Maximising a foundation's lifetime through monitoring: a case study from the Port of Rotterdam

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ABSTRACT

Geotechnical structures are often partially embedded, if not fully embedded, making it challenging to assess the remaining lifetime and reusability of a foundation. In-situ monitoring offers a solution. By attaching different types of sensors to a foundation, the foundation's response and reliability can be assessed at various stages of a structure's life cycle. To illustrate this, an example of a "smart quay wall" is taken from the Port of Rotterdam. During the design phase, fully instrumented pile tests showed that the design could be optimised, leading to substantial financial and carbon emission savings. During construction, movements and forces in the quay wall were closely monitored and were used to validate a numerical model, thus providing a reliable tool at later stages during the quay wall's lifetime when reuse or readaptation of the quay wall is being considered. Lastly, ongoing measurements during the operational phase of the quay wall have shown a large amount of residual capacity, particularly when compared to the pile load tests.

Keywords: long-term monitoring, maritime structures, digital twins, pile testing

INTRODUCTION

As the largest port in Europe and the owner of hundreds of kilometres of deep-sea quay walls, the Port of Rotterdam is one of the major stakeholders in the Dutch foundation industry. To keep up with the persistent growth in global trade, new quay walls are still being constructed. However, while many of the existing quay walls have reached the end of their design lifetime, a lot of these quay walls are still in good condition. As a result, the Port of Rotterdam's focus has shifted to the maintenance, rehabilitation and adaptation of existing quay walls (Roubos 2019).

Establishing the current reliability of a foundation is one of the first steps in determining a foundation's potential for reuse. While theoretical methods, numerical models and similar case studies give indications regarding a foundation's reliability and potential for reuse, active monitoring remains one of the most effective and direct ways of evaluating a foundation. Once a foundation's reliability is established, readaptation or targeted lifespan extension measures can be undertaken.

Monitoring has therefore become a core component of the "smart quay wall" methodology at the Port of Rotterdam. Through pile load test programmes and instrumented quay walls, the geotechnical performance of quay walls can be more accurately assessed and modelled. This, in turn, helps to maximise the capability of the foundations while minimising the financial and environmental costs associated with construction and rehabilitation.

Using a case study from the port, this paper presents ongoing research into different stages of a quay wall's lifetime:

1. **Design:** optimising foundation design through pile testing.
2. **Construction:** validating numerical models using construction monitoring data.
3. **Operation:** understanding a quay wall's long-term response.

Each stage is explained in the context of foundation reuse and optimisation, highlighting how monitoring and digital twin integration can be used to reduce the costs and carbon emissions associated with construction.

PORT OF ROTTERDAM CASE STUDY

Measuring 2.2 km in length, the quay wall has a total retaining height of 29 m, facilitated by a retaining wall known as a "combi-wall." The combi-wall derives most of its stiffness from 1.4 m diameter open-ended piles spaced at 3.3 m centre-to-centre. Sheet piles span the gap between the open-ended piles, preventing soil flow across the wall and into the sea. The combi-wall is tied in by Müller Verpress (MV) anchors: large steel I-beams (0.6 m in height, 0.3 m in width) that are driven simultaneously with grout injection from the anchor tip. A concrete slab known as a relieving platform provides additional support. Cast continuously along the entire length of the quay wall, the relieving platform uses the weight of the overlying soil to resist overturning moments, meaning a smaller size is needed for the MV anchors. Underneath the relieving platform, two rows of compression piles have been installed. These are 609/850 mm diameter screw injection piles which are—like the MV anchors—installed with grout injection from the pile tip, albeit with a screw-in force rather than hammering.

In terms of soil conditions (Fig. 1), the upper 10–15 m consists of artificially deposited sand from earlier land reclamation at the site and from quay wall construction. Naturally deposited soils then follow: first, a 5–10 m thick layer of Holocene-era clay and sand, followed by Pleistocene-era sand. The Pleistocene sand is dense to very dense, with Cone Penetration Test (CPT) tip resistances of up to 80 MPa. This sand is also the primary load-bearing layer, with all the piles and anchors founded in this region.

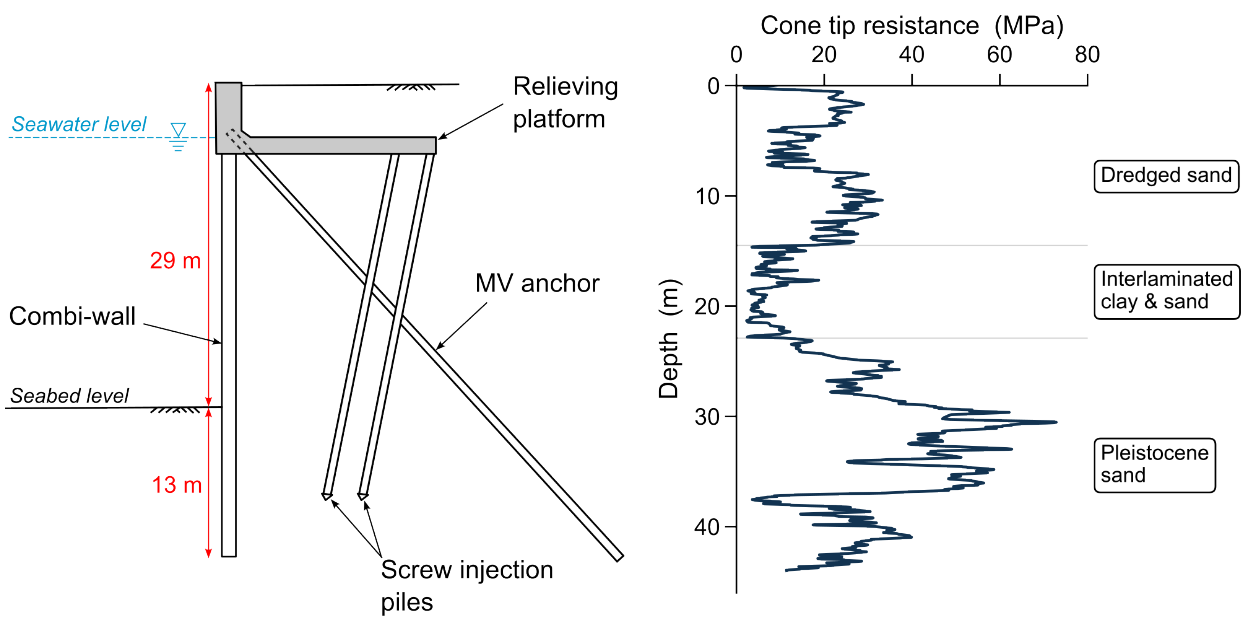

Fig. 1. Cross-section of a quay wall and a CPT profile from the site

With thousands of screw injection piles and MV anchors installed along the length of the quay wall, several sections of the quay wall have been targeted for monitoring. Fibre optic sensors (Fibre Bragg Grating) monitor the normal force across the MV anchors and the screw injection piles. Manual inclinometers are used to measure the deformation of the combi-wall along its entire length. Monitoring wells measure water levels both in front of and behind the retaining wall and verify that the drainage systems are working properly and no build-up of water pressure has occurred behind the quay wall.

STAGE 1: OPTIMISING FOUNDATION DESIGN THROUGH PILE TESTING

While the Pleistocene sand is a suitable load-bearing layer for foundations, its high density makes installation challenging (Duffy et al. 2024; Gijt et al. 2019). Driven concrete and driven steel piles risk reaching refusal and getting damaged. The steel casings of cast-in-situ piles may also become stuck and irretrievable. Alternatively, the concrete quality of cast-in-situ piles may also be affected by the high radial stresses imposed by the soil after installation.

To combat these issues, a variety of pile installation methods have been used across the port. This includes grout fluidisation, like in the case of the MV anchors and screw injection piles. Open-ended piles are often vibrated through the upper layers and then driven into the Pleistocene sand layer. Driven cast-in-situ piles, locally known as "vibro piles," have also been a resilient and flexible alternative for other projects.

Reducing excessive conservatism through optimised design methods can also reduce installation risk. However, a lack of test data on full-scale piles in very dense sand means many design standards approach these soil conditions with caution (Duffy et al. 2023), an uncertainty often manifesting as a limiting resistance on the maximum base and shaft capacity that can be mobilised. For example, the Dutch design code for anchors, CUR 166 (2008), states that the cone tip resistance should be limited to 15 MPa when determining the shaft resistance. For the Pleistocene sand layer, where cone resistances are around 40–50 MPa, this could represent a significantly conservative component of the design code.

Prior to quay wall construction, several load tests were also been performed on MV anchors (van Paassen and van Dalen 2009; Putteman et al. 2019), yet little of these tests were performed to geotechnical failure and so the true design factors were not precisely known. With this in mind, six MV piles were tested to geotechnical failure through tensile static load tests, reported in Putteman et al. (2019), Westerbeke (2021) and Spruit et al. (2022). The piles were almost identical in design to those used for the quay wall itself, inclined at 42.5–47.5° and with a total length of up to 60m. All six piles reached maximum test loads of 8.8–12.0 MN (e.g. Fig. 2a), with unload/reload cycles applied after each load step. During loading, the shaft response was measured with distributed fibre optic sensors (Brillouin Optical Time Domain Analysis; BOTDA). The measurements showed that average shaft resistances across the Pleistocene sand reached up to 400 kPa, almost twice as much as limiting resistances in the design code CUR 166.

With an improved certainty of the pile response at high cone resistances, a site-specific design method could be approved and the total pile sizes were reduced. This reduction led to a direct savings of €4.5 million for the project and a 4.5 kiloton reduction in CO_2 emissions associated with pile production and installation (Roubos et al. 2024). The results have also supported the deepening of the dredged level at other quay walls in the port, showing how pile tests can also be used to reassess and quantify the remaining capacity of a structure.

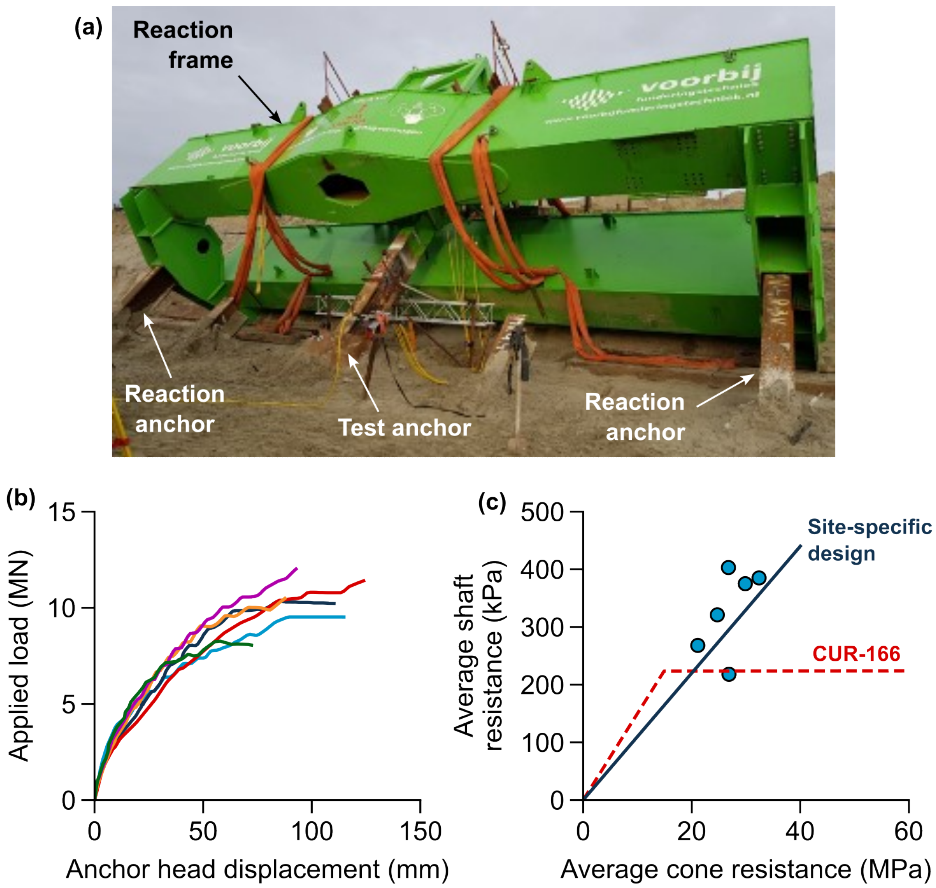

Fig. 2. (a) Reaction frame used to load each anchor in tension (b) Load-displacement results of the six anchors, excluding unload/reload cycles (c) Average shaft resistance mobilised across the Pleistocene sand for each pile

STAGE 2: VALIDATING NUMERICAL MODELS USING CONSTRUCTION MONITORING DATA

Designing a quay wall requires an understanding of how different geotechnical elements interact with one another. For instance, the high density of piles and anchors means that much of the quay wall response is governed by soil-structure interaction mechanisms such as pile group effects, soil arching and combined axial and lateral loading. Load testing the quay wall itself is a direct means of establishing quay wall capacity, although this is seldom performed because of financial and technical constraints. Quay wall design therefore relies on finite element modelling, incorporating the findings from the site investigation and pile load testing into the model inputs. However, variability in soil and material properties means uncertainty is always present with the realised model. Validation of the models is therefore a vital step in assuring the long-term safety and lifetime of the structure.

Movements of a quay wall can be used to validate a numerical model. One of the final phases in quay wall construction involves dredging material in front of the wall—a phase which incurs the largest quay wall movements during its lifetime. A cross-section of the quay wall was modelled in Plaxis 2D (Fig. 3a) and the site investigation data was used to establish the likely range of each input parameter. For instance, the removal of around 7 m of material in front of the quay wall resulted in at least 20 mm of deformation in the wall (Fig. 3c). Correspondingly, the anchor force increased by at least 50%, from 1.0–2.0 MN (Fig. 3b), well within the ultimate capacity of the anchors. In both situations, the numerical model captured the point of maximum quay wall movement relatively well, although further refinement is needed at the top of the wall, where the structure transitions from a steel combi-wall to a concrete superstructure. The validated model forms a good basis for assessing future changes to the wall, for instance, with regards to changes in subsurface loads or increase in dredged depth in front of the quay wall.

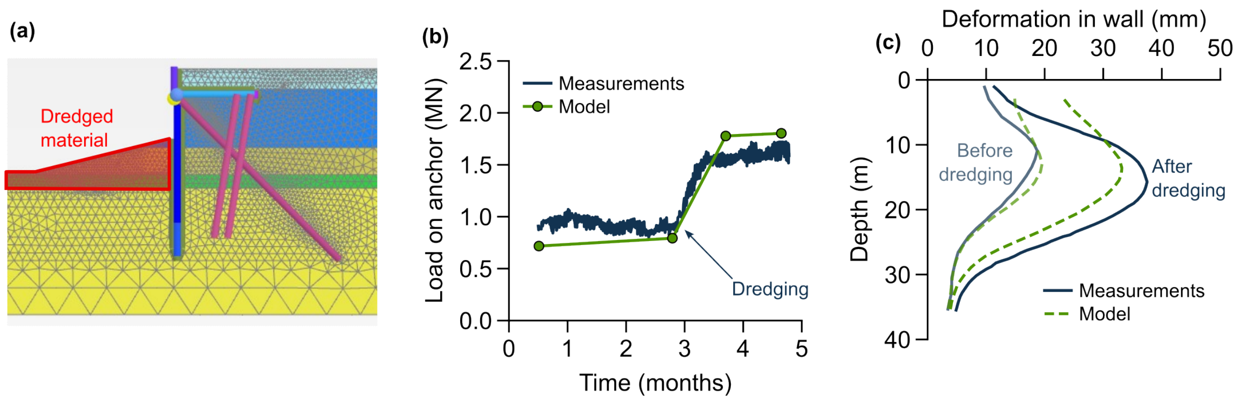

Fig. 3. (a) Simulation of the construction phase in Plaxis 2D where 7 m of material was dredged in front of wall (b) Influence of the dredging on the tensile load in the anchor (c) Influence of the dredging on the combi-wall deformation

STAGE 3: UNDERSTANDING A QUAY WALL'S LONG-TERM RESPONSE.

Sustained monitoring of a structure can provide information on a structure's remaining lifetime, suitability for reuse, as well as an impending failure. For example, the long-term reliability of a quay wall can be affected by sudden events such as direct collisions by ships, overloading of the quayside, or soil flow from the landside to quayside due to interlock openings between sheet piles (Gijt et al. 2019). Alternatively, some other progressive forms of deterioration can include corrosion-induced degradation (Roubos et al. 2020) or propellor-induced scour in front of the quay wall (Roubos et al. 2014).

To a certain degree, many of these can initially be assessed above ground level. On the other hand, determining the effect of these events on the geotechnical elements requires planning in advance of construction. Many of the elements, such as the retaining wall or piles, are almost fully embedded so measuring the desired parameters means the sensors need to also be fully embedded. This makes it difficult, if not impossible, to retroactively maintain or replace sensors and so these sensors need to be robust enough to match the service life of the structure. Since 2008, most of the smart quay walls in the port of Rotterdam have been instrumented with fibre optic sensors. These sensors have been shown to reliably withstand the harsh conditions of installation and concrete pouring, whilst taking up little cross-sectional area and providing a stable measurement over time.

Although not yet in full operation, some interesting insights can be gained from long-term monitoring at the quay wall case. After construction and dredging in front of the quay wall, the load in the anchors reaches 1.5–2.0 MN (Fig. 4), much lower than the ultimate capacity reached during the static load tests. In the period since construction, no significant loading changes have occurred both in front of and behind the quay wall. However, annual fluctuations of around 0.5–1.0 MN still occur in the measurements, roughly 25–50% of the mean operational load. The trend of the anchor force slowly increases with time and corresponds with an increase in combi-wall deformation (not shown). These trends come in spite of the measurements being compensated for thermally induced changes on the sensors themselves, often referred to as the "apparent" change in strain.

The primary influencing factor and long-term implications of these thermal cycles is still being investigated. The effect is expected to be more prominent in quay walls, where the exposure of the wall to changes in both ambient and seawater temperature means thermal cycles on the foundations are also expected to be larger compared to other structures. Nevertheless, when the measurements are considered in the context of the pile tests (Fig. 2), the measurements also show the substantial margin of safety included in the geotechnical design.

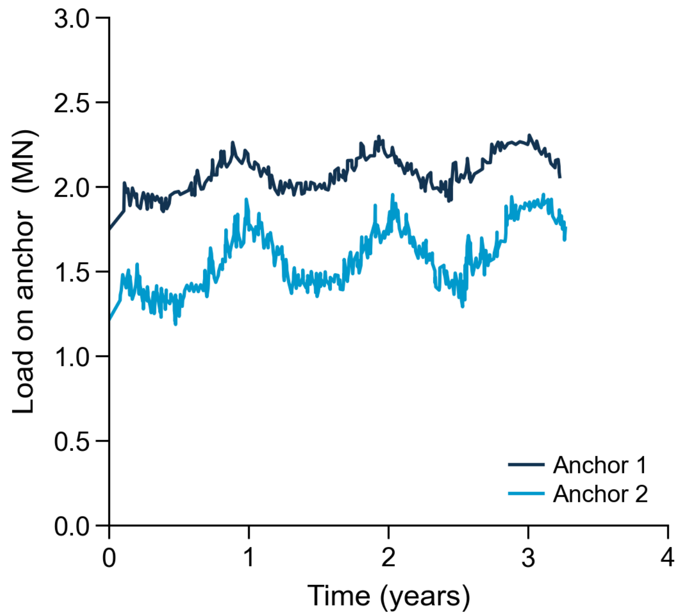

Fig. 4. Measurements of anchor force across a four year period

FUTURE OUTLOOK: DIGITAL TWINS

Monitoring equipment alone offers limited value to asset managers or engineers. Data needs to be collected, visualised and interpreted so that insights can be gained into the performance of the structure. The role of a digital twin is to integrate the physical and digital spaces together through a connection space (Fig. 5)—with this active connection being what distinguishes digital twins from other digital models, such as Building Information Modelling (BIM) (Bolton et al. 2018). Digital twins have brought radical improvements in procedures, quality control and productivity in sectors such as the automotive, manufacturing or aerospace sectors. However in the construction sector, apathy towards new innovations and adherence to the status quo has stifled possible growth and improvement and are therefore still a relatively conceptual level (Craveiro et al. 2019; Maskuriy et al. 2019), with geotechnics being no exception (Wu et al. 2022).

The case study in this paper, along with nine other demonstration cases, was integrated into a digital twin as part of a European Union Horizon 2020 project known as ASHVIN. The project has focussed on developing an open-source digital twin platform with a toolbox of ten smart building tools (Fig. 6). Each tool focusses on seamlessly integrating the physical and digital spaces, as well as interpreting and visualising the data to provide key performance indicators of the physical asset. The demonstration cases have also been used to help with the development of a European standard for digital twins in the built environment, with the project highlighting the need for proper interoperability between technology providers and improving the integration of different datasets onto one unified platform.

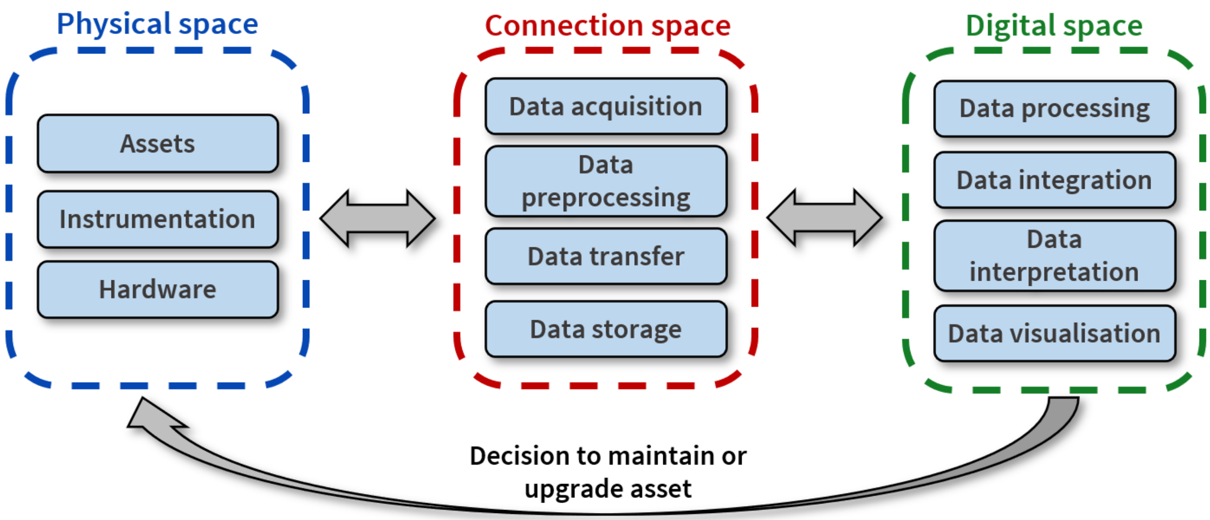

Fig. 5. Architecture of a digital twin

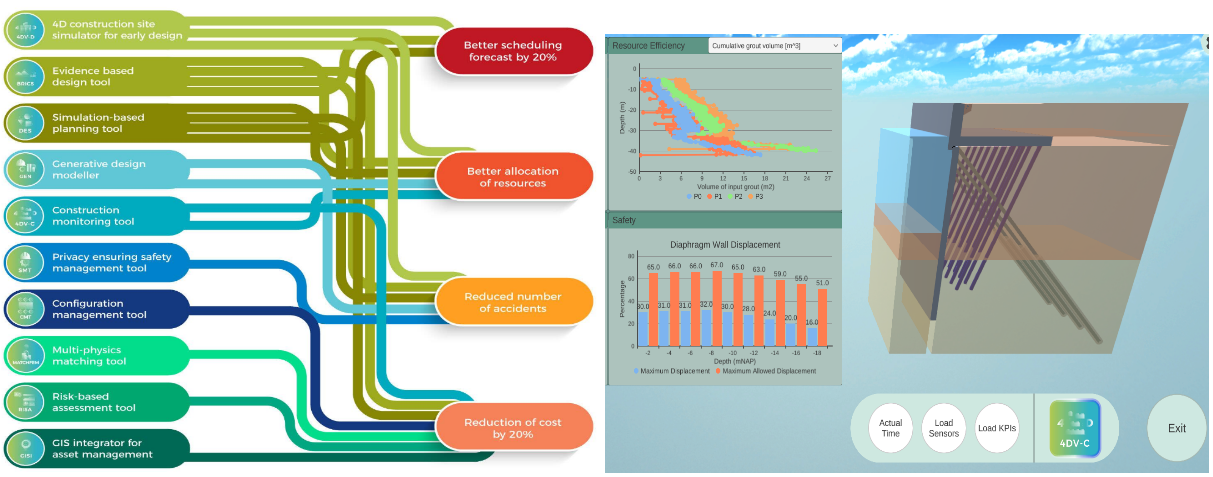

Fig. 6. ASHVIN digital twin toolbox and quay wall demo case on the ASHVIN platform

CONCLUSION

Active monitoring of foundations can provide valuable information regarding the lifetime of the structure and its potential for reuse. Using an example from the Port of Rotterdam, monitoring has provided some useful insights at different phases of a quay wall's lifetime:

- Through full-scale pile load tests, the design of the quay wall foundations was refined, reducing the size of the foundations and reducing the costs and carbon emissions associated with foundation installation.
- Monitoring during construction has been used to validate numerical models of the quay wall, providing a suitable model where readaptation of the quay wall can be tested.
- Long-term monitoring has shown thermally induced loading on the quay wall, leading to fluctuations in anchor forces and wall deformations over time.
- At all stages of the quay wall lifetime, fibre optic sensors have shown to be a robust and reliable form of instrumentation.

By implementing monitoring programmes at all stages throughout a project life cycle, informed decisions can be made for maintenance programmes, as well as with establishing a foundation's suitability for reuse or readaptation.

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