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DOI
10.3997/2214-4609.202320023

Publication date
2023

Document Version
Final published version

Published in
3rd Conference on Geophysics for Infrastructure Planning, Monitoring and BIM

Seismic imaging of a historic quay wall using a high-resolution S-wave reflection survey

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Summary

The structural health of historic quay walls needs to be evaluated well in light of the new conditions they are subjected to. For that, information about their current subsurface structure and condition of their subsurface constructional elements, but also information about the surrounding subsurface structure is crucial. Such information can be supplied by seismic imaging and characterization. We show preliminary results from a high-resolution S-wave survey we performed at a historic quay wall in Overamstel, the Netherlands. We recorded data along four lines – two parallel and two perpendicular to the quay wall. We used a sledge-hammer and a beam as a source and 10-Hz horizontal-component geophones, both oriented in the crossline direction. We show that applying simple processing along the two parallel lines to obtain stacked sections already allowed extracting useful structural information of the subsurface.

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Introduction

The structural condition and safety of the historic quay walls in cities in Europe like Amsterdam are difficult to determine as there is insufficient information about the load they can still handle (Han and Vaziri 1992; Gemeente Amsterdam, 2020; Korff *et al.* 2022; Hemel *et al.* 2022). In many cases, the wooden and masonry components of the quay walls are damaged or deteriorated (Klaassen 2008), and owing to their age, proper documentation of the construction and potential repairs is often missing. In addition, large areas behind the quay walls are prone to ground-instability phenomena, such as soil mobilization and cavity formation, caused by intensified urban developments, heavy road traffic, and climate change-induced extreme weather and subsidence (Schokker *et al.* 2015).

While geotechnical investigations (e.g., borehole drilling, cone penetration tests, pit excavations, wood sampling) may yield important mechanical and hydrological properties of the soils surrounding quay wall structures and the construction itself, they only provide limited information about the spatial distribution of the soils and the extent of structural deterioration. Moreover, these investigations are costly and often require entire streets and canals blocked for a long period of time, which results in logistical problems and disruption of the daily life of the city.

Seismic reflection imaging of near-surface sediments has been customarily used, especially with S-waves, to determine subsurface boundaries of geological and hydrogeological nature (Konstantaki *et al.* 2015). A seismic modelling study demonstrated that it is possible to image the historic quay wall structure using measurements from the water side and to identify the possibilities and limitations of the method to detect structural deterioration (Balestrini *et al.* 2021). Yet, a field experiment to inspect the quay-wall structure and its surrounding soils from land was still missing.

In this scope, we performed a high-resolution S-wave reflection survey along a quay-wall site which resembles those in the historic city centre of Amsterdam (Figure 1). To calibrate the seismic data, the survey was supported by a dense array of cone penetration tests (CPTs) and a couple of seismic CPTs to measure directly the seismic-wave velocities and derive dynamic in-situ soil properties such as the low-strain shear modulus.

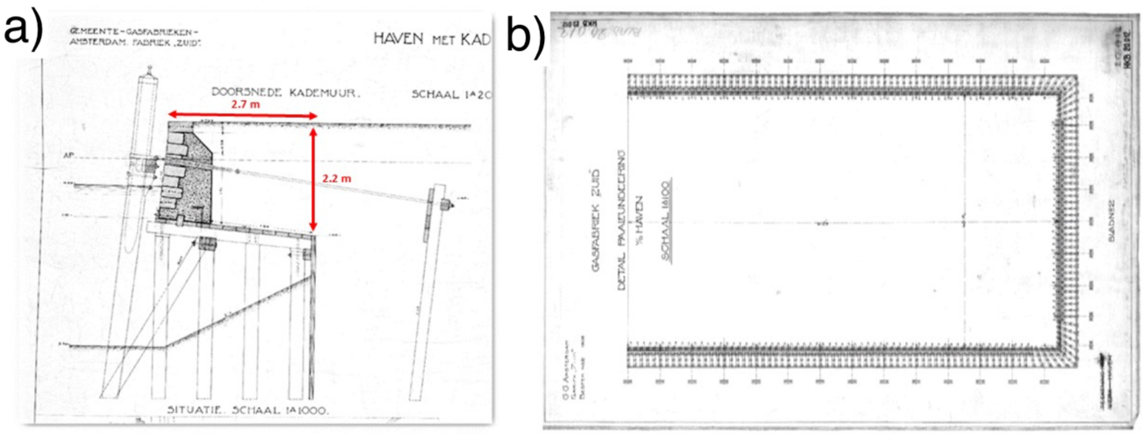

Figure 1 *Archival documentation of the Overamstel quay-wall structure:* ***a)*** *cross-section and* ***b)*** *top view. The quay-wall construction consists of a brick cantilever wall on a timber deck supported by four timber pile rows as well as a sheet-pile wall behind the fourth pile row. Red arrows indicate depth and*

distance of the wooden sheet pile from the edge of quay wall. Source: archive of the municipality of Amsterdam.

Field acquisition

We performed an S-wave reflection survey on 28 and 29 April, 2021, along four lines (Figure 2): two perpendicular (Line 1 and 2) and two parallel to the quay wall at 3.5 m (Line 3) and 7 m (Line 4) from its edge, respectively. As a seismic source we used a hammer hitting against a plastic beam with aluminium plates (Figure 2d) in the crossline direction. The source spacing was 0.5 m along the perpendicular and 1.0 m along the parallel lines. We used 10-Hz geophones, recording the crossline, horizontal particle-velocity component at 0.5 m interval.

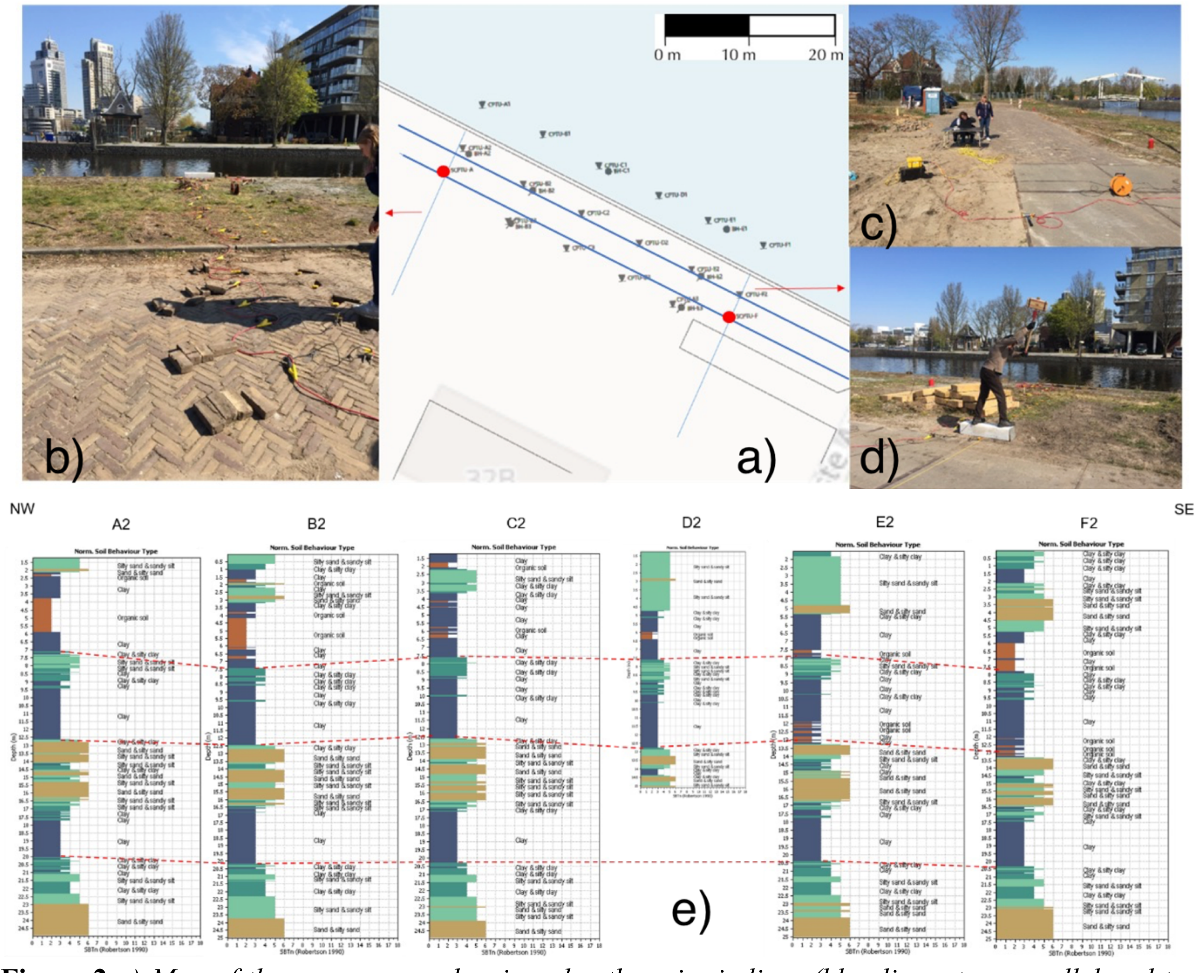

Figure 2 ***a)*** *Map of the survey area showing also the seismic lines (blue lines; two parallel and two perpendicular to the quay wall) and the location of CPTs (triangles) and SCPTs (red dots).* ***b)*** *Placement of the horizontal-component geophones corresponding to Line 1,* ***c)*** *data acquisition and quality control in the field, and* ***d)*** *excitation of seismic waves along Line 2 using a sledge-hammer.* ***e)*** *Profiles of soil type obtained from CPTs located along Line 3.*

Seismic processing

Figure 3a shows an example of five shot gathers at the middle of Line 3. These are shown in Figure 3b after application of band-pass filtering between 12 Hz and 200 Hz and automatic gain control (AGC) with a 150 ms window. Strong surface (Love) waves are present in the data which exhibit similar velocities and frequencies to reflection and diffraction events. We identify prominent reflection events and use them to estimate a stacking velocity (Figure 3c). We ensure that the event is well picked and it appears both in the shot gathers and in the stacked section. Because the stacking velocity is assigned to the reflection event, it partly supresses the linear surface waves during the stacking.

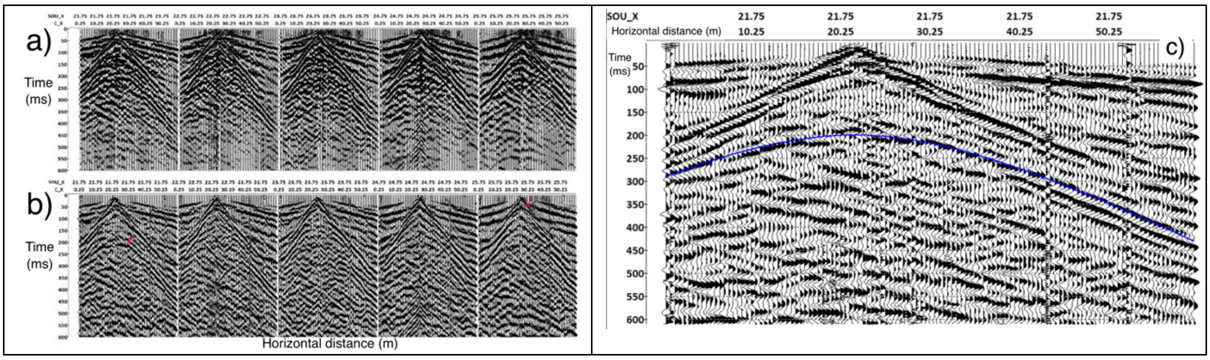

Figure 3 *Five middle shot gathers along line 3:* ***a)*** *raw and* ***b)*** *processed gathers using band-pass filter 12-200 Hz and AGC with a 150 ms window. Red arrows in the leftmost and rightmost gathers point to reflection events.* ***c)*** *Best-fitting hyperbola (blue line) giving a typical velocity of 100 m/s.*

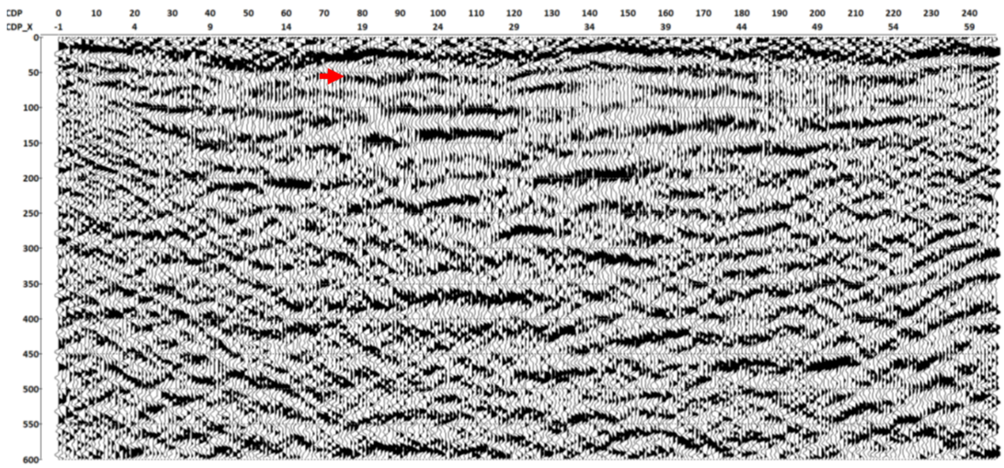

Figure 4 *Time-stacked section of shear-wave reflection data with spectral shaping 25-130 Hz flat (Line 3). Red arrows points at interpreted sheet pile.*

Figures 4 and 5 show the stacked sections along Line 3 and 4, respectively, using a stacking velocity of 100 m/s. The sections have been spectrally shaped between 25 Hz and 130 Hz. AGC with a window of 150 ms is applied. Despite the fact that surface waves stack at earlier times and thus interfere with shallow reflectors, we notice that the shallow reflector identified by the red arrow in Figure 4 at ~2.25 m (~50 ms multiplied by half the stacking velocity) that corresponds well with the top of the sheet pile in Figure 1a. Such information may be beneficial for the improvement of quay-wall maintenance as the absence of a sheet pile may lead to soil mobilization and cavity formation behind the quay walls. In Figure 5, we see two prominent reflectors at ~7.5 m (~150 ms multiplied by half the stacking velocity) and ~12.5 m (~250 ms multiplied by half the stacking velocity), which correspond well with the presence of a silt layer (wadzandlaag) at 7 m and the first sand layer at 12.5 m depth, respectively, as seen in the SCPT profiles in Figure 5. Identifying the presence and continuity of the silt layer is crucial, as there is evidence that it increases the stability of the historic quay-wall structures in the city centre.

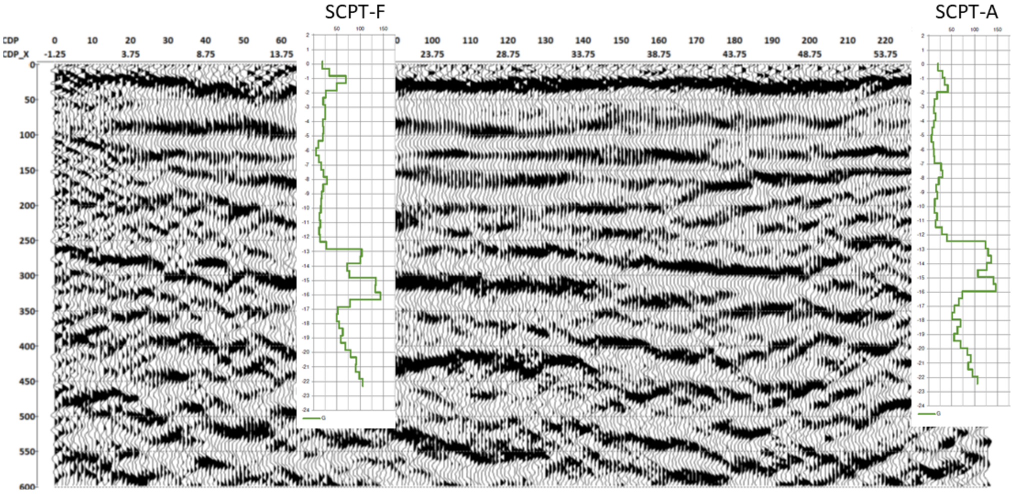

Figure 5 *Time-stacked section of shear-wave reflection data (Line 4). Superimposed derived shear modulus (in MPa) from SCPT-F and SCPT-A at 14.5 m and 56 m, respectively.*

Conclusions

We performed a high-resolution S-wave seismic reflection survey along lines located at a quay wall in Overamstel, The Netherlands. We used a sledge-hammer S-wave source and 10-Hz horizontal-component geophones, both oriented in the crossline direction. The acquisition and processing allowed us to obtain a high-resolution (~ 25 cm) image. Through simple processing to obtain the stacked section along the lines, we could derive useful information of the subsurface. We succeeded to identify the top of a sheet pile at ~2.25 m depth and two important shallow layers – a silt layer (wadzandlaag) at ~7.5 m and the first sand layer at ~12.5 m. The knowledge of the presence of the sheet pile and mapping the depth of the two layers in space are required for planning of adequate maintenance work.

Acknowledgements
The authors thank Jens van den Berg, Johno van IJsseldijk, and Aukje Veltmeijer for their help during the acquisition of the seismic data.

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