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**Publication date**

2025

**Document Version**

Final published version

**Published in**

IABSE Congress Ghent 2025

**Citation (APA)**

Messali, F., Esposito, R., Sharma, S., Longo, M., & Jain, U. (2025). Advanced finite element modelling and material characterisation procedures in support to the structural assessment of urban masonry quay walls: the Amsterdam case study. In D. Leonetti, H. H. Snijder, B. De Pauw, & S. van Alphen (Eds.), *IABSE Congress Ghent 2025: The Essence of Structural Engineering for Society* (pp. 2265-2273). International Association for Bridge and Structural Engineering (IABSE).

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## Advanced finite element modelling and material characterisation procedures in support to the structural assessment of urban masonry quay walls: the Amsterdam case study

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### Abstract

Masonry quay walls are vital infrastructure in many historic cities, serving both functional and historical purposes. Originally designed as gravity retaining walls, they now face increased vehicle loads and widespread material degradation, particularly in timber foundations. Traditional assessment methods are often overly conservative, lacking standard procedures for multi-wythe masonry characterisation. With over 200 km of quay walls in Amsterdam requiring renovation, there is an urgent need for practical, reliable assessment methods. This paper provides an overview of recent research conducted at TU Delft with focus on the response of masonry superstructure, presenting and discussing key advancements in the development of high-fidelity static and dynamic finite element models and minor-destructive testing for masonry mechanical property characterisation.

**Keywords:** quay walls; multi-wythe unreinforced brick masonry; nonlinear finite element analysis; dynamic analysis; material characterisation; core testing; timber piles; foundation degradation; traffic loading.

### 1 Introduction

Historic masonry quay walls are integral to urban infrastructure, particularly in cities with extensive canal networks, such as Amsterdam, Hamburg, and Venice. These structures not only support the city's functionality but also serve as vital heritage assets. Originally constructed as gravity retaining walls, they were designed to manage static loads associated with historical transportation methods. However, over time, these walls have been subjected to increasing demands from modern vehicular traffic, leading to elevated stress levels on their superstructure and substructure.

Additionally, material degradation, particularly in the timber foundations, might further diminished their structural reliability.

In the Netherlands, the city of Amsterdam alone boasts over 200 km of masonry quay walls, much of which potentially requires renovation [1]. While these structures continue to play a pivotal role in urban life, their structural behaviour under current loading conditions remains inadequately understood. Existing assessment methods often rely on standardised procedures that are not tailored to the unique characteristics of multi-wythe masonry. Consequently, such approaches tend to yield overly conservative results, which

may lead to unnecessary and costly interventions. A critical gap exists in developing tailored methodologies that balance accuracy with complexity, enabling an efficient evaluation of this important infrastructure.

To address these challenges, a comprehensive investigation has been carried out by researchers at TU Delft under the program Bridges and Quay walls. Multiple aspects of quay walls have been studied, ranging from the assessment of quality and degradation of foundation piles [3]-[6], to the response of laterally loaded piles [7], and the remote monitoring of the displacements of quays [8][9] and adjacent bridges [10].

This paper provides an overview of the research conducted on the structural quay wall response, inclusive of masonry superstructure and timber foundation, which focused on advancing both finite element modelling and material characterisation techniques tailored to historical masonry quay walls. High-fidelity dynamic finite element models have been developed to capture the interaction between masonry structures and adjacent soil under traffic loading, allowing for a detailed understanding of load redistribution mechanisms. Simultaneously, minor-destructive testing methods have been refined to characterise the mechanical properties of historical masonry materials, enabling a more reliable input for structural analyses. Together, these innovations aim to bridge the gap between theoretical accuracy and practical applicability, providing robust tools for the assessment and management of these complex structures.

## 2 Advanced numerical procedures for the assessment of historic quay walls under traffic loading

The numerical modelling strategy presented in this section is specifically designed to address the challenges associated with the structural assessment of historic quay walls subjected to vehicular traffic loads (Figure 1). It is particularly suited to scenarios where traditional methods either overestimate structural demands or fail to capture force redistribution in the masonry wall following partial failure of the timber foundation

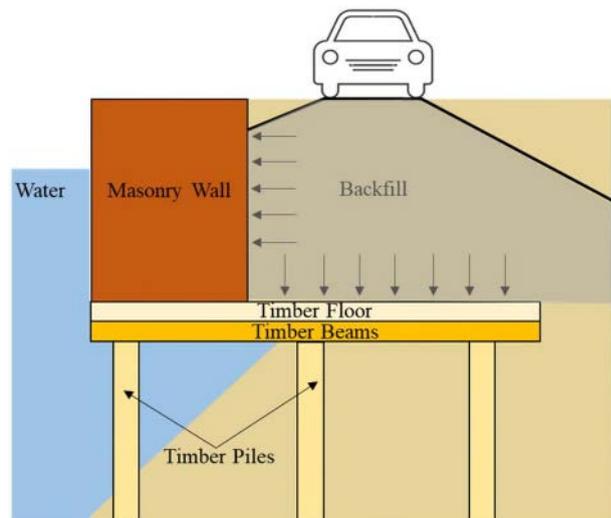


Figure 1. Schematic of a typical historic masonry quay wall (adapted from [11])

system. The methodology's flexibility allows it to adapt to different configurations and typologies, making it a valuable tool for assessing the stability, deformation patterns, and load redistribution capacities of historic quay walls under modern traffic conditions.

### 2.1 A tier-based analysis procedure

In order to efficiently address the complexities of soil-structure interaction, enabling the accurate prediction of structural safety, deformation, and load redistribution in quay walls subjected to modern traffic conditions, while significantly reducing computational demands, a two-tiered approach was proposed by the authors in [11]. This method simplifies the complexities of soil-structure interactions by dividing the analysis into two levels, or tiers, which enables a balance between computational efficiency and accuracy.

In the first tier, the focus is on modelling the interaction between the moving vehicle loads and the soil block next to the quay wall, and defining the loads that act on the structure (i.e., masonry quay wall and timber foundation system) corresponding to the application of an impulse loading on the roadway behind the quay. A three-dimensional model, including the soil, wall and road pavement is developed to simulate the propagation of vehicular loads through the soil to

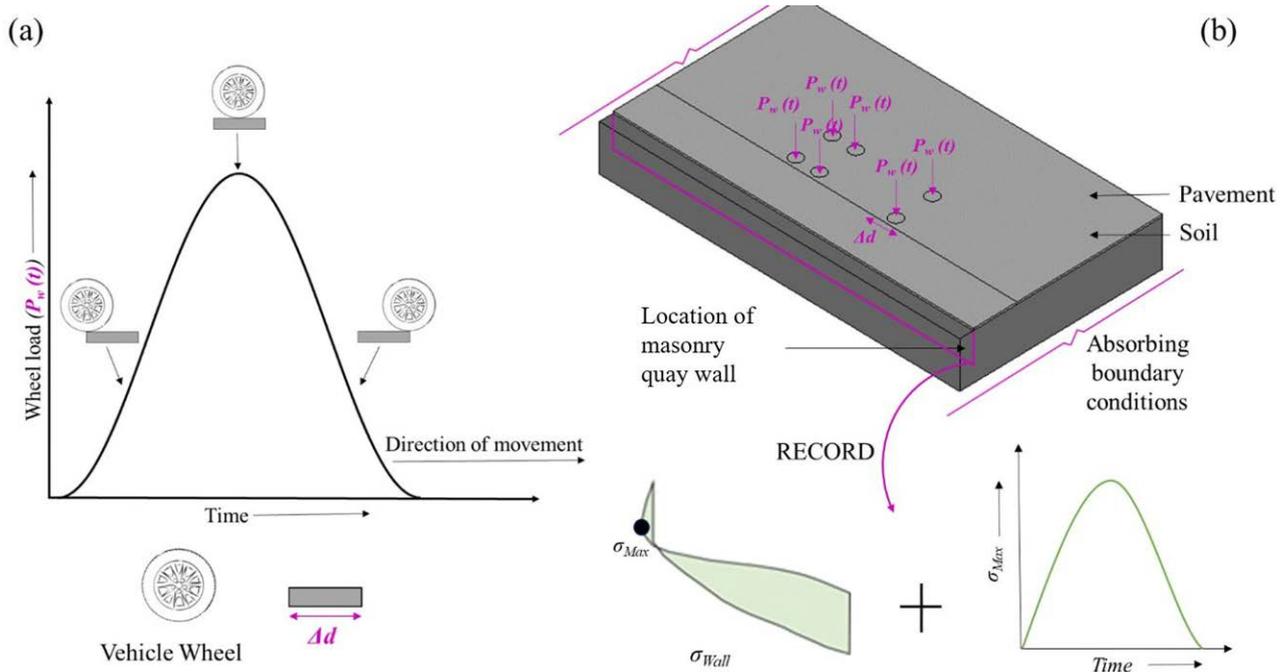


Figure 2. Schematic representation of Tier 1 analysis (from [12])

the quay structure (Figure 2). Linear elastic constitutive models are used for all the elements, while absorbing boundary conditions are applied to simulate the infinite extent of the soil, preventing wave reflections that could distort the results. The output from this tier includes time-dependent stress distributions at the locations of soil-wall, soil-floor, and soil-piles interaction, which serve as input for the subsequent tier.

The second tier shifts attention to the structural response of the quay wall itself. Unlike traditional modelling of quay walls, here, the wall is modelled three-dimensionally to capture its behaviour under the loads obtained from Tier 1. The surrounding soil is not explicitly included but is represented through boundary elements such as springs, which simulate the impedance provided by the soil. These springs play a critical role in capturing the soil-structure interaction and ensuring that the structural model reflects realistic boundary conditions. By incorporating these boundary elements, the model can efficiently account for the influence of the soil without the computational burden of fully integrating the soil block. The stiffness of these springs significantly affects the model's results, making their accurate estimation essential. Research conducted by Hemel et al. [7]

provide valuable insights into determining appropriate stiffness values for these elements.

To account for the complexities of the construction process, phased analyses are conducted, simulating the sequence in which the quay wall is constructed. This approach is particularly important because it ensures that the traffic loading is applied to a consolidated soil system, reflecting the actual conditions under which the quay wall operates. The masonry wall is modelled with nonlinear material properties, allowing the simulation of realistic structural behaviours such as cracking, force redistribution, and displacement. Static loads are first applied to simulate parking, while dynamic loads are applied sequentially along the length of the quay wall, replicating the movement of a vehicle and enabling the evaluation of both peak and residual structural responses (Figure 3).

Comparisons with simulations that integrate both the structure and the soil using non-linear properties (i.e., a coupled or non-tiered model) suggest the necessity of applying compensation loads to the timber floor to better replicate deformations caused by settlement rather than the out-of-plane bending of the wall. This adjustment aligns the tier-based model's outputs more closely

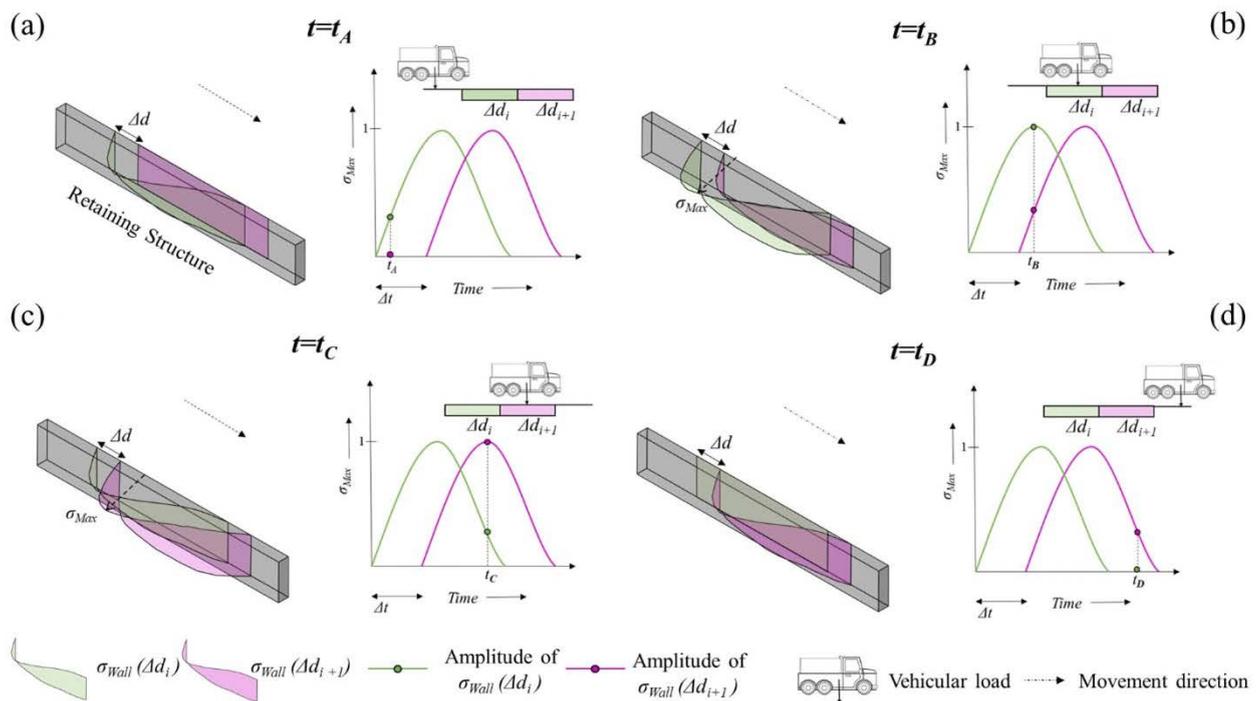


Figure 3. Time-dependent representation of stress distribution on the retaining structure during vehicle movement, as applied in Tier 2 analysis (from [12])

with those of the more computationally intensive coupled models, ensuring its predictions remain reliable while maintaining efficiency.

## 2.2 Alternative analysis procedures to account for load redistribution

The tier-based analysis procedure enables analyses where the traffic loading is applied as a moving dynamic load. However, this type of analysis remains time-consuming and not suited for the application to a large network of quay walls. For this reason, alternative advanced procedures to capture key load redistribution mechanisms have been proposed and compared with one another. These procedures encompass dynamic and static moving load simulations as well as monotonic loading approaches, as extensively described in [12]. The dynamic and static moving load procedures are used to evaluate the effects of vehicular movement along the retaining structure, while the monotonic loading procedures assess the structural capacity under gradually increasing loads. By comparing these approaches, the methodology quantifies the contributions of dynamic effects, three-dimensional structural configurations, and non-linear material behaviour

to the overall capacity of the retaining structure. The proposed framework is applied to a historic masonry quay wall in Amsterdam, demonstrating its ability to capture load redistribution mechanisms and assess structural performance up to failure, as shown for example in Figure 4.

## 2.3 Effect of pile degradation on the quay structural performance

The effect of pile degradation on the structural performance of quay walls was assessed using a tier-based analysis procedure, with a case study on the Marnixkade quay in Amsterdam. Multiple

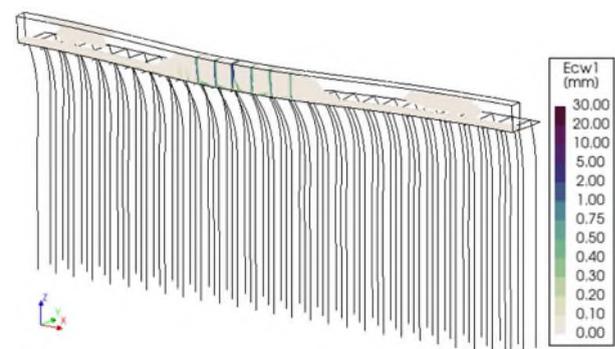


Figure 4. Deformed shape and crack width of the quay wall at failure (deformations x40 magnified)

scenarios were considered, including varying degrees of timber pile damage, expressed as median percentage reduction in pile diameter relative to its initial value. An initial set of dynamic analyses showed that pile degradation significantly affects the wall's structural response, leading to increased displacements, changes in load distribution, localized cracking, and reduced load-carrying capacity. A comparison between models with uniformly and randomly distributed pile damage revealed differences in failure mechanisms, ranging from global quay rotation to local wall overturning. This necessitated the performance of a second, more extensive set of analyses to explore the feasibility of investigating probabilistically the impact of the spatial distribution of damage in foundation piles on the quay's structural response. To reduce the computational demand, pushover simulations were conducted, demonstrating how increased degradation leads to reduced load-carrying capacity and higher variability in structural performance, as shown in Figure 5. These findings highlight the necessity of accounting for pile degradation in quay wall assessments to accurately predict failure mechanisms and structural capacity under operational loading conditions.

## 2.4 Preliminary comparison with large-scale in-situ testing

The methodology proposed in this study was preliminarily validated through comparisons with the results of a large-scale proof-loading experiment conducted in August-September 2024 at Rechtboomssloot in Amsterdam. The experiment involved two types of static loading conditions applied to the quay wall: first, the slow passage of a garbage truck replicated heavy vehicular traffic; second, gradually filling water containers placed along the wall simulated uniformly distributed loading conditions. Both loading cases were designed to evaluate the wall's response under operational conditions, providing insights into deformation patterns and structural behaviour. Organised by Deltares, Ingenieursbureau Amsterdam, and IV Infra [13][14], the experiment also served as a critical opportunity to assess the practical applicability and accuracy of the numerical procedures developed. Archival data

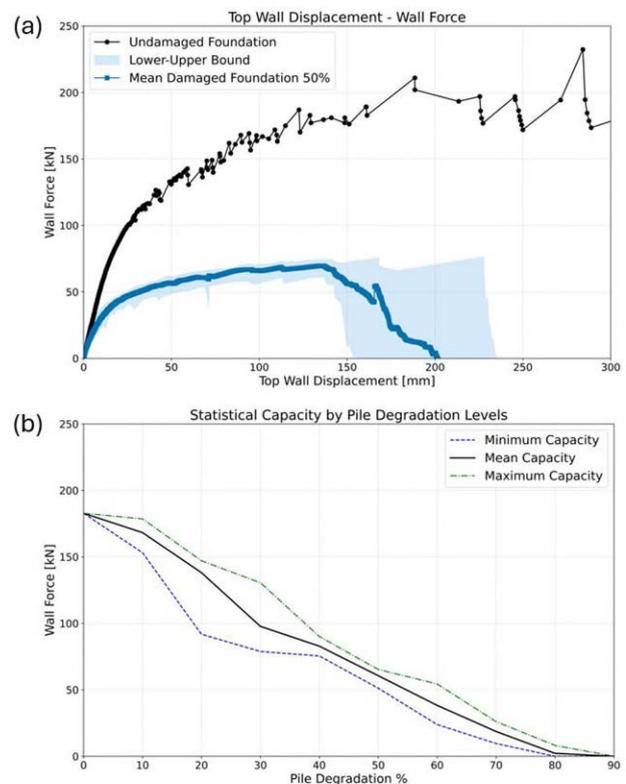


Figure 5. (a) Force-displacement curves for walls with either undamaged or damaged foundation; (b) statistical representation of load-carrying capacity as a function of pile degradation levels.

on the construction details of the quay wall and its foundation, as well as the surrounding soil conditions, were utilised to construct high-fidelity coupled finite element models. Initial comparisons between the numerical model and the results from the proof-loading experiment available as of January 2025 showed promising agreement, particularly regarding the magnitude and distribution of out-of-plane displacements. This alignment highlights the capability of the model to capture the key structural responses under operational loading conditions. Future calibration of the model using the full dataset from the experiment, including material characterisation and structural dynamic identification, will refine its predictive accuracy further supporting its application in the assessment and management of historic masonry quay walls.

### 3 Material characterisation

To understand and simulate the structural response of quay walls, the determination of mechanical properties of masonry is of relevance. In particular, advanced numerical models require information on compressive, shear and bond properties of masonry including the characterisation of elastic, strength and stiffness parameters. For Dutch urban masonry infrastructure, the masonry characterisation is challenging mainly due to two factors: i) the complex texture of the multi-wythe masonry, and ii) the difference in exposure conditions for various parts of the wall (i.e., submerged in water, in contact with air and/or soil).

Historical quay walls, but also bridges and underpasses, in the city centre of Amsterdam are made of multi-wythe masonry with thickness varying from 600 to 1200 mm. To achieve such thickness, bricks are arranged in a regular manner along the thickness. However, the exact arrangement is often not known and the thickness of the mortar joints presents large variations [15]. Usually fired clay brick are used together with lime mortars containing trass.

A characterisation of most representative masonry typologies for historical infrastructure in Amsterdam is currently being performed at TU Delft. Experiments on samples extracted from a bridge pillar built at the end of 19<sup>th</sup> century [15] revealed higher value of mechanical properties with respect to masonry typically used in Dutch buildings. For the case study analysed, a normalised brick compressive strength of ca. 26 MPa was obtained providing a compressive strength of masonry of ca. 12 MPa. A good bond was observed with value of flexural bond strength larger than 0.4 MPa and cohesion of 0.3 MPa. For quay walls, ongoing investigations show that the normalised brick compressive strength is lower with values around 14 MPa. This may suggest that the masonry has lower mechanical properties in quay walls with respect to bridges, most likely addressing a difference in vertical load to be borne.

The various exposure conditions for the masonry infrastructure seems to play a relevant role. Xi and Esposito show [15] the presence of a through-

thickness effect on mechanical properties of masonry above water level. Specimens extracted from the external side of the pillar, closer to canal water, exhibited a higher Young's modulus compared to those from the internal side ( $E_{\text{external}} = 5780 \pm 1522$  MPa,  $E_{\text{internal}} = 2949 \pm 754$  MPa). On the contrary, similar value of compressive strength of masonry were found independently from the exposure condition ( $f'_{m,\text{external}} = 12.3 \pm 1.9$  MPa,  $f'_{m,\text{internal}} = 12.7 \pm 2.1$  MPa). The flexural bond strength showed higher value inside the pillar with respect to the external region ( $f_{w,\text{external}} = 0.42 \pm 0.02$  MPa,  $f_{w,\text{internal}} = 0.75 \pm 0.10$  MPa). This may suggest the presence of deterioration mechanisms or difference in ageing conditions due to the exposure. In fact, properties of bricks and mortar were found to be similar in the various regions of the pillar, excluding the possibility of renovation.

It is expected that masonry mechanical properties may vary also along the height of the walls/pillars due the different exposure conditions, such as air-dry conditions, wet-dry cycles and water-submerged conditions. By comparing uniaxial compression tests on masonry prisms in air-dry and water-submerged conditions, Amde and co-authors [16] reported a 20% reduction in compressive strength, and an 8% reduction in elastic modulus due to saturation with moisture. They attributed these reductions to the loss in strength of the individual constituents, which for both bricks and mortar was around 10-15%. For both brick and masonry under uniaxial compression, Bompaa and Elghazouli [17] found a dependency of the results from the shape factor of the specimen tested. Moisture reduced compressive strength by approximately 5% in brick-only cylindrical specimens with height-to-depth ( $h/d$ ) ratios of 1.0 and by 13% in those with  $h/d$  ratios of 2.0. For masonry, an insignificant reduction of strength was found for wallets, while cylindrical specimens with only one bed joint showed higher variations due to presence of moisture. This was attributed to the confinement effect in masonry wallets that is able to contrast the negative impact of moisture in the mortar. Regarding the impact of wet-dry cycles, this is often study in conjunction with the effect of salt crystallisation. By comparing results for masonry prisms under wet-dry cycles, with various

concentration of chloride sodium, to reference specimens in dry conditions, Graus et al. [18] reported a reduction of 10 to 25% in masonry compressive strength and of 15% in masonry elastic modulus. The salt concentration appeared to worsen the effect on compressive strength, while it did not affect the variation in elastic modulus. On the contrary, Giacconi and co-authors [19] reports an improvement of masonry mechanical due to presence of salt crystallised in the pores. Preliminary investigations on field-extracted samples from a quay wall in Amsterdam show that masonry below water level has a compressive strength approximately 60% lower with respect to masonry above water level. These findings highlight the need of further investigation on the impact of water and wet-dry cycle to fully understand the response of multi-wythe masonry in urban infrastructure.

The characterisation effort for urban masonry infrastructure highlights once more the challenging in selecting appropriate testing methods for existing constructions. For multi-wythe masonry infrastructure, conventional tests on prismatic specimens as proposed by standards are often not applicable due to their invasiveness in sampling and difficulties in extraction procedures. On the other hand, non-destructive techniques may provide only qualitative information and, among others, would not allow to capture the through-thickness effect. For this reason, testing methods on cylindrical cores are currently being used [15]. However, their application to good bonded masonry opened up new questions on the core testing methods, as for example on the use of high-strength mortar cap in compressive tests on horizontally-loaded core. For this reason, the characterisation effort of masonry infrastructure has been coupled to the work of the international RILEM technical committee on testing methods for masonry cores [20].



Figure 6. Example of tests on masonry cores extracted from urban infrastructure.

## 4 Conclusions

This study presents the latest advances in research on the structural assessment of historic quay walls. As part of a broader research programme, this work focuses on both numerical procedures for assessing quay walls under traffic loading and material characterisation effort of multi-wythe masonry.

The proposed numerical modelling approach, centred on a two-tiered strategy, ensures computational efficiency while accurately capturing critical soil-structure interactions and dynamic load effects. Phased analyses and boundary elements are key to enable realistic simulations of structural behaviour, including cracking and force capacity at failure. The investigation of pile degradation highlights its significant impact on structural performance, emphasising the importance of considering varying damage distributions in assessments. Preliminary validation against large-scale in-situ testing demonstrates agreement between predictions and observed responses, providing a strong basis for adopting this approach to predict quay wall responses under operational loading conditions.

Information on mechanical properties of multi-wythe masonry in Dutch historical urban infrastructure are currently needed for the assessment. The thickness and masonry texture as well as the exposure to various conditions, such as air-dry, wet-dry cycles and water-submerged, provide a challenge for the characterisation effort. In this respect, the adoption of core testing methods seems the most suitable approach, but



further validation of the testing procedure is required and currently ongoing. Investigation on field-extracted samples will confirm the preliminary insights on the variation of mechanical properties along the thickness and height of the infrastructure due to different exposure conditions.

These advancements in modelling and material characterisation establish a foundation for reliable structural evaluations and effective preservation strategies for historic quay walls.

## 5 Acknowledgement

Funding for this study was provided by the Amsterdam municipality through the Amsterdam Institute for Advanced Metropolitan Solutions (AMS), under the Bridges and Quay Walls Research Programme (Programma Bruggen en Kademuren). The authors thank Rick Voortman and Berber Renckens from Ingenieursbureau Gemeente Amsterdam for supplying relevant data.

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