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Continuous monitoring of the depth of the water-mud interface using distributed acoustic sensing

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Abstract

Purpose Current surveying techniques used by port authorities to estimate the nautical depth are limited in depth resolution and temporal resolution. Because of this, certain heavily occupied quay walls cannot be optimised in terms of utilisation. Therefore, a permanent continuous measuring system with a higher depth resolution is needed to optimise the occupation at these quay walls. We show how this could be achieved with distributed acoustic sensing (DAS) using fibre-optical cables.
Materials We analyse recordings from a dual-frequency echo-sounder source along a standard communication optical fibre coiled vertically around a PVC pipe to represent vertical seismic profiling. This PVC pipe is placed inside a transparent plastic cylindrical tank which is partly filled with water and mud. This allows us to track the water-mud interface visually. We use a Silixa iDAS v2 and a Febus A1 DAS interrogator to convert the optical fibre into a seismic sensor. We use a wave generator to select the source frequency and an amplifier to amplify the output of the wave generator to a SIMRAD 38/200 COMBI C dual-frequency echo-sounder.
Results We identify standing waves and use them to make accurate depth estimates of the water-mud interface inside the column we measure. Due to the high apparent velocity, the standing waves are easy to identify in the time domain. Due to the constructive interference, standing waves also show the water-mud interface in a power spectral density plot. We demonstrate that these standing waves could be used with an on-demand permanent continuous measuring system using ambient noise sources.
Conclusion Our laboratory experiment showed that DAS could be used to estimate the water-mud interface. In addition, we showed the potential for on-demand monitoring in ports and waterways using DAS. Furthermore, due to the low cost of optical fibres, and the possibility of utilising ambient noise sources, DAS could be used for continuous depth monitoring purposes in ports and waterways.

Keywords Fibre optics · Water-mud interface · Standing waves · Distributed acoustic sensing (DAS)

1 Introduction

Port authorities regularly survey ports and waterways to measure the water depth. Current non-intrusive surveying methods are limited in accuracy due to, for instance, temperature fluctuations in water layers, but also in time due to their dependency on the availability of surveying vessels (Kirichek et al. 2018). The latter case especially poses problems after storm or dredging-related bathymetrical changes. A permanent monitoring system that can be operated remotely could be of special interest at busy docks, i.e.

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docks that are often occupied by ships. If one could monitor the depth at these locations on demand, the availability of these docks would increase.

Fadel et al. (2021) and Ma et al. (2021) showed that non-intrusive seismic measurements can be used for estimating shear strength in fluid mud.

Distributed acoustic sensing (DAS) could be used to create a vertical seismic profile (VSP) and using ambient-noise sources for subsurface imaging. This would allow one to measure the bathymetry on demand without the need to be at a monitor location. Multiple VSP setups could be installed. Such VSP setups would consist of no more than 300 m of optical fibre, which costs a little over 100 euros. In addition to their relatively low cost, optical fibres offer many other advantages over conventional sensors, e.g. being non-corrosive and non-conductive, making them well-suited with regard to safety and durability for long-term bathymetry monitoring.

During the last decade, there has been an evergrowing interest in DAS in geoscience (Lindsey et al. 2017; Jousset et al. 2018; Ajo-Franklin et al. 2019). One of the primary uses of DAS is to record VSPs in boreholes. Because in boreholes the fibre is permanently installed, there is no need to reopen the borehole or to keep the borehole open, which has significant economical benefits (Mateeva et al. 2014; Correa et al. 2017; Grandi et al. 2017; Götz et al. 2018). In a borehole, the fibre is often cemented inside the casing, in order to increase the coupling with the borehole. There are also various recordings where a temporarily installed wireline cable was used (Hartog et al. 2014; Borland et al. 2016; Yu et al. 2016). Here the fibre is not properly coupled, meaning it has a certain degree of freedom to move around. One clear difference between these two conditions is that in the latter case, ringing noise is observed (Daley et al. 2016; Willis et al. 2019).

This ringing noise appears as waves that propagate with infinite velocity, and is related to standing waves, which depend on the length of the fibre and the frequency. The source of this ringing noise was first identified by Martuganova et al. (2021). In this paper, the authors also proposed an elegant solution to filter these standing waves. They also showed that the length of the standing waves is related to the fundamental frequencies. This is important to note, because a similar approach could be used with a VSP setup to monitor the water-mud interface using standing waves. Standing waves could develop between the water-mud interface and the water/air interface due to constructive interference. For illustrative purposes, in Fig. 1, we show a schematic overview of standing-wave modes that could develop between two closed ends.

2 Setup

We want to measure reverberations, also known as standing waves, using a fibre-optical cable. For this aim, we use a standard single-mode optical fibre, which is coiled around a PVC pipe with a diameter of 0.125 m, which in turn is installed in a transparent column with a diameter of 0.4 m. In this way, we obtain a VSP setup. We partly fill the column with mud from the Port of Rotterdam, with an initial density of 1.17 kg l^{-1}w and a yield point of 35 Pa. The transparent column allows us to visually track the water-mud interface. A sketch of our setup can be viewed in Fig. 2 and a picture of the setup is shown in Fig. 3.

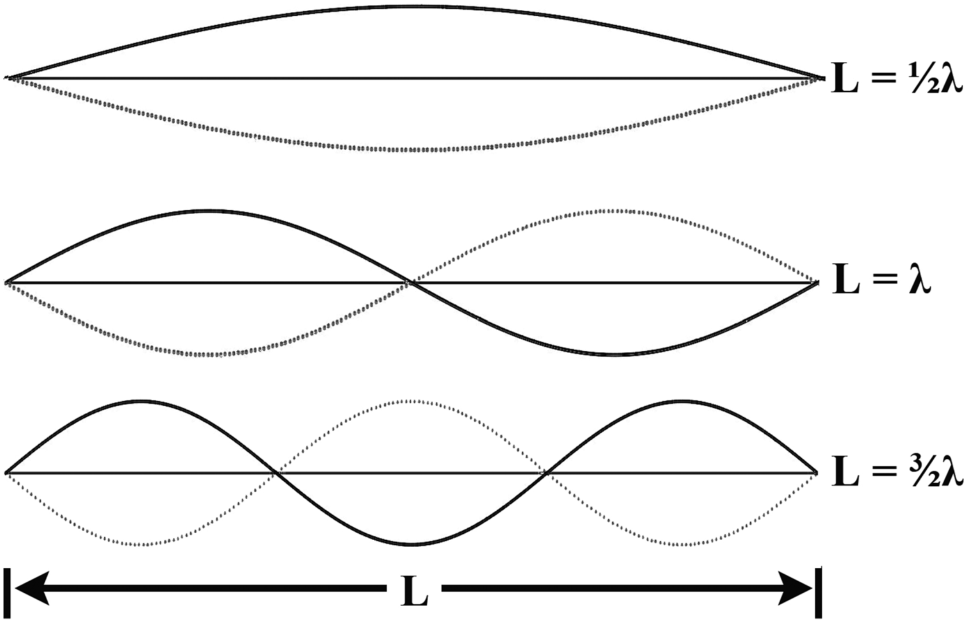

Fig. 1 A schematic explanation of the relation between the first three modes of standing waves that can develop between two closed ends, the wavelength λ, and the physical body length L with two fixed ends

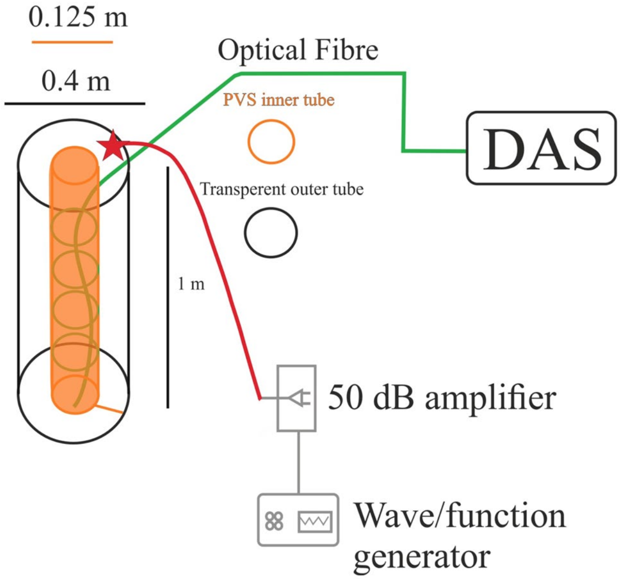

Fig. 2 Sketch of the laboratory VSP setup. During the measurements, the column is partly filled with water and mud

Optical fibres are then converted into seismic sensors using a Silixa iDAS interrogator, and a Febus A1 interrogator (Daley et al. 2013). DAS uses elastic Rayleigh scattering to measure the elongation and contraction of the fibre, which can be expressed in units of strain rate. For a more detailed explanation, the interested reader is referred to Lindsey et al. (2020), who gave a clear overview of the measuring principle of DAS, and iDAS in particular.

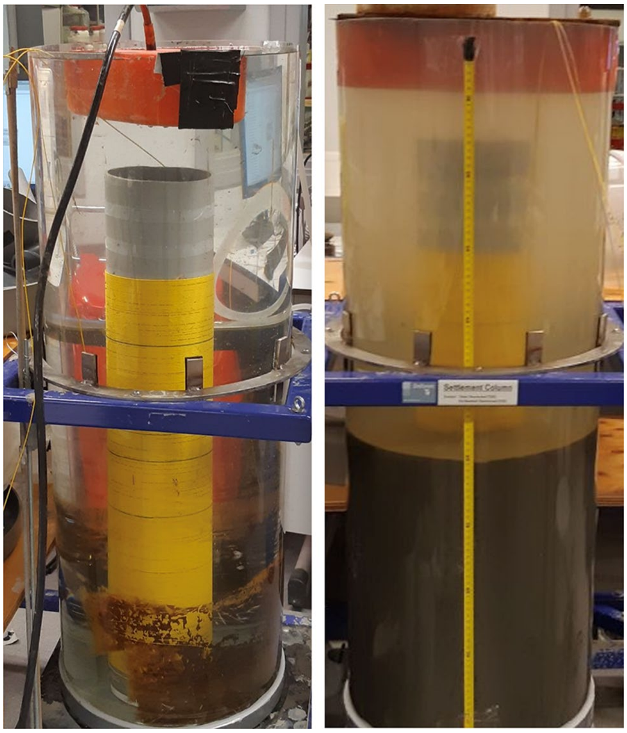

Fig. 3 Photograph of the laboratory VSP setup. On the left, the column is filled with water, and on the right, the column is partially filled with mud and water

On top of our column, we install a dual-frequency echo-sounder. This device is commonly used to measure the water depth in ports and waterways. The echo-sounder we use has two transducers, one with a center frequency of 38 kHz, and another with a center frequency of 200 kHz (SIMRAD 38/200 COMBI C). Due to the limited time sampling of 100 kHz, we only use the transducer with a 38-kHz center frequency. We connect this transducer to a wave/function generator, which allows one to choose for the source signal at any center frequency within the bandwidth of the generator. The signal is then amplified by a power amplifier.

We record for 0.1 s at 100 kHz with the iDAS interrogator, and 0.3 s with the Febus interrogator. The recording is repeated 10 times for a 0.1-s recording, and 30 times for a 0.3-s recording, which allows stacking the individual recordings 10 or 30 times, respectively. This stacking suppresses random noise and increase the signal-to-noise ratio (S/N).

3 Measurements

The result from the stacked recordings using the 38-kHz center frequency, set at 30 kHz with the wave generator, can be seen in Fig. 4. One feature that is very apparent in this figure is that the data seem to be partly aliased. This is likely related to the fact that the higher frequencies of the source signal are close to the Nyquist frequency for a time sampling of 100 kHz. We also observe oscillations which appear to propagate at an infinite velocity. This phenomenon can clearly be observed after 0.006 s, and seems to be bound to the water-mud interface, indicated by the blue line in Fig. 4. It can even be seen before the source pulse arrives, which is counter-intuitive but is possible because a triggering system was missing, and thus there are some oscillations from previous measurements before the pulse arrives from the current measurement. A part of this phenomenon appears a few centimetres below the water-mud interface. This can be related to the measuring principle of the iDAS system, which uses a gauge length of 10 m, meaning it averages measurements over 10 m of fibre.

It appears that there are more arrivals, and thus more energy, in the water layer than in the mud layer. If indeed so, we should be able to observe the same in a power spectral density (PSD) plot. To obtain a PSD plot, we transform the data using Welch's method (Welch 1967), which uses a discrete Fourier transform to transform data from the time-space domain to the frequency-space domain. The PSD can be viewed in Fig. 5. In this figure, we can observe a striking difference in the spectral density between the water, above the

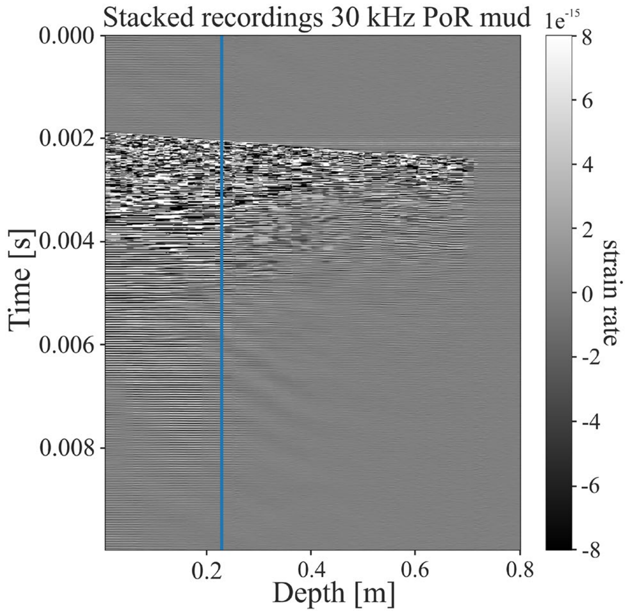

Fig. 4 Stacked traces along the optical fibre using a 30-kHz signal. The blue line indicates the water-mud interface

red line and the mud, and below the red line. It appears that there is far more energy in the water layer than in the mud layer at almost any frequency. This is likely due to damping of the wave energy in mud. The PSD also shows that there are dominant frequencies at approximately 11 kHz, 22 kHz and 33 kHz. Especially the 22-kHz signal is very strong and seems to cease to exist 2 cm below the water-mud interface.

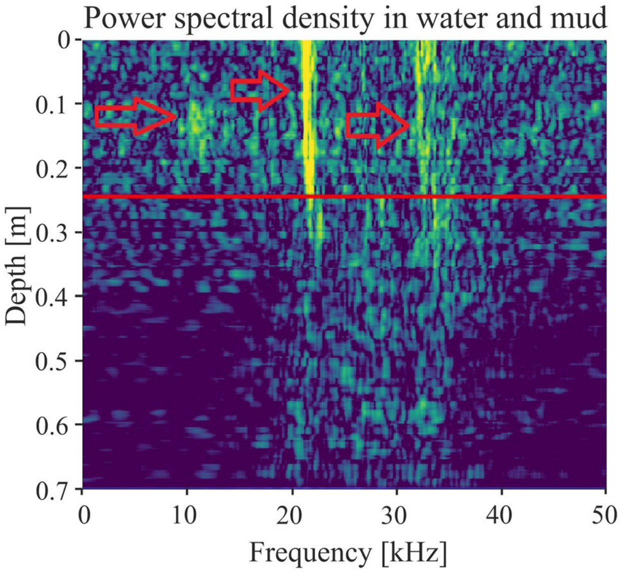

Fig. 5 Power spectrum density of Fig. 4 with a 30-kHz central source frequency. The red line indicates the water-mud interface. The arrows point to dominant frequencies at approximately 11 kHz, 22 kHz and 33 kHz

To validate that the waves with a high apparent velocity can be used for estimating the depth of the water-mud interface, we do the same experiment with a source frequency of 23 kHz in the same column but this time filled only with water. We perform these measurements using the Febus A1 interrogator instead of the Silixa iDAS interrogator. The PSD of this setup can be viewed in Fig. 6. In Fig. 6, we can see that high energy, characteristic of the waves with the very high apparent velocity, is now present along the complete length of the column. This shows that there is no water-mud interface, but only a water layer.

4 Discussion

Figures 4 and 5 clearly show that there is a large difference in arrivals and energy inside the water and the mud layers. When we zoom into the arrivals after 0.007 s in Fig. 4, arrivals with apparent velocities over 500000 m s^{-1} can be observed, as can be seen in Fig. 7. This is far above the normal longitudinal (P-) wave velocity in water, which is around 1480 m s^{-1}. Unlike the late oscillations, the first arrival from the source signal does propagate at approximately 1480 m s^{-1}. Clearly, these oscillations are not P-waves, and must be something else.

The most probable explanation for this oscillating phenomenon is that standing waves have developed in the water column, which in turn means that this extremely high velocity is related to an apparent velocity. Martuganova et al. (2021) showed that standing waves can be measured when they have developed with a loosely coupled fibre. This happens if the fundamental frequency coincides with the physical length

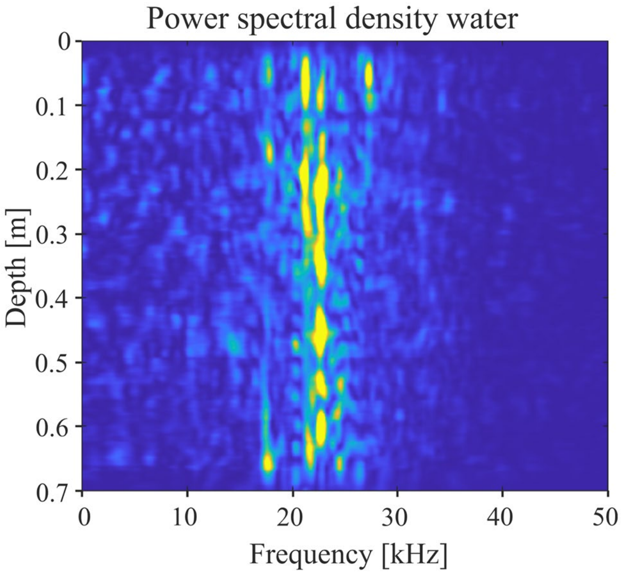

Fig. 6 Power spectral density of the same column as in Fig. 5, but filled only with water, and a central source frequency of 23 kHz

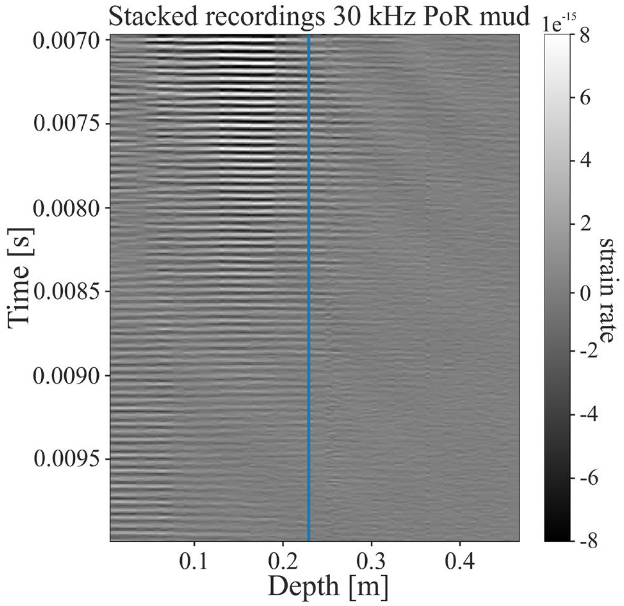

Fig. 7 Zoom of the oscillations in Fig. 4, which are likely standing waves. The blue line indicates the water-mud interface

of the body in which these standing waves occur, or when an overtone has developed. They also showed that there are harmonics related to the physical length in their wireline VSP. In Fig. 5, we observe 3 harmonics, namely at 11 kHz, 22 kHz and at 33 kHz. Because we send a frequency of 30 kHz, the harmonic at 11 kHz, which is the furthest away from the center frequency, has a lower amplitude compared to the other two harmonics. The exact dimension or dimensions that start to resonate is yet unknown. We also need to further investigate what type of standing waves we are dealing with — standing waves with two closed ends or with one closed and one open end. Notwithstanding we do not know the exact type and mode of the developed standing waves we observe, we clearly see that using the recorded standing waves we can estimate the depth of the water-mud interface. In fact, the estimate is very accurate with an accuracy of approximately 2 cm. Such an uncertainty is far smaller compared to the uncertainty of the standard non-intrusive methods used now in ports and waterways. Draganov et al. (2021) showed that the depth of the water-mud interface can also be estimated from the observations of the recorded propagating P-waves. The accuracy they achieved is 1.2 cm.

5 Distributed acoustic sensing using passive noise

Above, we showed that standing waves that have developed in the water layer from an active source, like the dual-frequency echo-sounder, can be very effectively used to estimate the depth of the water-mud interface. Ideally, one would like to operate a source remotely and on demand. However, permanent active installations at the water surface are not only expensive, but are also undesirable since they would form an obstruction for the shipping vessels; hence, a submerged measuring system is more desired. An interesting alternative as a source would be utilising the noise generated by passing or idle vessel. Using a ship's propeller noise as a source has already been proposed by Davies et al. (1992), for marine imaging. In their work, the frequency spectrum generated by the propeller's sheet cavitation, from a standard exploration vessel, is compared to the spectrum generated by a conventional 33-L airgun, as can be seen in Fig. 8. The propellers generated a noise with a broad frequency spectrum. Such a noise is promising as a source for developing standing waves. Choosing specific frequency bands, one could check whether standing waves have developed. In our laboratory experiment, standing waves could develop between the water surface and the water-mud interface, but also between the walls of the column. In contrast to that, in ports and waterways, standing waves will develop only between the water surface and the water-mud interface. Because of this, they will be characterized by one closed end (the water surface) and one either open or closed end (the water-mud interface). Knowing this, one can calculate what standing-wave modes could be developed for specific frequencies assuming certain depths. We take as examples the Port of Rotterdam and the Port of Hamburg with example depths to the water-mud interface of 22.5 m and 17 m, respectively. For such depths and velocity of the P-waves in the water layer of 1460 m s^{-1}, we calculate the first four

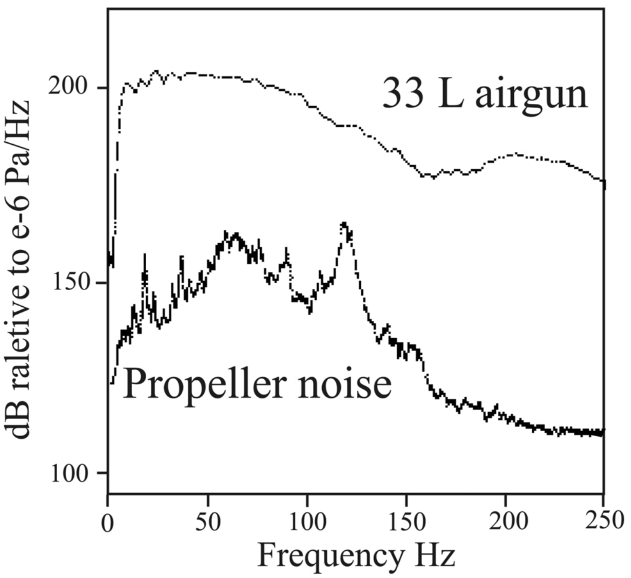

Fig. 8 Comparison of the amplitude spectrum between cavitation sweep and an airgun array (modified from (Davies et al. 1992))

Table 1 Frequencies of the first four modes of standing waves that could develop in the Port of Rotterdam and Port of Hamburg with a depth of 22.5 m and 17 m, respectively

Harmonic	1	2	3	4
Port of Rotterdam Hz	32	65	97	130
Port of Hamburg Hz	42	83	125	167

modes of the possible standing waves with two closed ends, see Table 1. We can see that the calculated frequencies fall within the frequency range of the noise produced by the propellers. This shows that the propeller noise should cause standing waves to develop in ports. Because of this, we strongly believe that we could use standing waves to accurately estimate the depth of the water-mud interface in ports using ambient noise, e.g. from propellers, where the estimation could be done remotely and on demand.

6 Conclusion

Using the results of our laboratory experiment, we showed the potential of using distributed acoustic sensing to record standing waves. We used a single-mode optical fibre to record signals from a dual-frequency echo-sounder with center frequency of 38 kHz. Our laboratory experiments show that standing waves are bound to water; therefore, standing waves can be used to accurately estimate the depth of the water-mud interface. Furthermore, we showed that the standing waves are easy to identify due to their high energy at the frequencies at which they develop, and due to the high apparent velocity they exhibit, which far exceeds the velocity of any other arrival.

Analysing ambient noise from cavitation of propellers in ports, we proposed that standing waves are likely present in ports and waterways. This implies that standing waves could be used in practice to monitor the depth of the water-mud interface. Unlike conventional surveying methods, the method we propose, i.e. using standing waves in the later layer from ambient noise, would be repeatable, non-intrusive, on demand and can be operated remotely. This could increase the availability of crowded docks, where there is limited accessibility for a dredging or surveying vessel. Furthermore, our proposed method could reduce costs, increase safety and reduce CO2 emissions because no surveying vessel is required on site.

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Declarations

Conflict of interest The authors declare no competing interests.

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