INNOVATIVE FREE FALL SEDIMENT PROFILER FOR PREPARING AND EVALUATING DREDGING WORKS AND DETERMINING THE NAUTICAL DEPTH

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Abstract: There is a continuous inflow of sediments in ports and access channels and therefore maintenance dredging is necessary. To determine when and how much there needs to be dredged the underwater sediment and mud layers must be monitored and analyzed. This paper presents an innovative vertical profiling technique measuring in a single free fall trajectory the depth, thickness, density and strength of underwater sediment layer. The instrument operates in free fall and impacts underwater sediment layers. During impact it measures penetration resistance and pressures.

The technique can be used in several aspects of the dredging process. In combination with acoustic methods like multibeam echo sounders it is used to visualize the sediment layers under a multibeam surface.

Another important aspect of soft sediment is the navigability. Ships can navigate through loose mud layers if the physical characteristics of the mud stay below a critical limit. Today the measured physical characteristic in many ports is density. Density was historically chosen as a substitute for strength. The proposed measurement technique allows visualization of a density and a strength profile and enables ports to evaluate alternative nautical depth criteria.

Keywords: Free Fall Penetrometer, Nautical Depth, Maintenance Dredging, Density, Rheology, Shear Strength, Cone Penetration Resistance

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1 FREE FALL PENETROMETER DESCRIPTION

A free fall penetrometer (Figure 1) accelerates under its own weight and penetrates the sediment. During penetration it analyses the underwater sediment layers. The instrument can penetrate fluid and consolidated mud layers for several meters. It has a weight of 7 to 10 kg and a terminal velocity of about 6,5m/s. The dimensions of the instrument are 0.9 m length and 0.05m diameter. The instrument measures the water depth with an accuracy of 0.05 m.

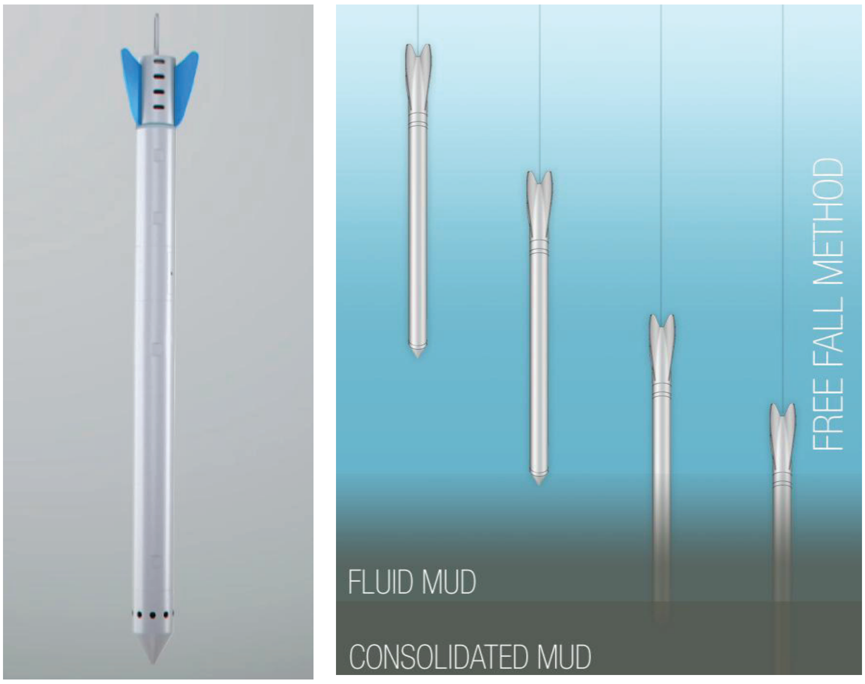

Figure 1. Free fall penetrometer

Today most of the European ports are characterizing loose of fluid mud layer via density measurements. Density is expressed in tons per cube [T/m³] and is compared with the density of water. An increased density level of mud against water is dependent on the content of mud building particles. Mud consists of inert particles like sand and silt and reactive particles like clay and organic material. Water is bounded with the reactive particles and in between the mud flocks water is enclosed. A density measurement of mud provides the bulk density of the building particles and water. In several European ports 1,2 T/m³ mud density depth level is used as criterion for determining the navigation level of ships through mud layers.

This criterion was originally derived from the assumed relationship between the density and the strength or resistance of mud. The rheology of mud is the plastic and elastic deformation under external forces. For a free fall penetrometer the external force is gravity. For a ship entering the mud layer the external force is the propulsion of the ship. When a tube like a free fall penetrometer is deforming mud, two types of resistance are occurring. First on the cone of the penetrometer the mud is pushed away and deformed. The energy E (expressed in Joule [J]) needed to push away a volume 'V' (expressed in cube [m³]) over a distance 'd' is called the cone penetration resistance or cone resistance expressed in [J/m³] or [Pa].
When the sleeve of the penetrometer is entering mud layers the friction of the mud along the sleeve is causing a resistant force. The resistant force expressed in Newton [N] divided over the surface 'A' of the sleeve expressed in square meter provides the shear strength. In Figure 2 the forces on the penetrometer are depicted.

Rheology and density evolve different in time and therefore a one on one relationship is not there.

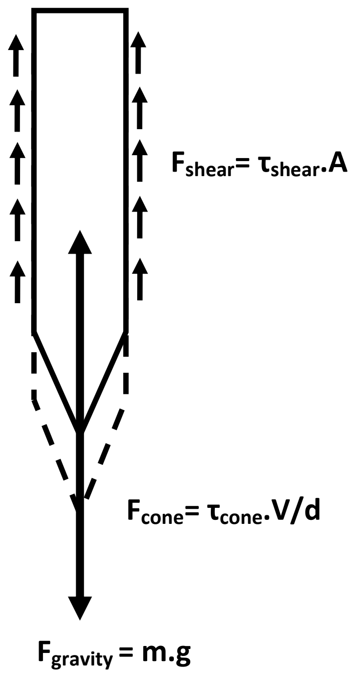

Figure 2. Forces on the penetrometer

Density and rheology of the sediment layers are measured by an independent set of sensors on board of the free fall penetrometer. Pressure sensors are used to determine the pore pressure in the soft sediment layers and derive the density, the requirement here is that the sediment is relatively fresh as such the pore pressure is equivalent to the sediment load. The data from on board accelerometers is used to derive speed and speed feeds a dynamic model. The model compensates for external force factors such as drag. The model is then used to normalize the measurements performed in the sediment. The outcome is a high accurate total cone penetration resistance and shear strength with an accuracy of 2% and several data points per centimetre of intruded material. Total cone penetration resistance is the total energy loss of the cone by displacing a unit volume of sediment. Shear strength are the energy losses distributed over the sleeve of the instrument per depth unit.

In a single drop the following characteristics can be provided. Figure 3 shows a drop characteristic of a port where the 1.2 ton/m^3 criterion is used to determine the nautical depth. Evaluating the undrained shear strength it becomes clear that this point is in a high resistant consolidated mud layer.

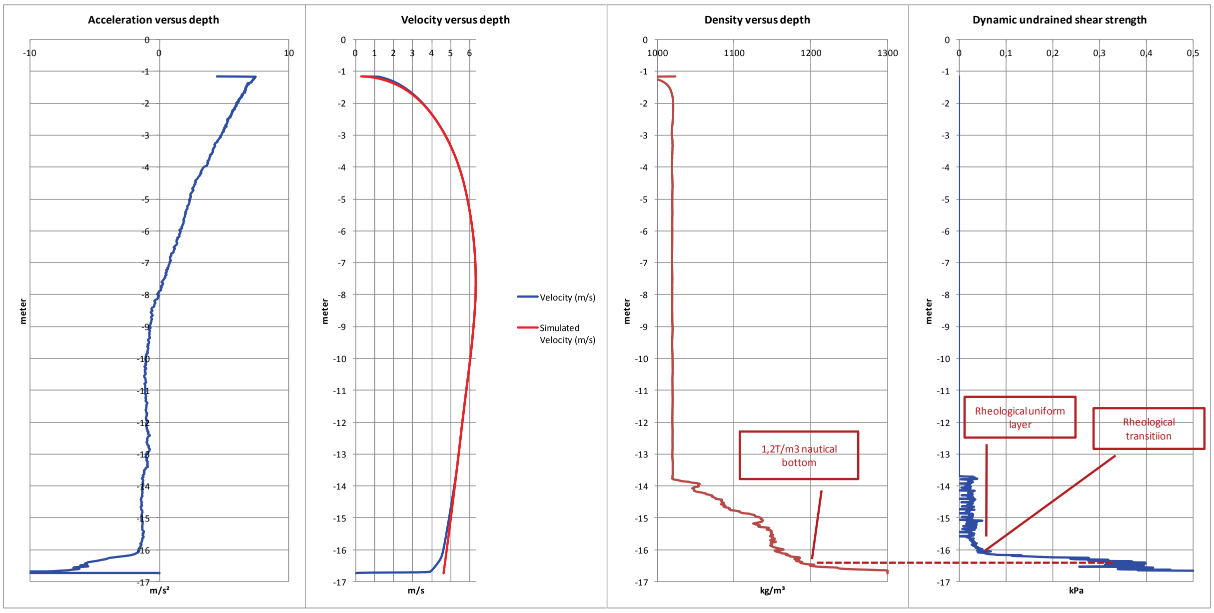

Figure 3. Density versus strength for one type of sediment

In another port (Figure 4) the same 1.2 ton/m³ criterion is used to determine the nautical depth. The undrained shear strength however is low at that specific level and does not change for another meter, indicating there is an opening for optimization.

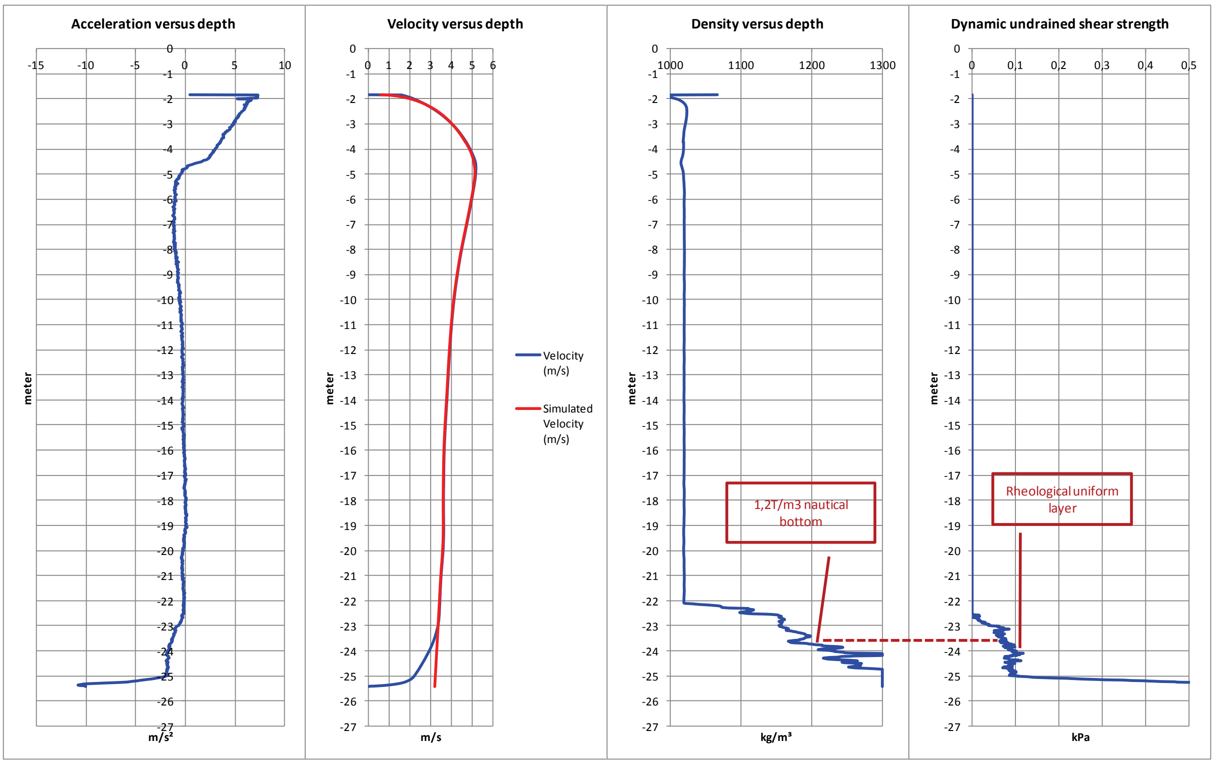

Figure 4. Density versus strength for another type of sediment

2 APPLICATION FIELDS

A free fall penetrometer can be applied to accurately determine the depth and thickness of underwater sediment layers. It provides additional information on the sediment structure and stratification under for example multibeam echosounder data.

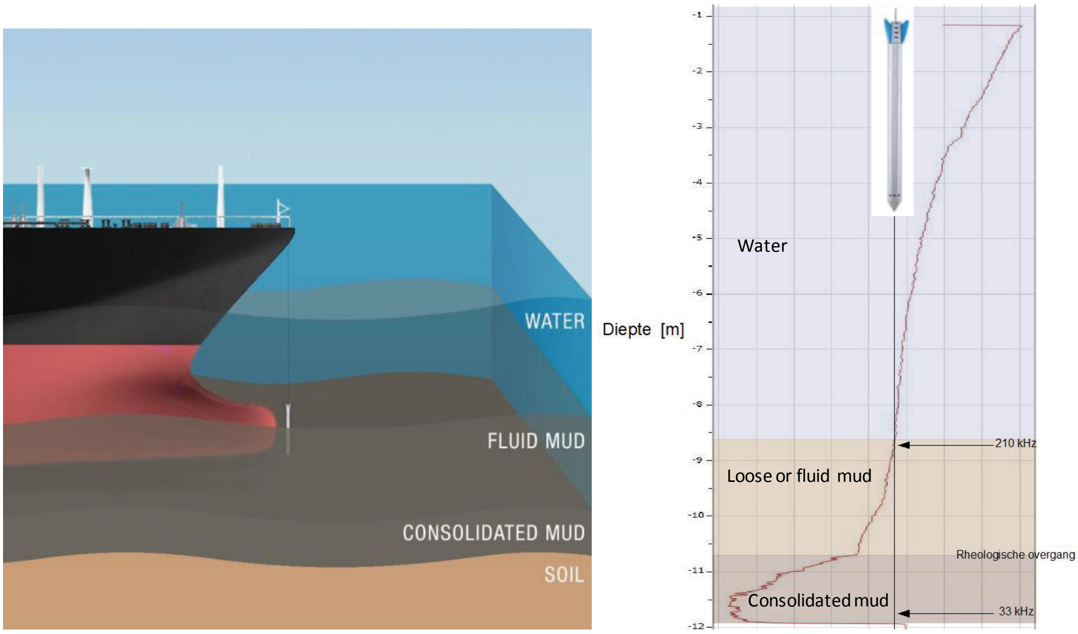

Figure 5. Complementary data for acoustics

In figure 5 a 210 kHz echosounder can determine the top of the sediment layer but a 33 kHz cannot determine the nautical bottom, a free fall penetrometer however delivers an entire strength or deceleration profile enabling correct assessment of the sediment.

There could be a close relationship between the behaviour of the free fall penetrometer in loose mud layers and the behaviour of a ship when navigating through mud. When navigating through mud there will be an influence zone on the bow of the ship related to mud displacement, under the hull friction will be dominant. A friction parameter can be derived from the shear stress. Under the assumption that the mud is isotropic, which means that the expected resistance is equal in every direction, the total cone penetration resistance on every position in the mud layer could be indicative for the energy needed to displace a volume of mud, while shear stress can be used to predict friction.

According to Abelev (2009), another crucial factor in predicting the interaction behaviour of an object with a mud layer is the speed of interaction. A free fall penetrometer has an average impact speed of 5 to 6 m/s in the first meters of the loose mud layer. Ships access a port with a speed of 5 to 6 knots which is a speed of 2.5 to 3 m/s. Due to the higher speed, the resistance predicted by a free fall penetrometer will likely exceed the actual resistance encountered by a ship.

3 NEW SEDIMENT INFLOW

A free fall penetrometer is being used regularly during surveys in the Beerkanaal at the Port of Rotterdam. An active sedimentation zone was selected to make a denser recording grid. The purpose is to evaluate new sediment layers in terms of density and strength evolution. Recently two multibeam charts with a month interval delivered a difference map revealing sediment accumulation (Figure 6). A maximum difference of 1,5m sediment growth has been observed, the majority of the sediment accumulation was 0.5 m to 1 m, where the 1 m accumulation could be explained as fill up of old dredging trenches.

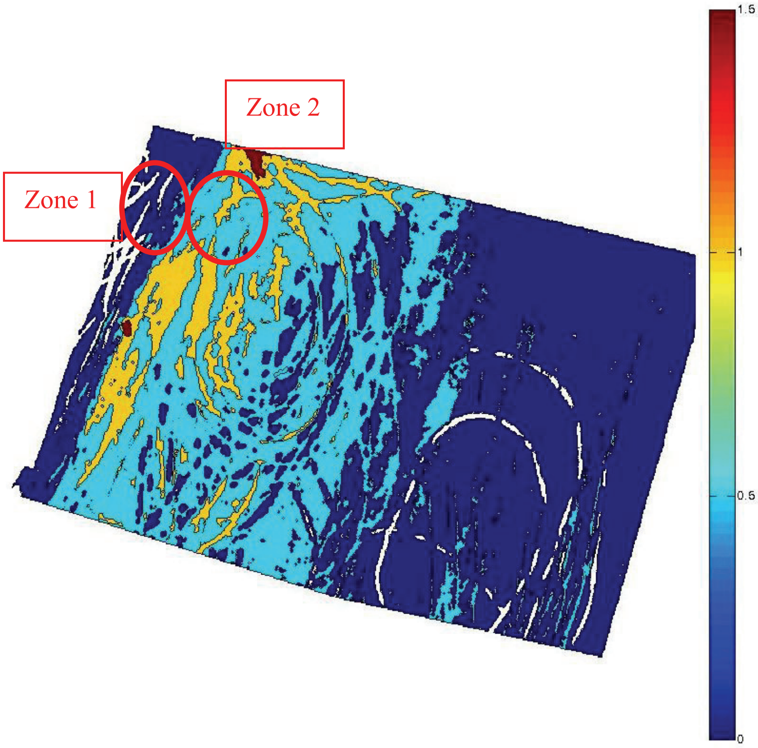

Figure 6. Difference multibeam chart

Two zones were investigated. In zone 1 on the inner west entrance of the Beerkanaal, no new sedimentation was deposited (dark blue). On the outer west entrance of the Beerkanaal, new sediment was deposited over a period of 6 weeks. The first measurement is called the T0 measurement, the second measurement after 6 weeks is called the T1 measurement.

The purpose was to investigate the relation between density and rheology of the new sediment layer on top of the existing mud layer and link them to simulations performed at a test facility (Staelens (2013)). The original mud layer was consolidated and was not dredged for a longer period. Strength profiles of the original mud layer display the following characteristics (Figure 7: blue graph).

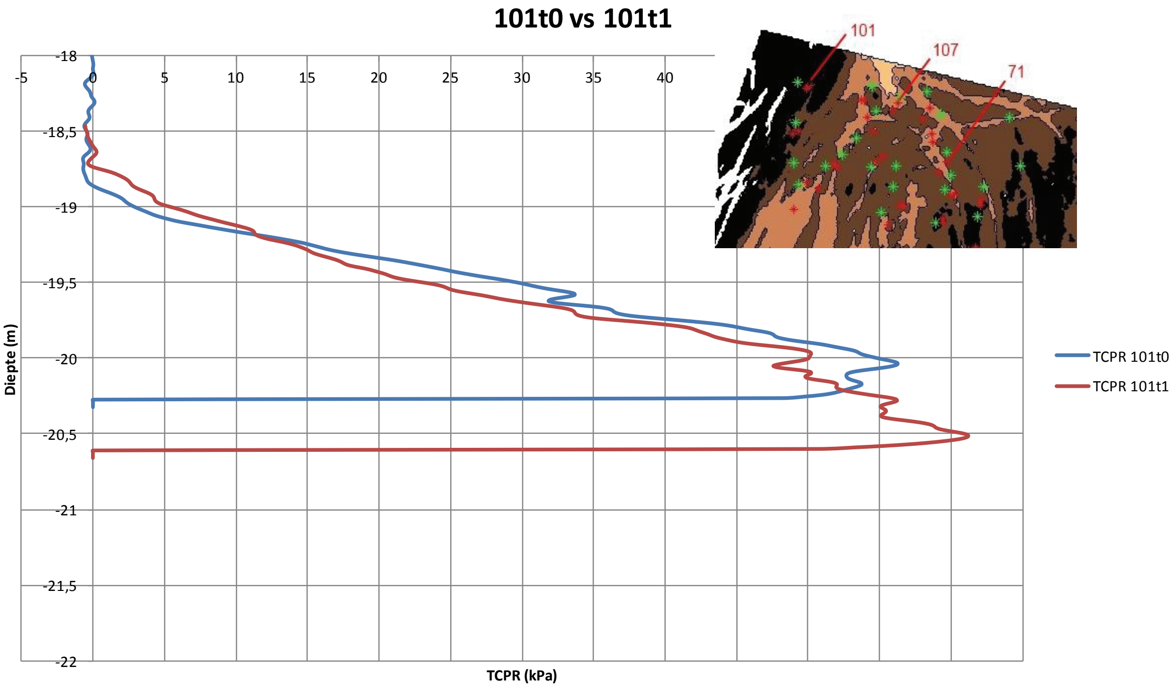

Figure 7. Two measurements on location 101 in zone 1

On Figure 7 two drops of the free fall penetrometer are depicted on location 101 in zone 1. One drop on T0 and one drop 6 weeks later on time T1. No significant difference is seen in total cone penetration resistance profile of the sediment layer. The top of the mud is on 18.7m depth.

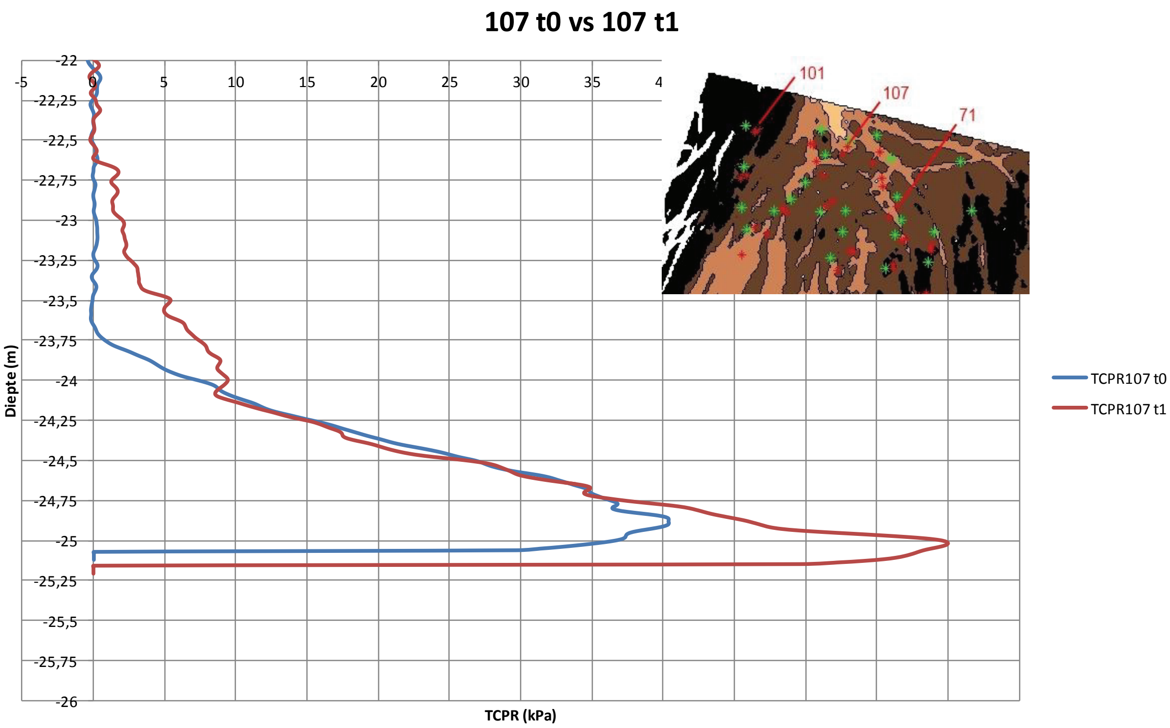

Figure 8. Two measurements on location 107 in zone 2

On Figure 8 two drops of the penetrometer on position 107 are depicted. For position 107 there is a difference of about one meter on the multibeam charts. A similar difference is seen an on strength profiles. At T0 the strength profile starts at 23,6m and at T1 the top of the mud is at 22,6m.

The total cone penetration resistance of the new mud layer is maximum 8kPa. The energy loss required for a total cone penetration of 8kPa is equivalent with a shear strength of 100Pa. 100Pa was suggested as a maximum yield strength of mud to be navigable in the PIANC (1997) report and in Wurpts R. (2005).

Based on these assumptions the new sedimented layer is still accessible for ships within the PIANC (1997) yield limit.

On the same positions the vertical beeker sampler was used to measure the density. A sample of the first meter was taken on position 107 where fresh sedimentation was measured. The sampler shows a uniform density from top mud to almost 1 meter below top mud (Figure 9).

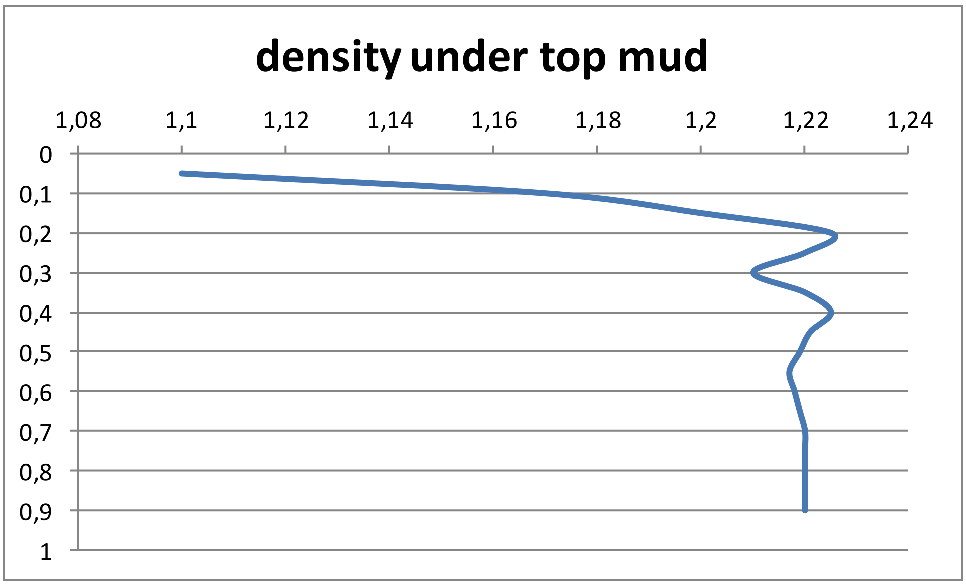

Figure 9. density profile new sediment

Based on a full scale simulation performed in a test facility on this mud, this density indicates that the deposition of this sediment happened less than 20 days ago (Figure 10, adapted from Staelens (2013)).

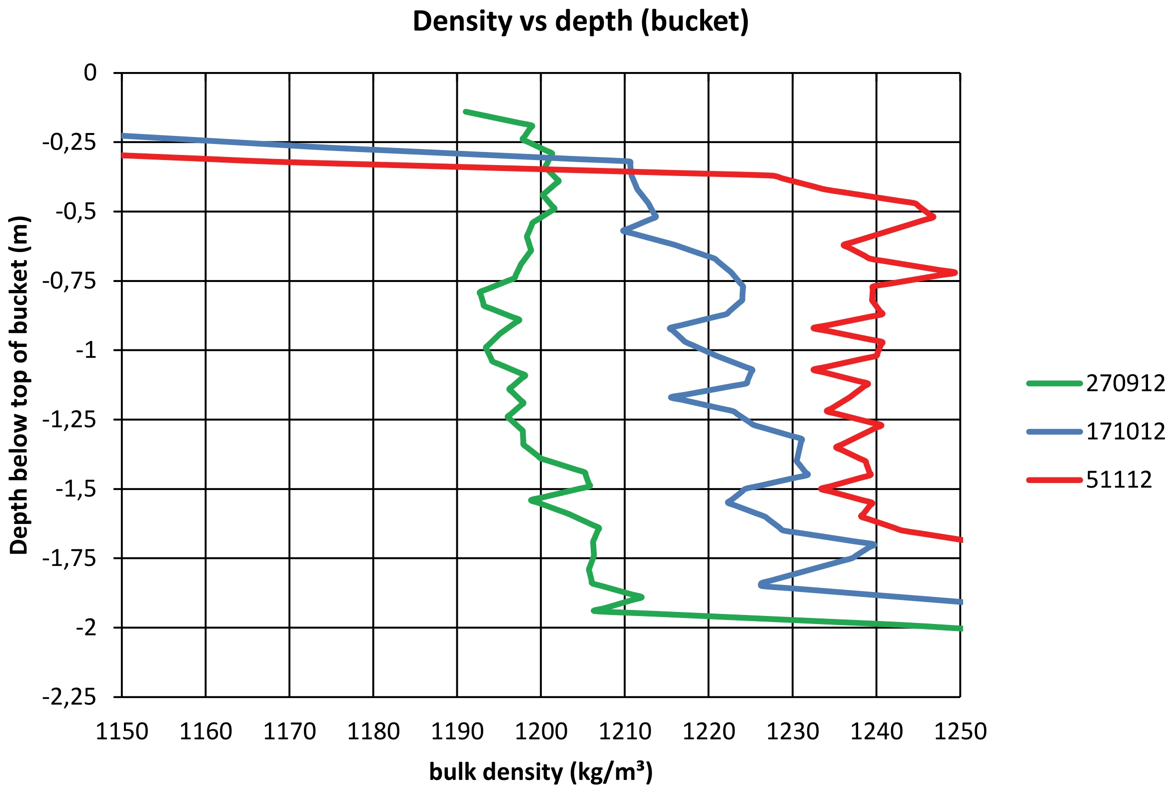

Figure 10. Density-time evolution in function of depth of the suspended Rotterdam mud below the water level in the bucket, the 0 value correlates with -17.75 m water depth in the test facility.

4 EXTRAPOLATION OF PENETROMETER TESTS

In the zone of interest, 24 free fall penetrometer measurements were taken. The results of these measurements were interpolated over the complete zone taking into account only the T1 multibeam map. Cross sections through the 3D generated strength volume were taken (Figure 11).

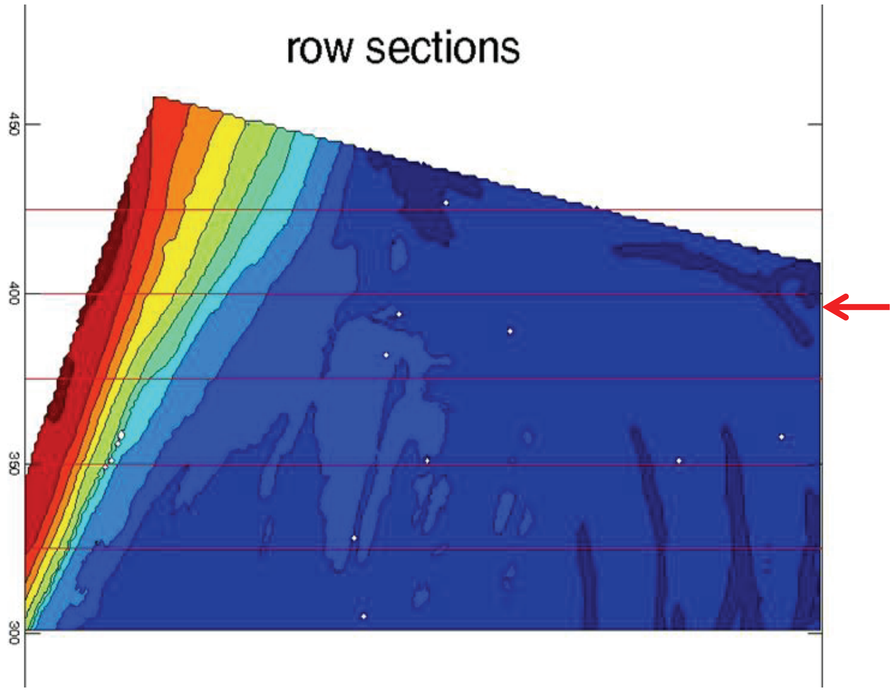

Figure 11. Row 400 cross section

In Figure 11 an overview of the sampled zone is depicted. A cross section on row 400 was taken. In Figure 12 cross section is shown. There are two magenta lines which are the multibeam levels at T0 and T1. The difference is the freshly deposited sediment. The strength of the sediment layers along the cross section remains largely below 8kPa cone penetration resistance or 100Pa shear strength.

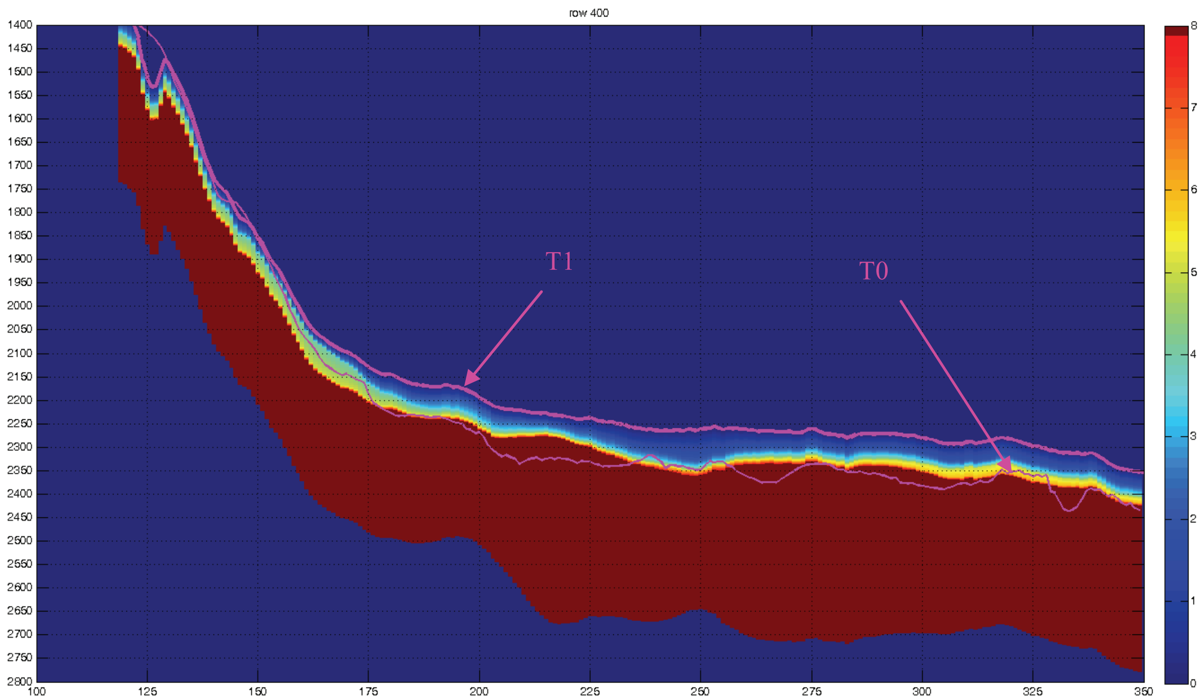

Figure 12. Interpolation of penetrometer strength profiles, the colour scale represents cone penetration resistance (kPa), all cone penetration resistances above 8 kPa are marked red.

5 DREDGING PLANNING AND EFFICIENCY

The Port of Rotterdam is currently using a density criterion to initiate, control and evaluate dredging works. The target depth is 23.65m. When the bulk density of the sediment above the target depth exceeds 1.2 t/m³, the sediment needs to be dredged. In the above described situation the fresh sediment layer fulfils the dredging condition. In this case, the top of the sediment is above 23.65m and the average density of the layer is 1.22 t/m³. From a strength perspective, the sediment layer is very loose and the shear strength has not yet reached the PIANC (1997) level of 100Pa.

Consolidation experiments covered in Staelens (2013) demonstrated that density during the first phase of consolidation evolves much faster than strength. Strength evolution of sediment appears to be driven by a combination of drainage of the sediment and the sediment load, while density evolution requires only drainage. Since most of the fresh sediment layer is between 0.5 m and 1 m thick, the load on the sediment in this specific case is relatively low. As a result the strength evolution is slow. This phenomenon has also been observed in the test facility; the observations done in the test facility appear to match with the field observations and enable accurate predictions of both strength and density evolutions.

The difference in variation between density and strength over time offers an opportunity to optimise dredging works. The cost of mobilisation and the fast response of dredgers can probably be reduced by following up the sediment strength parameters instead of a density parameter. Sediment strength can also be manipulated to further extend the reaction time and flatten out virtually any peak in the production.

During the first month after deposition, the loose sediment layer will gain strength and will predominantly consolidate under its own weight and the weight of new sedimentation. A possible optimisation in dredging effort might be possible by dredging the consolidated layers and leaving the fluid mud layers untouched or by keeping them loose.

6 CONCLUSION

A free fall penetrometer allows deep intrusion of sediment layers and provides accurate insight on sediment strength and stratigraphy. Time series of free fall penetrometer tests provide information on the rheological evolution of the sediment. In situ testing allows measurements without disturbing the sediment by for example sampling, allowing better measurements. Furthermore the free fall penetrometer intrudes the sediment with a speed in the upper speed range of ships. Therefore the expected resistances will be in line or higher than what ships might experience when navigating through mud. Ignoring the over estimation of the measured parameters, an optimization would still be achieved by using strength parameters for the nautical depth definition.

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