SETTLING VELOCITY AND EQUIVALENT SIZE OF MUD

SETTLING VELOCITY AND EQUIVALENT SIZE OF MUD

1. Introduction

The bed of a muddy tidal channel consists of a mixture of clay, silt, fine sand and organic/calcareous materials, which is generally known as mud. 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 sizes between 0.63 and 2 mm (63 to 2000 μm).
Sediment mixtures with a fraction of clay particles larger than about 10% have cohesive properties because electro-statical attraction 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.
A basic parameter for modelling of deposition is the in-situ settling velocity of the (flocculated) sediments. 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 5,000 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 settling 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 settling/consolidation tests by measuring the sinking 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 1.1** (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).
This note discusses three types of settling velocities, as follows:

- non-flocculated settling velocities of low-concentration suspensions ((< 200 mg/l) or deflocculated suspensions (using chemicals, peptiser);
- flocculated settling velocities of medium concentration mixtures (200 to 5000 mg/l);
- hindered settling velocities of high-concentration mixtures (> 5000 mg/l).

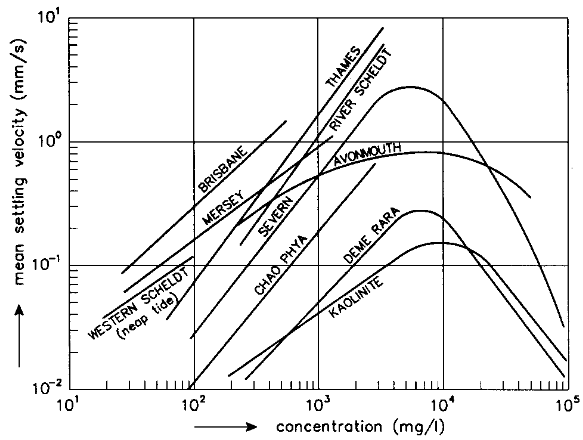


Figure 1.1 *The influence of sediment concentration on the settling velocity*

2. Mud particle size and settling velocity

2.1 Mud particle size and equivalent diameter

Sand and silt particles are almost spherical, but the fine sediment particles of the mud fraction have a flaky shape (plate-shaped) with an aspect ratio of d_{mean}/δ = 5 to 20 ($d_{mean}=0.5(d_{min}+d_{max})$, δ=plate thickness, d_{min}=minimum diameter, d_{max}= maximum diameter, see **Figure 2.1**).

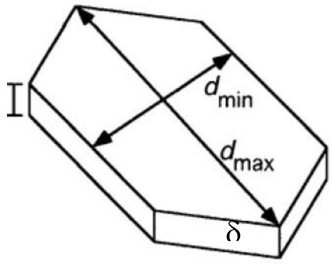


Figure 2.1 *Flaky plate-type clay/lutum particles*

Various methods are available to determine the particle size distribution of very fine sediments (clay, lutum), as follows:

- microscopic-analyis method (Conley, 1965);
- Photo/video cameras (both for diameter and settling velocity);
- Laser-Diffraction (LD) tests yielding an equivalent LD-diameter (Haverbeke 2013);
- Settling column tests (hydrometer-test; pipet-test; SEDIGRAPH-test) yielding the equivalent (spherical) settling diameter based on the Stokes settling formula.

<u>**LD instruments**</u>
The LD-method takes both the particle shape and its optic properties into account. A particle will scatter the incident light and through a number of detectors, the intensity and shape of this scattering pattern can be measured. The Fraunhofer or the Mie theory can be used to interpret the obtained pattern. Larger particles will scatter strongly over small angles, small particles will do so more weakly and over greater angles (**Figure 2.2**). Smaller particles pass through the light source more than once (they are suspended in a closed water circuit) with a different orientation each time, resulting in an 'equivalent spherical diameter'. That is, a sphere which would produce the same scattering pattern. The measuring range is 0.04 to 2000 µm.
In the case of very small disc-type or plate-type clay particles, it is not so clear what type of diameter is measured by the LD-method. Brown and Felton (1985) have found that the projected area of the plates (from which the LD-diameter d_{LD} is derived) as seen by the LD-instrument is equal to 0.25 times the total area of the plates (two flat sides and two edge sides).
Thus: $0.25\ \pi d_{LD}^2=0.25[2x0.25\pi d_{plate}^2+2x\delta\pi d_{plate}]$ or
$d_{LD}^2= d_{plate}^2\ [0.5 + 2(\delta/d_{plate})]$ or $d_{LD}= d_{plate}[0.5 + 2(\delta/d_{plate})]^{0.5}$ (2.1)
Assuming: δ/d_{plate}= 0.1, it follows that: $d_{LD} \cong 0.85 d_{plate}$ or $d_{plate}= 1.2 d_{LD}$ (2.2)

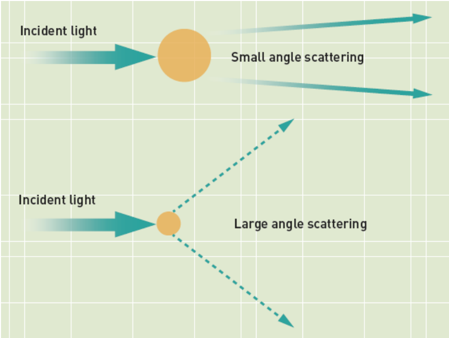


Figure 2.2 *Light scattering at small and large angles; LD-method*

To determine the particle size of the primary particles, the diluted sample can be pre-treated with a chemical anti-flocculant (peptiser) and ultrasonic stirring, which will destroy all flocs. The sample concentration should be as uniform as possible, which is achieved by continuous recirculation of the sample volume (by pumping) during the measurement time. A sample dispersion unit is available for sample preparation.
It is remarked that due to extensive ultrasonic treatment, sand particles may break up, resulting in an overestimation of the finer fraction. Sensivity tests (Deltares 2014) show that ultrasonic treatment should not be longer than about 10 minutes.

The LD-method is known to underestimate the clay fraction ($d < 2$ µm). The fines are partly shadowed by the larger particles. This can be partly overcome by separating the finest fraction from the bulk by means of a settling test, in which the finest fraction remains in suspension after one hour. The ratio of the mass of the finest fraction to the overall bulk mixture can be calculated, and the particle size distribution (psd) can be corrected with the psd of the finest fraction.

Settling tubes

Using a settling tube, the effective settling velocity is measured, which can be converted to an equivalent particle diameter.
The equivalent spherical settling diameter d_{sphere} follows from the Stokes settling formula, which reads as:
$w_s = (s-1)\, g\, (d_{sphere})^2/(18\, \nu)$
with: w_s= settling velocity, $s=\rho_s/\rho$= relative density, ρ_s= sediment density (2650 kg/m^3), ρ= fluid density, ν=kinematic viscosity coefficient, d_{sphere}= equivalent spherical settling diameter.

The settling velocity of a disc-type particle (thickness=δ, plate or disc diameter= d_{plate}) falling with its flat side normal to the vertical direction can be derived from the drag force and the submerged volume weight.
The drag force is: $F_{drag}= 8\, \rho\, \nu\, d_{plate}\, w_s$ (www.Clarkson.edu) and the submerged volume weight is:
$G_{plate}=0.25\, \pi\, d_{plate}^2\, \delta\, (\rho_s-\rho)g$.
The settling velocity is: $w_s =(s-1)\, g\, \delta\, d_{plate}/(32\nu)$

The settling velocity of a disc-type particle (thickness=δ, diameter= d_{plate}) falling with its thin side normal to the vertical direction can be derived from the drag force and the submerged volume weight.
The drag force is: $F_{drag}= 5.3\, \rho\, \nu\, d_{plate}\, w_s$ (www.Clarkson.edu) and the submerged volume weight is:
$G_{plate}=0.25\, \pi\, d_{plate}^2\, \delta\, (\rho_s-\rho)g$.
The settling velocity is: $w_s =(s-1)\, g\, \delta\, d_{plate}/(21.3\nu)$

Taken the settling of the disc and the sphere to be equal, it follows that:
- disc with flat side normal to vertical direction: $d_{plate}= 0.75\, (d_{plate}/\delta)^{0.5} d_{sphere} \cong 2.2\, d_{sphere}$ for $d_{plate}/\delta=9$ (2.3)
- disc with thin side normal to vertical direction: $d_{plate}= 0.55\, (d_{plate}/\delta)^{0.5} d_{sphere} \cong 1.7\, d_{sphere}$ for $d_{plate}/\delta=9$ (2.4)

If the settling velocity of very small plate-type clay particles is measured and converted to an equivalent spherical diameter using the Stokes settling velocity formula, the actual plate diameter of these particles is about 1.7 to 2.2 times larger than the equivalent spherical diameter (assuming $d_{plate}/\delta=9$).

If the particle size is based on the Laser-Diffraction (LD) method, Equation (2.2) yields: $d_{plate} \cong 1.2 d_{LD}$
Based on Equations (2.3) and (2.4), it follows: $d_{plate} \cong 2 d_{sphere}$ and thus: $d_{sphere} \cong 0.6\, d_{LD}$.

Based on Equations (2.1), (2.3), (2.4), a general expression is: $d_{sphere}/d_{LD}= 1.1(d_{plate}/\delta)^{-0.25}$ (2.5)
Pabst and Berthold (2007) have given: $d_{50,sphere}/d_{50,LD} = 2.5(d_{plate}/\delta)^{-0.5}$ (2.6)
Both results are plotted in **Figure 2.3**.

Hence, the equivalent sphere diameters derived from settling velocity data are considerably finer (factor 1.5 to 2) than LD-diameters (Equations 2.5 and 2.6).

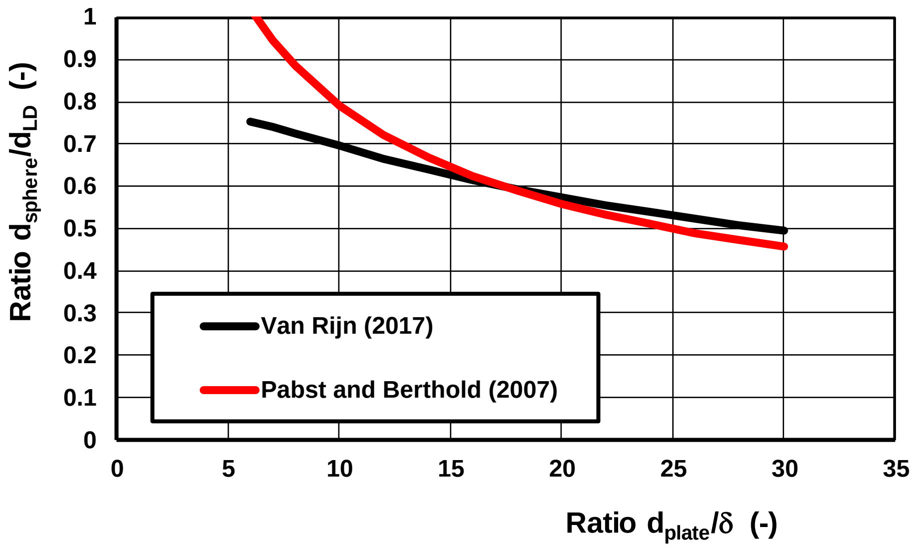


Figure 2.3 *Ratio of sphere diameter and LD-diameter as function of d_{plate}/δ*

2.2 Settling velocity equations

Shi and Zhou (2004) studied the effective settling velocity of fine flocculated sediments above mud beds in the Changjiang Estuary in China. Most of the sediments in this estuary are smaller than 32 μm. Acoustic profiling instruments and point water samples were used to measure the sediment concentration profiles in depth of 6 to 10 m. The concentration decreases from the bed region to the water surface: by a factor of about 5 in the near-bed layer (z<0.1h) and by a factor of 2 to 3 in the upper layer between 0.1h and h, which can only be explained by flocculated settling processes. Based on fitting of Rouse-type concentration profiles, the effective settling velocity was found to vary with the sediment concentration as follows: w_s=0.6 mm/s for c=0.2 kg/m^3, w_s=1 mm/s for c=0.5 kg/m^3 and w_s=2 mm/s for c=1 kg/m^3 (Shi and Zhou, 2004). The increase of the settling velocity with concentration is a clear indication of flocculation effects. Similar results have been found by Vinzon and Mehta (2003) at the mouth of the Amazon in Brasil and by Thorn (1981) for the Severn Estuary in the UK.

In high-concentration flows the suspended sediment particles cannot settle freely, because of the presence of the surrounding particles. This process is known as hindered settling and consists of various effects: flow and wake formation around the particles and the increase of density and viscosity of the suspension. Hindered settling effect was studied experimentally by Richardson and Zaki (1954) and Richardson and Meikle (1961) using glass-type particles (ballotini) with particle sizes in the range of 35 to 1000 μm and alumina powder with a particle size of about 5 μm . They found that the hindered settling effects can be represented as: $w_s=w_{s,o}(1-c)^n$ with c=volume concentration, $w_{s,o}$=settling velocity in clear water. The n-coefficient varies almost linearly from n=5 for Re=$w_{s,o}\, d/\nu$<1 to n=3 for Re=100.

The flocculation and hindered settling effects are extensively discussed by Van Rijn (2007).

Herein, a pragmatic approach is used to represent the concentration-dependent mud settling velocity, as follows:

$w_{mud} = \exp[\alpha_1 \ln(c) + \alpha_2 - \alpha_3]$; for flocculation range $c \leq 0.0025$ ($\cong$ 7 kg/m³) (2.7a)

$\alpha_1 = 0.18 \ln(w_{mud,max}/w_{mud,min})$

$\alpha_2 = 2.1 \ln(w_{mud,max})$

$\alpha_3 = 1.1 \ln(w_{mud,min})$

$w_{mud} = w_{mud,max}(1-c)^4$ for hindered settling range $c > 0.0025$ ($\cong$ 7 kg/m³) (2.7b)

with:

$w_{mud,max}$= maximum settling velocity at c=0.0025 ($w_{mud,max}$=0.0005 to 0.003 m/s or 0.5 to 3 mm/s; input value),
$w_{mud,min}$=minimum settling velocity at c=0.00001 ($w_{mud,min}$=0.00005 to 0.0001 m/s or 0.05 to 0.1 mm/s; input value).

Some characteristic values of the settling velocity w_{mud} are:

c=0.000025 (=0.066 kg/m³)	w_{mud}=0.000145 m/s	= 0.145 mm/s
c=0.00025 (=0.66 kg/m³)	w_{mud}=0.00038 m/s	= 0.38 mm/s
c=0.0025 (=6.6 kg/m³)	w_{mud}=0.001 m/s	= 1 mm/s
c=0.025 (=66 kg/m³)	w_{mud}=0.0009 m/s	= 0.9 mm/s
c=0.1(=265 kg/m³)	w_{mud}=0.00066 m/s	= 0.66 mm/s

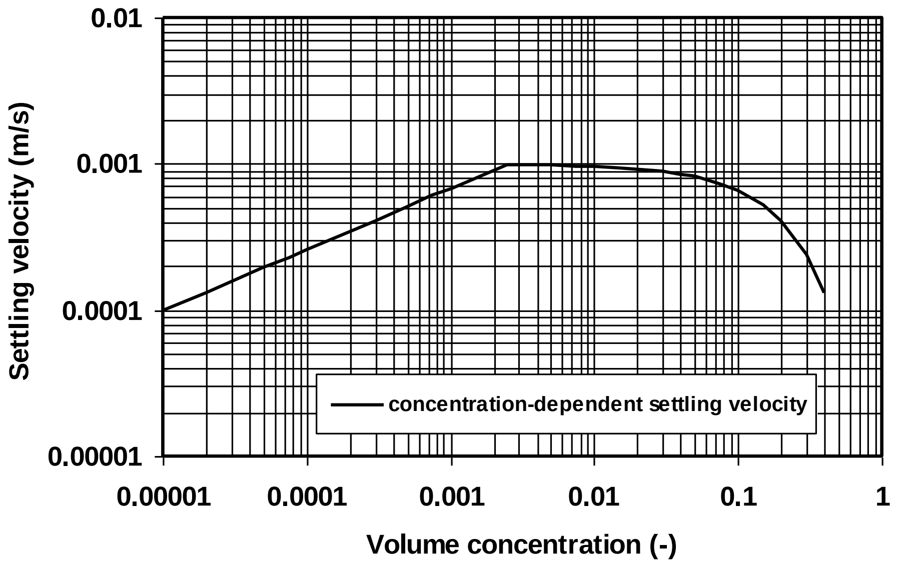


Figure 2.4 *Settling velocity as function of volume concentration; flocculation range for c<0.0025 and hindered settling range for c>0.0025; $w_{mud,max}$=0.001 m/s, $w_{mud,min}$=0.0001 m/s*

Figure 2.4 shows Equation (2.7) for $w_{mud,max}$=0.001 m/s (1 mm/s) and $w_{mud,min}$=0.0001 m/s (0.1 mm/s).

3. Instruments for particle size and settling velocity

3.1 Methods

Various methods/instruments can be used to determine the settling velocity of natural mud particles and flocs from water-sediment samples. The samples can be analyzed either in the laboratory or in the field. In the former case the sample is transferred from the sample location to the laboratory where it is resuspended by mechanical stirring, which may have an adverse effect on the floc formation and thus on the settling velocity. Therefore, immediate in-situ analysis of the samples is highly prefered.
The determination of the settling velocity of natural flocculated suspended sediments can best achieved by in-situ systems, as follows:

- in-situ settling tubes,
- in-situ video or photo-cameras,
- in-situ Laser-Diffraction (LD) instruments.

The settling velocity of flocculated mud can also be determined in the laboratory using a settling tube method, but this involves the transfer of mud from the field site to the laboratory, which may change the floc characteristics.
The determination of the settling velocity of the primary non-flocculated sediments can best achieved in the laboratory using a settling tube method and chemicals (peptiser) for deflocculation.

3.2 In-situ videocameras and Laser-diffraction instruments for flocculated mud

In-situ video camera instruments generally consist 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 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 LD-method (LISST-instruments, www.sequoiasci.com; **Figure 3.1**).

Figure 3.1 *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.
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.

3.3 In-situ settling tube for flocculated mud (WASED)

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 settling. The sediment concentration at a certain depth of the tube can be determined by withdrawing small subsamples at that height. Usually, eight or nine subsamples are withdrawn. The settling velocity can be determined from the decrease of the concentration in the tube as function of time, see **Table 3.1**.
The most simple method is to take a water-mud sample by using a trap sampler with side valves (see **Figure 3.2**). Extra weight and a small tailvin may be necessary in currents > 0.5 m/s.

Figure 3.2 *Horizontal sampling tube with volume of 2 litres and vertical settling tube with clamp tap (before and after test; WASED-method*

The trap sampler (**Figure 3.2upper**) 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, two methods can be used to perform the settling test:

A. the sampler tube is stirred (shaken) to create a uniform suspension and put into a vertical positon, after which the test starts; subsamples are taken at pre-fixed times (t=0, 1, 3, 6, 10, 20, 40, 60, 120 minutes) from a small tap (with simple clamp) just above the bottom valve (**Figure 3.2left**);

B. the water-mud sample is poured into a large bucket and then into separate settling column (length = 0.45 m; internal diameter= 0.09 m; volume≅2 litres) with a closed bottom and a small tap with clamp 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 100 ml are taken from the tap (0.07 m above the bottom) at pre-fixed times (t=0, 1, 3, 6, 10, 20, 40, 60, 120 minutes), see **Figures 3.2 middle and right**.

Various tests using the WASED sampler have been done to analyse the effect of the sampling procedure, see **Figure 3.4**. The WASED-tube was filled with a known amount of mud (Payra mud, Bangladesh; concentration of about 700 mg/l). Method A and method B were both tested. Two other tests in separate settling columns with the same initial mud concentration of 700 mg/l have been done simultaneously (**green curves**). The settling velocity curve (**black**) of Method B is quite smooth; the median settling velocity is about 0.5 mm/s. The settling velocity curve (**red**) of method A is irregular and the median settling velocity is about 0.2 mm/s. Most likely, the settling process of method A is disturbed by the presence of the rubber spring of the sidevalves and the internal thermometer. Small circulation flows may be initiated in the WASED-tube during the subsampling process. Based on this. method B is preferred (WASED-sampler is opened in a bucket; the water-sediment sample is poured into a separate settling column).

Sample	Sample time after start settling process (seconds)	Settling height from surface to tapping point (mm)	Settling velocity (mm/s)	Mud concentration (mg/liter)	Mass percentage smaller than (%)
1	5	261	≅ 100	2635 (initial)	100
2	60	250	250/60=4.17	2212	2212/2635x100= 84.0
3	180	236	236/280=1.31	1180	1180/2635x100= 44.8
4	300	225	225/300=0.75	754	754/2635x100= 28.6
5	600	211	211/600=0.35	481	481/2635x100= 18.3
6	1800	200	200/1800=0.11	262	262/2635x100= 10.0
7	3600	186	186/3600=0.052	174	174/2635x100= 6.6
8	7200	170	170/7200=0.024	107	107/2635x100= 4.1

Table 3.1 *Basic data of settling test (temperature of 18° C)*

The mud samples are filtrated (using glass fibre filter material with size of 0.45 μm and diameter=47 mm; each filter is numbered and preweighed; Whatman filters 0.45 μm, 47 mm diameter, art 516-1746, www.vwrbv.nl; Figure 3.3 right) and weighed to determine the mud concentration.

Figure 3.3 *Filtration instruments*

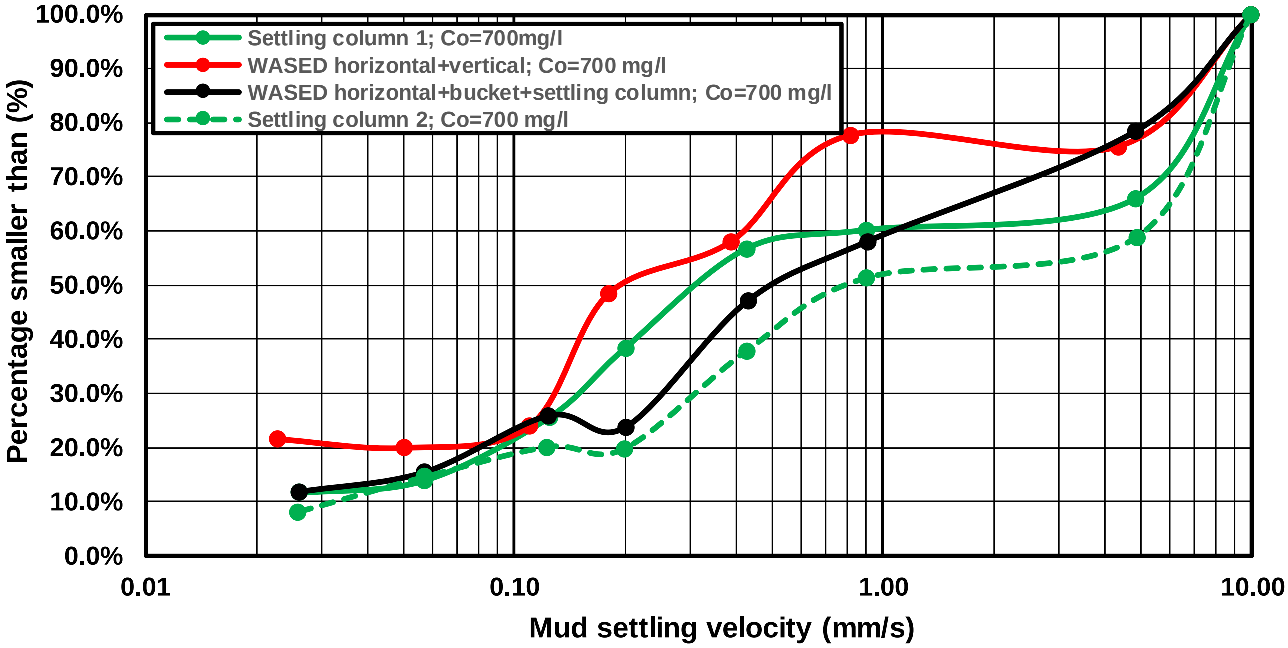
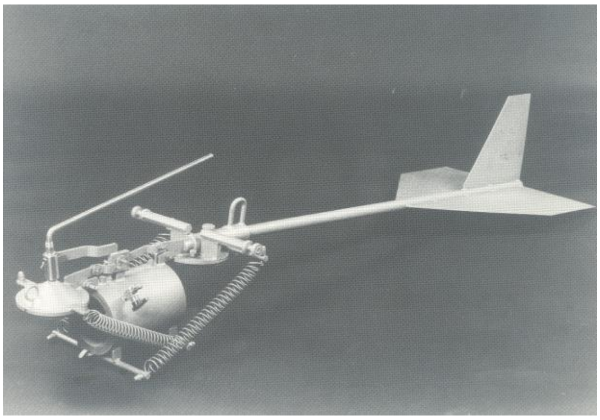


Figure 3.4 *Effect of sampling procedure*

A more sophisticated sampler is the FIPIWITU field instrument of Deltares (see **Figure 3.5**) 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.
The basic principle of this sampling method is to determine the decreasing sediment concentrations of an initially uniform suspension 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 initial mud concentration should be larger than about 200 mg/l to obtain accurate results. The precise analysis method is described by Van Rijn (2016).



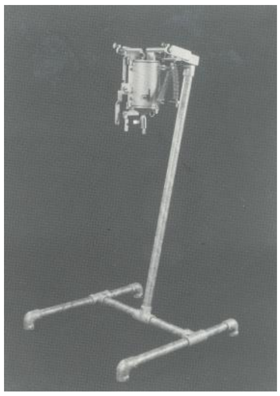


Figure 3.5 *In-situ settling tube (FIPIWITU); left=sampling position; right= settling position*

3.4 Laboratory settling tube for instruments for flocculated and non-flocculated settling velocity

Settling tube with tap

Two types of tests can be done in laboratory columns (**Figure 3.2**) with a clamp tap at the bottom:

- settling velocity of flocculated particles in suspension of native water (concentrations in the range of 200 to 5000 mg/l);
- settling velocity of primary, non-flocculated particles in suspension of fresh water with anti-flocculant (and initial ultrasonic stirring; concentration of about 1000 mg/l).

Subsamples are taken at various times to determine the decrease of the mud concentration as function of time from which the settling velocity can be determined (see **Table 3.1**)

Settling tube with underwater balance

Deltares (2016a) has developed a laboratory Sedimentation-Balance method to determine the settling velocity in the flocculation range of 0.1 to 1 kg/m^3, see **Figure 3.6**. The instrument consists of a temperature-regulated tube (double wall) with a height of 200 to 300 mm (about 0.5 to 1 litre) and an accurate weighing balance at the bottom of the tube. For reasons of accuracy, the mud concentration in the settling column should be in the range of 500 to 1000 mg/l.

Two types of tests can be done:

- settling velocity of flocculated particles in suspension of native water;
- settling velocity of primary, non-flocculated particles in suspension of fresh water with anti-flocculant (and initial ultrasonic stirring).

The sediment is dispersed in the tube by manual mixing to obtain a suspension with uniform concentration over the height of the settling tube; the balance bottom plate is connected to the electronic balance to weigh the accumulating sediment mass (under water) in time. The mass increase in time can be converted to settling velocity (known settling height) and to a particle size distribution using Stokes settling velocity formula.

Some results of Holwerd-mud (sample KG-14; Holwerd ferry channel, Wadden Sea, The Netherlands) with and without anti-flocculant using different analysis methods are shown in **Table 3.2**. Results of other methods are also shown. The particle sizes derived from the measured settling velocities are much larger than those from the Malvern-method and the Sedigraph-method. The latter two methods produce the size distribution of the primary dispersed particles, whereas the Sedimentation-Balance method produces the Stokes particles sizes of the sediments flocculating in the settling tube.

Figure 3.6 *Sedimentation-Balance method of Deltares (2016)*

Analysis method	Initial concentration; sample volume	$D_{10\%}$ (μm)	$D_{30\%}$ (μm)	$D_{50\%}$ (μm)	$D_{90\%}$ (μm)
Sedimentation-Balance method (3 tests; mud+ sand fractions without chemical dispersion)	≅ 1000 mg/l ≅ 1000 ml	20-30 (0.3-0.7 mm/s)	35-45 (0.8-1.8 mm/s)	45-95 (1.8-7 mm/s)	115-300 (10-70 mm/s)
MALVERN Laser-diffraction (1 test; mud+sand fractions without chemical dispersion)	100-1000 mg/l; ≅ 100 ml	4	8	15	120
SEDIGRAPH method (1 test; only mud fraction < 63 μm with chemical dispersion)	100 -1000 mg/l; ≅ 100 ml	< 1	3	20	90

Table 3.2 *Particle sizes using three different methods;*
Holwerd-mud (sample KG-14, Holwerd channel, Wadden sea)

3.5 Laboratory instruments for non-flocculated settling velocity and size

The settling velocity and size of non-flocculated fine sediments can be determined in the laboratory using deflocculation chemicals (peptiser). Various instruments are available.

Laser-Diffraction
The LD-method takes both the particle size, shape and its optic properties into account. The particles scatter the incident light and through a number of detectors, the intensity and shape of this scattering pattern are measured. The Fraunhofer or the Mie theory can be used to interpret the obtained pattern. Larger particles will scatter strongly over small angles, small particles will do so more weakly and over greater angles. Smaller particles will pass through the light source more than once (they are suspended in a closed water circuit) with a different orientation each time resulting in an 'equivalent spherical diameter'. That is, a sphere which would produce the same scattering pattern. The measuring range is 0.04 to 2000 µm.
The MALVERN Master Sizer (www.malvern.com) is an attractive laboratory instrument to determine the particle size distribution (PSD) of the primary particles because the measurement is fast and simple using diluted samples. The MALVERN measures the volume of the particles which are converted to sphere-diameters. The laser beam passes through a dispersed particulate sample and the angular variation in intensity of the scattered light is measured. Large particles scatter light at small angles relative to the laser beam and small particles scatter light at large angles, see **Figure 2.2**. The particle size is reported as a volume equivalent sphere diameter. The diffraction theory (Fraunhofer theory) is valid up to 10 times the wave length of the incident light, which means a lower limit of 7 to 8 µm. As the particles are circulated in suspension (by pump system), the particles pass the optical path many times at different orientations and so the shape effects are averaged out for spherical-type particles. Coarser and more angular sand particles are slightly overestimated (within 10%; Haverbeke 2013).

Hydrometer
The hydrometer test is based on the measurement of the decreasing sediment density by using a floating body in a column with settling mud particles, see **Figure 3.7**. The effective settling distance is the distance between the centre of gravity (centre of bulb) of the floating body and the surface of the suspension. The test method as used in the soil laboratory of Wiertsema (Tolbert, The Netherlands) consists of:

- preparation of a suspension with concentration of about 20 to 30 gram per liter (fresh water); peptiser is used for complete deflocculation (period of 24 hours);
- the column is shaken/stirred many times to create a homogenous suspension (after which the settling test starts);
- the scale of the floating body is read at the suspension surface at pre-selected times;
- the scale of floating body is read at the water surface of a column with clear water at the same temperature.

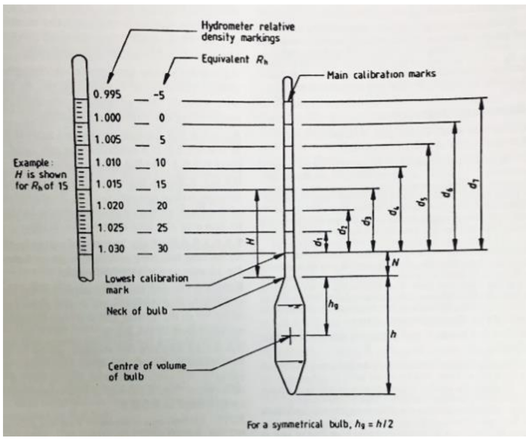


Figure 3.7 *Floating body of hydrometer test*

Sedigraph III

The SEDIGRAPH III-instrument can also be used to determine the settling velocities of the mud concentrations (fresh water with peptiser for deflocculation) in a small-scale settling cell. The mud concentrations are determined by direct (precalibrated) x-ray absorption. Using the known settling height, the decreasing mud concentrations in time are converted to settling velocities and to equivalent (spherical) sediment diameters with the Stokes settling formula.
The SEDIGRAPH uses a narrow beam of X-rays to measure directly the particle concentration in the liquid medium, see **Figure 3.8**. This is done by first measuring the intensity of a baseline or reference X-ray beam which is projected through the cell windows and through the liquid medium prior to the introduction of the sample. A homogeneously dispersed mixture of solid sample and liquid is next pumped through the cell. The attenuated X-ray beam is measured to establish a value for full scale attenuation. Agitation of the mixture is ceased and the dispersion is allowed to settle while X-ray intensity is monitored. During the sedimentation process, the largest particles fall below the measuring level, and progressively finer and finer particles do so until only the finest remain near the top of the measuring cell.

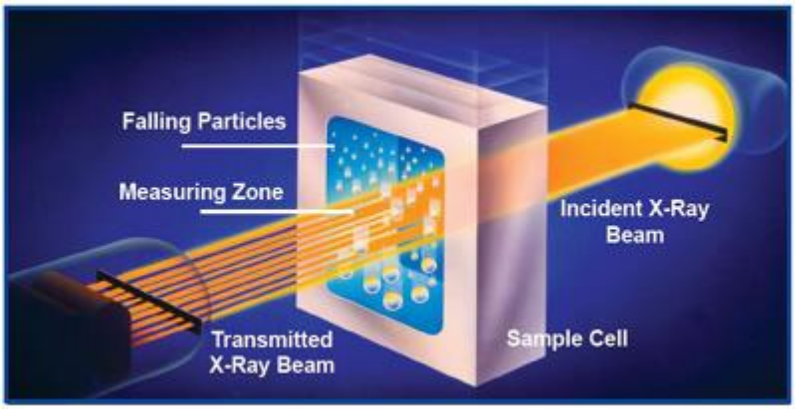


Figure 3.8 *X-ray absorption of SEDIGRAPH instrument*

The sample container is about 100 ml; the initial concentration is about 100 to 1000 mg/l; ultrasonic stirring to obtain a uniform suspension can be (automatically) performed. The sand fraction > 63 μm generally is removed from each sample (by wet sieving). Organic materials and carbonates need to be removed from the sample with hydrogen peroxide and acid. Anti-flocculant can be used for optimum dispersion. Tests with and without anti-flocculants should be done. The settling velocity is converted to a particle size distribution (psd) using Stokes' law. This conversion introduces an error, since Stokes' law is valid for spherical particles, whereas clays consist of plate-like particles which settle somewhat slower. Hence, the Sedigraph will underestimate the plate diameter in the clay/silt range and overestimate the clay fraction. The distribution of sediment with d > 63 μm can be determined by sieving, and subsequently added to the Sedigraph-measurements to obtain the full psd. **Table 3.2** shows comparative results.

3.6 Required procedure and equipment for WASED-settling test

The most efficient method to determine the in-situ settling velocity of suspended mud samples is, as follows:

- use the WASED-tube with side valves to take water-mud samples; the sampler should be lowered quickly to the sampling level, closed immediately and raised quickly;
- open the valves of the WASED tube in a large bucket; measure the water temperature of the sample; pour (using a funnel) the sample into a vertical settling column with a clamp tap on board of the survey vessel (3 settling columns can be used simultaneously to do 3 measurements during the flood/ebb period of the tidal cycle);
- make a uniform suspension in the settling column by gently stirring the sample and start the test (duration of 2 hours).

In semidiurnal tidal conditions over 13 hours (flood and ebb period), the following measurements schedule should be used:

- *sampling points*: 1 m above bed, mid-depth and 1 m below water surface (the sampler should not touch the bed or be used very close to the bed < 1 m, to prevent the stirring of bed sediments)
- *sampling times*: slack tide, maximum flow flood and maximum flow ebb (each test takes about 2 hours).

In all, 9 measurements of the settling velocity during a period of 13 hours at 1 location should be taken. Using this procedure, 9 measurements can be done with one sampling tube. This can be done by using 1 WASED-tube and 3 separate settling columns.

In most situations, 1 location per 5 km within the project area will be sufficient.
In the case of a long navigation channel (> 10 km), more locations should be considered.
The WASED-sampler can easily be operated by hand; use a nylon hoisting rope with knots at every 1 m to estimate the sampling depth.
It may necessary to use extra weight and a small rectangular tailvin attached to the sampler (behind the handle) in conditions with currents > 0.5 m/s (otherwise the sampler may spin and/or move away from the boat).

Equipment (Figure 3.9)

- WASED-tube with side valves and tap (with spring clamp);
- 5 plastic settling columns/cylinders with tap (length= 45 cm; diameter= 9 cm; footplate=14x16 cm; volume= 2 liters); plastic hose 10 mm and 5 spring clamps (wolfcraft.com);
- wheaton filtration 47 mm assembly (www.fishersci.se); fluid container on top of the filter should as large as possible (0.5 liter); diameter of filter should preferably be 47 mm (always use a strong spring clamp to prevent leakage around the filter paper, see **Figure 3.10**);
- glass fibre filters (Whatmann filters: diameter 25, 47, 90 mm; pore size 0.45 μm; each filter should be have a number and preweighed);
- vacuum pump (vacuubrand ME1; www.laboratorium-apparatuur.nl) or KNF laboport mini pump (www.knf.com);
- drying oven/stoof;
- precision balance scale (accuracy ± 1 mg); (www.stimag.nl);
- stirring rod (length 60 cm) to make uniform suspension in settling tube (before start test);
- 5 plastic graduated measuring cylinders (100 ml); precise volume of each sample should be noted;
- 80 closable transparent plastic bottles of 200 ml for storage of samples (for 9 measurements during tidal cycle of 13 hours; each bottle should have a number; use non-removable inkt, see measuring form Table 3.3); clear water in the bottles can be poured off before filtration;
- 2 laboratory washing bottles (1 liter);
- temperature/thermometer;
- non-removable marker pen to note sample numbers, data, etc.

Figure 3.9 *Equipment*

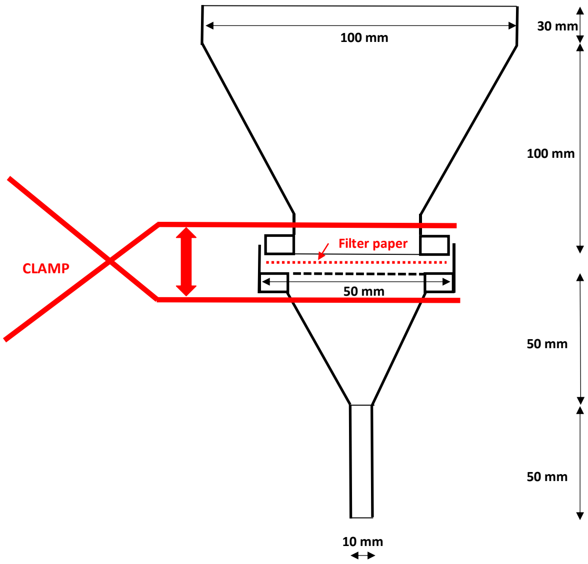


Figure 3.10 *Filtration funnel arrangement for 47 mm filters (strong clamp to prevent leakage)*

1 Sample data	Subsamples taken from settling column					Mass solids			Settling	
	2 Time of sub sampling (sec)	**3 Storage bottle number**	**4 Settling height (mm)**	**5 Volume of sub sample (ml)**	**6 Mud concen tration (mg/l)**	**7 Mass filter (mg)**	**8 Mass filter+ solids (mg)**	**9 Mass solids (mg)**	**10 Settling velocity (mm/s)**	**11 Percen tage smaller (%)**
Date:	after 1 s									
Location:	60									
Time:	180									
Level: 1 m above bed,	300									
mid-depth,	600									
1 m below surface	1800									
Temperature:	3600									
Tide: flood/ebb	7200									
Date:	after 1 s									
Location:	60									
Time:	180									
Level: 1 m above bed,	300									
mid-depth,	600									
1 m below surface	1800									
Temperature:	3600									
Tide: flood/ebb	7200									
Date:	after 1 s									
Location:	60									
Time:	180									
Level: 1 m above bed,	300									
mid-depth,	600									
1 m below surface	1800									
Temperature:	3600									
Tide: flood/ebb	7200									

Settling height= height between water surface in settling column and tap point (reduces in time due to subsampling)
Mud concentration= mass solids (9)/volume subsample (5)
Settling velocity=settling height (4)/settling time (2)
Percentage smaller= mud concentration (after time t)/initial mud concentration (after 1 s), see Table 3.1

Table 3.3 *Measuring form settling velocity*

4. Measured results

4.1 Overview

Suspended and bed samples of mud from various sites in tidal conditions are analyzed and discussed. Settling velocity results of flocculated and non-flocculated mud samples are presented.
The following sites are considered:

- Noordpolderzijl channel (N-mud), Wadden Sea, The Netherlands;
- Delfzijl harbour basin (D-mud), Wadden Sea, The Netherlands;
- Holwerd channel (H-mud), Wadden Sea, The Netherlands;
- Payra Port channel (P-mud), Bangladesh;
- Scheldt tidal river near Antwerp, Belgium.

Most of the mud sampling and analyses have been done by the students of the Hanze Technical School in Groningen (The Netherlands) with support of the technical staff of the soil laboratory of Wiertsema and Partners in Tolbert (The Netherlands).

4.2 Mud of Noordpolderzijl (N-mud)

4.2.1 Site description

The muddy tidal channel of Noordpolderzijl runs from a main channel in the Dutch Wadden Sea to the main land over a length of about 2.5 to 3 km through shallow marshlands, see **Figure 4.2.1**. A small harbour basin (length of 200 m, width of 20 m) is present near the mainland for small pleasure boats. The bed of the harbour basin and channel is almost dry (exposed) at low tide.
Muddy tidal channel: width= 5 to 15 m; depth= 0.3 m at low water and 2 m at HW.
Tidal range: about 2 m.

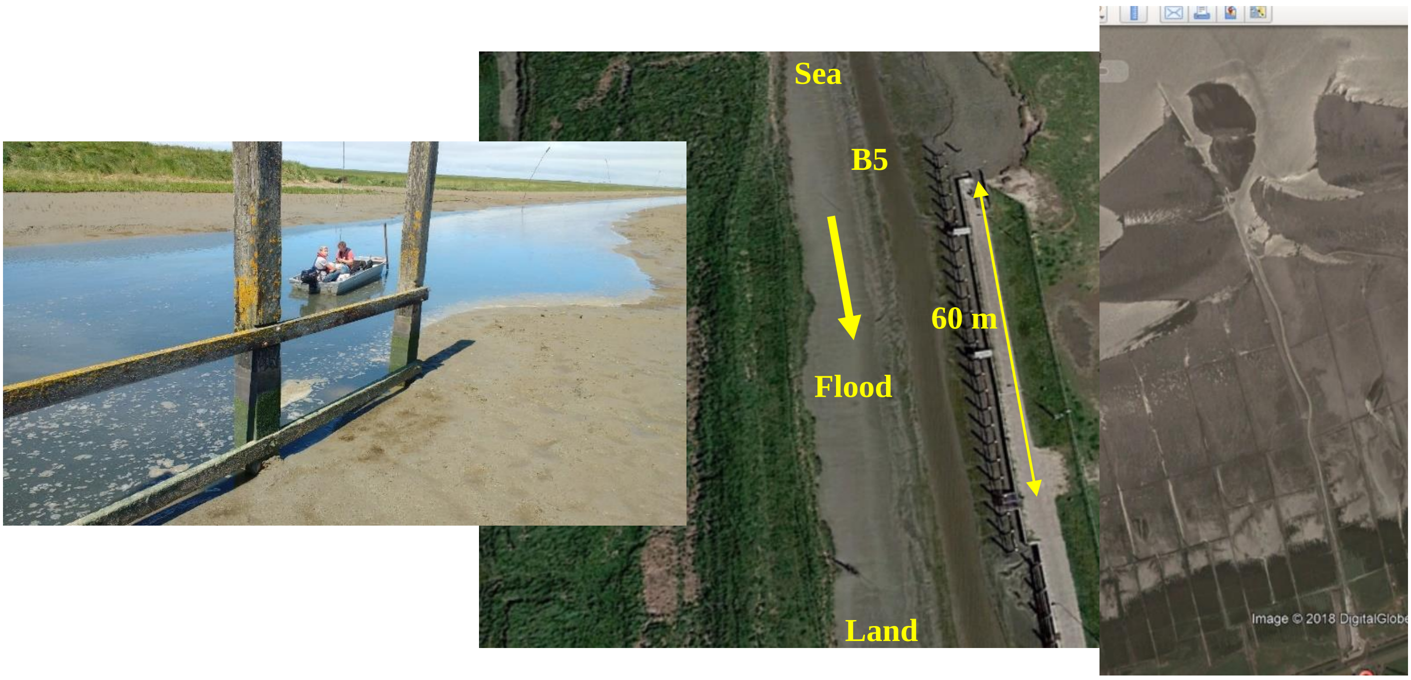


Figure 4.2.1 *Location B5 muddy tidal channel Noordpolderzijl, Wadden Sea, The Netherlands*

4.2.2 Bed composition

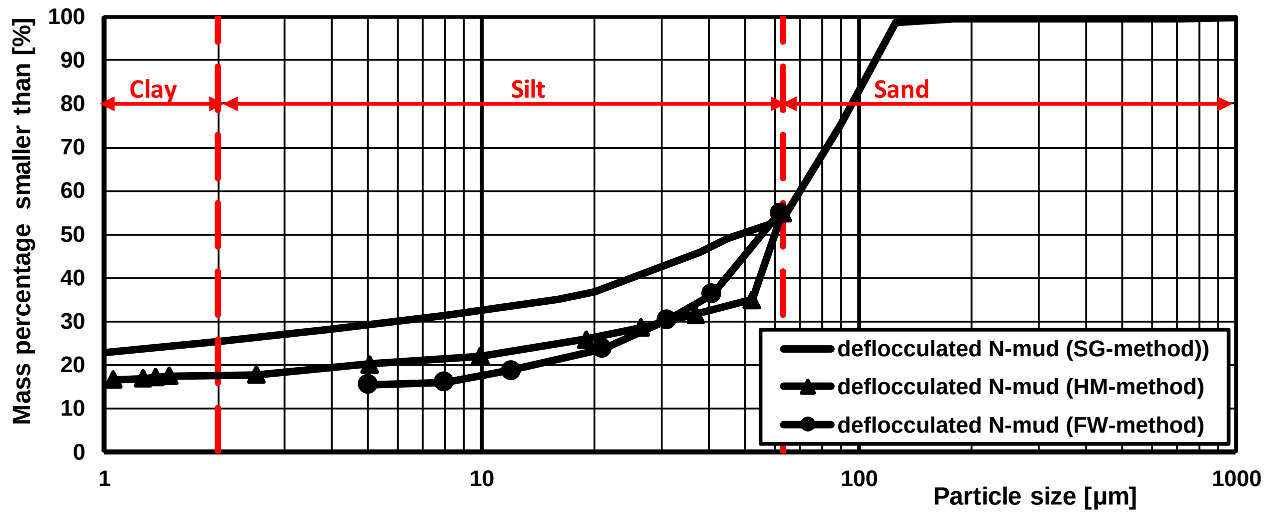
The mud bed of the harbour basin is exposed at low water. The mud bed consists of soft mud; a male person sinks about 0.5 to 0.7 m in the mud when walking over the mud bed.
The wet bulk density of the mud bed based on the analysis of 5 samples is (Van Rijn et al. 2018):

- November 2016: about 1440± 2% kg/m^3 (dry bulk density of 685 kg/m^3);
- March 2017: about 1275 ± 2% kg/m^3 (dry bulk density of 425 kg/m^3);
- June 2017: about 1400 ± 5% kg/m^3 (dry bulk density of 600 kg/m^3 in the toplayer of 0.1 m).

Based on the laboratory settling tests (**Table 4.2.1**), the mud from Noordpolderzijl (Harbour basin) is an almost perfect mud with an equal contribution of the three base fractions (clay, silt and fine sand), as follows: 35% clay (< 2 µm), 30% silt (2 to 63 µm) and 35 % sand > 63 µm (63-200 µm).
The percentage of organic materials (loss on ignition) varies in the range of 2.5% to 7%.

Parameter	**N-mud November 2016 (without treatment)**	**N-mud March 2017**		**N-mud October2017**	
		without chemical treatment	**with chemical treatment**	**without chemical treatment**	**with chemical treatment**
Wet bulk density (kg/m^3); mean of 5 samples (2 methods; large and small samples)	1440±10; 1390±50	1275±15	1275±15	1470±10	1470±10
Dry bulk density (kg/m^3); mean of 5 samples	685±20	425±15	425±15	755±10	755±10
Percentage organic material	2.5%-4%	5%-7%	0%	7%	0%
Percentage calcareous materials	15%	15%	0%	17%	0%
Percentage sediment > 63 µm	35%	30%	35%	40%	45%
Percentage fines between 2 and 63 µm	35%-45%	40%-55%	25%-35%	35%-40%	30%-35%
Percentage clay < 2 µm	20%-30%	15%-30%	30%-40%	20%-25%	20%-25%

Table 4.2.1 *Mud data from Noordpolderzijl channel (N-mud)*



SG=Sedigraph method; HM=Hydrometer method; FW=Filtration-Wased method;
S= Sieving method for sand fraction

Figure 4.2.2 *Particle size distribution of deflocculated sample N-mud (October 2017)*

Figure 4.2.2 shows the particle size distribution of the Noordpolderzijl-mud based on the Sedigraph-method (SG), the Hydrometer-method (HM) and the Filtration-Wased-method (FW). The SG-method yields a size distribution with smaller values ($d_{50}\cong$ 45 μm) than those of the HM and FW-methods ($d_{50}\cong$ 55 to 60 μm). The percentage of clay/lutum < 2 μm is about 25% based on the SG-method and about 10%-15% based on the HM and FW-methods.

4.2.3 Settling velocity of flocculated and non-flocculated bed mud samples

Settling velocities of bed samples have been determined using various methods: mechanical Wased-method, Hydrometer-method and SedigraphIII-method. Some samples have been deflocculated using a peptiser-solution to determine the settling velocity and size of the primary particles (Van Rijn et al. 2018).
Table 4.2.2 presents the data of a bed mud sample of November 2016. A suspension of seawater and mud (volume of about 2.5 liter) was prepared with an initial concentration of about 2600 mg/l. The mud was taken from the base container with N-mud (bed mud from Noordpolderzijl). The suspension was mixed thoroughly (manually) using a simple wooden mixing stick before the start of the settling process. Small samples (about 100 ml) of water and mud were taken after 5, 60, 180, 300, 600, 1800, 3600 and 7200 seconds to determine the decreasing mud concentrations over time. Immediately after each sample withdrawal, the water surface level of the settling column above the tap opening was measured. Most of the suspended mud has settled out to the bottom after 2 hours. The mud samples were filtrated and weighed to determine the mud concentration. The results are presented in **Table 4.2.2**.

Sample	Sample time after start settling process (seconds)	Settling height from surface to tapping point (mm)	Settling velocity (mm/s)	Mud concentration (mg/liter)	Mass percentage smaller than (%)
1	5	261	≅ 100	2635 (initial)	100
2	60	250	250/60=4.17	2212	2212/2635x100= 84.0
3	180	236	236/180=1.31	1180	1180/2635x100= 44.8
4	300	225	225/300=0.75	754	754/2635x100= 28.6
5	600	211	211/600=0.35	481	481/2635x100= 18.3
6	1800	200	200/1800=0.11	262	262/2635x100= 10.0
7	3600	186	186/3600=0.052	174	174/2635x100= 6.6
8	7200	170	170/7200=0.024	107	107/2635x100= 4.1

Table 4.2.2 *Settling test results of flocculated N-mud (WASED; temperature of 18° C); November 2016*

Figure 4.2.3 shows the settling velocities of flocculated N-mud (**Table 4.2.2**) based using a vertical settling column. The settling velocities of non-flocculated N-mud based on the Hydrometer (June 2017) and on the SedigraphIII (November 2016) are also shown.
It can be seen that the settling velocities of the non-flocculated mud ($w_{s,50}$= 0.25 mm/s) are much smaller than those of the flocculated mud ($w_{s,50}$= 1.5 mm/s). The $w_{s,90}$-values (≅ 6 mm/s; fine sand range) of both curves are about the same. The results of the SEDIGRAPH-method may be somewhat too small (see Section 3.4).
Figure 4.2.4 shows the settling test results of flocculated and non-flocculated suspensions of March 2017. The initial concentrations are in the range of 750 to 5535 mg/l. Most tests were done twice yielding very similar results. One test ($c_o\cong$300 mg/l; temperature =18° C) was done in fresh water with peptiser to determine the non-flocculated settling velocity. The settling velocities of the Sedigraph-method (SG-method) were done at a temperature of 36° and were corrected to 18° Celsius. The settling velocities increase with increasing concentrations due to the flocculation effect, see **Table 4.2.3**. The results of March-April 2017 and November-December 2016 are very similar.
Figure 4.6.1 shows the settling velocity of N-mud as function of the initial mud concentration.

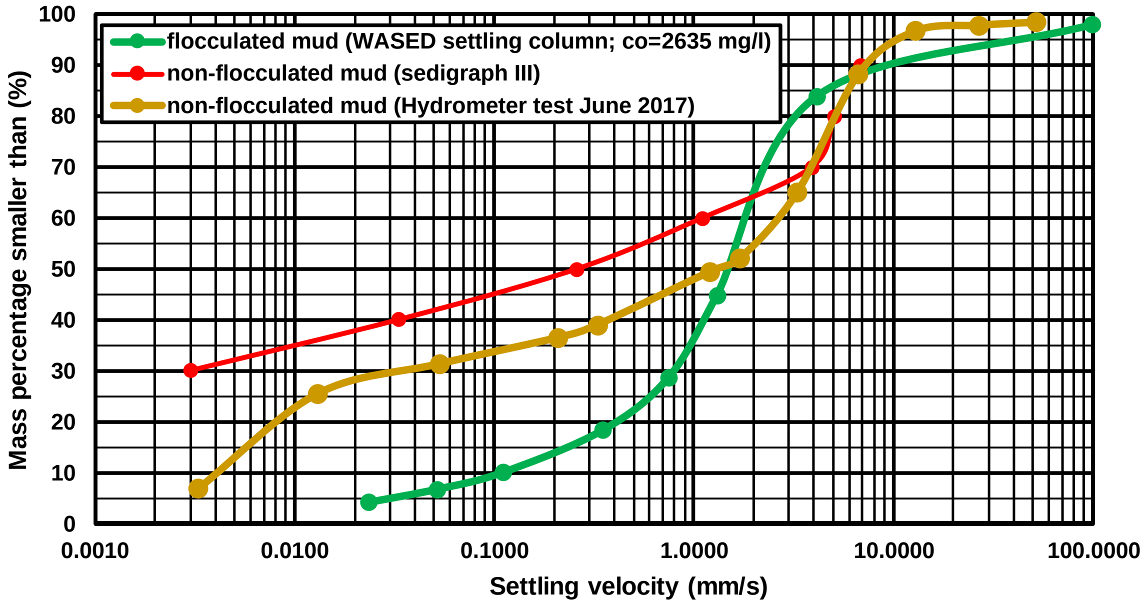


Figure 4.2.3 *Settling velocities of flocculated and non-flocculated N-mud (temperature= 18° C)*

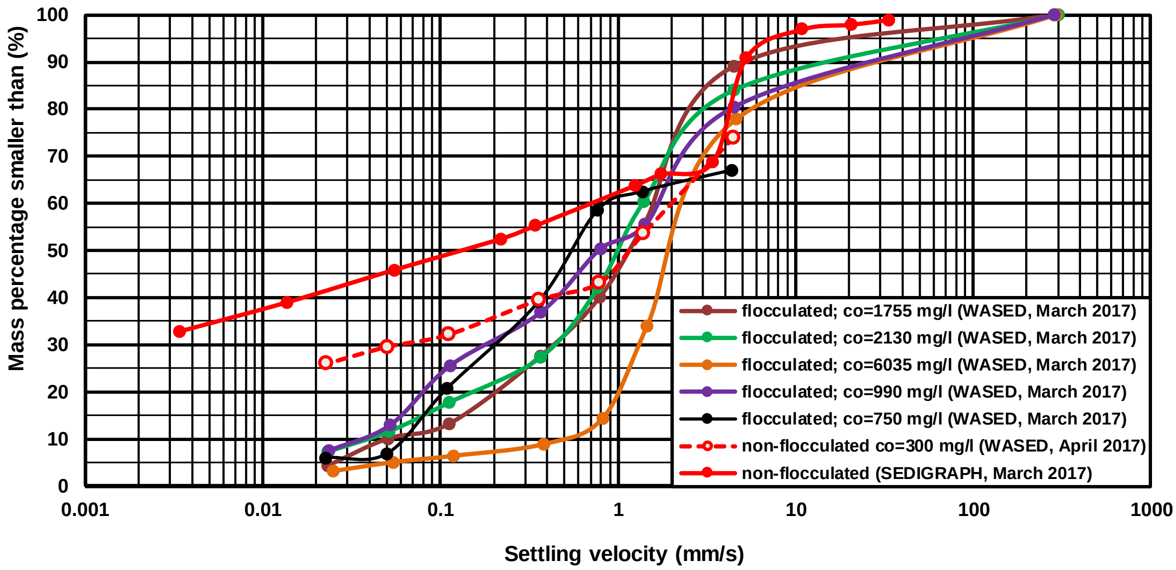


Figure 4.2.4 *Settling velocities of flocculated and non-flocculated N-mud (temperature= 18° C); March 2017*

WASED November 2016		WASED March 2017	
Initial concentration c_o (mg/l)	Flocculated settling velocity $w_{s,50}$ (mm/s)	Initial concentration c_o (mg/l)	Flocculated settling velocity $w_{s,50}$ (mm/s)
		750	0.55
		990	0.8
		1755	1.1
		2130	1.1
2635	1.5	6035	1.9

Table 4.2.3 *Settling velocity of flocculated N-mud as function of initial concentration; November 2016 and March 2017*

4.2.4 In-situ settling velocity of flocculated suspended samples

The WASED-method has been used to determine the settling velocity of in-situ flocculated suspended samples taken at location B5 of the muddy tidal channel on 4 July 2018 near Noordpolderzijl, Wadden sea, The Netherlands (**Figures 4.2.1** and **4.2.5**). The bed is almost dry (exposed) at low tide.
Muddy tidal channel: width= 5 to 15 m; depth= 0.3 m at low water and 2 m at HW.
Measurement location: B5 during flood tide; in middle of channel from anchored boat.
Tidal range: about 2 m.
Wind conditions: Beaufort 3 to 4 (3 and 4 July 2018).

Figure 4.2.5 *Location B5 muddy tidal channel Noordpolderzijl (flood tide), Wadden Sea, The Netherlands*

Flow velocities and mud concentrations

Based on float track measurements, the surface flow velocities are in the range of 0.05 to 0.4 m/s, see **Figure 4.2.6**. The velocities are highest early in the flood tide when the water depths are relatively small (<0.5 m). The surface velocity reduces to about 0.05 m/s when larger water depths are present.
Mud concentrations have been measured at 0.1 m above the bed and at 0.1 m below the water surface by taking water-mud samples of 0.2 to 0.3 litres using a peristaltic pump. The data are shown in **Figure 4.2.6**. The mud concentrations are highest just before the maximum velocities when the water depths are smallest.

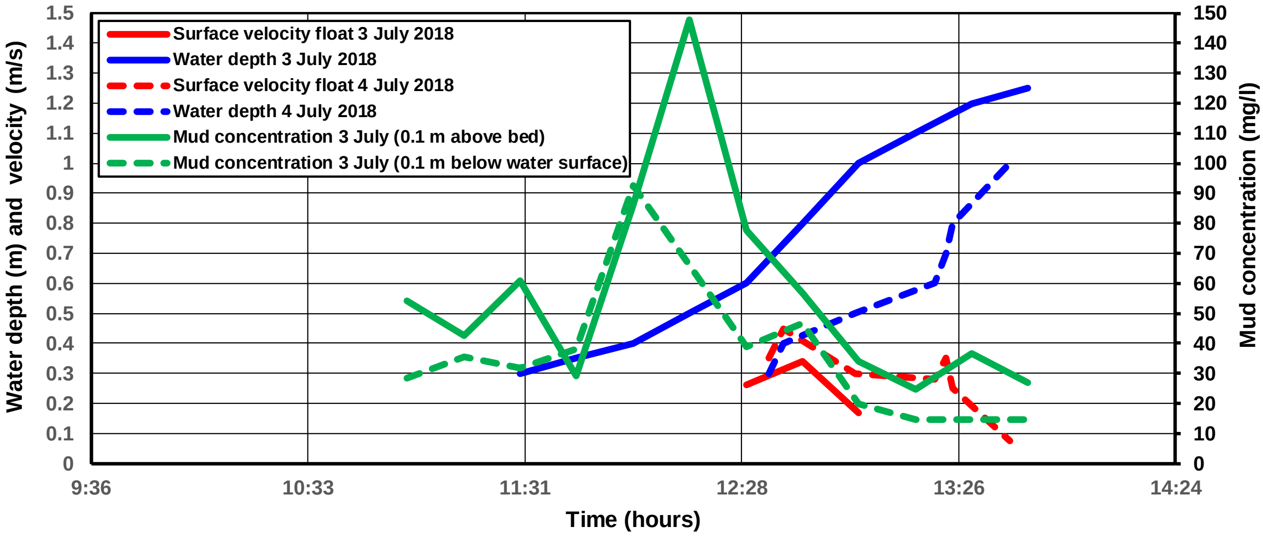


Figure 4.2.6 *Measured surface velocity, water depth and mud concentration at Location B5, Noordpolderzijl*

WASED in-situ settling velocity

The WASED-method consists of a mechanical horizontal trap sampler (tube with volume of 2 liters) with two side valves to trap a water-mud sample and a vertical settling tube, see **Figures 4.2.5** and **4.2.7**.

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 large closable bucket which is retured to the laboratory where the sample is poured into a vertical settling column (length ≅ 0.4 m; internal diameter= 0.1 m) with a closed bottom and a clamp tap at 0.07 m above the bottom. The suspension in the column is 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 100 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 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 (see **Table 4.2.2**). The initial mud concentration should be larger than about 200 mg/l to obtain accurate results.

Four suspended water-sediment samples have been taken at location B5 using the WASED tube, see **Figures 4.2.5** and **4.2.7.** Sample 1 had a very small initial mud concentration < 100 mg/l and was not used (inaccurate results.

A bed sample has been taken using the Van Veen Grab to determine the settling velocity of the bed mud in the laboratory. All samples were returned in large closable buckets to the laboratory

Figure 4.2.8 shows the settling velocity curve of the suspended samples (2, 3 and 4) and the bed sample.

The median settling velocity ($w_{s,50}$) varies in the range 0.4 to 1.5 mm/s (**Table 4.2.4**). The median settling velocity increases with increasing mud concentration (due to the flocculation effect. The settling velocity curve of a bed sample of June 2017 is also presented, showing similar results as the bed sample of July 2018.

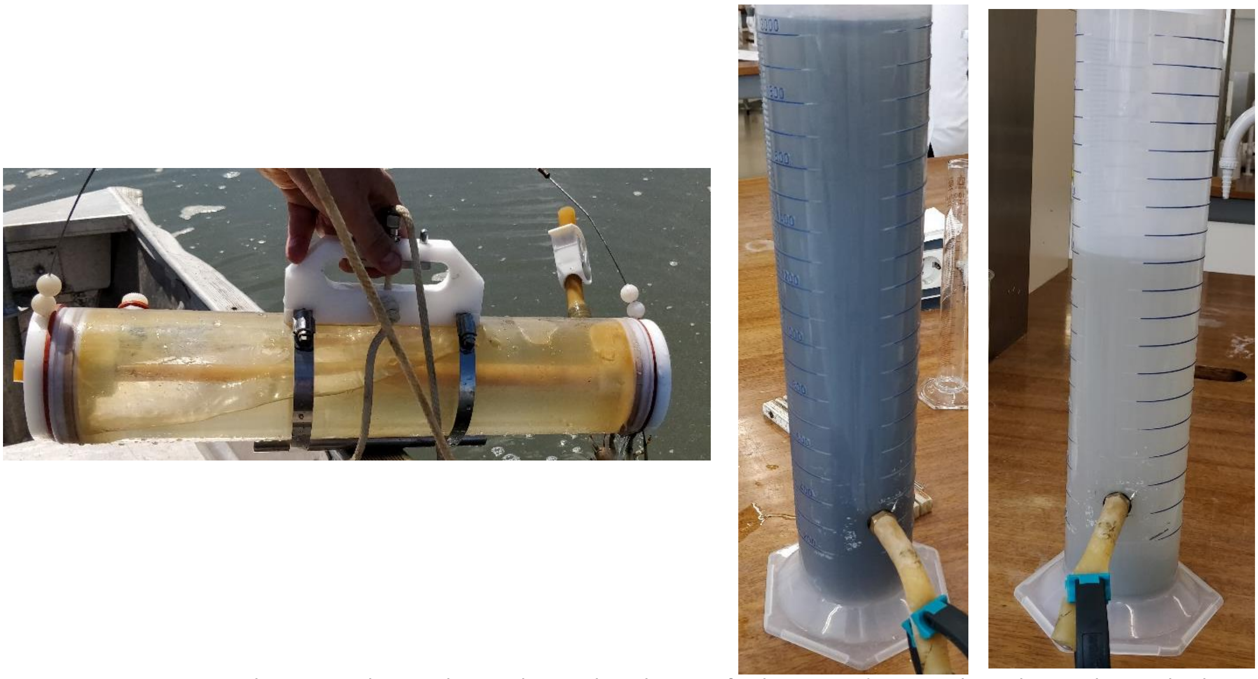


Figure 4.2.7 *WASED horizontal sampling tube with volume of 2 litres and vertical settling tube with clamp tap (before and after test)*

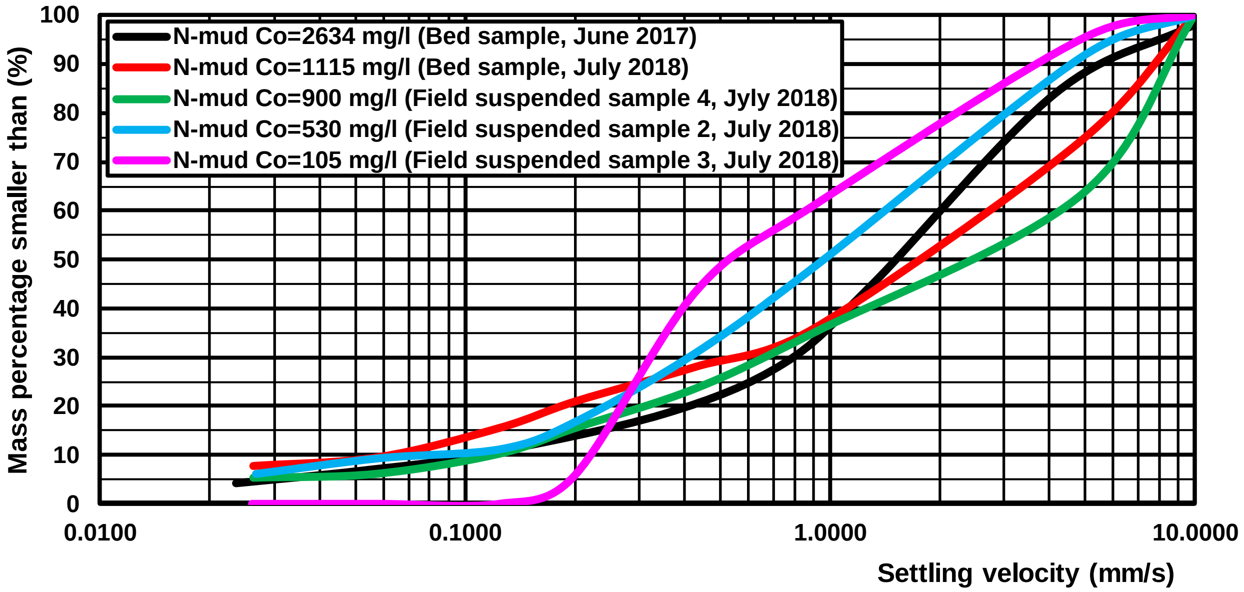


Figure 4.2.8 *Settling velocities of flocculated suspended mud samples and bed samples (N-mud); Noordpolderzijl, The Netherlands*

No	Type of sample	Time	Distance above bottom (m)	Water depth (m)	Initial mud concentration (mg/l)	Median settling velocity $w_{s,50}$ (mm/s)	Remarks
1	suspended	13.25	0.2-0.3	0.8	<100	-	undisturbed sample; not used (concentration too low for accurate results)
2	suspended	13.40	0.2-0.3	0.9	530	0.75	disturbed bed; bed upstream of wased-tube was stirred by Van Veen grab to generate mud cloud
3	suspended	13.55	0.2-0.3	1.0	105	0.4	undisturbed bed after close passage of 2 motorboats
4	suspended	14.05	0.2-0.3	1.0	900	1.4	disturbed bed; bed upstream of wased-tube was stirred by Van Veen grab to generate mud cloud
5	bed	14.10	-	1.05	-	1.2	bed sample; suspension was made in the laboratory (c_o=1115 mg/l)

Table 4.2.4 *Wased test results, location B5, 4 july 2018 Noordpolderzijl (N-mud)*

4.2.5 Hindered settling velocity of flocculated bed mud samples

The hindered settling velocity can be determined from tests with high concentrations in the range of 5 to 100 kg/m^3.

Settling tests have been done in saline water (native seawater) with initial suspension concentrations of c_o= 10, 30, 50, 100, 200 and 300 kg/m^3 (Van Rijn et al. 2018). The base mud container of N-mud has a dry density of about 685 kg/m^3 (November 2016). The suspension concentrations were made by dilution using the base mud.

The dilution formula reads as: $c_o= (V_1/V_o)\, c_{base}$, with c_o= initial concentration in settling tube (diameter of 60 mm), c_{base}= base mud concentration in container (≅685 kg/m^3), V_1= sample volume from base mud, V_o= settling tube volume (about 1.5 liter).

Each mixture was poured into a settling column (perspex cylinder/tube closed at bottom (see **Figure 4.2.9**) and stirred mechanically to create a homogeneous suspension of seawater and mud. After that, the settling starts and the position of the interface between the clear water and the suspension was recorded over time. **Figure 4.2.10** shows the relative height of the mud height (ratio of mud height and total height) as function of time for the tests of November 2016. The initial settling height is 360 mm for all six settling columns. The data of November 2016 are presented in **Table 4.2.5**.
The settling/consolidation process consists of two clear phases: 1) flocculation+hindered settling phase and 2) consolidation phase, see **Figure 4.2.10** to **4.2.12.** The end of the hindered settling phase is the transition from a concave to convex (hollow) curve. The dry density at the transition point is known as the gelling concentration (matrix/network structure).
The test with initial concentration of 10 kg/m³ shows a deviating behaviour in the sense that two (upper and lower) interfaces were generated in the initial phase. The upper interface is that of the suspension of very fine sediments, whereas the lower interface marks the deposited coarser silt and fine sand particles. This is an indication of segregation of finer and coarser sediments.

Figure 4.2.11 shows the dry mud density as function of time derived from the tests of November 2016. The dry density can substantially increase during the tidal slack period of 3 hours.
Figure 4.2.12 shows the relative height of the mud height (ratio of mud height and total height) as function of time for the tests of March 2017. The initial settling height is 365 mm for all six settling columns. The data of March 2017 are presented in **Table 4.2.6**.
Figure 4.6.1 shows the hindered settling velocity as function of the mud concentration for all test results. The maximum settling velocity due to the flocculation effect is about 2 mm/s at a concentration of about 6 kg/m³. The settling velocity decreases due to hindered settling effects to about 0.1 mm/s at a very high concentration of about 100 kg/m³.

Initial mud concentration (kg/m³)	**Hindered settling duration (s)**	**Hindered settling height (mm)**	**Hindered settling velocity (mm/s)**	**Dry density (or gelling concentration) at end of hindered settling phase (start of consolidation phase) (kg/m³)**	**Dry density after 280 hours (kg/m³)**
10	410/480	40/330	0.1-0.7	-	355
30	1000	250	0.25	100	430
50	1500	200	0.13	110	455
100	3000	160	0.055	180	525
200	3500	145	0.04	-	690
300	4000	100	0.025	-	715

Table 4.2.5 *Consolidation test results of N-mud (initial settling height= 360 mm); November 2016*

Initial mud concentration (kg/m³)	**Hindered settling duration (s)**	**Hindered settling height (mm)**	**Hindered settling velocity (mm/s)**	**Dry density (or gelling concentration) at end of hindered settling phase (start of consolidation phase) (kg/m³)**	**Dry density after 140 hours (kg/m³)**
15	300	255	0.85	75	300
30	800	220	0.27	85	330
50	1000	145	0.15	125	360
100	2000	110	0.054	150	370
200	-	-	-	-	435
300	-	-	-	-	460

Table 4.2.6 *Settling test results of N-mud (initial settling height= 365 mm); March 2017*

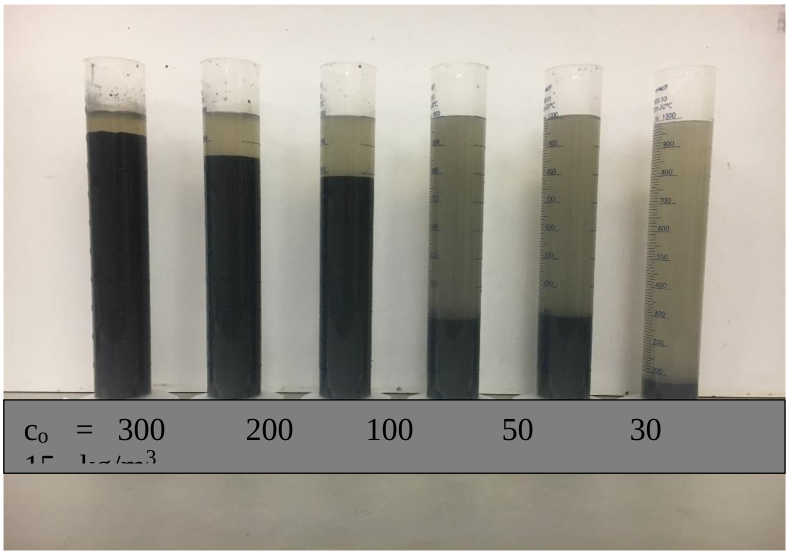


Figure 4.2.9 *Settling columns of N-mud (initial settling height=360 mm); November 2016*

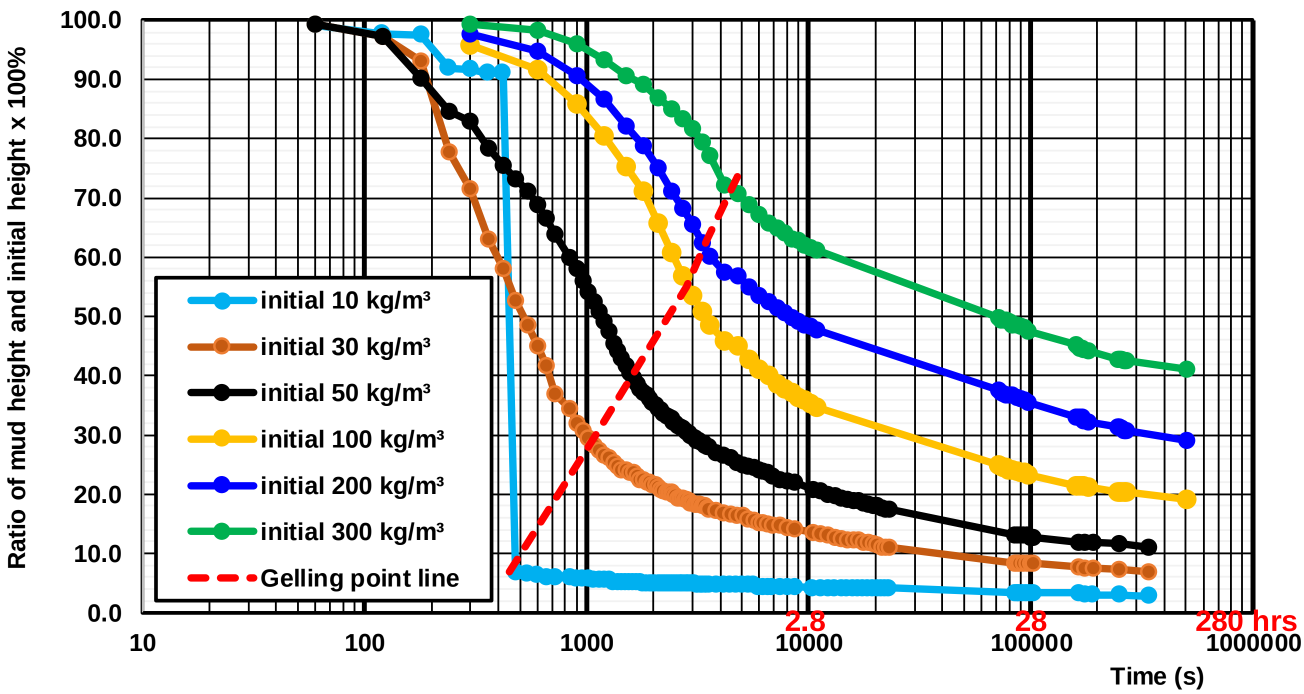


Figure 4.2.10 *Settling height as function of time based on settling tests N-mud (initial settling height=360 mm); November 2016*

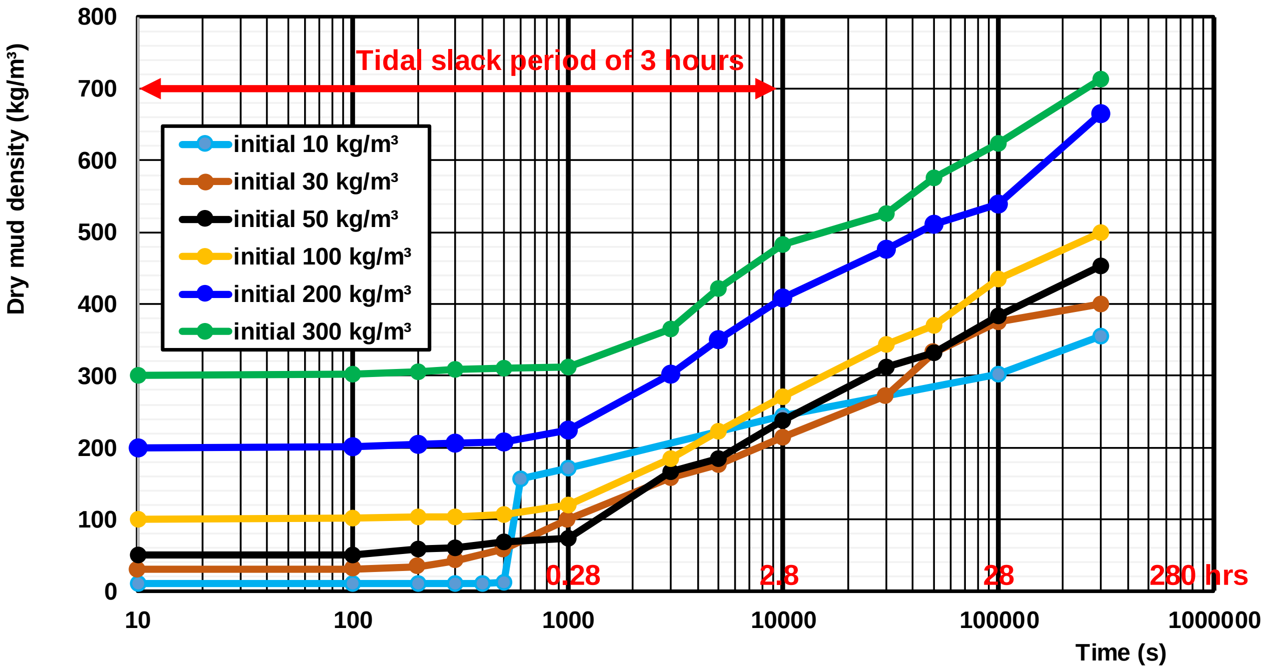


Figure 4.2.11 *Dry mud density as function of time based on settling tests N-mud; November 2016*

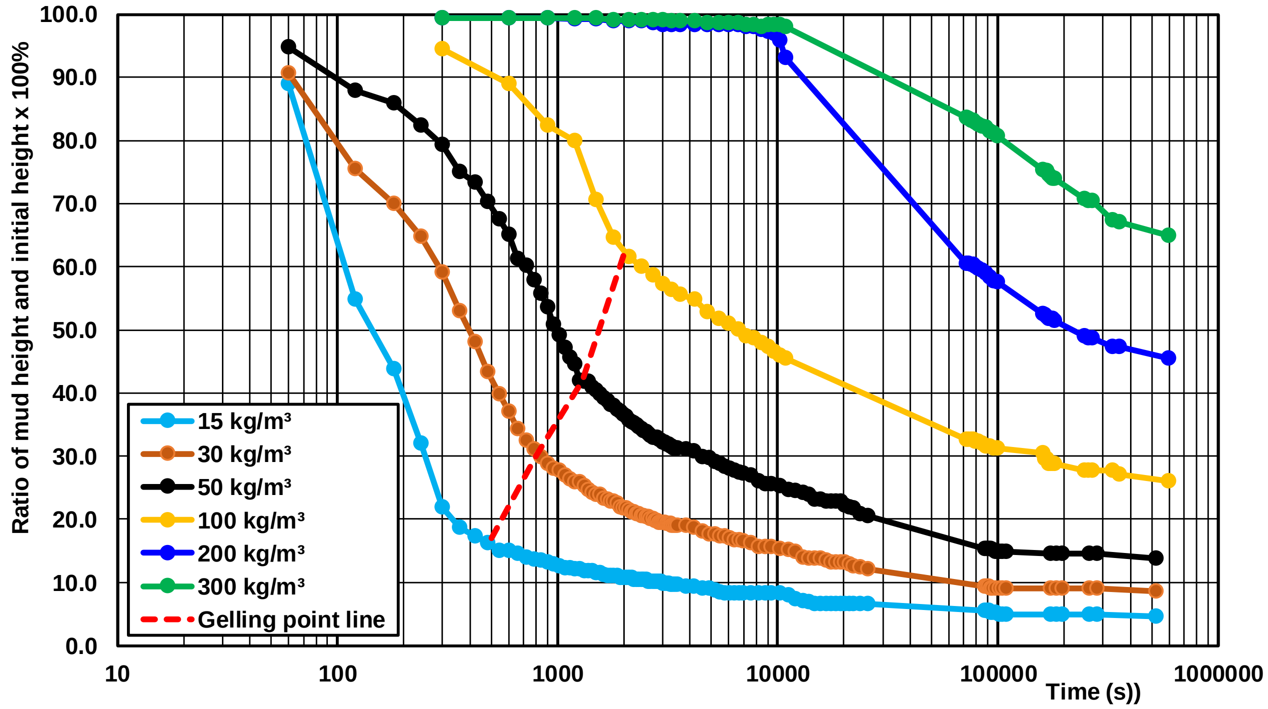


Figure 4.2.12 *Settling height as function of time based on consolidation tests N-mud (initial settling height=365 mm); March 2017*

4.3 Mud of Delfzijl harbour basin (D-mud)

4.3.1 Site description

The tidal harbour basin of Delfzijl is situated along the Wadden sea in the northern part of The Netherlands, see **Figure 4.3.1**. The basin dimensions are:

- planform area of basin is 2.2 10^6 m^2 (220 hectares);
- planform area of navigation channel is 1 10^6 m^2 (100 ha);
- bottom width of entrance is 220 m;
- depth of entrance to MSL is about 10 m.

The tidal data are (Deltares 1999):

- tidal range of about 3 m, tidal period of about 12.5 hours,
- maximum flow velocity outside entrance is about 0.8 m/s,
- maximum depth-averaged mud concentration outside entrance is about 200 mg/l with tidal variation of about 100 mg/l.

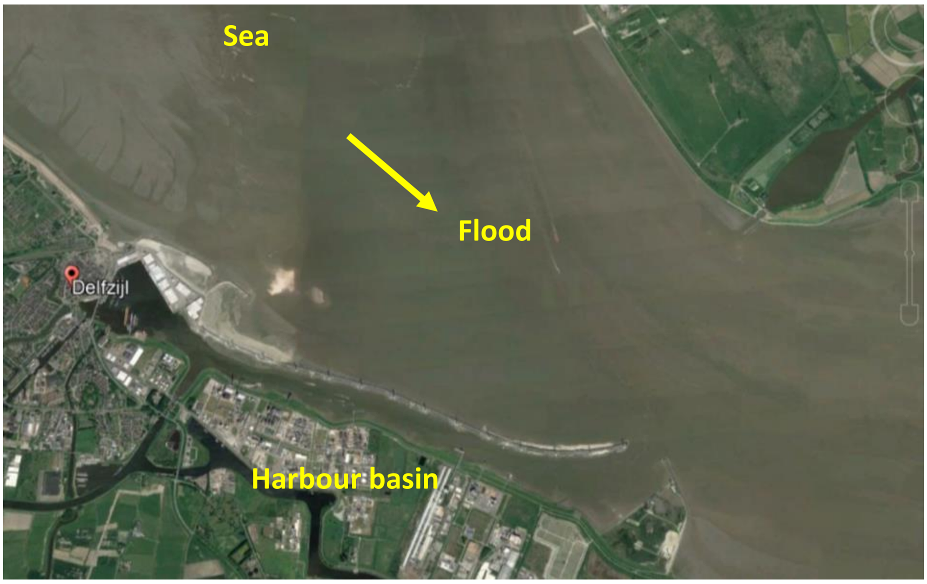


Figure 4.3.1 *Harbour basin of Delfzijl, The Netherlands*

4.3.2 Bed composition

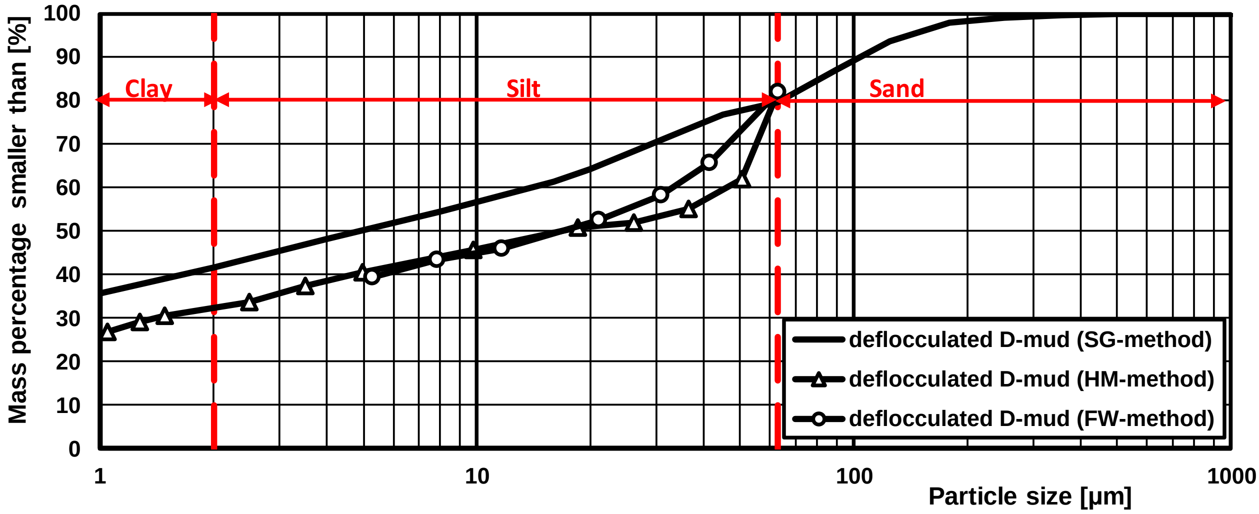
Weakly consolidated mud samples have been taken (November 2017) in the harbour basin of Delfzijl by using a VanVeen-Grab sampler in shallow water near the bank (depth of about 5 m), see **Figure 4.3.2**. The total volume of mud was about 80 liters. Furthermore, a container of 100 liters was filled with sea water.
The mud container and samples were carried to the laboratory of Wiertsema Soil Engineering, where it was stored at a temperature between 10° and 20 °C.
The mud properties of Delfzijl-mud (D-mud) are given in **Table 4.3.1**.

Parameter	D-mud (November 2017)	
	without chemical treatment	with chemical treatment
Wet bulk density (kg/m^3); mean of 5 samples (2 methods; large and small samples)	1310±10	1310±10
Dry bulk density (kg/m^3); mean of 5 samples	505±10	505±10
Percentage organic material	10%	0%
Percentage calcareous materials	18%	0%
Percentage sediment > 63 μm	20%	20%
Percentage fines between 2 and 63 μm	40%-50%	40%-50%
Percentage clay < 2 μm	30%-40%	30%-40%

Table 4.3.2 *Mud data from Delfzijl harbour (D-mud), The Netherlands*

Figure 4.3.2 *Mud sampling in harbour basin of Delfzijl, The Netherlands*

Figure 4.3.3 shows the particle size distribution of the D-mud sample based on the Sedigraph-method (SG), the Filtration-Wased-method (settling test based on filtration of concentrations) and the Hydrometer-method (HM). The percentage of sand is about 20%. The mud samples were tested in fresh water with peptiser (for deflocculation) to determine the settling velocity and particle size of the primary particles. The test was done at a temperature of 18° C and the settling velocity data were converted to particle diameter using the Stokes settling formula. The FW-method and the Hydrometer-method yield the same particle size distribution of the fine fraction. The SG-method yields much finer sediments. The percentage < 4 μm is about 40% for the FW-method/HM-method and about 50% for the SG-method. The cause for this discrepancy is not yet clear, but the fluid-sediment mixture in the small sedimentation cell may suffer from small temperature-driven circulation flows and wall effects (see Section 3.4). The main advantage of the SG-method is the rapid analysis of many samples.



SG= Sedigraph-method; HM=Hydrometer-method; FW= Filtration-Wased-method

Figure 4.3.3 *Particle size distribution of deflocculated bed mud samples (minerals only) from Delfzijl (D-mud; November 2017- February 2018)*

4.3.3 Hindered settling velocity of flocculated bed mud samples

The hindered settling velocity can be determined from tests with high concentrations in the range of 5 to 100 kg/m^3. The dry density of the base mud from the container is about 500 kg/m^3.
Four columns have been filled with Delfzijl-mud (D-mud) with initial concentrations of 50, 100, 200 en 300 kg/m^3. The initial height of the mud mixture in the columns was 0.9 m.
The sinking of the interface between the clear water and the suspension was recorded over time from which the settling velocity can be determined, see **Table 4.3.2**.
The hindered settling velocities as function of concentration are shown in **Figure 4.5.1**.

Column	Initial mud height (mm)	Initial mud concen tration (kg/m^3)	Hindered settling duration (s)	Hindered settling height during initial phase (mm)	Hindered settling velocity (mm/s)	Dry density (gelling concentration) at end of hindered settling phase (kg/m^3)
1E	900	50	10800	548	0.051	135
1F	900	100	21600	448	0.021	200
1G	900	200	86400	90	0.001	-
1H	900	300	86400	32	0.0003	-

Table 4.3.2 *Hindered settling results of D-mud (20% sand), Delfzijl harbour, The Netherlands*

4.4 Mud of Holwerd (H-mud)

4.4.1 Site description

Bed samples have been taken at various dates from the bed of the tidal ferry channel between the village of Holwerd at the Frisian Wadden coast and the island of Ameland. The muddy part of the channel (traject AC) has a length of about 4 km, a width of about 50 m and a minimum depth below mean sea level of about 4 m, see **Figure 4.4.1.**

The tide in the ferry channel is semidiurnal with a tidal range of about 1.8 m at neaptide and about 2.5 m at springtide.

Field measurements of flow velocities (ADCP-instrument) and mud concentrations (OBS and pump samples for calibration) have been done on 14 April 2016 in the channel between locations A and C (Deltares 2016; paper Van Rijn 2018; www.leovanrijn-sediment.com). Similar measurements have been done in the period February 2019 and September-October 2019.

The most important results are:

- flood flow has a duration of about 7 hours with maximum depth-averaged flow velocities of about 0.7 m/s in location A, and 0.6 m/s in B and C;
- ebb flow has a duration of about 5.5 hours with maximum depth-averaged velocities of about 0.6 m/s in A; 0.8 m/s in B and 0.4 m/s in C;
- the maximum flood velocity occurs about 3 hours before high water (HW);
- the depth-averaged mud concentrations increase rapidly to about 1000 to 1500 mg/l in the period before maximum ebb flow and maximum flood flow;
- the mud concentrations decrease to minimum values of 150 to 250 mg/l in the period of 3 hours after maximum flood flow;
- the mud concentrations near the bed (< 0.5 m) are much larger than the depth-averaged mud concentrations (factor 2 to 5).

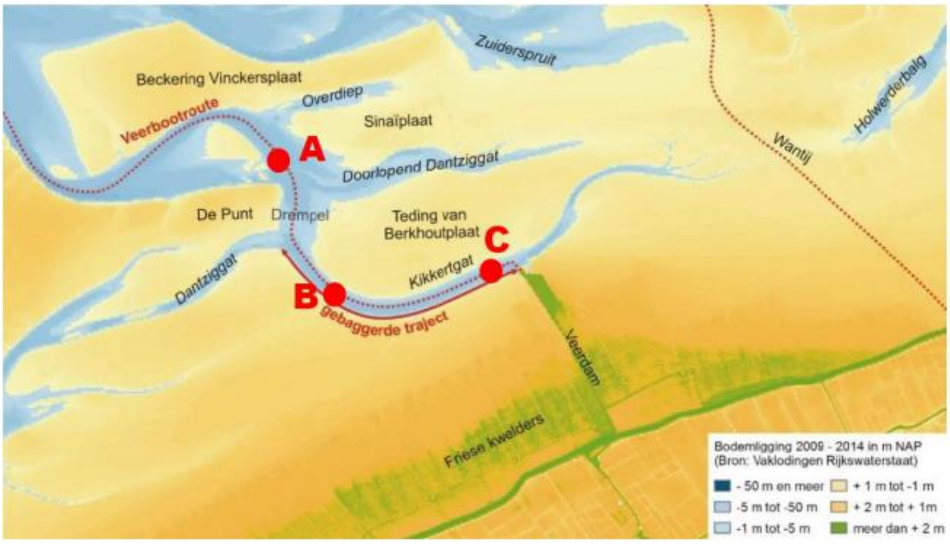


Figure 4.4.1 *Ferry channel between Holwerd and Island of Ameland, Wadden Sea, The Netherlands*

4.4.2 Bed composition

Bed samples have been taken at various dates along channel traject AC:

- 23 August 2002: sandy bed material with d_{50}-values in the range of 100 to 150 μm and mud percentages < 63 μm in the range of 5% to 25%; the mud percentage is largest near the ferry landing location (**Table 4.4.1**);
- 14 April 2016: silty bed material with d_{50}-values in the range of 20 to 70 μm; percentage of fines < 63 μm is up to 80%; the dry bulk density of bed samples is in the range of 750 to 950 kg/m^3; settling velocities are in the range of 1 to 2 mm/s. (**Table 4.4.1**);
- 7-20 February 2019: muddy bed near the ferry landing site and muddy-sandy bed in the ferrry channel, see **Table 4.4.2**.

Bed samples	d_{50} (μm)	Percentage sand (%)	Percentage mud < 63 μm (%)	Wet bulk density (kg/m^3)	Dry bulk density (kg/m^3)	Settling velocity of flocculated sediment (concentration of about 1 kg/m^3)			
						w_{10} (mm/s)	w_{35} (mm/s)	w_{50} (mm/s)	w_{75} (mm/s)
Location A									
KG07 (11.04 hrs)				1606	950				
KG13 (18.05 hrs)	18	20	80	1492	780				
Location B									
KG05 (10.41 hrs)	65	45	55	1575	930				
KG06 (10.41 hrs)	20	35	65	1552	880				
KG09 (16.34 hrs)	10	25	75	1467	750				
KG14 (18.15 hrs)	15	25	75	1491	790	0.1	0.4-0.8	1-2.2	2.5-11
Location C									
KG15 (18.35 hrs)	20	30	70	1604	960	0.1	0.4-0.8	1-2	4-8

Table 4.4.1 *Bed mud data of channel traject AC; 14 April 2016 (H-mud); Deltares (2016a,b)*

Date	Location	No.	Type/ method	Description sediment	In-situ wet/dry bulk density (kg/m³)
8 February 2019	near ferry landing		VVG during 13-hour measurements	soft mud p_{mud}=80%	wet: 1360±20; dry: 550±20
21 February 2019	near ferry landing		VVG during 13-hour measurements	muddy sand p_{mud}=32%	wet: 1660±50; dry: 1040±80
27 February 2019	near ferry landing	100	VVG	soft mud p_{mud}=90%	wet: 1365/1400; dry: 555/615
	near ferry landing		VVG	soft, buttery mud; not much org and shells	5 subsamples wet: 1460±40; dry: 710±50
	near ferry landing (at kwelderbank)		Bucket sample	soft smooth mud; not much sand and org./shells	3 subsamples wet: 1550±20; dry: 860±40
	km 0 from landing site	0	VVG	buttery mud p_{mud}=56%	wet: 1500/1585; dry: 780/920
	km 0,5 from landing site	1	VVG	buttery mud p_{slib}=62%	wet: 1485/1510; dry: 755/795
	km 1	2	VVG	buttery mud p_{slib}=60%-75%	wet: 1340/1370; dry: 520/565
	km 2	3	VVG	mud/sand p_{mud}=35%	wet: 1490/1625; dry: 765/980
	km 3	4	VVG	mud/sand p_{mud}=40%	wet: 1555/1580; dry: 865/910
	Channel 1	5	VVG	slib en zand p_{slib}=5%	wet: 1760/1915; dry: 1200/1455
	km 4	6	VVG	many shells	wet: not measured dry: not measured
	km 5	7	VVG	sand p_{mud}=4%	wet: 1990/1995; dry: 1575/1585
	Channel 2	8	VVG	sand p_{mud}=3%	wet: 1870/1930; dry: 1380/1480
	km 6	9	VVG	sand p_{mud}=3%	wet: 1875/1890; dry: 1390/1425
	km 6	10	VVG	sand p_{mud}=5%	wet: 1910/2015; dry: 1445/1615

VVG= Van Veen Grab; sample poured in bucket; subsamples taken for laboratory analysis; small 60 ml-glass pots for determination of bulk density; large 1 liter-pots for determination of sample analysis en erosion tests

Table 4.4.2 *Bed mud data of channel traject AC; 7-20 February 2019 (H-mud); WaterProof 2019*

4.4.3 Settling velocity of flocculated mud bed samples

Measurements April 2016

The settling velocity of bed mud sample KG14 at location B and sample KG15 at location C was measured by using the Sedimentation Balance-method of Deltares (2016), see **Figure 3.5**. The percentage of sand of these silty mud samples is in the range of 25% to 30%.

The SB-instrument consists of a temperature-regulated tube (double wall) with a height of 200 to 300 mm (about 0.5 to 1 litre) and an accurate weighing balance at the bottom of the tube.

The results are shown in **Table 4.4.1**. The median settling velocity ($w_{s,50}$) is in the range of 1 to 2.2 mm/s (initial concentration is about 1000 mg/l).

4.4.4 Hindered settling velocity of flocculated bed mud samples

Measurements April 2016

Deltares (2016) has determined the settling velocity of high-concentration suspensions of H-mud in vertical settling columns (with length of 0.6 m; diameter 0.1 m; volume of 3 liters; native water).

Before the start of the test, the sediment-water mixture is gently stirred (to prevent breaking of the flocs) to get a uniform distribution over the settling column. Over time, the sediments settle in the column and an interface between the water-sediment mixture and the clear water above becomes visible (hindered settling phase). The end of hindered settling phase is characterized by the gelling concentration c_{gel} at which a space-filling network develops, meaning that all particles are in contact with each other leaving no possibility for further settling.

Figure 4.4.2 shows the settling test results to estimate the effective settling velocity and gelling concentration of sample KG-14 of the Holwerd channel (Wadden Sea). The initial mud concentrations are 20, 40 and 60 g/l (kg/m^3). The gelling concentration can be roughly estimated from the mud height at the transition from settling to consolidation. The estimated gelling concentrations for KG-14 varies between 110 and 200 g/l. A rough estimate of the effective settling velocity can be estimated from the settling process resulting in: settling velocity= settling height/time $\cong$ 340 mm/150 s $\cong$ 2.3 mm/s for an initial concentration of 20 g/l and about 0.25 mm/s for an intial concentration of 60 g/l.

The settling velocities as function of concentration rare shown in **Figure 4.6.1**.

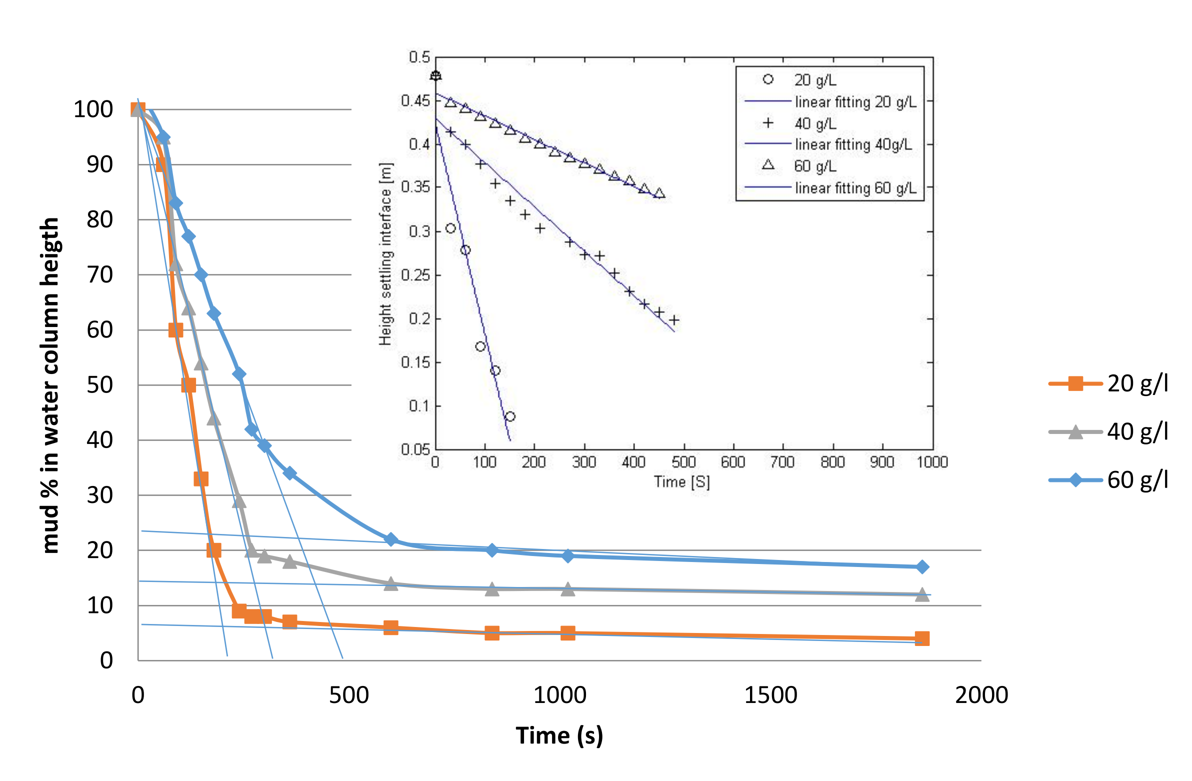


Figure 4.4.2 *Settling test results of sample KG-14, Holwerd channel (Wadden Sea); Deltares 2016*

4.4.5 Settling velocity of flocculated suspended mud

Measurements June 2017

The horizontal WASED-tube was used from the quay wall (see **Figure 4.4.3**) at the ferry landing near Holwerd (June 2017), The Netherlands. Four samples were taken at about 0.5 to 1 m above the local bed at about 2 hours after HW. The local water depth was about 3.5 m at the start of the tests and about 3 m at the end of the tests.

Particle size analysis of a bed sample and a suspended sample shows the following results:

- bed sample: percentage mud=53%; percentage sand=47%, d_{50}=55 μm;
- suspended sample: percentage mud=75%; percentage sand=25%, d_{50}=25 μm.

The test procedure was, as follows:

- samples 1 and 2: horizontal WASED-tube is lowered to the sampling point at about 0.5 m to 1 m above the bed; valves are closed after about 1 minute and the tube is raised; the water-sediment sample is poured into a large closable bucket, which is returned to the laboratory for analysis;
- sample 3: horizontal WASED-tube is lowered to the sampling point at about 0.5 m to 1 m above the bed; valves are closed after about 1 minute and the tube is raised; the water-sediment sample is poured into a large bucket; and then (using a funnel) into a vertical settling column (see **Figure 4.4.4 left**); the sample is stirred to make a uniform suspension and the settling test is started;
- sample 4: horizontal WASED-tube is lowered to the sampling point at about 0.5 m to 1 m above the bed; valves are closed after about 1 minute and the tube is raised; the Wased-tube is shaken and put into a vertical position and the settling process is started (**Figure 4.4.4right**);
- sample 5; a bed mud sample was taken using the Van Veen grab and a settling test was performed in the laboratory using a settling tube.

The settling curves are shown in **Figure 4.4.5**. The initial concentrations of samples 2 and 4 are extremely high as the samples are taken relatively close to the bed near the big steel poles of the quay wall creating additional turbulence resulting in high near-bed concentrations.
The median settling velocity ($w_{s,50}$) of samples 1, 2, 4 and 5 are in the range of 1.5 to 3.5 mm/s expressing the presence of fine sand.
The median settling velocity ($w_{s,50}$) of sample 3 is about 0.4 mm/s expressing the presence of fines in the water column.

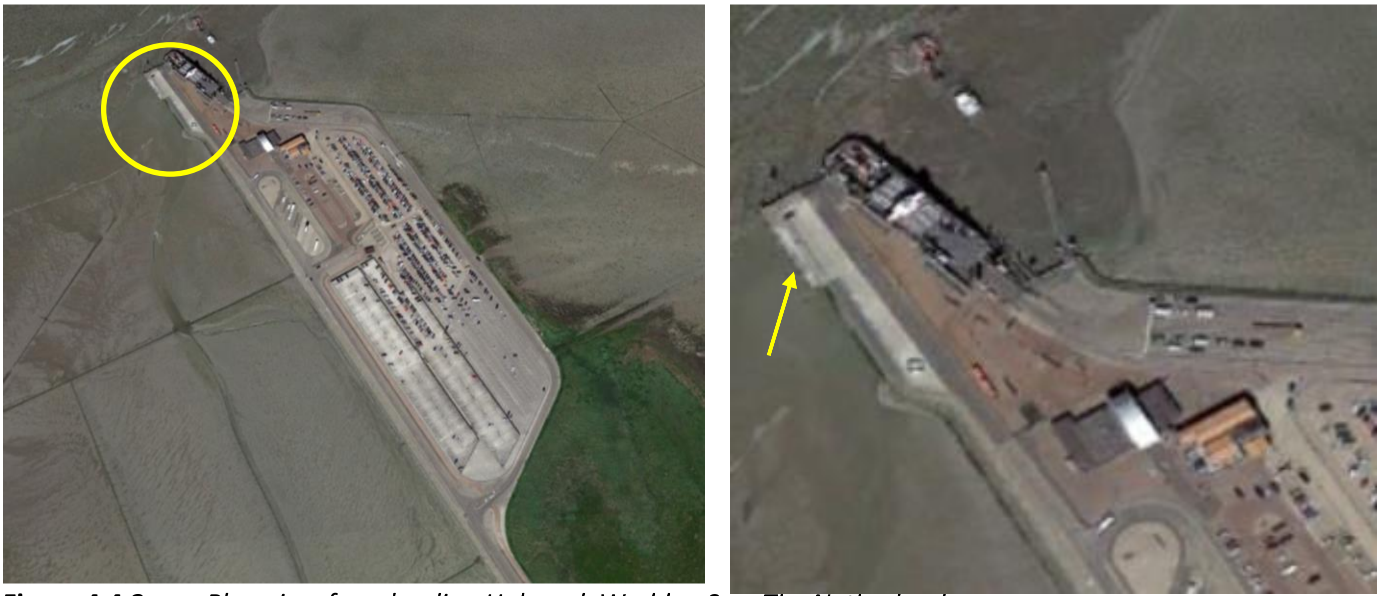


Figure 4.4.3 *Plan view ferry landing Holwerd, Wadden Sea, The Netherlands*

Figure 4.4.4 *Settling colums (left: standard settling tube; right: WASED-tube in vertical position)*

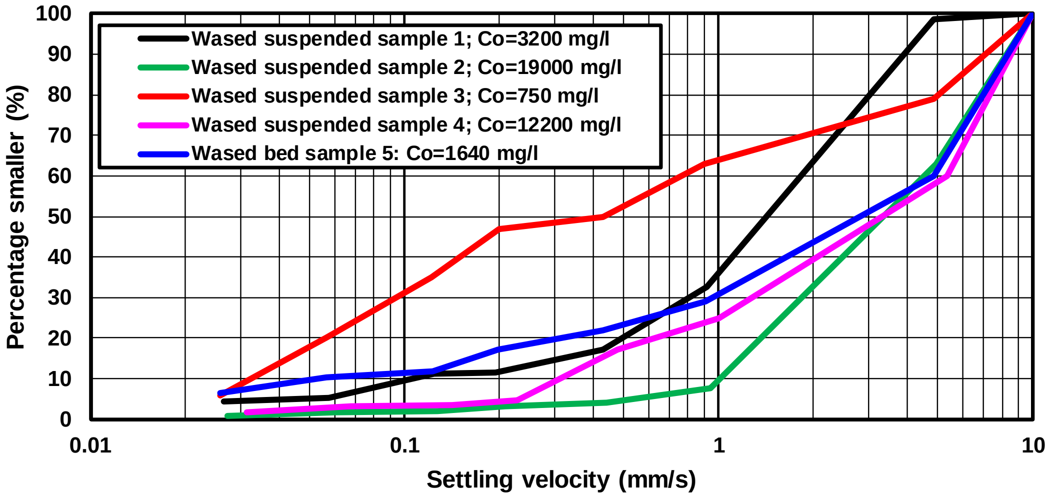


Figure 4.4.5 *Settling velocity curves of mud samples from quay wall near Holwerd, The Netherlands*

Measurements February and September 2019

Various suspended samples were taken by a sampler bottle (2 liter) in the ferry channel near Holwerd landing pier, The Netherlands. The samples were analyzed in the laboratory using settling tests in native saline water. The results are summarized in **Tables 4.4.3, 4.4.4** and in **Figures 4.4.6 to 4.4.8**.
In February 2019, the median settling velocity is relatively flow (0.1 mm/s) for low concentration of about 200 mg/land increasing to about 1 to 2 mm/s for high concentrations of 10,000 mg/l. The suspended material mainly consists of fine silt of 30 to 40 μm.
In September 2019, the median settling velocities are much lower in the range of 0.1 to 0.2 5 mm/s, because the mud concentrations are significantly smaller (500 to 1000 mg/l after summer period) than in February (5000 to 10000 mg/l in winter period with more wave activity).

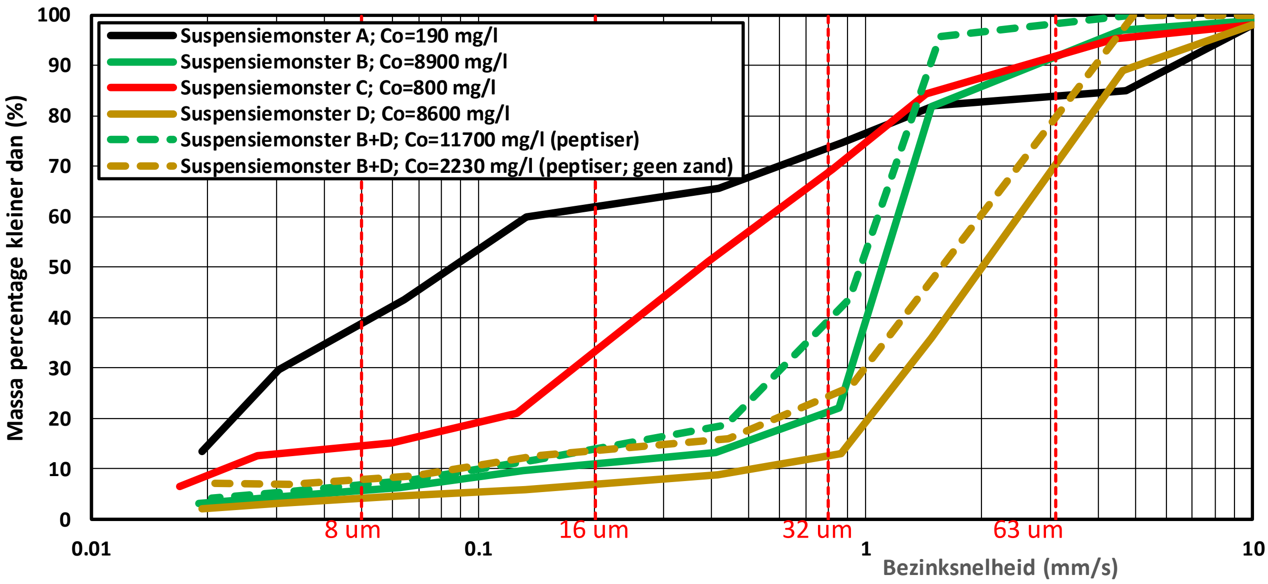


Figure 4.4.6 *Settling velocities of samples; Location near Holwerd ferry landing pier; 27 February 2019*

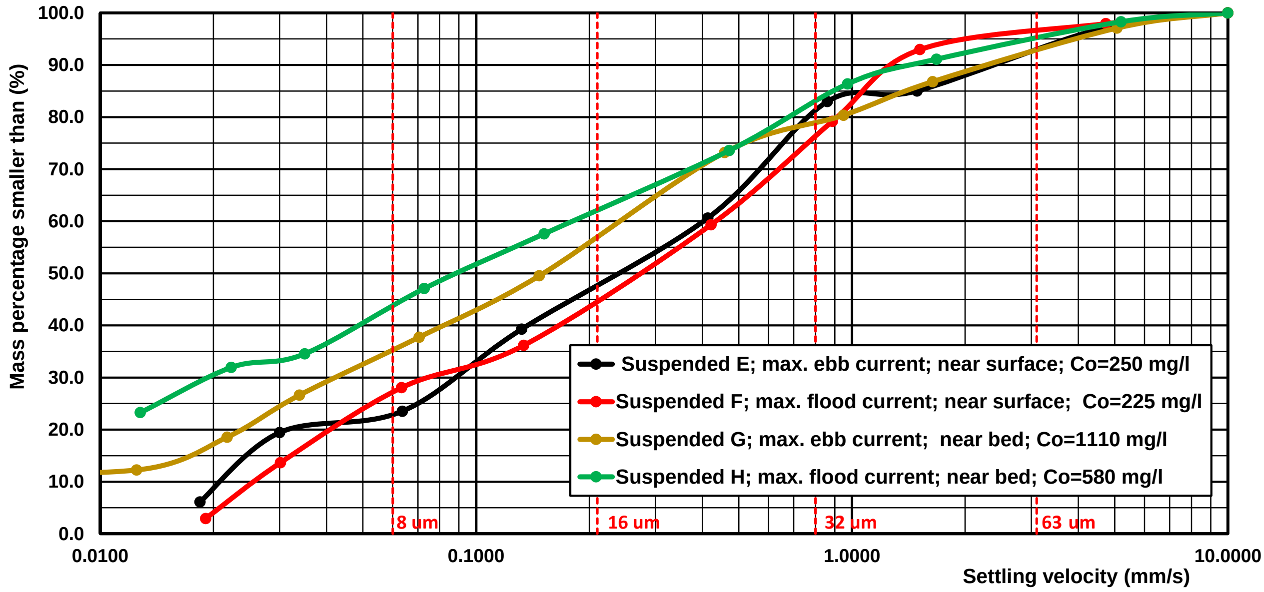


Figure 4.4.7 *Settling velocities of samples; Location near Holwerd ferry landing pier; 25 September 2019*

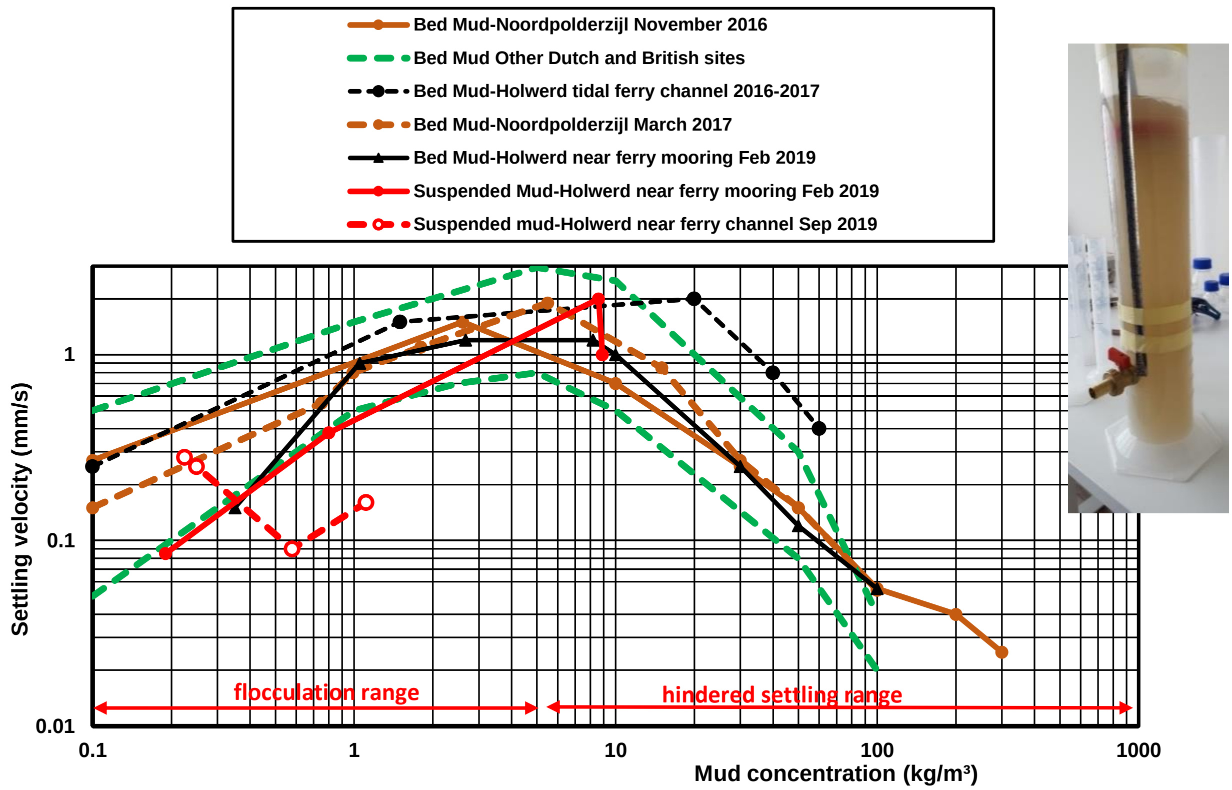


Figure 4.4.8 *Settling velocity as function of concentration*

Location of samples	Settling velocity in native saline water			
	Initial concentration (mg/l)	$w_{s,10}$ (mm/s)	$w_{s,50}$ (mm/s)	$w_{s,90}$ (mm/s)
Suspended sample A; water surface -0,5 m; 1 hour before max. ebb current	190	0.018	0.085	6.5
Suspended sample B; bed +0.2 m; max. flood current	8900	0.15	1.1	2.8
Suspended sample C; water surface -0,5 m; max. flood current	800	0.022	0.38	2.7
Suspended sample D; bed +0,2 m; 1 hour before max. ebb current	8600	0.05	2	5.0
Suspended sample B+D; with peptiser anti-flocculation agent	11700	0.1	1	1.6
Suspended sample B+D; with peptiser anti-flocculation agent; sand fraction removed by sieving 63 μm	2230	0.1	1.7	4
Bed sample	350	0.015	0.15	4
	1050	0.03	0.9	7
	2670	0.06	1.2	8
	8200	0.5	1.2	2
	10.000 (consolidation test)		1.0	
	30.000 (consolidation test)		0.25	
	50.000 (consolidation test		0.12	
	100.000 (consolidation test)		0.055	

Table 4.4.3 *Settling velocities in native saline water; Holwerd mud; 8 February 2019*

Location of samples	Settling velocity in native saline water			
	Initial concen tration (mg/l)	$w_{s,10}$ (mm/s)	$w_{s,50}$ (mm/s)	$w_{s,90}$ (mm/s)
Suspended sample E; water surface -0,5 m; max. ebb current	250	0.02	0.25	2.5
Suspended sample F; water surfasce -0,5 m; max. flood current	225	0.025	0.28	1.3
Suspended sample G; bed +0,15-0,65 m; max. ebb current	1110	0.01	0.16	2.2
Suspended sample H; bed +0,15-0.65 m; max. flood current	580	0.01	0.09	1.5

Table 4.4.4 *Settling velocities in native saline water; Holwerd mud; 25 September 2019*

4.5 Mud of Payra, Bangladesh (P-mud)

4.5.1 Site description

Payra Sea Port is being developed to be the third seaport of Bangladesh located on the west bank of Rabnabad Channel at Kalapari in Patuakhali, Bangladesh.
Payra Sea Port will be built as a deep seaport. The depth of Payra Sea Port is about 15 m below Chart Datum. The navigation channel to deep water offshore has a length of about 55 km
The spring tidal range is about 2.3 m; the neap tidal range is about 0.8 m
Measured velocities in the channel near the entrance of the estuary are in the range of 1 to 1.3 m/s.

The fresh water discharge of the Megna River passing Payra Port is 20,000 m^3/s (dry season) to 100,000 m^3/s (wet season).

4.5.2 Bed composition

Various bed samples taken in the coastal zone during the October-November field survey 2016 have been made available to LVRS-Consultancy for performing settling tests.
The bed samples were combined into two groups, as follows: sandy sample group (36) and muddy sample group (25). Subsamples were taken from each group and the particle size characteristics were determined by sieving of the sand fraction (> 63 μm) and settling analysis of the mud fraction (< 63 μm) using the Sedigraph III-method, yielding (**Table 4.4.1**):

- sandy samples: percentage of sand ≅ 93%; percentage fines=7% and d_{50} ≅ 115 μm; d_{90}=170 μm
- muddy samples: percentage sand ≅ 20%; percentage of fines (< 63 μm)≅ 80%; percentage of very fines (< 8 μm)≅ 40% and d_{50} ≅ 15 μm.

The dry mud samples were put in a bucket with saline water to make a dense suspension with a wet bulk density of about 1500 kg/m^3 (dry density of about 800 kg/m^3). This suspension had a fluid mud type of texture with a light grey colour and could easily by mixed by a stick. The sediment is almost pure without organic and calcareous materials.
The height of the suspension in the bucket was about 175 mm above the bottom (80 mm below bucket rim at wednesday 11 april 11.30 hrs (t=0) and 115 mm below the rim after 1 week). Settling data are:
-settling of 2 cm after 2 days to height of 155 mm (wet bulk density=1700 kg/m^3; dry density=1120 kg/m^3);
-settling of 3 cm after 4 days to height of 145 mm (wet bulk density=1800 kg/m^3; dry density=1280 kg/m^3);
-settling of 3 cm after 7 days to height of 145 mm (wet bulk density=1800 kg/m^3; dry density=1280 kg/m^3).

Type of sample	Percentage sand >63 μm (%)	Percentage fines < 63 μm (%)	Percentage clay < 8 μm (%)	d_{10} (μm)	d_{50} (μm)	d_{90} (μm)
Sandy sample group (based on sieving)	93	7	3	65	115	170
Muddy sample group (based on Sedigraph III)	20	80	40	<2	15	100

Table 4.5.1 *Composition of sandy and muddy bed sample groups, Payra mud, Bangladesh (P-mud)*

4.5.3 Settling velocity of flocculated bed mud samples

Settling tests have been done with uniform suspensions of P-mud in vertical settling columns (**Figure 4.2.7right**). Small samples of wet P-mud were suspended in a settling column. Uniform suspensions were made by stirring. Three tests have been done with initial concentrations in the range of 2275 to 455 mg/l.
The results are shown in **Figure 4.5.1**. The median settling velocity ($w_{s,50}$) of bed mud is in the range of 0.8 to 1 mm/s.
About 20% to 30% of the bed mud has a settling velocity smaller than 0.1 mm/s (clay-fine silt).
About 30% to 40% of the bed mud has a settling velocity smaller than 5 mm/s (fine sand).
The median settling velocity of suspended mud is expected to be somewhwat smaller in the range of 0.5 to 0.8 mm/s (suspended samples were not available for testing).

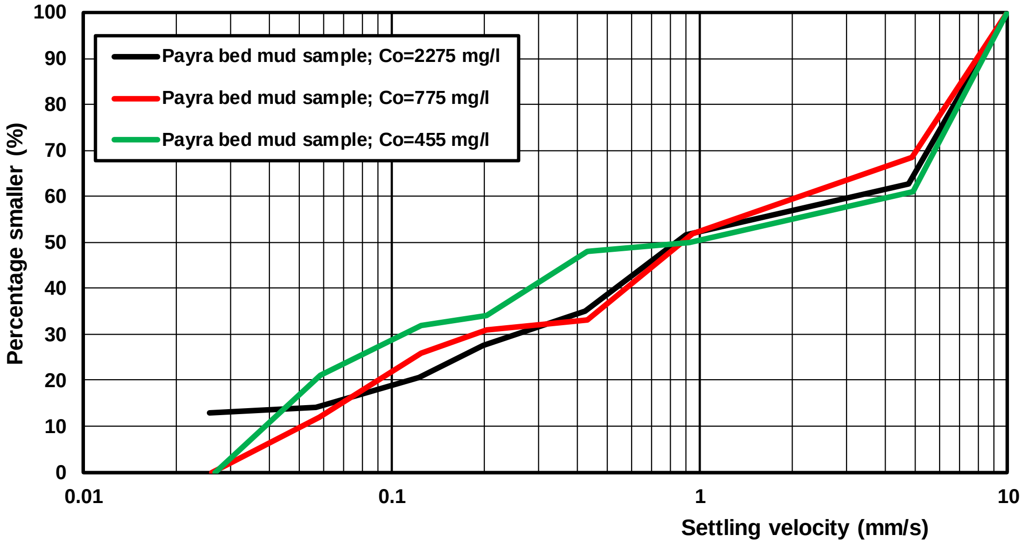


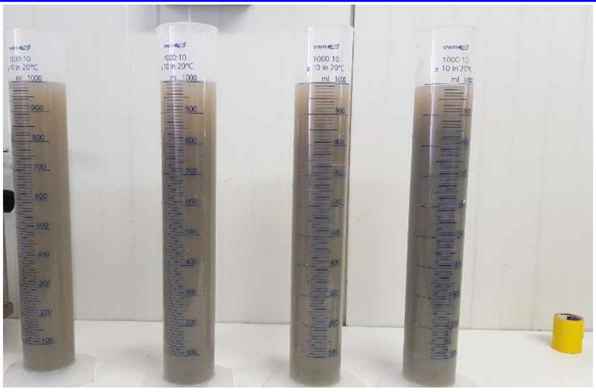
Figure 4.5.1 *Settling velocity curves of bed mud, Payra, Bangladesh (P-mud)*

4.5.4 Hindered settling velocity of bed mud samples

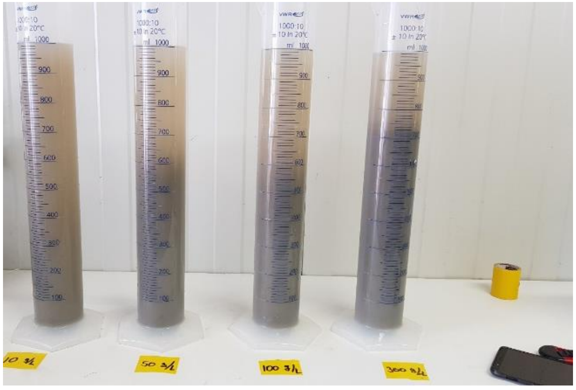
Five mud suspensions with initial mud concentrations of 10, 25, 50, 100 and 300 kg/m^3 were made in settling columns (P-mud). The height of the mud interface was measured at various times, see **Figures 4.5.2** and **4.5.3**. The initial height of the mud suspension was about 360 mm.
Table 4.5.2 shows the dry density values after 2 days, which are in the range of 500 to 1000 kg/m^3. The hindered settling velocity during the initial settling phase are in the range of 0.04 to 0.28 mm/s. The hindered settling velocity decreases with increasing mud concentration.
Figure 4.5.4 shows the mud settling velocity as function of the mud concentration.

Initial mud concentration (kg/m³)	Initial height (mm)	End height (mm)	Time at which end height was measured (hours)	End density (kg/m³)	Settling velocity during initial phase (mm/s)
10	360	7	48	515	340/1200=0.28
25	350	14	48	625	320/1300=0.25
50	360	26	48	690	300/2000=0.15
100	360	46	48	780	270/4000=0.07
300	360	109	48	990	200/5000=0.04

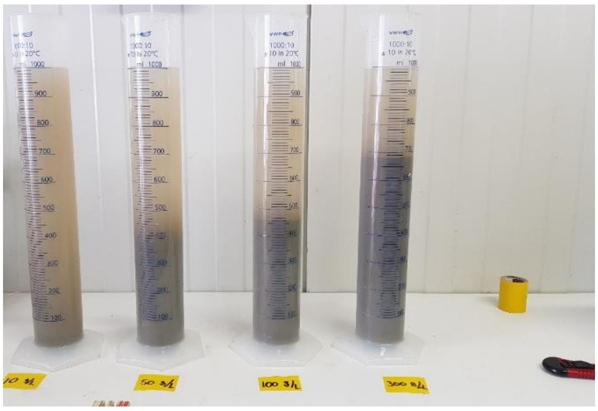
Table 4.5.2 *Settling and consolidation test results*



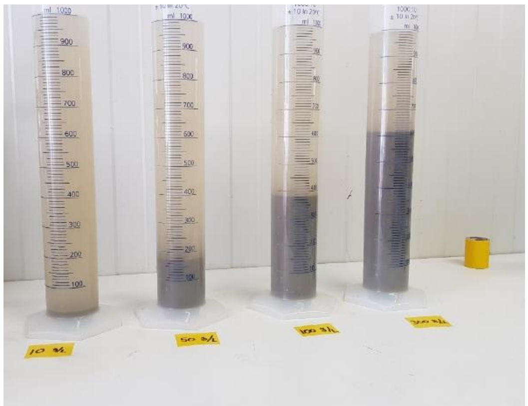
After 6 minutes



After 12 minutes



After 17 minutes



After 28 minutes

Figure 4.5.2 *Settling columns with initial mud concentrations c_o=10, 50, 100 and 300 kg/m³ (left to right)*

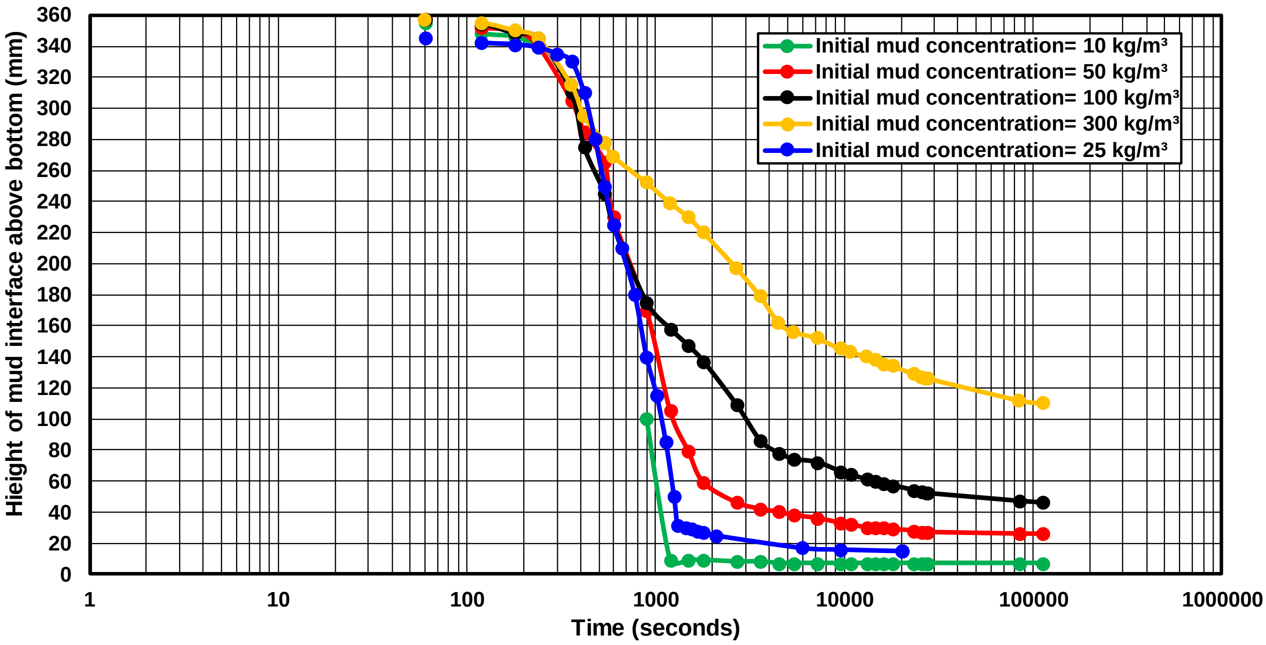


Figure 4.5.3 *Settling and consolidation test results*

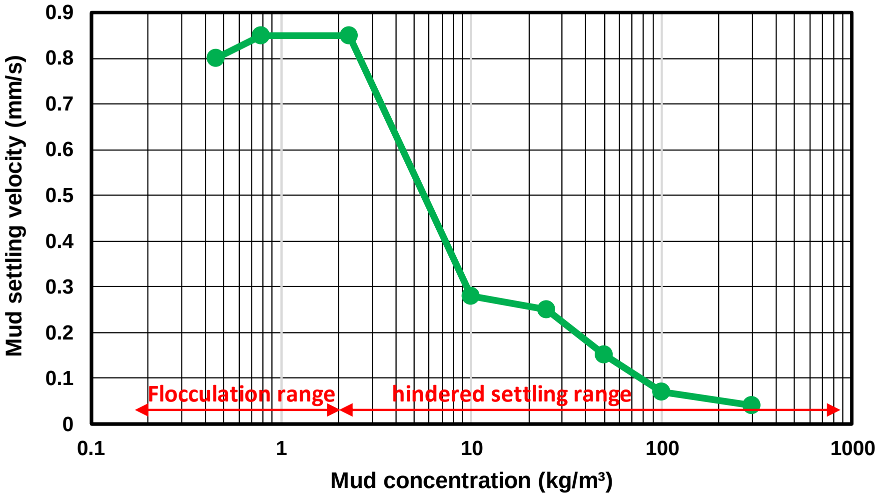


Figure 4.5.4 *Mud settling velocity as function of mud concentration*

4.6 Mud of Scheldt tidal river near Antwerp, Belgium

4.6.1 Site description

Sediment transport measurements have been done during spring tide on Friday 28 September 2018 in the tidal Scheldt river near Oosterweel/Antwerp (about 5 km north of Antwerp), see **Figure 4.6.1**. The survey vessel was moored at a small wooden pier construction near the left bank.

Figuur 4.6.1 *Tidal Scheldt river near Oosterweel/Antwerp, Belgium*

4.6.2 Bed composition

Based on soil information and bed material samples taken on 28 September, the bed of the river along the cross-section can be schematized, as follows:

- intertidal banks (width 25 to 50 m) with soft mud deposits (70% mud; 30% fine sand);
- underwater banks/slopes (width 50 to 150 m) with relatively hard bed consisting of stones, shells and sediment;
- alluvial river bed (width 400 m) with sand (d_{50}) of 150 to 200 μm and almost no mud (< 3%).

4.6.3 Settling velocity of sand and mud in suspension

Sand

Pump samples were taken at various levels above the bed during the tidal cycle. The samples were collected in bottles. The sand particles were separated by washing the bottle samples over a sieve of 63 μm. All sand samples were accumulated into a bulk sample which was used to perform a settling test in a long settling column yielding a median settling velocity of $w_{s,50}$ = 14 mm/s (equivalent median grain size $d_{50,sus}$ = 130 μm).

Mud

Various water-sediment samples were taken by a peristaltic pump. Some samples were taken by a VanDorn water sampler (see **Figure 3.2**). These latter VanDorn samples are undisturbed samples, whereas the fine sediments of the pump samples may have been disturbed by the pumping process.
The samples were analyzed in the laboratory to determine the settling velocity curve. Some samples were divided into 2 parts to study the effect of deflocculation chemicals (peptizer) on the settling velocity.
The results are shown in Table **4.6.1** and in **Figures 4.6.2, 4.6.3**.
The most characteristic features are:

- the settling velocity of Scheldt mud is rather low with $w_{s,50}$= 0.085±0.015 mm/s, which is an indication of minor flocculation effects; these settling values are markedly smaller (factor 5 to 10) than those of the Wadden Sea near Holwerd (Figure 4.6.3) with more flocculated mud and $w_{s,50} \cong$ 0.8 mm/s;
- the settling velocity at 1 m above bed is about 0.1 mm/s; the settling velocity at higher levels above the bed (3 to 6 m) is slightly lower with values between 0.04 and 0.1 mm/s;
- the equivalent particle size of the mud in suspension is about 10±2 μm.

The median settling velocity of the samples treated with peptizer (deflocculation) is smaller (factor 2) than that of samples without peptizer. The samples D-vandorn and D-pump were taken at the same level above the bed and can thus be compared. The mud concentrations are almost equal (155±5 mg/l). The median settling velocity of both samples is very low between 0.04 and 0.07 mm/s (0.055±0.015 mm/s). Based on this, it is concluded that the use of the peristaltic pump has no significant effect on the measured settling velocities of the samples involved.

Sediment in suspension

The sediment in suspension can be schematized, as follows:

- 40% clay and very fine silt < 8 μm with settling velocity < 0.1 mm/s;
- 30% fine silt 8-32 μm with settling velocity 0.4 mm/s (0.1-1 mm/s);
- 15% coarse silt 32-63 μm with settling velocity 2 mm/s (1-3 mm/s);
- 15% fine sand 63-200 μm with settling velocity 14 mm/s.

Sample	Sampling point above bed (m)	Initial concentration of sample (mg/l)	Settling velocity			Equivalent particle size (temperature 15 °C)		
			$w_{s,10}$ (mm/s)	$w_{s,50}$ (mm/s)	$w_{s,90}$ (mm/s)	d_{10} (μm)	d_{50} (μm)	d_{90} (μm)
A-pump	1; ebb	510	0.02	0.088	1.3	5	11	40
B-pump	3; ebb	295	<0.02	0.098	3.5	<5	11	67
C-pump	6; ebb	335	<0.02	0.067	1.3	<5	9	40
C-pump with peptizer	6: ebb	345	<0.01	0.03	1.3	<3	6	40
D-vandorn	5; ebb	160	<0.02	0.038	1.3	<5	7	40
D-pump	5; ebb	150	<0.02	0.068	1.3	<5	9	40
D-pump with peptizer	5; ebb	190	<0.01	0.03	0.2	<3	6	16
E	1; flood	390	<0.02	0.12	1.5	<5	12	44

Table 4.6.1 *Settling velocities and equivalent particle sizes of mud in suspension; 28 September 2018*

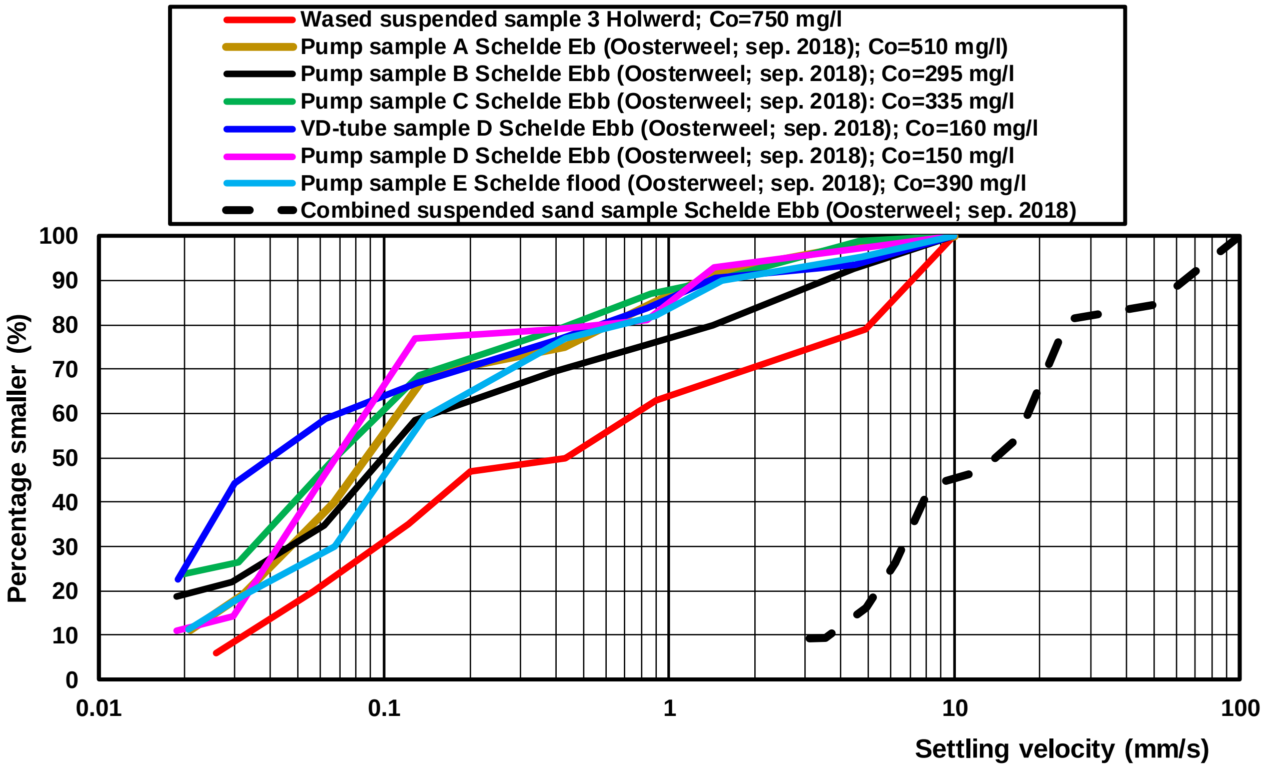


Figure 4.6.2 *Settling velocities of mud in suspension; Scheldt river near Antwerp, 28 September 2018*

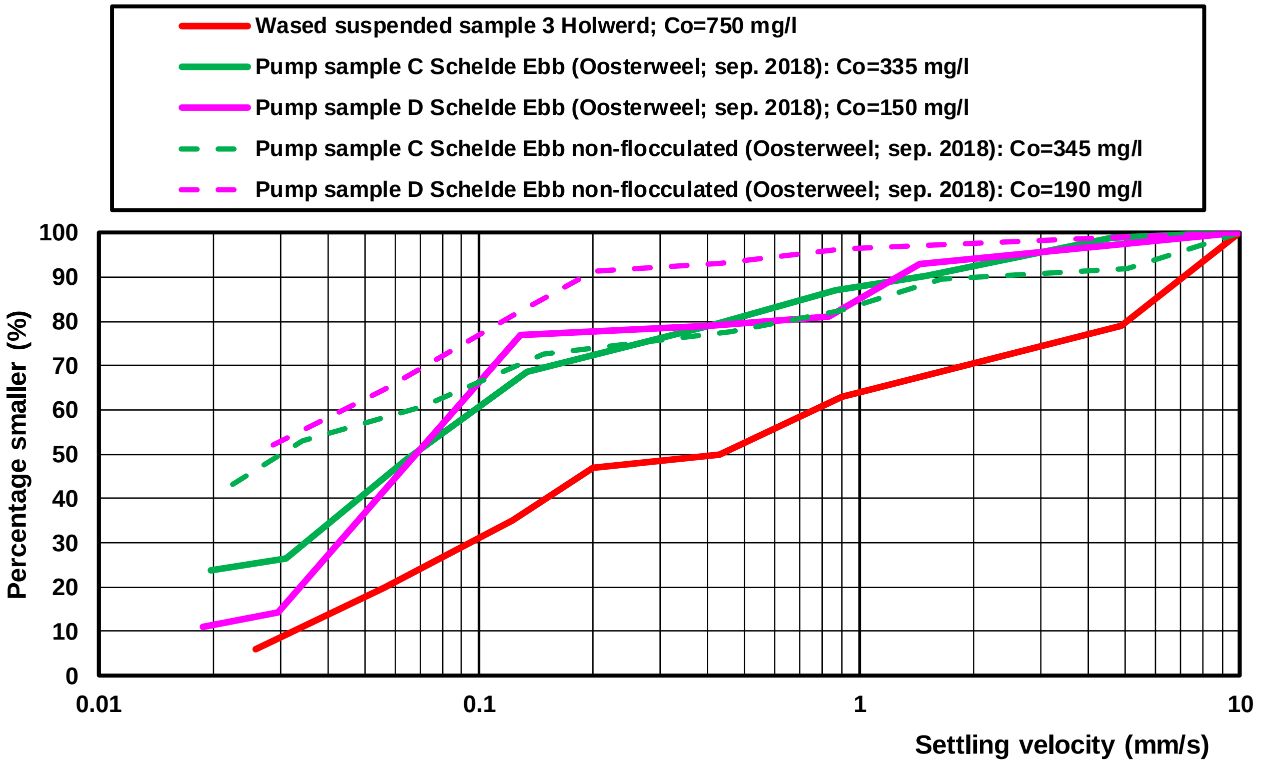


Figure 4.6.3 *Settling velocities;*
Scheldt river near Antwerp 28 September 2018 and Holwerd Wadden Sea June 2018

4.7 Mud of Posorja channel, Guayaquil, Ecuador

4.7.1 Site description

The navigation channel of Posorja is situated in the bay of Guayaquil, Ecuador, see **Figure 4.7.1**. The channel depth is 16.5 m below Chart datum (about 1.4 m below mean sea level). Swell type waves are present with maximum values in the range of 2 to 3 m (wave periods in the range of 10 to 20 s).
The tidal range is about 2 to 3 m and peak tidal velocities in the range of 0.8 to 1.2 m/s.

Figure 4.7.1 *Posorja channel, Ecuador*

4.7.2 Bed composition

The bed on the west sides of the channel consists of sandy materials (150 to 300 μm) with traces of fines (up to 20%). The bed on the east side of the channel consists of muddy layers with fines up to 95% (mud patch area with thickness up to 2 m). The mud patch is situated in an area where the waves are relatively low (wave divergence area based on wave model results). The top layer (upper 10 cm) of the muddy is assumed to have a dry density in the range of 200 to 300 kg/m^3 with a low erosion resistance. Mud can easily be eroded from the mud patch by tidal flows in combination with waves
The sediment deposits inside the channel mostly consist of mud and muddy sands with moderate to high erosion resistance. Sand transport in muddy sands is strongly suppressed.
The mud concentrations in the mud patch area are relatively large with peak values in the range of 400 to 900 mg/l at 2 to 3 hours after maximum flow conditions. The mud concentrations outside the mud patches are much lower with values in the range of 30 to 200 mg/l. The mud concentrations in the offshore area (end of channel) are relatively low (< 30 mg/l).

4.7.3 Settling velocities

Most values of the median settling velocity $w_{s,50}$ of suspended bottle samples from the mud patch area are in the range of 0.05 to 0.15 mm/s (0.1 ±0.05 mm/s), see **Figure 4.7.2**. These relatively low values are most likely caused by the presence of a relatively large clay fraction (about 30% < 8 μm). The $w_{s,80}$-values are in the range of 0.2 to 6 mm/s due to the presence of silty/ sandy sediments and mud flocs. Mud flocs with settling velocities of about 1 mm/s were clearly visible in the suspended sample bottles after gently shaking of the bottles. Mud flocs were easily destroyed by violent shaking of the bottles. Mud flocs were not formed during the settling process in the bottles.

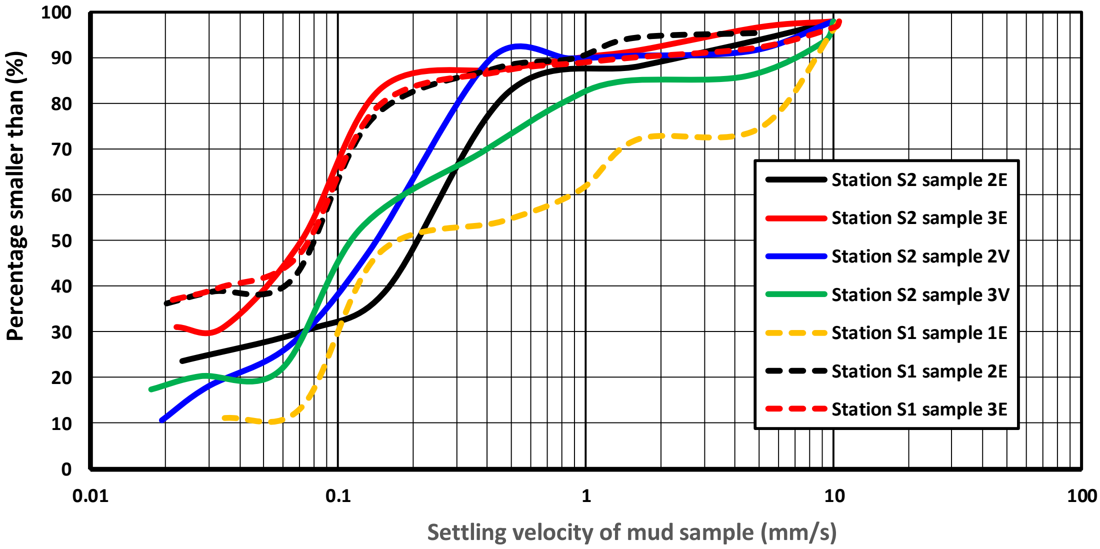


Figure 4.7.2 *Settling velocity distributions of suspended sediment samples taken by VanDorn tube at 1 to 1.5 m above local bed; Stations S1 and S2 along channel; December 2018 to January 2019.*

4.8 Mud from Tamar estuary (UK), Portsmouth harbour (UK) and Antwerp harbour (Belgium)

Manning et al. (2007, 2010) used the INSSEV-video camera system to measure floc sizes and settling velocities in an annular flume and in field conditions (Deurganckdok in Port of Antwerp).
The flume channel was filled with 45 l of saline water (salinity=20±0.2), to a level that reached the top of the annular ring (0.13 m depth). Pre-mixed mud/sand slurries of pre-determined ratios (75% mud and 25% sand; 50% mud and 50% sand; and 25% mud and 75% sand) were introduced into the mini-annular flume water column. Three total suspended particulate matter (SPM) concentrations were used at each ratio: 200 mg/l (±3%), 1000 mg/l (±4.3%) and 5000 mg/l (±4.7%).
For each run, four increments of rotational motor speed were used to shear the sediment slurries at shear stresses ranging from 0.06 to 0.9 Pa (at the floc sampling point). Sediment mixtures were sheared for 30 min at each stress increment. Each run was initiated at the fastest rotational velocity and decreased towards the slowest speeds as the run progressed.
Floc population sampling comprised careful extraction of a suspension sample from the same height in the water column. The floc sample was then quickly transferred to a perspex settling column, whereby each individual floc was observed using a high-resolution (10 µm lower limit) miniature underwater video camera as they were settling. Floc size D and settling velocity w_s were recorded during settling and the values obtained by video image post-processing. The video camera floc images are silhouettes enabling the floc/particle structure to be more visible.

The sand was the Redhill 110 type, which is a well-rounded and closely graded silica sand and has a d_{50} (d is sand grain size) of about 110 µm, with a d_{10} and d_{90} of 70 µm and 170 µm, respectively. The experimental mud sample was obtained from the surface down to a depth of about 50 mm from the Calstock region of the upper Tamar Estuary (UK).
The measured results for mud of the Tamar estuary are given in **Table 4.8.1** and in **Figure 4.8.1**.
The measured results for mud of Portsmouth harbour are given in **Table 4.8.2**.

Shear stress in flume (N/m²)	Concentration (mg/l)	Average settling velocity (mm/s) for various mud-sand fractions				Average settling velocities (mm/s)
		100% mud	75% mud 25% sand	50% mud 50% sand	25% mud 75% sand	
0.35	200	micro: 0.4 mm/s macro: 1.0 mm/s	0.7 (50-160 μm) 0.7 (160-200 um)	1.5 0.7	2.0 1.0	0.7-2.0 0.7-1.0
	1000	micro: 0.8 mm/s macro: 1.5 mm/s	0.7 1.0	1.0 1.3	3.0 1.0	0.7-3.0 1.0-1.3
	5000	micro: 0.6 mm/s macro: 3.5 mm/s	1.3 (50-160 μm) 3.0 (160-700 μm)	1.3 2.0	2.0 1.5	1.2-2.0 3.0-1.5
0.6	200	micro: 0.4 mm/s macro: 2.5 mm/s	1.0 1.5	2.5 1.5	2.0 1.0	1.0-2.5 1.5-1.0
	1000	micro: 0.8 mm/s macro: 3.0 mm/s	1.0 2.5	1.5 2.0	3.5 (40-160 μm) 1.5 (160-250 μm)	1.0-3.5 2.5-1.5
	5000	micro: 0.6 mm/s macro: 4.5 mm/s	2.5 7.0	3.5 5.5	4.0 3.5	2.5-4.0 7.0-3.5
0.9	200	micro: 0.4 mm/s macro: 1.0 mm/s	1.0 0.8	2.5 0.7	1.0 3.0	1.0-2.5 0.8-3.0
	1000	micro: 0.8 mm/s macro: 1.5 mm/s	2.0 1.0	2.0 1.5	1.0 3.0	2.0-1.0 1.5-3.0
	5000	micro: 0.6 mm/sa macro: 3.0 mm/s	2.5 3.5	2.5 (30-160 μm) 3.0 (160-250 μm)	2.0 3.5	2.5-2.0 3.0-3.5

microflocs: flocs< 160 μm with floc densities 200-1600 kg/m³; macroflocs: flocs > 160 μm with floc densities 20-200 kg/m³;
sand: d_{10}=70 μm; d_{50}=110 μm d_{90}= 170 μm; $w_{s,10,sand} \cong$ 3 mm/s; $w_{s,50,sand} \cong$7 mm/s;
water depth= 0.15 mm; samples taken at 0.022 m above bottom
(floc sizes are given between brackets)

Table 4.8.1 *Measured settling velocities of micro and macroflocs in annular flume with saline water using INSSEV-video camera system; mud from Tamar estuary (Manning et al., 2010)*

Shear stress in flume (N/m²)	Concentration (mg/l)	Average settling velocity (mm/s) for various mud-sand fractions	
		70% mud 30% sand	38% mud 62% sand
0.35	2000	micro: 2-8 mm/s (60-160 μm) macro: 4-12 mm/s (160-700 μm)	0.4-20 mm/s (30-160 μm) 1-10 mm/s (160-320 μm)

microflocs: flocs< 160 μm; macroflocs: flocs > 160 μm;
water depth= 0.15 mm; sampes taken at 0.022 m above bottom
(floc sizes are given between brackets)

Table 4.8.2 *Measured settling velocities of micro and macroflocs in annular flume with saline water using INSSEV-video camera system; mud from Portsmouth harbour (Manning et al., 2010)*

The results of the settling tests of Manning et al. (2010) are shown as function of the bed-shear stress in the flume in **Figure 4.8.1**. The vertical lines represent the settling velocities for various conditions. For the case of 100% mud (no sand), the lower end of the line is the settling velocity of the macroflocs and the upper end of the line is the settling velocity of the macroflocs. The length of the lines for mud fractions of 25%, 50% and 75% represent the variation range for concentrations of 200 to 5000 mg/l. The results for microflocs and macroflocs are represented by different line (dotted lines for microflocs and solid lines for macroflocs.

The most important characteristics are:

- settling velocities of microflocs in 100% mud suspensions are in the range of 0.4 to 0.8 mm/s;
- settling velocities of macroflocs in 100% mud suspensions are in the range of 1 to 4.5 mm/s;
- settling velocities of micro flocs in suspensions with mud and sand are in the range of 0.7 to 4 mm/s, which is partly caused by the enclosure of fine sand particles;
- settling velocities of microflocs and macroflocs are not very different for suspensions with mud and sand; most values in the range of 1 to 3 mm/s; an exception is the case with a shear stress of 0.6 N/m^2 with relatively large settling velocities of macroflocs up 7 mm/s;
- settling velocities are smaller for larger bed-shear stresses due to breakup of flocs by larger velocity gradient (shear stresses);
- results may be biased towards the settling of larger flocs, as it is more difficult to detect the very fine mud floc/particles (lower limit of camera is 10 micron).

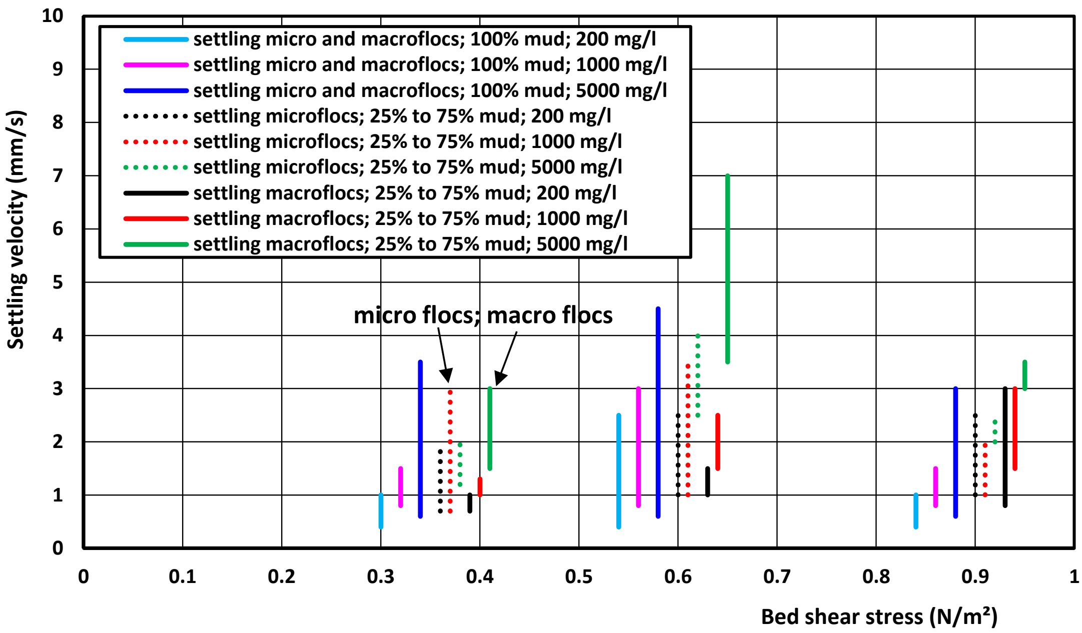


Figure 4.8.1 *Settling velocity of micro and macroflocs as function of bed-shear stress for different concentrations (Manning et al. 2010)*

The measured data of the experiments in the entrance of Deurganckdok in the Port of Antwerp are shown in **Table 4.8.3**.

The INSSEV-camera was operated at 0.65 m above the bed surface in a depth of about 17.3 m at HW during a neap tidal cycle with tidal range of 4.8 m. The peak velocity was about 0.6 to 0.7m/s. The local mud concentrations were in the range of 50 to 250 mg/l over the tidal cycle. Floc sizes and settling velocities were measured every 30 minutes. The results for three characteristic times are given in **Table 4.8.3**.

The data of **Table 4.8.3** can be interpreted, as follows:

- settling velocities of macroflocs up to 3 mm are highest during conditions with low velocities around the slack tidal periods;
- settling velocities of micro and macroflocs are in the range of 0.1 to 1.5 mm/s during peak tidal flow due to floc breakup by turbulent eddies (relatively high shear stresses);
- macroflocs have relatively low densities (< 50 kg/m^3) and are delicate aggregates which are easily broken down resulting in their original microfloc sub-structures.

Tidal stage	Current velocity (m/s)	Mud concen tration (mg/l)	Micro flocs			Macro flocs		
			Size (μm)	Settling velocity (mm/s)	density (kg/m³)	Size (μm)	Settling velocity (mm/s)	density (kg/m³)
HW+1 hrs	0.15	150	30-160	0.15-6	≅200	160-3000	0.4-1.5	<50
HW+2 hrs	0.65	70	60-160	0.15-1.5	≅200	160-280	0.1-1.5	<50
LW slack	0	60	70-160	0.15-2	≅200	160-700	0.5-4	<50

Table 4.8.3 *Measured floc sizes and settling velocities of micro and macro flocs in Deurganckdok, Port of Antwerp (Manning et al., 200&)*

Critical comments: The results of the video-camera system were not compared to results from settling test. This latter method could also have ben used during the annular flume tests. Samples extracted from the flume could have been used to do a settling test for comparison. The results of the INSSEV-camera may be biased towards the macroflocs which are more easy to detect. The sample extraction method is not explicitly described.

4.9 Summary of results

Most results of the tests presented in Sections 4.2 to 4.5 are summarized in **Table 4.9.1** and **Figure 4.9.1**. **Figure 4.9.1** shows the hindered settling velocity as function of the mud concentration for all test results. Results from other sites (Van Rijn 1993; Deltares 2016) are also shown.
The maximum settling velocityof N-mud due to the flocculation effect is about 2 mm/s at a concentration of about 6 kg/m³. The settling velocity decreases due to hindered settling effects to about 0.05 mm/s at a very high concentration of about 100 kg/m³.
Non-flocculated mud is mostly present at low concentrations < 100 mg/l around slack tide, whereas flocculated mud generally is present at high concentrations (> 500 mg/l) in the near-bed zone (within 1 m of the bed) around maximum flow.
The settling velocities of N-mud and P-mud are smaller than those of the H-mud, which may be caused by the larger clay fraction (about 30% for N-mud/P-mud and about 10% for H-mud).

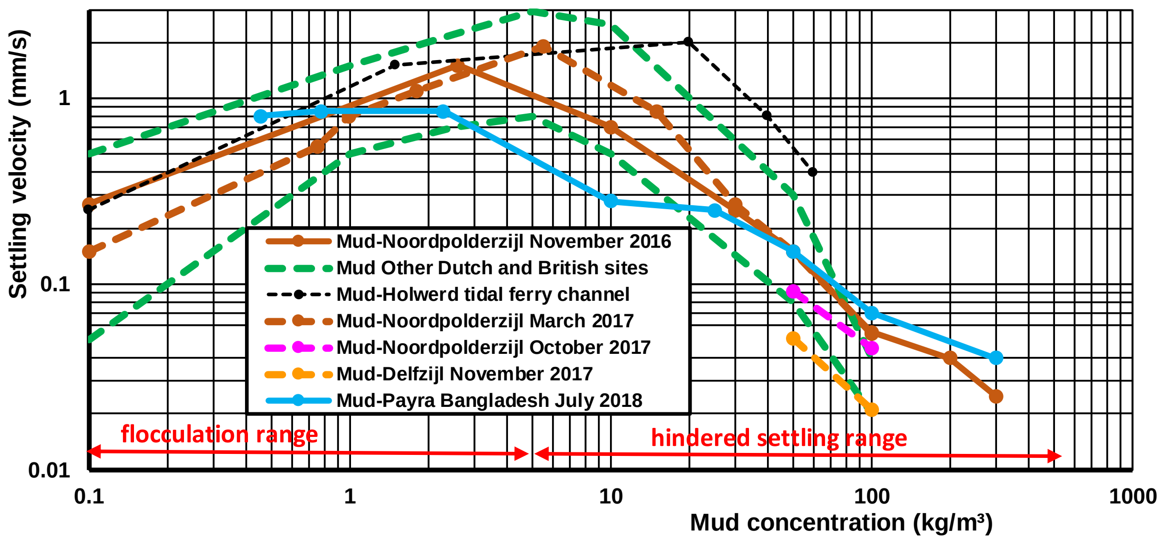


Figure 4.9.1 *Settling velocity as function of mud concentration of various mud samples*

Type of mud	**Settling velocity of bed samples**		**Flocculated settling velocity of in-situ suspended samples (mm/s)**
	flocculated settling velocity (mm/s)	**hindered settling velocity (mm/s)**	
N-mud NoordpolderzijlNL) p_{clay}= 20% p_{silt}= 45% p_{sand}=35%	$w_{s,50}$=0.55 mm/s (c_o=750 mg/l) $w_{s,50}$=0.8 mm/s (c_o= 990 mg/l) $w_{s,50}$=1.1 mm/s (c_o=1755 mg/l) $w_{s,50}$=1.1 mm/s (c_o=2130 mg/l) $w_{s,50}$=1.5 mm/s (c_o=2635 mg/l) $w_{s,50}$=1.9 mm/s (c_o=6025 mg/l)	w_s=0.85 mm/s (c_o=15 gr/l) w_s=0.25 mm/s (c_o=30 gr/l) w_s=0.15 mm/s (c_o=50 gr/l) w_s=0.055 mm/s (c_o=100 gr/l)	$w_{s,50}$=0.4 mm/s (c_o=105 mg/l) $w_{s,50}$=0.75 mm/s (c_o=530 mg/l) $w_{s,50}$=1.4 mm/s (c_o=900 mg/l)
D-mud Delfzijl (NL) p_{clay}=40% p_{silt}=40% p_{sand}= 20%		w_s=0.051 mm/s (c_o=50 gr/l) w_s=0.021 mm/s (c_o=100 gr/l)	
H-mud; Holwerd (NL) p_{clay}=25% p_{silt}=50% p_{sand}=25%	$w_{s,50}$=0.2-1 mm/s (c_o< 1000 mg/l) $w_{s,50}$=1-2.5 mm/s (c_o=1000 to 5000 mg/l)	w_s=2.3 mm/s (c_o=20 gr/l) w_s=0.5 mm/s (c_o=40 gr/l) w_s=0.25 mm/s (c_o=60 gr/l)	
P-mud Payra Bangladesh p_{clay}=30% p_{silt}=50% p_{sand}=20%	$w_{s,50}$=0.85 mm/s (c_o=2275 mg/l) $w_{s,50}$=0.85 mm/s (c_o=775 mg/l) $w_{s,50}$=0.8 mm/s (c_o=455 mg/l)	w_s=0.28 mm/s (c_o=10 gr/l) w_s=0.25 mm/s (c_o=25 gr/l) w_s=0.15 mm/s (c_o=50 gr/l) w_s=0.07 mm/s (c_o=100 gr/l) w_s=0.04 mm/s (c_o=300 gr/l)	
S-mud; Scheldt river near Antwerp p_{clay}=40% p_{silt}=45% p_{sand}=15%	$w_{s,50}$=0.85 mm/s (c_o=2275 mg/l)		

p_{sand}= percentage of sand >63 μm ; p_{clay}=percentage of fines < 8 μm; p_{silt}=percentage of fines 8-63 μm

Table 4.9.1 *Summary of settling velocities*

5. References

Brown D.J., Felton P.G., Direct measurement of concentration and size for particles of different shape using laser light diffraction, Chemical Engineering research and design 63 (2), 1985, 125-132

Conley, R.F., 1965. Statistical distribution patterns of particle size and shape in the Georgia Kaolins. Georgia Kaolin Research Laboratories. Elizabeth, New Yersey, USA.

Deltares, 1999. Oorzaken aanslibbing haven van Delfzijl. Rapport H3474. Delft, Nederland

Deltares, 2014. Mud dynamics in the Ems-Dollard, Phase 2: Analysis of soil samples. Report 1205711-001, Delft, The Netherlands

Deltares, 2016a. KPP Analysis tidal channel Holwerd-Ameland; Overview laboratory analyses. Report 1230378.002, Delft, The Netherlands

Deltares, 2016b. KPP Analysis tidal channel Holwerd-Ameland; Analysis of dredging data. Report 1230378.000, Delft, The Netherlands

Haverbeke, J.P., 2013. Comparison of Laser-diffraction method and Sieve-Hydrometer method for determination of particle size distribution of soil (in Dutch). Master Thesis, Department of Civil Engineering, University of Gent, Belgium

Manning, A.J., Martens, C., De Mulder, T., Vanlede, J., Winterwerp, J.C., Ganderton, P. and Graham, G.W., 2007. Mud floc observations in the turbidity maximum zone of the Scheldt estuary during neap tides. Journal of coastal research, SI50, 832-836

Manning, A.J., Baugh, J.V., Spearman, J.R. and Whitehouse, R.J.S., 2010. Flocculation settling velocities of mud: sand mixtures. Ocean Dynamics 60, 237-253. Doi: 10.1007/s10236-009-0251-0

Manning, A.J., Baugh, J.V., Spearman, J.R., Pidduck, E.L., and Whitehouse, R.J.S., 2010. The settling dynamics of flocculating mud-sand mixtures, part 1: empirical algorithm development. Ocean Dynamics 61, 311-350. Doi: 10.1007/s10236-011-0394-7

Pabst W., and Berthold C., A Simple approximate formula for the aspect ratio of oblate particles, part. syst. charact. 24, 2007, 458-463

Richardson, J.F. and Zaki, W.N., 1954. Sedimentation and fluidisation: Part I. Trans. Instn. Chem. Engrs., Vol. 32, p. 35-50

Richardson, J.F. and Meikle, R.A., 1961. Sedimentation and fluidisation: Part II. Trans. Instn. Chem. Engrs., Vol. 39, p. 348-356

Shi, Z. and Zhou, H.J., 2004. Controls on effective settling velocities of mud flocs in the Changjiang Estuary, China. Hydrological processes, Vol. 18, p. 2877-2892

Thorn, M.F.C, 1981. Physical processes of siltation in tidal channels. Proc. Hydraulic Modelling Maritime Engineering Problems, ICE, London, p. 47-55

Van Rijn, L.C. 1993. Principles of sediment transport in rivers, estuaries and coastal seas. www.aquapublications.nl

Van Rijn, L.C., 2007. Unified view of sediment transport by currents and waves, I, II, III. ASCE, Journal of Hydraulic Engineering, Vol. 133, No. 6, 649-667, 668-689, No. 7, 761-775

Van Rijn, L.C. 2016. Manual for sediment transport measurements. www.aquapublications.nl

Van Rijn, L.C., Riethmueller, R. and Barth, R., 2018. Erodibility of sand-mud mixtures 2018. www.leovanrijn-sediment.com

Vinzon, S.B. and Mehta, A.J., 2003. Lutoclines in high concentration estuaries:some observations at the mouth of the Amazon. Journal of Coastal Research, Vol. 19, No. 2, p. 243-253.

WaterProofBV 2019. Measurements Holwerd-Ameland; measurement results and laboratory analysis results measurements January-March 2019 (in Dutch) , Lelystad, The Netherlands

ANNEX A: Grain size distribution of mud samples

The size distributioin of a muddy bed sample can be determined by means of a sieve test for the sand fraction and a settling test for the mud fraction:

1. sieve analysis for sandy materials > 63 μm;
2. settling test for fines < 63 μm (with peptiser for deflocculation in fresh water)

Particle size distribution

1. wet mud sample of about 100 gram is spreadout on a tray (20x20 cm²) and dried in oven
2. weigh dry sample sample;
3. make sample wet and grind sample in mortar;
4. wash sample over a sieve mesh of 63 μm (A= sand fraction > 63 μm; B= mud fraction < 63 μm)
5. dry and weigh the sand fraction A and perform sieve test
6. take subsample (about 1 gram) from sample B to make a suspension of about 2 liter in bucket with a mud concentration of about 500 mg/l (use peptiser for deflocculation) and perform a settling test ;
7. convert settling velocities to particle sizes using Stokes settling formula;
8. make a particle size distribution curve by combining results of sample A and B (see **Figure A.1**)

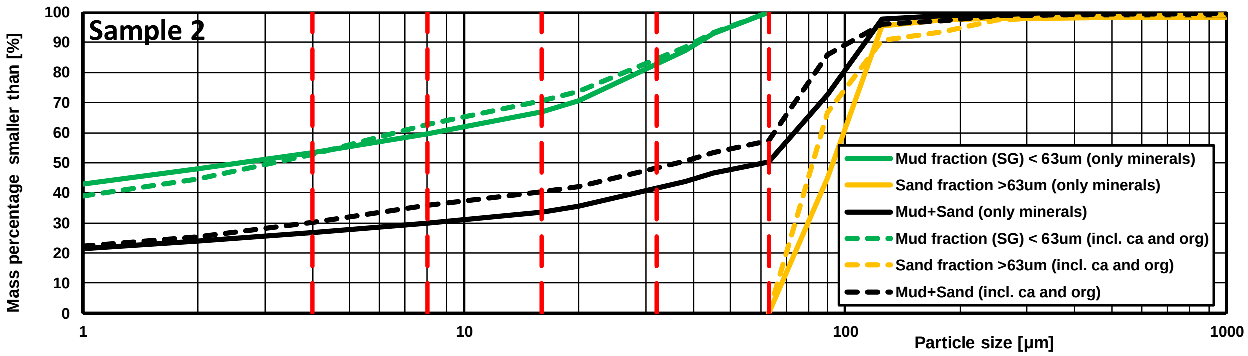


Figure A.1 *Example of particle size distibution*

<u>**Combining results of sieve test and settling test**</u>
This can be done in a spreadsheet (see below).

Input data are:

1. insert mass of sand fraction; mass of mud fraction; total mass (Table A1)
2. insert results of mud settling test (Table 2) from which the Stokes-diameter is computed: make a plot of Stokes-diameter versus percentage smaller than, see Figure A2 and read the characteristic values from this plot and insert these values in Table A3; compute the mass of each mud subfraction
3. insert results of sieve test (Table A4) and compute the cumulative values (Table A4)
4. Combine results of mud and sand per fraction, cumulative and percentages (Table A5); make a plot

Figure A2
mud fraction: p_{mud}=57% and $d_{50,sand}$ of mud fraction=15 μm;
sand fraction: p_{sand}=53% and $d_{50,mud}$ of sand fraction=90 μm
total fraction: d_{50}=55 μm (from plot);
estimate of $d_{50}=(p_{mud}/100)xd_{50,mud} + (p_{sand}/100)xd_{50,sand}$=0.57x15+0.53x90=56 μm

Table A1

INPUT DATA IN RED		
Date	19-Jan-20	
Sample number	102	
Location	Holwerd 102	
Type of water used	Fresh	
Deflocculation solution used	Yes	
Kinematic viscosity coeficient	0.000001	(m²/s)
Fluid density	1020	(kg/m³)
Sediment density	2650	(kg/m³)
Mass of sand=	64.76	(gram)
Mass of mud=	85.84	(gram)
Total mass=	150.6	(gram)

Make

Table A2

MUD SETTLING TEST RESULTS					
		Settling velocity (mm/s)	Percentage < (%)		Computed Stokes Diameter (um)
		10	100		107.1539124
		4.53	86.8		72.12023506
		1.43	75.6		40.52061715
		0.81	63.2		30.4965381
		0.38	62.9		20.88814294
		0.119	56		11.68911182
		0.056	37.8		8.018664556
		0.026	34.6		5.463798902
		0.016	32.5		4.286156495

Table A3

Diameter mud fraction	Percentager smaller than <		Mass of each fraction
(um)	(%)		(gram)
1	30	Mass 0-1 um	25.752
2	30	Mass 1-2 um	0
4	30	Mass 2-4 um	0
8	30	Mass 4-8 um	0
16	60	Mass 8-16 um	25.752
20	62	Mass 16-20 um	1.7168
32	65	Mass 20-32 um	2.5752
45	70	Mass 32-45 um	4.292
63	100	Mass 45-63 um	25.752
			85.84

Table A4

SAND SIEVE RESULTS						
Sieve analysis of sand fraction					cumulative	
Mass coarser than 0.063 mm	64.76	(gram)	Mass 63-90 um	34.13	34.13	(gram)
Mass coarser than 0.09 mm	30.63	(gram)	Mass 90-125	20.5	54.63	(gram)
Mass coarser than 0.125 mm	10.13	(gram)	Mass 125-150	4.8	59.43	(gram)
Mass coarser than 0.15 mm	5.33	(gram)	Mass 150-180	1.93	61.36	(gram)
Mass coarser than 0.18 mm	3.4	(gram)	Mass 180-212	0.67	62.03	(gram)
Mass coarser than 0.212 mm	2.73	(gram)	Mass 212-250	0.41	62.44	gram)
Mass coarser than 0.25 mm	2.32	(gram)	Mass 250-355	1.048	63.488	(gram)
Mass coarser than 0.355 mm	1.272	(gram)	Mass 355-500	1.272	64.76	(gram)
Mass coarser than 0.5 mm	0	(gram)	Mass 500-710	0	64.76	(gram)
Mass coarser than 0.71 mm	0	(gram)	Mass 710-1000	0	64.76	(gram)
Mass coarser than 1 mm	0	(gram)	Mass 1000-2000 um	0	64.76	(gram)
Mass coarser than 2 mm	0	(gram)	Total	64.76		

Table A5

			cumulative		Diameter	Perc. Smaller
MUD + SAND	Mass 0-1 um	25.752	25.752	(gram)	(um)	(%)
	Mass 1-2 um	0	25.752	(gram)	1	17.0996
	Mass 2-4 um	0	25.752	(gram)	2	17.0996
	Mass 4-8 um	0	25.752	(gram)	4	17.0996
	Mass 8-16 um	25.752	51.504	(gram)	8	17.0996
	Mass 16-20 um	1.7168	53.2208	(gram)	16	34.1992
	Mass 20-32 um	2.5752	55.796	(gram)	20	35.33918
	Mass 32-45 um	4.292	60.088	(gram)	32	37.04914
	Mass 45-63 um	25.752	85.84	(gram)	45	39.89907
	Mass 63-90 um	34.13	119.97	(gram)	**63**	56.99867
	Mass 90-125	20.5	140.47	(gram)	**90**	79.66135
	Mass 125-150	4.8	145.27	(gram)	**125**	93.27357
	Mass 150-180	1.93	147.2	(gram)	**150**	96.46082
	Mass 180-212	0.67	147.87	(gram)	**180**	97.74236
	Mass 212-250	0.41	148.28	(gram)	**212**	98.18725
	Mass 250-355	1.048	149.328	(gram)	**250**	98.4595
	Mass 355-500	1.272	150.6	(gram)	**355**	99.15538
	Mass 500-710	0	150.6	(gram)	**500**	100
	Mass 710-1000	0	150.6	(gram)	**710**	100
	Mass 1000-1400 um	0	150.6	(gram)	**1000**	100
		150.6				

Figure A2