
KW004 - Eastern
abutment.

Table 1 – General soil stratigraphy for the A9BaHo project

Layer unit no.	Layer unit description
01/01A	Sand, top layer (man-made / existing sand fill)
04	Clay, silty (organic at some places)
08	Peat, weak (Holland peat)
09	Old Sea Clay
10	Sand and clay interlayers (Wadsand)
11	Soft marine Hydrobia Clay
12	Base peat layer
13	Pleistocene sand layer

SUMMARY

This case study highlights the geotechnical design of civil structure "KW004", part of the A9BaHo project in the Netherlands, widening it from 37.5 m to 60 m. The existing foundation constructed with prefab concrete piles are reassessed in accordance with Dutch Standard NEN8707, while the extension will be constructed using bored soil displacement piles with permanent casing, designed

according to Dutch Standard NEN9997-1. All 208 existing piles can be re-used, saving an estimated 1211 tons of CO₂ emissions which includes materials, transport and installation. This case study shows that reusing foundations is both feasible and profitable, offering significant CO₂ savings alongside time and cost savings.

class factors (pre 2016) can be used in accordance with NEN8707 Appendix G. Otherwise, pile class factors according to NEN9997-1 should be applied. For two pile types, new and existing, used at KW004, dimensions and pile class factors are listed in table 2. For reference, the pile class factors for precast concrete piles (post 2016) are also added. The pile class factors consist of a factor used for the calculation of the bearing capacity of the pile tip, α_p , and pile shaft, α_s . These factors are pile type dependent. The factors and account for the influence of the shape of the pile tip.

The loads on the existing piles in the ultimate limit state (ULS) and the serviceability limit state (SLS) are:

- Western abutment (axis 1):
770 kN (ULS)
618 kN (SLS)
- Central support pillars (axis 2, 3 & 4):
1.035 kN (ULS)
882 kN (SLS)
- Eastern abutment (axis 5):
845 kN (ULS)
663 kN (SLS)

The expected maximum SLS load that the existing piles have experienced in their respective load history:

- Western abutment: 555 kN;
- Eastern abutment: 640 kN;
- Central support structure: 1.000 kN.

All pile loads were provided by the structural engineer. Based on the load history and new pile loads, it is determined that the load increase is lower than 15% and thus the old pile class factors are used in the calculations.

The following areas have been determined for the bearing capacity calculations of the existing piles:

- Western abutment
Northern deck
Southern deck
- Central support structure
Northern deck
Southern deck
- Eastern abutment
Northern deck
Southern deck

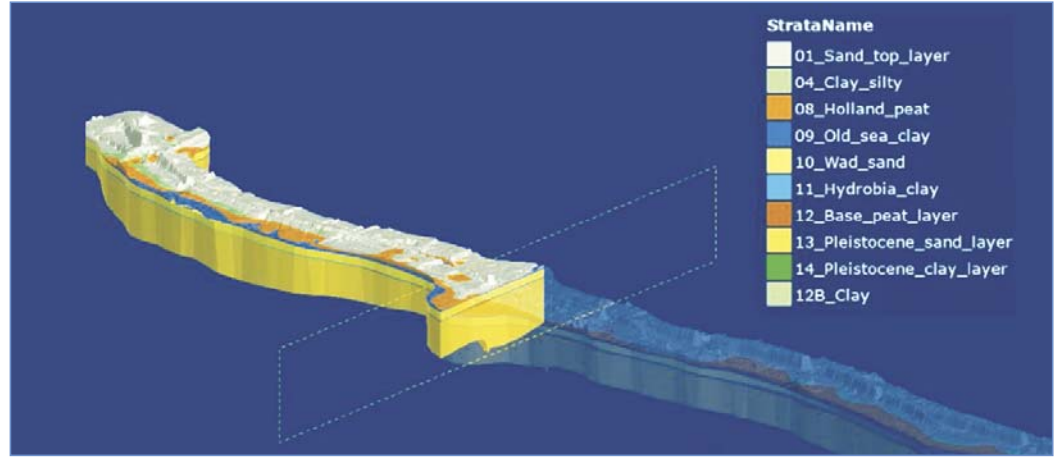


Figure 2 – Overview of 3D ground model of A9BaHo soil stratigraphy.

Table 2 – Overview of dimensions and pile class factors of piles used in the design.

Pile type	Dimensions [mm]	α_p [-]	α_s [-]	s [-]	β [-]
Precast concrete piles (pre 2016)	400x400	1.00	0.010	1.0	1.0
Precast concrete piles (post 2016)	n.a.	0.70	0.010	1.0	1.0
Bored soil displacement piles with permanent casing, with grout injection	∅ 457/560	0.63	0.009	1.0	1.0

CORRELATION FACTORS ξ_{3-4}

When calculating the bearing capacity (compressive), the correlation factors are an important aspect. These factors are depending on the amount of soil investigation (n) and whether a structure is stiff or non-stiff (NEN9997-1 §7.6.2). Essentially, correlation factors – ξ -factors – take into account the heterogeneity of the soil in the bearing capacity calculation. Whether a structure is considered stiff or non-stiff is determined by the structural engineer, by assessing the foundation behavior when a single pile of the pile group fails. Generally, the structure is assumed to be stiff when the settlement is smaller than 5 mm in SLS in the case that one pile is removed (NEN9997-1 7.6.1.1(c)).

For each (sub-)structure, the amount of soil investigation to be used must be assessed separately. As the number of CPTs increases ($n > 1$), the values for correlation factors ξ_{3-4} reflect less uncertainty in the heterogeneity of the soil and are therefore reduced. The condition for using lower correlation factors is that the coefficient of variation of the

bearing capacity must be lower than 12%. A coefficient of variation of 12% provides a minimum bearing capacity larger than 80% of the mean bearing capacity at a 5% probability of failure.

BEARING CAPACITY

According to NEN9997-1, the representative values $R_{b;k}$ and $R_{s;k}$ need to be calculated using:

$$R_{c;k} = (R_{b;k} + R_{s;k}) = \frac{R_{b;cal} + R_{s;cal}}{\xi} = \frac{R_{c;cal}}{\xi} = \min \left\{ \frac{(R_{c;cal})_{avg}}{\xi_3}, \frac{(R_{c;cal})_{min}}{\xi_4} \right\}$$

Where $R_{c;k}$ = representative value for the bearing capacity of the pile, $R_{b;k}$ = representative value for the bearing capacity of the pile tip, $R_{s;k}$ = representative value for the bearing capacity of the pile shaft, $R_{b;cal}$ = calculated value for the bearing capacity of the pile tip, $R_{s;cal}$ = calculated value for the bearing capacity of the pile shaft. ξ_3 and ξ_4 are the correlation factors which are dependent on the amount of CPT's, n , and are applied to:

– The average bearing capacity of all CPT's (ξ_3):

$$(R_{c;cal})_{avg} = (R_{b;cal} + R_{s;cal})_{avg} = (R_{b;cal})_{avg} + (R_{s;cal})_{avg}$$

– And the lowest bearing capacity of all CPT's (ξ_4):

$$(R_{c;cal})_{min} = (R_{b;cal} + R_{s;cal})_{min}$$

REDUCING THE COEFFICIENT OF VARIATION

If the coefficient of variation is larger than 12%, it can be considered to divide the area into several subareas to reduce the coefficient of variation. However, the existence of significant outliers could result in an illogical or unfeasible division in subareas.

Another possibility which was used for this case is to still consider the initially chosen area but remove the highest individual outliers in terms of bearing capacity. By doing so the coefficient of variation reduces while still considering a baseline

in terms of bearing capacity. The removal of highest outliers can be continued until the 12% threshold is met. Since only the highest outliers are omitted, locations with a lower bearing capacity are still considered when calculating the representative values $R_{b;k}$ and $R_{s;k}$ within a group of CPT's. Furthermore, the bearing capacity of these outliers will always be higher than average of the group and therefore never normative. The following paragraph provides an example of this process.

For the southern side of the central piers (axis 2, 3 & 4), the bearing calculation results of the individual CPT are shown in table 3. The coefficient of variation for this group is equal 14%, which is higher than the limit of 12%. By removing the highest outlier CPT S1240, the coefficient of variation is reduced to 12%. Subsequently the new highest outlier CPT S191 can also be removed to further reduce the coefficient of variation below the limit to 11%. Table 4 shows the result of the bearing capacity calculation. It can be seen the bearing capacity of the individual CPT's which have been removed from the group (S191 & S1240) is higher than the bearing capacity calculated for the remaining group.

Vertical spring stiffness

The vertical spring stiffness was determined for the pile tip excluding the elastic deformation of the pile as this was taken into account in the modelling done by the structural engineers. For the calculation of the vertical spring stiffness, only the settlement of the pile tip, s_b , is considered. The settlement of the soil layers underneath the pile

tip, s_2 , was not taken into account, since no compressible layers are present below the pile tip. The calculated values for the vertical spring stiffness were varied by a factor $\pm\sqrt{2}$ to get a high/low range of the vertical static spring stiffness. The vertical spring stiffness is calculated using the load-displacement curve according to NEN9997-1 §7.6.4.

In the calculation of the vertical spring stiffness of the existing piles, a distinction is made between the vertical spring stiffness for pile loads below the maximum load (SLS) in load history and pile loads above the maximum load (SLS) in load history. In the former case, pile unloading/reloading behavior is expected and thus the pile will have a higher stiffness. Once the load history threshold is reached the pile behaves according to the load-displacement curve under virgin loading.

The provided vertical spring stiffnesses, k_{stat} for virgin loading and k_{UR} for unloading/reloading, cannot be used linearly but must be applied in conjunction with each other depending on the actual loads of the piles.

Furthermore, specific attention was given to the differences in stiffness between generally less stiff existing piles versus stiffer new piles. Differences in stiffness can have a negative impact on the load distributions in the integral foundation. During the design process, various extensive meetings and discussions have taken place between geotechnical and structural engineers to ensure a proper modelling of the integral foundation.

Table 3 – Bearing capacity of each individual CPT ($n=1$) for central support structure-south side

CPT	Depth [m NAP]	$R_{c;cal}$ [kN]	$R_{c;net;d}$ ($n=1$) [kN]
S191	-12.5	2038	1246
S1235	-12.5	1814	1098
S1236	-12.5	1816	1100
S1240	-12.5	2202	1355
S1241	-12.5	1507	895
S1242	-12.5	1628	975
S1243	-12.5	1984	1211
S1248	-12.5	1537	915

Table 4 – Bearing capacity of combined CPT's ($n=6$) for central support structure-south side.

CPT	Depth [m NAP]	$R_{c;cal}$ [kN]
S191	-12.5	2038
S1235	-12.5	1814
S1236	-12.5	1816
S1240	-12.5	2202
S1241	-12.5	1507
S1242	-12.5	1628
S1243	-12.5	1984
S1248	-12.5	1537

cv [-]	$(R_{c;cal})_{gem}$ [kN]	$(R_{c;cal})_{min}$ [kN]	$R_{c;ca}$ [kN]	F_{nk} [kN]	$R_{c;net;d}$ [kN]
0.11	1731	1507	1493	101	1125

With number of tests resulting in (NEN9997-1 Table A10.b):

$$\xi_3 = 1.16 \quad \xi_4 = 0.925$$

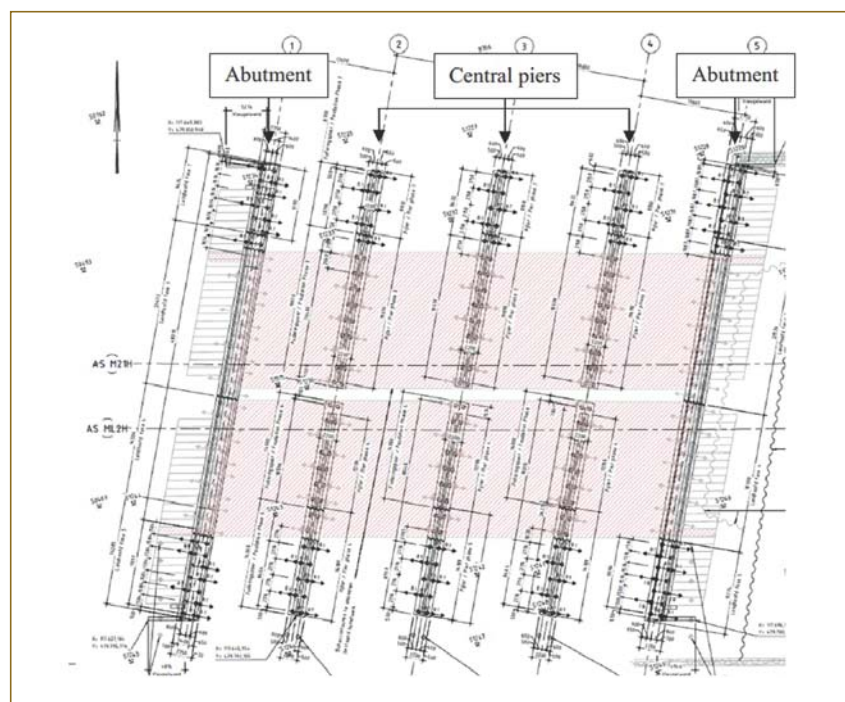


Figure 3 – Plan view Pile plan + Foundation (Existing civil structure outlined in red).

Life cycle analysis

The number of re-used piles underneath KW004 are summarized in table 5.

If reusing these existing piles would not have been possible, new piles would have to be installed instead, resulting in additional CO₂-emissions. Considering a fairly uniform pile load distribution within each axis, it is assumed that similar number of new piles would have been needed. It is noted that a uniform stiffness distribution could lead to a decrease of normative pile load and therefore a decrease in required pile lengths. However, no calculations with exclusively new piles have been performed for this civil structure, so this cannot be determined with certainty with the current information. In order to calculate the MKI-value (Environmental Cost Indicator) and equivalent CO₂-emission in the different life cycle analysis (LCA) phases, DuboCalc software is used. The life cycle of a piled foundation consists of the following phases:

- Production phase: raw material extraction, transport and production (A1-A3)
- Construction phase: transport to construction site (A4) and construction/installation (A5)
- Use phase: use, maintenance, repair, replace and renovation (B1-B5)
- End of life: deconstruction/demolition, transport, waste processing and disposal (C1-C4)
Subsequent production cycle: reuse, recovery and recycling (D)

The calculation for the LCA is based on bored soil displacement piles with permanent casing, with grout injection. The cast iron tip is lost during installation. Given the fact that the pile tip diameter is determined based on the pile shaft diameter and not on the pile length, the choice has been made to use the number of piles as input for the calculation. The steel tube and the grout are entered scalable per meter in the Dutch National Environment Database (NMD). The used length is 15 m. The scalable weights are determined to be 49.5 kg/m pile and 377 kg/m grout. With a pile length of 15 m, the total weight is 6,397.5 kg.

Results

In figure 4 the results of all existing piles within their respective subarea are summarized. The bearing capacity of the re-used piles are sufficient based on the provided loads.

Table 6 shows the results of the DuboCalc calculation of the MKI-value (in euros) and equivalent CO₂-emissions in the different LCA phases (%). The total CO₂-emissions in kg is given in the last row of the section 'MKI-values' in table 6.

The total CO₂ emission reduction for the civil structure is approximately 1,211 tons CO₂ equivalent. In terms of MKI-value the reduction is € 134,019 where the LCA-production phases (A1-A3) are responsible for the largest portion (84.5%) of the

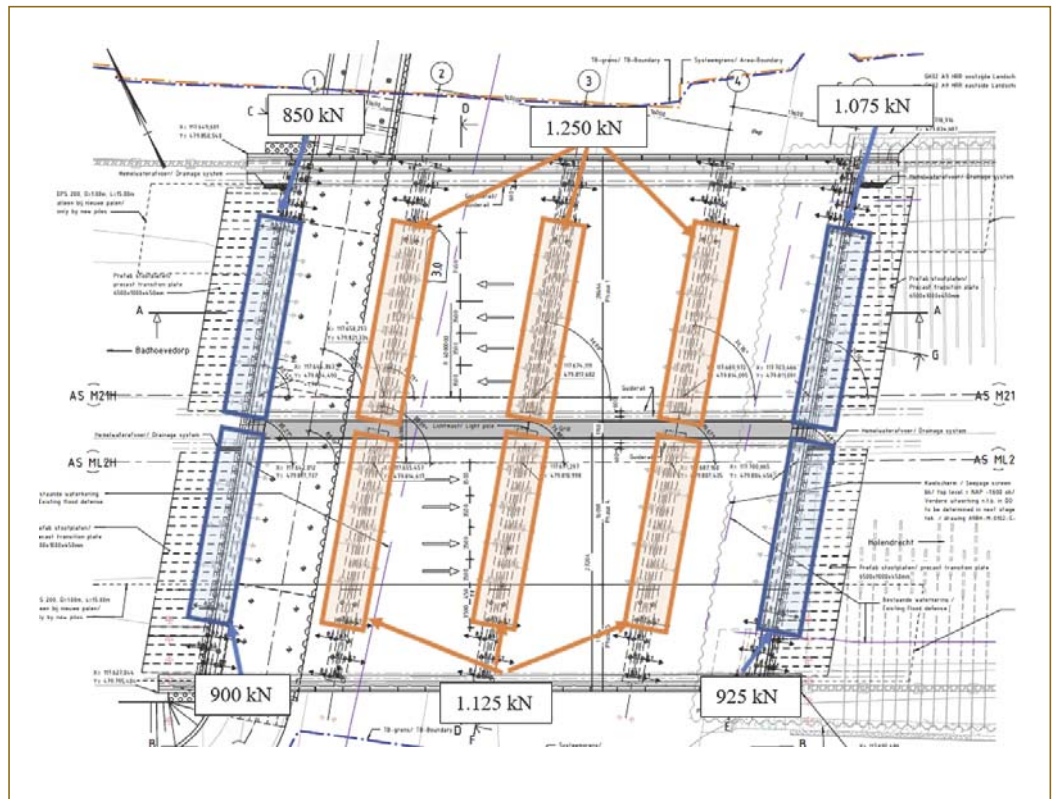


Figure 4 – Bearing capacity result for each subarea.

total excluding surcharge. The construction phase (A4-A5) makes up for 6.5%, the use phase (B1-B5) for 0% and the demolition and processing phase (C1-D) for 9.0% of the MKI-value.

Conclusion

The foundation design process for the reuse of existing pile foundation of civil structure KW004 for the A9BaHo project is performed according to the Dutch code (NEN9997-1 & NEN8707). Furthermore, an LCA-analysis according to ISO 14040 is performed based on the realized savings with respect to a fully new foundation.

Due to geotechnical expertise and extensive soil investigation, all 208 existing foundation piles can be re-used. The total CO₂ emission reduction is equal to approximately 1,211 tons CO₂ equivalent. In terms of MKI-value, expressed in euro's, a reduction of € 134,019 is realized.

From this case study it is concluded that re-using the foundations of civil structures is a feasible and profitable design approach which can result in a significant saving of CO₂-emissions in addition to saving time and money.

References

- Some documents are used for internal and project use only and therefore not publicly available.
- NEN8707 'Assessment of an existing structure in case of reconstruction and disapproval – Geotechnical constructions', 2018.
- NEN9997-1 'Geotechnical design of structures – Part 1: General rules', 2017. ●

Table 5 – Summary of re-used piles for civil structure KW004

Location	Axis	Amount	Length
Abutments (2x)	1 & 5	2 x 50=100	10 m
Central pillars (3x)	2, 3 & 4	3 x 36=108	9.5 m

Table 6 – Results DuboCalc calculation of realized reduction civil structure KW004

MKI-values		
MKI including surcharge (total)		€ 134,018.89
MKI excluding surcharge		€ 105,022.93
MKI surcharge		€ 28,995.96
Contribution		100 %
Production phase	Total	€ 88,769.71
	A1 – A3	€ 88,769.71
	Construction phase	
Construction phase	Total	€ 6,828.22
	A4	€ 1,803.33
	A5	€ 5,024.90
Use phase	Total	€ 0
	B1 – B5	€ 0
End of life	Total	€ 9,425.00
	C1 – C3	€ 0
	C4	€ 1,055.26
	D	€ 8,369.73
Total CO ₂ (kg CO ₂ -eq)		1,211,442.93
Details		
Amount		1
Lifespan (years)		100
Actual lifespan (years)		100



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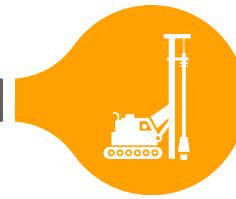
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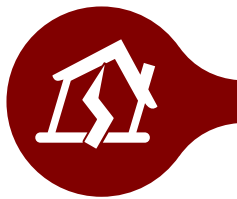
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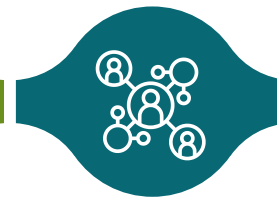
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THE FOUNDATION FOR A BRIGHT FUTURE

Our key take aways from the first edition of the Conference on Decarbonization and reuse of Foundations were:

- Ultimate decarbonization is not making any new foundation i.e. re-using existing foundations.
- Proper documentation of construction logs of projects facilitate future reuse or effective recycling.
- The impact on the carbon footprint by the reduction of fuel and energy consumption on projects is far less than is possible by the reduction of material usage.

As market leader in the Netherlands with an international ambition and a focus "to make a difference," we want to contribute to a sustainable construction industry by committing to the SDG's as formulated by the UN and especially by reducing our carbon footprint and direct emissions as much as possible.

Although the effect on our and our project's carbon footprint is limited, Van 't Hek is investing in zero emission equipment and vehicles. This also has a positive effect on other emissions, such as nitrogen, which is a very urgent topic on our home market in order to preserve biodiversity.

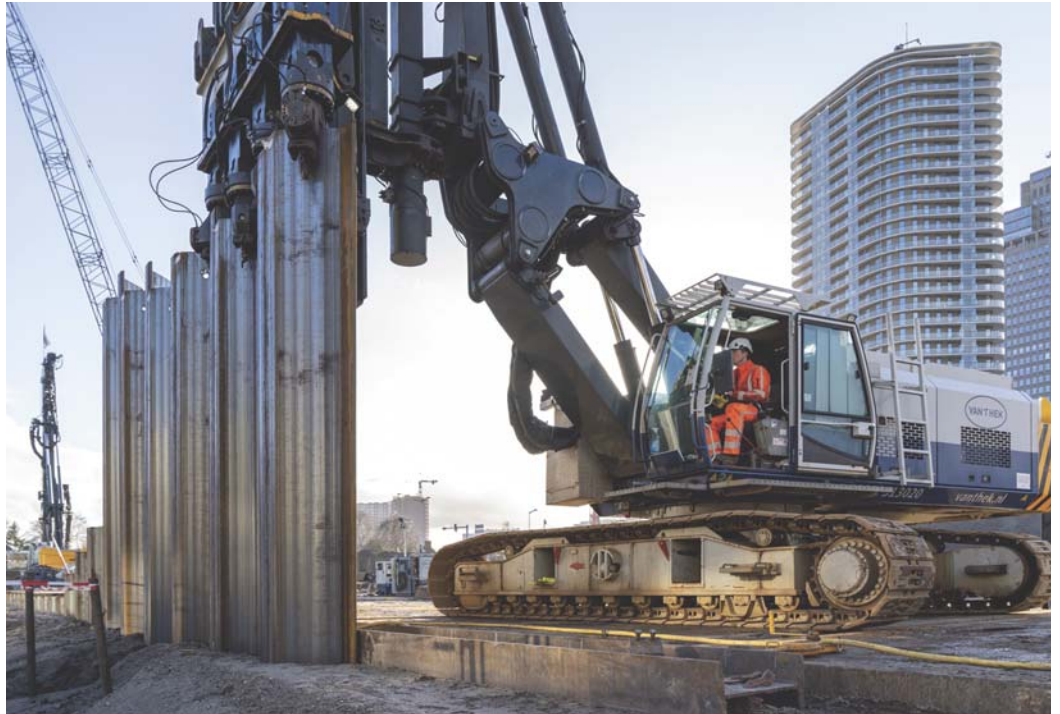
Except in plant and machinery we also invest in ICT solutions in order to be able to deliver extensive and correct project documentation and construction logs. "The data lake" behind our platform Infoundation (www.infoundation.net) is growing with every installed pile and will facilitate future data driven decisions on project solutions or facilitate future reuse of certain elements.



infoundation.net

The geotechnical engineers in our in-house engineering department (Hektec) are committed to offer optimized solutions for piling lay outs and retaining structures with a minimized carbon footprint in line with standards for structural safety. While circularity and recycling of steel sheet piles, tubes and H-beams has already been part of our daily business for decades, we are now expanding this to concrete elements and drill mud in our projects.

In all these fields we aim for continuous improvement and in order to achieve this, we work in close collaboration with our clients, suppliers and fellow piling companies through our national federation NVAF.



We are always open for discussion on how to improve our (mutual) achievements in sustainable construction and hope to meet you on our stand on the 2nd annual Conference on Decarbonization and

reuse of Foundations. If we didn't have a chance to meet during the conference but you are interested in an exchange, we would be delighted to get in touch! ●



Grout recycling

In the Netherlands a common pile type is a screw displacement pile, installed with the help of grout injection as a lubricant. If piles have to be installed in dense sands, in order to achieve the required bearing capacity, a lot of drill mud back flow can be expected. Where in the past years back flow of drill mud was treated on a project site as contaminated waste or (in the best case) could only be re-used as backfill material, Van 't Hek is investing in research on the feasibility of de-sanding drill mud and recycling the process water and binder directly on site. The goal is to reduce the use of valuable water and binder and to reduce the disposal of waste soil from project sites.



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Tony Sangiuliano
Ministry of Transportation
of Ontario, Canada



Brady Lin
Ministry of Transportation
of Ontario, Canada



Paul Carnaffan
Thurber Engineering Ltd,
Ottawa, Ontario, Canada

REUSE OF EXISTING STEEL PILE FOUNDATION STUDY

HALLECKS RD AND HWY 401 BRIDGE, BROCKVILLE, ONTARIO, CANADA

Introduction

The original Highway 401- Hallecks underpass bridge located in Ontario, Canada, was replaced with a new structure along the same alignment in 2023 under a Ministry of Transportation (MTO) contract (Contract 2021-4089). Although the existing foundations were not being used for the replacement bridge, a comprehensive study of the existing piles was undertaken within the above-mentioned contract. The study was established to gather relevant information to assess the integrity, capacity, durability, and the service life of existing piles.

The original structure, constructed in 1967, was a 59.7 m long four-span bridge. The superstructure was supported on conventional abutments and three piers. The abutments, center and south pier were supported by deep foundations (steel H-piles) driven to bedrock. The north pier was supported on a spread footing founded on bedrock. The replacement structure was designed to accommodate future widening of Highway 401 and is a 68.0 m two-span (34.0 m, 34.0 m) bridge, with integral abutments and a center pier on deep foundations.

The subsurface conditions generally consist of roadway embankment fill overlying stiff clay and loose to compact silt. At the north abutment, the silt layer overlies bedrock. At the south abutment a thin layer of glacial till is present between the base of the silt and the bedrock surface. The bedrock is located 6.6 to 11.9 m below grade. The bedrock surface dips from elevation 85m at the north abutment to elevation 80m at the south abutment. The groundwater level fluctuates but generally is at an elevation of 86m.

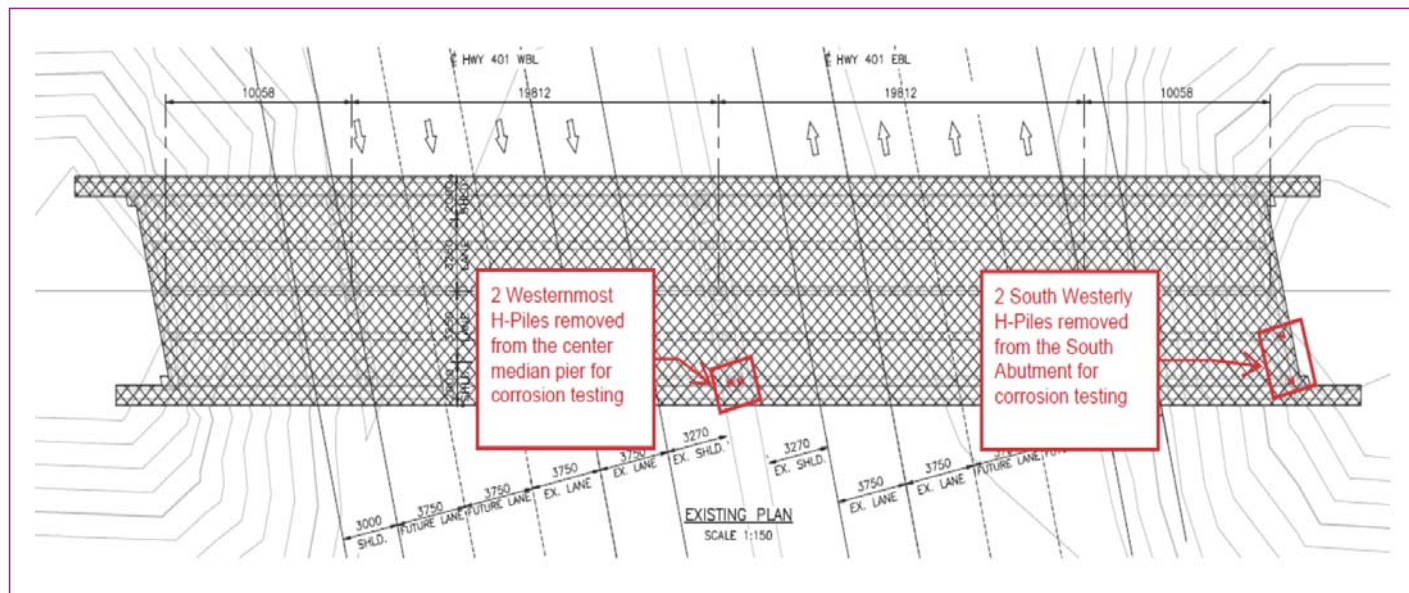


Figure 1 -
Plan illustrating
locations of pile
extraction.



Figure 2 - Four piles extracted.



Figure 3 - Black bitumastic-type coating present.



Figure 4 - Pile C2 showing no evidence
of corrosion.

SUMMARY

To continue support the reuse of existing foundations, an assessment of existing piles was implemented on a project in Brockville, Ontario, Canada, while the existing underpass structure built in 1967 was being demolished. This paper describes the scope and the results of the assessment program to evaluate the capacity, integrity, and durability of the existing steel H-piles. The program

included pile extraction, visual examination, ultrasonic thickness measurements, and strength testing. Soil and groundwater sampling and corrosivity testing were also conducted, along with geophysical testing including parallel seismic and borehole magnetometer testing to verify the pile lengths.



Figure 5 – Extracted abutment piles showing what appears to be a coal-tar epoxy coating and significant corrosion within the lower 300-600mm.



Figure 6 – The web of the A1 pile showing little sign of corrosion.



Figure 7 – The bottom 300mm of the A1 pile appears to be more heavily corroded with some scale being evident.

Pile Extraction

Four (4) piles were extracted to assess the degree of corrosion experienced by the piles: two (2) piles from the center pier (labelled C1 and C2) and two (2) piles from the south abutment, (labelled A1 and A2) as shown in figure 1.

The piles were extracted while work was being performed on the new bridge. The extracted piles were then subjected to:

- Visual examination of the pile surface,
- Ultrasonic thickness determination on the piles.

Visual Examination – Center Pier Piles

Segments of the extracted piles from the Center Pier are illustrated in figure 2. The piles appeared to be coated with a bitumastic-type black coating (figure 3). For the most part, the coating seemed intact, but there were sections where the coating had scraped off. Following cleaning, it was observed that the coating on Pile C1 was intact intermittently (~40 - 50%) over its surface, but no evidence of corrosion was visible. Pile C2 was in a similar condition (figure 4) with no evidence of significant corrosion identified.

Visual Examination – Abutment Piles

Two (2) abutment piles were also extracted for assessment. These piles appeared to be coated with a coal-tar epoxy and contained significant corrosion scale on the lower 300 - 600 mm (figure 5). A bitumastic coating appeared to be present as well on much of the pile, though there were several areas where it was absent.

The web of pile A1 appeared to be in reasonably good shape (figure 6).

The last or bottom 12"(30 cm) of the pile appeared to be more heavily corroded with some scale evident (figure 7).

At Pile A2, corrosion was apparent in the bottom 300–600mm. Significant deterioration was noted through the breaks in the coating on the flanges as well. This decreased moving up the pile. The web was in similar condition to the flanges. Heavy corrosion scale near the bottom of the pile was noted on the web similar to the flanges (figure 8).

Ultrasonic Thickness Testing

An ultrasonic thickness survey of the piles was performed on a grid pattern with a Dakota DFX 7+ ultrasonic flaw detector set in the thickness gauge mode with a .” 5MHz CT, dual-transducer and Sonotech Soundsafe gel for couplant using Thru-coat technology to eliminate the thickness of any coating. Thickness readings were taken on a grid pattern with readings taken at (30 cm) intervals for the length of the pile in two (2) rows by a CGSB 48.9712 UT-2 certified inspector in accordance with ASTM E797.

The above noted section loss measurements correspond to average annual section loss of 0.004, 0.005, 0.008, and 0.024mm respectively, over the past 56 years since the piles were installed in 1967. The calculated overall average annual section loss is below the values set in the Guidelines (e.g.



Figure 8 – Heavy corrosion scale near the bottom of the pile was noted on the web.

0.015mm per side of pile in Eurocode and BS8002 2015 and Ottawa LRT Specifications, and 0.025mm per side of pile in CALTRANS). It should be noted that the average annual section loss calculated does not account for the coating effect and the attack on the web and flanges would occur from both sides. Further, the corrosion mechanisms for buried piles are not linear, but rather they tend to follow a geometric function that increases with time. When discussing corrosion rates, it needs to be understood that these values are averages across specific time periods that are used to simplify complex corrosion mechanisms to make the comparison easy.

Soil and Groundwater Analysis

Two boreholes were advanced near the center pier location and monitoring wells were installed

Table 1 – Soil and groundwater chemical testing results

Parameter	Soil Sample 1 (S1)	Soil Sample 2 (S2)
pH	7.74	7.82
Resistivity	7,400 ohm-cm	4,300 ohm-cm
Chloride	Not Detectable	Not Detectable
Sulphate	Not Detectable	75 µg/g
Parameter	Water Sample 1 (MW1)	Water Sample 2 (MW2)
Alkalinity	240 mg/L	190 mg/L
Chlorine	Not Detectable	Not Detectable
pH	8.19	8.24
Resistivity	420 ohm-cm	1,500 ohm-cm
Sulphide	Not Detectable	Not Detectable
Chloride	520 mg/L	60 mg/L
Sulphate	100 mg/L	51 mg/L

in each of them. The groundwater level was measured at 1.0m to 1.2m below grade. Soil samples collected from each borehole were submitted for inorganics (pH and resistivity) and anions (chlorides and sulphates) analysis. Groundwater samples from the monitoring wells were submitted for inorganics (alkalinity, chlorine, pH, sulphide and resistivity) along with anions (chlorides and sulphates). A summary of the results is included in table 1.

The results of the soil and groundwater corrosivity tests were compared to table 2, 3, and 4 of the European Committee for Standardization EN1993-5, Eurocode 3 – Design of Steel Structures- Part 5, Piling.

The following conclusions can be drawn:

- Groundwater with chloride level at 520 mg/L indicates moderately corrosive.
- Chloride and resistivity results indicate that the soil is mildly corrosive, which is in agreement with those of two soil samples collected from north and south abutments during earlier foundation site investigation and design stage.
- pH content of the soils and groundwater tested indicates non-corrosive (alkaline) and neutral environment.

Geophysical Testing

Since no pile driving records were available for this site, two (2) different down-hole geophysical testing methodologies were employed to estimate the length of the vertical piles at the south abutment: 1) Borehole Magnetometer Testing, and 2) Downhole Parallel Seismic Testing.

The borehole magnetometer test results indicated an anomaly at a depth of approximately 8.5 m which is not present for the accelerometers. This is indicative of the presence of a strong magnetic (metallic) anomaly without a major change in

soil/rock density and is likely an indication of the bottom of the pile.

The downhole seismic testing also indicated a strong response at a depth of approximately 8.5 m. In this case, the wave generated by striking the pile travelled down the pile until a change in acoustic impedance was encountered, causing the wave to reflect back and be recorded by the geophones. The velocity of the wave travelling through the steel is around 5,000 m/s which contrasts with the soil and bedrock ($\leq 1,800$ m/s). The reflection of the wave was detected at a depth of approximately 8.5 m, which corresponds well with the inferred bottom of pile from the borehole magnetometer testing.

The estimated pile tip is at a depth of approximately 8.5 m below the top of casing for the down-hole geophysical testing, which corresponds to elevation 80.5 m. This agrees well with the top of bedrock (80.6 m) identified during the drilling to install the casing and elevation 80.4 m from a historical borehole from the original bridge construction.

Pile Capacity Assessment

The design load for the piles from the original bridge was not provided on the structural drawings.

Table 2 – Effects of chlorides on corrosion potential

Inorganic Chloride Concentration (ug/g)	Degree of Corrosivity
Above 600	Very Corrosive
200 to 600	Moderately Corrosive
50 to 200	Mildly Corrosive
Below 50	Non-Corrosive

Table 3 – Effects of resistivity on corrosion potential

Soil Resistivity (Ohm.com)	Degree of Corrosivity
Below 500	Very Corrosive
500 to 1,000	Corrosive
1,000 to 1,500	Mildly Corrosive
1,500 to 10,000	Progressively Less Corrosive

Table 4 – Effects of pH on corrosion potential

pH Range	Degree of Corrosivity
Below 5.5	Very Corrosive
5.5 to 6.5	Moderately Corrosive
6.5 to 7.5	Neutral
Above 7.5	None (Alkaline)

Table 5 – Pile factored structural resistances

Level of Corrosion	Pile Factored Structural Resistance (12BP53)
No pile corrosion or section loss	1200 kN/pile
12.5% section loss due to pile corrosion (2023 at 56 years of age)	1050 kN/pile
50% section loss due to pile corrosion (2058: 35 year service life extension)	600 kN/pile

The original geotechnical report indicated that if a piled foundation is used, the load capacity of both cylindrical and H section piles should be calculated on the basis of their ultimate structural capacity when considered as a short column.

The corrosion assessment carried out at the site indicated 12.4% section loss at the abutment piles in 2023 and based on the anticipated corrosion rate, predict 50% section loss within 35 years (i.e. by 2058).

The factored axial compressive resistance of the 8.0 m long 12BP53 piles assuming steel strength of 230MPa and applying the resistance factors from sections 6.11.4.4 and 10.22.2 of the CHBDC were estimated and are summarized in table 5.

The results of the geophysical testing suggest that the piles were installed to bedrock as indicated on the historical contract drawings. The bedrock at this site has an unconfined compressive strength of over 200MPa. Based on local practice, supported by empirical correlations and historical pile load tests, the factored geotechnical resistance at ULS would be greater than the structural resistance of the steel section for a steel pile driven to strong bedrock.

Conclusions

Visual inspection of the extracted piles revealed that the piles had been coated before being driven. The coating will have impacted the rate of corrosion over the life of the piles. At the center pier, little evidence of corrosion is noted along the webs and flanges. Corrosion was identified on the piles from the south abutment. Corrosion was more noticeable in the lower portion of the piles than the upper portion. The possible explanation would be 1) Coating in the upper portion remains intact providing good protection on steel piles; 2) Lower portion where coating was scraped off during installation leaving the steel exposed to soil/groundwater subjected to corrosion (anode). Relatively high chloride and low resistivity detected in groundwater could have accelerated the corrosion process; and 3) air/oxygen could travel down to the bottom of the short piles as groundwater is fluctuating.

The borehole magnetometer testing provided a good indication of the pile length, which in combination with the borehole data, provided confirmation that the piles had been driven to bedrock.

At this site, design loads were not available to make a direct comparison between the available resistance and demand loads. However, the estimated section loss (up to 50% within next 35 years) suggest that it would have been difficult to achieve an acceptable service life for a new superstructure while reusing the existing foundations.

This project is demonstrative of MTO's commitment to assess technologies and applications that support Ministry's initiative and operational needs and specifically to encourage the reuse of existing foundations.

Acknowledgements

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Contact

Tony Sangiuliano
tony.j.sangiuliano@ontario.ca
Brady Lin
brady.lin@ontario.ca
Paul Carnaffan
pcarnaffan@thurber.ca ●

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KELLER GROUND IMPROVEMENT WITH STONE COLUMNS FOR A LARGE WAREHOUSE IN EMMEN (NL)

Introduction

The project located in Emmen (NL) is a large warehouse of 60,000 m². The building structure and slab will be installed on ground improved with stone columns, in order to reduce the overall building settlement.

The design is carried out using Finite Element Method (FEM) software Plaxis 3D to take into account the three-dimensional behavior of isolated footings including stone columns underneath.

In the Netherlands, similar projects are usually constructed on piles, using large quantities of concrete and steel. The use of stone columns significantly reduces the carbon footprint of the material itself, even more considering Recycled Concrete Aggregate (RCA). The application of

stone columns is relatively unknown in the Netherlands, which presents new challenges for both the contractor and the reviewing municipality. Ultimately, the safety and usability of the building must be proven.

The expected properties of the used materials and behavior of the ground improvement need to be known. The purpose of the test program is to check whether the design matches with the tests and secondary what influence the constitutive material of the stone columns, either Natural Stone Aggregate (NSA) or Recycled Concrete Aggregate (RCA) might have.

Therefore, the material properties for the ground improvement design have been determined from

laboratory tests on the proposed materials and soil investigation on site. In situ static load tests were carried out after which the results were calibrated with the numerical model. Finally, the settlements will be monitored for some time during the building's reference period. In advance, clear requirements have been agreed in terms of bearing capacity, allowable settlements, and relative rotations.

Stone column definition

In the future Eurocode 7 part 3, ground improvement with stone columns is defined as follows: *Compacted stone columns are created in the ground to form a composite ground with the surrounding soil. Most often used in soft cohesive soils, but in granular soils as well to improve strength and stiffness of the overall system and accelerate drainage with possible densification of the surrounding soil depending on the soil type.*

The ground improvement with stone columns is classified as BI: Family B = Discrete element and Class I = Non-Rigid columns.

The execution standard EN 14731:2005 – Execution of special geotechnical works – Group treatment by deep vibration, refers to the stone columns installation.

Testing program details

Twelve stone columns were installed for three group load tests, four for isolated load tests and another four for additional in-situ or laboratory testing.

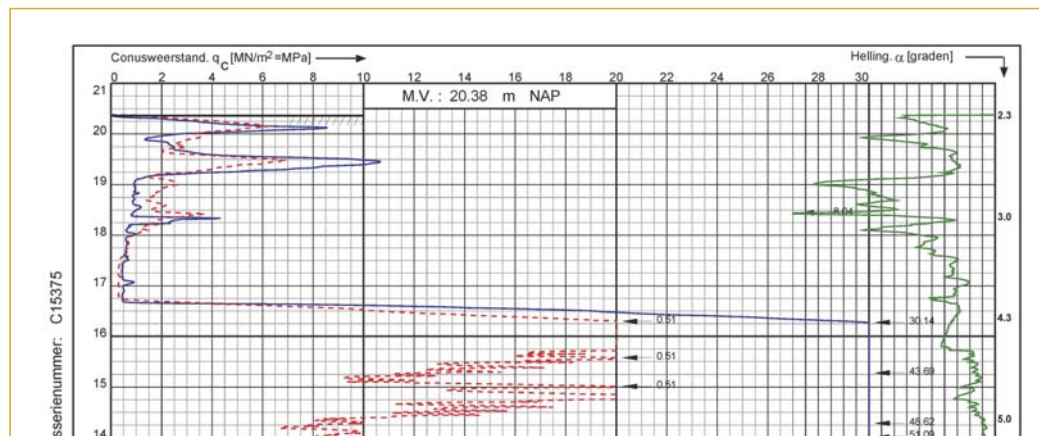


Figure 1 – Typical CPT profile.

Class	Family	
	A – Diffused	B – Discrete
I	AI – Diffused with no unconfined compressive strength The improved ground has an increased shear strength higher than that of the original ground. The improved ground can be modelled as a ground with improved properties.	BI – Discrete with non-rigid inclusions Inclusions, installed in the ground, with higher shear capacity and stiffness compared to the surrounding ground. The unconfined compressive strength of the inclusion is not measurable.
II	AII – Ground improvement zone with unconfined compressive strength The improved ground is modified from its' original natural state, has a measurable unconfined compressive strength and is significantly stiffer than the surrounding ground. Usually, it comprises a composite of a binder and ground.	BII – Discrete with rigid inclusions Rigid inclusions, installed in the ground, with unconfined compressive strength significantly stiffer than the surrounding ground. The inclusions can be an engineered material such as timber, concrete/grout or steel or a composite of a binder and ground.

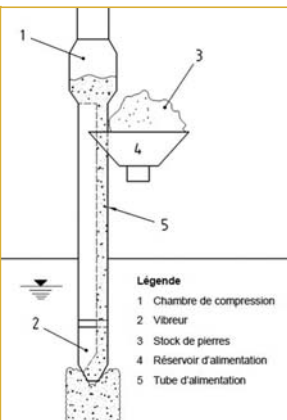


Figure 2 and 3 – Classification of ground improvement in the future Eurocode 7 part 3: EN 1997-3 and stone column installed by bottom feed system.

MATERIAL PROPERTIES

The material properties were classified according to European standard EN933-11: Tests for geometrical properties of aggregates – Part 11: Classification test for the constituents of coarse recycled aggregate. Table 1 compares the test results of NSA and RCA.

For RCA, a sulphate content of 20 mg/l (0.02%g/l) was measured, which is well below the requirements usually defined in literature as a variable upper limit from 0.2%(g/l) to 1.5%(g/l). This material also complies with the Dutch regulation establishing end-of-waste status of RCA.

For both materials, grain size analysis was performed.

SUMMARY

Keller has recently performed ground improvement with stone columns below both slab and structure of a large warehouse in Emmen (NL). The project was complemented by an extensive test program on the improved ground. In this test program a series of load tests and laboratory tests were made on two different aggregates, Natural Stone Aggregate (NSA) and Recycled Concrete Aggregate (RCA). The tests were conducted to validate Keller's ground

improvement design using Plaxis 3D for the warehouse to be built, as well as determining the suitability of using RCA in the columns. The testing program has shown good results which confirm the possibility to carry out low carbon footprint ground improvement for warehouses. Keywords: Ground improvement, Stone column, Load test, Natural stone aggregates, Recycled concrete aggregates, Plaxis 3D

med before and after installation. The materials show a coefficient of uniformity before installation of 3.0 and 1.5 for respectively NSA and RCA which increased to 14 and 20 after installation. The RCA shows a more graded material after installation which is in line with the Los Angeles test results of 46 compared to lower LA of 31 for NSA.

Using Creager's equation (1945) to calculate material permeability, permeability is still in the range of gravelly materials with respectively $2E^{-2}m/sec$ for NSA and $3E^{-3}m/sec$ for RCA. Therefore, whatever material is used, the column permeability stays well above the permeability of surrounding cohesive soils and the stone columns maintain the drainage capabilities.

Some CPTs were performed inside the installed stone columns with two CPTs for each material type. The results were fairly similar, showing cone penetration resistance q_c in the range of 10 to 12MPa for both materials.

The stone columns were also excavated in half-meter increments to two meters deep (ground-water level). At each level, the diameter of the stone column was measured, a nuclear density test was carried out and additional grain curve analysis was carried out as shown in P. Schaubert (2024).

Some direct shear tests were performed on non-compacted samples and at different confined stresses.

The RCA shows a residual friction angle of 44° , which is in the same order of magnitude of the mean value for NSA of 45° . The friction angle of 42° considered for the design is on a conservative side when compared to the peak and residual friction angles as shown in table 2.

LOAD TESTS RESULTS

In addition to the numerous laboratory tests carried out, the load tests provide the best comparison possible between the different materials used. The graph below shows the results of four isolated load test ($1.0m^2$ up to $600kN/m^2$) and two group load tests on four stone columns ($6.0m^2$ up to $400 kN/m^2$):

The results show corresponding behavior in the ground improvement performance. It is concluded

Table 1 – EN 933-11 classifications for both materials

Abbr.	Constituents	Unit	Natural stone aggregate (NSA)	Recycled concrete aggregate (RCA)
Rc	Concrete, concrete products, mortar, concrete masonry units	[%]	0	86
Ru	Unbound aggregate, natural stone, hydraulically bound aggregate	[%]	97	0.9
Rb	Clay masonry units, calcium silicate masonry units, aerated non-floating concrete	[%]	2.7	12
Ra	Bituminous materials	[%]	0	0
Rg	Glass	[%]	0	0
X	Other materials: plastics, rubbers, metals (ferrous and non-ferrous), non-floating wood, and stucco	[%]	0.2	0.2
FL	Floating particles	[cm^3/kg]	0	0

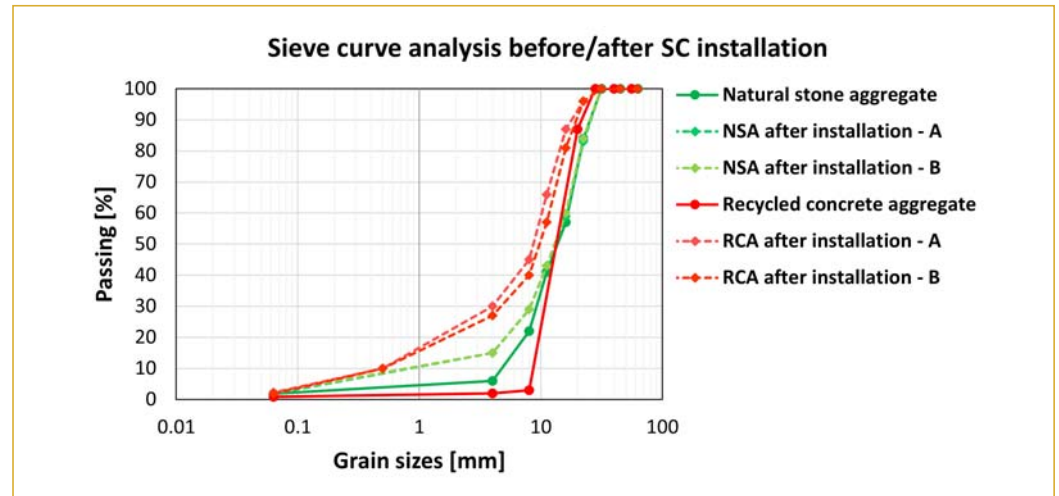


Figure 4 – Grain size analysis before/after stone column installation.

that the RCA, besides its more crushable behavior, is as efficient as NSA to mitigate the settlement and improve the soil bearing capacity.

Keller Stone Column Design

The design of the ground improvement within Keller is usually done using the Priebe method. For this project however, the design was carried out with Plaxis 3D which allows for more accurate soil modelling behavior, realistic construction sequence, as well as exact structural load input including axial horizontal load, as well as bending moment.

Table 2 – Friction angle extracted from direct shear test.

	Natural stone aggregate (NSA)			Recycled concrete aggregate (RCA)
	1	2	3	
c' (kPa)	0	0	0	0
ϕ' peak ($^\circ$)	54.0	48.3	48.4	46.0
ϕ' residual ($^\circ$)	46.5	44.1	44.0	43.7

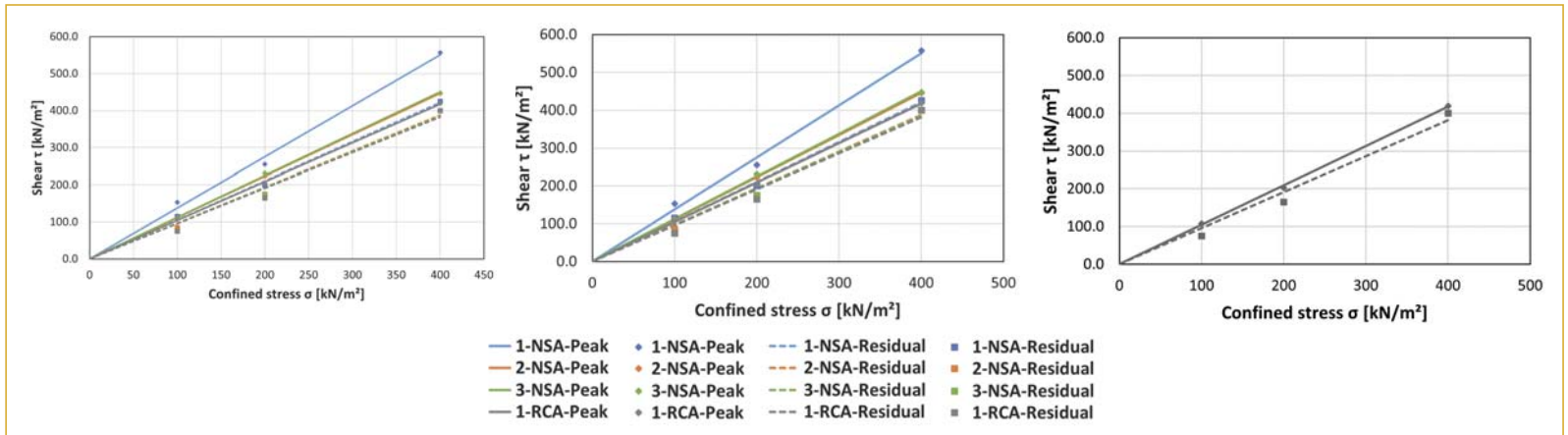


Figure 5a-b-c – Interpretation results of direct shear tests.

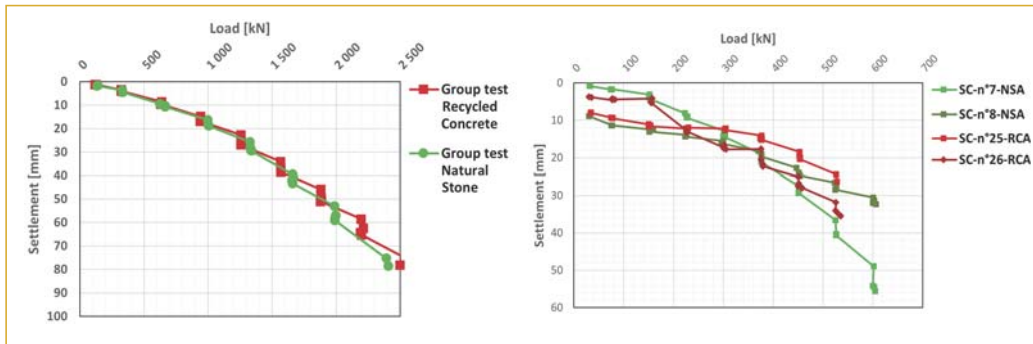


Figure 6a-b – Group and single load test results.

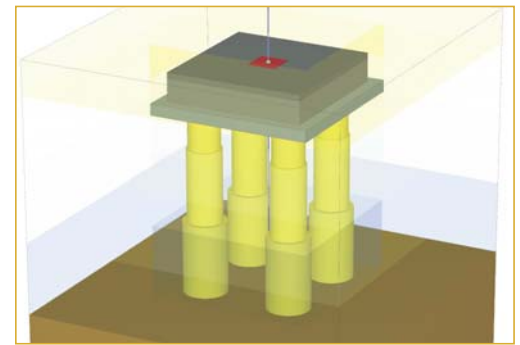


Figure 7 – Plaxis 3D model.

Carbon footprint comparison

A carbon footprint comparison has been made between HSP piles and stone columns, considering the two types of materials and detailed in P. Schaubert (2024). The CO₂ impact reaches about 1,100 tons with HSP piles when it decreases to 430 tons and even 270 tons for respectively stone column with NSA and RCA.

The combination of the stone columns carried out with RCA shows a carbon footprint impact so low that mainly the carbon impact of the rigs remains. The latter is currently being solved by the development of electric Keller VibroCAT rigs.

Conclusion

The load test program has shown that the ground improvement with stone column provides efficient settlement mitigation and bearing capacity improvements for both NSA and RCA. It also confirms the modelling assumptions using Plaxis 3D. The test results show that the loaded area should be large enough and loading time long enough to allow for complete settlement.

In overall, it confirms Keller on the suitability of the ground improvement solution with stone column below a warehouse for both slab and structure. Combining stone columns and RCA truly reduces the carbon footprint of the deep foundations compared to a classical piling solution.

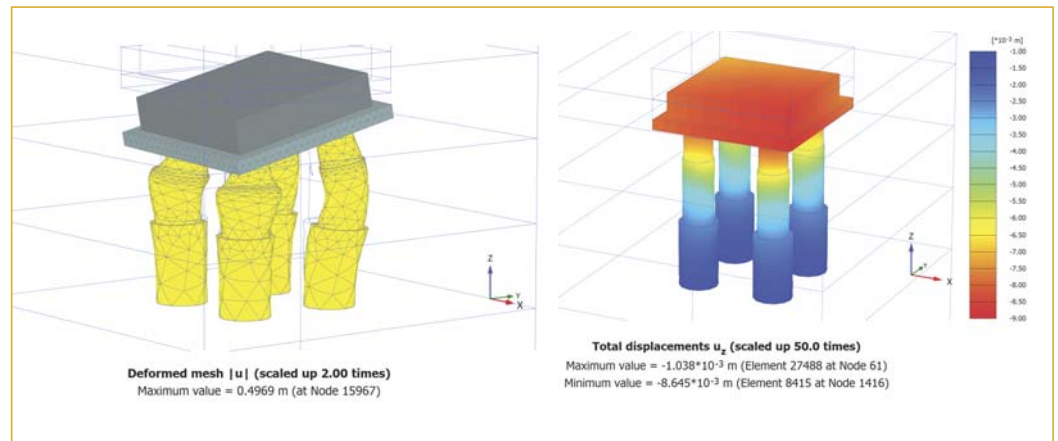


Figure 8a-b – Plaxis 3D results - deformed mesh at failure and settlement results.

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Contact

Aida Jusufagić
+31611123483, A.Jusufagic@emmen.nl
Pascal Schaubert
+33673415730, pascal.schauber@keller.com
Marcel Mertens
+31610026272, marcel.mertens@keller.com
Bas Snijders
+31643421572, snijders@cruxbv.nl
Hidde Wieringa
H.Wieringa@emmen.nl ●

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Geotechnical Consultant
Fugro, the Netherlands

SUSTAINABLE USE OF FOUNDATIONS IN CIVIL ENGINEERING INFRASTRUCTURE

In our commitment to reduce carbon footprint, it is increasingly common to investigate whether existing pile foundations can be partially or even fully re-used in the reconstruction or remodelling of existing buildings. However, such thinking is rarely applied on a large scale for critical infrastructure. This could all now change, thanks to Fugro's artificial intelligence (AI) generated ground modelling that has seen the reuse of foundations to viaducts in the widening of the A9 Badhoevedorp-Holendrecht.

Client vision

Rijkswaterstaat was keen to look at the possibility of reusing foundations to 11 viaducts being rebuilt as part of an 11 kilometre long widening scheme on the A9 motorway. This offered an opportunity to reduce carbon footprint by reusing viable parts of the pile structures, and also save on project time, cost and materials.

In its design tender, contractor, VeenIX, identified the foundations eligible for reuse. Fugro was then asked to recalculate the existing piles to help

determine absolutely the risks in each location and inform the design solutions.

Identifying geo-risks

Fugro planned and conducted its Geo-data mapping in stages, to create a detailed and accurate ground model of ground risk and recent change in soil properties. Together with the verification of the pile tip levels, this subsurface view was fundamental in forming confidence in solutions for the client and project team.



Photo 1 - Overview of A9 motorway near Amstelveen after reconstruction.



Photo 2 – No less than 2,500 CPTs and boreholes were conducted.

The process began with desk studies. The emphasis was on the analysis of existing soil investigations, including Fugro's own soil data and laboratory testing from previous site investigations in the area. Data retrieved during this research was vital in establishing the geotechnical soil parameters and criteria for the project site investigation involving no less than 2,500 cone penetration tests (CPTs) and boreholes.

In fast tracking usable information to the client in 3D, Fugro used AI to help identify and interpret the huge volume of CPT data, with quality control confirming almost 100 % dimensional accuracy. The rich data model allowed the client to readily identify specific risk areas in the subsoil, and track the course of any weak soils through the site, also in 3D.

With Fugro acting as the geoengineering partner to the design specialists, subcontractors and Rijkswaterstaat, its ground model plays a central role in all decisions on safe foundation reuse.

Quality control of the reconstructed foundations was assured by Fugro's monitoring plan. Deviations during implementation can be monitored by means of surveying rods, water pressure gauges, inclinometers and monitoring wells and immediately interpreted and validated against design requirements.

Complying with current standards

The success of the project rested partly on the reuse of foundations that had been constructed in the 1960s/1970s.

Standards for foundation design were different then, so special calculation standards exist for the reuse of old piles, the most important condition

SUMMARY

In our commitment to reduce carbon footprint, it is increasingly common to investigate whether existing pile foundations can be partially or even fully re-used in the reconstruction or remodelling of existing buildings. However, such thinking is rarely applied on a large scale for critical infrastructure.

This could all now change, thanks to Fugro's artificial intelligence (AI) generated ground modelling that has seen the reuse of foundations to viaducts in the widening of the A9 Badhoevedorp-Holendrecht.

being that the pile load does not increase by more than 15 %. Above this, the foundation redesign for the A9 viaducts would have had to comply with normal current standards and the existing piles would not have met the required bearing capacity. In conclusion, Fugro's data helped to verify that the pile foundations for 5 of the 11 viaducts could partially be re-used. Fugro has provided calculations for the foundation redesign concept for one of the viaducts, near Amstelveen.

Calculation rules

In close consultation with the structural engineers, the estimated weight increase that the existing piles would need to bear was 11 %. This was within the 15 % margins, although the initial design was short of achieving the pile-bearing capacity. However, the data model provided sufficient points of reference to proceed through the use of additional control measures.

In the case where bearing capacity is not achieved, it is permitted to conduct additional CPTs, for example, to further determine the homogeneity of the soil. A correlation factor for the number of soil tests is incorporated into the calculation rules. This often becomes more favourable with multiple soil surveys, enabling additional bearing capacity to be allocated to the existing pile foundation.

Other considerations in combining old and new

The existing piles combined with the new piles must ultimately form the foundation of the new viaduct. The old piles are less stiff, as they were driven down less deep into the Pleistocene sand. Using current calculation rules, the new piles needed to be installed much deeper to achieve the required bearing capacity. In the case of this specific civil structure, the new piles that are installed use a steel casing causing variations in stiffness of the foundation that can have a negative impact for the load distribution within the foundation, and must also be taken into account in the design. Consideration should also be given to preventing installation damage or a temporary reduction of the bearing capacity of the old foundation due to the installation of new piles.

Sustainability and cost efficiency

We included 208 existing piles in the final design



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



Photo 4 – Where bearing capacity is not achieved, it is permitted to conduct additional CPTs.

of the new foundation, saving approximately 1,200 tons of CO₂ emissions. Every pile that does not need to be installed saves on concrete, reinforcement and transportation, also saving time and money.

Foundation of this viaduct has been redesigned with the contribution of our Geo-data and

mapping, modelling and monitoring expertise. The reuse of this foundation alongside that of the other 4 viaducts will add significantly to the overall project sustainability and budget savings – proving that AI-enhanced Geo-data modelling is robust enough to shoulder foundation reuse on large infrastructure. ●



G.A. van Zwieten MSc
Volker Staal en Funderingen,
Dordrecht, The Netherlands



D. Werner MSc
Volker Staal en Funderingen,
Dordrecht, The Netherlands



E. van der Weij Bsc
Betontechnoloog.nl (former
Van Hattum en Blankevoort),
Leerdam, The Netherlands

REUSE AND TREATMENT OF SPOIL FROM THE JET GROUT PROCESS

Koopvaarderschutsluis

The “Koopvaarderschutsluis” is a lock, situated in the North of the Netherlands and forms a connection from a canal, the “Noord-Hollands kanaal” to the “Waddenzee”, at the city of Den Helder. The construction of the lock is a concrete lock head with mitre gates and a lock chamber of a sheet pile wall with a relief platform on top of it. The sheet pile wall is suffering from corrosion because of MIC and is degrading. In night shifts, patchwork has been done to solve problems for the short term, but this isn’t a durable solution. A solution is found in a collaboration with the Province of North Holland and Van Hattum en Blankevoort. An innovative solution was found to extend the technical lifespan of the lock by jet grouting. While the lock is under construction, the lock will remain in use. When the jet grouting is finished, the sheet pile wall may corrode. In figure 1, a cross section is shown of the technical solution.

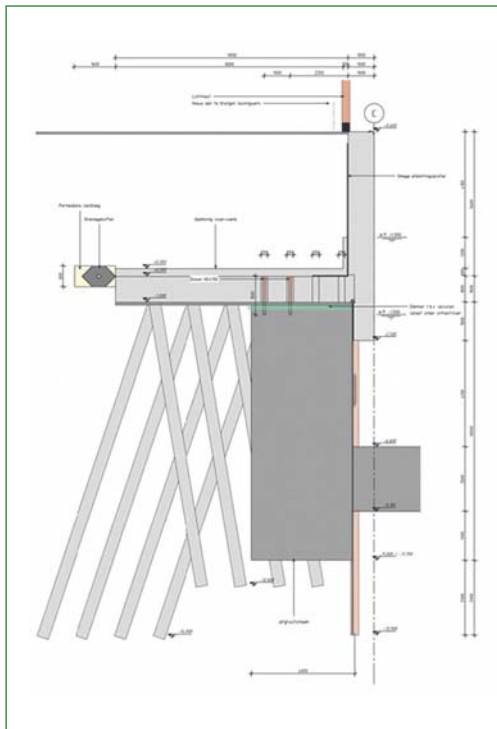


Figure 1 – A mass of jet grouting (dark grey) is made as a final construction, forming a retaining wall and foundation behind the patched sheet pile wall (orange), underwater concrete at the lock chamber side is also dark grey.

Jet grouting is done in a temporary building pit from lockhead to lockhead. Excavated to the topside of the relief construction. To make a good connection for the temporary building pit to the lock, also jetgrouting is used. In figure 2 a view of the rig in the building pit is shown.

Trail

The Netherlands is a river delta with a soil composition of thin layers of fine sediments including fine sands, silts, clay and peat. In Figure 3, a CPT is shown to have a view on the soil composition. To optimize quality and usage of materials, a test has been performed by producing nine jet grout columns. All the produced spoil was treated by an improvised temporary plant.

First step was desanding the pre-cutting and the jet grout spoil. After the first step, dewatering of the desanded slurry was done by a decanting centrifuge. So the work itself is like solids control, just like reusing bentonite when you are making a diaphragm wall with a hydrofrais. Would it be that simple, and why aren’t we doing this already? Main problem is a using a hydraulic binder, you can’t leave the binder in your machines, while it will gradually gain strength while a hydration process is commencing. If cleaning isn’t done properly, you won’t be able to keep it running, key is having equipment which is cleanable in its heart and not only at the positions you can have a visual inspection.

By not treating the spoil, you keep it KISS. But this will take a lot of space, which is not always available. You have to use some basins which enable for curing. As we all know, one will not be sufficient, three basins is a minimum, with one basin for a day production, a second for the curing of at least a day, a third for digging it out and prepare it for tomorrow’s day production. When the plan is less ideal, a fourth is needed, to have a longer curing time. Next to the basins, you have to have also room for your logistics, able to reach every corner of your basins. And have some room for stock of the cured spoil to load and transport. reuse can usually be questioned, because of different qualities within one stockpile, which makes it most of the time a low grade reuse product.

Maybe going not the KISS way, but trying to innovate to make not a waste product, but better try to make some semi-finished products which can be re-used, having a higher grade use. Some of the outcomes of the process may be used again in the process of the jet grouting, while others can be ideally re-used on site, or stocked for reuse elsewhere.

So the trail for the jet grout columns was multiple. Getting the right strength and stiffness of the columns, getting the right diameter, minimizing your footprint used for the whole process, getting reusable semi-finished products and knowing it’s quality and quantity and as always,



Figure 1 – Photo of the jet grouting rig on the relief platform in a temporary building pit.

SUMMARY

The ground improvement technique jet grouting always gives a large amount of return grout. The aim is to reduce the quantity of groutspoil and upgrade them to facilitate reuse. The “Koopvaarderschutsluis” project was used as a test project for the spoil treatment. While the technical lifespan of a lock is

being extended, the lock remained in use. You will be taken through the steps taken to reduce the carbon footprint. In the end, after conducting an initial trial, the feasibility was proven and the further steps can possibly be taken in future to take reuse of residual materials one step further.

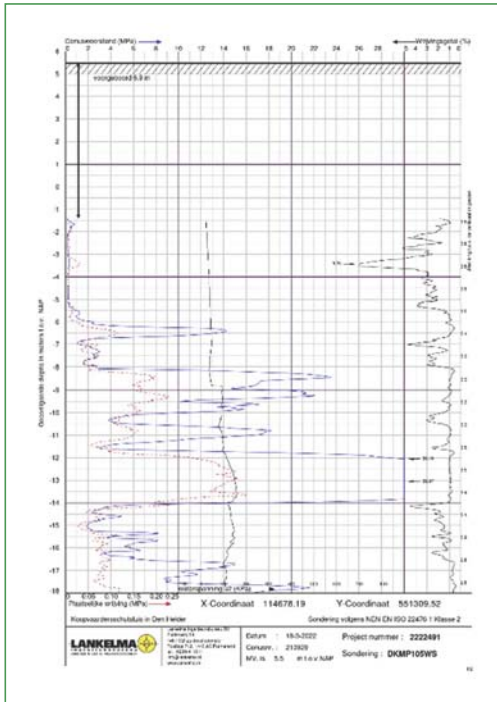


Figure 3 – CPT DKMP105WS.

also looking at the robustness and the financial feasibility. In figure 4, you can see the process

After the trail, decision is made to do pre-cutting on the upper half of the columns, since this was the best choice using the raw materials in an economical way, to get the right strength and stiffness in combination with a minimum carbon footprint on the jet grouting itself. Next to the jet grouting, a reduction on the footprint is achieved by reducing the quantity of the spoil with the treatment plant.

Treatment Plant

After doing the trail, some improvements were implemented since the equipment had to be made fit for purpose to handle the hydraulic binder, and having the right cleanability. Next to that, some buffers were made, to have some redundancy on the chain of equipment. Jet grouting is an equipment intensive ground improvement technique, and with adding the treatment plant to it, it is even more equipment intensive.

To get some idea of the materials in the spoil and also what sort of fines are in the soil, some sieve

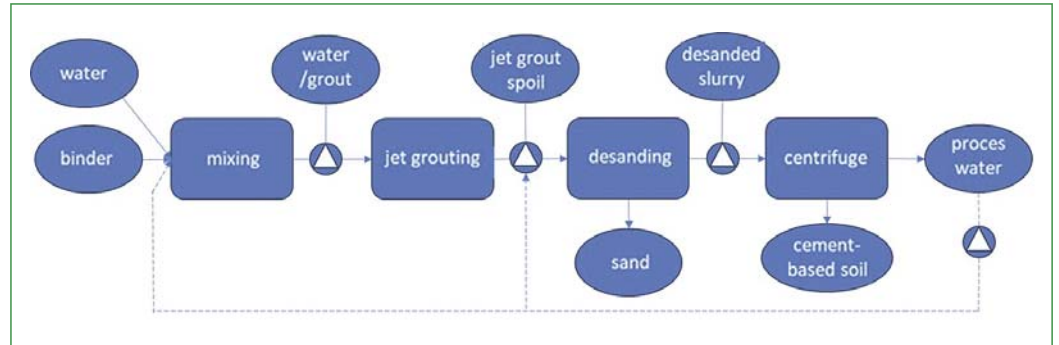


Figure 4 – Jet grout and spoil handling process.



Figure 5 – Spoil treatment plant, with desander, centrifuge and small laboratory (Topview-fotografie).

analysis are done by laser diffraction. In figure 5 some different curves are shown, the yellow and pink curves are clay and sand with less or more silt in it. The purple, red and green, are the untreated spoil, desander sand and the output of the centrifuge in a form we call cement-based soil or an also used name on site is cement-paste. It's like a clay with a lot of cement in it, think of a mass % of about 40% cement. On the right, a last curve is shown in brown, this curve is the same cement-based soil which has binned and is crushed. In figure 5, a photo of the treatment plant is shown.

Desanding of sand is also different when it is mixed with a hydraulic binder instead of a bentonite. It is of utmost importance to choose the right sieves and hydrocyclones to get a dewatered sand with right quantities of cement and fines for the reusability, but also getting enough fines out, before the stage of the decanting centrifuge. At first the cement content in the sand was on an average level of 7%_{m/m}. Later on,

we managed to decrease the cement content to 2-3%. In figure 6, the sieve curves are shown.

Carbon Footprint

Probably every country is looking and searching for a sort of scales to measure the impact of a technique. Carbon footprint is the most general one of these. In the Netherlands another scale is mostly used, named “Milieu Kosten Indicator”, in English this would be Environmental Cost Indicator. It is a method which takes eleven environmental effects into account. For the this paper, only the Carbon Footprint is looked at. At first an important disclaimer, some figures are made about carbon footprint, for jet grouting at the project of the lock. As jet grouting is a ground improvement technique, it can have all sorts of forms, sizes, strength, so you can't give a general value of what is the carbon footprint of a jet grout column, or what is the carbon footprint of spoil. What can be said in general about jet grouting, it uses a lot of binder, and the binder takes a lot of the footprint. So 2 figures are made, one with the

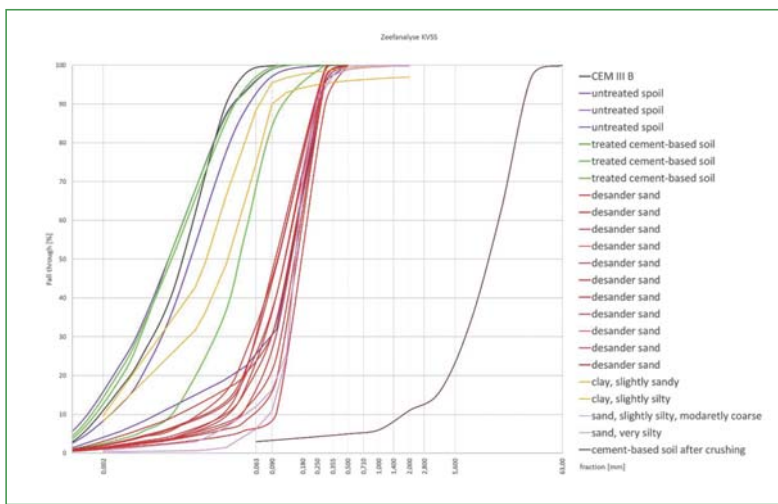


Figure 6 – Sieve curves of the soil, treated and untreated products of the jet grouting.

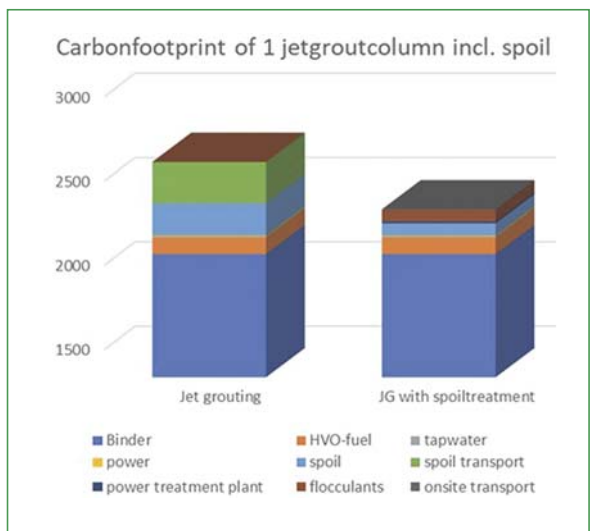


Figure 7 – Carbon footprint of 1 jet grout column at the project “Koopvaarderschutsluis.”

jetgrouting and spoil as a whole, and one taken out the jet grouting part, only looking at the spoil.

In figure 7, it’s clear that the binder is taking the vast majority of the footprint. At the lock project blast blast furnace slag cement cement is used, which has a better performance on footprint then a Portland cement. The difference in the two columns is the treatment of the spoil. Only the binder is responsible for 80 to 90% of the footprint. So a second figure is made, taking out the jet grouting itself, only looking at the spoil part. The total reduction of the carbon footprint of a jet grout column with spoiltreatment is 10%. The reduction of the carbon footprint for the spoil only by treating is 64%

Figure 8 – Carbon footprint of the spoil of 1 jet grout column at the project “Koopvaarderschutsluis.”

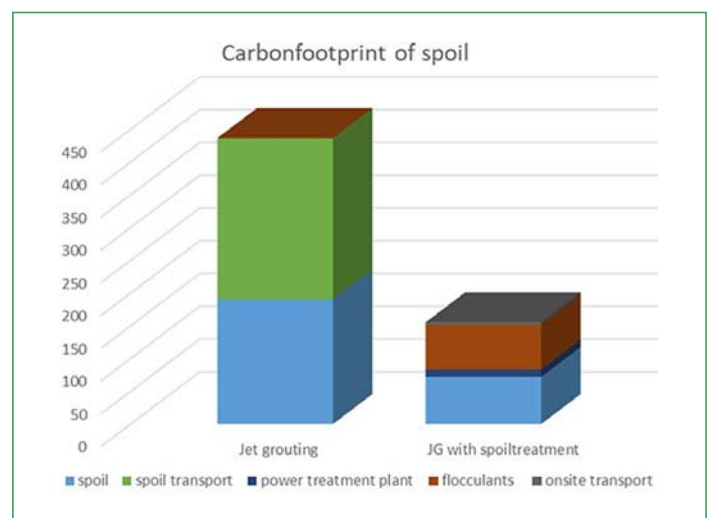


Figure 8 shows the spoil. The footprint of the non-treated spoil is made by tonnage of the waste and the transportation of it, in this case 50 km of transportation is chosen. As you see, like is said in the disclaimer, footprint is highly dependent on every project. The right column is the treated spoil, footprint is mostly affected by the tonnage of the dewatered spoil, as the sand is free of burden. Another part is taken by the flocculant. As the quantity added is small, the impact per kg of the flocculant is high, it is taking a large part of the footprint. Despite of this, it is obvious that, looking at the footprint, using spoil treatment is a good solution to lower the overall footprint, and making less waste tonnage and a better quality products for reuse. The proceswater taken out, can be re-used for the pre-cutting. When proceswater is discharged, it has to be neutralized, the water has a high pH because of the binder.

Further developments

As always, as first steps are taken, next steps will follow. So for the future, we want to explore further process reuse. It has become clear that the binder contributes a lot in carbon footprint, but is a very important part of generating strength and stiffness, like a steel structure, you can’t take

out the steel. With enough research it must be possible to check if the characteristic strength has enough safety, to lower the cement content and use for instance a part of limestone filler, or using a geopolymers binder. Care has to be taken off course, not to end up with a finished product which doesn’t comply, as the strength will always have a distribution, working with the local subsoil. Another step at the spoil treatment, could be, reusing a desanded grout. So the binder usage is also lowered, but as already is said, you have to keep an eye on the requirements of strength and stiffness by taking these steps. When using jet grouting in a sandy subsoil chances are better than having clay and fine silts in your subsoil, which has a comparable size to the binder. It is hard to separate solids of the same size. Having a small percentage in your grout of clay or silt, this will be of large influence on the strength.

Steps for the flocculant and automation of the cleaning are also on the mind, as cleaning will always take time.

Conclusion

Jet grouting will always be a technique which can be used to make a large element through a small hole in an existing construction. Makes it a good

technique for revitalisation and can be used on existing buildings and structures. While the overall carbon footprint of the technique can be high. Saving the effort of demolition and rebuilding a new building is the real gain on the environment. By using a treatment plant for groutspoil parting, the carbon footprint can be reduced by 10% or more for the whole and for the spoil part of the technique the carbon footprint is reduced by 64%. It is of importance to further innovate on the groutspoil treatment process.

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Contact

- G.A. van Zwieten G.vanzwieten@vsf.nl
- D. Werner D.Werner@vsf.nl
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Cécile Prüm
Author
ArcelorMittal Global R&D,
Esch sur Alzette
Luxembourg



José Humberto Matias de Paula Filho
Author, ArcelorMittal Global R&D
Esch sur Alzette, Luxembourg



João Martins
ArcelorMittal Sheet Piling
Esch sur Alzette,
Luxembourg



Oliver Gregor
ArcelorMittal Träger
und Spundwand
Bochum, Germany

LIFE CYCLE ASSESSMENT OF UNDERGROUND CAR PARKS - CASE STUDY GERMANY

The authorities of European cities promote heavily public transport to reduce traffic inside urban areas, but cars are still the preferred means of transport. The lack of parking spots grows, so that underground car parks (UCP) can be part of the solution. A recent study by a Dutch design engineering firm for ArcelorMittal analysed several retaining wall alternatives for the construction of the retaining walls of UCPs in the Netherlands and established that the solution with a permanent steel sheet pile wall is more cost-effective and has a lower carbon footprint. This solution is however rarely used for UCPs in Germany, despite their long experience with steel sheet piles in port construction. Hence, ArcelorMittal hired in 2022 a German design engineer to perform a similar study for the German market.

The technical analysis compares a retaining wall to be built in the region of Berlin, with its typical soil conditions (soft soils over a competent sand layer, with a shallow groundwater table). Four technically equivalent systems have been selected: a permanent steel sheet pile (SSP) wall, a temporary SSP wall with a permanent reinforced concrete (RC)

wall executed inside the excavation pit, a secant pile wall, and a diaphragm wall. A Berlin wall (soldier pile and lagging) and a Cutter Soil Mix (CSM) wall have been disregarded for technical reasons by the German engineers.

The cost analysis shows that the temporary sheet pile wall solution is slightly cheaper than the permanent SSP wall, whereas the two other concrete alternatives were around 20% more expensive.

A Life Cycle Assessment performed by ArcelorMittal considers all the life cycle stages according to ISO 14040, ISO 14044 and EN 17472, including the end of life (EoL) scenario and the loads and burdens after the EoL, for a service life of 50 years. It uses product specific Environmental Product Declarations (EPD) complying with the EN 15804+A2, except for data retrieved from databases (mainly OKOBAUDAT and Ecoinvent) for materials where no adequate EPDs were found.

The objective of the study is to compare solutions with the lowest embodied carbon footprint. The

previous LCA showed that the highest impact on the Global Warming Potential (GWP, an indicator of the carbon footprint, expressed in CO₂-equivalent) is generated by the steel and concrete elements. Hence, high strength steels from the Electric Arc Furnace (EAF) route such as EcoSheet-Pile™ Plus (XCarb®) sheet piles produced with 100% scrap and 100% renewable electricity, concrete based on a CEM IIA/B cement and rebars from the EAF route were carefully chosen. Corrosion of steel, fire-protection systems, and further design requirements are considered. The chosen functional unit is the perimeter of the retaining wall, consequently the LCA is limited to the impact of the elements of the retaining wall. It does not cover other structural elements of the UCP such as the bottom concrete slab, bracings and so forth, because these are identical for all alternatives.

The conclusion of the LCA for the base scenario – see figure 1 – is that over the whole life cycle (Modules A – D) the permanent steel sheet pile wall has the lowest GWP, followed by the temporary SSP wall (+7%), the secant pile wall (+156%) and the diaphragm wall (+180%). It is noteworthy that the reuse of the temporary SSP (on other projects) is largely offset by the impact of the internal RC wall.

Important notes: Additional environmental impacts will be analysed, a sensitivity analysis will be performed, and the LCA will be peer-reviewed by a panel of independent experts. The results cannot be simply transposed to other locations, to other configurations or timeframe.

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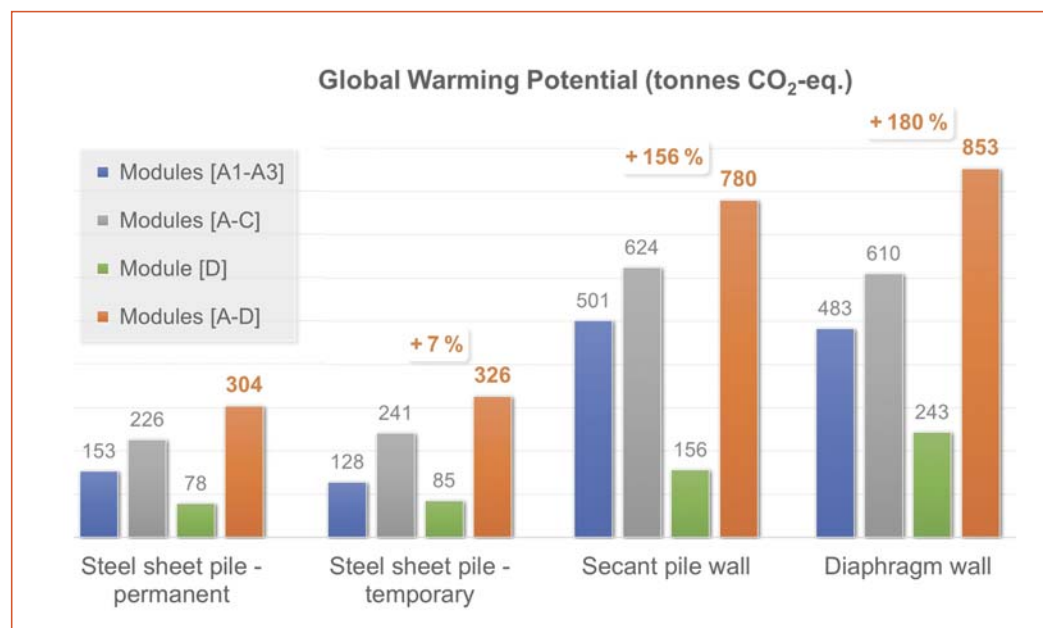


Figure 1 – Total Global Warming Potential of the retaining wall solutions by modules.

SUMMARY

Underground car parks (UCPs) are an option to increase the number of parking spots in densely populated areas. Many UCPs in the Netherlands incorporate permanent steel sheet pile (SSP) retaining walls, but not in Germany. This study compares retaining walls for a typical two level UCP in Berlin and shows that,

similarly to a recent study for the Dutch market, a permanent SSP wall is more cost-effective than a secant pile wall and a diaphragm wall (difference $\geq 18\%$). A Life Cycle Assessment (LCA) shows that the permanent SSP wall has the lowest carbon footprint (difference $\geq 156\%$).

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Contact

Cécile Prüm
cecile.prum@arcelormittal.com

José Humberto Matias de Paula Filho
jose.matias-de-paula@arcelormittal.com

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joao.martins@arcelormittal.com

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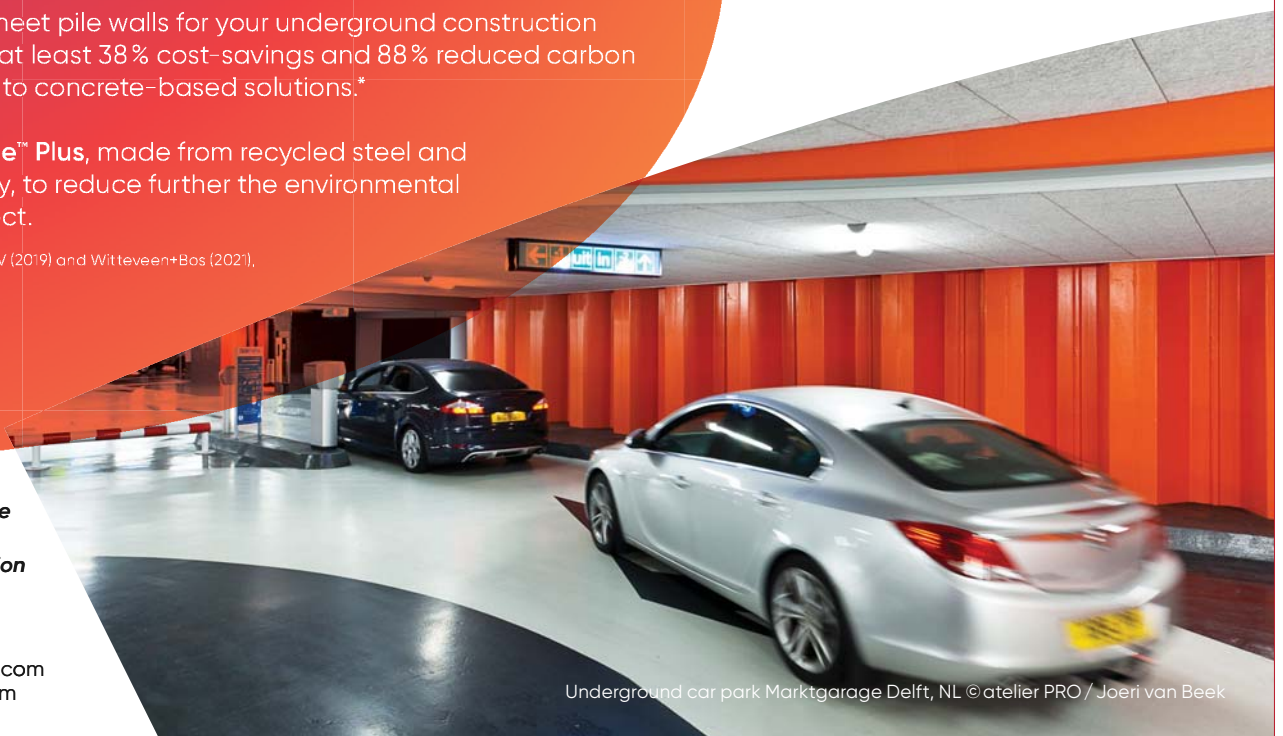
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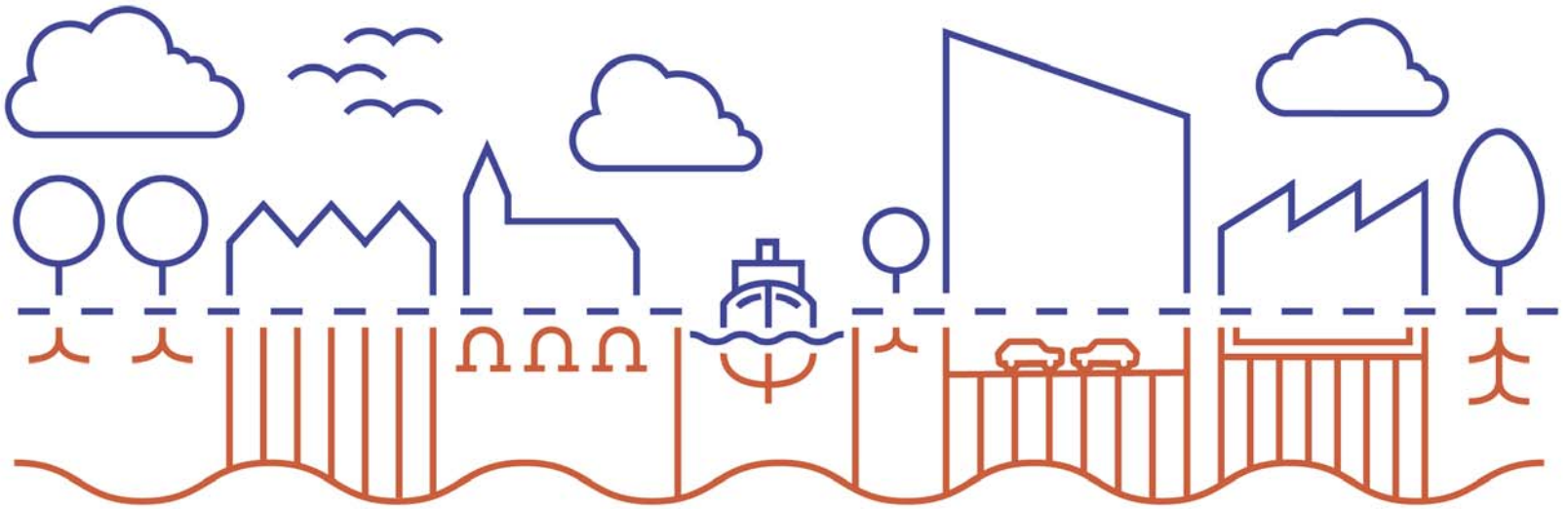
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