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# ULTRASONIC EXPERIMENTS FOR RETRIEVAL OF LAYER-SPECIFIC REFLECTIONS INSIDE FLUID MUD FROM PORTS WITH SEISMIC INTERFEROMETRY

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## Summary

Knowledge about the characteristics of fluid mud in ports and waterways would allow safer navigating through fluid mud. The properties of the fluid mud determine the feasibility of navigating vessels through the fluid mud. Seismic waves have the potential to help characterize the fluid-mud layers, especially when both P- and S-waves are used. To investigate the possibility of using reflections measurements for more accurate fluid-mud characterization, we perform ultrasonic reflection experiment on fluid mud from Port of Rotterdam. We apply seismic interferometry to the measurements to retrieve non-physical (ghost) arrivals from inside the fluid mud layer and to eliminate the kinematic influence of the water layer above it. We show how we retrieve P-wave ghost reflections and analogously how we can retrieve S-wave and P-to-S-converted ghost reflections.

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## Introduction

Characterization of fluid mud from ports and waterways gives more knowledge about navigating through fluid mud so that more cargo can be loaded on ships and less dredging is performed. The properties of the fluid mud determine the navigability of vessels through the fluid mud. Seismic waves have the potential to characterize the fluid-mud layers (Kirichek et al. 2018). In seismic surveys, seismic interferometry (SI) has been widely used to retrieve seismic traces (Shapiro and Campillo 2004; Wapenaar and Fokkema 2006). Draganov et al. (2012) and King and Curtis (2012) studied the application of SI in marine surveys and used non-physical (ghost) reflections to estimate layer-specific propagation velocities for layers in the subsurface. The seismic surveys for fluid mud are complex and are restricted by in-situ conditions. Our study shows an application of SI for seismic surveys of fluid mud to characterize the fluid mud through ghost reflections.

In seismic surveys for ports and waterways, keeping the sources and receivers at certain distance above the top of fluid-mud layers is favourable for two reasons. First, the surface of the sediments is most often not entirely flat and thus towing at a certain height above the top of the fluid-mud layers would ensure that the fluid mud is not disturbed. Second, unpredictable obstacles, i.e., objects discarded by humans and moved by the water flow, inevitably exist at the top part of fluid-mud layers. These obstacles could harm the seismic equipment during a survey. However, as a result of towing the sources and receivers inside the water at a distance above the fluid mud, a recorded reflection arrival would consist of a part propagating inside the water and a part propagating inside the fluid mud. The propagation inside the water is affected by the temperature and salinity of the water. Removing the water-propagation part would eliminate the influences. In order to extract reflections from inside the mud only, we make use of SI with ghost reflection. For this, we perform tests on ultrasonic laboratory data recorded using mud samples from the Port of Rotterdam.

## Methods and Materials

SI can be applied to recordings from source and receivers at (or near) the surface. Because such a configuration violates the requirement of enclosing sources (or receivers), the result contains retrieved ghost reflections resulting from cross-correlation of recorded primary reflections from different layers in the subsurface. Using SI specifically to retrieve ghost reflections, the physical sources and receivers could be turned into non-physical (ghost) sources and receivers as if planted directly at a layer boundary (Draganov et al., 2012; King and Curtis, 2012). The retrieved ghost reflections then have the kinematics of propagating only through specific layers. This conversion from physical sources and receivers to ghost ones enables the seismic surveys to use more flexible setups. In the fluid-mud scenario, we apply SI by cross-correlating reflections from the water bottom and fluid-mud bottom to eliminate the kinematics of wave propagation through the water.

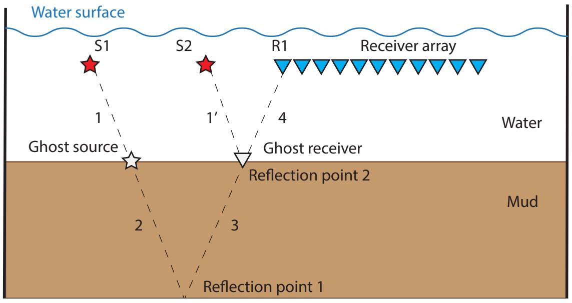

***Figure 1*** Application of seismic interferometry by cross-correlation in fluid-mud reflection tests. The two red pentagrams represent the seismic sources, S1 and S2. The blue triangles are the receiver array with the left-most receiver labelled R1. The white pentagram and triangle represent the ghost source

and receiver, respectively, which are retrieved by cross-correlating the reflection raypaths from S1 to R1 and from S2 to R1.

Figure 1 shows an example explaining the retrieval of ghost reflections using. Two identical sources, S1 and S2, are placed at the same depth under the water level. Seismic waves emitted from each source, including reflections from the water bottom and the mud bottom, are recorded by the receivers. A seismic signal, due to S1, is reflected by the mud bottom at Reflection point 1 and is recorded by receiver R1. The raypath is indicated by the dashed lines 1-2-3-4. The other source – S2 – emits a signal, which is reflected by the water/mud interface at Reflection point 2. This seismic signal arrives at receiver R1 allong the raypath indicated by the line 1′-4. Note that S1 and S2 are placed such that raypaths 1 and 1′ are parallel. The raypath 1-2-3-4 and the raypath 1′-4 share the reflection part 4, while the incidence part of the raypath 1 is equal to the raypath 1′. Cross-correlating the arrival at R1 that has traversed raypath 1-2-3-4 with the arrival that has traversed raypath 1′-4 results in effectively eliminating the overlapping parts (1 and 4) in the water from the raypath 1-2-3-4, leaving the raypath 2-3 as the reflected-wave propagation inside the fluid mud. After the elimination process, source S1 is virtually shifted to a new position at the mud surface as the ghost source and source S2 is effectively turned into a ghost receiver at Reflection Point 2 so that the retrieved signal can be seen as having propagated solely inside the mud from the ghost source to the ghost receiver. In practice, one will not know where R1 should be placed, so a summation over correlated recordings at multiple receivers is performed. When there are sources at more than two points, ghost reflections at multiple offsets could be retrieved. This would allow using the ghost events to estimate the propagation velocity of P- or S-waves inside the mud layer using velocity analysis.

## Laboratory Reflection Tests on Fluid Mud

We perform a seismic reflection test to test the retrieval of ghost reflections from inside fluid mud. We mix fluid mud, taken from Port of Rotterdam, with water, and pour the mixture in a glass tank. We let the mud settle during a couple of days. This results in the mud gradually forming a layer (Figure 2c). The mud layer can be used as a proxy to mimic underwater sediment structures in the port.

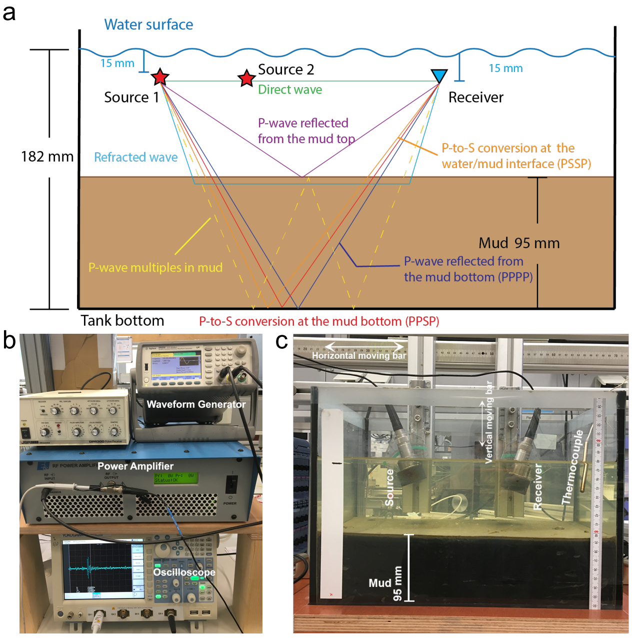

***Figure 2*** *(a) Laboratory reflection tests design and relevant seismic waves in the tests. These waves are plotted only for showing the wave types involved in the tests and do not represent the actual propagation*

*raypaths. (b) Equipment for controlling wave generation and monitoring waveforms recorded by the receiver. (c) The setup of the reflection tests showing transducers placement and positions adjustment.*

We use a pair of piezoelectric transducers (Figure 2c) as the source and the receiver. Both transducers can be moved horizontally for changing the offset and vertically for changing the depth, but also could be rotated for changing emitting/receiving angles. A waveform generator is used to initiate signals in multiple modes and frequencies. For our tests, we use a sinusoidal signal with centre frequency of 100 kHz. The generator signal is passed to an amplifier. As waves significantly attenuate when propagating through mud layers, this amplifier is used to boost the energy of the original signal. The output from the amplifier is connected with the source transducer. On the receiver side, the receiver transducer is connected to an oscilloscope for monitoring and recording the received signals.

We place the source transducer at a position as Source 1 (Figure 2a) 15 mm below the water surface. Then, we use the source transducer as a reference and adjust the position of the receiver transducer to place it at the same depth. The receiver is moved to the initial position, and a measurement is taken. Next, the receiver is moved horizontally to a new offset position away from the source for the next measurement. In this way, we build up a receiver array evenly distributed receivers along a line in the horizontal direction. After taking a measurement at the furthest receiver position from Source 1, we mode horizontally, but inline with the receivers, the source transducer to a new position as Source 2. We then use Source 2 to measure at each receiver positions. In this way, we end up with two common-source gathers observed at the same receiver positions.
The arrivals that we expect to have recorded are direct waves, P-wave reflections, P-to-S-wave conversions, and reflections. Figure 2a illustrates the different types of arrivals we expect. Using the same colour-coding, we indicate these type sof arrivals in the common-source gathers from Source 1 and Source 2 in Figure 3a and Figure 3b, respectively.

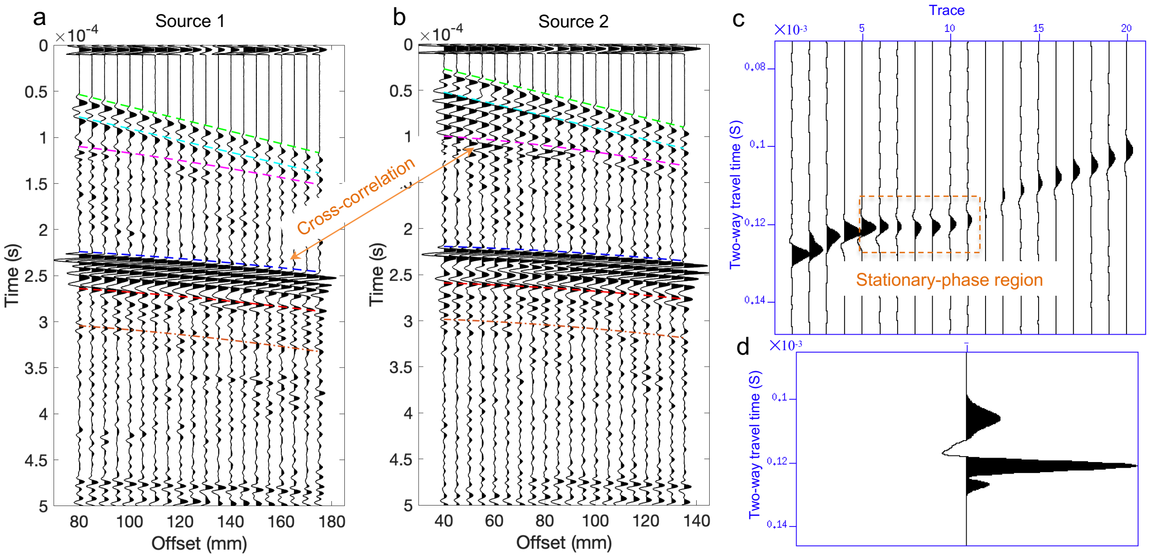

***Figure 3*** *(a) Common-source gather from Source 1. Arrivals are indicated using the colour-coding from Figure 2a: green for the direct wave, cyan for the refracted wave, magenta for the P-wave reflected from the mud top, blue for the P-wave reflected from the mud bottom (PPPP), red for the P-to-S conversion at the mud bottom (PPSP), and orange for the P-to-S at the water/mud interface (PSSP). (b) Common-source gather from Source 2 with the same colopur-coding. (c) Correlation panel for retrieval of a ghost reflection inside the mud layer obtained by correlating the magenta reflection in b with the blue PPPP reflection in a. The orange rectangle indicates the stationary-phase region. (d) The result of stacking the traces in the correlation panel in c.*

In order to retrieve a ghost reflection from inside the fluid mud, we use SI by cross-correlation. Specifically, we isolate (by muting) the P-wave reflection from the mud top (magenta in Figure 3b) and the P-wave reflection from the mud bottom (PPPP; blue in Figure 3a) and cross-correlated them trace by trace. The result is shown in Figure 3c, and this is known as correlation panel. It exhibits a relatively flat distribution from the 5th trace to the 11th trace – the stationary-phase region (Snider, 2004), which gives the dominant contribution to the retrieved final arrival in Figure 3d. This arrival is obtained after stacking the traces in the correlation panel in Figure 3c. The retrieved arrival in Figure 3d kinematically represents a reflection from inside the mud layer from a ghost source and a ghost receiver as if placed directly at the top of the mud. The horizontal distance between the ghost source and ghost receiver is equal to the horizontal distance between Source 1 and Source 2. Measuring the thickness of the fluid-mud layer, we can use the ghost reflection to calculate the velocity of the fluid mud. Alternatively, if an estimate of the P-wave velocity inside the mud is available, e.g., from velocity analysis of the original recorded data, the thickness of the fluid-mud layer can be estimated.

The retrieval of the PP ghost reflection in the test is obtained by cross-correlating the P-wave primaries from the mud top and bottom (PPPP). Similarly, we retrieve also the PS and SS ghost reflections from inside the fluid mud using the P-to-S conversion at the bottom of the mud (PPSP) and the P-to-S conversion at the top of the mud (PSSP), respectively, to replace the reflected P-wave primary from the mud bottom (PPPP).

## Conclusions

We applied seismic interferometry in seismic reflection tests of fluid mud to retrieve non-physical (ghost) arrivals from inside a fluid-mud layer and to eliminate the kinematic influence of the water layer above it. We used data from an ultrasonic laboratory setup that recorded reflection data using fluid mud from the Port of Rotterdam. The ghost-reflection approach can assist in retrieving seismic traces from inside the fluid mud to investigate the seismic characteristics of the fluid mud. Studies suggested that the shear-wave velocity of fluid mud could be used to estimate the shear strength of fluid mud. Using the ghost-reflection retrieval with seismic interferometry, retrieved converted-wave reflections or retrieved shear-wave reflections could be used in future studies to precisely estimate the shear-wave velocity of the fluid mud and thus its shear strength.

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