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Navigable waterdepth in waterways with muddy water bottoms

Parameters, models and measurement techniques

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Summary

The navigable water depth in waterways with muddy water bottoms is a complex concept. Although it seems easy to define with e.g. a density of 1.2 kg/L, this parameter is not the only one to determine the level of navigability and manoeuvrability of ships. In this report, an overview is given of the parameters that are relevant for mud. The most important parameters related to the mud are density and viscosity. Because of the transient behaviour of fluid mud, the time dependency is important. For the navigability and manoeuvrability of the ship, mud thickness and flow parameters are important.

Next, available techniques to measure in situ or in a laboratory some of the relevant parameters are described. It is clear from the overview that no perfect instrument exists for the determination of relevant parameters for fluid mud. Limitations are linked to the spatial distribution of data, which is often point measurements, whereas surface or 3D coverage is needed.

An innovative idea is presented: to use internal waves generated by the passage of ships. The behaviour of this internal wave is related to the fluid mud properties. To establish a proof of concept for this idea, both measurements and models are required. In this report, an investigation is made of models that might be suitable for this task, notwithstanding some modifications.

The final chapter presents a list of knowledge gaps. The list is by no means complete. Also, in various institutes and market consortia, research is done to fill some of these gaps.

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Contents

1 Introduction

RWS is looking for new ways to determine the nautical depth and the thickness of soft mud layers in the areas of their responsibility in the Netherlands, i.e. the Maasgeul (entrance of Port of Rotterdam) and IJmond (entrance to harbour of IJmuiden).

The general definition of nautical depth is given by PIANC (1997):

> *The level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability.*

For the Dutch harbours and waterways, the nautical depth is defined as the level at which the mud reaches a density of 1.20 kg/L. For other harbours, the threshold density typically varies between 1.15 to 1.35 kg/L (Table 1.1, McAnally et al., 2007). Traditionally, RWS uses point measurements with radioactive probes to determine the vertical density profiles of the water, fluid mud and consolidated mud. From that, they derive a map of mud thickness, defined as the difference in depth between the 1.05 and 1.20 kg/L density levels.

The composition of the mud, however, determines the properties such as viscosity. For a set density of 1.2 kg/L, the possibilities to sail through this mud might be different, even depending on the season. For example, according to maintenance dredgers, a density of 1.2 kg/L in winter represents critical conditions in IJmuiden (the Netherlands). The same density of 1.2 kg/L in the Maasmond (Rotterdam, the Netherlands) does not pose navigation problems.

Table 1.1 Density criteria for navigable depth (from McAnally et al., 2007).

Country	**Port**	**Density kg m^{-3}**
The Netherlands	Rotterdam	1.2
Thailand	Bangkok	1.2
Surinam	Paramaribo	1.23
Belgium	Zeebrugge	1.151-1.347
China	Yangtze	1.25
China	Liang Yungang	1.25-1.30
China	Yianjing Xingang	1.2-1.3
UK	Avinmouth	1.2
France	Dunkirk	1.2
France	Bordeaux	1.2
France	Nantes-Saint Nazaire	1.2

Within the CIP SMIT program[1] of RWS "New measurement techniques for depths of waterways" (translation of "Nieuwe meettechnieken vaargeuldiepten"), Deltares performed a number of studies:

A. Stakeholder consultation in an informal workshop: "Kenniscafé Onderhoud bevaarbaarheid (zee-)havens", held on September 30th 2011. Among the ca. 50 attendees were representatives from RWS, harbours, dredging companies, research

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[1] *CIP SMIT = Corporate Innovation Programme of RWS, cluster SMIT = Slim Inwinnen Meten en Testen (Smart collecting measuring and testing)*

institutes, pilots, consultants, PIANC and ship brokers. The general conclusion was that the stakeholders all feel that the water depth can be defined in a better way than the usual density level of 1.2 kg/L. To reach a better definition and measurement methods, all parties have to cooperate.

B. Web based inquiry among a larger group of stakeholders, May-June 2012. The results are described in a report (Kruiver, 2012), which is summarised in §2.1.

C. Investigation of relevant parameters and available models and measurement techniques for the determination of the navigable water depth. The results are described in chapters 4 and 5 of this report.

D. Interviews with selected stakeholders. The results are incorporated in the relevant sections of this report.

E. Identification of knowledge gaps and indication directions for innovation. In chapter 6 of this report, some general remarks are summarised. The full identification of knowledge gaps need to be determined in collaboration with experts in the field of geophysical measurements, mud behaviour, numerical modelling and ship behaviour.

2 Stakeholder analysis

2.1 Summary questionnaire

During the spring of 2012, a web based questionnaire was issued. More than a hundred stakeholders were asked to participate. The goals of the questionnaire were:

1. Determine a better definition of navigability for waterways with soft water bottoms.
2. To facilitate the possibility for ventilating views on this topic by all stakeholders.
3. To assess the possibilities for improvements.
4. To assess the need for improvements.

The results of the questionnaire are summarised below (Kruiver et al., 2012):

- **Response:** 105 people were asked to fill out the inquiry. 65 inquiries were started, 50 were completed.
- **Need:** 86% of the respondents indicate that a better measurement method for the determination of the navigable water depth is needed.
- **Definition navigability:** A large part of the respondents prefer a functional description, based on PIANC's definition. However, to cope with muddy water issues, an operational or technical definition is desired.
- **Operational definition of navigable water depth:** This definition should be based on more than one parameter (currently density). However, the relationship between measurable parameters of mud and navigation and manoeuvrability of ships is not entirely clear.
- **Measurement techniques:** Various organisations use a combination of single-beam and multi-beam measurements with a variety of other techniques.
- **Expected impacts of improvements:** E.g. improved reliability of navigable water depth, other types of contracts, dredging strategies. The impacts on frequency of dredging activities, the amount of dredged material and manoeuvrability are still unclear.

In the following sections, the questions regarding parameters and techniques are described.

2.2 Parameters in questionnaire

Respondents were asked which of the parameters should be measured to determine the water depth of waterways with soft water bottoms. More than one answer could be selected. The predefined list to choose from was:

- Density
- Viscosity
- Elasticity
- Flow
- Yield stress
- Thickness of fluid mud
- Time-dependent behaviour (strength/recovery after deformation)
- Degree of consolidation
- Vertical gradients
- Other (specify).

The majority indicated that density, viscosity and the thickness of the mud are the most important parameters (Figure 2.1). The other parameters that were mentioned were shear stress, percentage of clay or grain size curves, Atterberg limits, temperature, biological parameter, thixotropy, rheological boundary and internal waves.

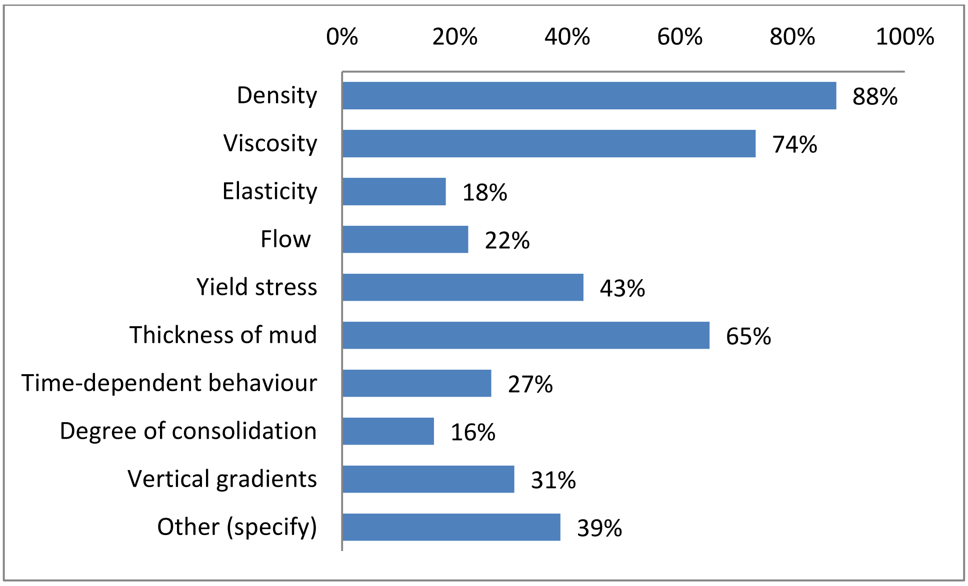

Figure 2.1 Relevant parameters for the detection of the navigable water depth, from questionnaire.

2.3 Techniques in questionnaire

Respondents were asked what techniques they use for the determination of the navigable water depth. This was an open question, techniques were provided by the respondents. In analysis, the techniques were classed (Figure 2.2). Several respondents do not perform measurements, but rely on data provided by other parties. Commonly, single-beam or multi-beam echosounder measurements are combined with other techniques, such as point measurements of the density with various probes.

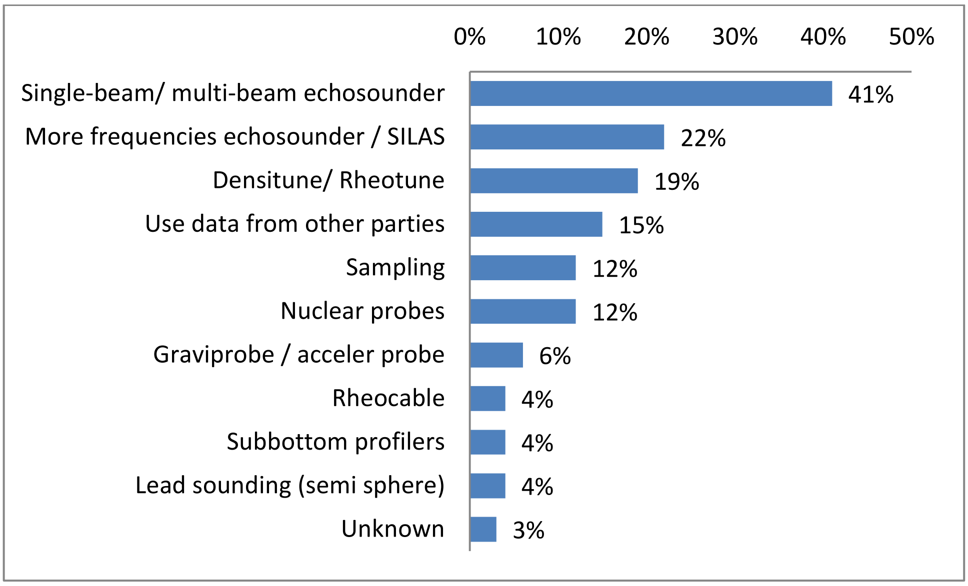

Figure 2.2 Current measurement techniques for the detection on the navigable water depth, from questionnaire.

3 Assessment of relevant parameters

3.1 Theory

The parameters that are related to the navigable water depth in waterways with muddy water bottoms can be classified into different categories:

A. Parameters related to the mud. Among these are the rheological parameters (see box).
B. Hydro dynamical parameters related to flow
C. Parameters related to the ship

The parameters related to the mud (group A) are the basic fluid/ mud material parameters:

- density ρ
- thickness of the mud layer
- viscosity μ/ thixotropy
- elasticity
- yield stress

The hydrodynamic parameters (group B) are:

- flow parameters, such pressure, flow velocities of the medium (water and fluid mud)
- vertical gradients of flow velocity

The parameters related to the ship (group C) are:

- the depth proportion of ship side in “water” and in “mud”
- ship dimensions and scale
- ship navigation properties (e.g. manoeuvrability, propulsion characteristics)
- ship speed

Information box: Rheology

Rheology is the study of the flow of matter, primarily in the liquid state, but also as 'soft solids' or solids under conditions in which they respond with plastic flow rather than deforming elastically in response to an applied force. It applies to substances which have a complex microstructure, such as muds and sludges. The rheological parameters are related to stress and strain. They are mean fluid velocity (v_s), dynamic fluid viscosity (μ), kinematic fluid viscosity (v) and fluid density (ρ).
Source: Wikipedia

In essence the parameters under group A and B are all related to (or partially govern) the dynamics of a large rigid body moving in a fluid of variable constitution. In that sense, they also heavily interact with the parameters of group C. For a given geometry and hydro-dynamical setting, the parameters do not govern the dynamics independently. Moreover, the interdependencies and influences are predominantly non-linear. Therefore, a clean-cut independent relation of each parameter towards the navigability will only be partial valid.

Nevertheless, to fathom the intrinsic relation to the navigation dynamics the principal influence of the parameters are stated below.

For the basic fluid / mud material parameters:

- Density: The primary “independent” interaction of density is the force (pressure) that is exerted on the ship in a static sense. Higher densities result in larger forces which are unevenly distributed on the wall and the bottom of the ship. As such, they define the ship's equilibrium during manoeuvring. For a moving ship, there is equilibrium between the propulsion, thrusters, rudder, pressure and friction on the skin.

- Thickness of the mud layer: The density and the thickness of the mud layer govern draught and mass displacement of the ship. Especially, the ratio of the mud layer thickness that is sailed through and the draught of the ship determine the manoeuvrability of the ship. Consequently, this parameter is of paramount importance to the navigability.

- Viscosity / thixotropy: When a velocity gradient is present, the viscosity contributes to the ship's equilibrium. In navigation, there are always velocity gradients, making viscosity of equal importance as density and thickness of the mud layer.
  In a situation where the mud exhibits thixotropic or shear thinning behaviour, the viscosity drops in value due to remoulding of the mud. After disturbance, the viscosity can recover to its original value within hours.

- Elasticity: This parameter is of minor to no importance, because the dynamic processes will always involve plastic deformations that are far larger than the elastic range.

- Yield stress: For stresses below the yield stress, the mud seems to be a solid material. This means that when the ship's impulse is too low to overcome the yield stress, it is stuck. For stress equal to the yield stress, the mud yields. For stresses larger than the yield stress, stresses in the mud are related to the strain rate. In this case the ship moves through a viscous fluid. Therefore, the importance of the yield stress for navigability depends on the viscosity characteristic. With a steep gain of viscosity with strain, the yield stress has a minor role and viscosity is dealt with by the apparent viscosity.

Several other factors related to the mud itself influence the properties of the mud:

- The *mineral composition* in mud defines the relation between the density and viscosity. Active clay minerals (e.g. Montmorillonite: μ = 10 Pa·s at ρ = 1.15 kg/dm^3) yield higher viscosity with density than inert minerals (e.g. Kaolin μ = 10 Pa·s at ρ = 1.35 kg/dm^3). With this parameter, a more site specific approach is possible.
- The *biological activity* can alter the viscosity of the mud, by formation of microbiological slime.
- Temporal parameters incorporating *time variability* of all mud parameters:
  - Time-dependent behaviour, such as strength/recovery after deformation. The time factor is of large importance. Density, viscosity and yield stress can and will change in time. The amount of change depends on the other parameters like flow parameters (amount of strain, turbulence), mineralogical composition, frequency of remoulding, time scale and aging of the mud.
  - Consolidation: During the process of consolidation, the dynamical properties of the mud will deteriorate very quickly. This means that the viscosity, yield stress and density increase, resulting in stiffer mud. Therefore, the degree of consolidation is of importance. At the start of the consolidation process, the mud might be navigable. When consolidation is complete, it is no longer possible to navigate through the mud. Commonly, consolidation of mud occurs in the order of weeks.

Hydrodynamic and spatial parameters:

- Flow parameters: all macro kinematic effects on the ship and the sediment, including pressures, flow velocities and directions within the medium, vertical gradients, transverse and undercurrents and salt wedges, both in the water layer and in the fluid mud layer. These flow parameters are of great importance. Like the density and the viscosity, they exert dynamical forces (kinematic pressures) on the ship.

- Vertical gradients: vertical gradients are of equal importance, because they define the variation of the pressures and thus the total equilibrium of the ship. An example of a vertical gradient is water flow over a static water bottom.

3.2 Parameters in interviews with selected stakeholders

During in-depth interviews with selected stakeholders, they indicate that all of the parameters mentioned in section 3.1 are important in relation to mud.

Additional remarks are summarised below:

- Viscosity is the parameter that everybody wants to measure, because they believe that viscosity is the most important parameter determining navigable water depth. The viscosity should be measured in situ.
- Although less directly related to navigable depth compared to viscosity, the density provides a reasonable approximation for the navigable depth, and is relatively easy to measure. Therefore, until mew methods are available, density remains the most important one to measure.
- Temperature is a relevant parameter. A change in temperature often signals a change in mud thickness.
- Elasticity: an observation is that the 1.2 kg/L level lies deeper when a thick mud layer is present. After dredging, the level moves up. This might be related to elastic behaviour.
- For the manoeuvrability of the ship, information on the flow parameters from the hard water bottom to the water level is relevant.
- Time dependent behaviour is interesting when related to Water Injection Dredging. From the time dependent behaviour, the efficiency of the dredging technique can be assessed.

3.3 Conclusions parameters

The dynamics of a ship's hull, its rudder, its propulsion and thrusters are influenced by parameters related to the media the ship moves through, partly water and partly viscous mud. The most important parameters are density and viscosity. The efforts should therefore be directed to the strength of the mud, rather than density only. Because of the transient behaviour of fluid mud, meaning that density and viscosity are changing over time, the time dependency is important. Not only material parameters, but also velocity parameters of ship, water and mud are important for the navigability and manoeuvrability of the ship.

4 Assessment of measurement techniques

In order to obtain a better definition of navigable water depth for waterways with muddy water bottoms, it is practical to know the possibilities and limitations of available measurement techniques. Although a lot of information on techniques is available, it is rather scattered. It can be found in journals, internal reports, experiences from users, etc.

In this chapter, an overview is given of the currently available techniques and their suitability to measure an aspect of the muddy water bottom. This can be the direct determination of a (set of) parameter(s) or parameter(s) derived indirectly from the measurements. The parameters listed in the questionnaire and in chapter 3 are taken as basis. In the overview, the focus is on in situ measurements. When relevant, e.g. when no in situ techniques are available, several laboratory techniques are mentioned as well. The list of laboratory techniques is not complete.

An overview of the identified techniques is given in Table 4.1, with the measured and derived parameters. Appendix A shows the full description of these techniques, including lab/ in situ measurements, spatial coverage, accuracy and conficence in the technique.

Table 4.1 Summary of techniques used for the detection of mud

Section	Technique	Measured parameter	Derived parameter
4.1.1.1	Mass weight by core sample	Volume and mass	Density
4.1.1.2	Lowering an object with a known density	Object penetration depth	Density
4.2.1	Dragging instrument on interface between low and high viscosity mud	Depth + electrical resistivity	Depth of viscosity transition
4.1.2	Nuclear probe	Radiation	Density
4.1.3.1	Tuning Fork	Resonance	Density, viscosity
4.1.3.2	Vibration needle	Attenuation of the vibration	Density
4.1.3.3	Vibration tube	Attenuation of the vibration	Density
4.1.4	Dual frequency Single beam Echosounder: 33 & 210 kHz	First acoustic reflection	Thickness between levels of high impedance contrast (when acoustic velocity is known)
4.1.4	24 to 33 kHz (full acoustic signal) combined with calibration	Acoustic impedances	Depth level of predefined density
4.1.4	Sub-bottom profiler (1-10 kHz)	Acoustic reflections	Depth to interfaces of high acoustic impedance contrasts
4.1.4	Single beam Echosounder	First acoustic reflection	Water depth
4.1.4	Multibeam Echosounder	First acoustic reflection	Water depth

4.1.4	Side scan sonar	Water bottom roughness	Contours of fluid mud at water bottom
4.1.4	Acoustic impedance probe	Acoustic impedance, sound velocity	Density
4.1.5	Laser/LIDAR	Light reflections	Water depth
4.1.5	Optical light	Migration of land-water boundary	Sea bed dynamics
4.1.5	Turbidity and suspended solids	Content SiO_2 in g/l or % TSS	Density
4.1.6.1	Geo-electrics	Electrical resistivity	Sediment type, shallow composition, depths to interfaces of high contrast in electrical resistivity
4.1.6.2	Ground penetrating radar	Di-electrical constant, resistivity	Sediment type, shallow composition, depths to interfaces of high contrast in di-electrical constant
4.1.7	Pressure sensor	Hydrostatic pressure	Density
4.1.8	Heating cable temperature-fibre optics	Temperature decay curve	Density
4.1.8	Temperature-fibre optics	Temperature change	Density
4.1.9	Friction resistance	Friction resistance	Depth information/ Composition (stratification) based on contrasts in friction resistance
4.2	Marsh funnel	Viscosity	Viscosity
4.2	Rotovisco test	Viscosity	Yield stress and viscosity
4.2	Capillary viscometer	Time for flow through tube	Kinematic viscosity
4.3	Scholte waves	Seismic velocity and attenuation	Stiffness/shear strength
4.3.2	Vane test	Shear strength	Peak shear strength and residual
4.3.2	Hydraulic consolidation test	Permeability and compression	Permeability, density and peak shear strength and residual strength
4.4	ADCP	Acoustic backscattering	Flow velocity and water bottom
4.7	Radiometry	Gamma radiation	Clay content
Not discussed	Remote sensing techniques from airplane and satellites	Water surface characteristics	Indirect: water depth

4.1 Density

The density of fluid mud varies between 1.05 and 1.3-1.4 kg/L and increases with depth due to consolidation. Local variations in density can occur due to generation of gas, related to biological activity in the fluid mud. There are several techniques to determine or derive the density of fluid and solid mud. Part of the descriptions of the density techniques mentioned this section is derived from an internal RWS report (*Advies slibdichtheidsmeter, 2010 and 2011*), by approval of RWS.

Several in situ density probes measure the vertical profile of density (measured based on varying principles) when the probe is lowered in the water. From the vertical profile, the top of the fluid mud is determined and the 1.2 kg/L level. The difference gives the thickness of the mud layer.

4.1.1 Mass determination

4.1.1.1 Mass weighting by core sample

The most straightforward method to determine density is to weigh a sample with a known volume. Both the volume and mass can be determined very accurately. Laboratory instruments can obtain accuracies of 0.001 g for a mass of for example 100 g. Accurate average densities can be determined for large volumes.

This method requires samples to be collected from the sea bottom and weighted in the laboratory. The division of samples into partial samples restricts the vertical resolution of the density determination of fluid to 2-5 cm. The sample is disturbed at rheological interfaces within the fluid mud.

4.1.1.2 Lower an object with a known density

The second method consists of lowering an object with known density (for instance 1.2 kg/L) in the fluid mud. The object will float in fluid mud having the same density as the object. By determining the location of the object, it is possible to determine the depth of the fluid mud layer with a density of 1.2 kg/L.

This is an in situ measurement. It requires time to achieve equilibrium of the object in the fluid mud layer. It provides only one density level, at point locations.

4.1.2 Radiation

For radiation techniques, the amount of absorption by the material depends on its density. With increasing density, an increasing amount of radiation is being absorbed, which is expressed by:

$$I = I_0 \exp(-\mu\rho D) \qquad \textit{Equation 4.1}$$

where I (MeV) is the measured radiation by the source I_0 (MeV), μ (m/kg) is the absorption density, D (m) is the medium thickness and ρ (kg/m^3) the material density. The parameter μ is well known for fluid mud. Radiation measurement instruments measure the radiation over a fixed medium thickness (D), such that the density of the medium can be determined from Equation 4.1.

Two types of radiation sources can be distinguished; a röntgen source (transmits röntgen radiation) and a radioactive source (transmits gamma radiation). To measure the density of mud in situ, the instrument is lowered vertically through the water column and the fluid mud layer, such that a vertical density profile is obtained.

The röntgen technique has the advantages that the measurements have a lower noise level and a controllable degree of radiation, whereas the radiation of a radioactive source is continuous and uncontrollable. However, the röntgen source is more complex and expensive than a radioactive source. It is recommended to perform frequent calibration measurements (~every year) for different media types with the röntgen instrument.

For measuring the density with a radioactive radiation source, different sources can be used, such as ^{137}Cs, ^{133}Ba, ^{60}Co and ^{226}Ra. Radioactive sources need to be calibrated frequently, to account for the reduction in intensity of radiation (resulting from half-life of the radioactive isotope) and the drift of the instrument.

Strict permits and procedures exist for storage and transport of a radioactive source, which restricts its transport application. These procedures do not exist for a röntgen source, which makes its transport and implementation more easy. For normal operation of both a röntgen- and radioactive source, the user requires an experience degree of minimal 5A for operation (RWS internal report, 2010, 2011).

4.1.3 Vibration technique

4.1.3.1 Tuning fork

The density can be determined based on a vibration generated by a tuning fork (Fontein 2006; McAnally, 2007), which is applied in-situ. The tuning fork consists of two prongs, of which one prong is being vibrated. Depending on the material in between the two prongs the other prong will react at a specific response vibration. The response vibration will depend on the rheological properties of the material within which the fork is present. The frequency power spectrum is determined during a measurement.

The tuning fork principle is less accurate for non-Newtonian or viscous fluids. Viscous matter will damp the signal of the responding prong too much. The measured density can only be corrected for a limited amount for variations in rheological properties.

The tuning fork measurements require separate calibration measurements for each new measurement location. The instrument is lowered vertically though the water and fluid mud to obtain a vertical depth profile of the density.

4.1.3.2 Vibration needle

A vibration needle measures the density of material with a needle that is being resonated using a piezo-electric element. The damping of the vibration is proportional to the density of the material that is being measured. The technique is applied in-situ. Compared to the tuning fork, the vibration needle is more robust and does not require location specific calibration measurements.

The Port of Rotterdam measures the density of fluid mud (collected from the bed using a specialised Beeker Sampler) at intervals (e.g. 5 cm) using a hand-held probe density meter based on a vibration needle principle.

4.1.3.3 Vibration tube

The vibration tube has a similar principle as the vibration needle. With this technique, the casing of the vibration tube is vibrating. The density is determined by measuring the damping of the vibration. The technique is being frequently used in the laboratory and has a high accuracy and reproducibility. The technique is only used for small volumes. It is currently not known whether is requires calibration measurements to obtain density values. In situ application of the technique is not known.

4.1.4 Acoustic techniques

The density can be determined using acoustic techniques. A jump in acoustic impedance along an interface is expressed by acoustic reflections with a specific reflection strength. The acoustic impedance (P) is defined by:

$$P=\rho.v \qquad \textit{Equation 4.2}$$

Where ρ is the density of the material and v is the acoustic velocity of the material. Thus, the impedance can in turn be translated to the material’s density. Probes exist that measure the vertical profile of the acoustic impedance and sound velocity in the water. From this, a density profile is derived.

Traditionally, the high frequency echosounder readings (single beam 210 kHz or multibeam) are considered as measures of the top of the mud. The first acoustic reflection of the low frequency echosounders (e.g. 33 kHz) are interpreted as the bottom of the fluid mud or the top of the consolidated mud. However, the determined levels highly depend on the settings of the instrument. Low frequency echosounders therefore sense neither density nor viscosity directly. They are considered to be unreliable in measuring fluid mud.

On the other hand, the full signal of echosounders (and not only the first reflection) can be used for density determination. For this, penetration of the acoustic signal in the fluid mud up to the desired density level is necessary. This means that echosounders with relatively low frequency (e.g. 24-34 kHz) need to be used, since high frequency echosounders (e.g. 210 kHz) do not penetrate into the mud. The impedance levels in the full acoustic signal need to be calibrated by independent point measurements of density. After calibration, line measurements of density can be determined.

Another acoustic instrument is the Side Scan Sonar. It measures the backscatter from a wide, fan shaped pulse and gives information on the texture of the seafloor. Side scan sonar is unsuitable to derive density information.

4.1.5 Light

By using optical, laser or infrared light the particle concentration can be determined in transparent water from optical damping or optical backscattering (Downing et al., 1981; Xylem Brochure, 2012). This is the most widely used method to determine suspended sediment concentrations at low concentrations, but is increasingly applied to high sediment densities as well.

Optical light can be measured with camera systems in order to monitor patterns on the water level, from which information on seabed dynamics can be derived. Although this method is currently only applied to derive information on sea bed dynamics, but might have potential for characterisation of fluid mud. This technique requires separate on-site calibration measurements.

There are new sensors available that use the backscatter of light to determine the concentration of particles in suspensions. For low concentrations, scattered light from particles directly is measured at an angle of 90°. For higher concentrations of suspended solids, particles will interfere with each other. In that case, a backscatter approach is used, with an angle of 60°.

4.1.6 Electrical conductivity and ground penetrating radar

4.1.6.1 Electrical conductivity

By using electrical conductivity the porosity and density can be derived. A current is conducted through a measurement volume, by using electrodes. The conductivity is proportional to the porosity.

This technique is relatively standard. It requires independent calibration measurements of the density and its performance decreases with increasing salinity of the water. Both laboratory and in-situ applications are known of this technique.

Electrical conductivity is a well known technique for the measurement of the density of sand layers on land and river bottoms. The method involves a combination of field and laboratory experiments. The field experiments involve the measurement of the electrical resistance (by cone) of the soil layer. The pore water has to be sampled separately. From the total electrical conductivity and the electrical conductivity of the pore water, the electrical conductivity of the soil can be assessed. If the soil consists of sand, the electrical conductivity is converted to porosity and to density. If the soil consists of (sand and) clay, the conversion to density is not straightforward, due to the electrical conductivity of the clay minerals.

4.1.6.2 Ground penetrating radar

The density of fluid mud can be determined in an indirect approach by using electromagnetic radiation. Close to the water bed an electromagnetic pulse, e.g. by ground penetrating radar, is generated that reflects on the water bed and at layer interfaces within the shallow subsurface. Based on additional information, such as corings, it might be possible to distinguish subsurface layers characterized different densities. There are no known examples of the application of this technique for mud and fluid mud.

4.1.7 Pressure

The pressure is another primary property of fluid mud. By using measurements of the total pressure, it is possible to determine density of a medium (i.e. water/fluid mud/sand) for the entire vertical using:

$$P = \rho\ g\ h \qquad \text{Equation 4.3}$$

Where P is the pressure, ρ is the density, g the gravitational constant and h is the height of the water column.

The density can be determined from the pressure by dividing the measured total pressure by the product of depth and gravitational constant. The depth dependency can be eliminated by using multiple pressure sensors. In consolidated mud, spatial structures are created by binding of particles. The particles in the consolidated mud can transfer mechanical forces and give strength to the mud. In that case, the water pressure is no longer equal to the static pressure. The transition between no interaction between particles and particles giving rise to strength is not clearly known yet. Moreover, there is limited practical experience with this technique.

4.1.8 Heat

A relative new technique is to determine soil parameters by using heat. The heat transport of the soil can be measured in-situ using for example temperature fibre optics. The density can theoretically be derived from heat measurements by solving the heat equation. Currently, temperature variations from fibre optics are used to derive locations of sedimentation and erosion of sand. However, it has not been applied to derive density yet. It is still unknown what assumptions need to be made to solve the heat equation and whether this will yield accurate density results.

4.1.9 Free-fall cone penetration test

The frictional resistance can be determined by dropping a cone in free-fall and measuring the depth and friction. This is similar to a cone penetration test, except that the cone is being dropped in free-fall. From the measured acceleration (in fact deceleration), the rheological parameters (such as undrained shear stress and viscosity) and the density are determined. With this instrument, the interface between fluid mud and consolidated mud can be determined, even in gassy environments (Ocean Nautical Innovations, 2012).

4.2 Viscosity

Viscosity is an important parameter during generation of fluid mud and in the consolidating stage. The viscosity of fluid matter is a measure of the resistance against deformation that can result from for example shear stress. In theory, viscosity can be used to define nautical depth criteria and for definition of the bottom of the water column (McAnally et al., 2007). However, nautical depths are defined based on density only (table 1 from McAnally et al., 2007).

The yield stress can be computed from the viscosity measurements.

The viscosity can be derived by using the following methods:

- Towing a cable through fluid mud (§ 4.1.1.3).
- Tuning fork principle (§ 4.1.3.1).
- Free-fall cone penetration test (§ 4.1.9).
- Rotovisco test: a laboratory viscosity test with a rotating vane or cylinder. During the test, the dynamic viscosity is measured at defined shear rate or shear stress. It determines the yield point with controlled stress as a function of density. It is a standard method for characterizing sludges.

- Marsh funnel: a laboratory test with a marsh funnel. This is a simple device for measuring viscosity by observing the time it takes for a known volume of liquid to flow from a cone through a short tube. It is standardized for use by mud engineers to check the quality of drilling mud.
- Capillary viscometer: a laboratory test in which the time taken by the fluid to flow in a capillary tube between two marks. This time is proportional to the kinematic viscosity.

From this list, it appears that several in situ methods are potentially available for the determination of viscosity. However, they are not scientifically proven yet or experience from users is inconclusive. The methods are potentially useful for fluid mud. Additional field tests and validations are needed.

4.2.1 Dragging instrument on interface of low and high viscosity

With this method a cable is towed through the mud at the interface between low viscosity consolidating mud and higher viscosity solid mud (Druyts et al., 2009, 2011). A depth sensor records the instrument’s depth and a short electric cable registers the electric conductivity. The cable tends to stay at the interface because the more viscous consolidating mud poses more drag on the cable, thus “pushing” it upwards. On the other hand, as soon as the cable is dragged in the fluid mud, the drag on the cable is lower and the instrument will drop to a lower level. The speed of the vessel is critical. There is a window of vessel speeds in which the cable will be dragged at the interface, but as soon as the speed is too high, the cable will be lifted into the fluid mud, rather than remaining on the transition. Therefore, the electric conductivity is measured as a check: as soon as the ship’s speed is too high, the cable will float within or above the fluid mud and the conductivity drops as soon as the instrument no longer ‘touches’ the higher viscosity mud. With the right vessel speed, the cable does not directly measure the viscosity of the mud, but it stays on the interface between two types of mud each with a different viscosity. It is the depth of this interface that is measured.

4.3 Elasticity and compressibility

4.3.1 Scholte waves

Elasticity can be determined indirectly from the compressional and shear velocities of mud. The compressional wave velocity can be easily retrieved by well developed acoustic technique. On the contrary, the determination of shear wave velocities is challenging and topic of on-going research. One of the most promising techniques involves the generation and acquisition of surface waves travelling along the sea-floor (Scholte waves). From the dispersion behaviour of these Scholte waves, the shear wave velocity profile can be derived for a certain location (Kruiver et al., 2010).

It is important to mention that in fluid mud the loose contact between grains is not sufficient to assure elasticity and shear strength. As result, the shear wave velocity (and therefore elasticity) can only be measured when mud has reached a certain consolidation at a certain depth. The level at which fluid mud gains sufficient shear strength to transmit shear waves is not known yet.

4.3.2 Compressibility

A HYDCON (HYDraulic CONsolidation) test is laboratory test and gives parameters that describe the compressibility and the permeability of sludge in the stress range of 0.5 to 25 kPa as a function of porosity or density (van Essen et al., 1995). In this test, a low density sludge sample from the field is inserted in a 2.5 m tube and is consolidated under a hydraulic gradient of 25 kPa. The covered stress range can be expanded by means of standard oedometer and permeability tests. Subsequently performed vane tests on the consolidated sample gives the relationship of the peak shear strength and remoulded strength as a function of density and stress. A database of approx. 40 mineral sludges is available.

4.4 Flow parameters

The macro kinematic flow of water and fluid mud is important for the behaviour of ships in the waterway.

The flow velocity can be measured using a ship-mounted ADCP. It performs simultaneous measurements of both water depth and flow velocity (along the vertical). Ship-mounted ADCP allows densely sampled measurements of major parts of the river cross-section (Stowa, 2009).

4.5 Thickness of fluid mud layer

The thickness of fluid mud is relevant for dredging, for navigation and manoeuvrability. As an example, a ship might be controllable sailing through 0.5 m of mud while 1.5 m might give problems.

Keeping in mind the problems regarding the definition of the thickness of mud (chapter 1), the following methods for determination are suggested:

- Density profiles with various methods. Determination of the difference in level of defined densities, e.g. 1.05 and 1.2 kg/L. Point measurements only.
- Acoustic techniques. Quantitatively: only if acoustic impedances can be linked to density by calibration. Qualitatively: to follow clear reflections that might indicate relevant levels in the mud.
- Electrical conductivity: it is expected that the interface between fluid mud and consolidated mud is characterized by a change in fluid content, resulting in a measurable conductivity change.

4.6 Degree of consolidation and time-dependent behaviour

Fluid mud is in a transient state. It changes on timescales of hours to days. For its behaviour it is important to know the phase of consolidation.

During consolidation of the mud, the density and strength will increase and the permeability will decrease. The HYDCON test (van Essen et al., 1995) in combination with model calculations with FSConbag (Greeuw, 1997) can be used to assess the relationship between time on one side and permeability, density and strength on the other. The program FSConbag is based on the finite strain theory which allows for the calculation of large strains. The in situ density can be used to estimate the degree of consolidation and the amount of settlement. From that, the time required to reach a certain degree of consolidation can be derived. The combination (Hydcon and FSConbag) is often used for the prediction of the consolidation of large sludge depots in the Netherlands.

In general, pressure measurements could be useful to determine the consolidation phase, using the combination of total pressure, water pressure and reference pressure. However, for sludge this method is not advised, due to the fact that the accuracy of the parameter (degree of consolidation) is expected to be low.

4.7 Composition

The behaviour of the mud is partly determined by its composition, both chemical and grain size distribution. The chemical composition can be measured in situ using the natural radioactive background radiation using a gamma-a measurement device. Different minerals, soil and sediment types can be distinguished as their concentration in radioactive matter differs. Each mineral has a radiometric fingerprint. The amount to which minerals differ in content depends on the type of mineral, its origin and its age.

Grain size distributions can be determined in the laboratory with numerous proven techniques, such as laser diffraction (Coulter or Malvern), settling columns and sieving.

4.8 Techniques in interviews with selected stakeholders

During in-depth interviews with selected stakeholders, they were specifically asked what instruments they use to determine nautical depth and mud thicknesses.

To measure density profiles, the interviewees use radiation probes, tuning fork or sampling combined with on-board measurement. Usually this is combined with acoustics, either qualitatively, or used as calibration of acoustic impedances. For a specific site (Delfzijl, the Netherlands), the maintenance depth is determined by 2/3 of the difference in level between 210 and 33 kHz echosounder. The nautical depth, interpreted as the top of the fluid mud, is usually determined by multibeam.

Almost all interviewees were positive about the free-fall penetration test. This is because of the possibility to obtain information about the viscosity in addition to density. This is a relatively new method for the application in fluid mud. The technique needs to be properly validated.

Although the interviewees do not always have clear ideas about what they want to measure, they can easily state the requirements for an instrument: it should be able to measure quickly, reliable, reproducible, in situ, preferably over a line or surface instead of on point locations. It should be robust, easy to handle, easy to transport (across borders). Additionally, the customer should have confidence in the instrument. For that, the results and the reliability should be proven.

Claeys et al. (2011) state that “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 ship. 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”.

4.9 Conclusions techniques

The full overview the techniques presented in this chapter is given in Appendix A. From the overview, it is clear that no perfect instrument exists for the determination of all relevant parameters for fluid mud. However, several instruments are adequate for their purpose of measuring one or several parameters. To determine all relevant parameters a combination of techniques and instruments is needed. At this stage, no statement is given on the best combination of instruments.

High capability techniques to measure relevant mud parameters are:

- In situ point measurements: Mass weight by core sample, dropping an object with known density, nuclear probe, tuning fork, vibration needle, acoustic impedance probe, turbidity and suspended solids probe and free fall cone penetration test.
- In situ line measurement: Full acoustic signal calibrated with point measurements of density and ACDP measurements.
- Laboratory measurements: marsh funnel, rotovisco test, capillary viscometer, vane test, hydraulic consolidation test. Waterbouwkundig Laboratorium Borgerhout (Belgium) currently runs a two year project to calibrate various laboratory instruments in order to be able to measure the absolute values of viscosity. The protocol for laboratory measurements is nearly ready and scheduled to be published at the end of 2013.

In harbours, mud distribution is highly variable in space and time due to dredging operations, tides and ship traffic. Therefore, 3D coverage of relevant parameters is wanted as well as sufficient time coverage. Point measurements, however, have limited representativeness in space. Line measurements fill the gaps between point measurements. An appropriate monitoring scheme should cover temporal variations.

A solution to the problem of inadequate spatial and temporal coverage and known techniques might be to look at the fluid mud matter from a completely different perspective. Until now, we tried to measure the dynamic mud from a static point of view: to measure one snapshot in time at a limited number of coordinates. Alternatively, we could excite the fluid mud by e.g. an internal wave and measure the transient behaviour. From theory, modelling and measurement of that transient behaviour, we might be able to derive the relevant rheological properties of the mud. This is further discussed in chapters 5 and 6.

5 Modelling of internal waves for navigable depth

5.1 Introduction

On the ocean, internal solitary waves are a common phenomenon. An Atlas of Internal Solitary-like Waves and their Properties (2004) shows numerous examples of internal waves all around the world, observed in e.g. satellite images (SAR or false colour). Internal waves in the North Sea can be generated either by the interaction of tidal flow with bathymetry, or by strong atmospheric disturbances (fronts) which frequently pass over the North Sea. Figure 5.1 shows an example of an image of an internal wave in the Skagerrak (Atlas, 2004).

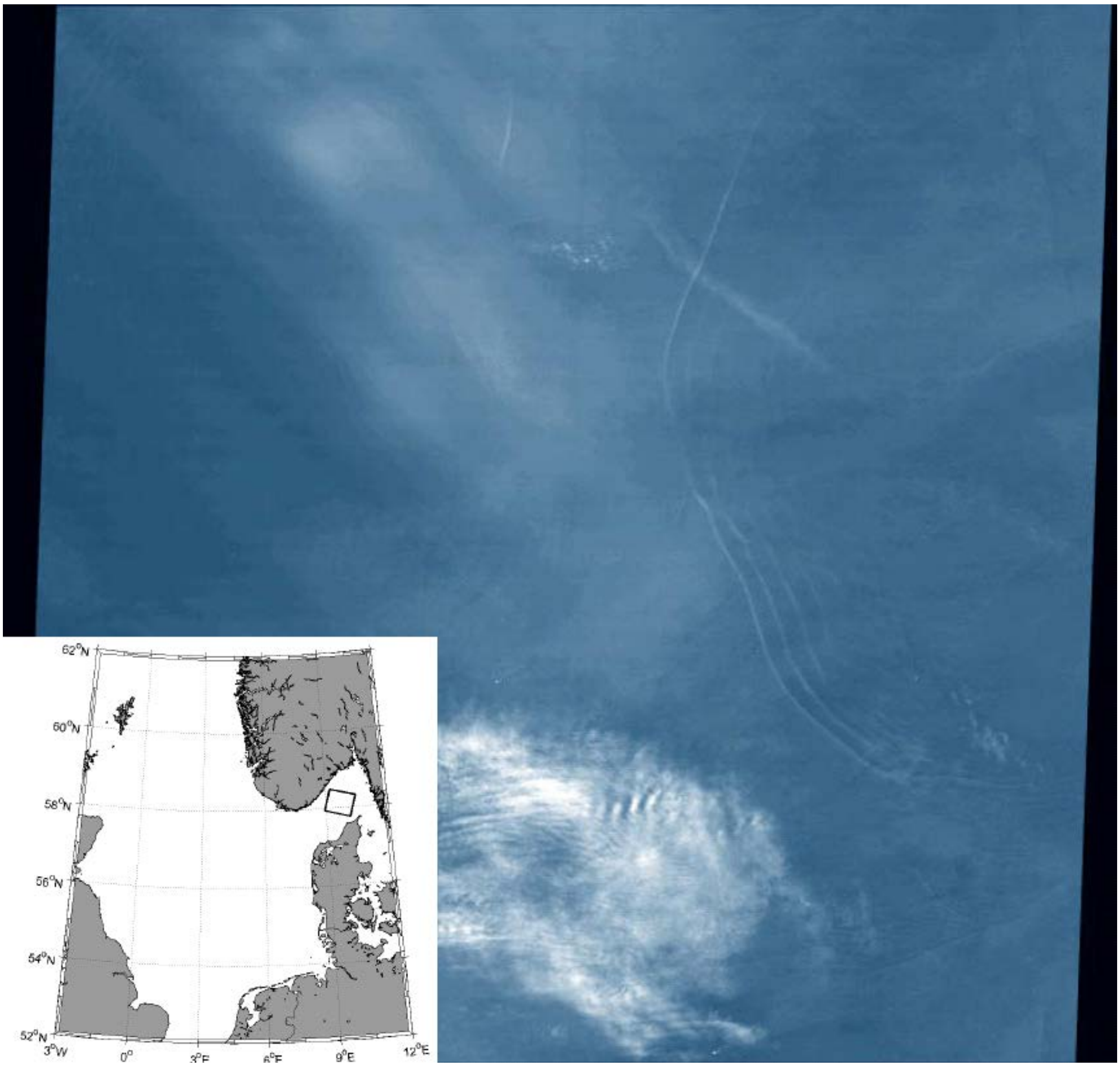

Figure 5.1 ASTER false-color VNIR image acquired on 9 July 2003 at 1049 UTC in the Skagerrak Strait area south of Norway. The image shows a large internal wave packet propagating westward. The imaged area is 60 km x 60 km. From An Atlas of Internal Solitary-like Waves and their Properties (2004)by C.R. Jackson.

The following description of internal waves is taken from the Atlas (2004):
“Internal waves (IWs) are, as their name implies, waves that travel within the interior of a fluid. Such waves are most familiar as oscillations visible in a two-layer fluid contained in a clear plastic box often sold in novelty stores. In the box, two immiscible and differently colored fluids fill the entire volume; when tilted or otherwise disturbed, a slow large amplitude wave is observed to propagate along the interface between the fluids. This is the internal wave and while it has its maximum amplitude at the interface, its displacements are zero at the top and bottom. It owes its existence to the stratified density structure of the two fluids, with a very sharp density change occurring along the interface and with the properties that the smaller the density contrast, the lower the wave frequency, and the slower the propagation speed. [Apel, 1987].”

An innovative idea is to use internal waves generated by ships to characterise the properties of the fluid mud layer which is present in harbours. Mud specialist prof. dr. ir. Han Winterwerp has observed an internal wave in the harbour of Rotterdam some decades ago. This internal wave could be distinguished on a Side Scan Sonar image. Since the frequency and propagation speed of internal waves are determined by the properties of the two fluids the wave is travelling between, the dynamics of an internal wave on a water-mud interface should reveal the dynamics of the mud layer. It is Winterwerp’s idea to use the principle of internal waves generated by the passage of large ships in harbours to derive the properties of the fluid mud in the muddy water bottoms of those harbours. In Figure 5.2 a schematic representation of a ship induced internal fluid mud wave is given.

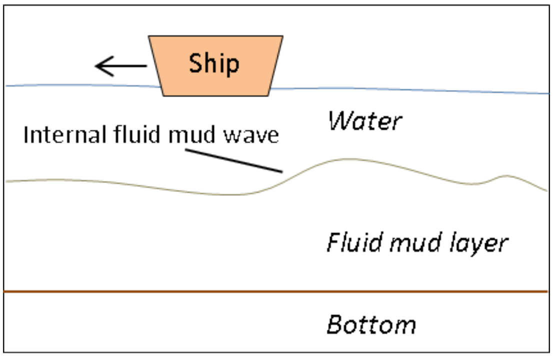

Figure 5.2 Schematic representation of a ship induced internal fluid mud wave.

In the method proposed here, internal fluid mud waves play an important role. Internal (fluid mud) waves are waves that occur on the interface between the water and a fluid mud layer. They can be induced by surface waves, tidal shear and/or ship movements. Here, we are mainly interested in ship induced internal fluid mud waves that are generated by ship induced pressure gradients. These pressure gradients depend on the size, draught and sailing speed of the ship. After being initiated, the internal fluid mud wave dynamics mainly depend on the fluid mud properties (bulk density, viscosity and thickness of the fluid mud layer). Internal waves may be damped by viscous dissipation in the fluid mud (which is relatively well-understood, and can be modelled with numerical models, e.g. SWAN-mud).

In order to elaborate on the innovative idea of using internal waves, several steps are needed:

1 Observations of internal waves (future work, proposed to perform in early 2013).
2 Numerical models to study the behaviour of internal waves (sections § 0 and § 0 and future work).

3 Inverse modelling: to match the observations to the models and derive the fluid mud properties (future work).
4 Implementation (future work).

The potential of internal waves to determine fluid mud properties can be investigated through field trials (step 1). These trials should include measurements of (1) internal waves (using sonar, ADCP, or other – see Table 5.1), (2) fluid mud properties (density, viscosity, thickness, etc.), (3) hydrodynamic conditions (flow velocity, water depth), and ship parameters (draft, sailing velocity, etc.). These observations should cover a sufficient range in fluid mud and internal wave conditions, in order to isolate the contribution of separate fluid mud, ship, and hydrodynamic conditions. The fluid mud properties can subsequently be related to the internal wave dynamics using a numerical model.

In order link the observed behaviour of the internal wave to fluid mud properties, models are needed (steps 2 and 3). In section § 0, different modelling methods are discussed and an inventory of available modelling packages is given. An overview, some conclusions and the advice are provided in § 0.

Eventually (step 4), it could be possible to set up a real time system in which the measurements in the channel are automatically processed and translated into fluid mud properties (for instance via a look-up table), or potentially even into a measure for navigability directly. The latter could be achieved by combining the measurements, model results and pilot experiences into one integrated system.

In summary, the process of gaining fluid mud information and translation to navigability is given in Table 5.1.

Table 5.1 Summary of steps needed to use internal waves for navigability.

Category	**Steps**
Measurements	Examples: • Side scan sonar • Array of sonar sensors along fairway • ACDP • Measurement of density profiles and viscosity with various instruments • Possible other measuring methods
Analysis & Modelling	• Analysis of measured data • Modelling of behaviour of internal waves in/over fluid mud • Inverse modelling • Relation between internal wave properties and fluid mud properties
Potential output	• Real time information on fluid mud properties at the scale of ships (bulk density, viscosity, fluid mud layer thickness) • Real time information on the navigability • Effects of gas implicitly included • Information on fluid mud and/or internal wave behaviour can be coupled to pilot experience in an expert system

5.2 Numerical models

In this section, the numerical modelling aspects are discussed. A large number of numerical models have been developed, so a selection of potential models is made. First a list of requirements is given, followed by a description of the modelling methods that could be used for the current application. Then a number of potential numerical models are discussed individually.

5.2.1 Model requirements

To be able to study the relation between internal fluid mud waves and the fluid mud properties the numerical model should fulfil a number of requirements.

Accuracy
The model should be accurate enough to be able to simulate internal fluid mud waves. For this, the model should preferably be phase-resolving, meaning that the full wave motion is simulated, and not averaged. Vertical gradients are relevant in internal waves, and therefore the model has to be non-hydrostatic and, preferably, depth varying (depending on the approach, see the next section). In addition, mixing between the two different liquids (water and fluid mud) should be limited (or better: zero).

Spatial distribution
To be able to apply the model to situations of turning ships (for instance when a ship sails from the navigation channel into the harbour basin), the model should be able to deal with both horizontal dimensions. Thus, taking into account the accuracy requirement (multiple vertical computational layers) as well, the model should preferably be three-dimensional.

Computationally efficient
The model should be usable for conducting sensitivity studies. In these studies a large number of simulations are usually conducted, making a computationally expensive model with long simulation times undesirable.

Extensibility
It is expected that (at least until some extent) modifications in the model source code will be necessary. Therefore, it is important that the code is well enough structured, and can be modified relatively easy.

State-of-the-art
The model should be state-of-the-art and still in development. In that case, the most recent scientific insights are taken into account, and the code will be maintained regularly. The implementation of new code will be easier that way.

Including ships
Preferably, the model should be able to include the effect of the ship in some way. In most models this is not possible (yet). In that case, it should be possible to include the effect of ships without too much trouble.

5.2.2 Modelling methods

5.2.2.1 Two liquid layer method

The most sophisticated way to model ship induced internal fluid mud waves is to model both the fluid mud and the water layer. In that case, it is important that the water layer has a free surface at the top so that surface waves can be simulated. Additionally, the model should be able to represent the short and internal waves accurately, which means the model may not neglect the vertical accelerations and has to be non-hydrostatic and phase-resolving (simulating the entire wave motion). In some modelling packages even the ship itself (and its effect on the water layer and fluid mud layer) can be included (e.g. OpenFOAM).

Regarding the technical aspects, modelling two different fluid layers with different density and viscosity properties can be done relatively easy, by assigning different fluid properties (density, viscosity, layer thickness) to the two fluid layers. However, problems might arise at the interface between the two layers. Numerical models that take into account the vertical variation of flow are usually discretized into a number of vertical layers. This discretization can be done in two ways: with the so-called z-layer or sigma-layer approach. In the z-layer approach (left panel of Figure 5.3), all the vertical computational layers have a fixed height (which can vary per layer). In the sigma-layer approach (middle panel of Figure 5.3), each layer has a height that is a fixed portion of the local water depth. In the z-layer approach, both surface waves and the internal waves move through different vertical layers, while in the sigma-layer approach only the internal waves move through the computational layers, since the layer thickness is a function of the water depth and not the fluid mud thickness. The problem of internal waves moving along different vertical computational layers is that additional mixing between the two fluids will occur. So in addition to the ‘normal’ fluid mixing at the interface of the two fluids, mixing will be enhanced due to the numerical discretization.

The numerical mixing is non-physical, and therefore undesired. It could partly be accounted for by increasing the vertical resolution near the water-fluid mud interface. A better solution would be to model both fluid layers as separate fluids, where the bottom of the upper fluid (water) acts as surface for the lower fluid (mud). In that case, both fluid layers have their own computational layers, and the hydrodynamic equations are solved separately, while the interaction between both layers is taken into account. The vertical discretization can then be done as shown in the right panel of Figure 5.3. An example of such model is described by Balkema (2009). He developed a simple two-layer model in which mixing between the two layers is neglected.

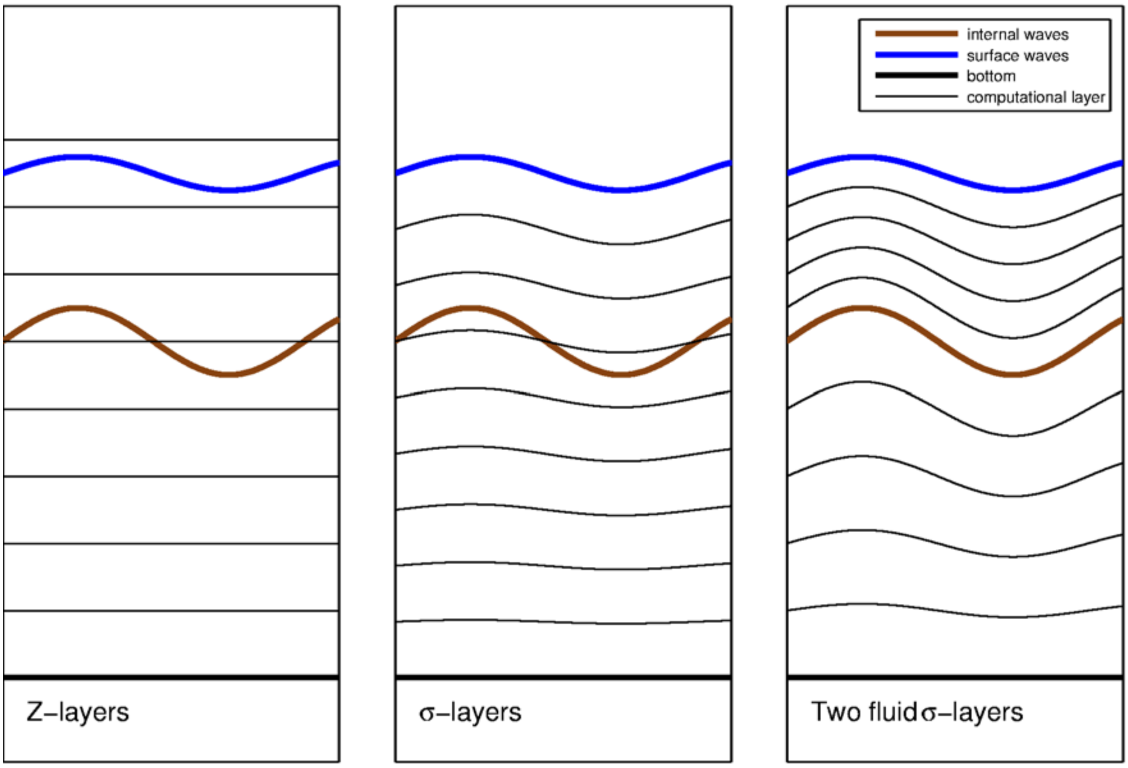

Figure 5.3 Schematic representation of the use of different methods for vertical discretization. Left panel (z-layers): all vertical computational layers have a constant thickness (although the thickness per computational layer may differ). Middle panel (sigma layers): the thickness of the computational layers is a fixed portion of the local water depth (the percentage could differ per computational layer). Right panel (two fluid sigma layers): computation layer thickness depends on the thickness of the fluid (water or fluid mud).

5.2.2.2 One liquid layer method

Another option is to neglect the water layer, and to model the internal fluid mud wave as a surface wave, but with reduced gravity (g'). Since the internal wave is measured (wave height, wave propagation velocity) and the propagation mainly depends on the fluid mud properties, there might not be a need for modelling the interaction of the fluid mud with the water (or even indirectly the ship).

The main advantage of this approach is that the currently available models will only need relatively small modification. Since the internal fluid mud waves are generally relatively short (in the order of a ship length) and steep, a non-hydrostatic approach is required (vertical accelerations cannot be neglected).

It is not clear whether the fluid mud layer can be represented by one or more vertical (computational) layers. For surface waves a higher resolution (two or more layers) is required when the relative water depth is too large:

$$kh > 1.4$$

Equation 5.1

where k is the wave number and h the local water depth. In that case, the assumption for depth averaged flow no longer holds, and the linear dispersion is not accurately represented by the model. Assuming this criterion also holds for the internal fluid mud wave, one vertical computational layer should suffice when:

$$k_{i,w} h_{mud} > 1.4 \qquad \text{Equation 5.2}$$

where $k_{i,w}$ is the internal wave number and h_{mud} is the fluid mud layer thickness. Note that this is a rather hypothetical statement and more research should be conducted to verify this.

5.2.2.3 *Phase averaged*

Above described methods all consider a phase-resolving way for simulating the (internal) waves. Another option is to simulate waves in a phase-averaged manner. In that case, the wave motion is not solved entirely, but represented by parameters such as wave energy, wave height, wave number etc. The propagation of internal fluid mud waves, as function of the fluid mud properties, has been modelled in this way before (e.g. SWAN-mud).

5.2.3 Potential modelling packages

There is no model yet that can compute fluid mud properties from the propagation of a (measured) internal fluid mud waves. Therefore, all model packages described below will have to be modified in some way, or used in a specific way (e.g. for generating a look-up table). The modelling packages considered will be discussed individually in the following sections.

5.2.3.1 *OpenFOAM*

OpenFOAM is an acronym for Open Field Operation and Manipulation and is an open-source numerical modelling package developed by OpenCFD Ltd. It can be used for a wide range of complex applications (e.g. fluid flows with chemical reactions, heat transfer, and turbulence). It can be used on a very small and detailed scale, thereby obtaining relatively accurate results.

OpenFOAM includes several solvers and functionalities, but for the current application (modelling of internal fluid mud waves), the *twoLiquidMixingFoam*-solver is particularly interesting. This solver is designed to model mixing of two incompressible fluids, in this case water and fluid mud. To obtain a more representable simulation case, an extra air layer can be added to the solver, which has also been done in the example shown in Figure 5.4. Another interesting addition is that the effect of sailing ships can be modelled, and that the water that is moved forward by the ship indirectly induces the fluid mud waves. In the other models mentioned in section 5.2.2, the effect of the ships can only be included by vertical pressure.

The large accuracy of the OpenFOAM package requires (very) small grid dimensions and computational time steps, making the model computationally expensive.

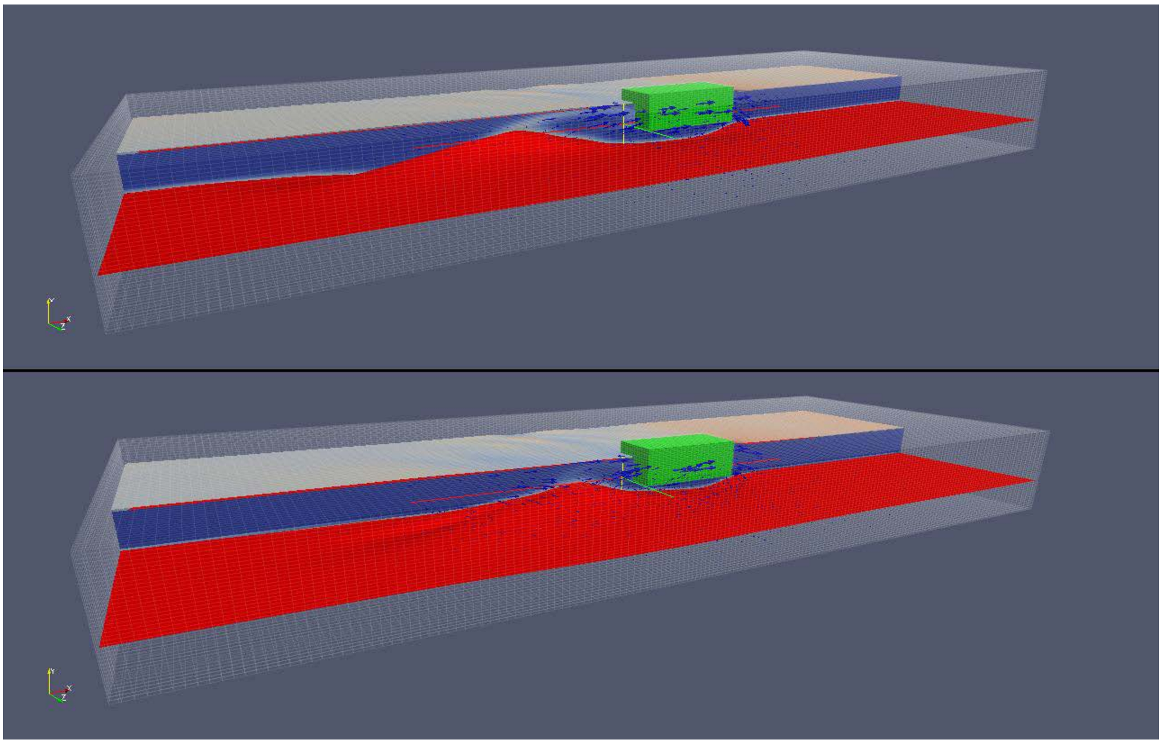

Figure 5.4 Example of numerical modelling of an internal fluid mud wave for a schematised ship (green box) moving from left to right over a fluid mud layer (red) of “light” mud (top panel) and “heavy” mud (bottom panel). Modelled using OpenFoam by A. Smale, Deltares.

5.2.3.2 SWASH

SWASH stands for Simulating WAves till SHore, has been recently developed by Delft University of Technology. SWASH can be used for simulating non-hydrostatic flows especially in complex situations like rapidly varying flow and wave transformations in coastal waters, ports and harbours.

For the current application, it can both be used in a two layer and one layer liquid way. For both, some small modifications in the model code are required to assign different density and viscosity values to different vertical layers (or even a spatial variation in fluid properties). In a two layer way (with fluid mud and water), SWASH will have the numerical mixing problem as described in section 5.3, since in the sigma layer approach the computational layer thickness is a percentage of the total water depth, and not of the individual fluid layers. This can partly be resolved for by increasing the vertical resolution near the interface. Another option would be to implement the two fluid sigma layer model of Balkema (2009) into the SWASH source code.

In one layer mode SWASH should be able to model internal fluid mud waves with some relatively small modifications. If needed, the model can also be set up with multiple vertical computational layers, which can be important for accuracy.

5.2.3.3 Delft3D

Delft3D is an open source modelling suite developed by Deltares, which simulates two-dimensional (in either the horizontal or a vertical plane) and three-dimensional flow, sediment transport and morphology, waves, water quality and ecology and is capable of handling the interactions between these processes. For the current application, the non-hydrostatic FLOW module is relevant (Delft3D-NH). In principle, this module is quite comparable to the SWASH model. Delft3D-NH is able to simulate wave propagation and flow in a phase-resolving, non-hydrostatic manner. However, it only includes the z-layer approach, while SWASH uses the sigma-layer approach.

Some years ago, a new module was developed for Delft3D specifically aimed at computing mud transports (Van Maren et al., 2007). The so-called Delft3D-mud (or Slib3D) module was developed for studying mud transport in the Scheldt river (commissioned by the Flamish Government), especially the exchange between the river and the Antwerp harbour basins. A number of mud-related processes (e.g. flocculation, consolidation of the bed) are not included in the standard Delft3D version, but are included in this additional module. Due to the inclusion of these processes, the model provides a very sophisticated way of modelling mud transport. However, the model is not part of the standard Delft3D development stream, and is therefore becoming increasingly incompatible with standard Delft3D functionalities. Using the model therefore requires some significant modifications in the code. Additionally, Delft3D-mud is a hydrostatic model (unlike the non-hydrostatic Delft3D version) and can therefore not be used for the current application.

5.2.3.4 XBeach

XBeach is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the near-shore area, beaches, dunes and back barrier during storms. It is an open source model that has been developed with funding by a consortium of UNESCO-IHE, Deltares, Delft University of Technology and the University of Miami.

XBeach also includes a non-hydrostatic module (XBeach-NH) which makes it possible to simulate short waves in a phase-resolving way. In essence, XBeach-NH is identical to SWASH. However, XBeach can only be applied in depth averaged mode (one vertical computational layer). This means that the two liquid layer approach - per definition - cannot be conducted with XBeach. The one layer liquid approach can be conducted with XBeach-NH, but due to the depth averaged restriction, only for low $k_{i,w}h_{mud}$-values.

5.2.3.5 SWAN-mud

SWAN-mud is a model developed by Delft University of Technology and Deltares that can be used to compute damping of surface waves in horizontal space over a given patch of fluid mud, with given thickness, viscosity and density. The standard model assumes a non-hydrostatic water layer over a hydrostatic fluid mud layer. The dissipation of wave energy is determined from a linear model. The relevant dispersion equation is added to the standard SWAN model, maintaining all regular features of SWAN. Output of the model is in the form of surface wave properties. Though fluid mud wave properties can be determined easily from the implemented equations, this has not yet been done.

In its current state, SWAN-mud is not applicable to resolving ship-induced internal waves, because it assumes a hydrostatic fluid mud layer. However, also a non-hydrostatic formulation for fluid mud waves is implemented in SWAN (the Dalrymple-Liu formulation). With some modifications, SWAN-mud can be made suitable for the current job. However, the evolution of wave properties is determined from a linear model, forbidding variations of mud properties within the mud layer.

5.3 Conclusion models

In section 0 an inventory has been made of a number of numerical models that can possibly be used to study the relation between internal fluid mud waves and the fluid mud properties. In Table 5.2 an overview is given of the models and to which extent they fulfil the requirements mentioned earlier. Note that the mud transport module is not included because it is a hydrostatic model and is therefore not suitable (as discussed earlier). In the case of accuracy, a judgment is given based on the possibility to use multiple vertical computational (sigma- and/or z-) layers in the model, as well as being phase resolving. For the ship requirement, it should be noted that this is already possible in OpenFOAM. For SWASH, the implementation of ships in the model is currently being investigated by a PhD student at Delft University of Technology, while this is also currently being done in the case of XBeach at UNESCO-IHE/Deltares.

Table 5.2 Overview of potential modelling packages and to which extent they meet the requirements presented earlier.

	OpenFOAM	***SWASH***	***Delft3D-NH***	***XBeach-NH***	***SWAN-mud***
Accuracy	++	++	+	0	-
Spatial distribution	+	+	+	+	+
Computational efficiency	--	0	0	0	+
Extensibility	+	++	+	++	+
State-of-the-art	+	++	0	+	-
Include ships	++	+	0	+	-

Based on the inventory, it is advised to use the SWASH model to support the fluid mud measurements in navigation channels and harbour basins. It can be used after only including some minor modifications, and provides opportunities to include more detailed processes. The accuracy of the model is high (multiple vertical sigma layers), while the simulation time is still relatively low.

In order to use the SWASH model to simulate internal waves, the model should be adapted as follows:

1 Add a vertically uniform viscosity and the effect of the ship induced pressure. The model results should than be analysed and compared with the measured data. For SWAN-mud the behaviour of internal fluid mud waves (e.g. dissipation) has been studied quite extensively (Kranenburg et al., 2011). Therefore, it is recommended to compare the behaviour for both models.
2 Add a spatially variable distribution of density and viscosity.
3 If required: implement a two layer model similar to the model of Balkema (2009).

Generally, it is expected that the modifications in the model code itself will not be time consuming. Most of the work will be the analysis of the results and comparisons with SWAN-mud and the measured data. The implementation of the effect of the ship will probably require most effort.

6 Gaps in knowledge

In the former chapters of this report, the parameters and techniques relevant for determining the navigation and manoeuvrability through muddy water bottoms were described. The most important parameters are density and viscosity for the mud and the macrokinematic flow parameters and the thickness of the mud for the behaviour of the ship. Because of the transient state of fluid mud, time dependence is a factor not to be neglected. In chapter 4, however, it became clear that it is not easy to measure the relevant parameters with sufficient spatial coverage and in situ. To repeat Claeys et al. (2011): "we are not there yet". In chapter 5, an innovative concept of using the internal wave to derive relevant parameters for fluid mud is postulated. To establish a proof of concept for this idea, both measurements and models are required.

The field of fluid mud, its behaviour, navigation through it combined with the behaviour of the ship is complex. It is not easy to pinpoint the gaps in knowledge. This is being discussed in various organisations and settings.

From the questionnaire, the in-depth interviews and input from Deltares experts, a preliminary list of general or more specific ideas on knowledge gaps and directions for innovations is formulated. It needs to be stressed that this list is not complete. The knowledge gaps need to be articulated in more detail in the next phase of the project.

6.1 Information from questionnaire and interviews with selected stakeholders

Many stakeholders added remarks in their answers to the questionnaire related to knowledge or to technique that is missing. In the in-depth interviews, the stakeholders formulated general and more specific ideas about what is needed.

The gaps in knowledge can be divided into several subcategories:

- Related to the mud
    - Focus on the strength of the mud rather than on the density.
    - Establish relation between density and other rheological parameters, specific for each location.
    - Need to define threshold values for a set of measurable parameters to detect the acceptable level from the PIANC definition based on behaviour of ships. E.g. instead of a definition of 1.2 kg/L for the Port of Rotterdam, a combination of density and viscosity values need to be defined for a certain harbour for various types of ships.
    - Knowledge of the behaviour of mud plumes.
    - Development of laboratory protocols for measurement of rheological parameters describing mud behaviour. Waterbouwkundig Laboratorium Borgerhout (Belgium) WLB and University KU Leuven (Belgium) developed this protocol. Publication is scheduled for the end of 2013. Measurement of absolute values of (dynamic) viscosity is included in this protocol.
    - Effects of sediment composition and biological activity on e.g. viscosity. This is included in the project "Slib test tank" of Waterbouwkundig Laboratorium Borgerhout (Belgium) WLB, 2013-2015.

- Related to ship's behaviour
    - Study the relation between the behaviour of ships (all aspects) and the most important mud properties (density, viscosity, composition and thickness of the mud layer).

  - Knowledge on friction energy loss and displacement forces, due to movement through the mud. Contribution of the mud layer to the total resistance of the ship.
  - Knowledge on the effect of thermal conductivity of the water, related to cooling water for ship's engines.
  - Need to perform full-scale studies (ship secured with tugs) in real situations.
  - Full-scale test in Delfzijl, conducted by Groningen Sea Ports in 2013. Including manipulation of the mud.

- Related to dynamics
  - Need to do scale studies on the effect of flow with a vertically stratified profile containing water and fluid mud.
  - Input of parameter ranges as observed in reality in computational models.

- Related to time dependency
  - Possibilities for monitoring systems that measure continuously, to increase knowledge on time dependency. Needs to be resilient against dredging activities (dredging-proof).
  - Knowledge about the thixotropy of mud.
  - Effects of consolidation and permeability.

- Related to other aspects
  - Extension from in situ point measurements to line, surface and space measurements.
  - Changes in dredging techniques, e.g. displacement of material in the same area instead of transporting to sea.
  - Possibility of zonation in open sea, confined harbours with different zones (passage or mooring positions) and rivers. Possibly also for time of the year (difference in behaviour during summer and winter).
  - Building with Nature: dredging strategies linked to natural processes. Situation now: dredging of harbour and taking the material out to sea, where natural processes bring it back to the harbour. Possible in future: smarter dredging and relocation, in such a way that natural processes help rather than counteract dredging activities.
  - Various stakeholders are enthusiastic about the idea to use internal waves to characterise fluid mud.
  - How does it all add up? What is the total effect of mud on the dredging costs?

Furthermore, stakeholders formulate the following requirements for innovations:

- A new method needs to be able to measure quickly, reliable, reproducible, in situ, preferably over a line or surface instead of on point locations. It should be robust, easy to handle, easy to transport (across borders).
- Innovations need to be scientifically proven.

In addition to the list above, Deltares identified two more aspects:

- The derivation of certain (relevant) parameters from the various sensors needs to be scientifically proven and documented. The desired parameters are often measured indirectly. The translation from the sensor reading to a value for a parameter needs to be validated. One step further, the derivation of parameters from that first parameter needs to be scientifically sound. For example, the sound velocity in water can be measured directly using a sensor containing a transducer and a reflecting surface. Alternatively, the parameters affecting the sound velocity (temperature, salinity and depth) are measured directly and the sound velocity is calculated by well established formulae.

- There is a need for independent validation of measurement techniques, including a comparison between old established techniques and new emerging techniques. There are some emerging techniques, e.g. free-fall cone penetration test, which many of the stakeholders regard as a promising technique. Their client, however, needs to be convinced that a new instrument is a good alternative to the instrument they are used to.

From this inconclusive list is it clear that there are many unknowns left related to the navigable waterdepth in waterways with muddy water bottoms. The most urgent gaps are related to measurement of absolute viscosity (covered by project of WLB), the translation of mud and flow parameters to ship’s behaviour with the complexity of the memory of the mud (thixotropy) and how does it all add up to reduce dredging costs while maintaining the safety in the waterway.

6.2 Concrete ideas for innovation

Groningen Seaports performs several real scale tests in 2013, sailing with different levels of keel clearance and experiments with manipulation or conditioning of the mud. The goal is to reduce dredging operations by periodic excitation of the mud. Moreover, if sailing through mud proves possible, than either larger ships can enter Delfzijl or dredging can be limited to a smaller depth. In their first experiment of April 2013, an internal wave was observed.

At this stage, another concrete idea for innovation is the use of internal waves to infer relevant parameters of fluid mud. In chapter 5, the steps needed to test this idea are described. In summary, a proof of concept involves the observation of internal waves and measurement by existing techniques. Subsequently, internal waves need to be modelled. The parameters need to be inferred from the measurements and inverse modelling. In chapter 5, it is concluded that the most suitable model available is the SWASH model. Tests for the proof of concept are planned to be performed in December 2013.

A Appendix: Techniques for fluid mud characterisation

Section	Technique	Lab /in situ/ monitor	Method	Measured parameter	Derived parameter	Density	Viscosity	Thickness of fluid mud layer	Yield stress	Time dependent behaviour	Elasticity	Degree of consolidation	Water depth	Else	Spatial coverage	Accuracy (from instrument specifications)
🟩 4.1.1.1	Mass weight by core sample	In situ	Weight a sample with a known volume	Volume and mass	Density	x		x					x		Point measurement (depth profile)	0.001 gr for a mass example 100 gr ; vertical resolution 2-5 cm
🟩 4.1.1.2	Dropping an object with a known density	In situ	Object floating in fluid mud with same density	Object penetration depth	Density	x		x					x		Point measurement	not known
🟨 4.2.1	Dragging instrument on interface between low and high viscosity mud	In situ	Dragging instrument and measure depth	Depth + electrical resistivity	Depth of viscosity transition		x							Depth of rheological transition	Line measurement	not known
🟩 4.1.2	Nuclear probe	In situ	Active radiation	Radiation	Density	x		x					x		Point measurement (depth profile)	Density: ~1%, Depth: ~5 cm
🟩 4.1.3.1	Tuning Fork	In situ	Vibration of one prong induces resonance of other prong	Resonance	Density, viscosity	x	x	x					x		Point measurement (depth profile)	less accurate for non-Newtonian of viscous fluids
🟩 4.1.3.2	Vibration needle	In situ	Vibration	Attenuation of the vibration	Density	x							x		Point measurement (depth profile)	Resolution: 1% and Accuracy: 1%
🟩 4.1.3.3	Vibration tube	Lab	Vibration	Attenuation of the vibration	Density	x									Point measurement	high accuracy
🟥 4.1.4	Dual frequency Single beam Echosounder: 33 & 210 kHz	In situ	Acoustic	First acoustic reflection	Thickness between levels of high impedance contrast(when acoustic velocity is known)			x					x	Water depth defined as top fluid mud of 210 kHz	Line measurement	not known
🟩 4.1.4	24 to 33 kHz (full acoustic signal) combined with calibration	In situ	Acoustic	Acoustic impedances	Depth level of predefined density	x		x					x		Line measurement	not known
🟧 4.1.4	Sub-bottom profiler (1-10 kHz)	In situ	Acoustic	Acoustic reflections	Depth to interfaces of high acoustic impedance contrasts			x?					(x)		Line measurement	vertical resolution: 10-40 cm
🟧 4.1.4	Single beam Echosounder	In situ	Acoustic	First acoustic reflection	Water depth								x	Water depth defined as top fluid mud	Line measurement	Vertical resolution of 2.5-25 cm for pulse length of 0.1-1 ms

Section	Technique	Lab /in situ/ monitor	Method	Measured parameter	Derived parameter	Density	Viscosity	Thickness of fluid mud layer	Yield stress	Time dependent behaviour	Elasticity	Degree of consolidation	Water depth	Else	Spatial coverage	Accuracy (from instrument specifications)
4.1.4	Multibeam Echosounder	In situ	Acoustic	First acoustic reflection	Water depth								x	Water depth defined as top fluid mud	Surface measurement	Vertical accuracy of ~5 cm for top of waterbed, lateral accuracy depends on accuracy of positioning system
4.1.4	Side scan sonar	In situ	Acoustic	Water bottom roughness	Contours of fluid mud at water bottom									Morphology	Surface measurement	Lateral accuracy depends on accuracy of positioning system
4.1.4	Acoustic impedance meter	In situ	Acoustic	Acoustic impedance, sound velocity	Density	x		x					x		Point measurement (depth profile)	Density: 10 g/L, depth: 10 cm
4.1.5	Laser/LIDAR	In situ /Mon.	Laser	Light reflections	Water depth								x	water depth	Surface measurement	
4.1.5	Optical light	Mon.	Camera system application on sea	Migration of land-water boundary	Sea bed dynamics								x?	Water depth/ top fluid mud?	Point measurement	
4.1.5	Turbidity and suspended solids	In situ /Mon.	Infrared light , based on (back)scattering	Content SiO_2 in g/l or % TSS	Density	x		x					x	Turbidity	Point measurement (depth profile)	repeatability <0.015%
4.1.6.1	Geo-electrical	In situ	Electrical (DC currents)	Electrical resistivity	Sediment type, shallow composition, depths to interfaces of high contrasts in electrical resistivity			x?							Line measurement	depends on electrode geometry and salinity of the water
4.1.6.2	Ground penetrating radar	In situ	Electromagnetic	Di-electrical constant, resistivity	Sediment type, shallow composition, depths to interfaces of high contrasts in di-electrical constant			x							Line measurement	depends on frequency of ground penetrating radar and salinity of the water
4.1.7	Pressure sensor	In situ	Pressure sensor	Hydrostatic pressure	Density	x							x	Primarily used to derive depths instead of density	Point measurement (depth profile)	
4.1.8	Heating cable temperature-fibre optics	In situ /Mon.	Heat capacity	Temperature decay curve	Density			x?		x					Line or surface measurement	0.1 deg. Celsius
4.1.8	Temperature-fibre optics	In situ /Mon.	Continuous temperature	Temperature change	Density			x?		x					Line or surface measurement	0.1 deg. Celsius
4.1.9	Friction resistance	In situ	Free fall cone penetration test	Friction resistance	Depth information/Composition(stratification) based on contrasts in friction resistance)	x	x							Friction, shear stress	Point measurement (depth profile)	Density: 2%
4.2	Marsh funnel	Lab	Simple viscosity measurement	Viscosity	Viscosity		x								Point measurement	not known

Section	Technique	Lab /in situ/ monitor	Method	Measured parameter	Derived parameter	Density	Viscosity	Thickness of fluid mud layer	Yield stress	Time dependent behaviour	Elasticity	Degree of consolidation	Water depth	Else	Spatial coverage	Accuracy (from instrument specifications)
🟩 4.2	Rotovisco test	Lab	Rotational rheology measurement	Viscosity	Yield stress and viscosity	x	x		x						Point measurement	~ 25 %
🟩 4.2	Capillary viscometer	Lab		Time taken for fluid to flow between two marks in capillary tube	Kinematic viscosity		x								Point measurement	
🟧 4.3.1	Scholte waves	In situ	Dispersion of surface waves	Seismic velocity and attenuation	Stiffness/shear strength						x	x?		Shear modulus	Line measurement	depends on hydrophone configuration
🟩 4.3.2	Vane test	In situ (on land)/ Lab	Rotating vane	Shear strength	Peak shear strength and residual		x							shear strength	Point measurement	~ 1kPa
🟩 4.3.2	Hydraulic consolidation test	Lab	Sludge consolidation test for low effective stresses	Permeability and compression	Permeability, density and peak shear strength and residual strength	x				x					Point measurement	~ 25%
🟩 4.4	ADCP	In situ	Acoustic doppler	Acoustic backscattering	Flow velocity and water bottom								x	Flow velocity and water depth defined as top fluid mud	Line measurement	0.3 to 0.5 cm/s for flow velocity
🟧 4.7	Radiometry	In situ	Passive radiation	Gamma radiation	Clay content									Composition	Line measurement	not known
🟥 Not discussed	Remote sensing techniques from airplane and satellites	Mon.	Radar	Water surface characteristics	Indirect water depth, not sufficient for quality according to Nederlandse normen voor hydrografie								x?	Water depth/ top fluid mud?	Surface measurement	not known

🟩 High capability
🟧 Moderate capability
🟥 Low capability
🟨 Capability to be determined

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