Monitoring settling and consolidation of fluid mud in a laboratory using ultrasonic measurements

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Abstract

Ultrasound measurements are routinely used to evaluate the safe depth for ships navigation - nautical depth - at waterways and ports using single-beam dual-frequency echo-sounders. The nautical depth is routinely defined by suspension density in the range of 1100–1300 kg/m3 in the mud layer. While ultrasound measurements have a weak sensitivity to density variations, calibration is always needed to convert ultrasound measurements into reliable indicators for nautical depth levels in the mud layers using densely distributed density rheological in-situ measurements.

We present a laboratory ultrasonic transmission experiment to monitor the fluid mud's settling and consolidation processes using a sample from the Port of Rotterdam. We use P- and S-wave ultrasonic transducers in the frequency range between 200 to 1000 kHz. Our results show that the P-wave velocities slightly increase during the consolidation and settling process while the P-wave amplitudes decrease. On the other hand, we observe a high S-wave velocity that increases together with amplitudes over time. The P- and S-wave amplitude and S-wave velocity variation over time correlate well with the mud average density variation. The presented results can be very useful for fluid-mud monitoring at a lab scale, besides possible utilization for large-scale monitoring field campaigns.

Introduction

Ultrasound measurements are routinely used to evaluate the safe depth for ships navigation – nautical depth – at waterways and ports using dual-frequency single-beam echo-sounders (Figure 1; Kirby et al. 1980). The waterways usually consist of three layers: water, fluid-mud/mud, and seabed (rocks/sand/ consolidated mud). Fluid mud is defined as a high-concentration sediment suspension that typically behaves as a non-Newtonian fluid exhibiting shear-thinning rheological nature with weak thixotropic behaviour two-step yielding. (Shakeel et al. 2020). Areas with fluid mud typically show lutoclines that are defined by inflection points in the vertical density profiles (McAnally et al. 2016). The fluid-mud layer gradually consolidates with depth until it forms a consolidated mud layer that rests on the seabed (Kirby et al. 1980).

The dual-frequency echo-sounder measurements are routinely carried out at ports and waterways to characterize the fluid-mud/mud layer using two frequency ranges 180-220 kHz and 15-40 kHz (e.g., Alexander et al. 1997; McAnally et al. 2007). The high-frequency measurements within the range of 200-215 kHz are used to estimate the top of the fluid-mud layer (lutocline), while the measurements within the low-frequency range 15-40 kHz are used to estimate the depth to several meters below the fluid-mud top (e.g., Alexander et al. 1997; McAnally et al. 2007; Kirichek et al. 2018). These frequency-dependent measurements use P-wave pulse-echo reflections to give indications about the depths of the top of the fluid-mud layer and the variations of the reflected waves from several meters below (Kirichek et al. 2018; Carneiro et al. 2020). Although such ultrasonic measurements are routinely used, they do not provide any information about the physical and mechanical properties of the mud, e.g., shear strength and density (e.g., McAnally et al. 2016; Carneiro et al. 2020 [and references therein]). Therefore, additional in-situ density and rheological measurements are necessary to properly interpret the ultrasound measurements (McAnally et al. 2016).

Below, we present laboratory ultrasonic transmission measurements of a fluid-mud sample from the Port of Rotterdam. The measurements are carried out to monitor the settling and consolidation of the fluid mud. The experiment aimed to evaluate the development of the P- and S-waves during settling and consolidation processes. We first present the methodology of the lab-based measurements and then the results and conclusions.

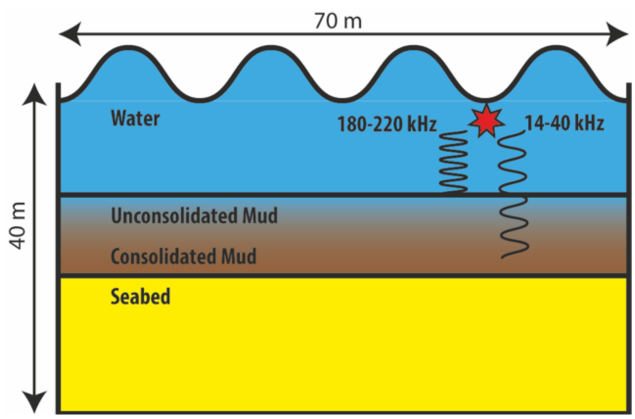

***Figure 1** A schematic cartoon explaining the concept of the dual-frequency single-beam echo-sounder (red star) showing the use of high (180-220 kHz) and low (15-40 kHz) frequency ranges.*

Methodology

The laboratory transmission measurements are carried out to monitor the ultrasonic P- and S-wave signals behaviour of the fluid-mud sample during settling and consolidation. The complete configuration of the experiment can be found in Figure 2. The central part of the experimental setup consists of a box that contains the fluid-mud sample. The box has a pair of Panametrics P-wave contact transducers with a centre frequency of 500 kHz. The transducers are facing each other and mounted on two opposite sides of the box. One transducer is used as a source and the other as a receiver. A similar pair of Panametrics S-wave contact transducers with 500 kHz central frequency is used in the same configuration and are located at a distance of 6 cm apart from the P-wave pair. The source signal is generated using an Elegant function generator to produce sine waves of 750 mV amplitude that are operated in a triggered burst mode with 10 mu interval. The sine wave is then amplified using Electronics & Innovation 240L Linear Power Amplifier to produce ~240 V (50 dB amplification) signal that is used by the source P- and S-wave transducers to generate the final ultrasonic source signal. The generated waves propagate through the mud sample and are recorded by the receiver transducers. The analogue signal is digitized and recorded by a 4-channels Yokogawa DL9140 oscilloscope using a 125 million-samples/second sampling rate. The digitized data is then transferred and processed on a laptop using Python.

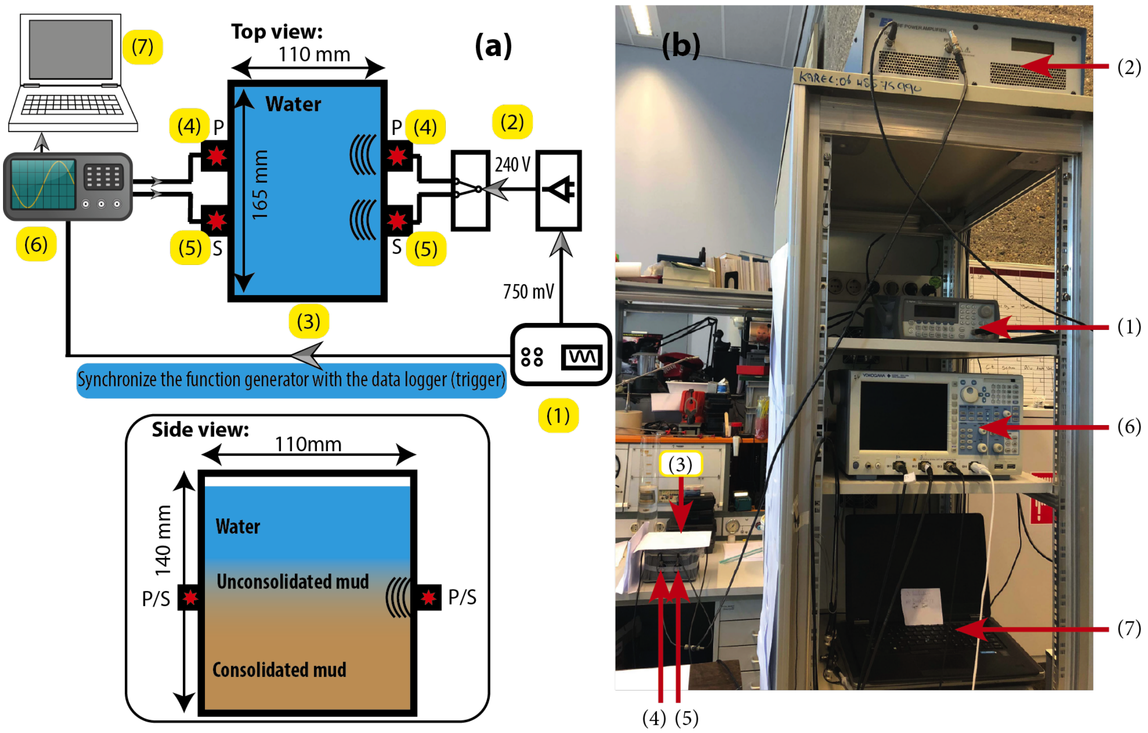

Figure 2 *(a) A schematic cartoon shows the design of the lab experiment. (b) A photo of the experimental setup. (1) Wave generator; (2) amplifier; (3) mud box; (4) and (5) P- and S-wave transducers; (6) oscilloscope; (7) laptop to retrieve the data from the oscilloscope. For more details about each component refer to the text.*

To monitor the settling and consolidation of the fluid mud, we prepare mud samples with different solid concentrations (20%, 40%, 60%, 80%, and 100%) by stirring the mud with water until they become a homogeneous mixture and then leaving the mixture to settle and consolidate over two weeks. This process aims to capture the density variation existing in the 1D water column of water and fluid-mud/mud. Each concentration sample was prepared at the beginning of the week (Monday) and monitored through the weekdays (excluding Saturday and Sunday). The measurements are collected twice a day – once in the morning and once in the late afternoon (approximately 12 hours difference) for P- and S-waves using frequencies between 200 kHz to 1000 kHz with a 100 kHz interval. For each measurement, we also record the temperature. The height of the mud inside the sample box is measured to estimate the average density of the mud sample at that time. Moreover, ultrasonic and temperature measurements are collected for a 100-%-water sample as a reference measure to compare with the measurements from the fluid-mud samples. Finally, we collect random measurements using either P- or S-wave source transducer, only to understand the influence of the P-wave source transducer on the S-wave receiver and vice versa.

The P- and S-wave travel-times were picked for all measurements from the P- and S-wave transducers for all frequencies. Furthermore, the maximum amplitude of the P- and S-wave envelopes is identified for the direct arrival and its first multiple.

Results

The laboratory-based transmission measurements of the settling and consolidation processes of the fluid-mud sample from the Port of Rotterdam have shed light on the influence of the settling and consolidation processes on both P- and S-waves. The results presented here are from the 60-%-mud concentration sample that went through ranges of average densities from 1150 to 1240 kg/m3 during the settling and consolidation processes, as summarized in Figure 3. In Figure 3-a and 3-b, we visualize the P- and S-wave first multiples because they have clearer signal and because the signals from the first arrivals were saturated by the strong signal from the first P-wave transmission impulse. The travel-time of the first multiple = 3 * the travel-time of the first arrival. The P- and S-wave first arrivals were observed between 0.07 and 0.012 ms (not shown here). In Figure 3-d, we also report the amplitudes of the first multiples instead of the first arrivals because the amplitudes from the S-waves first arrivals were contaminated by strong P-wave reverberations that slightly influences the estimated amplitudes. The results can be summarized as follows:

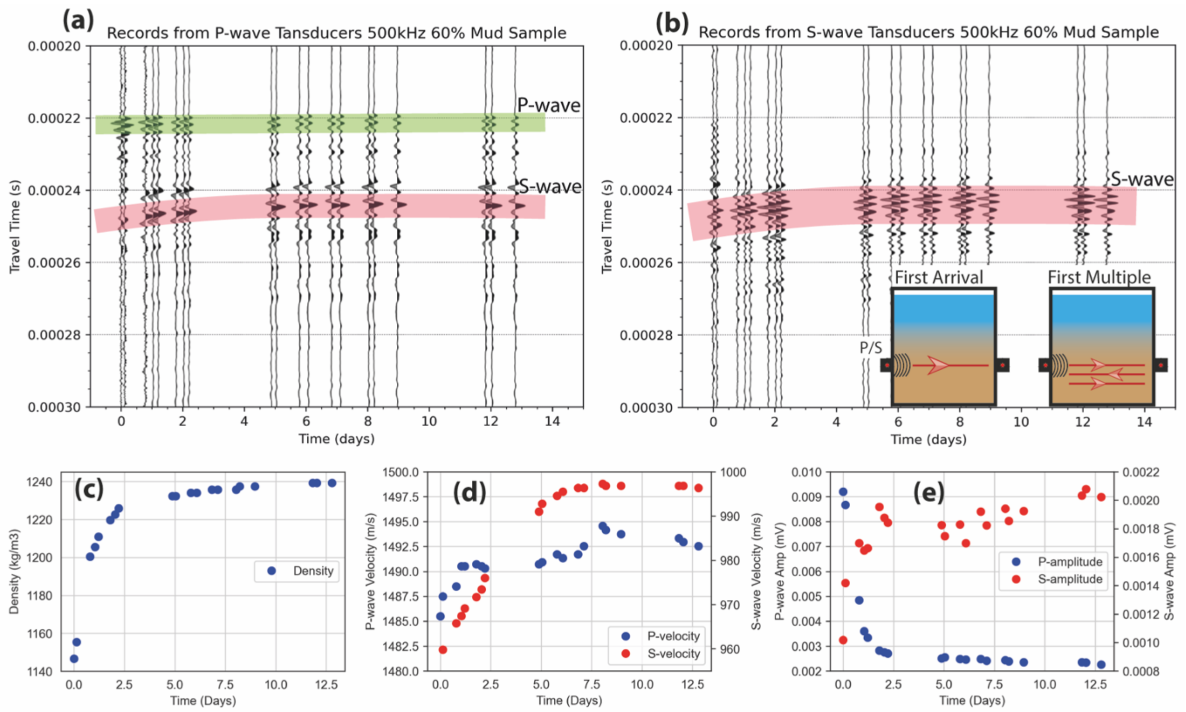

***Figure 3** (a) P- and S-waves recorded on the P-wave transducers for the 60-%-concentration mud sample at 500 kHz. The image is for the first multiples, as explained in the inset of (b). (b) Similar to (a) but for the dominant S-waves recorded by the S-wave transducers. **(a) and (b) show only 0.1 ms (between 0.2 and 0.3 ms) from the complete recording of 1 ms**. (c) Average density variation with time for the 60-% -concentration mud sample. (d) As (c) but for the P- and S-wave velocities. (e) The amplitudes of the first multiple P- and S-wave.*

1- The settling and consolidation processes has a very limited effect on the P-wave velocities, with the P-wave velocities faintly increasing with increasing consolidation. For example, the P-wave velocities of the 60-%-concentration sample shown in Figure 3-a in green have a slight variation over 10 m/s observed through the settling and consolidation processes (Figure 3-d).
2- The settling and consolidation processes has a negative effect on the P-wave amplitudes. For the 60-%-concentration sample, we observed a drop in the amplitudes of the first multiples from 0.0022 mV to 0.0008 mV (Figure 3-a and 3-e).
3- We observe a high S-wave velocity (average = 975 m/s) from the mud sample through the settling and consolidation processes; the settling and consolidation significantly influences the S-wave velocities and amplitudes, as expected.
4- The S-wave velocities increase significantly in comparison to the P-wave velocities observed through the settling and consolidation. For the 60-%-concentration sample, we observe an increase of 50 m/s

through the consolidation process, which correlates with the density variation (Figure 3-b, 3-c, and 3-d).

5- The S-wave amplitudes, opposite to the P-wave, increase with the settling and consolidation process. The increasing amplitudes correlate with the variation of the average density of the mud sample. For the 60-%-concentration sample, we observe an increase in the amplitudes of the first multiples from 0.0008 mV to 0.0022 mV through the settling and consolidation processes (Figure 3-b, 3-c, and 3-e). The observed opposite P- and S-wave amplitudes behaviour through time may be related to the de-gassing of the mud sample during the settling and consolidation process.

Conclusions

We showed results of laboratory ultrasonic transmission measurements on a fluid-mud sample. The results highlighted the influence of the settling and consolidation processes of the fluid mud on both P- and S-waves. We observed increasing velocities and amplitudes for the S-waves that correlates with the variation of the density through settling and consolidation time and can directly indicate the development of the shear strength of the material, which can be crucial for fluid-mud characterization in laboratory-based setup. The utilization of amplitude and velocity information from P- and S-wave could provide crucial input for innovative monitoring campaigns that aim to monitor the fluid-mud conditions in ports and waterways.

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