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Characterization of fluid mud layers for navigational purposes

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Abstract
The objective of this study is to get a new insight into in-situ characterization of fluid mud layers. Water Injection Dredging has been performed to create a fluid mud layer in the 8th Petroleumhaven at the Port of Rotterdam. Four measuring tools, conventional multi-beam echo-sounder, DensX, Graviprobe and Rheocable have been used to monitor the fluid mud layer properties over the time. The results suggest that the currently employed density-based nautical depth criterion has to be revised to ensure more efficient navigation in the vicinity of fluid mud layers.

Introduction
The detection of fluid mud layers at ports and waterways is of primary importance to safeguard navigation. For practical reasons, the nautical depth (ND) is defined within the fluid mud layer as the depth where the mud density does not exceeds a density of 1.2 kg/l (PIANC, 2014). This layer typically consists of water-sediment mixture and has weak shear strengths.

Echo-sounding measurements have been successfully used to assess the ND (Hamilton and Bachman, 1982). As the acoustic impedance along can be correlated to density. Currently, multi-beam echo-sounders are utilized to determine fluid mud deposits. Two frequencies of the emitted acoustic signal, 200 kHz and 38 kHz, are used to detect the approximate size of the fluid mud layer. However, the low-frequency (18-45kHz) signal has to be calibrated using the SILAS system, which correlates the measured acoustic impedance to in-situ density measurements. Typically, the density measurements are done with penetrometer-type tools or mud samplers. The acoustic impedance of the mud of density 1.2 kg/l is then correlated to the low-frequency echo-sounder signal and corresponding depth is used as a nautical depth. This method is currently employed the Port of Rotterdam and Rijkswaterstaat.

In our experiments we would like to estimate which of the density or the rheological properties of the mud are the most effective criteria for navigation in the vicinity of fluid mud layers. For this purpose, we compare two penetrometers, DensX and Graviprobe, which provide vertical profiles of the density and cone penetration resistance, respectively. DensX is an X-ray based direct measurement density profiler. It measures the densities of a water-mud column between 1.0 kg/l and 1.5 kg/l with an accuracy of 0.25 %. Graviprobe measures the cone penetration resistance and pressures while falling free in a water-mud column. The cone penetration resistance is then correlated to the undrained shear strength of the fluid mud layer.

The Rheocable method (Druyts and Brabers, 2012) is based on the physics of a towing body. Towed within a certain velocity window the position of the Rheocable is then related to the interface between fluid and consolidated mud. The depth of the cable is recorded by measuring the hydrostatic pressure. An electrode array is positioned along the length of the cable. The electrical resistivity of mud is linked to the density of mud using the calibration performed in the laboratory. During the Rheocable survey the resistivity is monitored and the velocity of the towing is adapted in or order to always keep the cable within the fluid mud layer at the ND.

Field experiment
The 8th Petroleumhaven has been selected for this study. The water depth in this harbour is varies from 23m to 27m. Initially, the Water Injection Dredging method was employed to mobilize the mud from the bottom and create a fluid mud layer up to 1.5m. The total area of 500×200 m^2 has been monitored on a weekly basis. The Rheocable measurements are compared to the results of conventionally used low-frequency acoustic sounding technique. The rheological properties in terms

of undrained shear strength is shown in the Graviprobe figure. The DensX measurements have been used to calibrate the echo-sounding data.

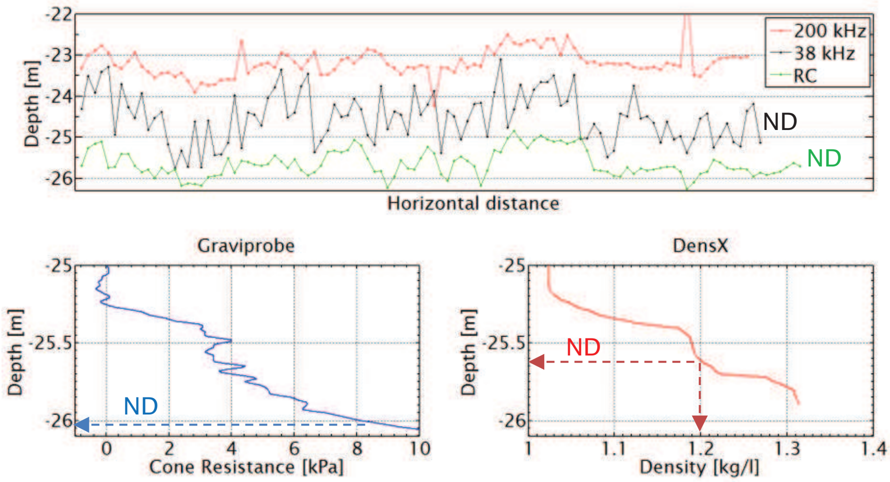

Fig. 1. Characterization of the fluid mud layer by means of the echo-sounder, Rheocable, Graviprobe and DensX. 'ND' stands for the nautical depth.

Discussion

Figure 1 clearly indicates the differences between the ND's found by conventional echo-sounder and the Rheocable method, which can be attributed to inaccuracies of the measuring techniques or calibration limitations.

The output of penetrometers DensX and Graviprobe also give a different ND estimate. The analysis of the complete dataset of the Graviprobe and DensX depth profiles confirm the non-linearity between density and shear strength of mud. Density measurements do not reflect the thixotropic effect of mud. Therefore, a more complete definition of the ND should be derived that includes the rheological properties as key criteria for safe and cost-efficient navigation.

The non-linear relationship between density and rheological properties is investigated further by means of laboratory consolidation and rheological experiments. We found that the undrained shear strength of mud develops slower with time than the density which confirms the experiments of Staelens *et al.* (2013). A remaining open question is whether the output of the Graviprobe technique is correctly related to the rheological properties of mud.

Conclusion

This study provides a new insight into the non-linear relationship between density and rheological properties. Rheological properties are sought to be the relevant parameters for defining the nautical depth to safeguard navigation in the vicinity of the fluid mud layer.

In order to get detailed bathymetry mapping, acoustic signal of echo-sounders could then be related to rheological properties of mud instead of density.

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