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Meshkati, Ebi; Terwindt, Jarno ; van Kessel, Thijs ; Kirichek, Alex ; Talmon, A.M.; Bezuijen, Adam

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Shear strength measurement in soft mud deposits: application of GraviProbe and RheoTune

Mesure de la résistance au cisaillement dans les dépôts de boue molle: application de GraviProbe et RheoTune

Ebi Meshkati & Jarno Terwindt & Thijs van Kessel
Deltares, The Netherlands, ebi.meshkatishahmirzadi@deltares.nl

Alex Kirichek & Arno Talmon
Deltares & Delft University of Technology, Delft, The Netherlands

Adam Bezuijen
Deltares & University of Ghent, Belgium

ABSTRACT: Soft mud deposits are increasingly encountered around the world, from natural offshore deposits and mud layers in estuaries, ports, and waterways to progressively growing leftover from treatment and extraction facilities, mines, and oil refineries. Reliable monitoring of the temporal and spatial strength buildup in such deposits is crucial to optimize their sediment management plan. In this study, two well-established shear strength profilers i.e. GraviProbe 2.0 (dotOcean) and RheoTune (Stema Systems) are investigated. Their working principles are described, and their performance is compared against direct strength measurement. Finally, capabilities, limitations, and points of improvement of both instruments are discussed.

RÉSUMÉ : Les dépôts de boue molle sont de plus en plus rencontrés dans le monde, depuis les dépôts naturels en mer et les couches de boue dans les estuaires, les ports et les voies navigables jusqu'aux vestiges de plus en plus nombreux des installations de traitement et d'extraction, des mines et des raffineries de pétrole. Une surveillance fiable de l'accumulation de résistance temporelle et spatiale dans ces dépôts est cruciale pour optimiser leur plan de gestion des sédiments. Dans cette étude, deux profileurs de résistance au cisaillement bien établis, à savoir GraviProbe 2.0 (dotOcean) et RheoTune (Stema Systems) sont étudiés. Leurs principes de fonctionnement sont décrits et leurs performances sont comparées à la mesure directe de la résistance. Enfin, les capacités, limites et axes d'amélioration des deux instruments sont discutés.

KEYWORDS: Soft mud deposits, strength measurement, rheology, yield stress, GraviProbe, RheoTune

1 INTRODUCTION

Soft mud deposits are increasingly encountered around the world, from natural offshore deposits and mud layers in ports and waterways to leftover from treatment and extraction facilities, mines, and oil refineries. The upper part in soft mud deposits can have potential for mobility and in that case is called fluid mud (McAnally et al., 1988). These fluid mud usually characterized by their relatively low solids content (<32 weight%) and low strength (< 0.5 kPa undrained shear strength). Knowledge on temporal and spatial shear strength build-up in such soft mud deposits is essential for defining and optimizing sediment management strategies (Kirichek and Rutgers, 2020; Kirichek et al., 2020).

Over the last decades, an extensive amount of work has been carried out to develop reliable and relatively pragmatic solutions for strength profile measurement in soft mud deposits. These solutions can be generally classified into three main groups of instruments: cone penetration tests (CPTs) instruments, full flow penetrometers (e.g. T-bar), and free-fall penetrometers. The accuracy and reliability of such instruments in soft mud deposits is still under research and has not been yet fully achieved. The main underlying challenges are the range of targeted shear strength in such deposits in relation to the sensitivity of instruments, as well as the completeness of physics used to translate the measured raw data by an instrument to actual (shear) strength. In this study, two well-established European instruments designed for in-situ shear strength profile measurements i.e. GraviProbe 2.0 (dotOcean, Belgium) and RheoTune (Stema Systems, The Netherlands) are selected to study their ability to provide shear strength profiles under controlled laboratory conditions. Experiments were conducted at Geo-facility of Deltares, Delft, The Netherlands. The study was focused on natural marine fluid mud layers in ports. The study provided an insight on the working principles of GraviProbe 2.0 and RheoTune. Additionally, the measurements are compared against direct shear strength measured by a rheometer on core-sub-samples. This study also touches upon capabilities as well as points of improvement of the instruments. Lastly, recommendations are provided to help problem owners with a better understanding of the boundary condition for the in-situ deployment of these two instruments.

2 DIRECT SHEAR STRENGTH MEASUREMENT

In clay-rich soft sediments, several yield points may exist (Anton Paar, DIN technical report npo.143). Different engineering applications require knowledge on one or all these yield points, depending on the application as well as the physio-chemical properties of the material. In this study, two yield points are considered: 1) static yield stress (SYS): defined as the minimum stress required for initiating the flow in a stagnant material under stress, or in other words the yield point at which material transitions from solid-like to fluid-like state. SYS is a material property and corresponds to the yield point at which viscous flow in the material starts. SYS is not a function of shear rate but the inherent property characteristics of a material. SYS values are close to undrained static shear strength ($S_{u,ref}$) often used in geo-mechanics; and 2) dynamic yield stress (DYS): defined as the minimum stress required for maintaining a material in motion, or in other words the yield point at which material transitions from fluid-like to solid-like state. In this state, the material is considered (fully) remolded. A more detailed description of yield points in soft muds can be found in Cheng (1986) and Meshkati et. al. (2021).

To evaluate the performance of the instruments, direct roto-viscometry on core sub-samples was conducted using a HAAKE MARS I rheometer. A ramp-up controlled shear stress (CSS) protocol with bob-cup geometry was used for the measurements following the protocol proposed by Shakeel et al. (2019). In this study, the fluidic yield stress defined by Shakeel et al. (2019) is applied as static undrained shear strength $S_{u,ref}$ which is close to SYS. The $S_{u,ref}$ values from direct roto-viscometry are compared to the output from GraviProbe 2.0 and RheoTune.

3 WORKING PRINCIPLE

3.1 *GraviProbe 2.0*

The GraviProbe 2.0, manufactured by dotOcean in Belgium, is a free-fall impact instrument designed to measure the shear strength of underwater sediment layers during its intrusion. It is torpedo-shaped with 960 mm in length and 50 mm in diameter, about 8 kg mass in air, and approximately 6.1 kg equivalent effective mass underwater (dotOcean, 2020). Figure 1a shows a picture of GraviProbe 2.0. This instrument is equipped with two single-axis accelerometers in the cone, a pressure sensor at the cone tip, and a pressure sensor at the tail. There is no tip and sleeve friction sensor in the device since they would have been easily destroyed due to impact. These accelerometers measure the vertically-oriented acceleration during the free-fall to a maximum of 1.7g (for accurate measurements of limited accelerations) and 70g (for significant accelerations), respectively. The instrument accelerates in the water column right after its release and starts to decelerate after hitting the mudline until it comes to a complete halt usually a few meters deep in deposit. Integration of deceleration allows to obtain velocity profile of the probe and integration of probe' velocity leads to displacement profile of the probe. Additionally, the pressure sensors in GraviProbe 2.0 provide the displacement in the water column. This is particularly of importance in longer trajectories in the water column when the instrument travels close to or at its terminal velocity where neither acceleration nor deceleration occurs. In this study, with limited depth, two times integration of the accelerometer results was accurate enough to estimate the probes' position and its displacement.

The GraviProbe 2.0, or in general free-fall cone penetrometers, provide an indication of resistance in a deposit. This resistance is the resultant of two main components: resistance on the tip and resistance on the shaft (sliding cylinder behind the tip). The output of GraviProbe 2.0 includes static undrained shear strength ($S_{u,ref}$) and dynamic undrained shear strength (S_u) profile. These two parameters, i.e. $S_{u,ref}$ and S_u give an indication of the total resistance felt by the instrument and does not distinguish between the tip or shaft resistance. Having said that, there are empirical and benchmark free-fall cone methods that can be used to proportionate $S_{u,ref}$ over strength measured at tip and strength measured at shaft. By doing so, both static strength and remolded strength of soft deposit can be estimated. This, however, is outside the scope of the current paper. GraviProbe 2.0 can be deployed in soft mud deposits with an undrained shear strength up to 10 kPa. Above this range, it is expected that the instrument's penetration depth to be limited up to the length of the instrument (Bezuijen et al., 2018).

The dynamic undrained shear strength (S_u) is shear rate dependent which changes with depth (i.e. as the probe velocity decreases), in contrary to the static undrained shear strength ($S_{u,ref}$). Therefore, $S_{u,ref}$ is comparable to SYS. S_u and $S_{u,ref}$ relate to each other by ratio of shear rates (Bezuijen et al., 2018):

$$S_{u}= S_{u,ref}\left(\frac{d_{cpt}v_p}{d_p v_{cpt}}\right)^{-\beta} \tag{1}$$

where v_p is the velocity of the GraviProbe, v_{cpt} is the velocity of a CPT (=0.02 m/s), d_p is the diameter of the GraviProbe, d_{cpt} is the diameter of a CPT cone (=0.036 m), β is an exponent coefficient in order magnitude of 0.1. The acceleration measured by GraviProbe 2.0 is a function of the acceleration of gravity, the flow resistance and the undrained shear strength (s_u) of soft sediment in which it penetrates. When the influence of gravity and flow resistance are known, the undrained shear strength can be obtained. Bezuijen et al. (2018) proposed a model by which the static undrained shear strength ($S_{u,ref}$) can be calculated from the measured acceleration:

$$S_{u,ref,n}= \frac{W_g - m a_n - F_B - f_f \sum_{i=1}^{n-1} S_{u,ref,i}\left(\frac{d_{cpt}v_p}{d_p v_{cpt}}\right)^{\beta} .O_p \Delta z_i}{N_c f_{d,n} A_p} \tag{2}$$

where W_g and m are the weight and mass of the GraviProbe respectively, a_n is the measured acceleration at point n along the depth, F_B is the buoyancy force, f_f is the friction factor, O_p is the circumference of the GraviProbe, N_c is the bearing capacity factor, $f_{d,n}$ is the depth factor, A_p is the cross-sectional area, i is a counter, Δz_i is the thickness of small slice of mud defined as:

$$z = \sum_{i=1}^{n} \Delta z_i \tag{3}$$

with z the penetration depth. For more elaboration on derivation of Eq. 2 consult Bezuijen et al. (2018).

3.2 *RheoTune*

The RheoTune, manufactured by Stema Systems, in the Netherlands, is a (self-weight) penetrating probe with 750 mm in length and 150 mm in diameter. Its mass is about 15 kg (in the air), and additional weights can be optionally added to the device (StemaSystems, 2016). Figure 1b shows a picture of RheoTune. The factory output from RheoTune according to the manufacturer includes density up to 1500 kg.m^{-3} and yield stress (Bingham) up to 500 Pa. The measurement principle of RheoTune is based on a tuning fork which is positioned at the tip of the device. Tuning fork-based measurement devices measure the fluid's response to oscillation frequency and amplitude of vibration of their tuning fork. RheoTune at its current state estimates the density values from a database, in which oscillation frequency and amplitude of vibration of the tuning fork are correlated to direct density measurement. This is the so-called density calibration domain (Pedocchi et al., 2015), in which different density values are characterized by a set of diverging straight lines on a graph with oscillation frequency on the horizontal axis and amplification voltage on the vertical axis (Figure 2). Each line on this graph represents a density. Scatter along each line (density) provides information on the elastic and viscous properties of the material (see Pedocchi et al. (2015) and Groposo et al., (2015) for more elaboration on the density calibration domain). Note that, density calibration domain may be unique to a sediment type depending on its physio-chemical properties, meaning that a universal density calibration domain may not exist. In addition to a density calibration domain database, Stema Systems built a secondary database in which RheoTune's outputs are correlated to their corresponding shear strengths. These strengths are measured by controlled shear rate ramp-up rheological protocol using Brookfield rheometer. This implies that the yield stress is derived from the un-remolded state of the material in the testing procedure, thus the Bingham yield stress reported by RheoTune should be close to static undrained shear strength $S_{u,ref}$.

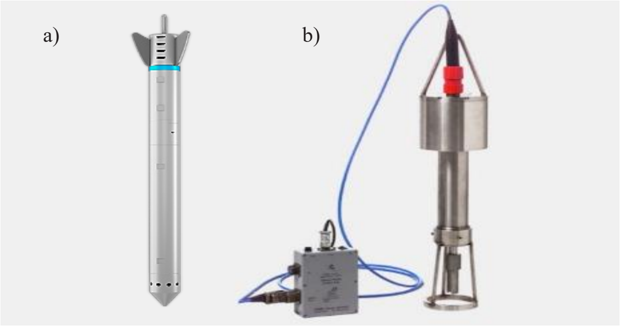

Figure 1. a) GraviProbe 2.0 (ref: dotOcean, 2020); b) RheoTune (ref: StemaSystems, 2016).

To the knowledge of authors, to date, the tuning fork principle is not yet being used in RheoTune to measure linear rheology, through alternation between +45- and -45-degree phase shifts (Allwright, 2002). Doing so, RheoTune will be equipped with potentially a new interesting and useful feature by which shear modulus and linear viscosity can be obtained. In tuning fork-based instruments, usually, deformations are small, and the material does not fail (un-remolded state). For the relevant mud conditions, sediment is in the so-called Linear Visco-Elastic (LVE) regime where the main governing rheological parameters are shear modulus and linear viscosity.

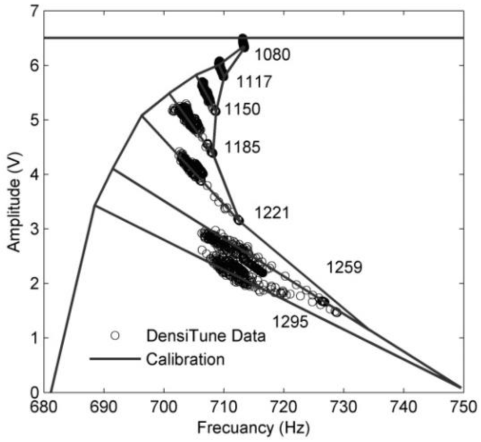

Figure 2. A typical density calibration domain; numbers on the graph are in kg.m^{-3} (ref: Pedocchi et al., 2015).

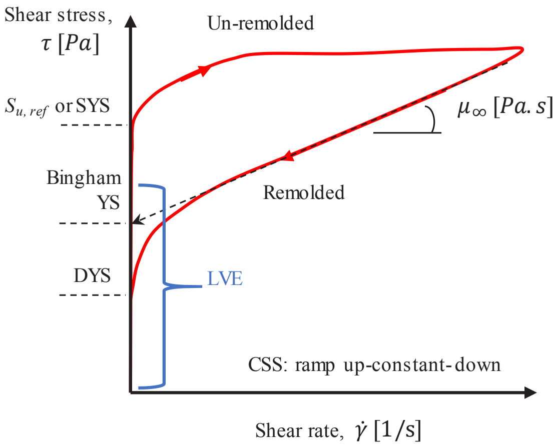

Figure 3. Rheology sketched: flow curve (in red), Bingham parameters, $S_{u,ref}$, SYS and DYS (in black), Visco-Elastic regime (in blue).

Note, plastic viscosity and linear viscosity should be distinguished. The former refers to the viscosity of the fluid in presence of relatively large plastic deformation and the latter refers to the viscosity of the fluid in relatively small elastic deformation. Figure 3 highlights the difference. Linear rheological properties can be important to the navigation of sailing vessels over/through fluid mud (Miloh, 1995). Fundamental relations between the linear and plastic rheological properties of the mud should be explored and exploited.

4 EXPERIMENTAL SETUP & DESIGN

The test setup included a mud reservoir, a mixer, a positive displacement screw-type pump, and a cylindrical test container (see Figure 4a). The cylindrical test container consisted of four steel cell rings mounted on top of each other. The inner diameter of each cell ring was 1250 mm and the height of a single cell ring was 500 mm, resulting in a 2-meter-high cylindrical test container. The bottom cell ring was filled with a 0.3 m thick sand layer. This layer was placed in order to prevent damage to the probes, particularly the GraviProbe 2.0.

4.1 *Deployment of the instruments*

For testing with GraviProbe 2.0, an additional water column was provided above the testing container, making sure the instrument accelerates for a (limited) distance before hitting the mud in the test container. This was realized by adding a 4.3 m high acrylate cylinder column above the test container (see Figure 4b). The cylinder had an inner diameter of 280 mm and was made up of two 2000 mm high segments. These were mounted on a top cover, which in turn was mounted on top of the steel cell rings. The instrument was positioned inside the cylinder using an overhead crane. Free fall was initiated by an electronically operated magnetic release. A nylon rope was attached to the end of the instrument for retrieval, with enough excess rope to ensure a smooth, uninterrupted free fall. RheoTune was positioned just above the mudline with an overhead crane. A 1.6 m long, 7.4 kg weighing steel profile was positioned on top of RheoTune in order to ensure a vertical penetration path. Upon lowering the overhead crane, RheoTune penetrated the mud under its self-weight. The probe was retrieved by hoisting the crane back up.

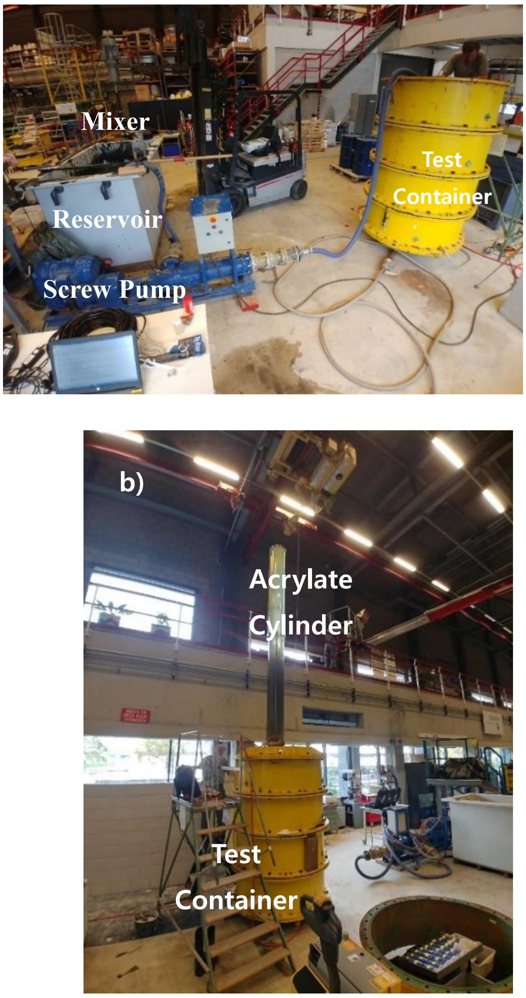

Figure 4. (a) The test setup for RheoTune; (b) The test setup forGraviprobe 2.0.

4.2 *Softs sediment types and preparation*

Two types of sediments were used namely from Calandkanaal in Port of Rotterdam (PoR), the Netherlands and the Port of Hamburg (PoH), Germany. The mixing was done in two stages. The first stage consisted of pre-mixing the mud in the original barrels by use of an electrical mixer until the mixture appeared homogeneous. Then, the barrels were emptied into the mud reservoir, in which mud was diluted with tap water to a desired density, if necessary. Mixing in the reservoir was done by the same mixer and an additional screw type pump, which circulated the mud inside the reservoir. The same screw type pump was used to transport the mud from the reservoir to the test container.

4.3 *Test plan*

The test program consists of using two types of soft sediments, and for each sediment type two different densities, and two different resting times before deployment of the instruments (i.e. 24 or 72 hours). Table 1 provides an overview of the test plan. Upon completion of the GraviProbe 2.0 and/or RheoTune deployments, a core sample was taken using the Beeker sampler at a location which was not disturbed by the penetration of the other two probes. Then, the direct shear strength measurements were conducted on sub-samples. The top view of the layout for the deployment of GraviProbe 2.0, RheoTune, and Beeker sampler is shown in Figure 5.

Table 1. Overview of Test Program

Probe type*	Test no.	Mud origin**	Target density kg·m^{-3}	Resting time (hr)	Mud thickness (m)
RT	1	PoR	1250	24	1.52
RT	2	PoR	1250	72	1.53
RT	3	PoR	1150	24	1.53
RT	4	PoR	1150	72	1.53
GP	1	PoR	1250	24	1.52
GP	2	PoR	1250	72	1.53
GP	3	PoR	1150	24	1.52
GP	4	PoR	1150	72	1.53
RT	5	PoH	1200	24	0.87
RT	6	PoH	1150	24	1.12
GP	5	PoH	1200	24	0.87
GP	6	PoH	1150	24	1.12

*) RT refers to RheoTune, GP refers to GraviProbe.

**) PoR refers to the Port of Rotterdam, PoH refers to the Port of Hamburg.

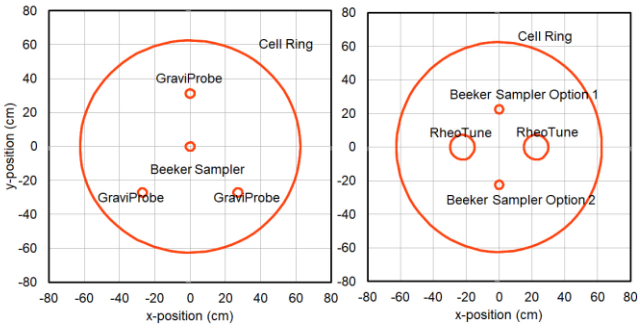

Figure 5. Top-view of test layout for a) GraviProbe 2.0 deployments; b) layout for RheoTune deployments.

5 RESULTS & DISCUSSION

5.1 *GraviProbe 2.0 versus direct measurement*

Three representative GraviProbe 2.0 test results are shown in Figures 6-8. Each figure consists of three panels: the acceleration versus depth (left panel), velocity versus depth (middle panel) and the static undrained shear strength versus depth (right panel). The right panels contain both the direct strength measurements (circles) and repeated GraviProbe 2.0 measurements (lines). The depth 0 in these figures refers to the mudline. Figures 6 - 8 depict that the output of Graviprobe 2.0 is close to measured $S_{u,ref}$ values (circles). It is unclear why the strength of the mud is decreasing near the bottom of the barrel while physically you would expect an increase in strength near the bottom.

It is observed that GraviProbe 2.0 inherently tends to estimate larger strength with increasing depth, while muds' shear strength was fairly homogeneous along the depth. The tendency to output larger strength with depth might be because this instrument relies on several assumptions for material properties to translate de-acceleration to static undrained shear strength such as for the mud density, drag coefficient, and tip correlation factor. Each of these input parameters is associated with its own uncertainty, contributing to uncertainty in the derived undrained shear strength. Thus, in practice it is crucial to obtain those material parameters prior to deployment of the instrument. By doing so, we expect the quality and reliability of measurements can be further improved. The results are generated through a try and error process by which the required material parameters are tuned so that the best "fit" could be achieved.

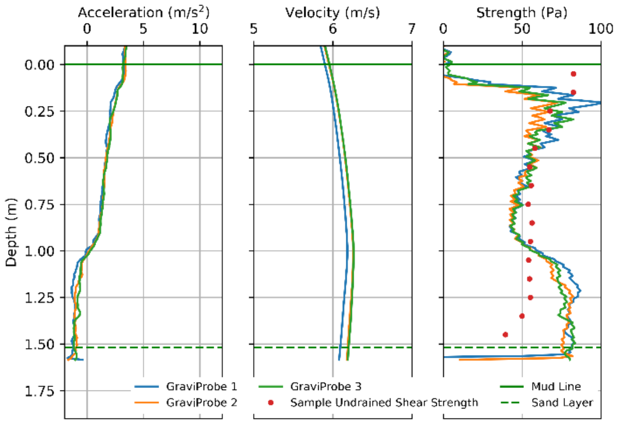

Figure 6. Three free-fall attempts into the test container with mud from the PoR, 152 cm mud layer thickness, initial average density of 1250 kg.m^{-3}; prior to the tests 24 hr resting time was given to mud.

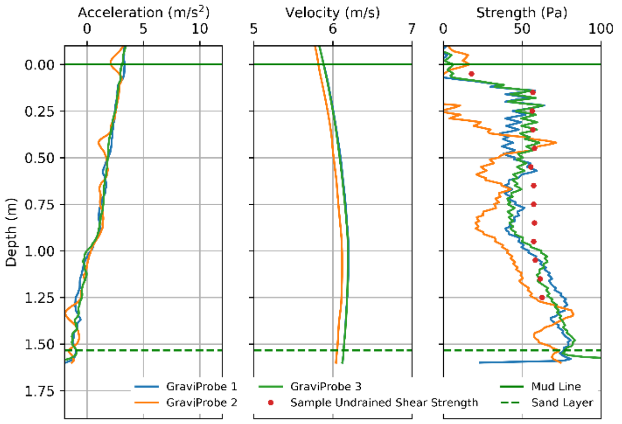

Figure 7. Three free-fall attempts into the test container with mud from PoR, 153 cm mud layer thickness, initial average density of 1250 kg.m^{-3}; prior to the tests 72 hr resting time was given to mud.

5.2 *RheoTune versus direct measurement*

Three representative RheoTune test results are shown in Figures 9 - 11. Each figure consists of two panels: strength versus depth (right panel) and density versus depth (left panel). The direct density measurements (measured by Anton Paar DMA 35) and $S_{u,ref}$ measurements are shown by crosses and circles in these figures, respectively.

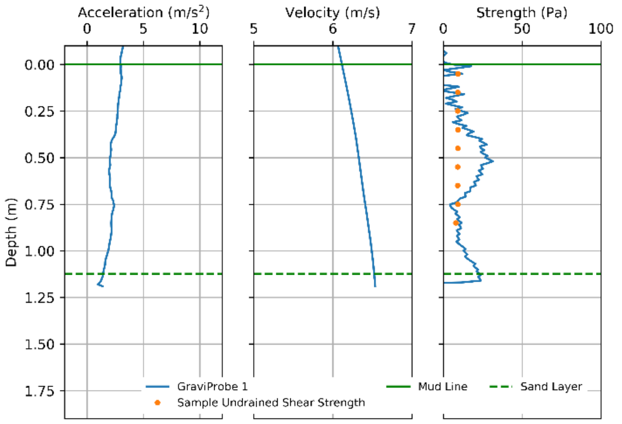

Figure 8. One free-fall attempt into the test container with mud from PoH, 112 cm mud layer thickness, initial average density of 1150 kg.m^{-3}; prior to the tests 24 hr resting time was given to mud.

The data is presented "as-is", i.e. no further processing was performed. In general, only by relying on default calibration, RheoTune exhibited a consistent and acceptable performance. Additionally, in most test cases, RheoTune correctly recognized the pattern of density and strength profiles. The reported strength values by RheoTune for the mud from the Port of Rotterdam was found to be accurate. Having said that, it is observed that, in case of mud from the Port of Hamburg, the strength outputted form RheoTune deviated from the measured $S_{u,ref}$.

For an initial density of 1250 kg.m-3, RheoTune estimates higher strength values for lower densities in deeper parts of the test container (depth larger than 0.8 m), see Figure 9 and 10. Although no direct measurements are available to validate RheoTune's performance at this depth range, it is generally expected to observe a decreasing strength with decreasing density. A bottom effect and/or clogging of the tuning fork might be an explanation for this. Such trend, however, is not observed for lower initial densities (e.g. density of 1150 kg.m-3 in Figure 11).

Based on the calibration procedure, the instrument could potentially perform better if it was calibrated for the mud form the Port of Hamburg prior to the tests. In this study, we intentionally did not calibrate the device to critically evaluate its performance only based on the default calibration database. It is also observed that, for mud from the Port of Rotterdam after 72 hr resting (Figure 10), the density values reported by RheoTune are slightly larger (50 to 100 kg/m3 higher) than the density values measured directly. No conclusion could be made on whether this discrepancy comes from DMA 35 or RheoTune. The upper limit of density in DMA35 is 1300 kg.m^{-3}.

It also appears that, under the employed test conditions, despite following the correct calibration procedure, the RheoTune had difficulties in giving correct depth. Clogging of the pressure sensor by sediment seems the obvious reason, as trials in pure water did not show this behavior. Overlay, it is observed that downward measurements by RheoTune were more accurate than the upward measurements especially when the deposit consists of denser material. In such cases, sediment can stick to or between the tines of the tuning fork and affect their performance, resulting in lower quality measurement data points.

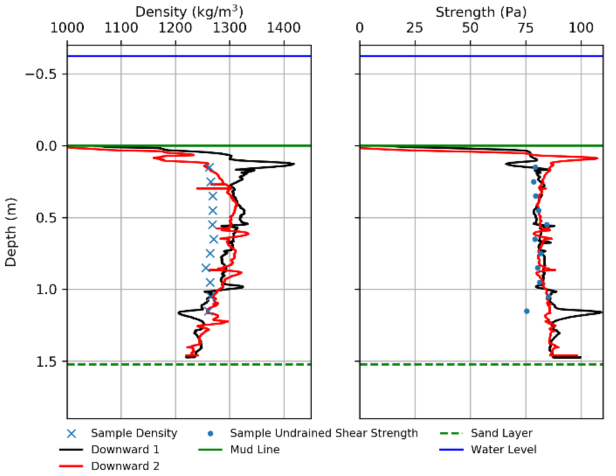

Figure 9. Two measurements (each contains data from downwards and upwards trajectory) into the test container with mud from PoR, with 152 cm mud layer thickness, an initial average density of 1250 kg.m^{-3}; prior to the tests 24 hr resting time was given to mud.

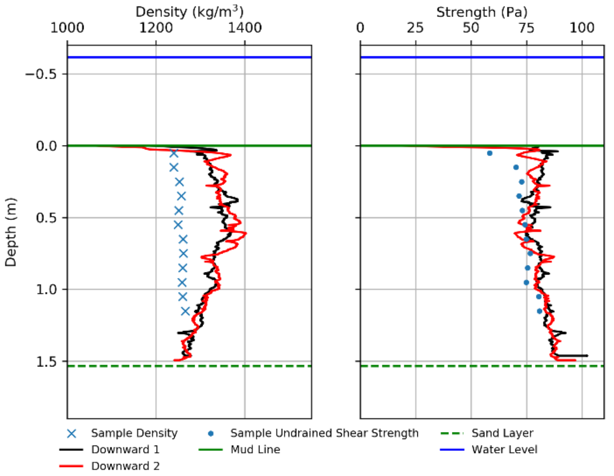

Figure 10. Two measurements (each contains data from downwards and upwards trajectory) into the test container with mud from PoR, 152 cm mud layer thickness, an initial average density of 1250 kg.m^{-3}; prior to the tests 72 hr resting time was given to mud.

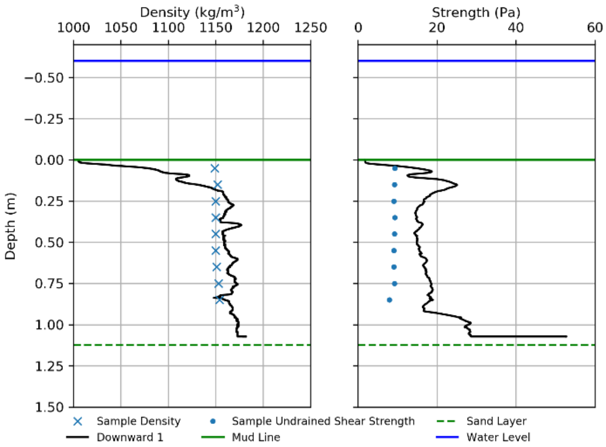

Figure 11. One measurement attempt into the test container with mud from the PoH, 112 cm mud layer thickness, an initial average density of 1150 kg.m^{-3}; prior to the tests 24 hr resting time was given to mud.

6 CONCLUSIONS

In the studied shear strength range of <0.1 kPa, GraviProbe 2.0 required a pre-study/quantification of material parameters to update the required model inputs in the postprocessing software. The post-processing software of GraviProbe 2.0 can potentially be improved by considering flow resistance, the effect of turbulence, and a more realistic assumption of density in its force balance equation. The latter is particularly important as it alters the estimated buoyancy force and hence deceleration of the instrument in the deposit. GraviProbe can potentially be used for shear strength measurement in soft mud deposits with larger shear strength up to 10 kPa (Bezuijen et al., 2018).

On RheoTune it is concluded that: RheoTune provides reasonably accurate density and strength profile measurement for the studied density (below 1300 kg.m^{-3}) and strength range (below 0.1 kPa). The accuracy of the instrument could have potentially increased, if it was calibrated for the sediment type under study prior to deployment of the instrument. In denser depots, the reported depth from RheoTune was affected by clogging of the pressure sensor at the tail of the instrument. In some of RheoTune official leaflets, it is indicated that the instrument measures Bingham yield stress. Generally, Bingham rheological modelling though applies to the material at its remolded state (see Figure 3). In this study, we found, otherwise, a correspondence between RheoTune's output and static undrained shear strength i.e. rheology of mud at its un-remolded state. To date, the tuning fork principle is not being used in RheoTune to measure linear rheology i.e. shear modulus and linear viscosity.

7 ACKNOWLEDGEMENTS

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