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Application of the Observational Method to historic structures: quay walls

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ABSTRACT: In the asset management of historic structures the observational method can be very useful as an approach to assess and potentially prolong the remaining technical lifespan of the structures beyond their theoretical lifespan. This paper describes how this can be implemented along the lines of the example of inner city quay walls in a historic city. This paper describes three levels of application of the OM for historic structures (Level 1 expert based, Level 2 modelling based and Level 3 evolving/updating based). The expert based approach can qualitatively assess the historic structures condition and potential necessity for measures. The modelling based approach quantitatively assesses the condition while the evolving approach includes a full probabilistic approach with integrated feedback loops based on monitoring data. The three levels are applied to historic quay walls in the city centre of Amsterdam.

KEYWORDS: observational method, existing structures, quay walls, structural health monitoring.

1 INTRODUCTION

1.1 *Objectives*

The objective of this paper is to provide an approach for the use of the OM for historic structures, based on the examples of the assessment of historic quay walls in the city of Amsterdam. The current assessment approaches are described in three different levels, that are all being used at this moment for the asset management of the historic quay walls.

2 HISTORIC QUAY WALLS AMSTERDAM

2.1 *Infrastructure backlog*

Our physical infrastructure is under increasing pressure from underinvestment, the demands of population growth, exposure to natural hazards, climate change, and degradation due to ageing. Cities, public asset owners and citizens currently struggle with necessary measures to keep the infrastructures of the urban areas safe, in adequate condition and open for traffic. This problem is not unique for Amsterdam or The Netherlands. Asset owners are in urgent need of reliable and transparent tools to support decisions on prioritisation and lifetime extension.

Over the last decades, the backlog of condition assessments and maintenance interventions has increased to a problematic level for public infrastructures as these are deteriorating faster than investments are made. This leads to potentially unsafe situations and even unexpected structural failures (e.g. Grimburgwal, Staalmeesterbrug). Often decisions on strengthening and renewal as well as (emergency) measures have to be taken reactively and based on limited information, leading to unnecessarily conservative actions and pressure on the system.

Concluding, both public and private asset owners need significant cost reduction as well as increased safety in the management of their infrastructure. This is where the Observational Method can play an important role.

2.2 *Challenges*

The City of Amsterdam alone is responsible for the maintenance of over 1800 bridges and 600 km of bank protection. About 165 kilometres of these are quay walls of which about 25% is over 100 years old (mostly masonry wall supported by timber piles). No or limited as-built information is available. There are many variations of such quay walls; they consist of different materials, geometry and usage. Over the years the loading of the quay walls has increased and foundations have degraded resulting in large uncertainties when assessing the remaining structural capacity. These retaining structures are built (at least partly) in the ground with limited access, so inspections are challenging and expensive.

Quay walls can fail due to many different failure mechanisms, whose origin and evolution are not all fully understood (De Gijt & Broeken, 2013). Predicting the moment when the retaining structures are no longer safe is an important challenge in their end-of-life assessment.

For each structure specifically, the asset owner needs to assess its condition, and assess its remaining life span and the risk (i.e. likelihood and consequences) of failure. Currently, assessment tools exist for bridges, but only very limited guidelines exist for the assessment of historic quay walls. Deformation and structural cracks in quay walls arise over decades and monitoring and sensing can help to measure, predict and record these processes. However, no existing sensor can measure and/or predict the remaining life span directly. Assessment models currently cannot or not efficiently deal with the large amount of information about the structure's condition coming from various sources of monitoring. As a result, the reliability of assessments is low and hence safety margins that engineers adopt in the assessment are large. A high percentage of the structures technically or theoretically fail, while perhaps in reality they can remain in service.

2.3 *Organisation*

From a situation with little insight into the condition of the bridges and quay walls, visible overdue maintenance and a low replacement rate, a program was set up in 2019 to investigate the condition of Amsterdam's bridges and quay walls on a large scale and to repair them where necessary. The Amsterdam Programme for Quay Walls and Bridges is a large-scale, long-term municipal initiative to tackle the urgent maintenance and renewal of its historic quay walls and bridges. The programme aims to ensure the safety, functionality, and heritage preservation of Amsterdam quay walls and bridges. Goals are to get to more predictable investment rates, more focus on sustainability: reduce new materials (renovation instead of renewal reuse of materials), preservation of trees while renovating, and adding more functions to (new) quay walls, for example energy generation or climate adaptive. The program is structured as an interdisciplinary program organisation within the municipality, bringing together technical experts, project managers, communication specialists, and external contractors. The program employs area-based prioritisation, digital monitoring, and modern contracting methods such as innovation partnerships. This program plays a central role in urban management and planning in Amsterdam, interfacing closely with mobility, water management, sustainability, and heritage preservation policies. It is one of the city's most visible infrastructure renewal efforts, reflecting Amsterdam's commitment to maintaining a liveable, accessible, and safe urban environment.

2.4 *Link with research projects*

One of the pillars of the program are the Living Labs and Field Labs, where innovative approaches are tested and evaluated. One of these Living Labs is dedicated to Predictive and Data Driven Maintenance, led by the co-author of this paper, and features the link between Monitoring and Assessment of the historic structures. The approach of the Program related to the assessment of the historic structures can be seen as a form of Observational Method. Amsterdam initiated the research program of UrbiQuay, in which LiveQuay is a large multiparty public private research project, led by the lead author of this paper. The aim of LiveQuay is to provide an integrated assessment of the safety and performance of bridges and quay walls by designing a decision support platform based on the principles of the Observational Method. Asset owners will be able to assess more accurately and faster than currently possible, whether their structures are still safe to operate or approaching failure. If existing structures can remain in function longer, investments can be postponed and the impact on cities and people can be reduced significantly.

3 OBSERVATIONAL METHOD

The definition of the Observational Method is: a continuous, managed, integrated process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate (Nicholson et al., 1999). For existing structures, sometimes, Structural Health Monitoring (SHM) is used that involves the observation and analysis of a system over time using periodically sampled response measurements to monitor changes to the material and geometric properties of engineering structures.

For historic structures, both approaches can be combined, where design is not the main item as for new structures, but assessment of their remaining lifespan and evaluation of necessary measures is. The authors of this paper are of the opinion that a major overlap in the approaches of OM and SHM exist. Both concepts involve data collection (monitoring) and analysis and aim to enhance safety and optimise resource allocation. Both concepts require a continuous approach and decision making on the need for predefined, potential measures.

The paper will focus on the OM approach, but can most certainly be read with SHM in mind also.

4 LEVEL 1 EXPERT BASED APPROACH

4.1 *Description*

The first level of the OM approach for quay walls in Amsterdam is called ARK (Amsterdam Risk assessment Quay Walls) (Neijzing & Wesstein, 2023) and consists of the quantitative evaluation of 22 risk factors, based on geometrical data, monitoring- and inspection results and expert judgement. The focus of the ARK is on historic masonry quay walls on timber piles and on concrete L-shaped walls found on piles, together making up 75% of all walls in the city, as shown in Figure 1.

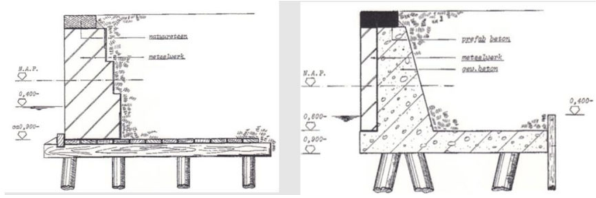

Figure 1. Most common types of historic quay walls Amsterdam

The 22 risk factors are grouped into Load factors, Deformation factors, Bed slope assessment, Foundation and substructure assessment, Superstructure assessment and Street level assessment. Deformations are obtained from satellite, photogrammetry or traditional monitoring. The assessment is further based on historical documents, construction details, usage data and field inspections (above and below water) to visually identify damage or signs of instability.

Each of the factors are scored on a scale of 1-4 and given a relative weight factor. In principle, the scoring is a proxy for the probability of failure, the consequence of failure is assessed separately when deciding on the potential measures if needed.

As an example, the risk factor for deformations is shown in Table 1.

Table 1. Risk scores for deformation of the quay wall (combination of horizontal and vertical deformation and speed of deformation)

Deformation speed (mm/month)	Total deforma-tion (mm)	Probability of failure	score
<0.5	<5	Low	1
0.5 – 1.0	5-15	Medium	2
1.0-2.0	15-25	High	3
>2.0	>25	Very high	4

4.2 *Measures*

Based on the outcome of the risk score, measures can be advised, ranging from urgent safety measures to complete renovation. Urgent safety measures (within 6 - 12 months) may include:

- Setting a weight restriction on the parking spaces / on the roadway / closing to crowds
- Removing trees
- Reinforcement (using a sheet pile construction)
- Moving ships/jetties to other places

Programmable measures for the longer term include:

- Function change
- Renovation
- Renewal

The measures are selected based on a lifespan assessment and the outcome of the monitoring data as shown in Figure 2. Decisions on measures follow an integral approach; by combining the technical state of the quay wall with environmental impact, the decision making approach aims to ensure long-term structural safety, informed decision-making

with focus on sustainability, cost reduction, and proactive asset management.
If the need or feasibility for measures is not immediately clear, the quay wall is assessed in Level 2.

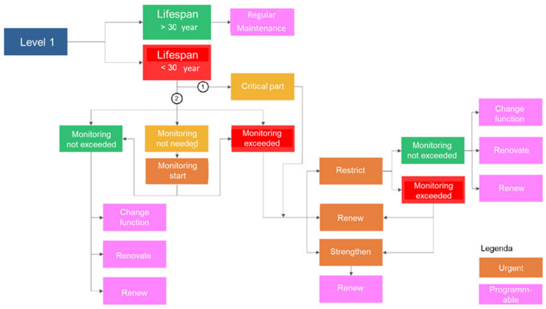

Figure 2. Overview of potential measures based on Level 1 Assessment

4.3 *Example*

An example is given of a quay wall section in the city centre of Amsterdam that contains the two main typologies, a historic masonry quay wall over 205 m, part A, and a concrete L shaped wall over 43 m, part B, both figured in Figure 1. The overall ARK score in this example is 3,5 for part A (high probability of failure) and 1,5 for part B (low probability of failure), given in Figure 3.

Part A contains multiple critical elements in the substructure in combination with a visible bulging of the masonry wall in the superstructure. In combination with critical monitoring results (Figure 4), the necessary safety cannot be guaranteed. Strengthening of the quay wall is advised. This results into full renewal following the schedule of Figure 2. Part B, containing a low probability of failure due to stable deformation results in combination with the absence of any critical structural elements, is advised for regular maintenance.

	Results loads			Results condition quay wall																		
	Critical loads			Critical assessment parts																		
				Deformation			Foundation / substructure						Superstructure						Street level			
	Trafic load	Tree load	Loads from water	Vertical	Horizontal	Waterbed	Timber piles	Tilting of the piles	Kesps	Pile kesp connection	Floor	Soil ret. screen	Amount of cracks	Crack width	Local masonry failure	Local hor. deformation	Tilting of masonry	Hor. timber beam	Expanding joints	Settlement above floor	Settlement in street	Renovated street
Weight	1.0	1.0	1.0	1.0	3.0	2.0	3.0	2.0	2.0	2.0	1.0	2.0	2.0	2.0	1.0	3.0	3.0	1.0	1.0	2.0	1.0	1.0
Part																						
Part - A	3.0	2.0	2.0	2.0	4.0	2.0	4.0	3.0	4.0	4.0	3.0	3.0	2.0	2.0	2.0	4.0	1.0	3.0	3.0	3.0	1.0	3.0
Part - B	4.0	1.0	2.0	1.0	1.0	2.0	3.0	0	0	1.0	1.0	3.0	1.0	1.0	1.0	1.0	1.0	0	1.0	1.0	1.0	1.0

Figure 3. Risk scores for Level 1 Assessment

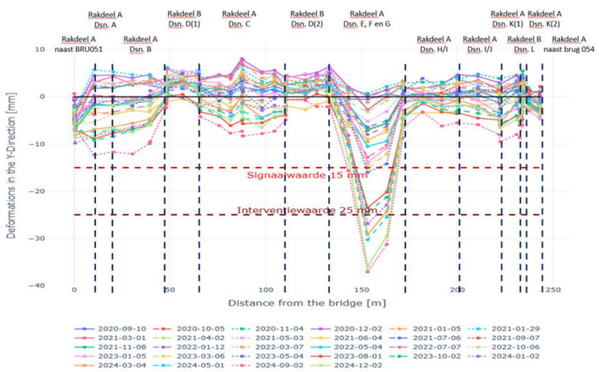

Figure 4. Monitoring results of example quay wall with sections A and B, tachymetry on top of the wall. Horizontal displacement (positive towards land, negative towards water) per date of inspection. Signal values of 15 mm and Intervention values of 25mm have been exceeded for part A.

5 LEVEL 2 MODELLING BASED APPROACH

The Level 2 approach is called TAK (Dutch abbreviation of Assessment Framework Quay walls) and includes modelling of the quay wall cross section. Different failure mechanisms are assessed, often numerically using Finite Element Models (FEM). Advanced structural models are applied, using available geometry, soil and material properties, mooring, wind and traffic loads. For the assessment a numerical model is made in 2D for both SLS and ULS and for three different time intervals; 1 year, 15 year and 30 year, including pile degradation mechanisms. The quay walls are classified in Eurocode Reliability Classes 1 or 2 depending on the consequence of their failure. The Level 2 approach is not a real OM application, it must be seen as intermediate step. Some of the characteristics of the wall, length of the piles, diameter and tapering of the piles and strength of the timber as well as (ground)water levels and geotechnical parameters, are taken from measurement databases with local results. If the Level 2 approach fails, monitoring results (e.g., inclinometers, strain gauges, sonar) and load tests may be used to verify wall behaviour. Results are interpreted with respect to safety margins, uncertainty, and usage demands.

The results of the Level 2 approach are also used to calibrate the 22 weight factors of the Level 1 approach and to determine threshold values for monitoring.

6 LEVEL 3 EVOLVING/UPDATING APPROACH

The Level 3 Approach is a probabilistic approach, allowing for reliability updating and the concept of proven strength. The probabilistic approach is loaded with inspection results to decrease the uncertainty in the geometrical input variables. As the exact geometry of these quay walls is often unknown, the number of piles, pile length, pile diameter and pile degradation all have to be estimated from city wide datasets, with local inspection data wherever present. A detailed overview of these datasets is given in Voortman et al. (2025).

The concept of proven strength takes this approach a step further and takes into account the fact that the quay walls are currently functioning, although with unknown safety level. Historic and current loading conditions or intentional test loading conditions can be used to update the probability of failure of the structure by rearranging the failure potential of the load survived. A full probabilistic approach currently is in use for the assessment of the bridge foundations, and under development for the quay wall assessment. For bridge foundation this has resulted in significant longer remaining life spans. Supporting the development of such an approach on quay walls, a test loading on a full scale quay wall in the historic city centre took place in the fall of 2024 (Figure 5) and for more details Karamitopoulos et al. (2025).

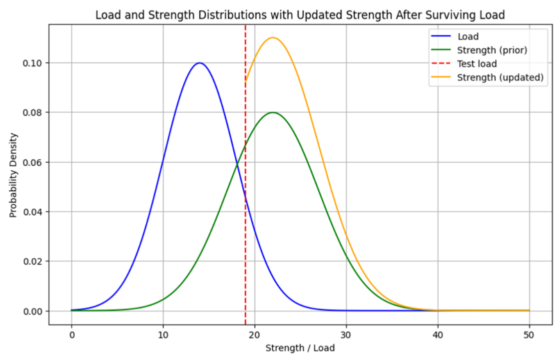

Figure 5. Principle of proven strength for test load of 19 kPa

Figure 6. Test loading of historic quay wall along Rechtboomssloot in Amsterdam

An even more advanced approach is being developed as part of the LiveQuay project at TU Delft, based on a physics informed machine learning model. This model will assess not a single but a population of structures, utilising known physics to improve model accuracy and interpretability while inferring uncertain physical parameters from monitoring. For this Bayesian probabilistic methods are being scaled and both tachymetry as well as InSAR data are integrated with structured probabilistic models to achieve population level prediction results. The first steps of this model are presented in Koune et al. (2023).

7 ESSENTIAL ADDITIONS TO OBSERVATIONAL METHOD

When the OM is being used, all failure mechanisms need to be very well understood. For complex, historic and buried structures, this is not always the case, and additional information is necessary. For a successful use of the OM, it is essential to continuously update the understanding of the way the walls fail and how they behave approaching failure. FEM models are not sufficient for that. That is why the following two additions are suggested for the understanding and assessment of historic structures.

7.1 *Full Scale Testing*

The second essential addition to the OM for historic structures is full scale testing. With full scale testing, such as performed to failure in Amsterdam and analysed and reported by (Hemel, 2023), Figure 7, a unique opportunity arises to link failure criteria to deformations measured, making room for future more solid assessments of the reliability of structures based on measurements and the Observational Method.

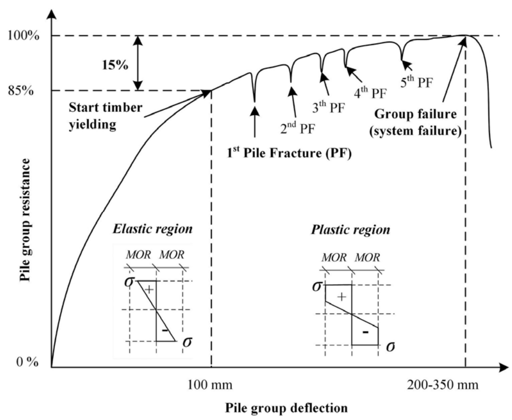

Figure 7. Deformation of the pile group under the Overamstel full scale field test (Hemel, 2022)

7.2 *Forensic Engineering*

The first useful addition is the investigation forensically of failed quays and quays demolished for renewal. The failed quays provide understanding of the limit states while the demolished quays can be used for validation of local geometrical datasets. One example of such a forensic investigation is the analysis of the Grimburgwal collapse in Korff et al (2022). From this analysis the failure pattern was established, the ductile nature of it as well as the warning signs from InSAR and the characteristics of the masonry wall and the timber piles present. As failed quay walls are not always monitored (one does not always see the failure coming) full scale testing is an alternative in which failures can be controlled and studied in a lot of detail.

8 CONCLUSION

The use of the Observational Method for historic structures is developed out of the need of dealing with the inherent uncertainties of old, largely varying, buried structures. With traditional methods many walls would have to be renovated or renewed, while their current performance in practice does not reflect such low reliability levels.

Before a full (Level 3) OM can be implemented for a large number of quay walls such as in a historic city like Amsterdam, this requires 1) a more detailed understanding of the failure modes and paths to failure for historic quay walls, 2) the development and validation of signal and intervention levels of deformation. At this moment, important steps are taken in developing proven strength approaches, performing load tests as well as failure tests at full scale. In the meantime, decision makers continue implementing necessary measures, and are doing this based on Level 1 and Level 2 applications, which also benefit from further understanding of the failure modes and deformation levels.

9 ACKNOWLEDGEMENTS

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