FIELD SURVEY FOR SEDIMENT PARAMETERS IN MUDDY ENVIRONMENTS

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1 Introduction

Sediment mixtures with a fraction of clay particles larger than about 10% have cohesive properties because electro-statical forces comparable to or higher than the gravity forces are acting between the particles. Consequently, the sediment particles do not behave as individual particles but tend to stick together forming aggregates known as flocs whose size and settling velocity are much larger than those of the individual particles. Most clay minerals have a layered (sheet-like) structure. The most important types of clay minerals are: kaolinite (two-layer structure), montmorillonite (three-layer structure), illite (three-layer structure) and chlorite (four-layer-structure).

Clay is generally defined as sediment with sizes smaller than 0.004 mm (< 4 μm); silt as sediment with sizes between 0.004 and 0.063 mm (4 to 63 μm) and sand as sediment with size between 0.63 and 2 mm (63 to 2000 μm). Mud is defined as a fluid-sediment mixture consisting of (salt) water, sands, silts, clays and organic materials.

In muddy environments there is a continuous transport cycle of mud material consisting of erosion, settling, deposition, consolidation, erosion and so on, see **Figure 1**.

As a result of the complexity and the lack of fundamental knowledge, the description and modeling of the various processes in mathematical models are largely empirical and thus site-specific. Most information is based on laboratory experiments and field surveys. Laboratory results are, however, often not representative because the biogenic mechanisms and the organic materials are missing, the water depths are small, the deposition and the consolidation history of the bed is different from that in nature. Therefore, in-situ field measurements are essential to identify the basic parameters of the most dominant processes at a given site and to reduce the overall mathematical modeling errors involved.

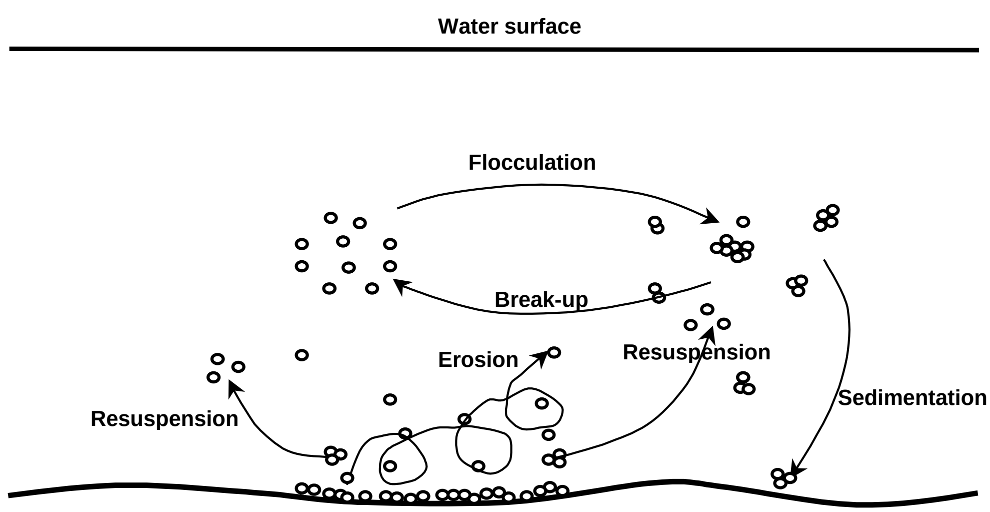


Figure 1 *Transport cycle of mud aggregates*

2 Brief summary of basic mud processes

The most important properties and processes are summarized herein:

- *cohesion, viscosity and yield stress*
- *flocculation,*
- *settling,*
- *deposition,*
- *saturation,*
- *consolidation,*
- *erosion.*

Cohesion

If a cohesive soil sample with a low water content is submitted to shear stresses (τ) under various normal pressures (σ) to the point of failure, the relationship between τ and σ can be expressed as (Law of Coulomb): $\tau=\tau_y+\sigma \tan\varphi$, with τ_y = yield stress and φ= angle of internal friction.
The yield stress is generally interpreted as the "cohesion" of the sample. Thus, a cohesive sediment sample is able to withstand a finite shear stress for σ= 0 (no deformation). The angle of internal friction represents the mechanical resistance to deformation by friction and interlocking of the individual particles.
Plasticity is the property of cohesive material to undergo substantial permanent deformation without breaking.
Dilute suspensions with concentrations smaller than 10 kg/m^3 generally show a Newtonian behavior (linear relationship between shear stress and velocity gradient. Deviations from this latter behaviour tend to occur at concentrations larger than 10 kg/m^3. High-concentration (> 50 kg/m^3) suspensions of water, fine sand, silt, clay and organic material usually have a pseudo-plastic or a Bingham plastic shearing behaviour, which means that the relationship between shear-stress τ and shear rate (du/dz) is non-linear

Flocculation

Most of the individual clay particles have a negative charge. The mutual forces experienced by two or more clay particles in close proximity are the result of the relative strengths of the attractive and repulsive forces. The attractive forces, also known as Van der Waals-forces, are due to the interaction of the electrical fields formed by the dipoles of the individual molecules. The repulsive forces are due to ion clouds of similar charge repelling each other. Positive ions present in the fluid form a cloud of ions around the negatively charged clay particles (double layer theory). The result can be either attraction or repulsion depending on the relative strengths (depending on number of positive ions) and the distance between the particles. In fresh water suspensions (few positive ions) the repulsive forces between the negatively charged particles dominate and the particles will repel each other. In saline water the attractive forces dominate due to the (abundant) presence of positive sodium-ions forming a cloud of positive ions (cations) around the negatively charged clay particles resulting in the formation of flocs (aggregates).
Other binding forces are chemical forces (hydrogen bonds, cementation, coatings of organic materials).

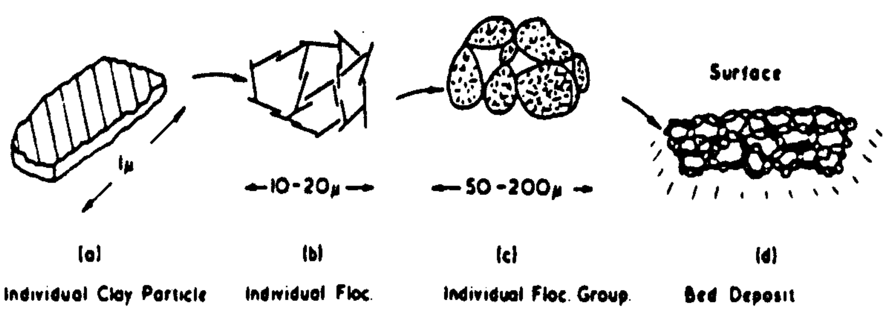


Figure 2 *Sizes of individual clay particles, flocs and floc groups*

The presence of organic materials in and on the flocs significantly intensify the flocculation process, because of the binding properties of the organic materials. The binding forces become larger due to the presence of organic material (biogenic forces) and the flocs are becoming larger.
Break up of the flocs is caused by large shearing forces in the fluid when these forces are larger than the strength of the flocs; the flocs are broken into smaller flocs or particles. Large shearing forces exist close to the bottom where the velocity gradients are largest. Large shearing forces also exist in small-scale eddies everywhere in the fluid. Under the influence of turbulent forces there is a continuous process of flocculation and break-up resulting in a dynamic equilibrium of the flocs (size, density and strength).
Analysis of under-water photographs shows the presence of macroflocs with sizes in the range of 0.1 to 1 mm, miniflocs with sizes in the range of 0.01 to 0.1 mm and single mineral particles smaller than about 0.01 mm (see **Figure 2**).
When the flocs grow larger, the floc size increases but the density of the flocs (consisting of sediment, fluid, organic materials) becomes smaller. Individual clay particles will have an excess density of about 1600 kg/m^3. Large flocs of about 1 mm may have a density in the range of 1 to 10 kg/m^3 in excess of the fluid density, because most of the floc consists of (pore) fluid.

Settling

An important parameter in sedimentation studies of cohesive materials is the settling velocity of the flocs. Analysis of laboratory and field data has shown that the settling velocity of the flocs is strongly related to the salinity and the sediment concentration.
In saline suspensions with sediment concentrations up to about 1000 mg/l an increase of the settling velocity with concentration has been observed as a result of the flocculation effect both in laboratory and in field conditions.
When the sediment concentrations are larger than approximately 10,000 mg/l, the settling velocity decreases with increasing concentrations due to the hindered settling effect. Hindered settling is the effect that the settling velocity of the flocs is reduced due to an upward flow of fluid displaced by the flocs. At very large concentrations the vertical fluid flow can be so strong that the upward fluid drag forces on the flocs become equal to the downward gravity forces resulting in a temporary state of dynamic equilibrium with no net vertical movement of the flocs. This state which occurs close to bed, generally is called fluid mud. In the laboratory the hindered settling velocity can be quite accurately determined from consolidation tests by measuring the subsidence of the sediment-fluid interface.
Settling velocities based on in-situ settling measurements as a function of concentration in saline conditions from all over the world are shown in **Figure 3** (Severn, Avonmouth, Thames, Mersey in England; Western Scheldt in The Netherlands; River Scheldt in Belgium; Brisbane in Australia; Chao Phya in Thailand, Demerara in South America; Van Rijn, 1993).

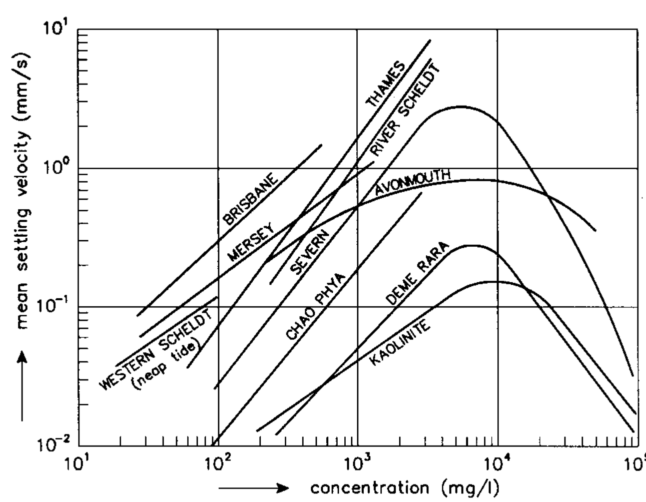


Figure 3 *The influence of sediment concentration on the settling velocity*

Deposition

Deposition is predominant when the bed-shear stress falls below a critical value for deposition (τ_d).

Basically, two critical bed-shear stresses for deposition can be distinguished: lower (minimum) value $\tau_{d,min}$ and upper (maximum) value $\tau_{d,max}$. All sediment will settle out if the applied bed-shear stress is smaller than the lower value: $\tau_b<\tau_{d,min}$. No sediment will settle out if the applied bed-shear stress is larger than the upper value: $\tau_b>\tau_{d,max}$. Partial deposition of the larger flocs and particles will occur for: $\tau_{d,min}<\tau_b<\tau_{d,max}$.

Experimental values of $\tau_{d,min}$ are in the range of 0.05 to 0.15 N/m^2; experimental values of $\tau_{d,max}$ are in the range of 1.5 to 2 N/m^2.

Saturation

When the velocities are decreasing after peak flow in tidal conditions, the sediments start to settle to form a layer of fluid mud, creating a two-layer fluid system. At the interface between the two layers, vertical turbulent mixing is damped strongly resulting in an overall decrease of the sediment-carrying capacity in the water column. At a certain moment the turbulence field collapses and the sediment concentrations are greatly reduced. The mud concentration just prior to this collapse is denoted by the term 'saturation concentration'. The conditions with concentration larger and smaller than the saturation concentration are defined as supersaturation (overloading) and subsaturation (underloading). The concept of the saturation concentration for cohesive sediment is based on empirical evidence that when the flux Richardson number at a specific level in the water column exceeds a critical value (of about 0.2), the turbulent field collapses above this level.

Consolidation

The increase or decrease of the fluid-bed interface is equal to the rate of deposition (from the suspension) or erosion minus the rate of consolidation (of the bed). Consolidation is a process of floc compaction under the influence of gravity forces with a simultaneous expulsion of pore water and a gain in strength of the bed material.

The consolidation process is strongly affected by the:

- initial thickness of the mud layer (h_o),
- initial concentration of the mud layer (c_o),
- permeability (k) of the mud layer (sediment composition and size, content of organic material, salinity, water temperature).

The consolidation of natural muds proceeds relatively fast in a thin layer and relatively slow in a thick layer. Mud samples with a low initial density tend to have a somewhat lower final density than the samples with the higher initial density.

Erosion

Sediment particles, flocs or lumps of the bed surface (including fluid mud layers) will be eroded when the applied current-induced or wave-induced bed-shear stress (τ_b) exceeds a critical value for erosion (τ_e), which depends on the bed material characteristics (mineral composition, organic materials, salinity, density etc.) and bed structure. Experimental results show that the critical bed-shear stress for erosion is strongly dependent on the deposition and consolidation history.

The critical bed-shear stress for erosion is (by many researchers) found to be larger than the critical bed-shear stress for full deposition ($\tau_e >\tau_{d,min}$). Experimental work shows partial deposition (and no erosion) of mud material for (high) bed-shear stresses up to 1.5 N/m² in steady flows, because the bed consisted of strong dense flocs deposited during high-shear conditions in which the weak flocs could not be deposited. Thus, τ_e may be very large when the top layer of the bed consists of strong flocs deposited at relatively high velocities ($\tau_e >\tau_{d,max}$).

In tidal conditions with decreasing velocities (near slack tide) the weak flocs will be deposited on top of the strong flocs deposited earlier at higher velocities. At increasing velocities of the next tidal cycle, these weak flocs can be eroded rather easily at low velocities.

Various types of erosion are distinguished in the literature: (i) particle or floc erosion (surface erosion) which is the one by one removal of particles and/or aggregates and (ii) mass erosion which is the erosion of clusters or lumps of aggregates due to failure within the bed. Many attempts have been made to relate the τ_e values to basic parameters as plasticity index, voids ratio, water content, yield stress and others. Generally-accepted relationships, however, are not available. Determination of the τ_e values must, therefore, be based on laboratory tests using natural mud or on in-situ field tests.

Transport of mud in tidal flow

Erosion of mud will occur in accelerating tidal flow when the applied bed-shear stress exceeds the critical value for erosion ($\tau_b > \tau_e$). Similarly, deposition will take place in decelerating flow when the applied bed-shear stress falls below the critical value for deposition ($\tau_b < \tau_{d,max}$). Deposition is maximum around slack water because the floc destruction due to turbulent shear stresses is minimum and floc growth due to differential settling is maximum. As a result of these processes the mud concentrations vary in time and space. The concentrations decrease near the slack water period (deposition) and increase towards maximum flow (erosion). Maximum concentrations generally occur at a certain (lag) period after maximum flow because it takes time to transport the particles or flocs to the upper layers. The lag period is relatively large near the water surface and relatively small near the bottom. The small settling velocities of the individual particles prevent settling of all particles during slack water. Thus, the concentration remains always larger than zero (background concentration).

The spring-neap tidal cycle may have a marked influence on the vertical structure of the mud suspension. During spring tides the flow velocities are relatively large resulting in a nearly uniform (or well-mixed) mud concentration distribution at maximum flood and ebb velocities and the formation of fluid mud interfaces (lutoclines) near the bottom during slack water. During neap tides the tidal velocities are generally too small to cause erosion at the near-bed fluid mud layer; the fluid mud layer may survive several tidal cycles as a stationary layer.

In (partially) stratified estuaries the maximum silt and mud concentrations are usually found in the region where the salt wedge is migrating during the tidal cycle. This region is known as the turbidity maximum. Heavy sedimentation will occur in the salt wedge region resulting in the formation of soft mud layers (fluid mud) on the channel bottom.

During the ebb tide, the river flow erodes the landward end of the mud layer. Near the toe of the salt wedge the fresh river water is lifted from the bottom and flows seaward over the heavy saline water. Intensive mixing will occur at the interface between the fresh and saline water. In the salt wedge the bottom current is landward. This saline water meets the fresh water near the toe of the salt wedge where it is carried upwards.

The mud carried by the river enters the area of the salt wedge together with the mud eroded from the landward end of the mud layer. This mud is mixed (near the interface) with mud already suspended in the saline water resulting in additional flocculation and increased settling velocities. Settling will occur seaward of the sharp salt wedge interface where the mixing is reduced. The mud particles fall towards the bottom where they are transported landward again by relatively strong bottom currents of saline water. Summarizing, there are relatively strong landward bottom-currents with high mud concentrations during flood tide and relatively weak seaward bottom-currents with low mud concentrations during ebb tide resulting in a net transport of mud in landward direction.

Generally, a three-layer system will occur in estuaries (see **Figure 4**), as follows:

- *Consolidated mud layer* at the bottom with concentrations larger than about 300 kg/m³. The flocs and particles are supported by the internal floc framework.
  The mud interface is detectable by echosounding instruments (30 kHz).
- *Fluid mud suspension layer* with concentrations in the range of 10 to 300 kg/m³. The layer thickness is of the order of 0.1 to 1 m in normal conditions and up to 5 m in extreme conditions. Marked interfaces (lutoclines) can be observed from echosounder recordings or from nuclear density (gamma ray) recordings. The flocs and particles in the fluid mud layer are supported by fluid drag forces exerted by the escaping fluid (hindered settling effect). The fluid mud layer can be subdivided into a turbulent upper layer (mixed fluid mud; 10 to 100

kg/m³) and a laminar (viscous) lower layer (100 to 300 kg/m³), depending on conditions. The turbulent upper fluid mud layer will try to (i) mix mud from the laminar lower layer into the upper turbulent layer and (ii) mix fluid from the upper dilute suspension layer into the fluid mud layer if the upper fluid mud layer is more turbulent than the dilute suspension layer (in accelerating spring tide flow). This results in a decreasing concentration in the upper fluid mud layer and a rise of the upper interface between the dilute layer and the fluid mud layer. If the dilute suspension layer is more turbulent than the fluid mud layer (in neap tide flow), the fluid mud layer will be relatively thin (much more stratified) and mud will be mixed up from the fluid mud layer into the dilute suspension layer by vortices from that layer. Stratified fluid mud near the bed is enhanced by salinity stratification during neap tide (damping of turbulence) at the frontal zone between river water and sea water.

- *Dilute mud suspension* with concentrations in the range of 0 to 10 kg/m³ (see Figure 4) which are detectable by optical methods and mechanical sampling. Mud will be mixed into dilute suspension layer from the fluid mud layer if the the upper dilute layer is more turbulent than the fluid mud layer. Flocculation is dominant in the dilute suspension layer. The flocs and particles are supported by turbulence-induced fluid forces and transported by tide-driven and wind-driven currents.

Vertical layers of different densities are influenced by gravity processes which oppose the mixing processes. The stability of the system can be characterized by the gradient Richardson number (Ri). For Ri larger than unity (based on experimental data) a stable system will be present (interfacial instabilities will die out).

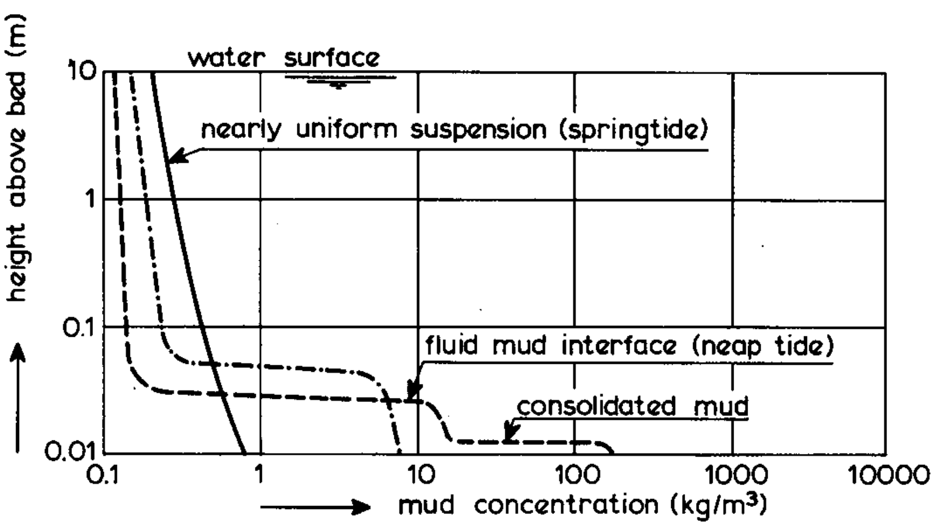


Figure 4 *Vertical distribution of mud concentrations*

3 Main parameters and instruments

Mathematically, the transport of silt and mud in a stratified estuary can only be described by the time-dependent three-dimensional convection-diffusion equation. The erosion of bed material is represented by an erosion function specifying the erosion rate at the bed. The settling effect is represented by the settling velocity. The threshold values for deposition and erosion can be determined by calibration using measured mud concentrations. In 3D models the representation of the vertical variation of the settling velocity due to flocculation and hindered settling effects is essential. Flocculation and hindered settling can be taken into account if measured settling velocities are available. The entrainment function describing the exchange processes at the bed is of essential importance. Calibration requires the measurement of mud concentrations close to the bed.
At present stage of knowledge most of the parameters involved are site specific and have to be determined by field measurents.

A field survey in muddy environment should focus on the following set of parameters:

- **mud concentrations at three points (near-bottom, mid-depth and near-surface) above the bottom as function of time over the tidal cyle (13 hour measurements) at key locations within the estuary and coastal zone;**

- **particle size distribution of bed samples and suspended samples at key locations;**

- **in-situ settling velocity at three points above the bottom during slack tide and during maximum flow at key locations;**

- **in-situ dry density of bed deposits at key locations;**

- **fluid mud determination by sailing echo-sounding tracks.**

3.1 Mud concentrations

Basically, three types of instruments are available to determine the variation of the mud concentrations over the depth and over the tidal cycle at a selected location, as follows:

- mechanical trap to collect instantaneous water-mud samples,
- mechanical pump sampler to collect time-averaged water-mud samples,
- electronic optical and acoustical sensors to collect continuous data of mud concentrations.

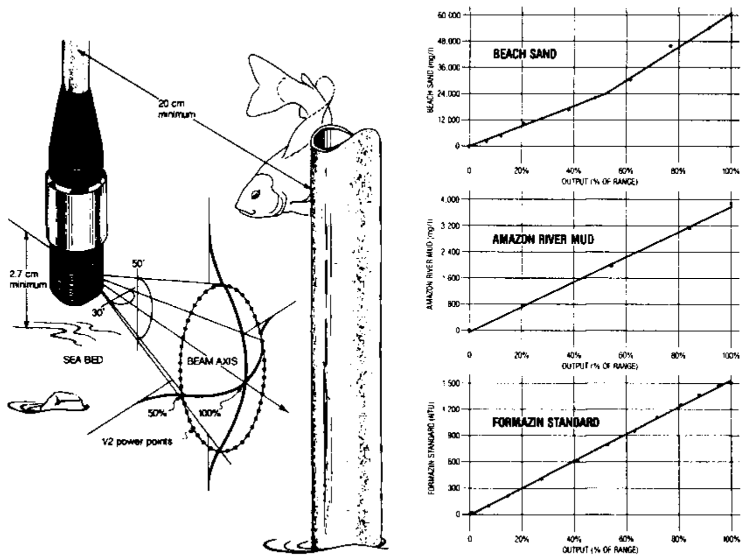
It is most efficient to use both optical, acoustical and mechanical samplers to determine the mud concentrations. Optical and acoustical sensors are very efficient to collect time series of data, whereas mechanical sampling can be used to regularly take water-mud samples for calibration purposes.

3.1.1 Optical samplers

Optical sampling methods enable the continuous and contactless measurement of sediment concentrations, which is an important advantage compared to the mechanical sampling methods.

Optical sampling methods are most suitable for silt particles (< 63 μm). Laboratory experiments using an optical sampler, have shown that the addition of sand particles with a concentration equal to the silt concentration increased the output signal with about 10%. The upper concentration limit for optical samplers is about 25,000 mg/l.

Accurate results using optical samplers require an in-situ calibration, if possible under representative flow conditions covering the entire range of flow velocities and measuring positions (close to bed and water-surface).
To minimize synchronity errors, the optical and mechanical samples should be taken at the same time and at the same point above the bottom.



A. OBS SENSOR B. CALIBRATION CURVES

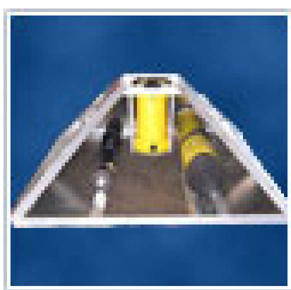
Figure 5 *OBS-instrument (www.d-a-instruments.com; www.seapoint.com)*

A good example of an optical sensor is the OBS (Optical Backscatter Sensor), which is a small optical sensor for measuring turbidity and suspended solids concentrations by detecting infrared light scattered from suspended matter (see **Figure 5A and 5B**). The diameter of the sensor is about 0.02 m (see **Figure 5**); the length is about 0.05 m. The response of the OBS sensors strongly depends on the size, composition and shape of the suspended particles. Experimental work shows that the OBS response to clay of 2 μm is 50 times greater than to sand of 100 μm of the same concentration. Hence, each sensor has to be calibrated using sediment from the site of interest. The sampling frequency generally is 2 Hz.
The performance of the OBS-sensor is claimed to be superior to most other in-situ turbidity sensors, because of: small size and sample volume, linear response and wide dynamic range, insensitivity to bubbles and phytoplankton, ambient light rejection and low temperature coefficient and low cost.
OBS sensors are supplied by D&A instruments (www.d-a-instruments.com) and by Seapoint-instruments (www.seapoint.com).

3.1.2 Acoustical backscatter sensors

Acoustic backscatter (ABS) measurement is a non-intrusive technique for the monitoring of suspended sediment particles in the water column. An acoustic backscatter instrumentation package comprises acoustic sensors, data acquisition, storage and control electronics, and data extraction and reduction software. Smaller frequencies (0.5 MHz) are better suited for the mud range and larger frequencies (4.5 MHz) for the sand range. An overview of the ABS-technique is given by Smerdon, Rees and Vincent (www.aquatecgroup.com). Shi et al. (1999) have used an 0.5 MHz ABS to detect the mud concentrations in the Yangtze (Changjiang) Estuary in China with concentrations up to 5 gr/l.

The basic principle of the acoustic backscatter approach is that a short pulse (10 μs) of acoustic energy is emitted by a sonar transducer (0.5 to 5 MHz). As the sound pulse spreads away from the transducer it insonifies any suspended material in the water column. This scatters the sound energy, reflecting some of it back towards the sonar transducer, which also acts as a sound receptor. With knowledge of the speed of sound in water, the scattering strength of the suspended material and the sound propagation characteristics, a relationship may be developed between the intensity of the received echoes and the characteristics of the suspended material. With typical acoustic ranges in excess of 1 metre, the acoustic head remains outside the area of study and therefore makes the instrument non-intrusive. The magnitude of the backscattered signal can be related to the sediment concentration, particle size and the time delay between transmission and reception. The acoustic backscatter intensity from a uniform field of particles of constant concentration is assumed to be an inverse function of the distance from the source with corrections for attenuation due to water and particles. Calibration in uniform suspensions is required to find this relationship.



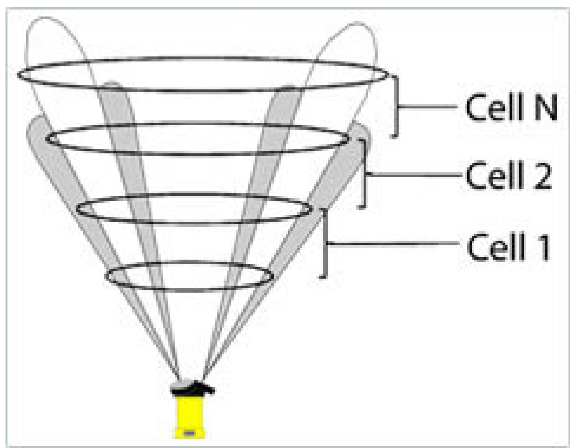


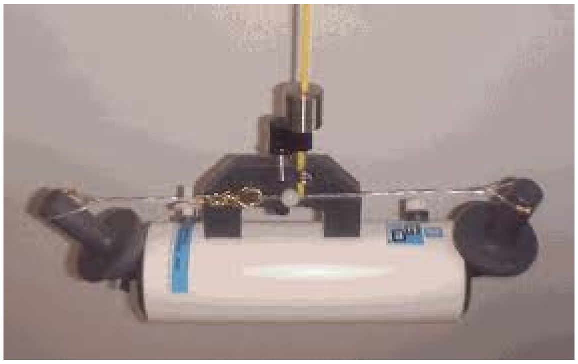
Figure 6 *ADCP in bed-mounted frame or tripod*

Acoustic Current Doppler Profilers (ADCP) are standard instruments (single frequency of about 0.5 to 1 MHz) for measuring velocity profiles either from a bed-mounted frame or tripod (upward profiling; **Figure 6**) or from a ship (stationary or drifting downward-profiling). ADCP can also provide data of suspended sediment concentrations using the echo intensity signal of scattered sound energy (Wall et al, 2006). Hence, ADCP can produce simultaneous data of velocity and concentration, which is a great advantage of this instrument. However, the software for measuring concentrations is limited and considerable post-processing is required by specialized staff. Furthermore, intensive field calibration based on water-sediment samples is required to obtain accurate results.

ABS and ADCP deployed in a frame or tripod standing on the bed are very efficient to provide the variations in sediment transport over the spring-neap tidal cycle. The downward-profiling ABS covers the the near-bed zone and the upward-profiling ADCP covers the water column. Although the data may not be very accurate in absolute sense (if calibration is absent), the normalized data are very valuable in relative sense (spring-neap cycle variations).

3.1.3 Mechanical trap sampler

The basic principle of all mechanical bottle and trap samplers (**Figure 7**) is the collection of an instantaneous water-sediment sample to determine the local sediment concentration, transport and/or particle size by physical laboratory analysis. The sample volume should be about 3 liters.



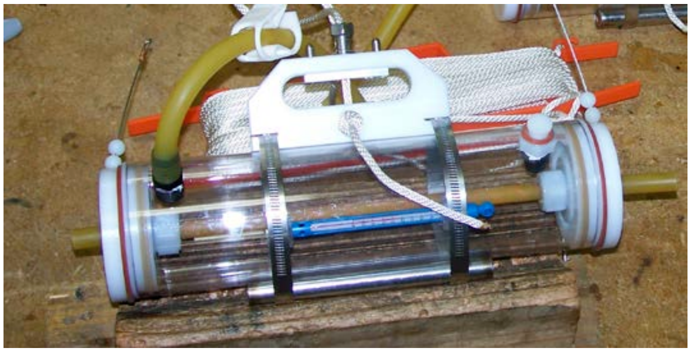


Figure 7 *Water-mud trap samplers (left:www.generaloceanics.com; right: length=0.43 m; diameter=0.1 m, www.wiertsema.nl)*

Accurate sampling of a water-sediment volume by means of a mechanical instrument requires an intake velocity equal to the local flow velocity (iso-kinetic sampling) or a hydraulic coefficient, defined as the ratio of the intake velocity and local flow velocity, equal to unity (hc=1).
Differences between the intake velocity and local flow velocity result in sampling errors. Sampling at a lower velocity than that of the ambient flow would result in a higher sediment concentration than present in the flow due to diverging flow lines, which cannot be followed by the sediment particles, being of higher density than the water particles. Conversely, sampling at a higher velocity than that of the ambient flow would result in a lower sediment concentration. The magnitude of error due to incorrect intake velocities in mud suspensions are relativelty small (<5%).
A trap sampler often consists of a horizontal or vertical cylinder equipped with end valves which can be closed suddenly (by a messenger system) to trap a sample instantaneously. The sampler is lowered to the desired point.
Many samples have to be taken to obtain accurate mean values. This is a problem in rapidly varying tidal flow with continuously changing mud concentrations.
Time-averaging can be efficiently obtained by using a pump sampler to take water-mud samples.

3.1.4 Mechanical pump sampler

In tidal flow an efficient measuring period is about 2 to 5 minutes to average out the turbulent fluctuations.
Usually a pump sampler consists of a submergible intake nozzle, a deck-mounted pump and a flexible hose connecting the intake nozzle and the pump. The hose diameter should be as small as possible to reduce the stream drag on the hose. In case a deck-mounted pump is used the maximum suction lift will be about 7 m. Assuming a static lift (= height of pump above water level) of about 2 m, the suction lift available for operation of the pump will be about 5 m resulting in a maximum hose length of about 50 m (Van Rijn, 2007).
Peristaltic pumps (24 volt/220 volt) (see www.globalw.com; see **Figure 8**) have proven to be very efficient for pump sampling in river and coastal conditions. The discharge is relatively small (0.5 to 1 litres/min) yielding a relatively small water-sediment sampling which can be handled easily. The hose diameter is extremely small (6 mm), which reduces the fluid drag forces on the hose. The pump direction can be easily changed to remove small objects (shell fragments, organic materials, etc.) blocking the intake nozzle. The maximum hose length is about 50 m using a deck-mounted pump, which enables sampling in channels with flow depths upto 25 m.

The pump intake nozzle combined with the OBS, a current meter and an echo-sounder or pressure sensor (for vertical position determination) should be combined onto a small submergible instrument carrier (small streamlined/fish-type body), see **Figure 9**.
This set-up produces the most accurate results of local sediment transport from bottom to surface over the tidal cycle of 13 hours at a fixed anchor station. Measurements very close to the bed can be made by placing the carrier onto the bed (**Figure 9**).

Figure 8 *Small peristaltic pump SP200 (1 litre per 2 minutes; www.globalw.com)*

Figure 9 *Instrument carrier with pump intake nozzle, current meter, echo-sounder or pressure sensor for vertical position.*

3.2 Particle size distribution of bed and suspended samples

3.2.1 Bed samples
Grab-type samplers can be used to collect a surface sample of the compacted bed material. Grabs are applicable when the bed material consists of non-cohesive sandy material or firmly deposited mud materials. A relatively simple sampler is the VAN VEEN grab (**Figure 10 left**).

Samples of soft deposits can be taken by using a box-core type of grab (**Figure 10 bottom**) or by a gravity drop corer with a length of the order of 1 m (**Figure 10 right**).
The Ekman Box-core type sampler (volume=3.5 litre; 0.15x0.15x0.15 m^3) is designed for sampling in soft bottomed lakes and rivers composed of muck, mud or fine peat. As the sampler is lowered, two hinged upper lids swing open to let water pass through and close upon retrieval preventing sample washout. When the

sampler reaches the bottom, a messenger is sent down the line tripping the overlapping spring-loaded scoops. Each sampler is constructed of stainless steel including the springs, cables and fasteners. Also available is a 1.5 to 3 m extension handle for operating the sampler in shallow water instead of a cable and messenger. The sampler is also available as a kit which includes stainless 300 gm messenger, 30 m cable and carrying case (ordered separately).

Drop corers generally produce relatively long, disturbed samplers. In the case of stratified bed material or deposits only corers should be used. Core sampling consists of driving a tube into the bed material through the use of gravity. Free-fall corers can cause compaction of the vertical structure of the sediment samples, while shock waves generated ahead of the descending sampler may wash away the fine fraction of the sediment bed. The latter effect can be minimized by using samplers with openings to create a flow-through system during descent.

Samples of soft deposits can also be taken using divers. The diver should swim to the bed and push a pvc tube with length of about 0.3 m and diameter of 0.04 m vertically into the bed. The tube can be simply closed on both sides by the diver using rubber stops or corks.

Figure 10 *Left=Van Veen grab sampler and right= gravity drop corer (www.kc-denmark.dk); Bottom= Ekman-box core grab (www.eijkelkamp.com; www.rickly.com)*

3.2.2 Suspended sediment samples

Suspended sediment samples can be simply taken from the samples using the trap method or the pump method.

3.2.3 Particle size determination

The basic particle size distribution of bed samples and suspended samples can be determined in the laboratory by using electronic particle sizers based on the Laser-diffraction method (www.malvern.com; www,beckmancoulter.com). Small subsamples should be taken and fully dispersed and treated with commercially available deflocculants (sodium carbonates) to break down flocs.

3.3 In-situ settling velocity

Suspended sediment particles and associated settling velocities in estuaries and coastal seas generally consist of solid and aggregated (flocs) materials. In-situ measurements of sediment particles and flocs in these conditions is essential as natural flocs are disrupted easily by physical manipulation such as sampling by bottles or pumps. The true settling velocity of natural flocculated suspended sediments can only be achieved by in-situ systems. This can be done by means of:

- in-situ settling tubes,
- in-situ video or photocamaras,
- in-situ Laser-diffraction instruments.

3.3.1 In-situ videocameras and Laser-diffraction instruments

In-situ video camera instruments geneally consists of a small vertical tube with a closed end at the bottom in which particles are settling down in still water. Two small windows are present in the tube for enlighting (light beam) and for video-recordings. The instrument is connected by a signal cable to the survey ship which floats with the current during sampling. Floc sizes and settling velocities are obtained from the recordings by computer analysis.
Various instruments are available to determine the concentration, particle/floc size and settling velocity of suspended sediments based on the laser-diffraction method (LISST-instruments, www.sequoiasci.com; **Figure 11**).

Figure 11 *LISST-STX instrument (www.sequoiasci.com)*

The LISST-100X is a submersible instrument which delivers the size distribution of suspended sediments in 32 logarithmically spaced size classes. The LISST-STX is a submersible field instrument developed for in-situ observation of the size-dependent settling velocity distribution of suspended particles. It incorporates a mechanized settling column. In a settling experiment, a water sample is drawn and trapped. The evolution of the size distribution near the base of the settling column during the settling experiment is interpreted to estimate settling velocities. The LISST-STX is an extended version of the LISST-100X, with an added settling tube

(ST stands for Settling Tube). This instrument is designed to perform submerged settling experiments to obtain settling velocities of 8 size classes.

3.3.2 In-situ settling tube

Mechanical in-situ settling tubes are based on the settling of suspended sediments from a uniform suspension in a small tube, which is used for both sediment sampling and setlling. The sediment concentration at a certain depth of the tube can be determined by withdrawing small subsamples samples at that height. Usually, eight or nine subsamples are withdrawn.

The most simple method is to take a water-mud sample by using a trap sampler (see **Figures 7** and **12**). The trap sampler is lowered from the survey boat to the sampling point in a horizontal position with opened valves. After closing the valves, the tube is raised. On board of the survey boat, the water-mud sample is poured into a separate settling column (length = 0.4 m; internal diameter= 0.1 m; double wall in tropical conditions) with a closed bottom and a tap at 0.07 m above the bottom. The suspension in the column should be stirred carefully by a wooden stick with a perforated bottom plate to create a homogeneous suspension after which the settling process starts (start of clock). Small subsamples of 50 ml are taken from the tap (0.07 m above the bottom) at pre-fixed times (t=0, 3, 6, 10, 20, 40, 60, 120 minutes). The basic principle of this method is to determine the decreasing sediment concentrations of an initially uniform suspension (dispersed system) at a pre-fixed point (depth) below the water surface as a function of settling time. Particles having a settling velocity greater than the ratio of the depth and the elapsed time period will settle below the point of withdrawal after the elapsed time period. The precise analysis method is described by Van Rijn (2007, 2016).

Figure 13 shows an example of measured settling velocities of flocculated and non-flocculated mud. The latter has been determined using the SEDIGRAPH III-instrument after mixing the sample with peptizer (for defloccution).

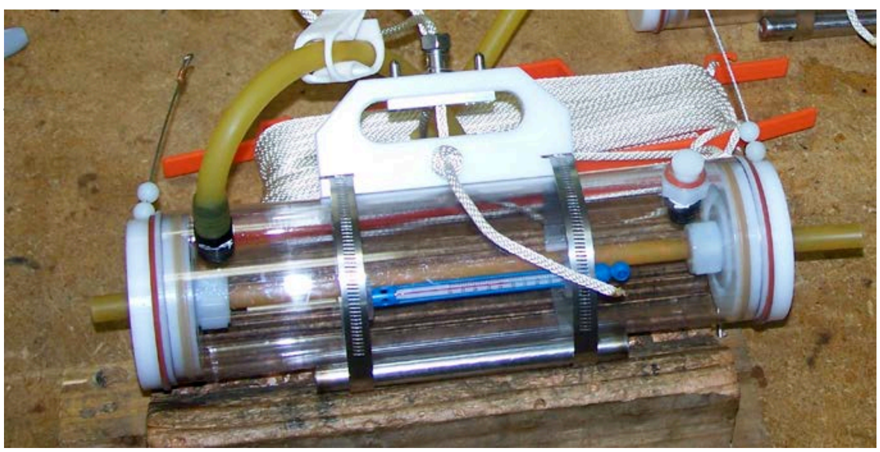


Figure 12 *Sampling tube and settling column for in-situ settling velocity (WASED; www.wiertsema.nl)*

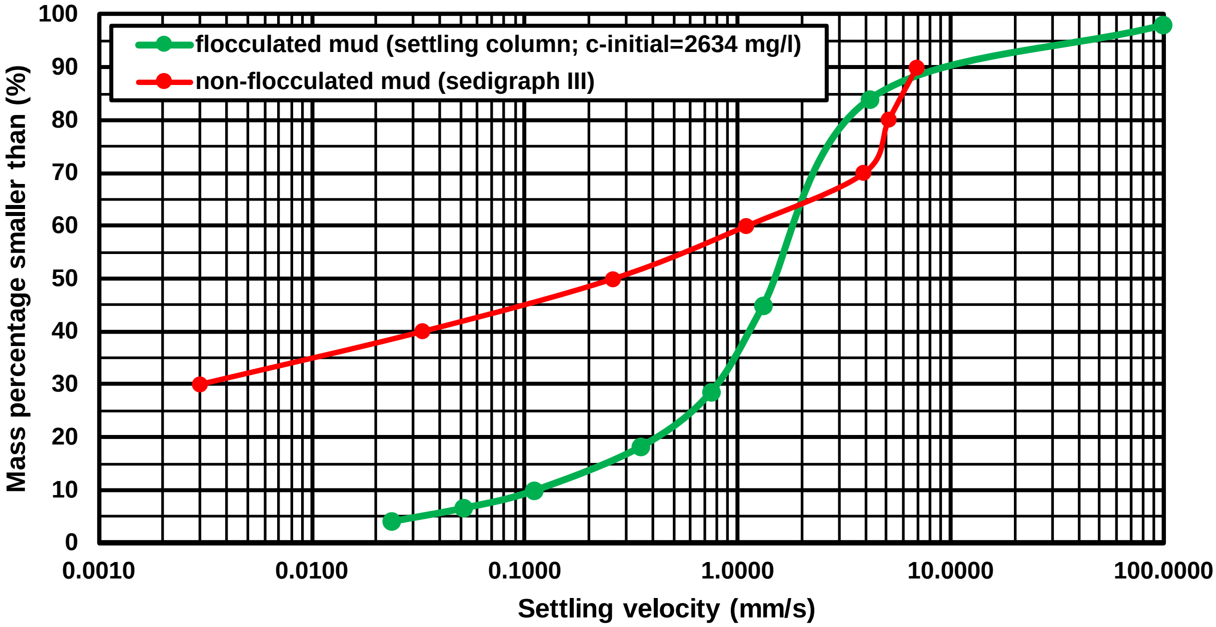
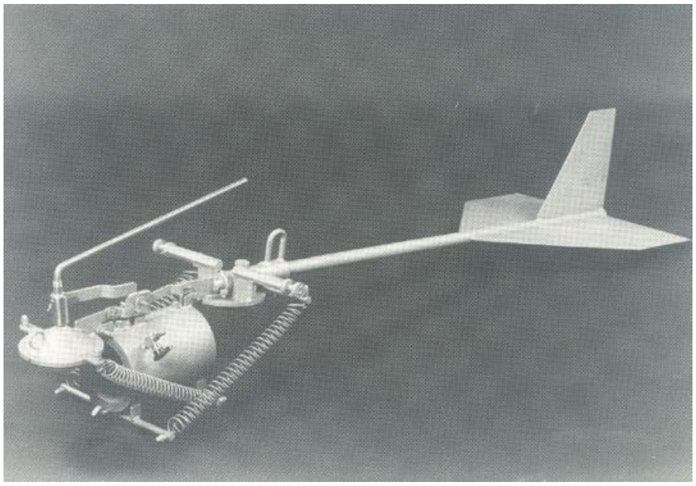


Figure 13 *Settling velocities of flocculated and non-flocculated mud; Noordpolderzijl, Netherlands*

A more sophisticated instrument is the FIPIWITU field instrument of Deltares (see **Figure 14**) which consists of a stainless steel tube (double wall) with a length of about 0.3 m and an internal diameter of 0.12 m. The tube is used for sample collection as well as for the determination of the fall velocity distribution by means of a settling test. Therefore, the tube is equipped with two valves on both ends and a double wall for temperature control. The tube is lowered from the survey boat to the sampling position in a horizontal position with opened valves. After closing the valves, the tube is put in a vertical position (start of settling process, t= 0) and raised. On board of the survey boat small water-sediment withdrawals (subsamples) are taken at pre-fixed times.



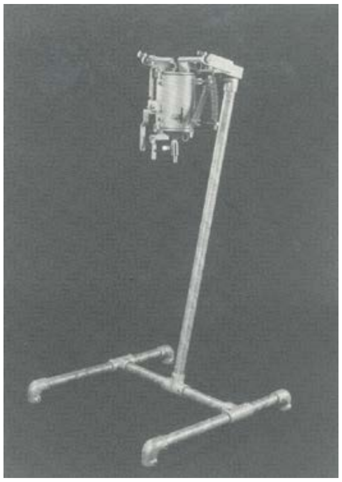


Figure 14 *In-situ settling tube (FIPIWITU); left=sampling position; right= settling position*

Both the in-situ videocameras and the laser-diffraction instruments may not give optimum results in muddy environments with relatively high mud concentrations reducing the light penetration of the samples. Furthermore, these instruments are highly sophisticated instruments, which need the experience of specialized technicians.

3.4 In-situ dry density of bed deposits

In deposition and navigation depth studies of muddy areas the dry density defined as the dry mass of the water-sediment mixture per unit volume is an important parameter.
Various methods are available to determine the dry or wet bulk density: mechanical core sampler, acoustic sensor, nuclear radiation sensor (gamma ray sensor), vibrating fork sensor and electric conductivity sensor. These sensors are also known as densimeters.
Electric conductivity probes and pressure transducer probes are not generally applicable. Electric conductivity probes are very sensitive to the fluid salinity which should be known beforehand. Pressure and vibration transducer probes can only be used in unconsolidated fluid muds (low density < 1200 kg/m^3). Nuclear radiation sensors (gamma ray sensor) can only be operated by specially trained staff, rigid safety controls and special licenses. Herein, only mechanical, acoustical and vibration methods are discussed.

3.4.1 Mechanical core sampler

A basic requirement is undisturbed sampling of bed material. Various mechanical box-core and gravity core-samplers are available to take undisturbed bed material samples of the surface layers (upper 0.5 m of the bed), see **Section 3.2.1**. Most samplers can only be used during low velocity conditions to ensure vertical penetration of the bed. After sampling, it is common practice to make slices by a machined ring of the same internal diameter as the core. The core content is extruded into the ring until it is full of the water-sediment mixture. A thin plate is then introduced between the ring and the core to isolate the sample. As the core diameter is known and fixed and the slice thickness is fixed by the ring, the volume can be calculated.
Bed deposit samples can also be taken using a diver pushing a plastic tube (length=0.3 m, diameter = 0.04 m) into the soft bed, see **Section 3.2.1**. Preferably, the tube should be pushed vertically into the bed, but if the bed too compacted it can also be pulled horizontally through the upper layer of the bed.

The mass of the sample (M) can be simply weighed on board of the survey boat using a digital scale. As the volume is known from the dimensions of the pvc tube, the dry mass (ρ_{dry}) of the sediment volume can be determined from the relationship:

$$\rho_{dry} = M_s/V = \rho_s V_s/V$$

with: M_s= sediment mass in sample, V_s= volume of sediment= $(M-\rho_w V)/(\rho_s-\rho_w)$, V= volume of sample tube, M= mass of sample (water and sediment) ρ_s= sediment density (2650 kg/m^3), ρ_w = fluid density of seawater (1030 kg/m^3).

Some samples can be returned to the laboratory to determine: the precentages sand, silt and clay and the particle size distribution.

3.4.2 Acoustic densimeter

Acoustic instruments are composed of acoustic transducers producing a series of acoustic waves. An envelop sound detector connected to a micro-processor is used to process the received signal, which is compared with the signal in clear water. Calibration of the instrument is required. The linear dry density range is in the from

100 to 500 kg/m^3 (wet density of 1050 to 1300 kg/m^3) with an inaccuracy of ± 30 kg/m^3. Deltares has produced the UHCM sensor for this range of densities. The instrument can be lowered and raised by a winch for vertical measurements. A pressure sensor can be used for determination of the vertical position. The sensor can also be attached to a submersed carrier and towed horizontally through fluid mud layers to determine the bed density.

3.4.3 Vibration fork densimeter

A vibrating fork (www.viscoanalyser.com; www.odomhydrographic.com) is a sensor with two small legs; one leg sends out a vibrating signal, while the response vibration frequency of the other leg is measured and analysed to produce a density value based on calibration using local sediments (**Figure 15 left**).

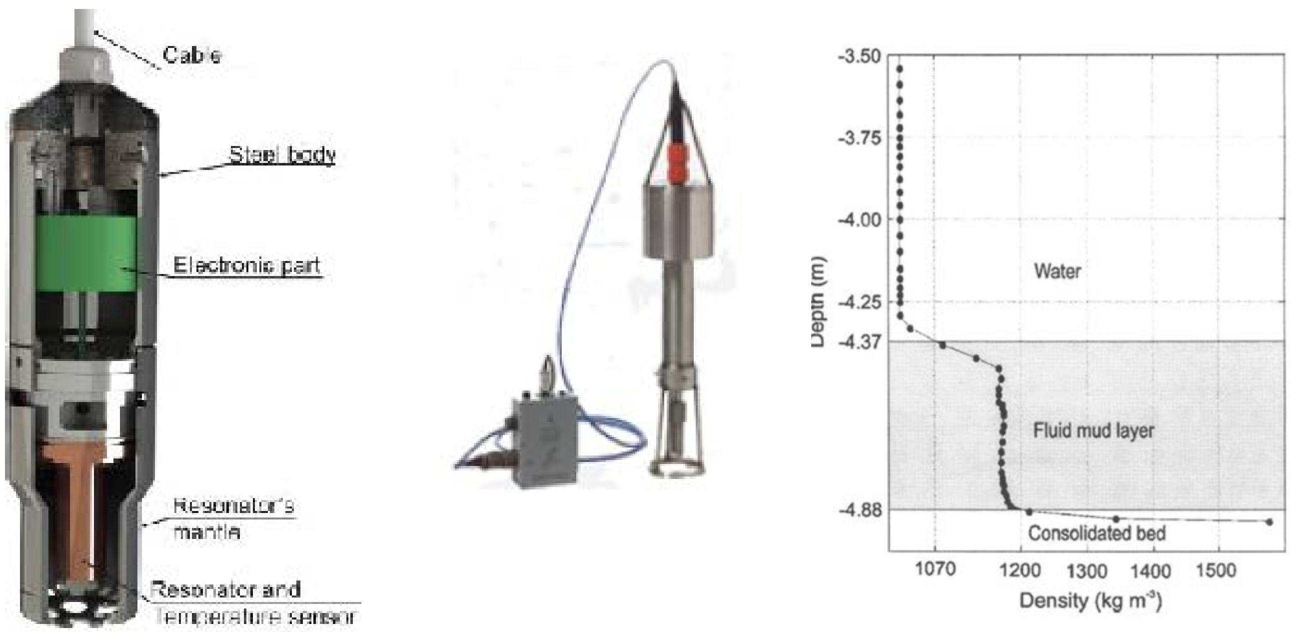


Figure 15 *Left= **v**ibrating fork densimeter (www.viscoanalyser.com); middle= densitune sensor (www.odomhydrographic.com), right= density profile*

The calibration can be simply done on board of the survey boat using a local mud sample in a bucket. The density of the mud sample can be determined by weighing the mass of the sample, see Section 3.4.1. The fork is lowered into the mud sample to read the output signal. Smaller density values can be produced by stepwise addition of known volumes of clear sea water. Using this method a calibration curve can be produced over the range of interest.

Once calibrated, the instrument can be lowered at a constant speed (about 0.5 m/s) through the water column and the soft bed until the compact subsoil is reached. A pressure transducer attached to the instrument can be used for accurate determination of the vertical position. **Figure 15 right** shows an example of a measured the density profile (wet bulk density).

This method is used by dredging companies to detect the density profiles of fluid mud layers.

3.5 Fluid mud layers

The position of the surface of consolidated mudlayers can be determined by means of echo-sounding instruments. Common practice is the usage of a dual-frequency echosounder. The higher frequency is usually 200 or 210 kHz, the lower frequency is 25 or 33 kHz. The higher frequency can be used to detect the upper surface of the fluid mud. The lower frequency can penetrate into the soft mud until a suitable density impedance is encountered, being the transition of the fluid mud to the more compacted layer at the base of the fluid mud, see **Figure 16**.

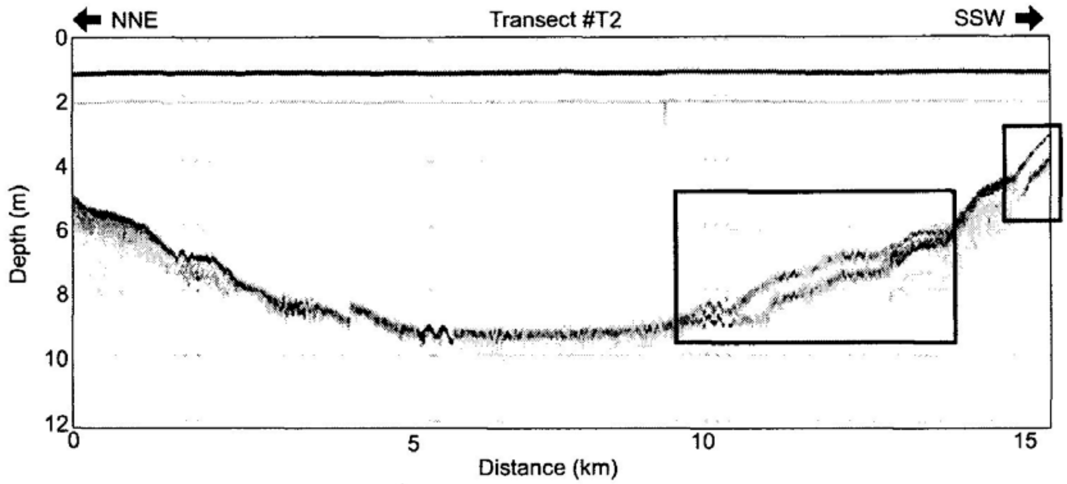


Figure 16 *Fluid mud layer detected by dual frequency echo-sounder (Schettini et al., 2010)*

3.6 Laboratory analysis

Sample analysis usually consists of determining the following parameters:

- sediment concentration,
- sediment compostion (size and settling velocity),

3.6.1 Sediment concentration

The two most commonly used methods are evaporation and filtration (**Figure 17**). The filtration method (with vacuum pump) may be somewhat faster for samples of small concentrations. However, large concentrations tend to clog the filter material (silt concentrations > 100 mg/l). Using non-hygroscopic filters, the filters should be weighed directly after drying to prevent absorption of moisture by the sediment materials.

Figure 17 *Filtration unit*

3.6.2 Particle size

Muddy environment
Preparation of samples prior to analysis is of the utmost importance if accurate and reproducible results are to be obtained. Samples containing clay minerals or organic material are very liable to cracking on drying and care should always be taken to avoid samples drying out prior to analysis. However, when samples may have dried out naturally when collected on a mudflat or bank, then the aggregates should be broken down (hydrogen peroxide treatment).
Complete removal of organic material is necessary for all samples to be analyzed for particle size or fall velocity because the organic material may bind together the sediment particles.
The samples should be analyzed as soon as possible after collection (within 3 days). The samples should be treated for removal of organic material; deflocculants (sodium carbonates) can be used for deflocculation.
The particle size distribution of the silt-clay fraction can be determined using the standard pipet test or the Laser-diffracrion method (Malvern).
The principle of the pipet method is to determine the sediment concentrations of an initially uniform suspension (dispersed system) at a pre-fixed depth below the water surface as a function of settling time. Particles having a settling velocity greater than the ratio of the depth and the elapsed time period will settle below the point of withdrawal after the elapsed time period.
The sediment concentration at a certain depth can be determined by withdrawing samples at that height. Usually, eight or nine samples are withdrawn. The laboratory instrument consists of a 1 liter-cylinder with an internal diameter of 0.075 m for suspensions with an initial concentration larger than 1000 mg/l, while a 25 ml-pipet is used for withdrawing the samples. A 3-liter cylinder (internal diameter of 0.1 m) in combination with a 200 ml-withdrawal volume should be used for suspensions with an initial concentration in the range of 100 to 1000 mg/l. For accurate results the initial settling height should be 0.3 m. The analysis period is about 2 hours for separation to about 5 μm.

Sandy-silty environment
When the sand fraction is sufficiently large, the sample should be washed over a 63 μm-sieve to separate the sand fraction from the sample. The particle size fraction of the sand fraction can be determined by sieving or using a standard settling analysis in a visual accumulation tube. Single sand samples can be put together to obtain a sievable quantity.
The silt and clay fraction can be analysed using the standard pipet method (settling test) or by the Laser-diffraction method (Malvern)
Detailed methods are given by Van Rijn, 2007

4 Recommendations

The basic mud parameters for mathematical modelling (Delft3D model) are:

- concentrations,
- particle sizes of bed and suspended samples
- in-situ settling velocity of mud flocs,
- in-situ dry density of bed,
- thickness of fluid mud layers.

Recommendations for field measurements to determine these parameters accurately in a muddy environment are given in the following **Table 4.1**.
These data should be collected at key locations covering the total length of the shipping channel. Two stations in the inner channel, two stations in the outer coastal channel and two stations in the transional section (mouth region) between inner and outer channels.

Type of measurements	**Instrument**	**Location/Position**	**Laboratory analysis**
Mud concentration	OBS (optical back scatter) + pump sampler on carrier ABS+ADCP in bed mounted frame	Five points over the depth; 13 hours over tidal cycle in fixed anchor station Spring-neap cycle in fixed station	Filtration of water-mud samples (calibration) Post-processing of data series
Muddy bed samples	Gravity corer Diver samples (pvc-tube)	Bed surface	Pipet and sieve analysis Laser-diffraction analysis (Malvern)
Sandy bed samples	Van Veen grab	Bed surface	Sieve analysis
Suspended mud samples	Pump sampler Trap sampler	Near-bed, mid-depth, near-surface	Pipet analysis, Laser-diffraction analysis (Malvern)
In-situ settling velocity tests	Trap sampler and separate settling column (double walls in tropical conditions for temperature control)	Near-bed, mid-depth and near-surface	Filtration of water-mud samples
In-situ dry density	Acoustic Vibration sensor Diver samples (pvc-tube)	Bed surface	Pipet and sieve analysis, Laser-diffraction analysis
Fluid mud detection	Dual-frequency echo-sounder (33 kHz and 210 kHz)	Bed surface	None

Table 4.1 *Summary of field sampling programme in muddy environments*

5 References

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