Rheology as a Survey Tool

“We Are Not There Yet”

To reduce the dredging cost many harbour authorities and governmental bodies are seeking for a more suitable and a rheology-related survey tool. The in situ instruments available on the market are based on mechanical, acoustical, optical or radioactive measuring principles. But before one will be able to map the real nautical bottom, we need to understand the influence of the mud properties (micro scale) on a vessel (macro scale). This article gives an overview of the general reaction forces of the mud which definitely play an important role in the vessel behaviour when sailing into it. Without naming any commercial devices, this article explains the intrinsic difficulties related to the different measurement principles. But we are not there yet! Even if all these methods could be translated and absolutely or relatively related to the mud rheology, when compared with the laboratory rheograms, we still need to distinguish the most important nautical-related parameter and relate the magnitude of it to the influence on the vessel. Major research is required to make up internationally accepted laboratory protocols and the relating in situ measuring protocols. Meanwhile, surveys will have to be carried out with the conventional density based instruments.

HOW A VESSEL ‘FEELS’ THE MUD

is based on the reaction forces exerted on the vessel when sailing into or above the mud. To relate the sediment and complex sediment properties to the navigational problems when the bottom in navigation areas is covered with mud is just one of many unsolved problems, in addition to the complex hydrodynamics issues arising when sailing into the water column.

Before one can understand the influence of the mud properties on a vessel (macro scale) we need to focus on the behaviour of the mud itself (micro scale). Distilling the most important navigation-related (rheological) parameters out of a mix of mud properties is already a challenging task.

**Behaviour of Mud**

Without going into the rheological details, one can distinguish reaction forces which definitely play an important role in the vessel behaviour when sailing through a mud layer:

- Density differences influencing the buoyancy of the vessel and the generation of internal waves at the mud-water interface
- Stickiness, triggered by the interaction between the dispersive adhesion properties of mud and the roughness of the vessel surface (frictional resistance)
- Bearing capacity (effective stress)
- Deformation of the mud, due to the contact with the vessel (pressure resistance).

Due to induced influence triggered by hydrodynamic activity (internal wave), a vessel can also get in contact with the mud when sailing above it.

Deformation of the mud is influenced by its rheological parameters and the...
shape parameters of the deformation body. Depending on the composition of the mud, the rheology of the mud is based on its thixotropic behaviour. This means that the dynamic viscosity is deformation and time dependent. The prehistory of mud manipulations influences the future mud behaviour (disturbance of the mud by passing vessels / dredging activities (even without relocation)).

Even if one were successful in modelling all significant relations between the properties and the vessel, measuring mud properties in situ is another challenge. The in situ instruments available on the market are based on mechanical, acoustical, optical or radioactive measuring principles. Because all in situ devices are derived from laboratory setups, the same principles are used to calibrate these field surveys by performing controlled laboratory tests on sampled mud. Often, large errors are already induced when obtaining lateral and vertical referenced in situ mud samples. Many attempts have already been made to compare the latter in the field (at cm resolution) with simultaneous profiled devices, but this resulted in limited useful data.

Therefore, the Flemish Government (Flanders Hydraulics Research, funded by Maritime Access) constructed a Sediment Test Tank (STT) to execute controlled comparison measurements. The STT is filled with Zeebrugge (Belgium) mud and different artificially created rheological transitions were measured. With these rheological transitions we do not aim to create the real nautical bottom level, but aim to simulate measurable vertical rheological variations in the mud.

Linking the measured data of the different devices to the rheograms obtained from laboratory analyses of the STT samples has been done successfully. This does not mean that the data can be transparently related or clearly associated with each other. These anomalies are based on the difficulty to relate different measurement principles and protocols to the analyses executed in the laboratory. The complexity of the relations is triggered by the differences in physical methods used and the difficult and complex thixotropic behaviour of the mud. Also the prehistory (see above) of the mud will be important in interpreting the measurements.

Without mentioning any commercial devices, this paper explains the intrinsic difficulties related to the different measurement principles. The discussion of preferring towed bodies to vertical profiling devices is not discussed in depth in this paper.

**Destructive Contact Methods**

The mechanical based instruments are all destructive contact methods, meaning they need to disturb the mud during measurements: 'feeling.
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the mud'. We can distinguish different types of mechanical interaction with the mud: vibration, towing, rotation, and deceleration.

A tuning fork is based on the vibration of a body in close contact with the mud. The force needed to maintain the applied vibration at a chosen frequency (read shear rate), when the surface of the sensor is profiled in the mud, is a measure for the shear stress of the sediment. It gives us real-time shear stress related information for a certain chosen deformation (vibration) during profiling. It does not give us information for different applied deformations, which could be important when taking the thixotropy of the mud into consideration. The restriction of the method is bound to a good calibration as one needs to seek the correct position on the shear stress-shear rate rheogram. This only makes sense when steady state conditions are present. These systems are also used in slurry pipes in the industry and give good results for density when properly calibrated.

Towing to aim a 'viscous drag' of a body on a nautical related depth level is another contact method. The behaviour of the towed body is caused by similar reaction forces (density difference, stickiness, deformation of the mud) as mentioned above for a vessel when sailing into the mud. At first sight this method is the closest to what a vessel could experience. On the other hand, controlling and relating the forces on the body, together with the recalculation of shape parameters and rescaling the data needed to relate the behaviour of the towed body with a vessel, is a very difficult task. If the body stays on a depth level for a chosen towing speed frame, it cannot be concluded directly that this level is the nautical bottom related level. For example, it is plausible that the buoyancy, caused by the difference in density between the towed device and the mud, keeps the device at a certain level. In addition, the grain skeleton of the mud has a bearing capacity (compared with effective stress, which increases with depth). Hence, the weight per unit area of the towed object can be carried at a certain depth where it is in equilibrium with effective stress, even in a homogeneous layer (Prof. Toorman).

Also cutting into the mud, because a sharp shape will result in different depth levels than a dull shaped instrument. The shape parameters of the towed body together with the applied towing speed result in the applied deformation (read shear rate). For the vessel, different applied deformations will result in different behaviour of the mud. As mentioned earlier, it is important to map the deformation dependent dynamic viscosity of the mud (thixotropy) to predict the vessel behaviour and it can therefore not directly be related to a towed random body. But a carefully designed body with smooth surface and chosen density could, theoretically, be successfully used. Still one needs to consider that using such a device can only give us a depth level but no information of the above or under laying mud layers. This leads us to the discussion concerning towing or vertical profiling, see further.

The use of a rheometer type of instrument which collects the data by rotating a chosen rod into the mud is the closest to the laboratory reference instruments. Ideally a shear stress or shear rate controlled device should be available which can cover a whole

Mechanical interaction with the mud include vibration, towing, rotation, and deceleration
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With the new generation of accelerometers and velocimeters, a fourth mechanical measuring method is based on the deceleration of a free falling body. Similar surveys, using a free-fall cone penetrometer (FF-CPT), are widely executed for mapping geotechnical information of underwater soils in deep-sea trenching, cable burial activities, etc. All possible interactions with mud during free fall penetration are based on the same reaction forces as described for a towed body. An important difference is that the device records, almost continuously, acceleration and deceleration information. Integration of the obtained data gives us speed information of the moving device. With the new generation of acceleration sensors, a very accurate image of the applied forces and the reaction forces of the mud can be mapped. Still, we cannot yet distinguish the differences between forces caused by density-difference, stickiness or rheology. But also here, a carefully designed body with smooth surface (or surface with a known influence on stickiness), chosen density and size (weight to be able to penetrate deep enough) could, theoretically, be successfully used. Unlike with a towed body, information can be obtained for the entire mud column. Together, when using a rapid retrieving free fall winch, one can vertically and laterally quickly cover a large area.

Apart from these methods, experiments are being executed to evaluate/visualise the flow in profiling tubes by measuring pressure differences. These flows can be directly related to the viscosity of the mud.

The results of all the above destructive methods are influenced by the thixotropy of the sediment. If one keeps their method to a chosen deformation or applied force (= only one point on the rheogram), no information will be present on the real behaviour of the mud. Because different moving or mechanical parts of the vessel will cause different dynamic viscosities, the result of a chosen applied deformation/force will only result in restricted information.

Further Research Required

When applying other measurement principles, not directly related to the mechanical properties, the translation into rheological properties requires an intermediate step. It is not always clear and/or proven that the applied methods can obtain sufficient information on the rheology of the mud. Optical, radioactive and acoustical methods are mainly based on the density properties of the mud. Still, in combination with the registration of the speed of sound, pressure differences on point-samples or small volumes, one could obtain rheological (or rather 'structural') information.

Because there is a missing direct link, these methods lead to an extra translation difficulty and are an extra source of discussion.

Even if all these methods could be translated and absolutely or relatively related to the mud rheology, when compared with the laboratory rheograms, we still need to distinguish the most important nautical-related parameter and relate the magnitude of it to the influence on the vessel. Major additional research is needed to make up internationally accepted laboratory protocols and the relating in situ measuring protocols. We are not there yet, but we want to tackle this huge challenge. In the meantime, we will continue to survey with the conventional density based instruments. The tests in the STT have proven that other density-related devices, other than the radioactive devices, are perfectly usable in the field. For the moment we need to stick to the density defined nautical bottom levels, as long as a safe keel clearance is taken into account. However, the many discussions on the applicability of density sensors triggered an international joint co-operation between different harbour authorities and governmental bodies (Rijkswaterstaat, Port of Rotterdam, Emden Harbour, Flemish Government). A comprehensive series of density based tests on different mud conditions in the STT has been performed.

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