# Monitoring shear-stress changes using seismic measurements from controlled sources and ambient noise and optical fibres

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# MONITORING SHEAR-STRESS CHANGES USING SEISMIC MEASUREMENTS FROM CONTROLLED SOURCES AND AMBIENT NOISE AND OPTICAL FIBRES

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**Abstract:** Monitoring the nautical depth is vital for the safe passage of water transport. Port authorities worldwide have different navigable depth criteria and use various methods to ensure the safe navigability and manoeuvrability of ships in ports and waterways. These measurements often require a surveying vessel and are limited in repeatability and accuracy. Often, it is challenging to survey at heavily occupied quay walls; this may hinder economical activities. Additionally, because the current monitoring techniques depend on a surveying vessel's availability, monitoring significant changes in the nautical depth after, for instance, storms, is challenging, especially over large areas. Reliable continuous depth measurements could therefore help to optimise ships' docking operations in heavily occupied areas.

We show how the nautical depth can be measured and demonstrate the potential for estimating shear stresses using distributed acoustic sensing. Our laboratory study and our field test show that the acoustic energy differs for non-Newtonian fluids with different shear strength. For our laboratory experiment, we use natural and synthetic sediment suspensions for measuring the difference in acoustic attenuation with an optical fibre wrapped around a polyvinyl chloride (PVC) pipe. Our first acoustic measurement conducted one hour after mixing has a shear strength of 17 Pa and shows very high attenuation. The second laboratory test recorded 24 hours after mixing, with the shear strength of 48 Pa, reveals a tremendous signal-attenuation decrease and thus amplitude increase. In our field experiment, we observe a similar increase in amplitude with increased shear strength when recording propeller noise from passing vessels for frequencies < 60 Hz. We also observe a reverse trend for frequencies > 100 Hz. This difference in amplitude with depth might be related to a difference in fibre coupling and a difference in attenuation of acoustic waves. Additionally, our field experiment shows the potential to use Distributed Acoustic Sensing for continuous depth measurements.

**Key words:** Distributed Acoustic Sensing, Shear strength, Fibre Optics, Fluid mud, Continuous monitoring

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# 1 RESEARCH OBJECTIVE

Ports and Waterways subjective to high siltation rates must be regularly surveyed to ensure safe passage of vessels. Dredging maintenance must be carried out to ensure that the navigability of ports and waterways is maintained. Various port authorities apply different technics to monitor the water depth and have different definitions of the nautical depth. For example, the navigable depth criterion of the Port of Rotterdam and the Port of Lianyungang is based on a density of 1200kg/m$^3$ and 1250-1300 kg/m$^3$, respectively, whereas the Port of Emden has a nautical bottom definition derived from a yield stress of 100 Pa (McAnally et al., 2007). This difference in nautical criterion and surveying techniques can be related to the variety of the sediments that deposits due to natural processes, often in the form of (fluid) mud. The relation between fluid mud's density and shear strength is non-linear (Kirichek & Rutgers, 2020).

The properties of the fluid mud can differ substantially over small distances (Shakeel et al., 2020). In addition, the properties are affected by the organic matter content, which plays a significant role in flocculation and sediment transport processes (Chassagne & Safar, 2020). Decaying organic matter creates gas pockets in the mud layers. These gas pockets hinder surveying methods based on longitudinal (pressure) waves due to the attenuation of these waves when passing through the gas. Furthermore, the organic-matter content in fluid mud affects the shear and yield stresses of the fluid mud. Especially the latter case is interesting because it affects the navigability of the fluid-mud layers. Currently, the nautical-depth estimation is often based on density (Kirichek et al., 2018), mainly because of practical reasons. A critical aspect of measuring shear stresses with conventional laboratory methods is that once the mud has been sampled, the yield stresses of a sample are changed, making it an ambiguous and challenging process to standardise. Therefore, non-invasive in-situ methods are desired. Recent developments in this field include measuring transverse waves, also called shear waves, as described by Ma et al. (2021) and Fadel et al. (2021). Shear waves can be of great use for estimating shear stresses in fluid mud because they only depend on the shear moduli and density. In contrast, the pressure waves depend on the bulk moduli, shear moduli, and density:

$$c_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \tag{1}$$

$$c_s = \sqrt{\frac{\alpha}{\rho}} \tag{2}$$

where $c_p$, $c_s$, $K$, $\alpha$, and $\rho$ represent the pressure-wave velocity, shear-wave velocity, bulk modulus, shear modulus, and density, respectively. The relation between an increase in shear strength (fluidic yield stress) and an increase in shear-wave velocity over time was shown in Buisman (2019) for two different types of mud samples.

Because shear waves cannot propagate through liquids or gases, they can only travel through the solid parts of the fluid mud. Therefore, shear waves are almost unaffected by gas pockets in the fluid mud, which is not the case for conventional echo-sounder surveying techniques that rely on pressure waves.

Fadel et al. (2021) used a piezoelectric shear-wave transducer as a source and receiver. They observed an increase in shear-wave velocity in fluid mud during the sedimentation and consolidation processes. The interesting part about using shear-wave velocities is that this method is non-intrusive. Because of this, one could repeat such measurements on the same sample, opposed to conventional methods that often involve a rheometer that damage the sample. Ma et al. (2021) used a similar laboratory setup to estimate shear stresses as Fadel et al. (2021). One key difference is Ma et al. (2021) used pressure transducers and estimated shear-wave velocity from converted pressure to shear waves. Using pressure sources allows placing sources in the water instead of directly in the mud, making it a more realistic approach for in the field. Additionally, this setup mimics a marine seismic survey, often used by surveying companies for subsurface imaging. These measuring layouts usually consist of one or multiple sources (airguns) and multiple hydrophones (streamers) lines. The length of the streamers is often equal to the maximum exploration depth and could potentially be used in rivers. Using conventional marine seismic methods would not be without practical challenges (the most challenging is surveying transitional zones, where the depth is too shallow for marine seismic methods), such as the need to sail in a straight line and the need for a high-frequency source with a large beam angle.

Buisman et al. 2022a showed that distributed acoustic sensing (DAS) could be used to measure the water/mud interface using a laboratory setup. A similar approach was applied for data recorded in the Port of Rotterdam.

Buisman et al. (under review) showed that ambient noise generated by propellers of passing vessels and recorded by DAS could be used to (continuously) estimate the water/mud interface. An essential advantage of DAS over conventional surveying techniques is that fibres can be (semi) permanently installed, allowing for continuous or on-demand measurements. Furthermore, DAS does not require a surveying vessel and can be used even when a quay wall is occupied. It is important to note that heavily occupied quay walls are often unavailable for surveying vessels. Additionally, storms can cause significant bathymetrical changes over large areas, requiring extensive and time-consuming surveying.

Below, we give a proof of concept for estimation of the shear stresses of bentonite clay in a laboratory setup and estimation of the shear stresses of (fluid) mud in the Port of Rotterdam based on signal penetration and coupling conditions of the fibre to its surrounding, respectively.

### 1.1 Overview of distributed acoustic sensing

DAS is a novel technology that allows using optical fibres to measure vibrations. The vibrations cause the fibre to elongate or contract, causing an increase or decrease in optical path length, respectively. Due to density variations in the fibre, a portion of the laser sent by a source (interrogator) is backscattered in the form of Rayleigh backscattering. The exact location of such density variations is unknown; however, the total distribution is assumed to be homogenous and time-invariant (Lindsey et al., 2020). The enthusiastic reader is referred to Lindsey et al. (2020) for an overview of how single-pulse coherent light DAS interrogators work. In the experiments we describe below, we use two DAS interrogators of this type – Silixa iDAS v2 and Febus A1.
There has been a large increase in the number of DAS applications over the last few years, for example, in teleseismic earthquake monitoring (Ajo-Franklin et al., 2019; Jousset et al., 2018), vertical seismic profiling (Daley et al., 2016; Martuganova et al., 2021; Mateeva et al., 2014), and earthquake phase identification (Lindsey et al. 2017; Yu et al., 2019). One of the reasons why DAS has gained a lot of attention is because standard telecommunication fibres can be used with DAS interrogators to form a seismic array. By using out-of-service telecommunication fibres, so-called "dark fibres", seismic arrays can be formed that used to be prohibitive in cost, such as described in Cheng et al. (2021), where an already existing ocean-bottom fibre was used to create a dense broadband array for submarine structural characterization. Due to the large dynamic range of the DAS interrogators, which have been reported to be up to 171 km (Waagaard et al., 2021), there are even ideas to implement DAS to create underwater seismic monitoring for an earthquake early warning system (Lior et al., 2021).

### 1.2 The laboratory setup

To show the potential of the DAS measurement techniques for estimation of shear stresses, we perform both a laboratory experiment and a pilot field experiment in the Botlek, Rotterdam, the Netherlands. The laboratory setup consists of an optical fibre with a length of 140 m tightly wrapped around a polyvinyl chloride (PVC) pipe of 0.8 m in height and a diameter of 0.125 m; the wrapped cable thus covers 0.5 m of the height of the PVC pipe. This PVC pipe is then installed inside a transparent cylindrical tank with a height of 1.1 m and a diameter of 0.4 m, filled at the bottom with sand, followed by a suspension of bentonite in water, and finally a pure water layer (Figure 1, left).

Figure 1. Left: A picture of the laboratory setup. A transparent cylindrical tank was filled with the following layers: sand at the bottom, a bentonite suspension, and water. Right: A picture of the drill used to homogenize the bentonite suspension.

In this way, the acquisition scheme imitates vertical seismic profiling (VSP). It allows having a dense array of receivers with a very short vertical spacing of 1 mm while permitting visual confirmation of the location of the suspension. As a source, a piezoelectric transducer with a centre frequency of 200 kHz frequency was used in combination with a wave generator and an amplifier. The source sends pulses with a centre frequency of 40 kHz. Buisman et al. (2022) provides a more detailed description of the setup used for data recording in the laboratory environment. Synthetic bentonite suspension displays thixotropic behaviour along with high values of shear stresses and yield stresses even at low concentrations (Abend & Lagaly, 2000; Goh et al., 2011). We use this type of suspension in our experiments because the shear strength increases over a short period, while other parameters, such as density, remain constant.

We create this bentonite suspension by partly filling up a separate column with a mixture of bentonite and water. After a failed attempt to create a homogenous mixture with a hand drill, which broke down and had to be thrown away, we used a powerful mixer to create a homogenous bentonite suspension (Figure 1, right). After the suspension becomes homogenous, we measure the density and the shear strength of the suspension; we then put the suspension in our measuring tank and use water to fill up the measuring tank completely. We then let the shear strength build-up for three days and measure the density and the shear strength once a day. This allows us to track the rheological changes and relate these changes to the difference in signal attenuation from our DAS recordings. We perform DAS recordings with a duration of 0.1 s using a Silixa iDAS v2 interrogator, during which we send ten source pulses. The measurements from the individual pulses are summed together to obtain a final signal with an increased signal-to-noise ratio (SNR).

### 1.3 The field experiment

For our field measurements, we use a similar approach as with our laboratory setup. We again tightly coil a fibre, but this time around a steel mantle. We use 750 m of fibre to cover 1 m in height of the steel mantle, as shown in Figure 2.

Figure 2. The measuring setup used for a field test in the Botlek, Rotterdam, the Netherlands. Left: a picture of two steel mantels with a fibre optical cable partially wrapped around them to form a receiver array for the experiment. Right: One of the sensing mantels is lowered onto a massive steel pole for continuous monitoring.

This mantel is lowered onto a steel pole until it is completely submerged in mud. This allows us to record in the upper 1 m of (fluid) mud. Afterwards, the mantel is raised by 90 cm, such that the upper 66 cm is in water, and the bottom 34 cm is in mud. With this setup, we can measure with different coupling conditions, namely, in water, where our fibre can move to a certain extent, in fluid mud, where our fibre is more fixed in place, and in consolidated mud, where the fibre is almost completely fixed in place. Compared to the laboratory setup, we now use ambient noise instead of a controlled transient source, and we use a Febus A1 interrogator, instead of the Silixa iDAS v2 interrogator, to record for various days. A more detailed description of this setup can be found in Buisman et al. (submitted)

## 2 RESULTS

### 2.1 Laboratory experiments

The shear strength of the bentonite suspension is measured with a rotational rheometer equipped with a vane (controlled stress sweep test). As expected, the density remains constant at 1.036 kg/l. This agrees with the observations of our cylindrical tank, where we can visually confirm that the level of the bentonite suspension remains constant. From our initial experience, we expect that the changes in shear strength occur during the first 24 hours after mixing. Afterwards, little to no change is expected in shear strength. Again, this is confirmed by performing the third consistent stress sweep test that indicated the same shear strength. Although the density of our bentonite suspension differs only little from that of water, the shear strength of our bentonite suspension – 16-18 Pa – is only slightly different on the first day from the shear strength of a fluid-mud sample from the Port of Hamburg – 20.5–22.5 Pa (Shakeel et al., 2020). The shear strength tripled in value to 48 Pa on the second day. This drastic increase in shear strength can be seen in our acoustic measurements in Figures 3 and 4. Our first DAS measurement is taken one hour after the column is filled with the bentonite suspension and water, allowing any suspended matter to settle. We observe in Figure 3 that the source signal is immediately attenuated once it reaches the bentonite suspension, indicated by the blue vertical line. On the other hand, 23 hours later, i.e., on the second day, the attenuation of the source signal in the bentonite is only slightly higher than that in the water. This can be observed in Figure 4, where we notice that the source signal easily reaches the bottom of our sensing fibre.

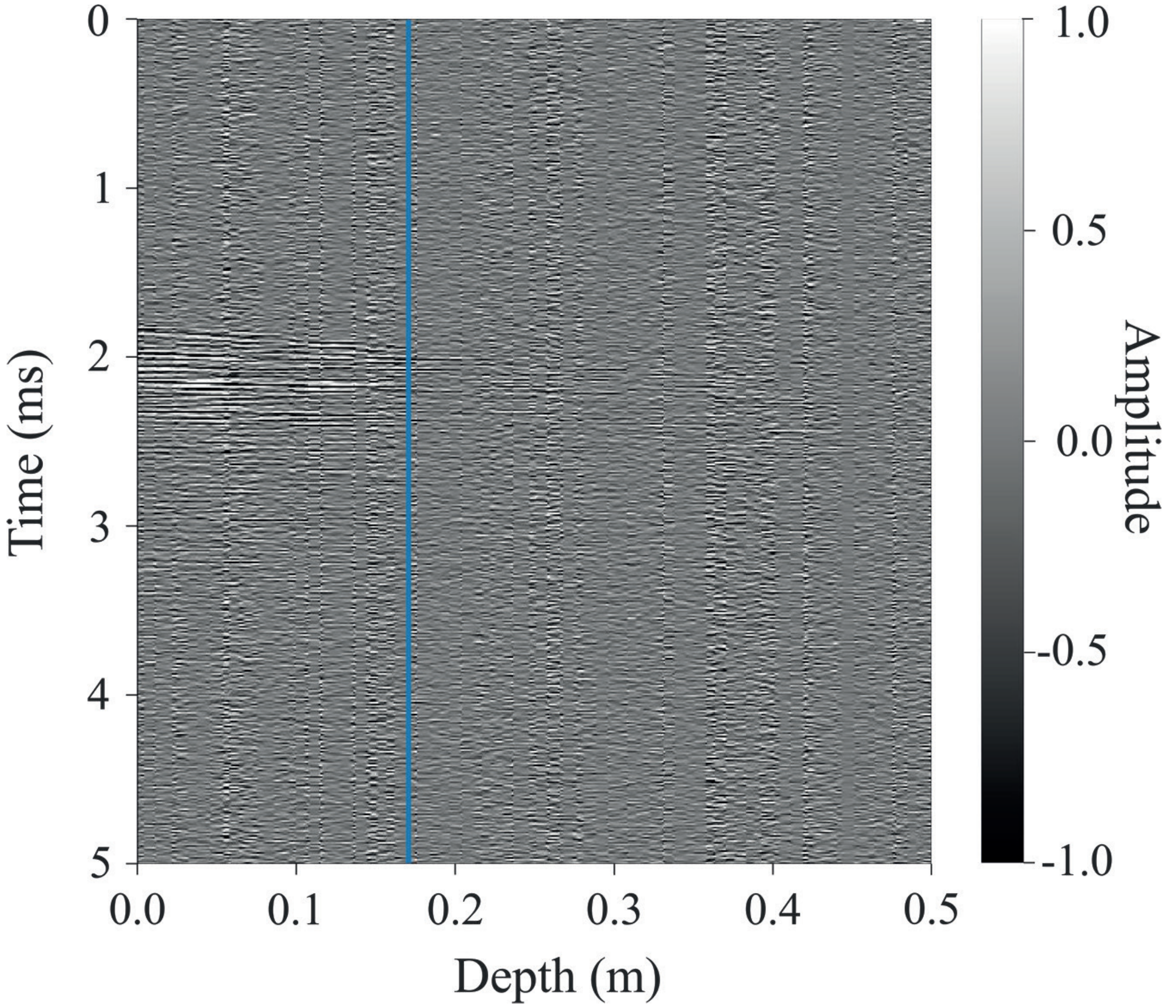


Figure 3. A common-source VSP gather recorded one hour after mixing the bentonite suspension. The gather is generated by stacking recordings from 10 separate source bursts. The source frequency is set at 40 kHz, the time sampling is 100 kHz. The blue line indicates the water-bentonite suspension boundary. A clear difference in acoustic attenuation is visible between the water layer and the bentonite suspension.

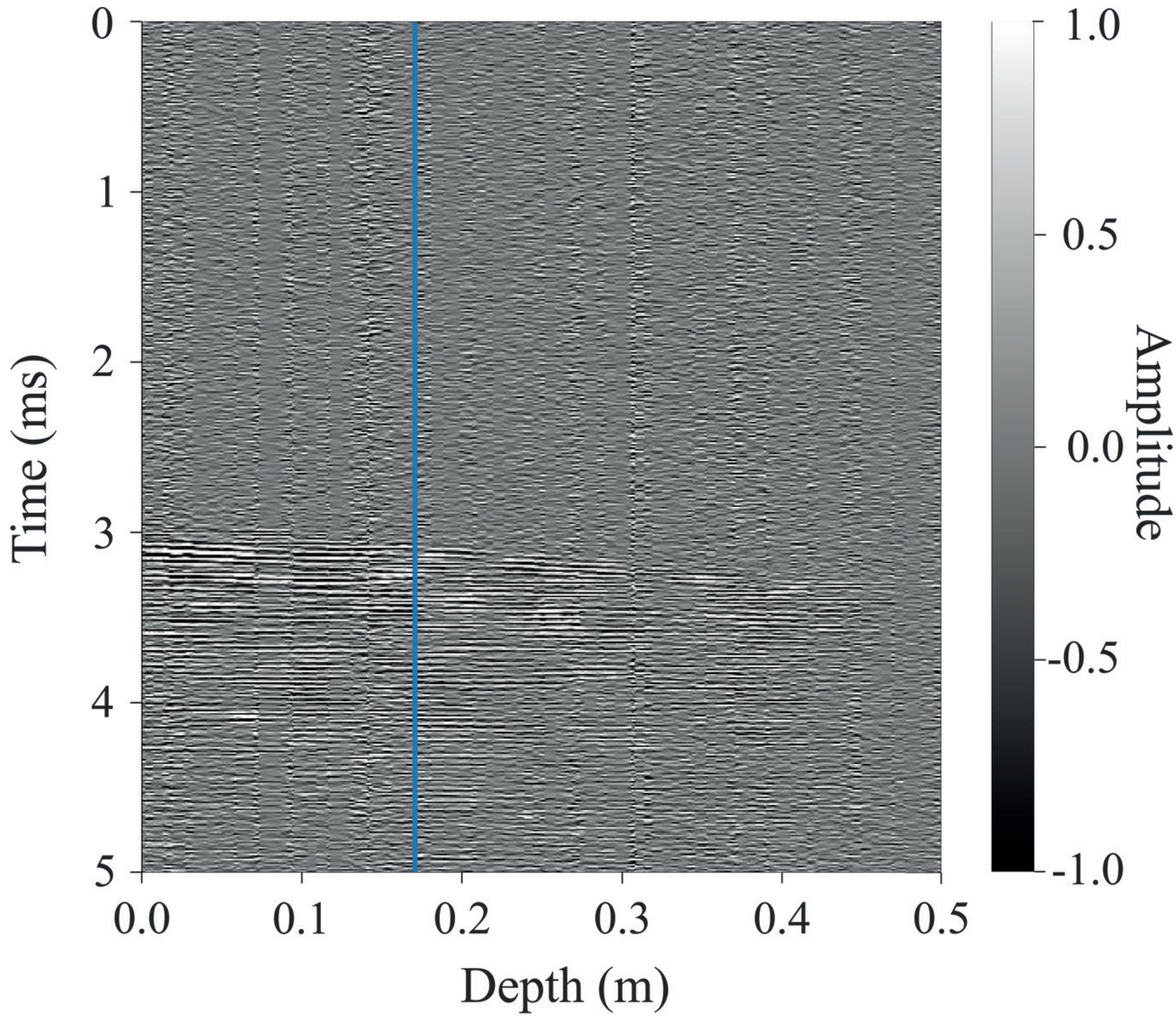


Figure 4. A common-source VSP gather recorded 24 hours after mixing the bentonite suspension. The gather is generated by stacking recordings from 10 separate source bursts. The source frequency is set at 40 kHz, the time sampling is 100 kHz. The blue line indicates the water-bentonite suspension boundary. The arrival time at depth 0 differs due to the absence of a trigger, which is why the signal starts at 3 ms in comparison with 1.9 ms for the recording presented in Figure 3.

### 2.2 Field experiment

With the field experiment, we face different layers with unknown shear strength. Furthermore, the coupling conditions differ, our medium is inhomogeneous; our source is unknown (noise), and the sediments in the Botlek contain organic matter. Nonetheless, we can assume that the shear strength increases with increasing depth because of consolidation processes. Therefore, we expect increasing amplitudes of the recorded signals with increasing depth. However, our laboratory experiments already showed that the signal attenuation could be substantial in the upper unconsolidated layer, which raises the question of how much signal will be left to reach the bottom of our sensing mantel. To visualize the acoustic energy, we transform the data from the time domain to the frequency domain using Welch's method (Welch, 1967). This frequency-domain data thus shows the recorded frequencies at all the channels. Despite the possibility of high attenuation in the upper unconsolidated layer, our results in Figures 5 and 6 still agree with our expectations of having higher-amplitude data with depth due to the higher shear stresses in the lower frequency spectrum, i.e., < 60 Hz. On the other hand, Figure 7 shows higher amplitudes in water for the higher frequencies, i.e., > 100 Hz. However, the low frequencies shown in Figure 6, namely < 60 Hz, seem to be absent in water. Besides, when we look at a depth of 5.5 m in Figure 7, where we observe an anomaly. This anomaly is in water and does not occur at the same position in Figures 5 and 6 when our sensing mantle was in the mud. This is related to repair works at this location. Unfortunately, our fibre broke due to unknown circumstances. After repairing the fibre with a fusion splice, we used some expensive high-quality elastic tape covering about 4 m of fibre and, by doing so, unintentionally created a control experiment to see how the coupling condition affects the low-frequency content of our VSP data.

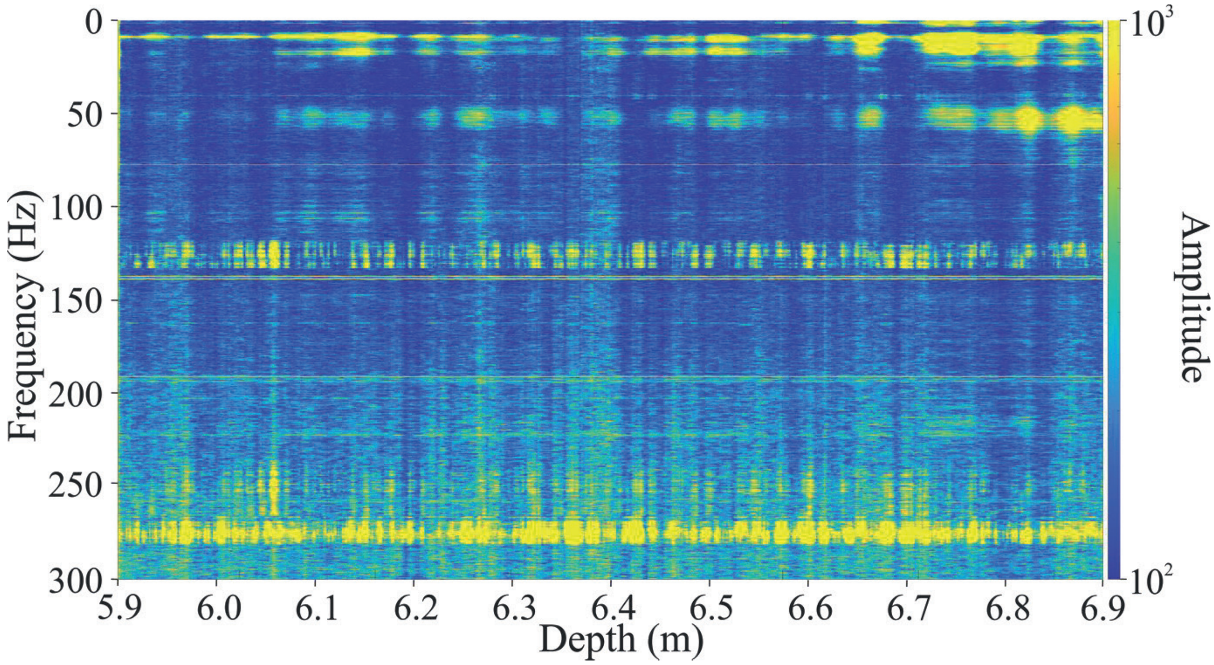


Figure 5. Power spectral density calculated from data acquired in the field experiment in Botlek, Rotterdam, the Netherlands. An increase in the amplitude of the spectral values can be noticed with an increase of the depth for the frequency range < 60 Hz. Furthermore, there are faint signals around 108 Hz at the depth interval from 5.9 m to 6.35 m. Unlike the lower frequencies, these signals do not increase in amplitude with depth. Additionally, machine noise can be observed around 130 Hz and 270 Hz.

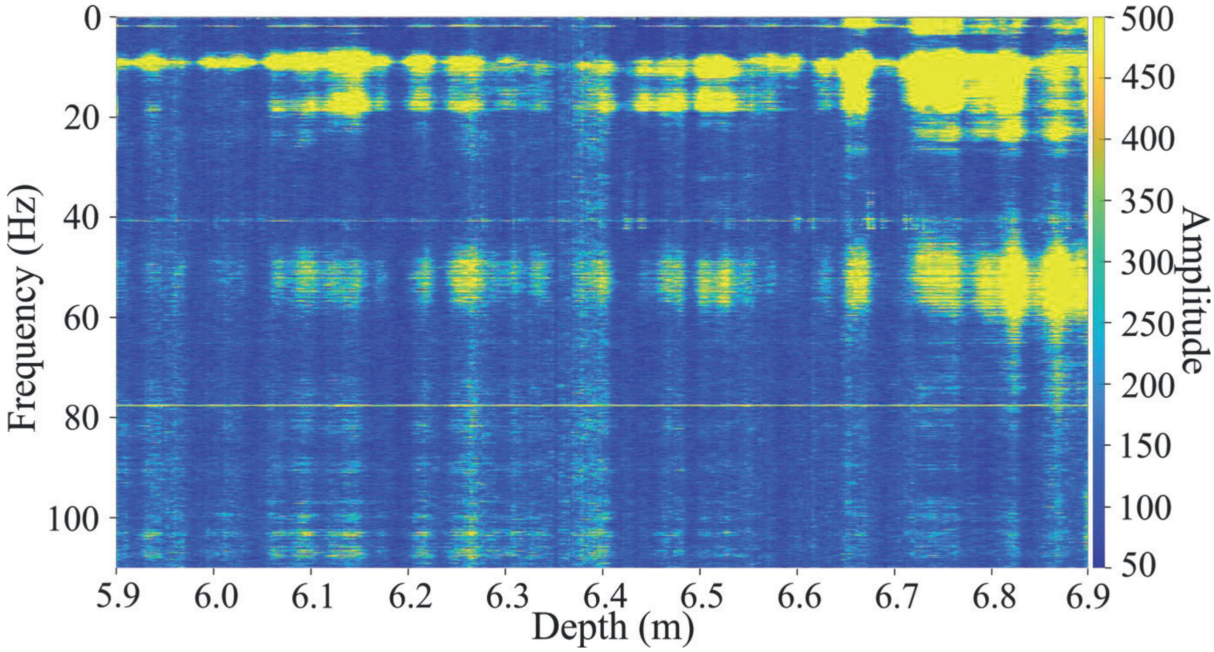


Figure 6. A zoom-in of Figure 5 to show the difference in amplitude increase with depth for frequencies < 60 Hz and in amplitude decrease for frequencies > 100 Hz.

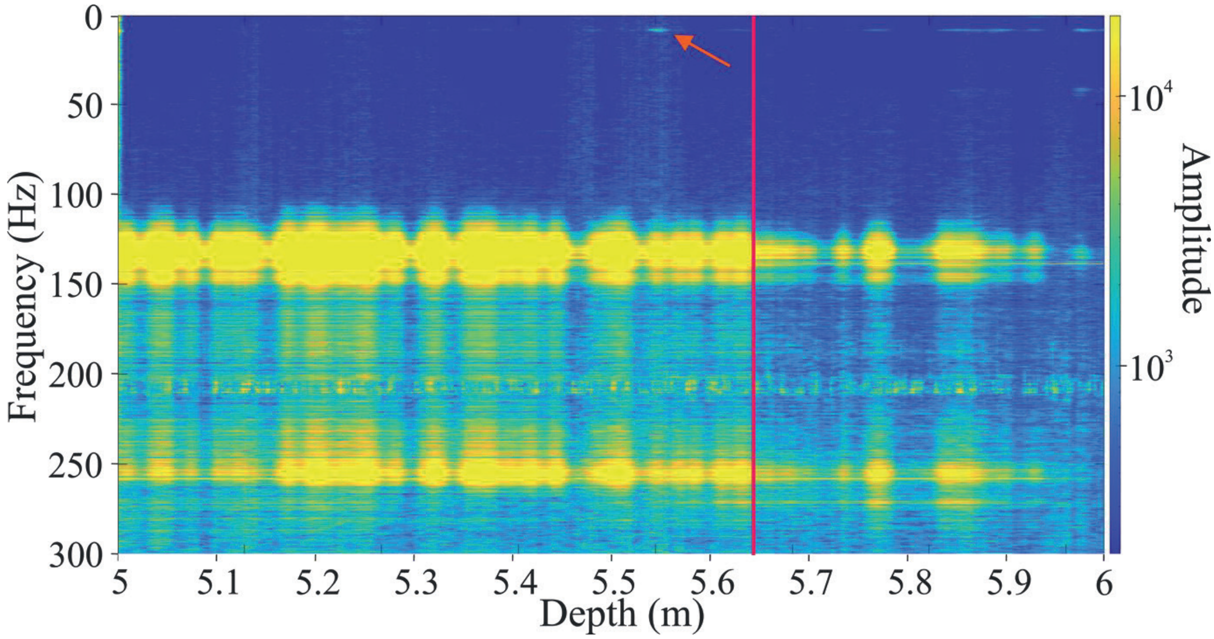


Figure 7. Power spectral density calculated for the field-experiment data from Botlek, Rotterdam, after the sensing mantel was raised by 90 cm. The red line indicates the water-mud interface, and the red arrow shows the anomaly caused by improved coupling obtained by the tape wrapped around this depth section. It can be noticed that in water there are mainly frequencies ranging from 110 Hz till 260 Hz. Low frequencies start to occur at a measuring depth of about 5.75 m.

## 3 INTERPRETATION

### 3.1 Laboratory experiments

We were limited by the maximum time sample of 100 kHz. Therefore, we are very close to the Nyquist criterion with our source frequency of 40 kHz, making our data partly aliased. Nevertheless, our laboratory DAS data shows a tremendous difference in signal attenuation due to increased yield stress. In the laboratory, we can quantify this change in the shear strength and relate a change in amplitude predominantly to a change in signal attenuation. Additionally, the coupling condition improves over time in our laboratory experiment, leading to even higher amplitudes with a higher yield stress. It is most likely that the change in coupling conditions can be disregarded in our laboratory setup. The reason for this is that our source signal was almost completely attenuated just after reaching the bentonite suspension on the first day. In this case, the difference in attenuation between water and bentonite suspension can predominantly be related to a difference in rheological properties since our coupling conditions in the bentonite suspension was equal, if not better, in comparison with the coupling conditions in the water. In contrast to our measurement on the first day, our source signal on the second day easily propagates through the whole column. This shows that the acoustic attenuation decreases dramatically with increased shear strength.

### 3.2 Field experiment

Our field experiment shows similar results as our laboratory experiments for the lower frequency spectrum of < 60 Hz. Since we use ambient noise sources, a similar setup as our field experiment could be used for continuous measurements, given that there is traffic nearby. Unlike our laboratory experiment, the signal from ambient sources travels (almost) horizontal because our depth ranges from 5 to 6.7 m, and our noise source can be as far as 1 km away. Because the signal from propellers propagates close to horizontal, it is plausible that both guided waves and surface waves, such as Scholte waves, propagate through mud layers, which could explain why we observe an increase in amplitude in the deeper section.

Another plausible reason is the difference in the coupling condition of our fibre. The importance of coupling is validated by the section covered in tape. This section appears as an anomaly in the low-frequency content of the VSP data. The improved coupling conditions due to the tape are clearly visible in the lower frequency spectrum yet seems to have little to no effect in the higher frequency content. A possible explanation for the difference in coupling conditions in the lower frequencies could be because the fibre might be moved by low-frequency vibrations when poorly coupled; such is the case in the water. Poor coupling conditions can cause the fibre to displace rather than be elongated and compressed, and our interrogator cannot measure this displacement. When the fibre is fixed in consolidated mud, the coupling conditions improve, and thus the fibre is less likely to be displaced. The exact effect of the coupling conditions on the frequency content is still unclear. Nevertheless, what is interesting to note is that the frequency content increases in the lower frequency spectrum < 60 Hz but decreases in the high frequencies > 100 Hz. The difference in signal attenuation could potentially be used to estimate shear stresses and distinguish between water and mud.

Furthermore, the lower frequencies could indicate surface waves, commonly used to perform a surface wave inversion. From a surface wave inversion, shear waves velocities could be estimated.

## 4 CONCLUSION

We have shown that DAS can estimate the shear strength of non-Newtonian fluids. Our laboratory results show vastly different results in terms of attenuation caused by a change of shear strength in the bentonite suspension. Additionally, we show that DAS can be used in the field for estimating the shear strength of fluids using ambient noise. Our field results also show the complexity of using ambient noise to estimate shear strength. Although there is a clear difference in both the frequency content and amplitudes between water and (fluid) mud, and while this difference can likely be used to estimate shear strength to measure both the location of the water-mud interface, as well as estimating the shear parameters of fluid mud, the very nature of what causes this difference is still unknown. The results clearly show that the low frequencies < 60 Hz increase in amplitude when the fibre is tightly coupled to the surrounding medium, as is the case for consolidated mud. The increase in low frequencies due to an improvement of coupling is validated by the part taped to the sensing mantle, improving the coupling conditions of the fibre mantle.

For higher frequencies > 100 Hz, the reverse trend can be observed. While coupling conditions do improve when the fibre is embedded in mud, the higher frequencies are likely attenuated to such an extent that these frequencies dissipate in mud and thus are not measured.

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