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CLARION: Smart & sustainable climate resilient Quay Walls

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ABSTRACT: In 2024, the CLARION Project was launched to enhance the resiliency and sustainability of port infrastructures and hinterland transport networks. This initiative brings together a multidisciplinary team of 20 partners from 11 European countries. CLARION aims to develop and implement innovative solutions to mitigate the impacts of climate change on port infrastructure through 10 dedicated pilot demonstrations, ensuring the transferability of results to other ports. This paper focuses on the pilot demonstration related to smart and sustainable quay walls. The primary aim of this demonstration is to reduce the carbon footprint of new quay walls while considering climate change impacts, extending the lifespan of existing quay walls by 25 years, improving functionality, and assessing resilience. Data from smart quay walls, fully equipped with advanced sensors and installed in the port of Rotterdam, were used to reduce uncertainties in finite element modelling and to develop a numerical digital twin of the structure. Machine learning techniques were employed to predict future stresses and forces using environmental data, such as tidal effects and temperature. The calibrated numerical digital twin can then be used to study the effects of climate change on quay-wall behaviour, including extreme water levels and temperature fluctuations. By embracing these pilot demonstrations, CLARION aims to contribute to Europe's collective efforts to combat climate change and build a sustainable future. This aligns with the European Commission's EU Strategy on Adaptation to Climate Change and the European Green Deal, helping to achieve climate neutrality by 2050.

KEYWORDS: Quay Wall, Monitoring, Digital Twin, Finite Element Modelling, Resilience

1 INTRODUCTION

1.1 *CLARION*

CLARION is a collaborative project funded by the Horizon Europe Programme 'Climate Resilient Port Infrastructure' that addresses the resiliency and sustainability of port infrastructures and hinterland transport networks (both land and water connections) in the event of disruptions caused by climate change or other human-related incidents. This project helps in responding to crisis situations that may halt port operations, leading to business losses and service interruptions. By focusing on ensuring resiliency, CLARION also promotes the safety and security of port access and operations while minimizing the environmental impact of construction, maintenance, operation, and decommissioning of port infrastructure. Bringing together a multidisciplinary team of 20 partners from 11 European countries, CLARION will specifically develop and implement innovative solutions to mitigate the impacts of climate change on port infrastructure through 10 dedicated pilot demonstrations (Table 1), which are expected to ensure the transferability of the results to other ports.

Table 1. Pilot Demonstrations of Clarion Project

PD	Title	Port
1	Smart & sustainable climate resilient quay walls	Rotterdam
2	Monitoring and management system for the corrosion of port infrastructure	Antwerp
3	Shore tension for Roll-On-Roll-Off and Container Roll-On-roll-Off terminals	Antwerp
4	Flood impact control	Hamburg
5	Dredged sediment reuse	Rotterdam
6	Nature Based Solutions for maritime ports	Rotterdam
7	Hinterland transport resilience	Rotterdam
8	Digital Twin for extreme weather forecasting	Hamburg
9	Federated learning for cadastral measurements and inland water level forecasting	Constanta
10	European Metrological Society for extreme weather events	All

By embracing these initiatives, CLARION aims to contribute to Europe's collective efforts to combat climate change and build a sustainable future, aligning with the European Commission's EU Strategy on Adaptation to Climate Change and the European Green Deal, helping to achieve climate neutrality by 2050. CLARION has a project budget of approximately €7 million euros, spanning 48 months and intends to conclude in April 2028.

1.2 *Pilot demonstration Smart & sustainable climate resilient quay walls.*

Both port and waterway infrastructures are under constant pressure to change. Growing vessel sizes and increasing cargo flows have triggered major infrastructure investments since the 1980's and many quay walls are reaching the end of their original design service lifetime of about 50 years (Roubos, 2019). More recently, the impact of climate change manifests itself more prominently. Recent research has shown that quay walls respond to temperature and tidal fluctuations (loads in foundation vary and cyclic displacement of the wall increases over time). While accelerating sea level rise is an anticipated threat (with potential far reaching impacts in the coming decades), water scarcity and reductions in water level during times of drought pose a risk to basin uplift problems at deep sea quay walls.

This paper mainly discusses the scope and preliminary results of Pilot Demonstration project PD1 Smart & sustainable climate resilient quay walls. The first's pilot demonstration focus will be to improve carbon footprint of seaport quay walls, taking into account the effects of climate change. Lifetime extensions of existing quay walls for at least 25 years will be explored along with improved functionality that will increase the draft by at least 1m and support at least 25% increased crane loads. Methods will be developed to strengthen existing quay walls and risk-based and data-driven assessment will be done using a unique quay-wall data set provided by the Port of Rotterdam.

2 SMART QUAY WALLS

In 2008, the Port of Rotterdam implemented its first smart quay wall (Figure 1). This diaphragm type of quay wall was primarily equipped with fibre optic strain and pressure sensors, installed mainly for asset management purposes, such as setting alarm and intervention thresholds to prevent functional misuse.

Since then, the initiative has expanded: ten smart quay walls have now been constructed in the Port of Rotterdam, and a comprehensive sensor strategy has been developed. The motivation for investing in smart quay walls is sixfold:

1. Enhancing quay wall functionality.
2. Ensuring structural safety.
3. Predicting extreme loads.
4. Forecasting degradation and extending service life.
5. Reducing construction and maintenance costs while optimizing the carbon footprint.
6. Advancing knowledge on climate change impacts and improving current design codes and standards.

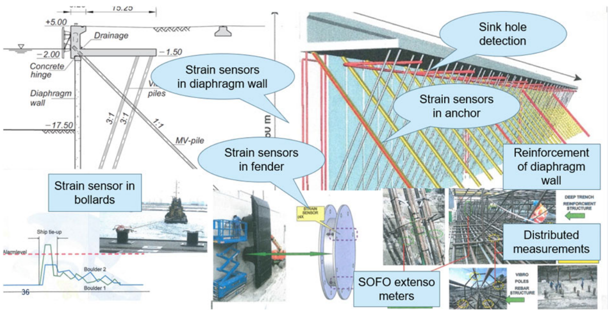

Figure 1. Impression of the first smart quay wall, realized in 2008 at the Yangtzekanaal in the Port of Rotterdam, Maasvlakte 2.

As more quay walls are equipped with sensors, a great deal of data has become available. This data supports predictive modelling, reverse engineering, and enhances reliability and safety. It also lays the foundation for data-driven, risk-based decision-making to optimize maintenance strategies (Figure 2). Moreover, sensor data contributes to a deeper understanding of quay wall behaviour and enables the application of Bayesian updating (Klerks, 2024). Combined with finite element models, this data forms the foundation for numerical digital twins, virtual models that can be used to refine functional requirements and unlock new business opportunities. Data-driven research is also essential for maintaining and validating design guidelines and developing innovative methodologies.

Figure 2. Concept of a smart quay wall (Roubos, 2019).

3 NUMERICAL DIGITAL TWIN

One of the key objectives of this CLARION demonstration project is the development of a numerical digital twin for the newly constructed quay wall in the Amaliahaven port basin. Although the project is still ongoing, this section outlines our current approach to reducing uncertainty in numerical modelling.

The Amaliahaven quay wall features a concrete relieving platform directly supported by a steel combi-wall and concrete foundation piles (Figure 3). At the back of the concrete reliving platform grout anchors are installed.

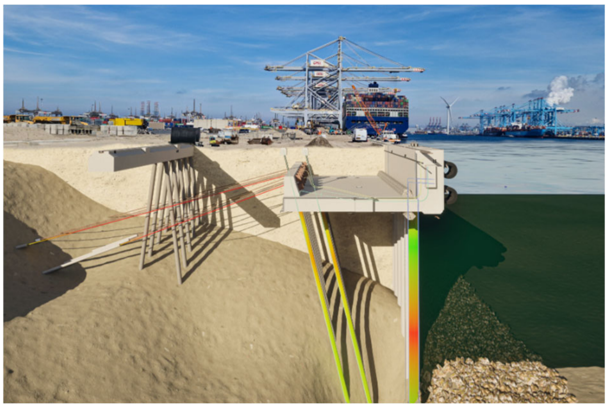

Figure 3. Impression of the latest smart quay wall realized in 2025.

Figure 4. Impression fibre optic strain sensors.

The Amaliahaven quay wall is instrumented with fibre optic strain sensors along the full length of the steel tubes in the combi-wall, the cast-in-situ concrete foundation piles (Figure 4), and the screw injection grout anchors. It is worth noting that load cells were installed to verify the anchor force measurements in order to reduce uncertainty introduced by temperature influences. Additionally, fibre optic sensors beneath the relieving platform detect potential sinkholes. Deformations are monitored through periodic inclinometer measurements of the foundation piles and the concrete relieving platform via tacheometry. Furthermore, the ground and outer water levels are measured via piezometers. For more details regarding the sensors installed on the Amaliahaven quay wall the reader is referred to Putteman et al. (2026).

During the design phase, a comprehensive geotechnical investigation was conducted, including Cone Penetration Tests (CPTs) and boreholes, typically spaced every 25 meters. These investigations provided the initial input for the numerical model. For the design of this quay wall, finite element analyses (Figure 5) were performed using the Hardening Soil model to simulate soil behaviour. The model parameters were determined using two different approaches: CPT-based correlations and conservative assumptions for characteristic values.

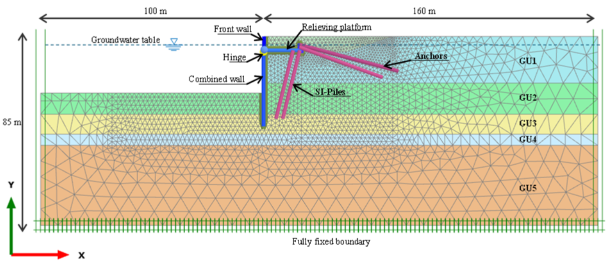

Figure 5. Numerical model of the quay wall at Amaliahaven.

To develop a reliable digital twin that closely reflects real-world behaviour, we aim to refine the model inputs using the following strategies:

1. **Structural Properties Update**: As-built construction data, including actual dimensions and material test results (e.g., steel tensile tests and concrete compression tests), will be used to update structural parameters.
2. **Geotechnical failure test anchors:** Full-scale failure tests were conducted on the grout anchors during construction. These anchors were instrumented with fibre optic sensors along their entire length. The test results are used to refine the stiffness properties of the anchors and the soil-anchor interface behaviour.
3. **Foundation Pile Testing:** In 2019, vertical bearing capacity tests were performed on the cast-in-situ concrete foundation piles (Duffy, 2024). In 2023, full-scale field tests were conducted on the steel tubular piles (Lange et al., 2025). Both tests included fibre optic instrumentation along the full pile length, enabling realistic modelling of the foundation system and combi-wall.
4. **Synthetic CPT Development via Machine Learning:** A machine learning model was developed to correlate CPT data with installation parameters (Yusuf, 2025). This resulted in the first synthetic CPTs, offering detailed insights into local variations in cone resistance (Figure 6).
5. **Biaxial Soil Testing:** In 2025, biaxial tests were conducted on Pleistocene Maasvlakte sand to investigate plane strain effects. Although the results are not yet published, preliminary findings were used to update soil strength parameters. A ratio between triaxial and biaxial test results was established, depending on relative density and stress rate.
6. **Use of Sensor Data**: Sensor data collected during the construction phase, particularly specific excavation levels recorded during dredging, has been used refining the geotechnical properties of various soil layers. In addition to these construction-related insights, long-term monitoring data from other smart quay walls has revealed that temperature variations can significantly influence quay wall behaviour. To account for this, historical temperature-related performance data has been analysed to determine how thermal effects can be incorporated into the numerical model. This allows for a more accurate simulation of structural responses under varying environmental conditions, further enhancing the reliability of the digital twin.
7. **Full-Scale Load Testing:** A full-scale load test on the new quay wall is planned (Figure 7). This test will serve as a critical validation step for the digital twin.
8. **Additional soil investigation:** Additional boreholes will be drilled at the load test location to capture local soil conditions. Triaxial tests will be conducted to further refine soil property inputs. As part of the CLARION project, geophysical surveys using geophones were conducted at the full-scale test site. These data will be integrated into the model to enhance subsurface characterization.

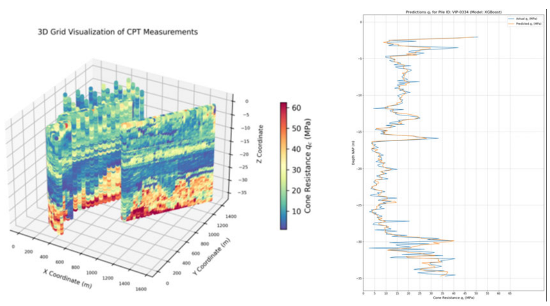

Figure 6. First synthetic CPTs for the Maasvlakte area, generated using installation data (Yusuf, 2025).

Figure 7. Preparation for the full-scale field test of the quay wall at Maasvlakte 2, scheduled to begin in Q3 2025.

4 PRELIMINARY RESULTS

Currently, predictions are being made for the upcoming full-scale load test (Figure 7). Two approaches were adopted in the finite element analysis (FEA) for parameter estimation: a CPT-based approach and characteristic values (SLS), which are presented in Table 2. In general, the calculated lateral displacements based on the CPT-based correlated soil parameters show better agreement with the measured values, whereas the characteristic (conservative) soil parameters tend to overestimate the response (Figure 8). This discrepancy is not unique to the quay wall in the Amaliahaven but has been consistently observed across all smart quay walls.

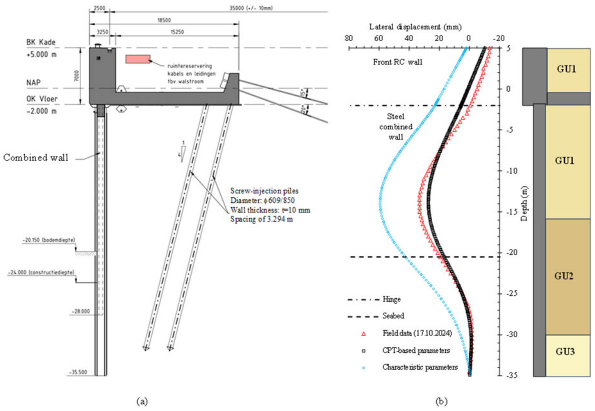

Figure 8. Predictions of lateral displacements in the Amaliahaven quay wall and comparison with the field measurements

Table 2. Soil parameters adopted in the FEA (CPT-based / characteristic)

Soil layer	Elevation (m)	q_c (MN/m^2)	ϕ_p' (°)	$E_{50,ref}$ (MN/m^2)
GU1	+5 / -16	15	37 / 32.5	57 / 45
GU2	-16 / -28	9	34 / 30	33 / 10
GU3	-28 / - 40	45	40 / 36	155 / 50

Nearly all smart quay walls show a seasonal correlation in anchor forces. Previous studies have demonstrated that quay walls tend to move toward the water during summer and shift back inland during winter (Patrikis, 2023; Lai, 2025). Within the CLARION project, a more detailed investigation into temperature effects is being conducted for the Alexiahaven quay wall at Maasvlakte 2.

Daily horizontal displacements of the quay wall, typically around 2 to 3 mm in Figure 9, are primarily driven by tidal-induced water head differences, caused by fluctuations between the groundwater level and the outer water level. These tidal effects also influence the anchor forces. However, a clear seasonal trend has been identified: anchor forces correlate strongly with changes in water temperature (Figure 10). Despite the significant increase during summer, the anchor forces remain well below the design capacity of 7500-8500 kN.

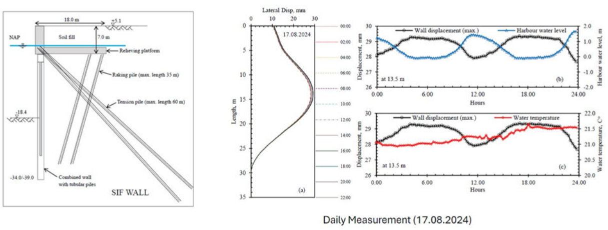

Figure 9. Relation between wall displacement and water head difference and water temperature of the Alexiahaven quay wall, Maasvlakte 2.

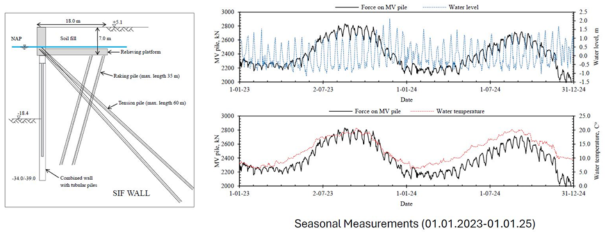

Figure 10. Relation between anchor force and water head difference and water temperature of the Alexiahaven quay wall, Maasvlakte 2.

5 DISCUSSION

Although the CLARION pilot demonstration project is still ongoing, preliminary findings already indicate that sensor data can significantly reduce both model and epistemic uncertainties, particularly in the soil parameters (e.g., angle of internal friction and soil stiffness). The sensor data, combined with as-built documentation and test results, is also being used as input for reverse engineering. The goal is that, after approximately one year, the design report for each new quay wall will be updated to include a detailed description of geotechnical and structural behaviour, documented in a soil-structure log file.

This approach is expected to enhance the overall functionality of smart quay walls. Early results from reverse engineering suggest that it may be feasible to deepen most quay walls by 1 to 2 meters, increase terminal loads by approximately 25%, or accommodate larger cranes. Another promising outcome is the potential to extend the service life of existing quay walls (Lai et al., 2025).

Sensor data has also provided new insights into quay-wall behaviour, revealing a strong correlation with seasonal water temperature. Notably, significant variations in anchor forces and bending moments have been observed between summer and winter, with higher forces typically recorded during the summer months (see Figure 11). However, current finite element-based quay-wall design methodologies do not account for temperature effects. While the seasonal influence is evident, the underlying mechanisms remain not fully clear. It is still possible that factors beyond the thermal expansion of the steel combi-wall contribute to this behaviour. Within CLARION we intend to further investigate the seasonal and long term temperature effects.

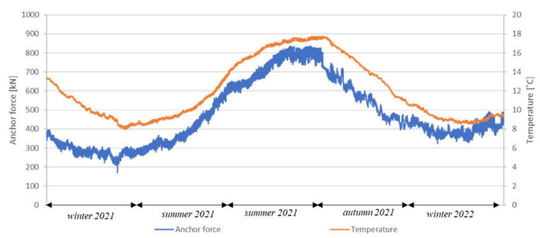

Figure 11. Relation between temperature and anchor force in the grout anchors of a quay wall in the Mississippihaven at the north side of the port basin, Maasvlakte 1.

Another important aspect is the use of installation data to update subsurface information. Studies by Yusuf (2025) and Westerbeke (2021) demonstrate that installation data can help reduce uncertainty in subsoil characterization. For example,

Figure 12 highlights the presence of a weak soil layer within the grout body of MV-pile anchor number 6. This weak layer, later confirmed by post-construction cone penetration tests (CPTs), resulted in significantly lower bearing capacity.

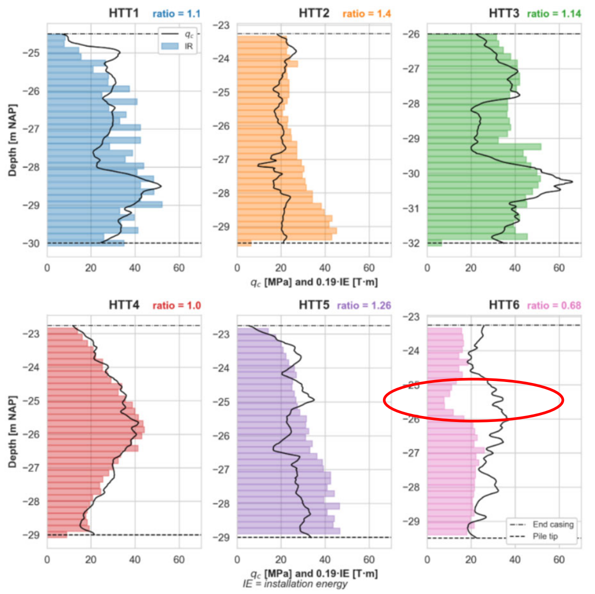

Figure 12. Installation energy and CPT before for 6 MV-pile anchors in the Mississippihaven at the south side of the port basin, at Maasvlakte 1 (Westerbeke, 2021).

Smart quay walls also offer a valuable opportunity to study the effects of climate change on structural behaviour. The Asset Management Department of the Port of Rotterdam envisions a future where quay wall inspections are primarily conducted through sensors. Ideally, each quay wall would be paired with its own numerical digital twin, providing real-time performance data and enabling predictive maintenance strategies.

6 ONCLUSION

The CLARION pilot demonstration on smart and sustainable climate-resilient quay walls has shown promising potential to transform the way port infrastructure is designed, assessed, and maintained. By integrating advanced sensor technologies, machine learning, and numerical modelling, the project has demonstrated the potential to significantly reduce both model and epistemic uncertainties in soil–structure interaction of quay walls.

Preliminary findings show that quay-wall sensor data can be effectively used to calibrate finite element models and develop numerical digital twins. These digital twins enable predictive analysis of quay-wall behaviour under varying environmental conditions, including temperature fluctuations and tidal effects—factors that are currently neglected in conventional design methodologies. Incorporating these effects is essential to accurately assess climate change impacts on port infrastructure.

Preliminary reverse engineering results suggest that existing quay walls can be deepened by 1 to 2 meters, terminal loads increased by up to 25%, and service life extended by at least 25 years. Additionally, the use of installation data and synthetic cone penetration tests has proven effective in identifying weak soil layers and enhancing subsurface characterization.

The preliminary findings of CLARION underscore the importance of data-driven, risk-based approaches in future quay wall design and asset management. As this demonstration project progresses, the integration of full-scale load testing and additional soil investigations will further enhance the accuracy and applicability of the digital twin models. Ultimately, smart quay walls represent a critical step toward climate-resilient, sustainable, and intelligent port infrastructure.

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