Vibration-Based Monitoring of the Historic Quay Walls of Amsterdam

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Abstract. More than 1700 km of historic quay walls exist in the Netherlands, of which many approach the end of their lifespan. Collapses of the structures have already occurred, such as the failure of the Grimburgwal in Amsterdam, which stresses the urgency of assessing these structures. The application of vibration-based monitoring (identifying and tracking modal properties over time) to assess quay wall structures is investigated in this paper by executing a vibration-based monitoring campaign at a historic quay wall in Amsterdam. Based on the preliminary results of this monitoring campaign, this study shows that vibration-based monitoring is a promising field to explore further for quay wall assessment.

Keywords: Historic quay walls · Monitoring campaign · Dynamic identification · Modal properties

1 Introduction

In September 2020, a part of a quay wall collapsed along the Grimburgwal in Amsterdam, the Netherlands [22]. The collapse of the Grimburgwal caused concerns about the safety of 200 km of structurally similar quay walls in Amsterdam that have existed since the end of the 16th century. The quay walls are not only heavily used, but the structures are also part of the UNESCO heritage site *Seventeenth-Century Canal Ring Area of Amsterdam inside the Singelgracht* [27]. Many Dutch cities besides Amsterdam, such as Leiden and Delft, face similar issues since the Netherlands has more than 1700 km of historic quay walls [16]. Hence, a methodology is required to assess the condition of these historic quay

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walls so that maintenance and interventions can be prioritised effectively to prevent similar collapses in the future.

Assessing the historic quay walls is a challenging task for multiple reasons. The structures, represented by a simplified cross-section in Fig. 1, consist of a masonry wall, a timber floor, timber beams, and timber piles. In addition to soil-structure interaction, the structures also experience fluid-structure interaction [15]. Moreover, the quay walls under assessment extend over a large area and exhibit significant spatial variability in their geometrical, material, and loading characteristics [22].

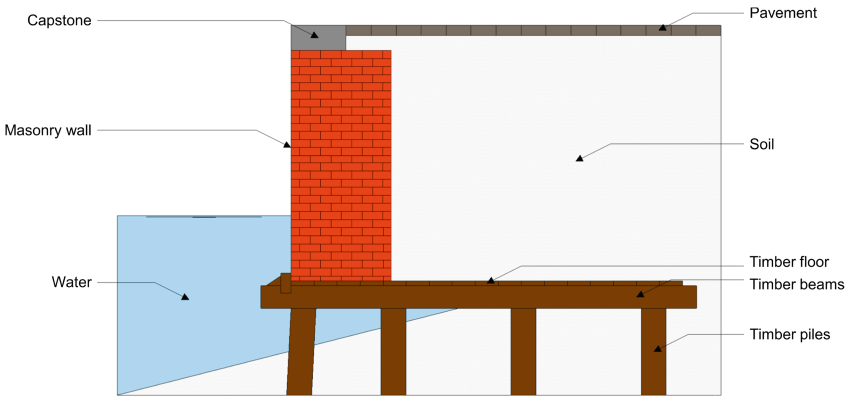


Fig. 1. Simplified representation (2D—schematic) of a historic quay wall.

A promising strategy to derive information about the current condition of a structure is the vibration-based monitoring method, in which vibration data of an investigated structure is collected to identify and track its modal properties (i.e. natural frequencies, mode shapes, and damping ratios) over time. Tracking those dynamic features over time can detect anomalies that might indicate damage. For example, damage might induce a stiffness reduction, which will cause a decrease in natural frequencies [7]. Vibration-based monitoring has often been successfully applied to large-scale civil engineering structures. Multiple examples exist in the literature of bridges [4,5], dams [6], offshore wind turbines [10,20], and lighthouses [3]. However, according to Negi et al. [24], vibration-based monitoring has hardly been performed during the various quay wall monitoring campaigns executed in previous years (e.g., [9,21,23]), despite its enormous potential and although it has been effectively applied to masonry structures [14,26] and comparable geotechnical structures, such as retaining walls [12,25].

The application of vibration-based monitoring to quay wall structures is investigated in this research by performing a vibration-based monitoring campaign at a historic quay wall located at the Recht Boomssloot, one of the historic canals in the city centre of Amsterdam, the Netherlands. Controlled structural damage was imposed on this quay wall by means of a proof load test executed by Deltares (a Dutch knowledge institution). During the proof load test, the quay wall was loaded statically by a truck first and afterwards by sea containers (partly) filled with water. Imposing controlled structural damage through a proof load test to this quay wall was feasible since the Municipality of Amsterdam started the renewal of this quay wall directly after the experiment.

Before and after the proof load test, forced vibration tests using an impulse hammer were executed at the quay wall at the Recht Boomssloot. Acceleration data was collected during these vibration tests to identify the structure's modal properties using the Bayesian Operational Modal Analysis (BAYOMA) technique [2,28]. Based on this study, this paper demonstrates whether it is possible to identify the modal properties of a quay wall and whether modal properties can be used to detect any damage induced by the proof load test.

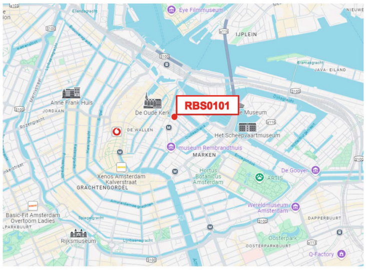
In this paper, the experiment executed at the Recht Boomssloot is extensively described in Sect. 2. Preliminary dynamic identification results of the vibration-based monitoring campaign are presented in Sect. 3. Finally, Sect. 4 discusses the application of vibration-based monitoring to quay wall structures.

2 Recht Boomssloot Experiment

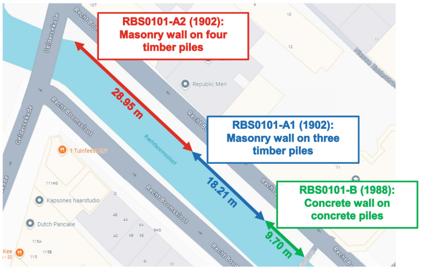
2.1 RBS0101 Quay Wall

The experiment site of the proof load test and the vibration-based monitoring campaign was the historic quay wall RBS0101 located at the Recht Boomssloot in the city centre of Amsterdam, the Netherlands (see Fig. 2a). According to archival research, diving inspections, and technical reports [13], RBS0101 dates from 1902 and was built of a masonry wall on top of a timber foundation having a varying amount of timber foundation piles along its length. In 1988, part of the quay wall's timber foundation was replaced by a concrete construction consisting of a concrete wall on concrete piles. The locations of these different segments of RBS0101 are specified in Fig. 2b, and their labelling throughout this paper is as follows: (1) RBS0101-A1—masonry wall on three timber piles; (2) RBS0101-A2—masonry wall on four timber piles; and (3) RBS0101-B—concrete wall on concrete piles.

Further available details of the experiment site are the technical drawings in Figs. 3a and 3b from the renewal of RBS0101-B executed around 1988 and the centre-to-centre distances between the first row of piles since diving inspections were performed [13]. Other relevant technical drawings (e.g., of RBS0101-A1 and RBS0101-A2) are lacking. Hence, Fig. 3a is used in this research to estimate the cross-section of RBS0101-A locations having a comparable height as RBS0101-B. Important to consider before adopting Fig. 3a for RBS0101-A are the following discrepancies: (1) Fig. 3a shows a foundation of four timber piles, while RBS0101-A1 exists of three timber piles; and (2) Fig. 3a shows that all timber piles are surrounded by soil, while the diving inspections discovered that at least the first row of piles is exposed to water.

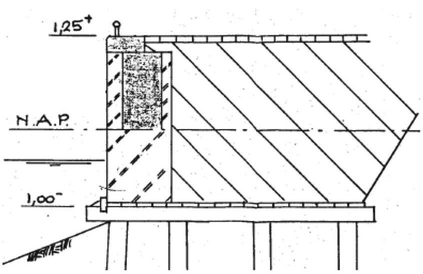


(a) Location.

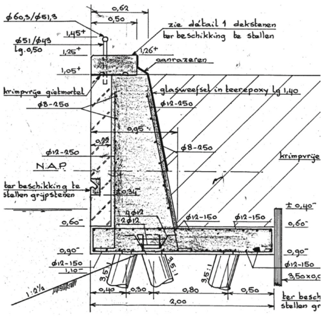


(b) Segments.

Fig. 2. Investigated quay wall RBS0101 at the Recht Boomssloot in Amsterdam, the Netherlands (retrieved and modified from Google Maps on 8 October 2024).



(a) RBS0101-B — before renewal.



(b) RBS0101-B — after renewal.

Fig. 3. Technical drawings RBS0101 originated from around 1987 [13].

2.2 Proof Load Test

The proof load test conducted by Deltares was a modified version of the full-scale proof load experiment at Amsterdam Overamstel executed by Hemel [15]. A heavy load was applied on segment RBS0101-A1 by means of a truck first (see Fig. 4a) and second by sea containers gradually filled with water (see Fig. 4b). The truck and the sea containers induced a maximum pressure of 20 kPa, which aimed to initiate the early stages of the common quay wall failure mechanism *lateral failure of the quay wall foundation* [15,17,18,22]. During the proof load test, the maximal horizontal displacement provoked by the applied load was limited to 10 mm to prevent a collapse of the quay wall. Eventually, the Municipality of Amsterdam can use the proof load test results to improve strength estimations of the historic quay walls and to update the predictions of their residual lifespan.

(a) Truck experiment. (b) Sea container experiment.

Fig. 4. Execution of the proof load test.

2.3 Vibration-Based Monitoring Campaign

During the vibration-based monitoring experiment, acceleration data of the quay wall was recorded for a short period with a sampling frequency of 512 Hz using eight uniaxial high-resolution servo accelerometers with a sensitivity of 1.3 V/g (QA-750 [19]) and two recorders (Dynamic Signal Analyzer—Abacus 901 [8]). An impulse hammer (Piezoelectric Impulse Hammer 5803A [11]) using its soft (brown) tip was applied to excite the structure.

Two measurement set-ups (resp. S1 and S2) were considered, of which S1 focused on the out-of-plane modes and S2 on the longitudinal ones. All accelerometers were located in segment RBS0101-A1 during the vibration-based monitoring campaign. Other segments of RBS0101 were omitted due to a limited number of accelerometers and because the proof load test examined RBS0101-A1. In both set-ups, the accelerometers recorded the horizontal vibrations of the quay wall, roughly perpendicular to the quay wall's frontal surface. The impulse hammer was applied approximately every 16 s on top of the capstone close to the middle of RBS0101-A1. In this paper, only S2 is presented (see Fig. 5) since the preliminary dynamic identification in Sect. 3 focuses on S2 datasets.

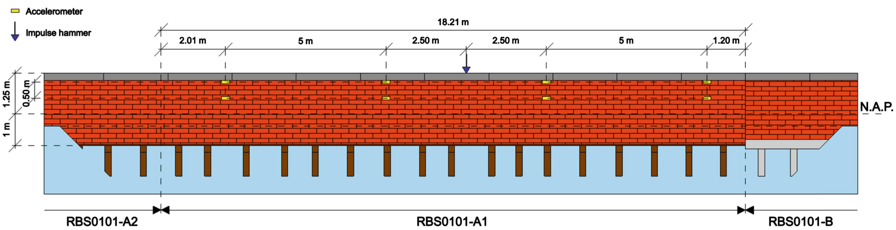


Fig. 5. Measurement set-up 2—S2.

Three repetitions using the same measurement set-up were carried out before (26 September 2024) and after (09 October 2024) the proof load test, as specified in Table 1. Multiple repetitions were conducted using the same measurement set-up to assess potential daily variations in the identified modal properties.

Table 1. Details vibration-based monitoring campaign.

Run	Date	Start	Duration	Set-up	Hammer	Temperature	Water level
1	26/09/2024	12:50	820 s	S1	✓	17°C	−0.4 m NAP
2	26/09/2024	14:23	841 s	S1	✓	18°C	−0.4 m NAP
3	26/09/2024	14:40	839 s	S1	✓	18°C	−0.4 m NAP
4	26/09/2024	15:32	810 s	S2	✓	18°C	−0.4 m NAP
5	26/09/2024	16:55	829 s	S2	✓	18°C	−0.4 m NAP
6	26/09/2024	17:11	831 s	S2	✓	18°C	−0.4 m NAP
7	09/10/2024	08:48	830 s	S1	✓	13°C	−0.4 m NAP
8	09/10/2024	10:13	831 s	S1	✓	14°C	−0.4 m NAP
9	09/10/2024	10:31	835 s	S1	✓	15°C	−0.4 m NAP
10	09/10/2024	11:07	818 s	S2	✓	15°C	−0.4 m NAP
11	09/10/2024	12:30	827 s	S2	✓	16°C	−0.4 m NAP
12	09/10/2024	12:45	831 s	S2	✓	16°C	−0.4 m NAP

3 Preliminary Dynamic Identification

A preliminary analysis of the S2 datasets (i.e. Run 4, 5, 6, 10, 11, and 12—see Table 1) is conducted in this paper. Preliminary results of the analysis carried out on Run 12 are illustrated in Fig. 6. The singular value peaks close to 8 Hz and 15 Hz consistently appear in every run and are, therefore, selected to be further studied using BAYOMA [2,28]. According to the BAYOMA analysis, the two singular value peaks in Fig. 6 correspond to two modes, of which the mode shapes are presented in Fig. 7. Mode 1 has a natural frequency of 7.97 Hz and a relatively high damping ratio of 17.58%, and mode 2 a natural frequency of 15.38 Hz and a damping ratio of 4.78%.

This analysis procedure is repeated for the other runs of S2, and the results are summarised in Table 2, which shows that the natural frequencies (f_1 and f_2) and damping ratios (ζ_1 and ζ_2) of the two modes remain approximately consistent across all runs. One exception is, however, that ζ_1 of Run 10 is significantly lower than the other identified damping ratios. In addition, the dynamic identification results are comparable before (Run 4, 5, and 6) and after (Run 10, 11, and 12) the proof load test. More details about the proof load test (i.e. initiated damage and maximum horizontal displacement) to clarify the comparable modal properties will become available later since the proof load test is currently being analysed by Deltares.

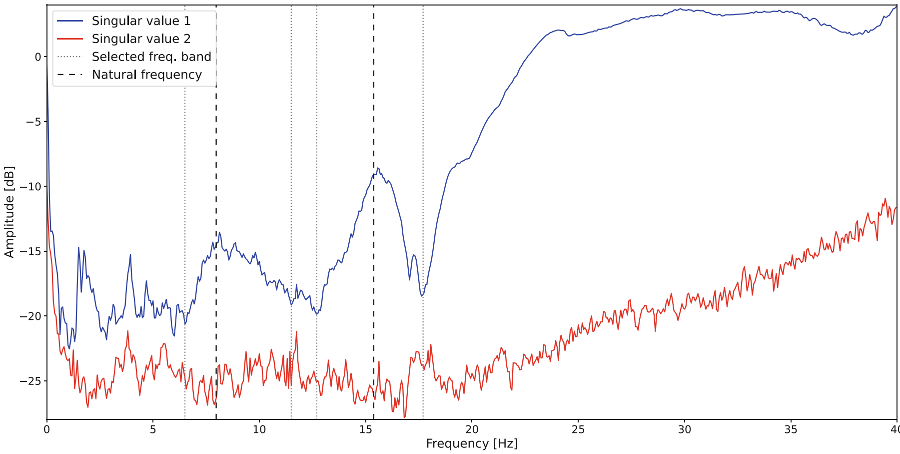
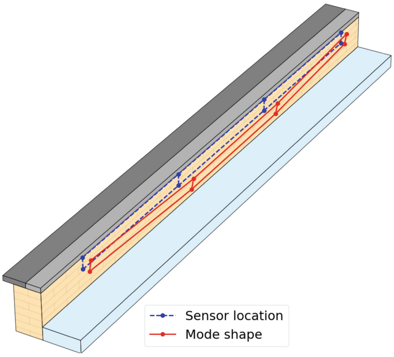
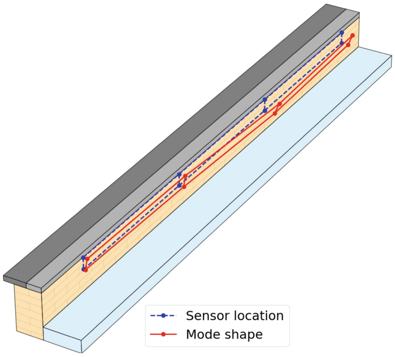


Fig. 6. Singular value spectrum Run 12; including natural frequency estimations using BAYOMA [28].



(a) Mode 1: $f_1 = 7.97\,\mathrm{Hz}$ & $\zeta_1 = 17.58\%$.



(b) Mode 2: $f_2 = 15.38\,\mathrm{Hz}$ & $\zeta_2 = 4.78\%$.

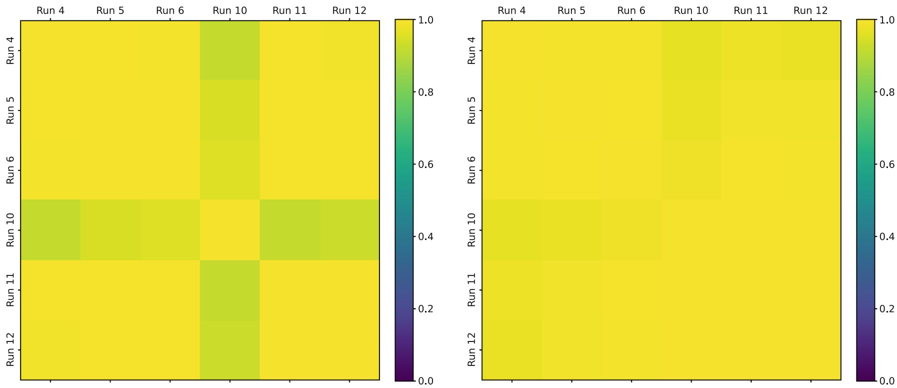
Fig. 7. Dynamic identification results Run 12 using BAYOMA [28]: (a) mode 1; (b) mode 2.

The Modal Assurance Criterion (MAC) [1] matrices for the two identified modes are presented in Fig. 8 and used to compare the identified mode shapes among the different runs. The identified mode shapes are consistent across all runs except for mode 1 of Run 10, which exhibits a notably lower MAC value.

The deviations of Run 10's mode 1 in terms of damping ratio and mode shape might indicate that additional (closely spaced) modes exist in this frequency range. This prediction is further reinforced by the relatively high damping ratios of ζ_1 in the other runs, which might imply that the dynamic identification procedure fuses the modal properties of multiple (closely spaced) modes. Further

Table 2. Dynamic identification results S2 using BAYOMA [28] (coefficient of variation in parenthesis).

	f_1 [Hz]	ζ_1 [%]	f_2 [Hz]	ζ_2 [%]
Run 4	7.87 (0.70%)	18.62 (4.15%)	15.14 (0.16%)	6.31 (3.54%)
Run 5	7.79 (0.62%)	16.16 (3.84%)	15.26 (0.15%)	6.05 (3.50%)
Run 6	7.85 (0.55%)	16.06 (3.65%)	15.30 (0.14%)	6.55 (3.01%)
Run 10	7.66 (0.17%)	5.78 (3.52%)	15.25 (0.13%)	5.67 (3.17%)
Run 11	7.93 (0.47%)	16.94 (3.49%)	15.30 (0.11%)	5.23 (2.91%)
Run 12	7.97 (0.47%)	17.58 (3.65%)	15.38 (0.10%)	4.78 (2.85%)



(a) Mode 1: $f_1 = 7.97\,\text{Hz}$ & $\zeta_1 = 17.58\%$. (b) Mode 2: $f_2 = 15.38\,\text{Hz}$ & $\zeta_2 = 4.78\%$.

Fig. 8. MAC matrices—S2: (a) mode 1; (b) mode 2.

analysis will be conducted to verify whether additional closely spaced modes are present in this frequency range.

4 Conclusions

The results presented in Sect. 3 indicate that the modal properties of the historic quay wall RBS0101 in Amsterdam remained stable throughout the measurement period. The identified natural frequencies, damping ratios, and mode shapes exhibit consistent values across nearly all runs of S2. These findings suggest that quay wall modal properties can be effectively identified. However, before applying vibration-based monitoring for quay wall assessment, further studies will be conducted by performing experiments in which more significant controlled damage will be imposed to investigate how this damage affects the quay wall's modal properties.

In addition, a more detailed analysis of the S1 and S2 datasets, employing different operational modal analysis techniques, is necessary to corroborate the results further. This analysis will be carried out as part of ongoing research.

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