ERODIBILITY OF MUD-SAND MIXTURES; December 2018

by

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Content

1. Introduction

This paper paper adresses the problem of the erodibility of mud and mixtures of mud and sand at the bottom of tidal channels. Mud is defined as a mixture of clay and silt particles with sizes < 63 μm and fine sand particles.
Various laboratory and field studies (September-December 2016; March-June 2017, March-June 2018) have been done to determine the critical shear stress for erosion as function of basic sediment properties (bulk density, permeability, etc.). Several insitu field instruments are available to test the critical bed-shear tests for initiation of motion/erosion. Herein, the attention is focussed on the EROMES-tube (Geesthacht 1991, 1995).
Mitchener and Torfs (1996) have summarized experimental results on the erodibility of mud-sand mixtures in laboratory and field conditions. Their results, which originate from both laboratory and field experiments, describe the physical processes related to the erosion behaviour of mud/sand mixtures. It was found that by adding sand to mud (or vice versa) the erosion resistance is increased and the erosion rates are reduced. Their laboratory beds consisted of homogeneously mixed beds and layered beds tested in flume experiments.
The present study results are based on flume tests and EROMES tube tests. The EROMES has been calibrated and used in several erosion studies in Germany (Geesthacht 1991, 1995). The original EROMES system was developed by the GKSS Research Centre (Germany) to investigate the erodibility of natural muddy sediments in the laboratory. A portable field-version of the original EROMES has been designed, built, calibrated and tested (Andersen 2001). The main advantages of the portable EROMES is that it is a simple instrument that it is able to produce data on the erosion thresholds of sand-mud mixtures and that the measurements can be done quite rapidly.
The present study is focussed on:

- recalibration of the EROMES-instrument using results of flume tests (Section 4);
- testing of mixtures of sand and mud in the flume and in the EROMES tube (Section 5).

The experiments have been done by the students: B. Koetsier, N. Simmes in 2016; A. Klomp and M. de Boer in 2017, J.J. Miedema and L. van de Wofshaar in 2017, T. Braaksma and R. Haagen in 2018 of the Hanze Technical School in Groningen (The Netherlands) under supervision of Dr. L.C. van Rijn.

2. Flume, instrumentation, sediments and test programme

2.1 Flume

The experiments have been carried out in a laboratory flume (length= 10 m, width=0.4 m) of the Hanze Technical School in Groningen, The Netherlands. The experimental setup is given in **Figure 2.1**.

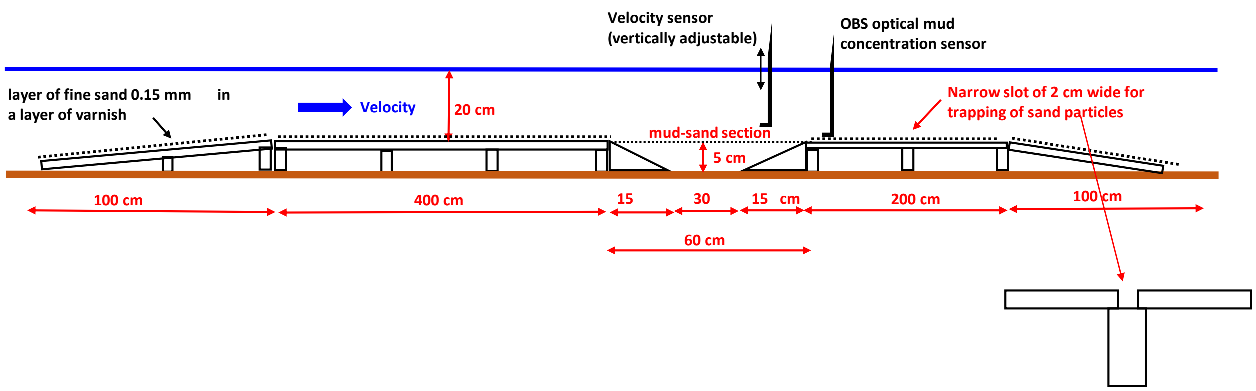


Figure 2.1 *Experimental setup*

A false floor was installed in the fume with a small deepened section for the sediment bed of sand/mud (depth= 5 cm, length= 60 cm; ramps with slopes of 1 to 3 on both sides to prevent the generation of scour holes; volume=10 litres). A narrow slot was present in the floor panels (see **Figure 2.1**) at about 0.5 m from the sediment section to trap the sand particles moving over the flume bottom. The bottom surface of the flase foor was painted with varnish on which fine sand of 0.2 mm was sprayed to create a fixed rough bottom. The water depth upstream of the mud/sand bed was about 0.2 m during the tests. The depth-mean flow velocity upstream was in the range of 0.2 to 0.6 m/s depending on the grain size in the movable bed section.

2.2 Vectrino flow velocity sensor

The flow velocities were measured by a three-dimensional vectrino-instrument (NORTEK; diameter measuring volume ≅ 3 mm; measuring time= 2 minutes; see **Figure 2.2**) used in the near-bed region of the water depth and by a mechanical Ott-propeller (measuring diameter ≅ 20 mm) used in the near surface region of the water depth.

Figure 2.2 *Sand bed (0.74 mm), Vectrino acoustic velocity sensor and Ott-propeller meter*

The lowest measurement point of the Vectrino was at z=5mm above the fixed bottom.

The velocities were measured above the false floor (with sand roughness of about d_{50}=200 μm) just downstream of the sediment bed. It was problematic to measure the flow velocities above the sediment surface due to the generation of small scale ripples of maximum 5 mm high and due to acoustic reflections of the Vectrino-instrument. Furthermore, the wall origin is difficult to define in case ripples are present (test with sand of 0.18, 0.37 and 0.52 mm). The instrument was adjusted to a vertically movable rod to precisely position (within 1 mm accuracy) the sensor at the measuring points. The vectrino sensor was only used in the tests with fine sand of 180 μm.

2.3 Calibration of optical sensors

Two optical sensors have been used In November and December 2016:

- NEP152 Analyte (McVan-instruments), which is the standard optical sensor used in the EROMES-tube;
- OBS3+ (Campbell instruments), which was supplied by NORTEK-instruments.

Both sensors were calibrated over the range of 50 to 5000 mg/l in a bucket with a 6 liter-mixture of mud and (native) seawater from the small harbour basin of Noordpolderzijl. The target mud concentrations were made from small subsamples consisting of wet mud taken from the base container (after thorough mixing). The wet mud samples consisted of 25% sediment and 75% seawater (see **Table 3.1**). The offset values of both sensors were measured in a bucket filled with native seawater, which was almost clear water but may have had a mud concentration (very fine mud fraction) in the range of 1 to 10 mg/l. After each test, a small subsample of about 100 ml was taken from the bucket to determine the real concentration by filtration, drying and weighing. This method was not accurate for tests 1 to 3 as the wrong filter paper was used (very hygroscopic paper; attraction of moisture).

The basic calibration data are given in **Table 2.1**. The output of the NEP152 is given in ADC, which is digital output number derived form the output voltage (Analog Digital Conversion). The output of the OBS3+ is given in millivolts.

Test	Target mud concen tration (mg/l)	Dry mud mass in bucket of 6 liter (mg)	Wet mud mass in bucket of 6 liter (mg)	Added mass (mg)	Measu red real mud concen tration (mg/l)	Best estimate of mud concentration in bucket (mg/l)	Output NEP152 (ADC)	Correc ted Output NEP152 (ADC	Output OBS3+ (Millivolt)	Corected Output OBS3+ (Millivolt)
0 clear water	1-10	-	-	-	-	1-10	19.3 (offset)	1	428 (offset)	1
1	50	300	1200	1200	-	75±25	23.4	4	414	10
2	150	900	3600	2400	-	200±50	32.4	13	564	136
3	300	1800	7200	3600	500	400±100	43.0	24	807	379
4	400	2400	9600	2400	510	500±100	69.1	48	1080	652
5	500	3000	12000	2400	740	625±125	70.9	52	1171	743
6	700	4200	16800	4800	1170	950±250	103.2	84	1468	1040
7	1000	6000	24000	7200	1430	1250±250	125.2	106	1598	1170
8	2000	12000	48000	24000	2800	2500±500	175.8	156	1888	1460
9	3000	18000	72000	24000	4700	4000±1000	238.5	219	2134	1706
10	5000	30000	120000	48000	6500	6000±1000	246.3	227	1978	1550

Corrected value= Output value minus offset value

Table 2.1A *Calibration data of optical sensors (NEP152 and OBS3+)*

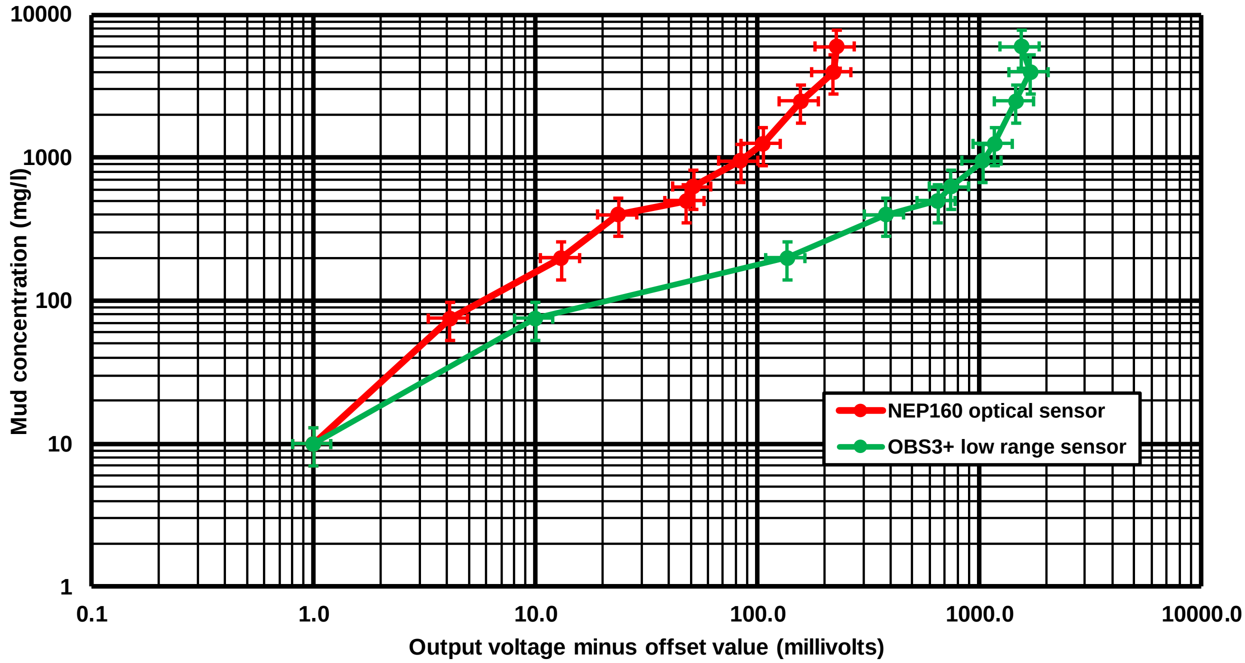


Figure 2.3A *Calibration curves of optical sensors; November-December 2016*

Figure 2.3A shows the calibration curves of both optical sensors using mud in seawater (density of 1025 kg/m^3) from Noorpolderzijl. The output values minus the offset value (from test 0) is given on the horizontal axis. The vertical error range of the mud concentration is about 30%. The clear water concentration is set to 10 mg/l (offset value). The saturation mud concentration is about 1000 to 2000 mg/l for both sensors. Both sensors are not very sensitive for mud concentrations below 50 mg/l. The output values for clear water and a suspension of about 50 mg/l are almost the same for the NEP152. The OBS3+ even gives a lower reading for a suspension of 50 mg/l.

A similar calibration has been done for the OBS3+ sensor used in March-April 2017, see **Table 2.1B/C** and **Figure 2.3B**. The calibration plots show the sensor output minus the offset value (measured in almost clear water).
The OBS-sensor has a horizontal optical path with a length scale varying with the mud concentration. In relatively clear water, the optical path is quite long (order of 0.5 m). Hence, the OBS should be calibrated in a relatively wide bucket, otherwise the OBS will see the bucket wall in conditions with low concentrations. The offset value in the EROMES-tube was found to be quite high (see tables) as the sensor sees the propeller shaft and the tube wall. As a result, the concentrations smaller than about 100 mg/l are not very accurate.
The offset value in a standard bucket of 10 litres was about 500 counts. The ofsset value in the flume with clear water and no obstacles was about 50 counts.

Test	Target mud concen tration (mg/l)	Measured real mud concen tration (mg/l)	Output OBS3+ analog1 (Counts) (Millivolts)	Corrected Output OBS3+ analog1 (Counts) (Millivolts)	Output OBS3+ analog2 (Counts) (Millivolts)	Corrected Output OBS3+ analog2 (Counts) (Millivolts)
0 (clear water)	0	<3	518 offset (39)	0 (0)	2011offset (153)	0 (0)
1	50	35	963 (74)	445 (35)	3798 (290)	1787 (147)
2	100	100	1414 (108)	896 (69)	5602 (427)	3591 (274)
3	150	135	1885 (144)	1367 (105)	7488 (571)	5477 (418)
4	200	200	2393 (183)	1875 (144)	9526 (727)	7515 (5740
5	300	280	3309 (252)	2791 (213)	13198 (1007)	11187 (854)
6	500	460	4781 (365)	4263 (326)	19099 (1457)	17088 (1304)
7	700	650	6146 (469)	5628 (430)	24770 (1890)	22759 (1737)
8	1000	910	7837 (598)	7319 (559)	31349 (2391)	29338 (2238)
9	2000	1800	11029 (841)	10511 (802)	44146 (3368)	42153 (3215)
10	3000	2830	13526 (1032)	13008 (993)	54157 (4132)	52146 (3979)
11	5000	4820	15585 (1189)	15067 (1160)	62288 (4752)	60277 (4599)

Corrected value=output value minus offset value
1 count= $[1/(2^{16}+1)] \times 5000 = [1/65537] \times 5000$ millivolts

Table 2.1B *Calibration data of optical sensors (OBS3+) in bucket; March-April 2017*

Tet	Target mud concen tration (mg/l)	Measured real mud concen tration (mg/l)	Output OBS3+ analog1 (Counts)	Corrected Output OBS3+ analog1 (Counts)	Output OBS3+ analog2 (Counts)	Corrected Output OBS3+ analog2 (Counts)
0 (clear water)	0	<5	2000	0	8000	0
1	50	65	3085; not used	-	12340; not used	
2	100	95	2600	600	10390	2390
3	150	120	2805	805	11210	3210
4	200	150	2775	775	11010	3010
5	300	260	3600	1600	14400	6400
6	500	390	4870	2870	19495	11495
7	700	600	7005	5005	28045	20045
8	1000	910	8540	6540	34205	26205
9	2000	1890	11910	9910	47715	39715
10	3000	2600	14305	12305	57315	49315
11	5000	4670	16080	14080	64360	56360

Corrected value=output value minus offset value
1 count= $[1/(2^{16}+1)] \times 5000 = [1/65537] \times 5000$ millivolts

Table 2.1C *Calibration data of optical sensors (OBS3+) in EROMES-tube; March-April 2017*

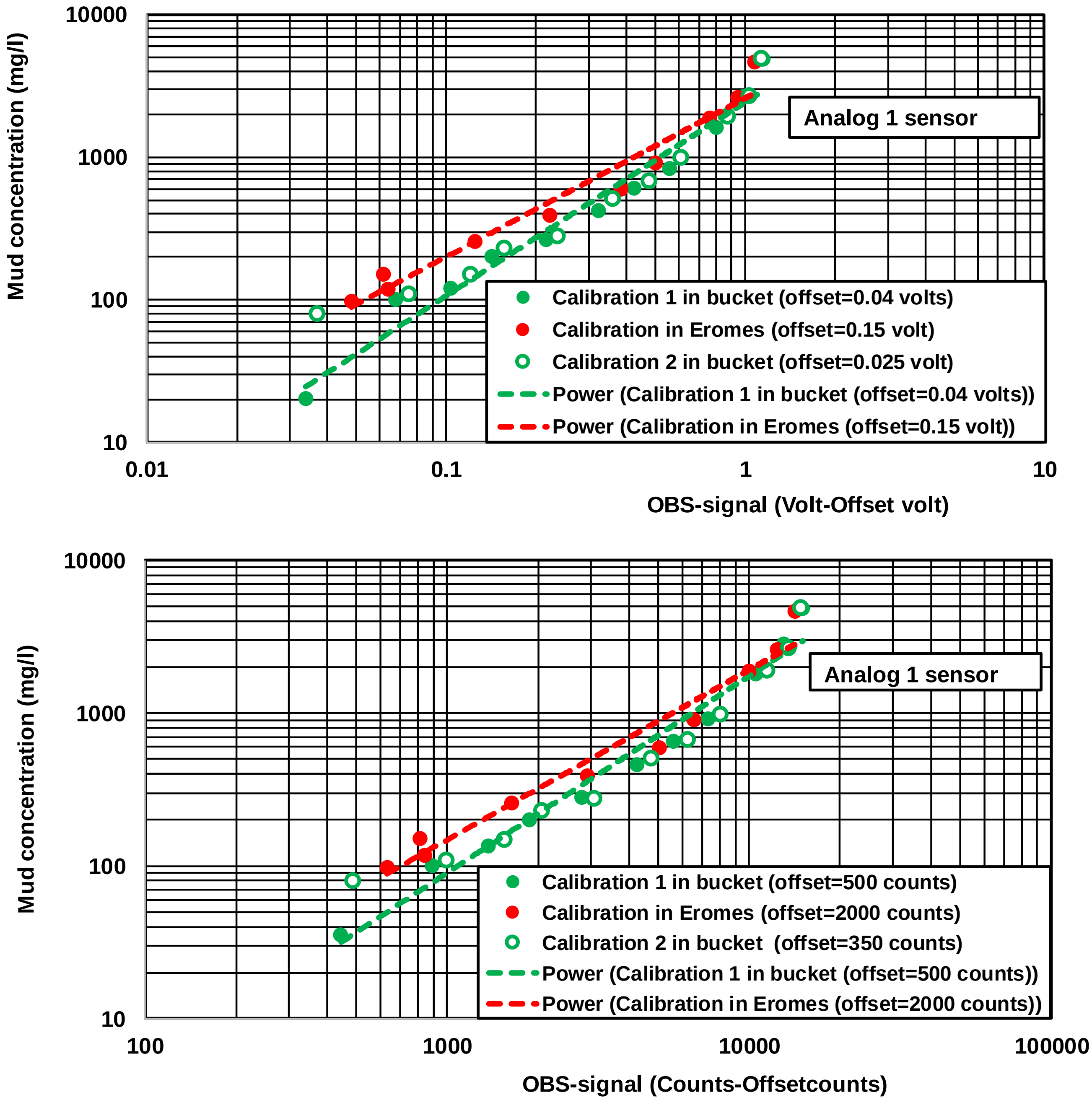


Figure 2.3B *Calibration curves of optical sensors; March-April 2017*
Upper: volts; Lower: digital counts

2.4 EROMES-instrument

2.4.1 Instrument description

Basically, the EROMES erosion instrument (**Figure 2.4**) consists of a 100 mm diameter perspex tube that is pushed gently into the sediment bed. The tube is gently filled with local seawater and the eroding unit with propeller is placed on top of the tube. This eroding unit consists of a propeller that generates a primarily jet-type flow which hits from above the sediment surface at the bottom of the tube and is returned along the tube wall. The rotational flow in the tube is significantly reduced by placing a series of vertical baffles around the inner tube wall.

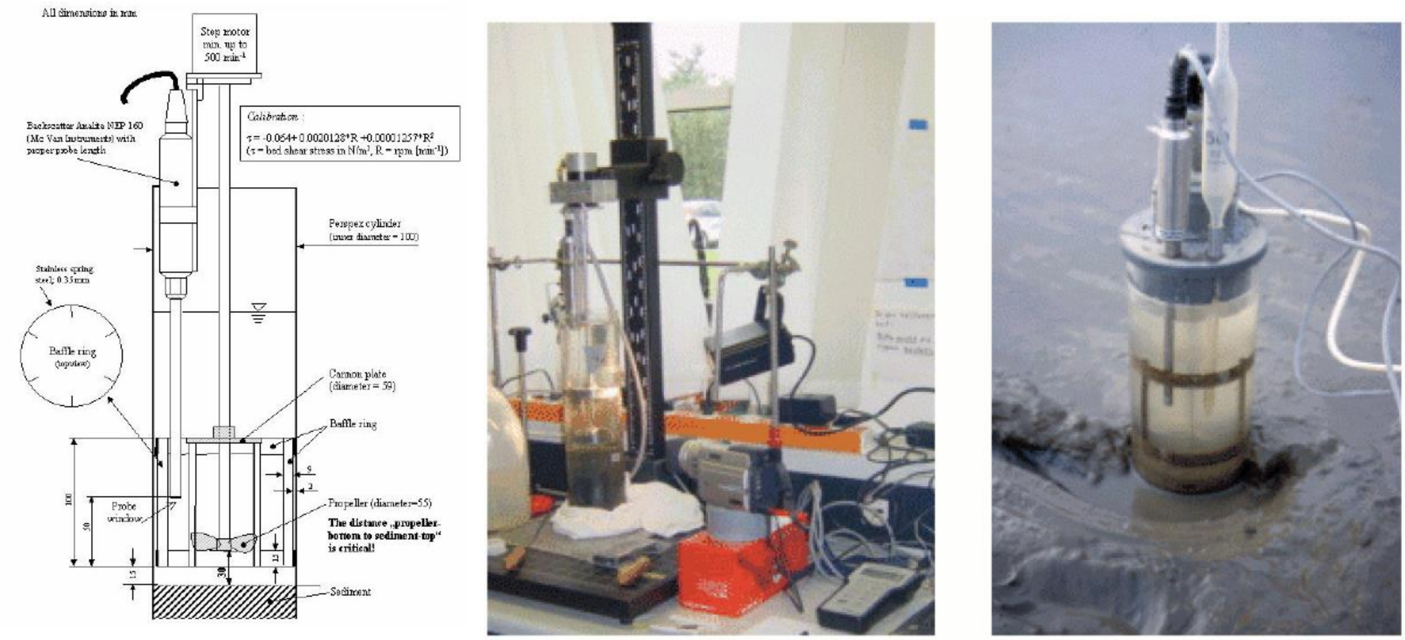


Figure 2.4 *EROMES instrument*

An optical-sensor inside the tube monitors the changing suspended sediment concentration. The propeller revolutions are transferred to bed shear stress by use of a calibration curve based on the onset of erosion of quartz sands with known critical erosion shear stress.

One of the disadvantages of EROMES-system is that the fluctuations of turbulence generated by the propeller are large and the turbulent energy spectrum exceeds those found in natural channel flows.

The instrument can be used with or without a larger storage/mixing tube. Using the storage/mixing tube with 2 propellers, the suspension is continuously mixed and pumped (≅ 1.5 litres/minute) from the instrument tube to the storage tube and back. Sand is not allowed to return to the instrument tube by using a separator. The suspension concentrations in both tubes are measured continuously by using optical sensors. The sediment concentrations in the storage tube are smaller than those in the instrument tube.

Problems during test runs are:

- redeposition of sand particles on top of the sediment bed during a run (although this may also occur in nature);
- generation of a thin layer of rolling sand particles (acting as armour layer for mud particles);
- decreasing visibility due to increasing mud concentrations; the propeller in the middle of the tube is not visible anymore when the mud concentrations are larger than about 800 to 1000 mg/l (based on special tests), which is equivalent with the erosion of a layer of about 0.5 mm ($\delta_e = c_{mud}\, h_w/\rho_{dry}$; c_{mud}= 1 kg/m³, h_w=water depth=0.15 m; ρ_{dry} = 300 kg/m³; Equation 5.1.1).

2.4.2 EROMES shear stress calibration GKSS

A propeller generates a jet-type rotational flow by accelerating the rear water, see **Figure 2.5**. About 50% of this acceleration takes place in front of the propeller, and the other 50% behind the propeller. The velocity vector consist of two main components: the axial velocity parallel to the propeller axis and the radial velocity (or angular velocity; also known as the swirl velocity) normal to the propeller axis. The amount of swirl depends on the rotational speed. The radial velocity at the propeller tip is about equal to $V_{tip,radial} = 2\pi R\ N_{rev}$ with R= propeller radius and N_{ps} = number of revolutions per sec, yielding $V_{tip,radial}$= 0.3 m/s for N_{ps}= 2 (120 per minute) and R=0.025 m. The swirl angle (about 5°) may cause non-symmetrical flow conditions on parts behind the propeller.
When the jet flow of the EROMES-propeller hits the sediment surface at the bottom of the tube, the jet will be forced outwards into a return flow along the side walls of the tube, (see sketch in **Figure 2.5 upper**). In the middle zone above the sediment surface, pressure gradients will be generated to force the outward flow. These additional pressure gradients are not present in an open channel flow parallel to the channel bottom. The pressure gradients will have an (unkown) effect on the initiation of sediment particle movement. Thus: particle movement in the EROMES-tube is caused by the combined effect of shear stresses and pressure gradients. Most likely, the bottom shear stress in open channel flow causing similar particle movement will be somewhat larger than in the EROMES-tube because the pressure gradients related to jet flow processes are absent in open channel flow.
To find the relationship between the bed-shear stress at the sediment bed beneath the rotating propeller and the number of propeller revolutions, various calibration experiments have been done by GKSS, as follows:

A. measurement of wall-shear stresses using a hot-film anemometer at bottom of EROMES-tube;
B. initiation of motion of various narrow-graded sand samples (sand fractions) in EROMES-tube.

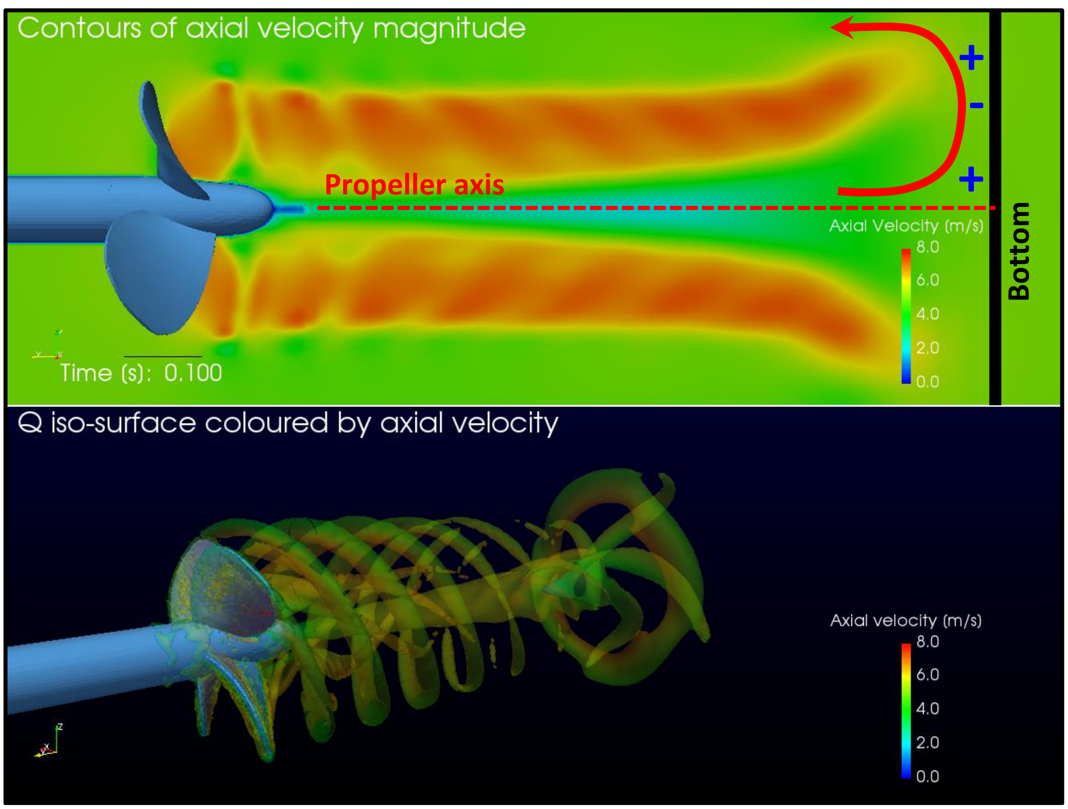


Figure 2.5 *Propeller-induced jet-type flow in air (+ zone of high pressure; - zone of low pressure)*

A. Measurement of turbulent flow velocities

A flush-mounted hot film anemometer (DANTEC M55; sampling rate 50 Hz) has been used to measure the wall shear stress at the smooth bottom of the tube at various distances (r= 0, 20, 30 and 40 mm) from the centre axis of the tube (Geesthacht 1995; Müller et al. 1995). The radius of the bottom plate of the tube is 50 mm (inner tube diameter =100 mm). The propeller diameter is 50 mm (radius=25 mm). The propeller height was set to 30 and 40 mm above the bottom plate.

A hot film anemometer is made of a thin, structured, metallic resistive film ("heater") which is placed onto a (quartz) substrate, see **Figure 2.6**. The sensor is mounted in a hole in the wall in such a way that the sensor is flush with wall surface. The sensor is oriented perpendicular to the flow direction. The hot film is heated by electrical power at a constant temperature. A fluid or air flow with velocity (V) cools the heater down until an equilibrium heat loss is reached. The heat loss increases with increasing velocities. The sensor can be calibrated in a setup where the velocity and or wall-shear stress is known.

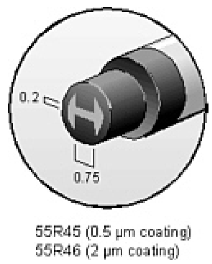


Figure 2.6 *Hot film anemometer*

The measured shear stress at the smooth bottom plate is largest at the locations r= 20 and 30 mm from the centre axis, see **Table 2.2.** The measured values are significantly smaller (factor 2) at r= 0 mm (centre) and at r= 40 mm (close to the side wall).

The calibration based on the hot film data is only valid for hydraulically smooth-wall flow conditions as present during a test with a smooth muddy bed surface.

The average value of the measured values at r= 20 and r=30 mm is shown in **Figure 2.7**. The variation range of the shear stress is indicated by the error bars.

Revolutions per minute	Propeller height= 30 mm				Propeller height= 40 mm			
	r=0 mm	r=20 mm	r=30 mm	r=40 mm	r=0 mm	r=20 mm	r=30 mm	r=40 mm
50	0.016	0.030	0.041	0.029	0.011	0.013	0.023	0.022
100	0.045	0.082	0.097	0.077	0.025	0.045	0.069	0.051
150	0.075	0.149	0.180	0.112	0.050	0.095	0.117	0.086
200	0.117	0.259	0.210	0.154	0.078	0.155	0.206	0.130
250	-	0.411	-	0.203	0.117	0.258	0.219	0.168
300	0.226	0.610	0.394	0.239	0.143	0.385	0.515	0.251
350	0.296	0.925	0.874	0.327	0.183	0.592	0.757	0.310
400	0.420	1.312	1.172	0.419	0.265	0.869	1.074	0.414
450	0.624	1.831	1.578	0.519	0.316	1.250	1.301	0.531
500	0.824	2.491	1.904	0.658	0.341	1.699	1.624	0.678
550	1.165	3.817	2.857	0.792	0.529	2.284	2.349	0.861
600	1.377	4.263	3.726	1.003	0.716	2.805	2.645	0.993
650	1.781	5.056	4.189	1.187	0.916	3.487	3.268	1.185
700	1.977	6.200	5.539	1.486	1.334	3.818	3.210	1.357

Table 2.2 *Measured wall shear stress (N/m^2) based on hot film sensor DANTEC M55 (Müller et al. 1995)*

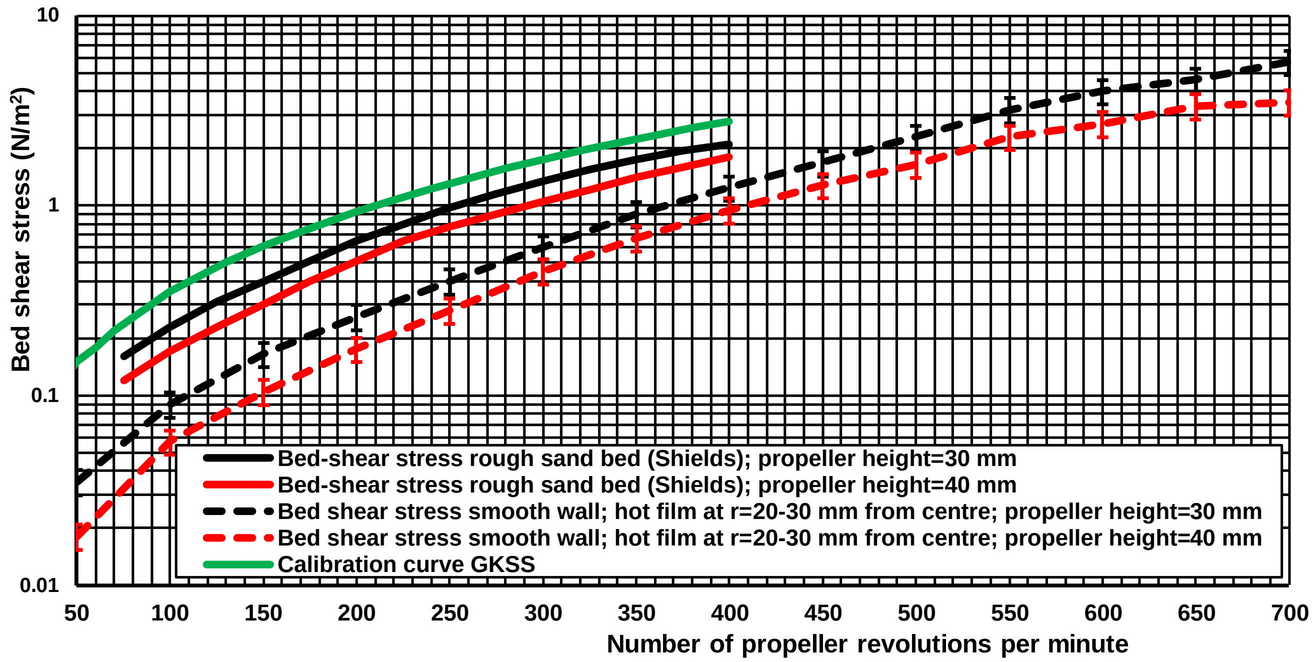


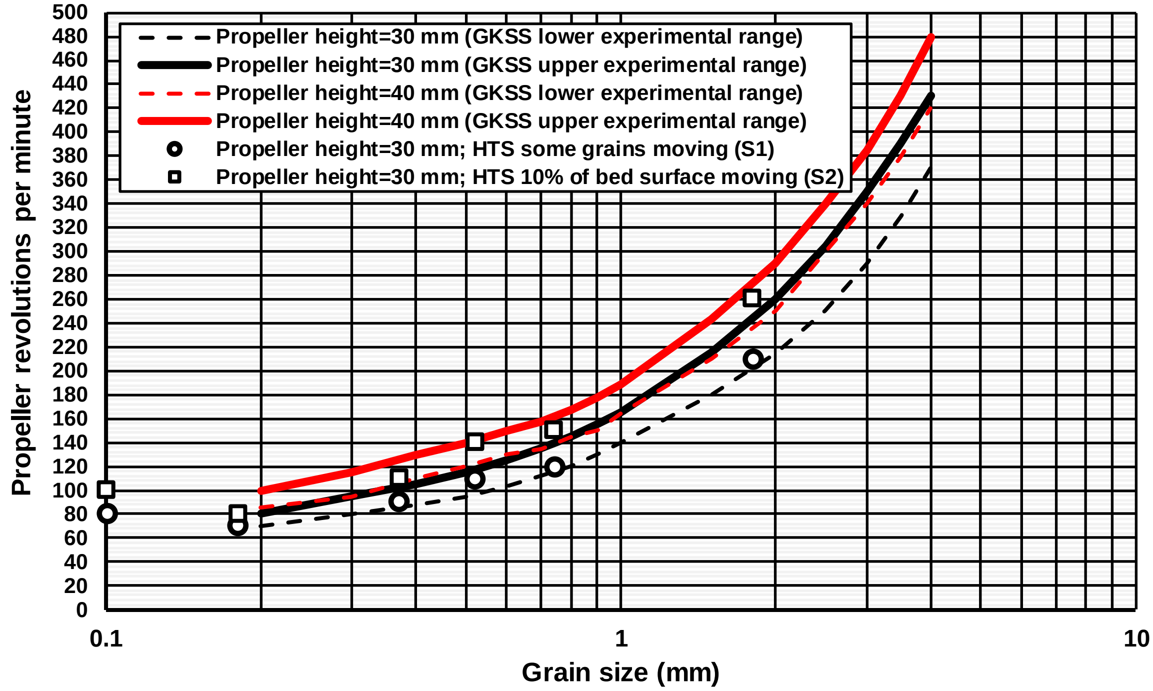
Figure 2.7 *Bed-shear stress as function of propeller revolutions based on GKSS-data*

B. Initiation of movement of various narrow-graded sand samples

Geesthacht 1991 presents data of calibration experiments with various sediment fractions obtained by sieving. The smallest sand fraction was 0.2-0.25 mm and the largest fraction was 3.55-4 mm. Each sediment fraction was tested in the EROMES-tube. The thickness of the sediment layer was about 10 mm for fine sand fractions to about 30 mm for coarse gravel fractions. Each test run was executed by two persons. The number of propeller revolutions was increased until the beginning of transport was visually observed (defined as the stage when a particle was displaced over a noticeable distance of various particle diameters and continued moving). Each run was repeated seven times.

Figure 2.8 show the number of revolutions at the beginning of movement for a propeller height of 30 and 40 mm above the sediment surface (distance between the underside of the propeller and the sediment surface). The number of revolutions increases by about 15% to 20% for a propeller height of 40 mm in stead of 30 mm. The experimental range is about 10% to 15% for each propeller height.

Assuming that the Shields curve is valid for the sand and gravel fractions used, the critical bed-shear for initiation of movement can be plotted as functions of the number of revolutions, see **Figure 2.7** (Geesthacht 1991). The bed-shear stresses based on the Shields curve are significantly larger (factor 2) than those measured by the HFA (hot film anamometer). It is known that the Shields curve represents a stage with almost general transport. Hence, the Shields bed-shear stress values of **Figure 2.7** represent conditions with general transport rather than initiation of movement.



GKSS= Geesthacht 1991 Germany; HTS=Hanze Technical School Groningen

Figure 2.8 *Initiation of movement for sand and gravel particles in EROMES-tube*

3. Sediments and test programme HANZE Technical School (HTS)

3.1 Sand beds

Six size classes (narrow graded fractions) of sand have been used to determine the critical bed-shear stresses and bed-load transport rates just beyond initiation of motion. **Table 3.1** specifies the sand properties.
Each type of sand was tested in the flume and in the EROMES focussing on 4 stages of movement, defined as follows:

- Stage S1: movement of single particles at some locations;
- Stage S2: frequent movement of particles at many places (10% of sediment surface is moving; initiation of ripples for fine sand particles);
- Stage S3: movement of many particles at most places (50% of sediment surface is moving);
- Stage S4: movement of all particles at all places (100% of sediment surface is moving).

The flume tests with sand bed consisted of:

- preparation of flat sediment surface (as flat as possible) in test section;
- increasing the flow rate until particle movement of Stage 1 is observed to be present;
- measurement of velocity profiles (10 points over the water depth);
- removal of sediment from the bed load slot and from the floor (some isolated ripples) between the sediment section and the slot;
- increasing the flow rate until particle moveent of Stage 2, and so on.

Parameter	**Sand**					
	A 0.1 mm (Asser sand)	B 0.18 mm	C 0.35 mm	D 0.52 mm	E 0.74 mm	F 1.8 mm
Graindiameter d_{10} (mm)	0.045	0.10	0.12	0.24	0.53	1.4
Graindiameter d_{50} (mm)	0.095	0.18	0.35	0.52	0.74	1.8
Graindiameter d_{90} (mm)	0.13	0.24	0.55	0.65	0.95	2.2
Percentage fines < 63 μm	15%	<1%	<1%	0%	0%	0%
Percentage fines < 8 μm	5%	0%	0%	0%	0%	0%

Table 3.1 *Sand data*

3.2 Mud beds

3.2.1 Mud sampling sites

Mud was sampled at three sites: Harbour basin of Noorpolderzijl (N-mud); 2) tidal channel of Noordpolderzijl (N-mud) and 3) harbour basin of Delfzijl (D-mud)

<u>Harbour basin Noordpolderzijl (N-mud)</u>
Weakly consolidated mud was taken from the small harbour of Noordpolderzijl (November 2016; March 2017 and June 2017), located at the Dutch part of the Wadden Sea, see **Figure 3.1**.
The mud bed of the harbour basin is exposed at low water and a container of 100 liter (using a bucket of 10 litres) was filled with mud at a location that was a few metres from the end of the quay wall. Furthermore, a container of 100 litres was filled with saline water. The mud bed is so soft that a person sinks about 0.7 m in the mud when walking over the mud bed.

In addition (November 2016 and march 2017), five mud samples (M1-M5) were taken for the top layer (5 cm) of the mud surface, **Figure 3.1**.
The mud container and samples were carried to the laboratory of Wiertsema Soil Engineering, where it was stored at a temperature between 5 and 10 ^oC.
In june 2017, various samples were taken over the depth of the toplayer of 0.4 m (sample spacing of about 0.05 m) to study the vertical variation of the wet bulk density.
Various methods were used to take the samples, as follows:

1. transparent perspex tube with diameter of 40 mm pushed into the mud; tube with mud was cut into sections of 50 mm and the wet bulk density was determined by weighing and the known sample volume; problem: sampling is hindered by wall friction resulting in disturbed samples (small sample height and sample campaction inside the tube);
2. transparent perspex tube (Beeker tube) with diameter of about 70 mm was pushed into mud; sample was taken by suction (vacuum pump); sample was pushed out of tube by mechanical piston+rod; problem: sample is disturbed and compacted by pushing the sample out of the tube;
3. digging of a small pit will an almost vertical side wall over a depth of about 0.5 m; take small samples with vertical spacing of 50 mm using small standard steel rings with volume of 100 ml (see **Figure 3.1**).

Method 3 is simple and easy to use in conditions with an exposed (dry) channel bed.

Various basic mud tests have been done to determine the mud properties, see **Tables 3.2A, 3.2B, 3.3** and **3.4**.
The wet bulk density of the mud bed based on the analysis of 5 samples taken randomly from the container is:

- November 2016: about 1440$\pm$ 2% kg/m^3 (dry bulk density of 685 kg/m^3);
- March 2017: about 1275 $\pm$ 2% kg/m^3 (dry bulk density of 425 kg/m^3);
- June 2017: about 1400 $\pm$ 5% kg/m^3 (dry bulk density of 600 kg/m^3) in the toplayer of about 0.1m; about 1500 $\pm$ 15% kg/m^3 (dry bulk density of 800 kg/m^3) in the toplayer of about 0.4 m.

The percentage of organic materials (loss on ignition) varies in the range of 2.5% to 4%.
The variations are caused by sampling errors and natural variations depending on the degree of consolidation/compaction. The consolidation time of the topmost layer of about 0.4 m is of the order of of 6 to 12 months depending on the dredging interval of the harbour basin.

Based on the wet bulk density, the pore volume of the base mub sample (M0) can be determined as:

- November 2016: $p= (\rho_s-\rho_{wet})/(\rho_s-\rho_{water}) \cong 0.75$; the mud consist of 25% sediment and 75% seawater;
- March 2017 : $p= (\rho_s-\rho_{wet})/(\rho_s-\rho_{water}) \cong 0.85$; the mud consist of 15% sediment and 85% seawater

The mud sample from location M_0 (base mud) was analyzed in the laboratory to determine the particle size distribution, as follows:

- sample of about 300 grams is spreadout on a large tray (0.4 m length) for drying in oven;
- subsample of about 50 grams is taken and weighed;
- subsample is mixed with peptiser solution (for deflocculation) and washed through a sieve of 63 μm to separate fine mud fraction and the sand fraction (> 63 μm);
- drying, weighing and sieving of sand fraction;
- settling analysis of mud fraction (subsample) using SEDIGRAPH III; results are converted to grain sizes using Stokes settling formula.

Based on the analysis results, the mud from Noordpolderzijl is an almost perfect mud with an equal contribution of the three base fractions (clay, silt and fine sand), as follows:
NoordpolderzijlL: 35% clay (< 2 μm, 30% silt (2 to 63 μm) and 35 % sand > 63 μm (63-200 μm);

For comparison, the data of a mud bed sample taken in May 2016 from the Holwerd tidal ferry channel in the Dutch Wadden sea (about 50 km west of Noordpolderzijl) is given. This latter sample contains much more silt (sandy silt).
Holwerd channel: 10% clay (< 2 μm, 65% silt (2 to 63 μm) and 25 % sand > 63 μm (63-200 μm).

Sample location	**November 2016**		**March 2017**	
	Wet bulk density (kg/m³)	**Dry bulk density (kg/m³)**	**Wet bulk density (kg/m³)**	**Dry bulk density (kg/m³)**
M0 Base mud from upper 0,3 to 0.5 m	1440±15	685±15	1275±15	425±15
M1 Sample from upper 5 cm	1385	580	1345	535
M2 Sample from upper 5 cm	1390	590	1215	325
M3 Sample from upper 5 cm	1395	600	1170	250
M4 Sample from upper 5 cm	1325	490	1305	475
M5 Sample from upper 5 cm	1210	300	1130	190
M6 Sample from upper 5 cm	-	-	1375	585
Mean of sample **M1** to **M6**	1300±100	500±100	1250±100	400±200

$\rho_{dry} = (1\text{-}p)\ \rho_s$; $\rho_{wet} = p\ \rho_{water} + (1\text{-}p)\ \rho_s$; $\rho_{wet} = \rho_{water} + [(\rho_s\text{-}\rho_{water})/\rho_s]\ \rho_{dry}$

ρ_{water}= density of seawater (kg/m³), ρ_s= sediment density (≅2650 kg/m³), p= porosity factor.

Table 3.2A *Wet and dry bulk density of mud samples (November 2016 and March 2017)*

Location	**Depth below mud surface (m)**									
	0	**0.05**	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**	**0.35**	**0.4**	**0.45**
M3 steel rings		1520 (800)	1590 (940)	1370 (560)	1430 (680)	1720 (1140)				
M3 Steel rings		1470 (730)	1410 (630)	1700 (1100)	1735 (1150)	1695 1100)	1745 (1160)	1695 (1100)		
M4 Steel rings		1400 (610)	1460 (710)	1525 (810)	1655 (1015)	1485 (790)	1459 (710)	1470 (715)		
M5 Steel rings		1340 (520)	1390 (600)	1450 (700)	1475 (720)	1400 (610)	1400 (610)	1335 (510)		
M5 Steel rings	1350 (530)	1360 (545)	1375 (570)	1565 (890)	1510 (800)	1635 (1000)	1450 (700)	1325 (490)	1330 (500)	1395 (600)
M5 plastic tube cut in pieces of 5 cm long				1495 (770)	1590 (925)	1445 (685)	1370 (570)	1450 (690)	1360 (550)	

Table 3.2B *Wet bulk density and dry bulk density* ***(red)*** *of mud samples (19-28 June 2017*

Sample	Date	% sand > 63 um	% mud < 63 μm % clay < 2 μm	Mud-Sand sample			Sand fraction		Mud fraction
				d10 (μm)	d50 (μm)	d90 (μm)	d50 (μm)	d90 (μm)	d50 (μm)
M0	Nov. 2016	35	65; 30	< 1	15	100	85	150	<4
M0-1	March 2017	30	70; 45	< 1	10	90	70	150	< 4
M0-2	March 2017	30	70; 45	< 1	10	90	70	120	< 4
M0-3	March 2017	30	70; 45	< 1	10	90	70	300	< 4
M6	March 2017	45	55; 25	< 1	40	100	80	150	< 4
M5	March 2017	5	95; 55	< 2	< 2	30	90	350	< 2
M4	March 2017	30	70; 30	< 1	15	100	70	150	< 4
M3	March 2017	25	75; 35	< 1	15	80	80	150	< 4
M2	March 2017	20	80; 35	< 1	10	70	80	250	< 4
M1	March 2017	35	65; 30	< 1	25	100	80	150	< 4

Table 3.3 *Particle size data of mud samples (November 2016 and March 2017)*

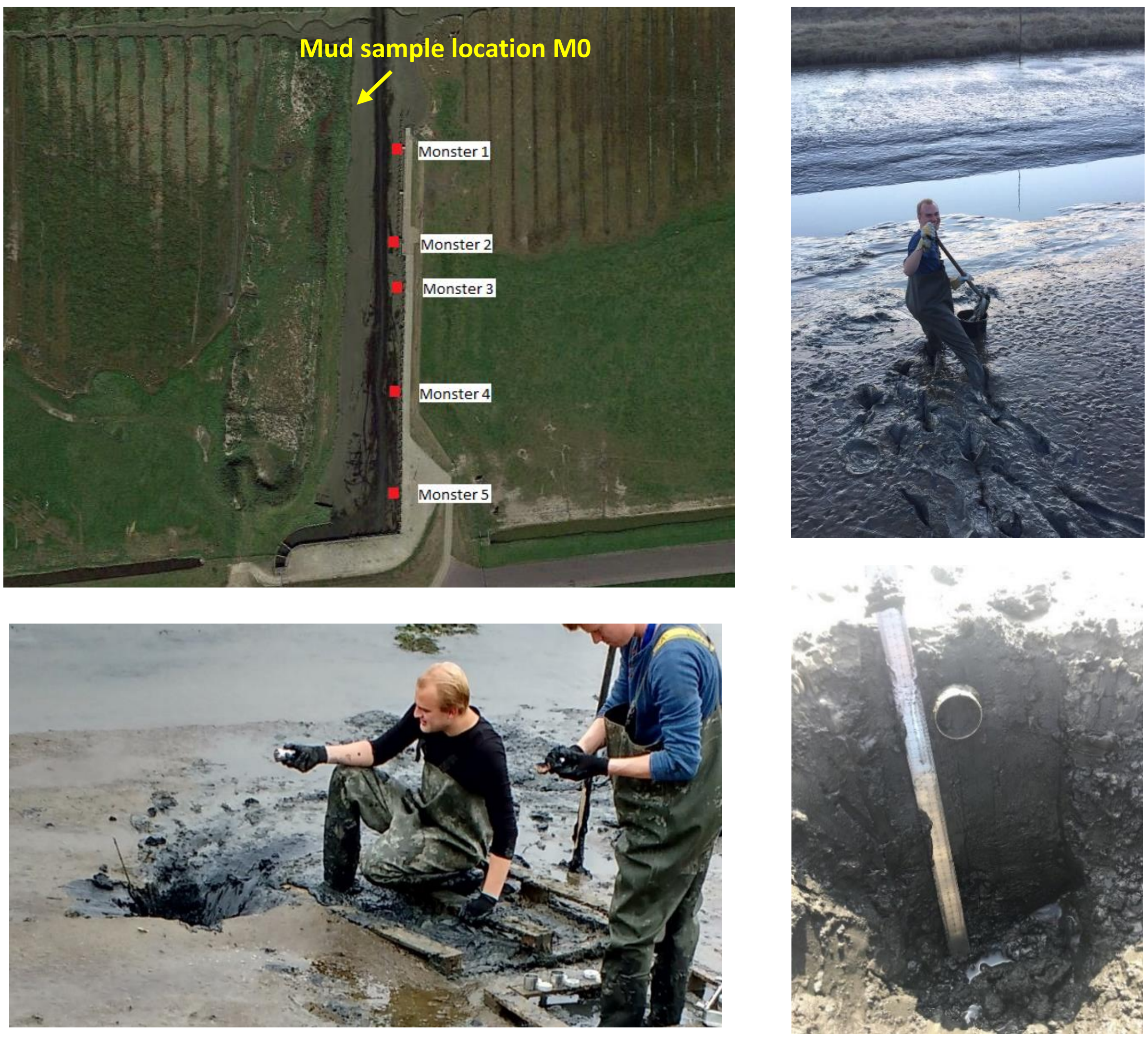


Figure 3.1 *Mud sample location Noordpolderzijl, Groningen, The Netherlands*

Parameter	N-mud November 2016 (without treatment)	N-mud March 2017		N-mud October2017		D-mud November 2017	
		without chemical treatment	with chemical treatment	without chemical treatment	with chemical treatment	without chemical treatment	with chemical treatment
Particle size diameter mud-sand d_{10} (μm)	< 2	<2	< 2	<2	<2	<2	<2
Particle size diameter mud-sand d_{50} (μm)	15	10	10	30	30	4	5
Particle size diameter mud-sand d_{90} (μm)	100	90	95	110	110	100	100
Median particle size d_{50} (μm) mud fraction < 63 μm	3	< 1	<1	3	3	2	2
Median particle size d_{50} (μm) sand fraction > 63 μm	85	80	100	85	85	120	120
Largest particle size d_{90} (μm) sand faction > 63 μm	170	280	<300	170	170	300	300
Fluid density seawater (kg/m^3)	1025	1025	1025	1010	1010	1007	1007
Sediment density (kg/m^3)	2615	2650	2650	2570	2570	2560	2560
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	1310±10	1310±10
Percentage seawater (porosity) and sediment (%)	75%/25%	85%/15%	85%/15%	70%/30%	70%/30%	80%/20%	80%/20%
Dry bulk density (kg/m^3); mean of 5 samples	685±20	425±15	425±15	755±10	755±10	505±10	505±10
Percentage organic material	2.5%-4%	5%-7%	0%	7%	0%	10%	0%
Percentage calcareous materials	15%	15%	0%	17%	0%	18%	0%
Percentage sediment > 63 μm	35%	30%	35%	40%	45%	20%	20%
Percentage fines between 2 and 63 μm	35%-45%	40%-55%	25%-35%	35%-40%	30%-35%	40%-50%	40%-50%
Percentage clay < 2 μm	20%-30%	15%-30%	30%-40%	20%-25%	20%-25%	30%-40%	30%-40%
Settling velocity deflocculated $w_{s,50}$ (mm/s) of mud fraction at Te=15 ^oC; SEDIGRAPH-method	0.007 (3 μm)	< 0.003 (< 2 μm)	n.m	n.m	n.m	n.m	n.m
Settling velocity deflocculated $w_{s,50}$ (mm/s) of sand fraction at Te=15 ^oC; Stokes-formula	5.5 (85 μm)	5 (80 μm)	n.m	n.m	n.m	n.m	n.m
Settling velocities $w_{s,50}$ (mm/s); WASED-test at c_{mud}= 0.01, 1, 10, 100 kg/m^3	0.25; 1.1; 0.7; 0.055	0.02; 0.8; 1.3; 0.054	n.m	n.m	n.m	n.m	n.m

n.m.= not measured; Sedigraph-method yields largest percentage < 2 μm

Table 3.4 *Mud data from Noordpolderzijl channel (N-mud) and Delfzijl harbour (D-mud)*

Tidal channel Noordpolderzijl (N-mud)

In June 2017, various mud samples were taken at different locations along the tidal channel of Noordpolderzijl which is situated between the landward harbour basin and seaward Wadden Sea, see **Figure 3.2**.

The length of the tidal channel is about 3000 m; the width is about 10 to 20 m.

The channel bed is exposed (almost dry) at low water.

Bed samples were taken over the upper 0.5 m in the middle and at the eastern side of the channel bed at low water with exposed bed. The dry bulk density and the percentage of sand (> 63 μm) have been determined in the laboratory, see **Table 3.5A**.

The characteristic diameters of the sand fraction (> 63 μm) are shown in **Table 3.6**.

The d_{50} of the sand fraction varies between 95 μm at the landward end to about 120 μm at the seaward end.

Figure 3.3 shows the dry bulk density as function of the percentage sand. The dry bulk density increases for increasing percentage of sand. The dry bulk density of sand-mud deposits in tidal channels strongly depends on the bed composition (percentage clay, silt, sand). The bed composition is muddy at the landward end and sandy at the seaward end.

The dry bulk density data can be fairly well represented by (trend line, see **Figure 3.3**):

$$\rho_{dry} = 400\,(p_{clay}/100) + 800\,(p_{silt}/100) + 1600(p_{sand}/100) \qquad (2.2)$$

The ratio of the fraction of clay/lutum (< 8 μm) and silt (8-63 μm) is about 1 to 2; ($p_{silt}=2p_{clay}$).

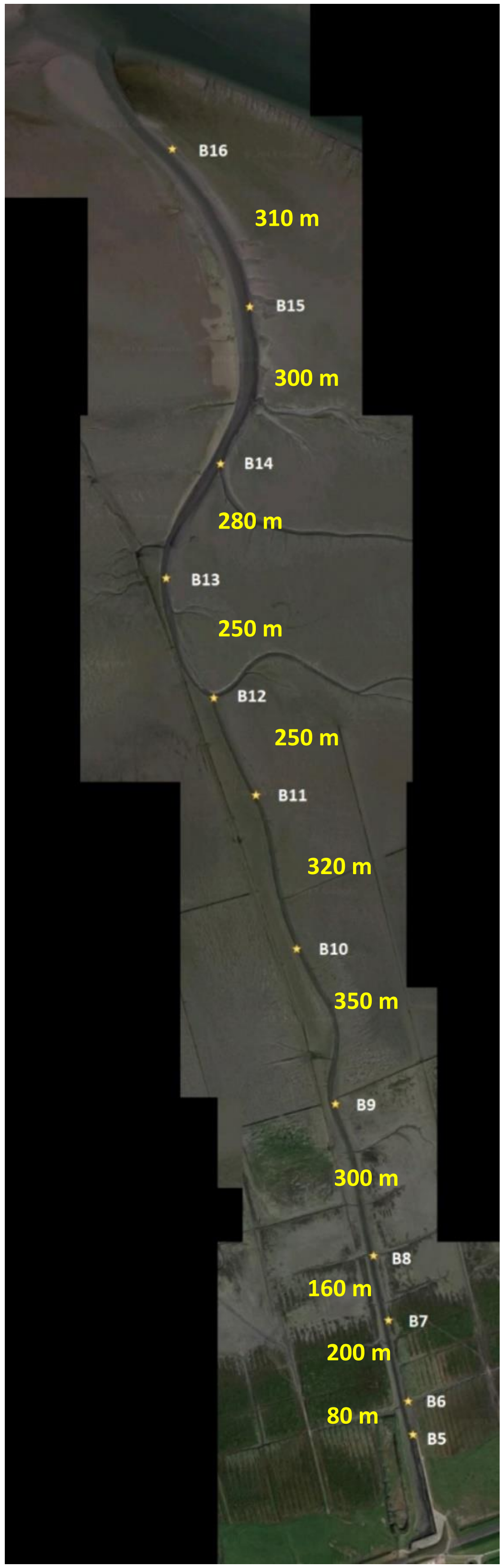


Figure 3.2 *Sampling locations along eastern side of tidal channel; B5 near landward harbour basin and B19 at most seaward end of channel (channel length of about 2.5 to 3 km)*

Location	Depth below sediment surface (m)							
	0.025	**0.075**	**0.125**	**0.175**	**0.225**	**0.275**	**0.325**	**0.375**
B5 wet bulk density (kg/m³)	1350	1360	1375	1565	1510	1635	1445	1325
percentage sand (%)	15	25	20	40	40	50	25	5
B6 wet bulk density (kg/m³)	1640	1555	1685	1755	1720	1775	1500	1605
percentage sand (%)	55	45	60	70	65	65	40	50
B7 wet bulk density (kg/m³)	1240	1625	1585	1665	1580	1685	1715	1680
percentage sand (%)	30	60	60	70	65	70	75	65
B8 wet bulk density (kg/m³)	1455	1355	1560	1590	1595	1730	1710	1610
percentage sand (%)	65	45	65	70	70	80	70	65
B9 wet bulk density (kg/m³)	1670	1645	1685	1710	1745	1615	1455	1635
percentage sand (%)	75	75	80	75	85	80	60	75
B10 wet bulk density (kg/m³)	1290	1660	1580	1660	1620	1635	1565	
percentage sand (%)	40	70	65	65	65	70	65	
B11 wet bulk density (kg/m³)	1435	1305	1350	1385	1745	1665	1725	1735
percentage sand (%)	25	40	40	35	70	70	70	80
B12 wet bulk density (kg/m³)	1575	1775	1810	1615	1365	1650	1655	1650
percentage sand (%)	50	55	60	30	20	50	45	55
B13 wet bulk density (kg/m³)	1855	1910	1965	2010	1915	1870		
percentage sand (%)	90	90	90	95	90	85		
B14 wet bulk density (kg/m³)	2005	2010	1875	1915	1985	1775		
percentage sand (%)	90	90	80	85	90	85		
B15 wet bulk density (kg/m³)	1705	1830	1815	1635	1650	1785		
percentage sand (%)	65	80	95	80	80	85		
B16 wet bulk density (kg/m³)	1750	1830	1715	1675	1790			
percentage sand (%)	85	95	85	80	85			

Table 3.5A *Wet bulk density and percentage of sand (**red**) of mud samples (19-28 June 2017*

Location	**Characteristic diameters of sand fraction > 63 μm**		
	d_{10} (μm)	**d_{50} (μm)**	**d_{90} (μm)**
B5	70	95	150
B6	70	85	130
B15	90	115	180
B16	100	120	180

Table 3.6 *Characteristic diameters of sand fraction (based on sieving)*

Figure 3.4 shows the wet bulk density and the percentage of sand of 4 layers along the tidal channel.
The following features can be observed:

- wet bulk density of top layer of 0.1 m is about 1400 kg/m³ in harbour basin (x=0); wet bulk density of top layer is about constant at about 1500 kg/m³ in the landward part of 1.5 km of the channel; wet bulk density increases to about 1900 kg/m³ in the most seaward part of 1 km of the channel;
- wet bulk density is larger in deeper layers; the wet bulk density is about 1600 kg/m³ in the layer 0.1-0.4 m in the landward part of 1.5 km; wet bulk density is about constant at 1900 kg/m³ in vertical direction (over layer of 0.4 m) in the seaward channel section of 1 km.

In March and April 2018, various mud surface samples were taken at the same locations B5 to B16 in Noordpolderzijl as in June 2017, see **Figure 3.2.** Small samples were taken to determine the wet bulk density. EROMES-tube samples were taken at the same time to be tested in a local field laboratory, which was setup in the building of the pumping station. The EROMES-tube is pressed into the dry bed, the surrounding mud is removed and the tube is closed by using a bottom plate. Four locations could be sampled in one walk at low tide; the tubes were placed in a small sledge which was towed to the field laboratory.
The dry bulk density and the percentage of sand (> 63 μm) have been determined in the laboratory, see **Table 3.5B** and **Figure 3.3**.

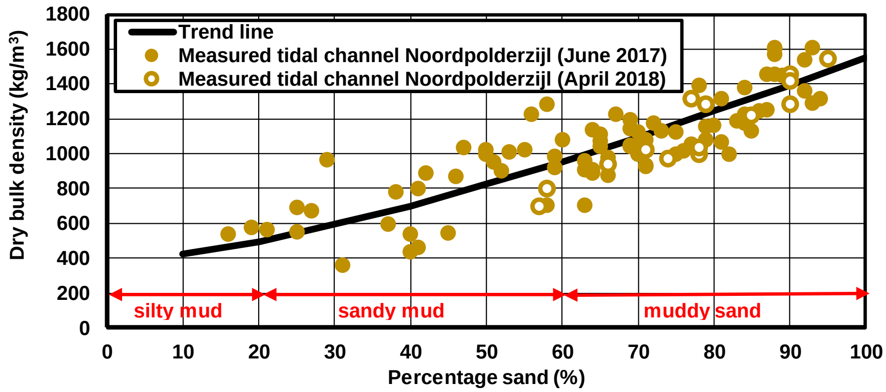


Figure 3.3 *Dry bulk density as function of percentage of sand; tidal channel Noordpolderzijl, Wadden Sea, The Netherlands*

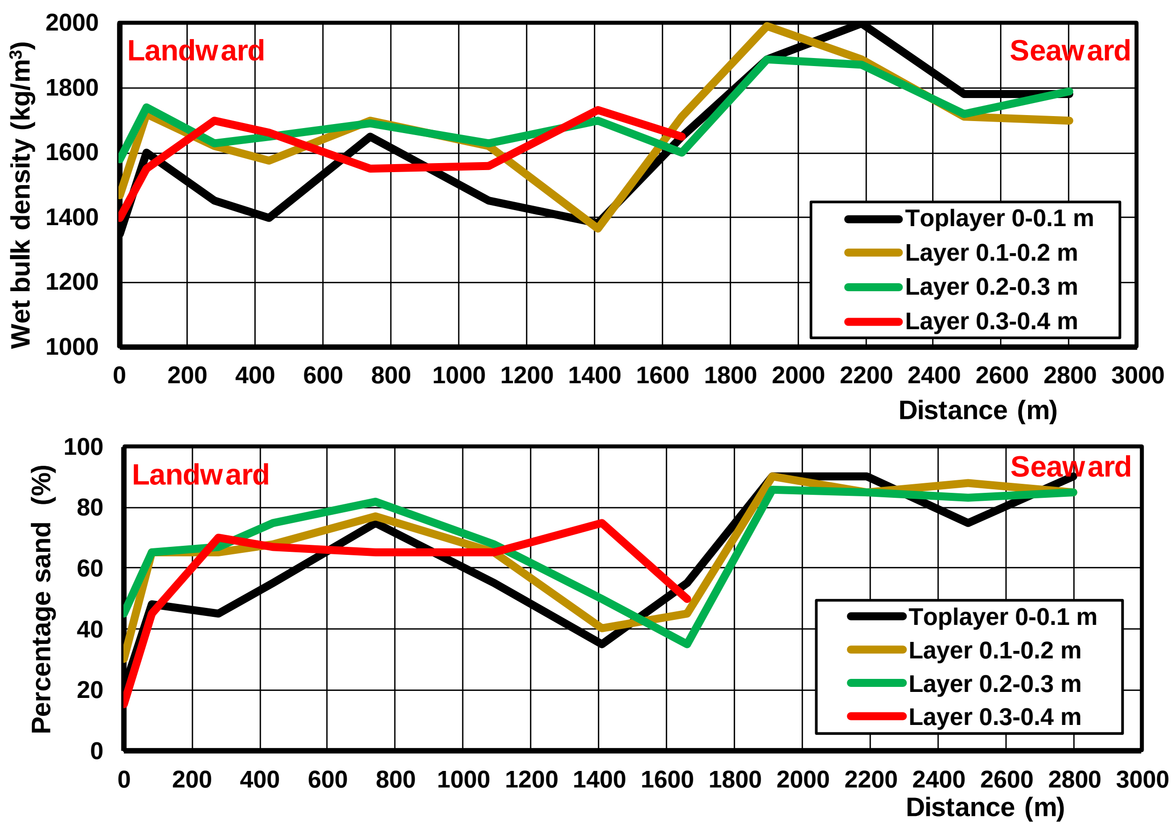


Figure 3.4 *Wet bulk density (upper) and percentage of sand (lower) along tidal channel Noordpolderzijl, Wadden Sea, The Netherlands; June 2017*

Time	Sample location	Wet and dry bulk density (kg/m³)
March 2018	B5 (March); ps=57%	1450; 670
	B6; ps=71%	1650; 1020
	B7; ps=66%	1605; 950
	B8; ps=58%	1510; 800
	B9; ps=78%	1635; 990
	B10 middle; ps=74%	1620; 970
	B10 side; ps=74%	1885; 1400
	B11; ps=78%	1660; 1025
	B12; ps=95%	1970; 1545
	B13; ps=90%	1915; 1450
	B14; ps=85%	1770; 1220
	B15-1; ps=90%	1895; 1410
	B15-2; ps=77%	1830; 1310
	B15-3; ps=79%	1810; 1280
	B16; ps=90%	1810; 1280
April 2018	B5; ps=55%	1500; 800
	B7; ps=70%	1810; 1290
	B9; ps=80%	1855; 1350
	B15; ps=90%	1905; 1450

Samples B13 to B16 were taken at seward end of channel; feet sank into bed over 10 to 20 cm during sampling

Table 3.5B *Wet bulk density and percentage of sand (**red)** of mud samples, Noordpolderzijl (March-April 2018)*

Harbour basin of Delfzijl (D-mud)

Some 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 3.5**. The total volume of mud was about 80 litres.Furthermore, a container of 100 litres 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 shown in **Table 3.4**.

Figure 3.5 *Mud sampling in harbour basin of Delfzijl, The Netherlands*

3.2.2 Particle size of deflocculated mud

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 3.6**).

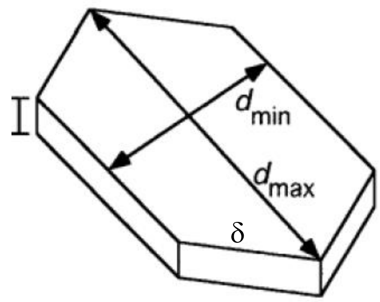


Figure 3.6 *Flaky plate-type clay/lutum particles*

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

- microscopic analyis method (Conley, 1965);
- settling column tests (hydrometer test; pipet test; SEDIGRAPH-test) yielding the equivalent (spherical settling diameter based on the Sokes settling formula);
- Laser-Diffraction (LD) test yielding an equivalent diameter (Haverbeke 2013).

LD takes both the particle shape and its optic properties into account. The particle will 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). This should allow particles to pass with a different orientation each time, and thus let it define 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 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 laboratory of Wiertsema 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 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.

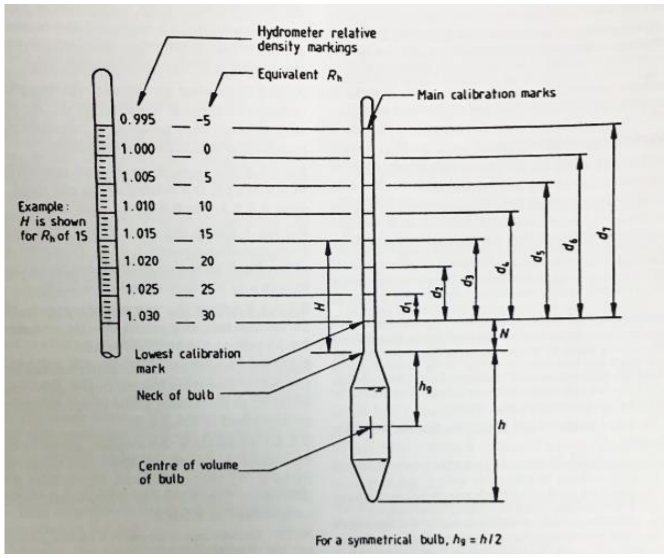


Figure 3.7 *Floating body of Hydrometer test*

In this study, the SEDIGRAPH III-instrument (Wiertsema Soil laboratory) has been also used to determine the settling velocities of the mud concentrations (fresh water with peptiser for deflocculation) in a small-scale settling column. 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 Sokes settling formula.

Figure 3.8 shows the particle size distributions of the Noordpolderzijl-mud sample (base mud M0) based on the SEDIGRAPH-instrument (particles < 63 μm) in combination with sieve-method (particles > 63 μm). Analysis results from the mud samples collected in November 2016 and March 2016 are shown. Sample SS March 2017 is a special sample treated chemically to remove the organic materials and the calcium carbonate fragments showing very similar results as the untreated sample except for the fraction < 10 μm. The particle size distribution of Kaolin (also known as China clay; all fractions < 10 μm; Hydrometer test of Haverbeke 2013) is shown as reference sediment material. The basic data of mud from Noordpolderzijl are given in **Table 3.4**.

The d_{50} of the mud bed sample is about 15 μm for November 2016 and about 10 μm for March 2017.

The d_{90} is about 90 μm.

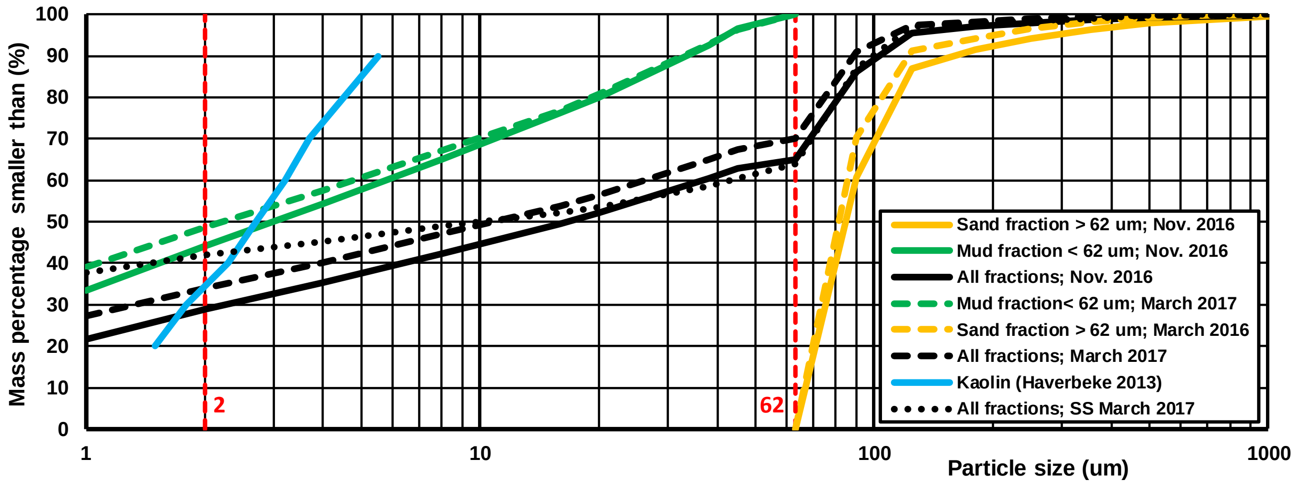
The mud fraction with particles < 63 um is about 65% to 70%.

The clay/lutum fraction < 2 μm is about 30% to 35% (which is similar to that of Kaolin).

The silt fraction between 2 and 63 μm is about 35%.

The d_{50} of the sand fraction is about 70 to 90 μm.

Summarizing, the percentages of three basic fractions clay, silt and sand are approximately equal (30% to 35%). These types of samples are known as clay loam (''kleiige zavel'' in Dutch).



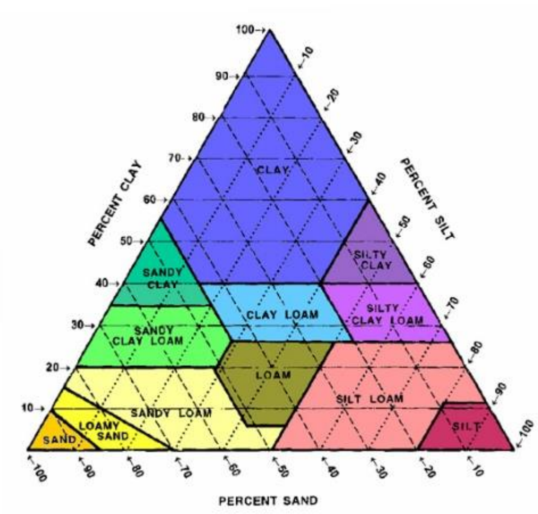


Figure 3.8 *Particle size distribution (incl. calciumcarbonate and organic materials) of mud bed samples (M0) based on Sedigraph-Sieve method; Mud from Noordpolderzijl, The Netherlands*

Figures 3.9A,B show the particle size distribution of deflocculated mud samples from Noordpolderzijl (N-zijl) and Delfzijl (D-mud) based on the Sedigraph-method (SG), the Filtration-Wased-method (settling test based on filtration of concentrations) and the Hydrometer-method (HM). For reference, the particle size distribution of Kaolin is also shown (Figure 3.9A). The Delfzijl-mud is significantly finer; the percentage of sand is smaller and the percentage of clay/lutum is larger (see **Table 3.4**).
The Filtration-Wased method is described in **Section 3.2.3**. The mud samples were tested in fresh water with peptiser (for deflocculation). The test was done at a temperature of 18^o C and the settling velocity data were converted to particle diameter using the Stokes settling formula. All methods yield the same percentage (about 65%) of particles smaller than 63 μm. The FW-method and the Hydrometer-method yield the same particle size distibution of the fine fraction. The SG-method yields much finer sediments. The percentage < 4 μm is about 25% for the FW-method/HM-method and about 40% 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-dreven circulation flows and wall effects. The main advantage of this method is the rapid analysis of many samples. The results of the SG-method should at present be used in relative sense (comparison of samples) rather than in absolute sense (Personal communication Th. van Kessel, Deltares). The FW and HM-methods produce more accurate results in absolute sense.

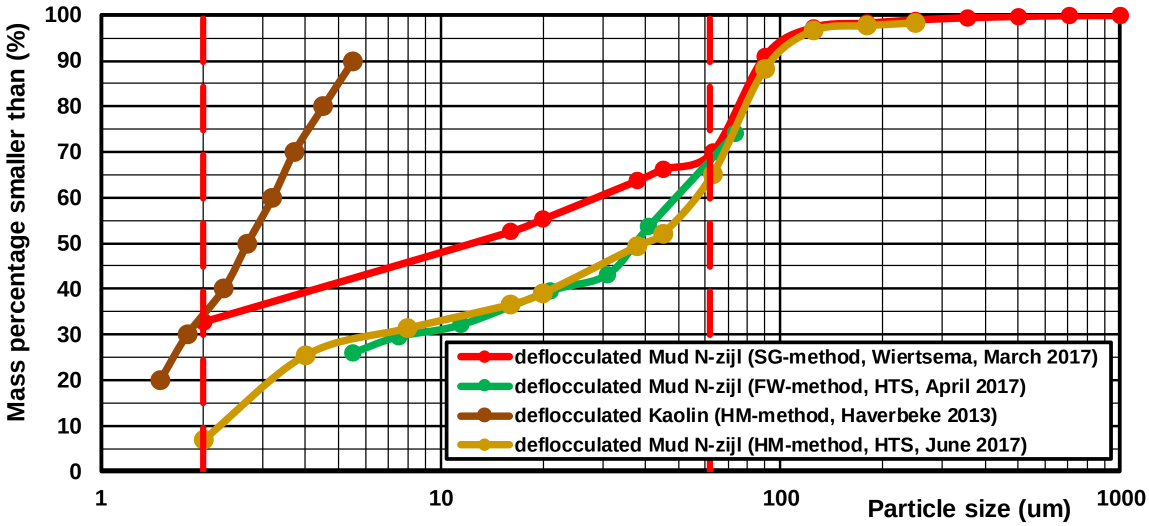
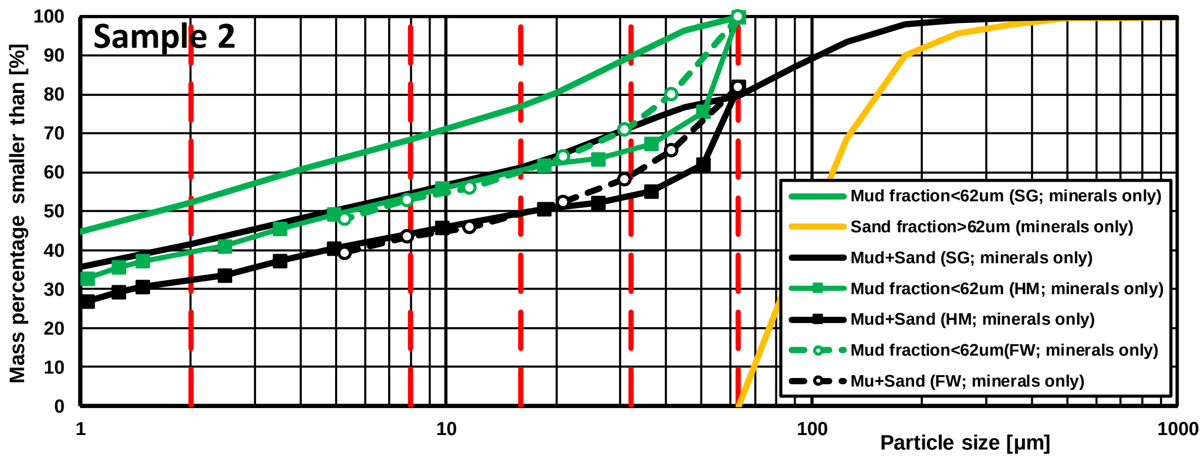


Figure 3.9A *Particle size distribution of deflocculated mud samples (minerals plus calciumcarbonate and organic materials) from Noordpolderzijl (March-April 2017)*



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

Figure 3.9B *Particle size distribution of deflocculated mud samples (minerals only) from Delfzijl (November 2017- February 2018)*

3.2.3 Settling velocity tests of flocculated mud

Settling velocities have measured using the mechanical Filtration-Wased-method (FW-method). This method is based on the settling of suspended sediments in a settling column consisting of a perspex cylinder with internal diameter of 100 mm and height of about 0.5 m, see **Figure 3.10**. A small plastic tapping tube (hose with a clamp) is present at about 70 mm above the bottom of the column. A suspension of seawater and mud (volume of about 2.5 liter) was prepared with an initial concentration of about 2600 mg/l (initial concentration should be larger than 1000 mg/l). 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 (using glass fibre filter material with size of 0.45 µm and diameter=47 mm; each filter was numbered and preweighed; Whatman filters 0.45 µm, 47 mm diameter, art 516-1746, www.vwrbv.nl; **Figure 3.10 right** corner) and weighed to determine the mud concentration. The results are presented in **Table 3.7**.

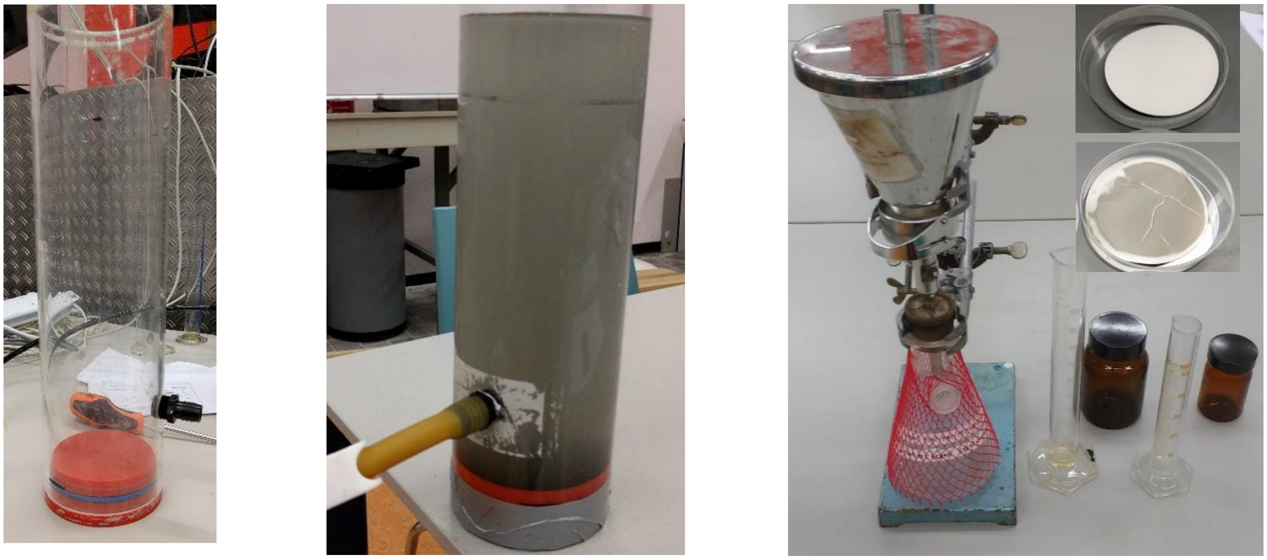


Figure 3.10 *Perspex Wased-settling column of FW-method (internal diameter=100 mm) and filtration unit*

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	2634 (initial concentration)	100
2	60	250	4.17	2212	2212/2634x100= 84.0
3	180	236	1.31	1180	1180/2634x100= 44.8
4	300	225	0.75	754	754/2634x100= 28.6
5	600	211	0.35	481	481/2634x100= 18.3
6	1800	200	0.11	262	262/2634x100= 10.0
7	3600	186	0.05	174	174/2634x100= 6.6
8	7200	170	0.024	107	107/2634x100= 4.1

Table 3.7 *Basic data of settling test (FW-method; temperature of 18^o C); November 2016*

Figure 3.11 shows the settling velocities of flocculated mud (WASED-Settling column, **Table 3.7**) and non-flocculated mud based on the SEDIGRAPH III-instrument (November 2016) and the Hydrometer (June 2017). The settling velocities were derived from the particle szie curves based on the SEDIGRAPH-method (black curve for November 2016 given in **Figure 3.2**) and Hydrometer-method using the Stokes settling velocity formula (temperature =18^o C). 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.
This means that mud suspended in the tidal channel of Noordpolderzijl most likely will have an effective settling velocity ($w_{s,50}$) in the range of 0.25 to 1.5 mm/s depending on the degree of flocculation. 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.
It is uncertain to what extent the flocs generated in the tube by mechanical mixing represent natural conditions. The organic matter in sea beds is highly refractive and has different, most probably much lower stickiness than pelagic (deposited) material. Futhermore, most time the suspended matter is dominated by advected material with little contact with the seabed.

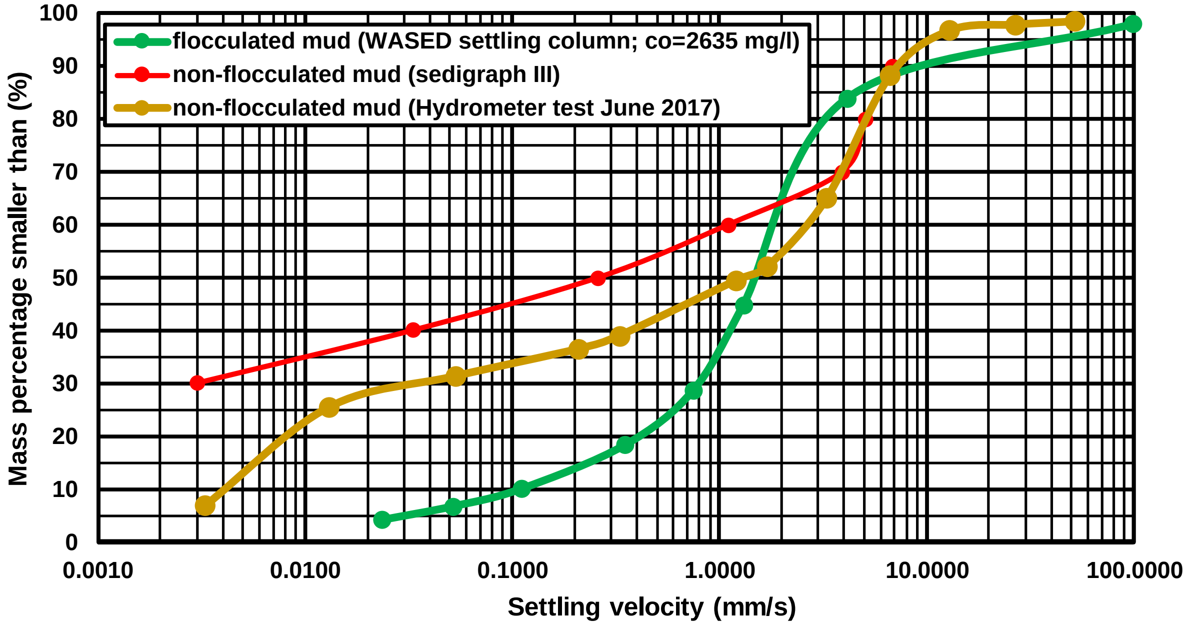


Figure 3.11 *Settling velocities of flocculated and non-flocculated mud (temperature= 18° C)*

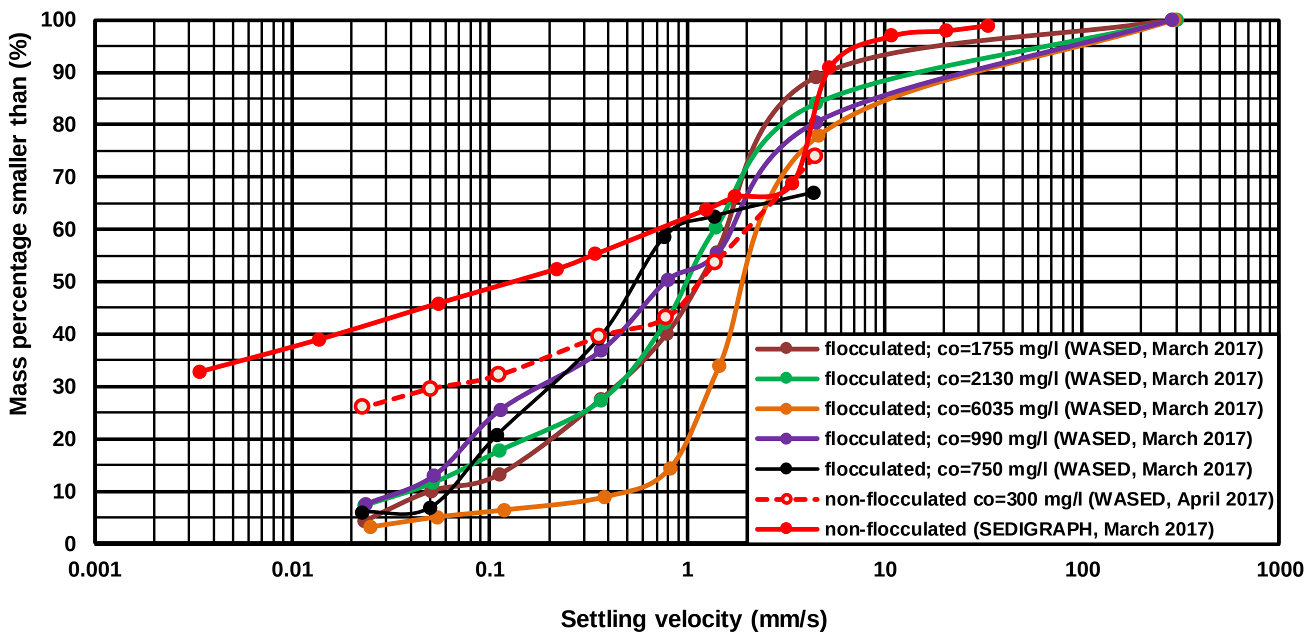


Figure 3.12 *Settling velocities of flocculated and non-flocculated mud (temperature= 18° C); March 2017*

Figure 3.12 shows the FW-data of March 2017. The FW-settling velocities were measured at a temperature of 18° C. The initial concentration varies in the range of 750 to 6035 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 get non-flocculated settling. The settling velocities of the 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 3.8**. The results of March-April 2017 and November-December 2016 are very similar.

FILTRATION-WASED November 2016		FILTRATION-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 3.8 *Settling velocity as function of initial concentration; November 2016 and March 2017*

3.2.4 Consolidation and hindered settling tests

Consolidation 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. The base mud suspension 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 consolidation 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= consolidation tube volume (about 1.5 liter).
Each mixture was poured into a settling column (plastic cylinder/tube closed at bottom (see **Figure 3.13**) and was 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 3.14 shows the relative height of the mud height (ratio of mud height and total height) as function of time for the data of November 2016. The initial settling height is 360 mm for all six settling columns. The data of November 2016 are presented in **Table 3.9**.
The consolidation process consists of two clear phases: 1) flocculation+hindered settling phase and 2) consolidation phase, see **Figure 3.14.** The end of the hindered settling phase is the transition form a concave to convex (hollow) consolidation 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 3.15 shows the dry mud density as function of time derived from the consolidation tests of November 2016. Mud suspensions with initial concentrations of 10 to 100 kg/m^3 (as present in near-bed layers) can reach a dry density of about 200 to 250 kg/m^3 during a period of 3 hours, which is a typical value for the tidal slack period when deposition takes place. Initial concentrations of 200 to 300 kg/m^3 can reach a dry density of 400 to 500 kg/m^3 after 3 hours.
Figure 3.16 shows the relative height of the mud height (ratio of mud height and total height) as function of time for the data of March 2017. The initial settling height is 365 mm for all six settling columns. The data of March 2017 are presented in **Table 3.10**.
Figure 3.17 shows the settling velocity as function of the mud concentration for all test results including the values from Figures 3.4 and 3.5. The maximum settling velocity due to the flocculation effect is about 2 mm/s at a concentration of about 6 kg/m^3. The settling velocity decreases due to hindered settling effects to about 0.1 mm/s at a very high concentration of about 100 kg/m^3. Results from other sites (Van Rijn 1993; Deltares 2016) are also shown. The Holwerd mud sample is taken from the ferry channel at a depth of about 4 to 4.5 m below mean sea level (Wadden Sea). The median sediment size of the Holwerd mud bed sample is about 15 to 20 μm; the percentage of sand > 63 μm is about 25%; the percentage of clay < 4 μm is about 5% to 10%.

The mean sediment size of the Noordpolderzijl sample also is in the range of 5 to 20 μm; the percentage of sand is about 30%, but the percentage of clay is much larger at about 35% to 45% (see **Figure 3.8** and **Table 3.4**). Therefore, the settling velocities (in the flocculation range) of the Noordpolderzijl sample are much smaller than those of the Holwerd sample.
The gelling concentrations are in the range of 75 to 150 kg/m^3 (for initial concentration smaller than 100 kg/m^3) and are reached after settling times of less than 1 hour, which is much less than the slack water period of a tidal cyle (2 to 3 hours). The tests with initial concentrations of 200 and 300 kg/m^3 donot have a marked hindered settling phase as these concentrations are larger than the gelling concentration. Dry densities of 400 to 700 kg/m^3 can be obtained after about 3 days of consolidation at a depth of 0.3 to 0.4 m below the surface of the mud bed. The top layer (upper 50 mm) of the mud bed with concentrations of 50 to 100 kg/m^3 in the tidal channel of Noordpolderzijl can reach a dry density of about 300 after 1 day increasing to 350 kg/m^3 after 3 days.

Initial mud concentration (kg/m^3)	**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/m^3)**	**Dry density after 280 hours (kg/m^3)**
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 3.9 *Consolidation test results (initial settling height= 360 mm); November 2016*

Initial mud concentration (kg/m^3)	**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/m^3)**	**Dry density after 140 hours (kg/m^3)**
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 3.10 *Consolidation test results (initial settling height= 365 mm); March 2017*

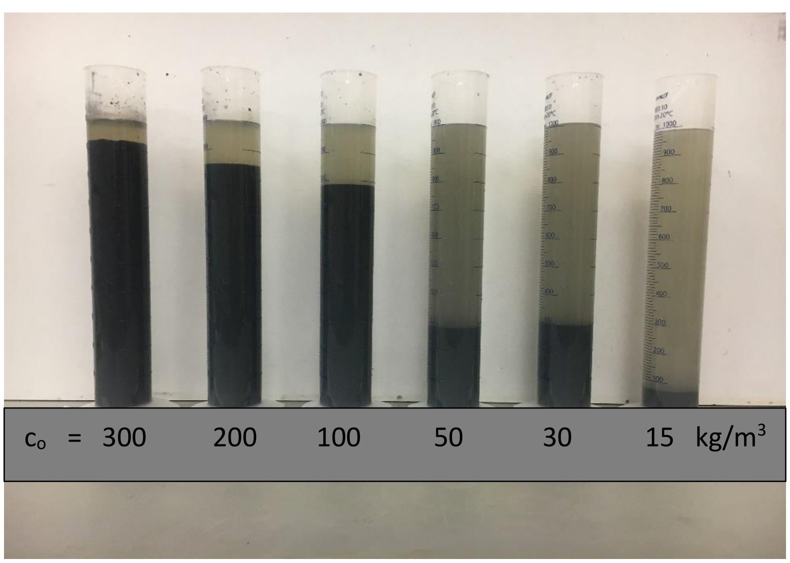


Figure 3.13 *Consolidation columns (initial settling height=360 mm); November 2016*

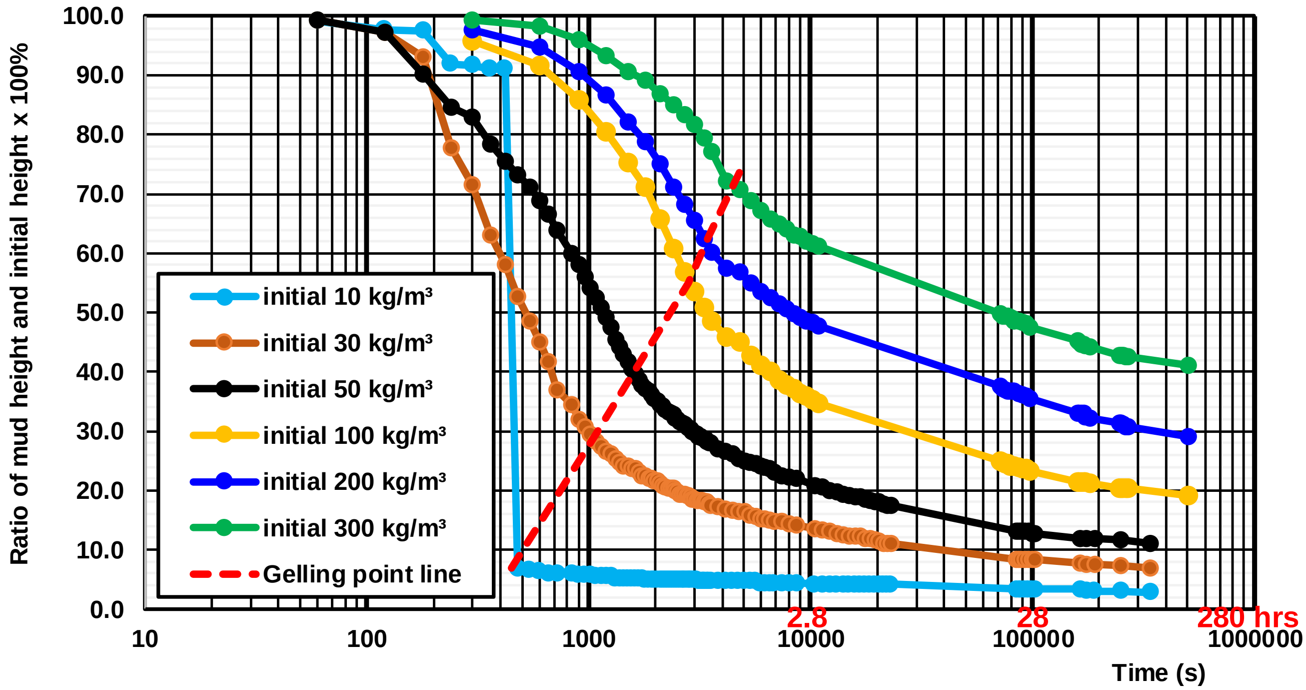


Figure 3.14 *Settling height as function of time based on consolidation tests (initial settling height=360 mm); November 2016*

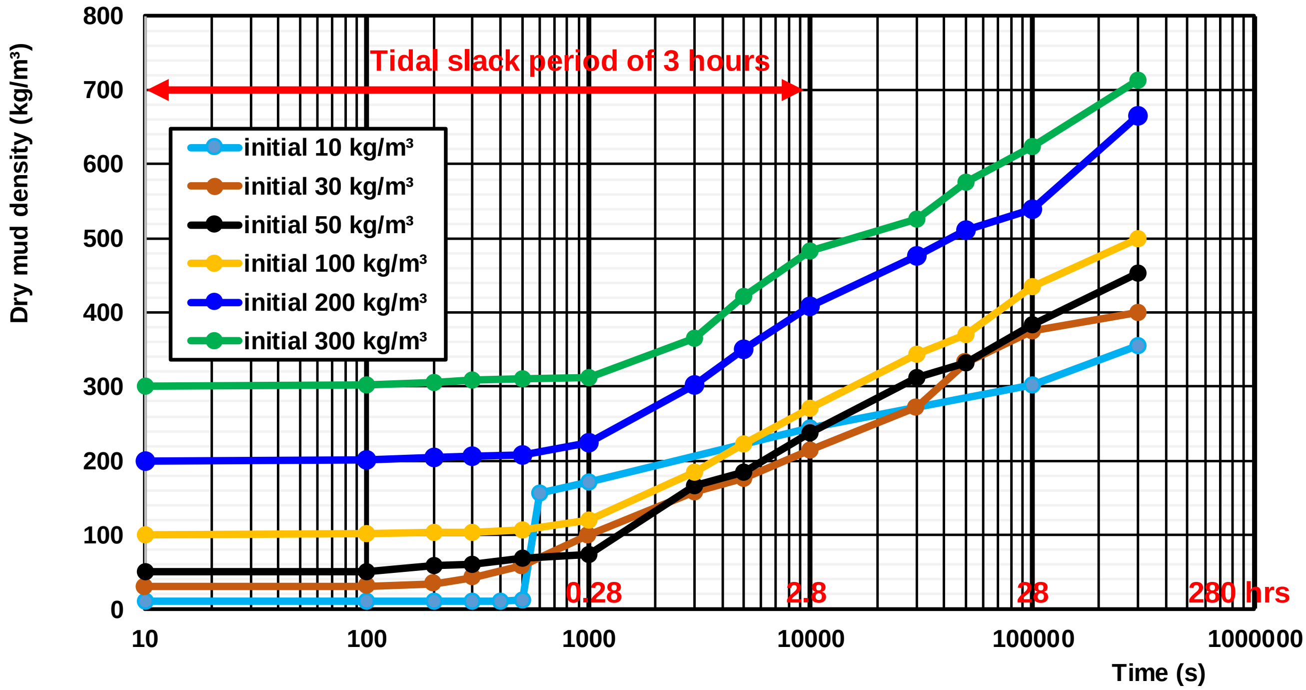


Figure 3.15 *Dry mud density as function of time based on consolidation tests; November 2016*

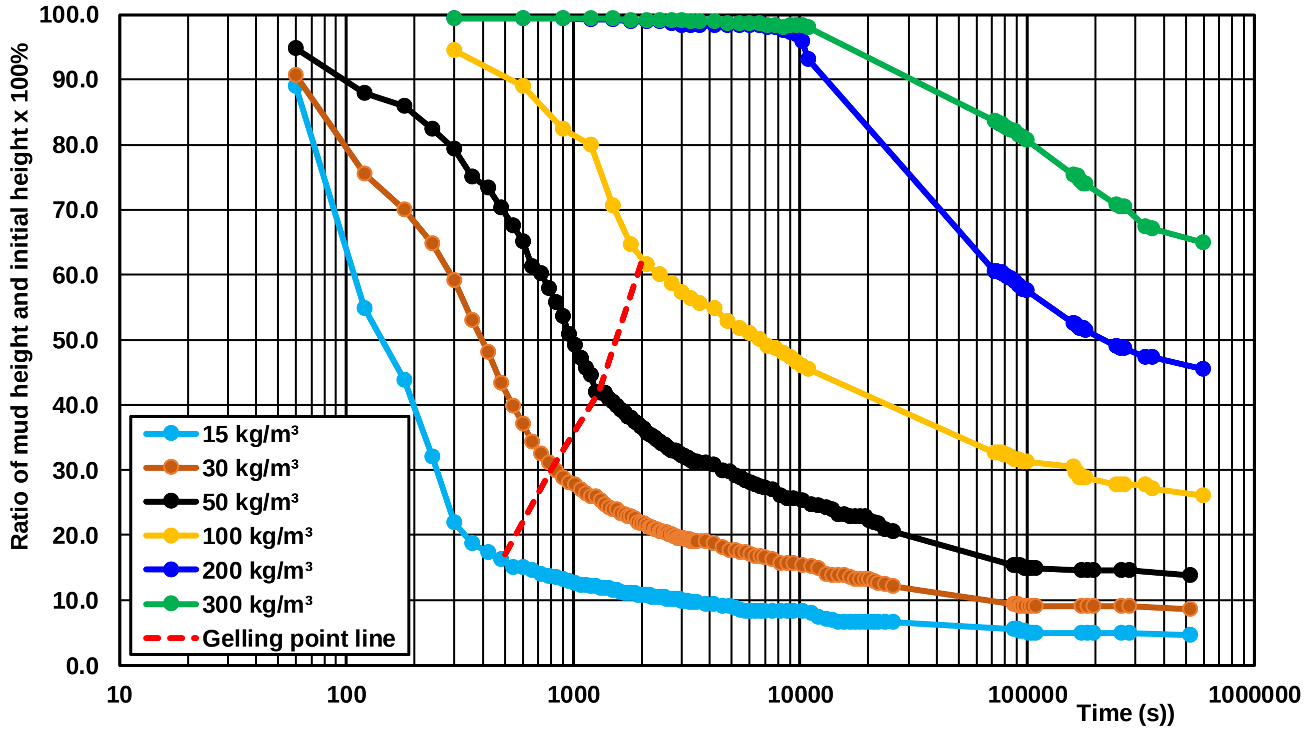


Figure 3.16 *Settling height as function of time based on consolidation tests (initial settling height=365 mm); March 2017*

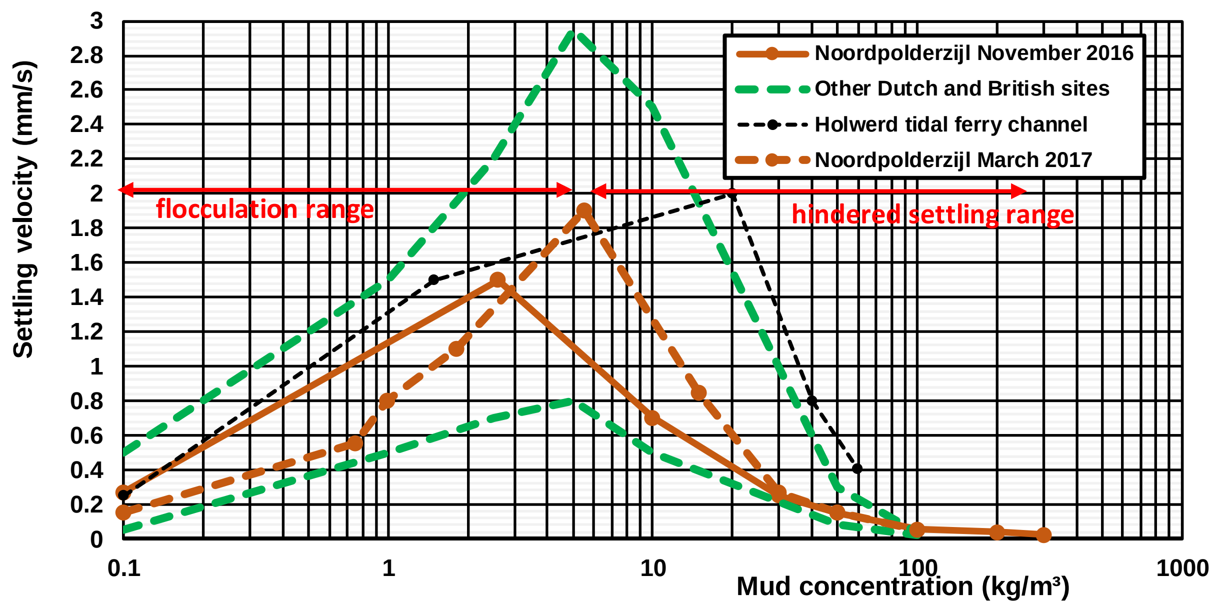


Figure 3.17 *Settling velocity as function of mud concentration (mud from Noordpolderzijl, The Netherlands)*

3.2.5 Flow point stresses

The Brookfield rotoviscometer has been used to determine the flow point stresses from plots of shear stress against shear rate. The mixtures have been made by dilution from the base mud container.
Figure 3.18 shows an example plot for dry density of 685 kg/m^3 (November 2016). The flow point stress is about 355 N/m^2 for this test. All test results are given in **Table 3.11** and plotted in **Figure 3.19**. The measured flow point stress values are relatively small compared to those of other mud samples. This may be caused by the presence of fine sand (30% to 35%) in the mud samples of Noordpolderzijl. The flow point stress increases considerably (factor 1.5 to 5) after 2 days of consolidation.

Period	Dry density (kg/m^3)	Flow point stress (N/m^2)	
		immediately after preparation	after consolidation of 2 days
November 2016	170	6	
	340	12	
	377	27	
	470	50	
	565	100	
	680	355	
March 2017	300	5	30
	350	15	45
	420	35	50

Table 3.11 *Flow point stress data; November 2016 and March 2017*

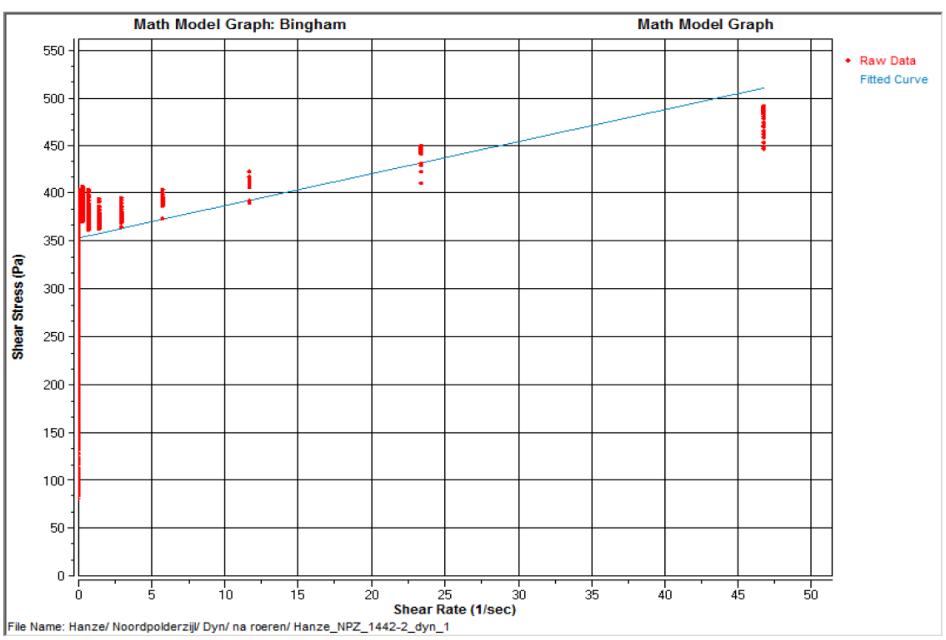


Figure 3.18 *Shear stress (vertical) against shear rate (horizontal) for test with dry density of 685 kg/m^3; November 2016*

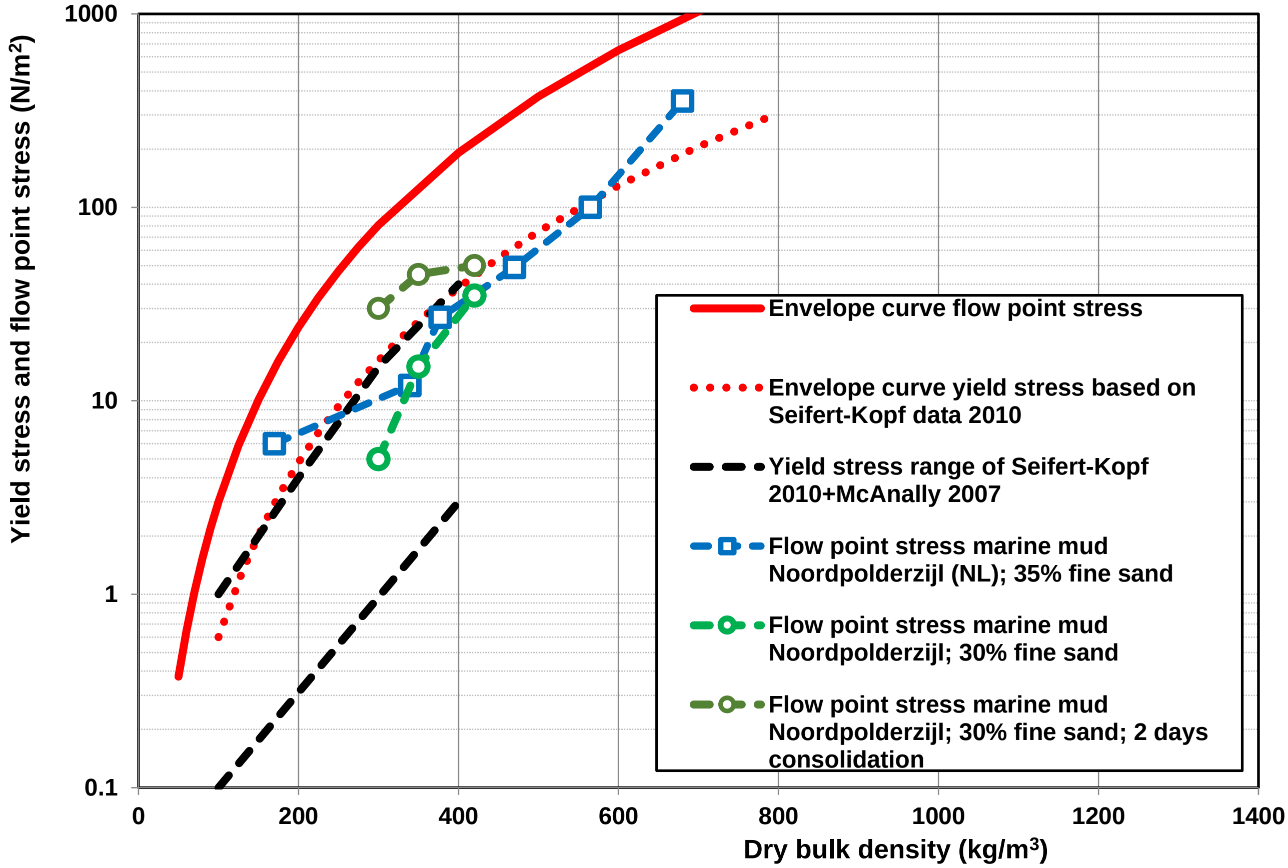


Figure 3.19 *Flow point stress and yield stress as function of dry bulk density*

3.2.6 Compressibility tests

Mud from Noordpolderzijl (N-mud)

The base mud from November 2016 was used to perform a compressibility (Oedometer) test in the soil laboratory of Wiertsema (Tolbert). Two mud sample were taken (15 March 2017) from the base mud container (November 2016) after a consolidation period of 3 to 4 months. Excess water was siphoned off. The dry density of the samples was measured to be in the range of 690 to 760 kg/m^3 (wet bulk density of about 1450 to 1500 kg/m^3).The base mud had a soft buttery-type of texture after a consolidation period of 3 to 4 months.
A ring with thickness of about 20 mm was filled with mud and subjected to an Oedometer test under a series of external loads. The results of sample 2 based on the Terzaghi- analysis method are given in **Table 3.12**. The permeability is computed as: $k=\rho_w\, g\, c_v\, m_v$ with ρ_w =1020 kg/m^3. The results of sample 3 are given in **Table 3.13**. After 7 steps (of 40 hours each; loading up to 128 kpa = 128,000 N/m^2 or 12.8 ton/m^2 or 1.3 kg/cm^2), the total settlement of sample 2 is about 7.3 mm (about 35% of the initial value of 20 mm), see **Figure 3.20**.
The compressibility m_v-coefficient decreases by a factor of about 50 between step 1 and step 7 (sample 2).
The k-value decreases strongly by a factor of 20 between step 1 and 7. As the sample is more compressed/compacted, the permeability (k-value) will decrease.
A separate permeability test with an external load of 3.5 Kpa (=3500 N/m^2) has also been done yielding a permeability value of k=3.9 10^{-10} m/s.

Test steps	**Settlement (mm)**	**c_v-coefficient (m^2/s)**	**m_v-coefficient (m^2/N)**	**k-permeability (m/s)**
1 (0-2 kpa) 2500 minutes	20.00-18.06	log t-method 5.2 10^{-10}	45 10^{-6}	2.3 10^{-10}
2 (2-3.6 kpa) 2500 minutes	18.05-17.32	log t-method 4.5 10^{-10} $t^{0.5}$-method 3.6 10^{-10}	24 10^{-6} 31 10^{-6}	1.1 10^{-10} 1.1 10^{-10}
3 (3.6-8.3 kpa) 2500 minutes	17.32-16.32	log t-method 5.5 10^{-10} $t^{0.5}$-method 4.5 10^{-10}	11 10^{-6} 13 10^{-6}	0.58 10^{-10} 0.58 10^{-10}
4 (8.3-16.2 kpa) 2500 minutes	16.32-15.43	log t-method 6.2 10^{-10} $t^{0.5}$-method 6.0 10^{-10}	6.3 10^{-6} 7.0 10^{-6}	0.38 10^{-10} 0.41 10^{-10}
5 (16.2-32 kpa) 2500 minutes	15.42-14.53	log t-method 7.9 10^{-10} $t^{0.5}$-method 7.9 10^{-10}	3.2 10^{-6} 3.4 10^{-6}	0.25 10^{-10} 0.26 10^{-10}
6 (32-63.6 kpa) 2500 minutes	14.53-13.60	log t-method 10.1 10^{-10} $t^{0.5}$-method 10.3 10^{-10}	1.8 10^{-6} 1.8 10^{-6}	0.17 10^{-10} 0.18 10^{-10}
7 (63.6-128.3 kpa) 2500 minutes	13.60-12.66	log t-method 12.9 10^{-10} $t^{0.5}$-method 13.3 10^{-10}	0.9 10^{-6} 0.9 10^{-6}	0.11 10^{-10} 0.11 10^{-10}
$\sum$loads= 2+3.6+8.3+16.2 +32+63.6+128.3 = 254 kpa		Weighted-average value of log t-method = (1/254) x (2x5.2+3.6x4.5+ +8.3x5.5+16.2x6.2+ +32x7.9+63.6x10.1+ +128.3x12.9) 10^{-10} = 11 10^{-10}	Weighted-average value of log t-method =(1/254)x (2x45+3.6x24+ +8.3x11+16.2x6.3+ +32x3.2+63.6x1.8+ +128.3x0.9) 10^{-6} = 3 10^{-6}	k= ρ_w g c_v m_v= 1020x9.81x 11 10^{-10}x3 10^{-6} =0.33 10^{-10}

Table 3.12 *Oedometer test results; Sample 2 Noordpolderzijl; mud after 3-4 months of natural consolidation; dry density of 700 kg/m³ (wet density of 1450 kg/m³)*

The TERZAGHI-consolidation model (Van Rijn, 2017) has been used to compute the end settlement of a layer with thickness of h=1 m with dry bulk density of 700 kg/m³ under an external load of q=100000 N/m² (about 10 ton/m²) using the expression;

s_{end} =-0,99 m_v q h= -0.99 x 3$\pm$1 10^{-6} x 100000 x 1 $\cong$ -0.2 to -0.4 m
s_{end}/h= 0.2 to 0.4 or 20% to 40%.

The time after which this settlement is completed is given by the expression (dewatering in upward direction only):
T_{end} = 0.5 h^2/c_v = 0.5x1^2/(11$\pm$4 10^{-10}) $\cong$ 3.5 to 7 10^8 s= 4000 to 8000 days (about 10 to 20 years).

Mud from Delfzijl (D-mud)

Mud samples from Delfzijl with initial dry density values of about 410 kg/m³ were used to perform a standard compressibility (Oedometer) test which gives information of the long term consolidation behaviour. Excess water was siphoned off. The base mud had a soft buttery-type of texture after a consolidation period of about 1 month. A ring with thickness of about 20 mm was filled with mud and subjected to an Oedometer test under a series of external loads. The results based on the Terzaghi-analysis method) are given in **Table 3.13**. The permeability is computed as: k=ρ_w g c_v m_v with ρ_w =1010 kg/m³.
After 7 steps consisting of 40 hours each with loading up to about 200 kpa (or 2.0 kg/cm²), the total settlement is about 6 mm which is about 30% of the initial value of 20 mm.
The compressibility m_v-coefficient decreases by a factor of about 50 to 100 between step 1 and step 7.

The k-value also decreases by a factor of 50 to 100 between step 1 and 7. As the sample is more compressed/compacted, the permeability (k-value) increases. The mud from Delfzijl has a slightly smaller permeability (in the end phase) as the percentage of sand is larger.
The consolidation time scale for D-mud is 5 to 10 years, because the c_v-coefficient is much smaller.

Sample	**Maximum loading (N/m^2)**	**Total settlement (mm)**	**Dry and wet density (kg/m^3) and percentage sand (%)**	**c_v-coefficient (m^2/s)**	**m_v-coefficient (m^2/N)**	**k-permeability (m/s)**
N-mud (sample 3)	$202\ 10^3$	20.07-13.75 = 6.26 (31,3%)	initial=760; 1490 end= 1115; 1525 ps=40%	initial= $200\ 10^{-10}$ middle= $90\ 10^{-10}$ end= $120\ 10^{-10}$	initial= $22\ 10^{-6}$ middle= $2\ 10^{-6}$ end= $0.4\ 10^{-6}$	initial= $42\ 10^{-10}$ middle= $2\ 10^{-10}$ end= $0.5\ 10^{-10}$
D-mud (sample 1)	$201\ 10^3$	20.03-13.70=6.33 (31.6%)	initial=410; 1265 end= 940; 1515 ps= 20%	initial= $20\ 10^{-10}$ middle= $20\ 10^{-10}$ end= $15\ 10^{-10}$	initial= $80\ 10^{-6}$ middle= $50\ 10^{-6}$ end= $1\ 10^{-6}$	initial= $15\ 10^{-10}$ middle= $1\ 10^{-10}$ end= $0.2\ 10^{-10}$

Table 3.13 *Oedometer results of Noordpolderzijl-mud (N-mud) and Delfzijl-mud (D-mud)*

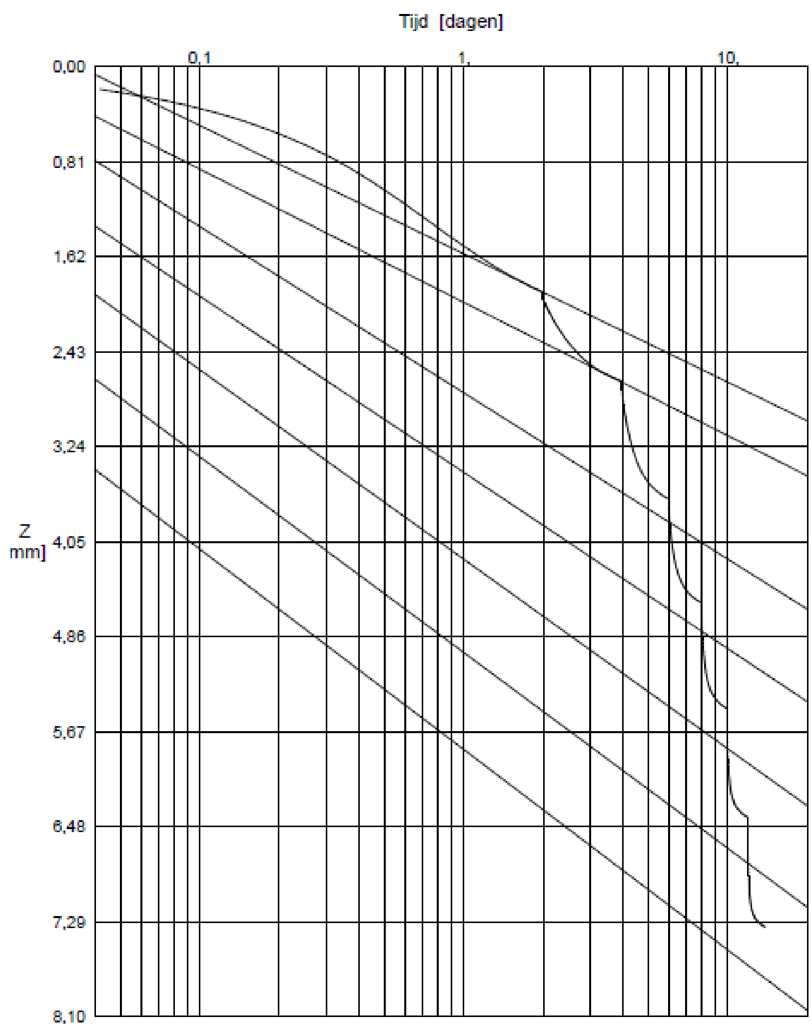


Figure 3.20 *Settlement (mm) as function of time (days); Sample 2 Noordpolderzijl*

4. EROMES calibration tests of HANZE Technical School

4.1 Flume test results with sand beds

4.1.1 Basic data of flume tests

The basic data of the sand bed flume tests are presented in **Table 4.1**.
Two methods have been used to determine the bed-shear stress, as follows (see **Table 4.1**):

- using $\tau_b = \rho\,(u_*)^2$ with u_* from the fit of the measured velocities by a logarithmic function $u_z/u_* = \kappa^{-1}\ln(z/z_o)$ with u_z= measured flow velocity at height z, $z_o = 0.11\upsilon/u_* + k_s/30$= zero velocity level, u_*= bed-shear velocity, κ= coefficient Von karman (=0.4), τ_b = bed-shear stress, ρ= fluid density, k_s=equivalent roughness of Nikurade; υ=kinematic viscosity coefficient;
- using $\tau_b = \rho\, g\, (u_{mean}/C)^2$ and C= Chézy coefficient = $5.75g^{0.5}\log(12h/k_s)$, u_{mean}=depth-averaged flow velocity and $k_s = 1d_{50}$-$2d_{50}$.

Figure 4.1 shows the measured bed-shear stress values of method 2 of Stages S2, S3 and S4 for the five sediment beds (d_{50}= 0.18, 0.37, 0.52, 0.74 and 1.8 mm). The critical bed shear stresses of the Shields curve are also shown (**red** values). The Shields curve data are between Stage S2 (10% moving) and S3 (50% moving) for the coarser beds (d_{50}> 0.35 mm). It has been noticed by others (Van Rijn 1993) that the Shields curve is most representative for a stage of movement defined as frequent particle movement at nearly all locations. Based on the present data, the Shields curve is equivalent with a transport stage of about 30% moving particles. All measured bed shear stress values of the fine bed of 0.18 mm are smaller than the Shields bed-shear stress, which is an indication that the Shields curve is not really valid for fine sediments as noticed by many other researchers (Van Rijn, 1993).

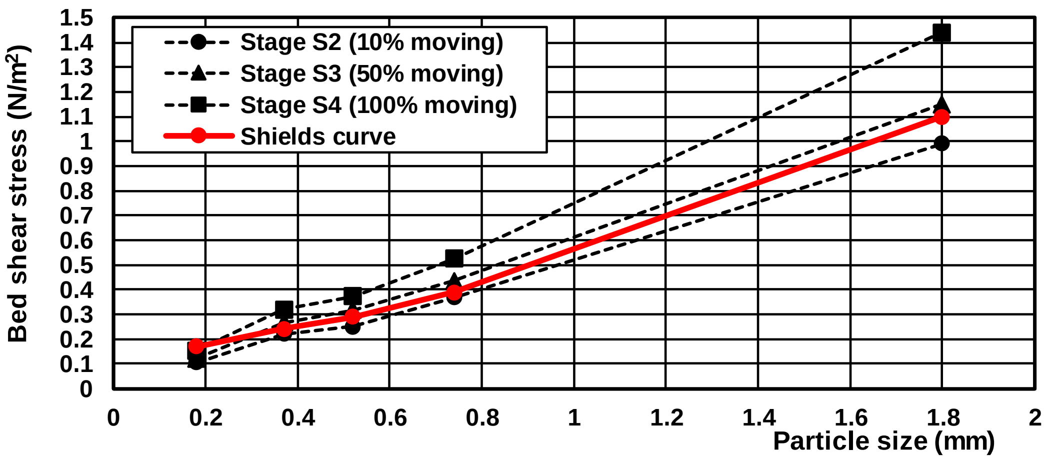


Figure 4.1 *Bed shear stress based on Chézy-coefficient compared with critical bed-shear stress according to Shields for different sand beds*

4.1.2 Flow velocity profiles

Flow velocity profiles using the vectrino-sensor were only measured for the test with 0.18 mm sand.
Figure 4.2 shows measured velocity profile data for 0.18 mm-sand. The data can be represented by a logarithmic velocity function with fitted parameters: u_*=0.0109 m/s; k_s=0.00017 m; κ=0.4; υ=0.00000105 m²/s. The fitted k_s-value is equal to 0.00017 m, which is in good agreement with the sand roughness of the fixed flume bottom (d_{50}= 0.0002 m).

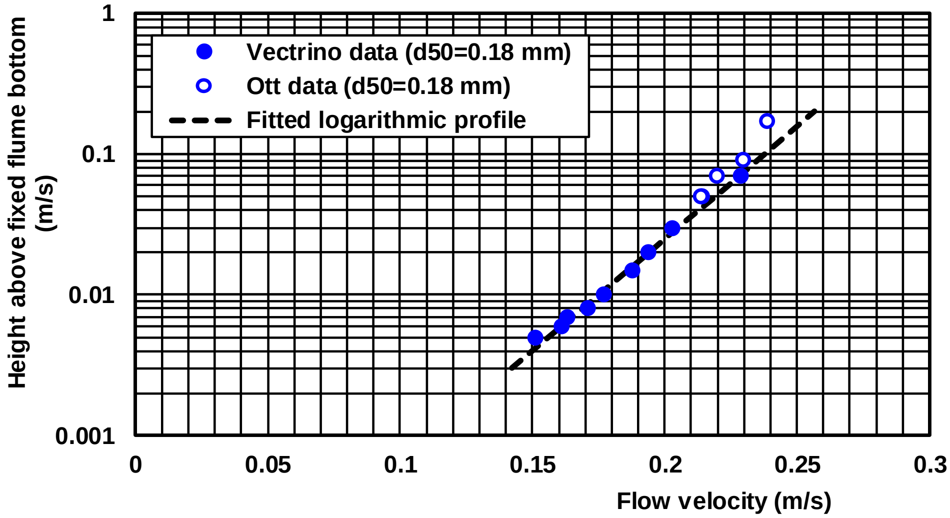


Figure 4.2 *Measured velocity profiles at the fixed flume bottom (with sand roughness)*

Parameter	**Sand B; d_{50}=0.18 mm**			**Sand C; d_{50}=0.35 mm**			**Sand D; d_{50}=0.52 mm**		
	S2 (10%)	**S3 (50%)**	**S4 (100%)**	**S2 (10%)**	**S3 (50%)**	**S4 (100%)**	**S2 (10%)**	**S3 (50%)**	**S4 (100%)**
Water depth (m)	0.2	0.195	0.195	0.205	0.205	0.205	0.205	0.21	0.2
Depth-mean vel. (m/s)	0.226	0.242	0.272	0.301	0.331	0.362	0.307	0.346	0.374
Bed forms	IR	IR	IR	IR	IR	R	IR	R	R
Bed load tr. (g/m/s)	0.0029	0.002	0.021	0.0036	0.0078	0.089	0.0098	0.031	0.0634
Bed roughness k_s (m) from velocity profile	0.00017	0.00009	0.00006	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
Critical bed-shear stress (N/m^2) Method 1	0.0109	0.12	0.097	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
Critical bed-shear stress (N/m^2) Method 2	0.106 (68.8)	0.121 (68.8)	0.153 (68.8)	0.221 (63.4)	0.267 (63.4)	0.32 (63.4)	0.251 (60.7)	0.318 (60.7)	0.372 (60.7)
Critical bed-shear stress Shields (N/m^2)	0.17			0.23			0.29		

Parameter	**Sand E; d_{50}=0.74 mm**			**Sand F; d_{50}=1.8 mm**		
	S2	**S3**	**S4**	**S2**	**S3**	**S4**
Water depth (m)	0.2	0.195	0.2	0.17	0.195	0.19
Depth-mean velocity (m/s)	0.354	0.385	0.422	0.5	0.55	0.61
Bed forms	None	None	None	None	None	None
Bed load transport (gram/m/s)	0.014	0.088	0.771	0.055	1.34	2.9
Bed roughness k_s (m)	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
Critical bed-shear stress (N/m^2) Method 1	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.
Critical bed-shear stress (N/m^2) Method 2	0.369 (57.7)	0.436 (57.7)	0.524 (57.7)	0.99 (49.6)	1.15 (50.6)	1.44 (50.4)
Critical bed-shear stress Shields (N/m^2)	0.39			1.1		

n.m.= not measured; IR=Isolated Ripples 5 to 10 mm

S1= Stage 1= few particle moving; ; S2= Stage 2= 10% of bed surface moving;

S3= Stage 3= 50% of bed surface moving; S4=Stage 4= 100% of bed surface moving

Method 2 (Chézy-coefficient using k_s=1d_{50}-2d_{50} between brackets (m$^{0.5}$/s))

Table 4.1 *Basic data of flume tests with sand beds*

4.1.3 Bed load transport data

The bed load transport data derived from the sand particles accumulating in the slot downstream of the sand bed are shown in **Figures 4.3** and **4.4**. **Figure 4.5** shows ripple generation in the tests with fine sand (d_{50}= 0.1 mm).

Figure 4.3 shows the bed load transport as function of the depth-mean velocity. The bed load transport of the very fine particles of 0.1 mm (Asser-sand) is strongly underestimated at higher velocities, because the fine particles are partly washed over the slot. The bed load transport increases strongly with increasing velocities. Based on the present data, it is found that: $q_b \sim u_{mean}^{10}$ for velocities between 0.3 and 0.4 m/s.

Figure 4.4 shows the dimensionless transport parameter $T = q_b/[\rho_s(\rho_s/\rho-1)^{0.5} g^{0.5} d_{50}^{1.5}]$ on the vertical axis as function of the dimensionless Shields parameter $\theta = \tau_{b,method3}/[(\rho_s-\rho)gd_{50}]$ on the horizontal axis. The bed load transport data of Paintal 1971 are also shown for comparison. The present data are somewhat larger than those of Paintal who used coarser sediments (2.5, 8 and 22 mm).

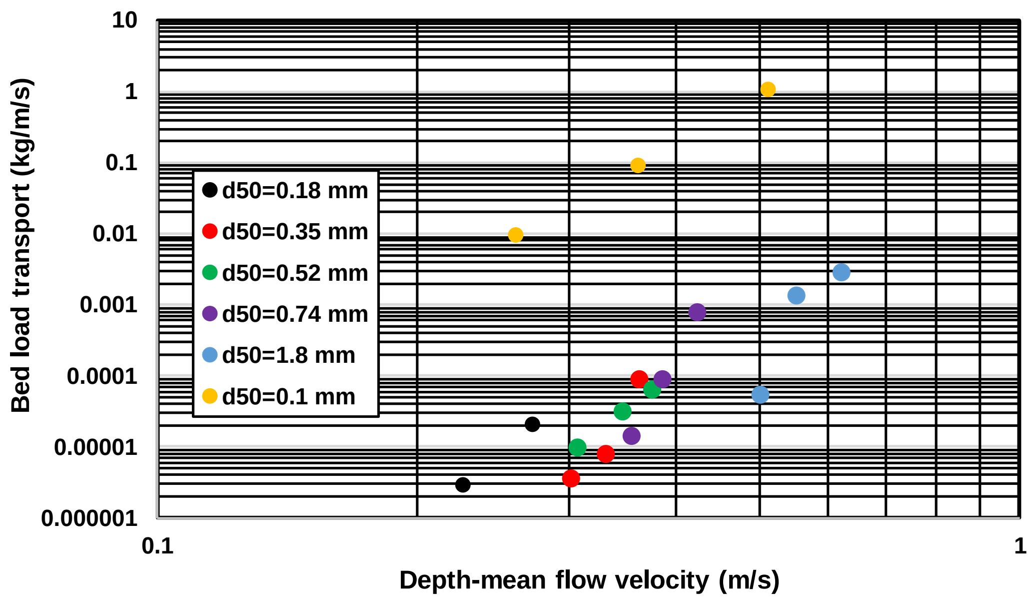


Figure 4.3 *Bed load transport as function of depth-mean velocity*

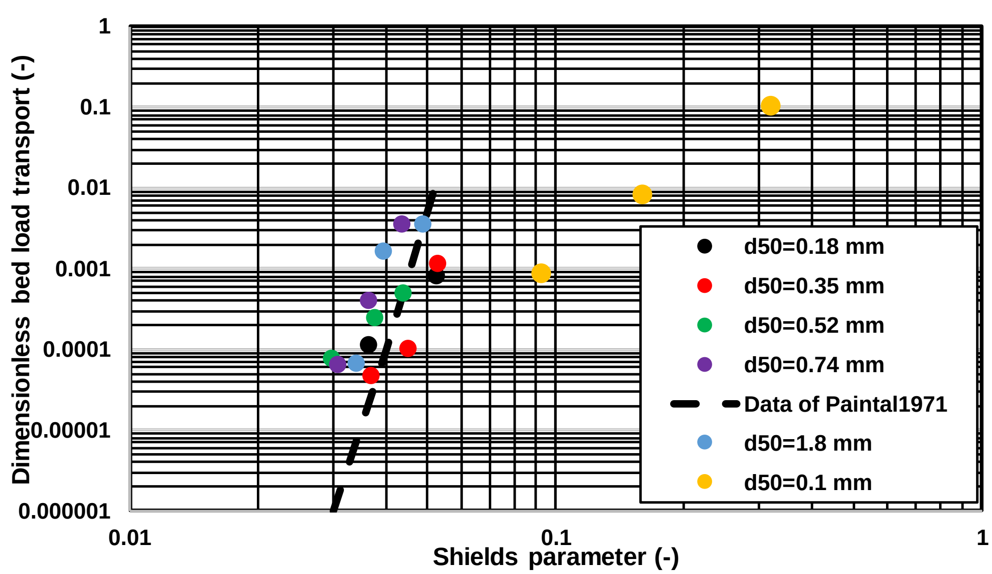


Figure 4.4 *Dimensionless bed load transport as function of dimensionless bed-shear stress (Shields parameter)*

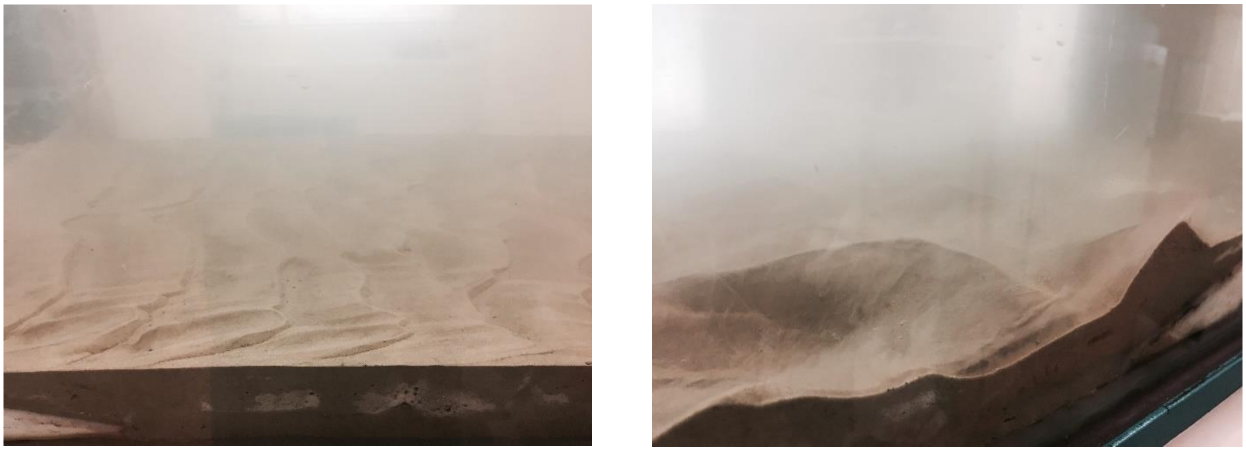


Figure 4.5 *Ripple generation along sand bed with d_{50}= 0.1 mm (Asser sand); depth-mean velocity v=0.3 m/s (left) and v=0.4 m/s (right)*

4.2 EROMES tests with sand beds

4.2.1 Bed shear stresses of rough sand beds

The six sand beds (thickness of about 5 cm and a flat surface) have also been tested in the EROMES-instrument. The propeller was set to 30 mm above the bed and the propeller speed (revolutions per minute) was increased until particle movement S1, S2, S3 and S4 was observed visually by two persons. The basic data are shown in **Table 4.2**.

Figure 2.8 shows the measured propeller speed as function of the grain size for the Stages S1 (some grains moving) and S2 (10% moving). The data match very well with the earlier GKSS data.

Figure 4.6 shows the bed shear stress values of Stages S2 (yellow open dots), S3 (red open dots) and S4 (purple open dots) as function of the propeller speed of the EROMES-instrument. All present results (HTS) can be represented by the **solid red curve**, which is the calibration curve (HTS) for rough sediment beds.

The calibration curve (**green solid curve**) for rough beds used by GKSS is also shown. This latter GKSS calibration curve yields relatively high values above the Shields calibration curve and yields much larger values (factor 1.5 to 2) than the calibration curve of HTS. The hot film calibration curve is only valid for very smooth bed surfaces.

Parameter	**Sand A; d_{50}=0.1 mm**				**Sand B; d_{50}=0.18 mm**				**Sand C; d_{50}=0.35 mm**			
	S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**
Number of revolutions per minute	80	90	100	110	70	80	100	120	90	110	130	150

Parameter	**Sand D; d_{50}=0.52 mm**				**Sand E; d_{50}=0.74 mm**				**Sand F; d_{50}= 1.8 mm**			
	S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**
Number of revolutions per minute	110	140	170	200	120	150	180	210	210	260	300	330

S1= Stage 1= few particle moving; ; S2= Stage 2= 10% of bed surface moving;
S3= Stage 3= 50% of bed surface moving; S4=Stage 4= 100% of bed surface moving

Table 4.2 *Basic data of EROMES tests with sand beds*

4.2.2 Bed shear stresses of smooth mud beds

The EROMES-instrument is designed to determine the critical bed-shear stress of smooth mud beds. It is most logic to assume that the relationship (curve) of bed-shear stress against revolutions for a smooth mud bed will lie between the curves for a rough sand bed and a smooth (perspex) wall, see **Figure 4.6**.
Two flume tests with a mud bed have been done to determine the critical bed-shear for initiation of erosion of a mud bed. These data sets are discussed in **Section 5.2.1** and **5.2.2**.
Based on the data of the two mud flume tests (see **Section 5.2.2**), a tentative calibration curve (propeller at 30 mm above the bed surface) for mud beds is proposed, which reads as (see **brown curve** of **Figure 4.6**):

$$\tau_{bed,\,mud} = 0.00000001\ N_p^3 + 0.000005\ N_p^2 + 0.0006\ N_p + 0.0029$$

with N_p= number of propeller revolutions per minute.
At some tests with the fine sand surface (d_{50}= 0.11 mm), the propeller was placed at 10 mm above the surface. The fine sand particles were set in motion at a N_P-value which was about 20% smaller.
Based on this, the bed-shear stress is estimated to be about 40% higher at the same N_p-value (with propeller at 10 mm above bed surface).

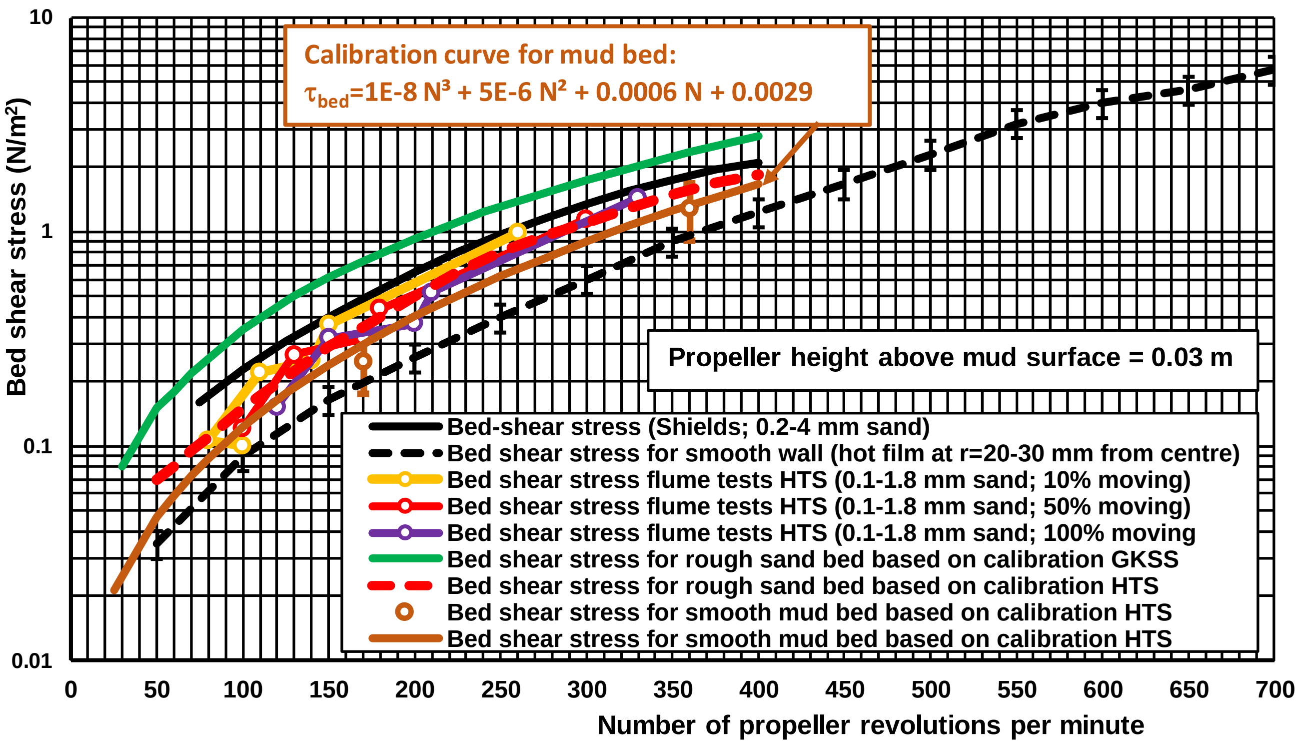


Figure 4.6 *Bed-shear stress generated by propeller flow of EROMES (propeller at 30 mm above bed surface)*
Bed-shear stress is 40% higher if propeller is at 10 mm above surface (at same N_p-value)

5. Erosion test results of moulded mud beds; critical bed-shear stresses of mud beds

5.1 Introduction and definitions

This chapter 5 describes the results of the erosion tests with moulded and unmoulded (undisturbed) mud-sand beds.
The moulded beds are beds made in the laboratory using natural and artificial mud-sand mixtures (Section 5.2 and 5.3).
The unmoulded beds (Section 5.4) are beds taken as slices of mud-sand (using a tray) from the natural tidal channel near Noordpoldderzijl and tested in the laboratory (flume and Eromes).

Once, sediment is eroded from the bed (flume or Eromes), the sediment concentration of the water will increase in time.

The sediment concentration (c_{mud} in kg/m^3) in the system (Eromes or flume) can be computed as:

$$c_{mud}= e_{mud}\ \Delta t\ A_s/V_w = (\rho_{dry}\ \delta_e/\Delta t)\ (\Delta t\ A_s/V_w)= \rho_{dry}\ \delta_e\ A_s/V_w =\rho_{dry}\ \delta_e/h_w \qquad (5.1.1)$$

with: $e_{mud} = \rho_{dry}\ \delta_e/\Delta t = h_w\ \Delta c_{mud}/\Delta t$ = erosion rate (kg/m^2/s),
Δt= elapsed time period (s), A_s= surface area of bed (m^2), $h_w= A_s/V_w$ = water depth (Eromes),
V_w= water volume (m^3), ρ_{dry} = dry mud density (kg/m^3), δ_e = thickness (m) of eroded bed layer after Δt.

An erosion rate of e_{mud}= 0.1 gram/m^2/s is approximately equivalent with an eroded layer of about 1 mm in 1 hour. This value can be used as the threshold erosion rate to define the critical shear stress for erosion.

EROMES example:
ρ_{dry} = 300 (kg/m^3), δ_e = 0.001 m (1 mm) after 1 hour, A_s= 0.008 m^2, V_w= 0.002 m^3 (2 liter) yields: c_{mud}= 1.2 kg/m^3=1200 mg/l.
If it takes 1 hour to erode a layer of 1 mm, the erosion rate is: e_{mud}= 300x0.001/3600=0.0001 kg/m^2/s= 0.1 gr/m^2/s.

FLUME example:
ρ_{dry} = 300 (kg/m^3), δ_e = 0.001 m (1 mm) after 1 hour, A_s= 0.4x0.6=0.24 m^2, V_w= 5 m^3 (5000 liter in pump reservoir) yields: c_{mud}= 0.024 kg/m^3= 24 mg/l; hence, the mud concentration in the water supply system will be about 20 to 25 mg/l.
If it takes 1 hour to erode a layer of 1 mm, the erosion rate is: e_{mud}= 300x0.001/3600=0.0001 kg/m^2/s= 0.1 gr/m^2/s.

The erosion rate depends on the applied bed-shear stress, the dry density of the mud, the sediment composition of the mud (percentage of clay, silt and sand; percentage organic materials).
The dimensionless erosion rate is defined as: $E= e_{mud}/(\rho_{dry}\ w_{mud,max})$ (5.1.2)
The dimensionless bed-shear stress rate is defined as: $T= (\tau_b - \tau_{b,cre})/\tau_{b,cre}$ (5.1.3)

with: e_{mud}= erosion rate (kg/m^2/s); ρ_{dry} = dry bulk density of mud (kg/m^3); $w_{mud,max}$= maximum settling velocity of mud (m/s); τ_b = bed-shear stress (N/m^2), $\tau_{b,cre}$= critical bed-shear for erosion (N/m^2).

5.2 Erosion tests of moulded mud beds

5.2.1 Noordpolderzijl mud; initial dry mud density of 685 kg/m^3 (November-December 2016)

Flume test F-N685-ps35%

The initial dry mud density of the base Noordpolderzijl-mud container (saline mud) is about ρ_{dry}= 685 kg/m^3 and percentage of sand is 35%. The mud of the base container is moulded (mixed) first and a bucket of mud is taken to fill the mud compartment of the flume. Based on this, the dry mud density of the mud bed with a thickness of about 50 mm is assumed to be about 685 kg/m^3. The bed surface is made flush with the upstream and downstream bottom sections by scraping a woooden stick in sideward direction. The excess mud was carefully removed and the glass windows were cleaned, see **Figure 5.2.1**. The time between the preparation of the mud bed and the start of the test was about 18 hours (overnight consolidation). Initially, the mud surface was black, but a very thin (0.1 mm) grey film layer of mud was formed at the bed surface. No thin fluffy surface layer was present, as often observed at field sites.
The Vectrino velocity sensor and the NEP152 optical sensor were installed above the rigid flume bottom at about 0.1 m from the mud bed section, see **Figure 5.2.1**. The NEP152 sensor did not function properly in the flume.
The velocity of the fresh water flow was raised in steps from 0.25 m/s to 0.85 m/s to observe the behaviour of the mud bed surface, see **Table 5.2.1**. Minor mud erosion was only observed at both transition zones to the rigid bed, where the mud bed surface was somewhat more irregular. The mud surface became black at the erosion spots (removal of thin grey mud film), see **Figure 5.2.1 Right Lower**. The erosion area was about 0.15 m in length and approximately uniform over the width (0.4 m) of the flume. The maximum erosion depth close to the rigid bed was about 3 mm decreasing to about 0 mm at 0.15 m from the rigid bed resulting in a mean erosion depth of about 1.5 mm.
The total erosion volume after the test of 2 hours is about 2x0.4x0.15x0.0015= 0.00018 m^3 or 0.18 liter.
Given a dry density of 685 kg/m^3, this yields an eroded mass of 0.123 kg after 2 hours or an erosion rate per unit area of E_{mud}= 0.123/0.12/7200 = 0.000143 kg/m^2/s = 0.15 gr/m^2/s at both transition zones. The erosion rate in the middle section of the mud bed is much less (factor 10 to 20). The eroded surface layer is of the order of 0.1 mm or 100 μm. The eroded mass of about 120 grams consists of mud, silt and sand particles eroded from the top layer of 0.1 to 1 mm at the transition sections. The eroded silt and sand particles were partly trapped in the slot downstream of the mud section. The trapped particles were removed at two time moments. The trapped sediment consisted of very fine silt and sand in the range of 30 to 100 μm. The bed load transport rates are of the order of 0.001 gr/m/s, which is extremely small.
At the end of the flume test, a mud sample was taken in the middle of the mud section from the top layer with a thickness of about 1 cm. The dry mud density was 615 kg/m^3 (wet density of 1402 kg/m^3), which is about 10% smaller than that of the base mud container.
The complete test was reapeated using the same mud conditions, except the overnight consolidation period. The mud bed was prepared and the test was immediately started. The grey mud film was not present. Everywhere, the mud surface was black. The erosion results are similar to those reported in **Table 5.2.1**.

Based on the results of this test, the critical bed-shear stresses for a mud bed with dry density of about 685 kg/m^3 are assumed to be:

- initiation of surface erosion of sand (minor bed load transport); $\tau_{b,cr,e}$ = 0.5-0.8 N/m^2;
- initiation of surface erosion of mud; $\tau_{b,cr,e}$ = 1-1.5 N/m^2.

Figure 5.2.1 *Mud bed in flume (initial dry density of about 685 kg/m³); fresh water in flume; Left= before the test; Upper-right = before the test; Lower-right Lower= during the stest*

Time (hrs)	Mean flow velocity (m/s)	Water depth (m)	Bed-shear stress N/m²	NEP152 values	Mud concentration (mg/l)	Erosion of bed surface	Bed roughness; Chézy (mm) ($m^{0.5}/s$)	Bed load transport (g/m/s)
11.45	0.25 no v.p.	0.2	0.09 0.13	n. m.	< 10	clear water; no surface erosion in middle of mud section; rolling particles (silt-sand 30-100 μm)	0.1-0.3 (80-70)	0.0002 (measured over 1 hour)
12.45	0.33 v.p.	0.2	0.17 0.22	n. m.	< 10	clear water; no surface erosion in middle of mud section; rolling particles (silt-sand 30-100 μm), but less	0.1-0.3 (80-70)	
12.55	0.5 no v.p.	0.2	0.38 0.56	n.m.	< 50	almost clear water; no surface erosion in middle of mud section; erosion at both transition zones to rigid bed (1 to 2 mm); rolling particles (silt-sand 30-100 μm)	0.1-0.5 (80-66)	0.0015 (over 40 min.)
13.35	0.55 v.p.	0.2	0.46 0.68	n.m	< 50			
13.40	0.78 no v.p.	0.15	1.0 1.5	n.m.	< 50	almost clear water; no general surface erosion in middle of mud section; erosion at both transition zones to rigid bed (1-3 mm); rolling particles (silt-sand 30-100 μm)	0.1-0.5 (77-64)	n.m.
13.50	0.85 no v.p.	0.13	1.25 1.80	n.m.	< 50		0.1-0.5 (75-63)	n.m.

n.m.= not measured; v.p. = velocity profile measured in 10 points; water temperature≅ 15° C

Table 5.2.1 *Erosion tests with mud bed in flume (dry mud density= 685 kg/m³); fresh water*

EROMES-test E-N685-ps35%

The initial dry mud density of the base Noordploderzijl mud container is about ρ_{dry}= 685 kg/m^3 (percentage of sand =35%). The mud of the base container is mixed first and a bucket of mud is taken to fill a small wooden frame with mud (the frame is covered with plastic sheet; frame surface area of 15x15 cm^2; thickness of frame =50 mm, see **Figure 5.2.2**). The mud surface is scraped horizontal by moving a wooden stick over the frame. The perspex tube is pushed vertically into the mud surface of the frame. Then, the frame is taken away (dismantled) and the excess mud is removed from the plastic sheet. After that, the plastic sheet is cut circular and taped (ductape) around the perspex tube to prevent any leakage through the mud layer in the EROMES-tube. The tube is partly filled by spraying seawater over a height of about 1 to 2 cm above the mud surface.

The time between the preparation of the mud bed in the tube and the start of the test was about 16 hours (overnight consolidation). Initially, the mud surface was black, but a very thin (0.1 mm) grey film layer of mud was formed at the bed surface. No thin fluffy surface layer was present, as often observed at field sites. The mud surface in the middle of the tube was about 3 to 5 mm higher than at the sides.

Just before the test, the tube was carefully filled with seawater (about 2 liter). The propeller was installed at the prescribed 30 mm above the mud surface. The NEP152 optical sensor was mounted with its sensor at 80 mm from the mud surface.

The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 50 to the maximum value of 360 to observe the behaviour of the mud bed surface, see **Table 5.2.2**. The total test duration was about 1.5 hours. No surface erosion was observed during the test. The propeller jet was not able to cause any significant erosion. The maximum mud concentration was estimated to be about 50 m/l (almost clear water). This value is equivalent with an eroded mud layer of 0.1 mm (100 μm). Fine silt and sand particles have been eroded from the top surface layer with a thickness of about 0.1 m (100 μm). As no more mud was eroded, the amount of fine silt and sand particles in the tube was very limited.

Based on the results of this test, it is assumed that the mud bed surface with dry density of 685 kg/m^3 is eroded for $N_P \geq 360$. Herein, it is assumed that this is equivalent with a critical bed-shear stress of surface erosion $\tau_{b,cr,e} \geq 1.3$ N/m^2 for a mud bed with dry density of 685 kg/m^3 (Flume test F685).

Thus: $N_P \geq 360$ of EROMES-test is equivalent with $\tau_{b,cr,e} \geq 1.3$ N/m^2 of the flume test, see data point (brown open circle) of **Figure 4.7**.

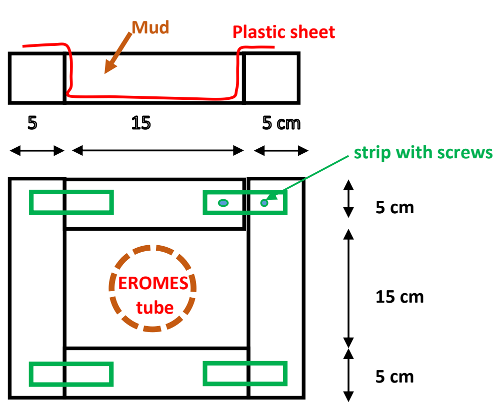


Figure 5.2.2 *Wooden frame for mud bed of EROMES-test*

Number of revolutions (N_P) per minute	Mud concen tration (mg/l)	Erosion of bed surface	Estimated bed-shear stress (N/m²)
50-70	< 10	clear water; no mud erosion of surface; rolling and suspended particles (silt-sand 30-100 μm) eroded from top surface layer	<0.1
70-100	< 10	similar	0.1 ±0.05
100-150	< 10	similar	0.2 ±0.1
150-200	< 30	similar	0.35 ±0.15
200-250	< 50	similar	0.4 ±0.2
250-300	< 50	similar	0.7 ±0.3
300-360	< 50	similar	1.0 ±0.4
360	< 50	similar	1.3 ±0.4

Table 5.2.2 *Erosion results of EROMES test E-N685; dry bulk density=685 kg/m³ (seawater)*

5.2.2 Noordpolderzijl mud; initial dry mud density of 325 kg/m³ (November-December 2016)

Flume test F-N325-ps35%

The mud of the base Noordpolderzijl mud container (about ρ_{dry}= 685 kg/m³; p_{sand}=35%) was mixed first and a mud mixture of about 300 kg/m³ was made in a bucket. A mud layer with a height of 0.07 m was made in the mud compartment (maximum depth of 0.05 m) of the flume which was enclosed by temporary woorden walls on both sides. After a consolidation period of 20 hours (overnight) the mud layer thickness was about 0.06 m, which was about 0.01 m above the surrounding flume bottom. Based on this, the dry bulk density of the mud layer is about 7/6x300=350 kg/m³. The excess mud layer of 0.01 m was removed by scraping horizontally in downstream direction using a window wiper. This resulted in a flat horizontal mud surface flush with the flume bottom, see **Figure 5.2.3**.

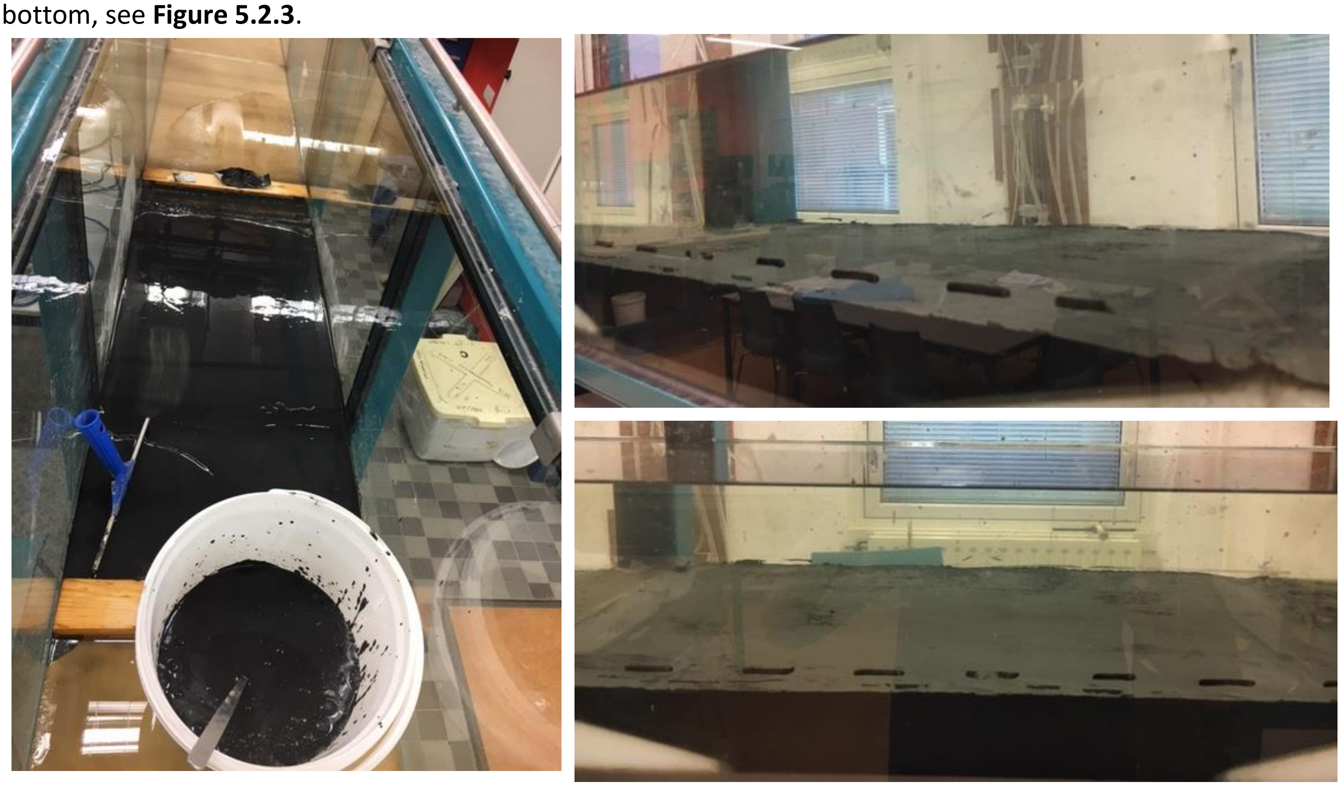


Figure 5.2.3 *Mud bed in flume (initial dry density of about 325 kg/m³); fresh water in flume; Test F325*
Left = mud surface preparation; Right= mud surface just before the test

Time (hrs)	Mean velocity; velocity at 1 cm above bed (m/s)	Water depth (m)	Bed-shear stress N/m²	Mud concen tration OBS3+ (mg/l)	Erosion of bed surface	Bed rough ness; Chezy (mm) ($m^{0.5}$/s)	Bed load tran sport of fine sand (g/m/s)
13.42/ 13.58	0.205; n.m.	0.2	0.05/ 0.08	<10	small particles are eroded locally near irregulariteis	0.03-0.3; 90-70	n.m.
14.10/ 14.50	0.306; 0.247; v.p.	0.2	0.12/ 0.18	<50	small erosion pits/grooves are generated; mud layer in middle part is wavy due to pressure fluctuations; layer is not wavy at transitions	0.03-0.3; 90-70	0.0005
14.53/ 15.32	0.325; 0.258; v.p.	0.2	0.15/ 0.21	<50	mud grooves grow larger in length; flakes are eroded from surface	0.05-0.3; 85-70	0.001
15.36/ 16.13	0.35; 0.30; v.p.	0.2	0.16/ 0.25	<50	more grooves are generated; mud clouds are generated from the grooves;	0.05-0.3; 85-70	0.003
16.15/ 16.55	0.39; 0.30; v.p.	0.2	0.19/ 0.30	<50	many grooves (70% of surface); upper grey film layer is almost completey removed; grooves are 4 to 5 mm deep; mud clouds eroded from grooves; erosion rate=0.1-1 gr/m²/s	0.05-0.3; 85-70	0.01
16.59	0.45	0.18	0.30/ 0.40	100	many mud clouds from grooves	0.1-0.3; 80-70	n.m.
17.02	0.47	0.18	0.35/ 0/45	150	many mud clouds from grooves; grooves are 10 mm deep; visiblility decreases; erosion rate= 1 gr/m²/s	0.1-0.3 80-70	n.m.
17.06	0.50	0.18	0.5	200	many mud clouds from grooves; grooves are 10 mm deep; mud grooves not visible anymore; erosion rate = 1 gr/m²/s	0.3; 70	n.m.
17.13/ 17.20	0.59	0.18	0.6	250-500	mud layer is eroded away over 10 to 30 mm in the middle of test section; mass erosion of about 5 to 10 gr/m²/s	0.3; 70	

n.m.= not measured; v.p. = velocity profile measured in 10 points; water temperature≅ 15° C

Table 5.2.3 *Erosion flume tests with mud bed (dry mud density= 325 kg/m³); fresh water*

A mud sample was taken from the mud surface layer (upper 0.01 m) by moving a small cup through the mud. The small pit created by the cup was filled slowly by the surrounding mobile mud
The wet bulk density of the mud surface sample was 1260 kg/m³ resulting in a dry bulk density of 380 kg/m³.
The time between the preparation of the mud surface and the start of the test was about 2 hours.
Initially, the mud surface was black, but a very thin (0.1 mm) grey film layer of mud was formed at the bed surface. No thin fluffy surface layer was present, as often observed at field sites.
The Vectrino velocity sensor, the NEP152 and OBS3+ optical sensors were installed above the rigid flume bottom at about 0.1 m from the mud bed section. The NEP152 sensor did not function properly in the flume.

The velocity of the fresh water flow was raised in steps from 0.2 m/s to 0.6 m/s to observe the behaviour of the mud bed surface, see **Table 5.2.3**. Long and narrow grooves were generated in the mud bed surface at a mean velocity of about 0.32 m/s, see **Figure 5.2.4**. These grooves extended gradually in length and in width. About 80% of the mud surface was covered with grooves at a mean velocity of 0.4 m/s. Mud clouds were eroded from the grooves. The erosion rate from the grooves is about 0.1-1 gr/m^2/s at a mean velocity of 0.4. The erosion rate (mass erosion) increases to about 5 to 10 gr/m^2/s at a mean velocity of 0.6 m/s

Based on the results of this test, the critical bed-shear stresses for a mud bed with dry density of about 325 kg/m^3 are estimated to be about:

- initiation of surface erosion of sand (minor bed load transport); $\tau_{b,cr,e}$ = 0.2-0.25 N/m^2;
- initiation of surface erosion of mud (erosion rate <0.1 gr/m^2/s); $\tau_{b,cr,e}$ = 0.25-0.35 N/m^2;
- initiation of mass erosion of mud (bed failure); $\tau_{b,cr,e}$ = 0.5-0.7 N/m^2.

Figure 5.2.4A *Upper= velocity of 0.3 m/s; Middle= velocity of 0.4 m/s; Lower= mud clouds at velocity=0.45 m/s*

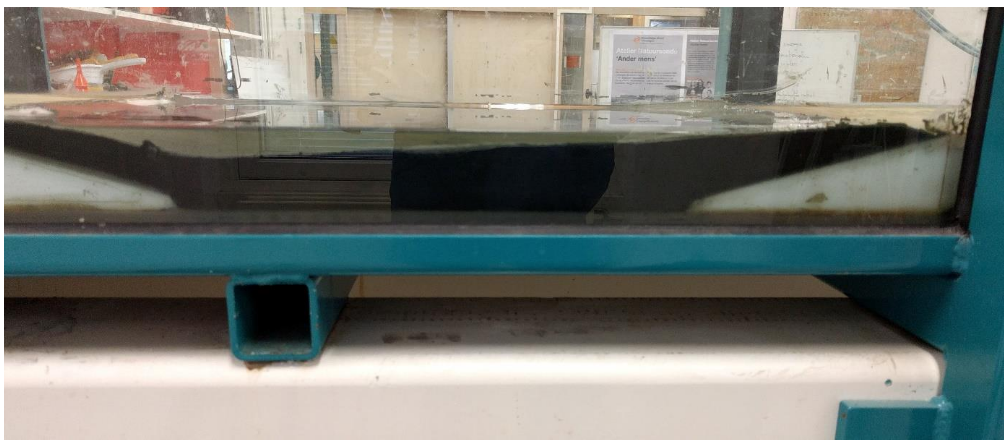


Figure 5.2.4B *Mud bed (top and side view) after test; erosion caused by velocities between 0.45 m/s and 0.6 m/s; scour in middle of test section of about 2 to 3 cm; Test F325-ps35%*

EROMES-test E-N350-ps35% and E-N400-ps35%

The Noordpolderzijl mud of the base container with dry mud density of about ρ_{dry}= 685 kg/m^3 is mixed first and mud concentrations (dry density) of about 200 and 300 kg/m^3 have been made in two buckets. The mixtures from the buckets were poured into two EROMES-tubes. The mixture in each tube was stirred to create an homogeneous suspension and the EROMES-tubes were allowed to settle/consolidate for two days (about 45 hours). After the EROMES-tests, the suspended mud in the tubes was allowed to settle for 1 hour and small mud samples using a 50 ml pipet were taken from the upper 1 to 2 cm of the mud layer. The basic data of the dry and wet densities are given in **Table 5.2.4.** The depth-averaged dry bulk density of the mud layer varies in the range of 350 to 400 kg/m^3. The dry density of the top layer (layer of 1 to 2 cm) varies in the range of 140 to 200 kg/m^3. Andersen (2001) reports dry density values of 200 to 400 kg/m^3 for the topmost 5 mm (taken by a 20 ml-syringe) of the mud layer for various field samples of the Danish Wadden Sea.

Test	Initial mud concen tration (kg/m^3)	Initial mud suspension height in EROMES-tube (cm)	Mud height after 2 days in EROMES-tube (cm)	Height of water column above mud surface (cm)	Dry bulk density of mud layer after 45 hours (kg/m^3)	Wet and dry bulk density based on pipet-sample of upper 2 cm after after the test (kg/m^3)
E400	200	24.8	12.6 (51%)	12.2	24.8/12.6x200 ≅ 400	1110; 140
E350	300	25.5	21.9 (86%)	3.6	25.5/21.9x300 ≅ 350	1150; 200

Table 5.2.4 *Wet and dry bulk density of mud layer in EROMES-tube; Tests E-N350-ps35% and E-N400-ps35%*

After consolidation of 2 days, the mud surface has a thin grey film on top of it (0.1 to 1 mm thick). No thin fluffy surface layer was present, as often observed at field sites. The height of the water column was sufficient in test E400. The water column height was too small in test E350 and seawater was supplied carefully to get a height of about 0.15 m above the mud surface. During filling, small mud flakes < 5 mm were dislodged from the grey mud film.

The propeller was installed at the prescribed 30 mm above the mud surface. The NEP152 optical sensor was mounted with its sensor at 80 mm from the bed surface.

The number of propeller revolutions (N_P) was raised in steps (10 to 20) from 50 onwards to observe the behaviour of the mud bed surface, see **Tables 5.2.5, 5.2.6** and **Figures 5.2.5, 5.2.6**. The total test duration for each tube was about 20 minutes.

The cumulative erosion rate (gram/m^2/s) can be computed as: $e_{mud}= h_w\ \Delta c_{mud}/\Delta t$, with h_w=0.15 m, c=concentration (1 mg/l= 1 gr/m^3), Δt = total time from start (t=0), Δc_{mud}= total concentration increase with respect to start t=0; see **Tables 5.2.5** and **5.2.6**.

The erosion rate is in the range of 0.1 to 0.15 gr/m^2/s for a shear stress of 0.25 $\pm$ 0.05 N/m^2 (see **Tables 5.2.5, 5.2.6**). Erosion of 0.1 mm is equivalent with a mud concentration in the tube of about 300 to 400 mg/l, which occurs at a bed-shear stress of about 0.25 N/m^2.

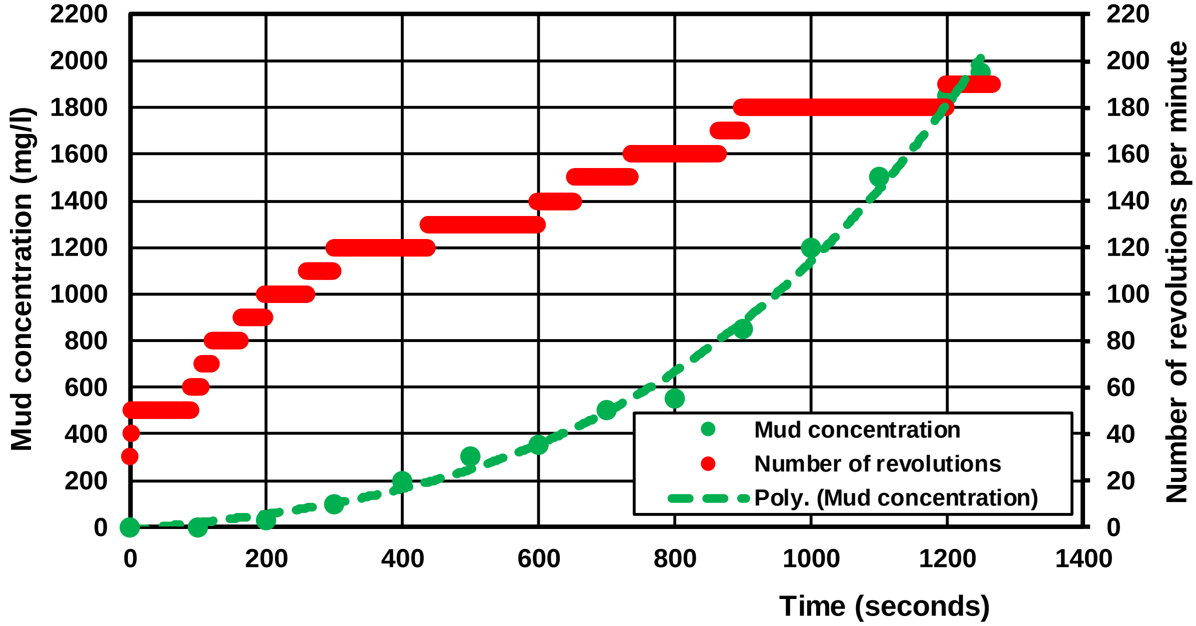
This value is assumed to be the critical bed-shear stress (10% of bed is moving) for a mud bed with a layer-averaged dry density of 350 to 400 kg/m^3 (Flume tests F-N350/F-N400), see also **Figure 4.7**. Mass erosion cannot be generated in the EROMES-tube.

The total erosion layer at the end of the EROMES-tests is approximately: $\delta_e= (c_{mud,end}/\rho_{dry})\ h_w$ = [(2 kg/m^3)/350 (kg/m^3)] x 0.15 (m) = 0.00085 m = 0.85 mm ≅ 1 mm after about 20 min.

Based on the EROMES-test results of the tests E350-ps35%, E400-ps35% and E685-ps35% with mud, a tentative calibration curve for mud beds is proposed, which reads as (see **Figure 4.7**):

$$\tau_{bed,\ mud}= 0.00000001\ N_p^3 + 0.000005\ N_p^2 + 0.0006\ N_p + 0.0029,$$

with N_p= number of propeller revolutions per minute.



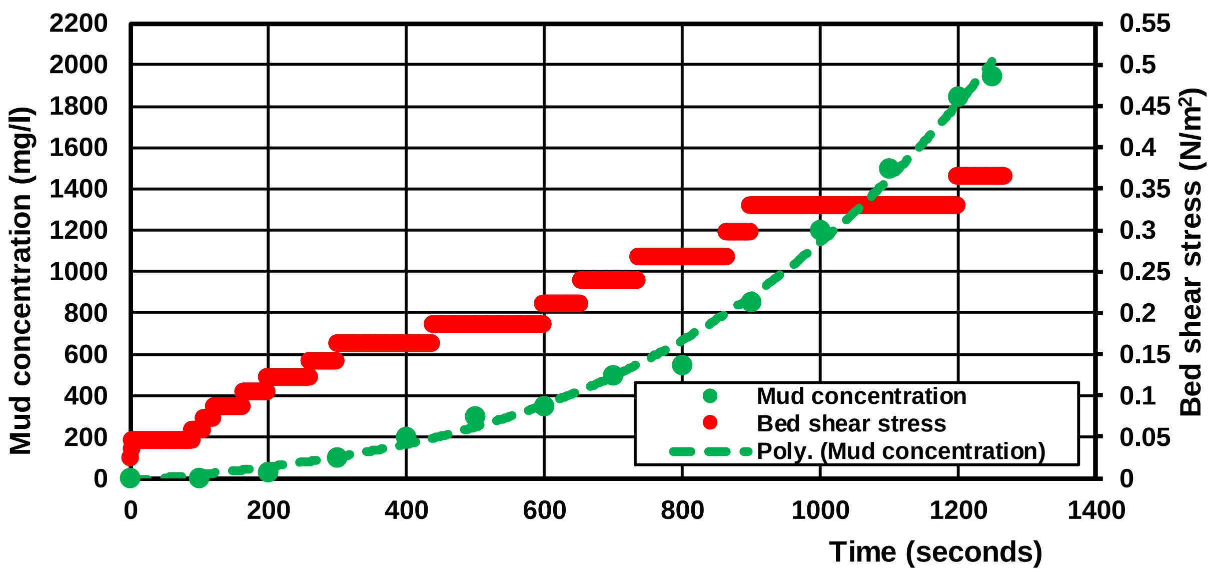


Figure 5.2.5 *Mud concentration of EROMES as function of time; Test E-N400-ps35%*
Upper= Number of revolutions on vertical scale right; Lower= bed-shear stress on vertical scale right

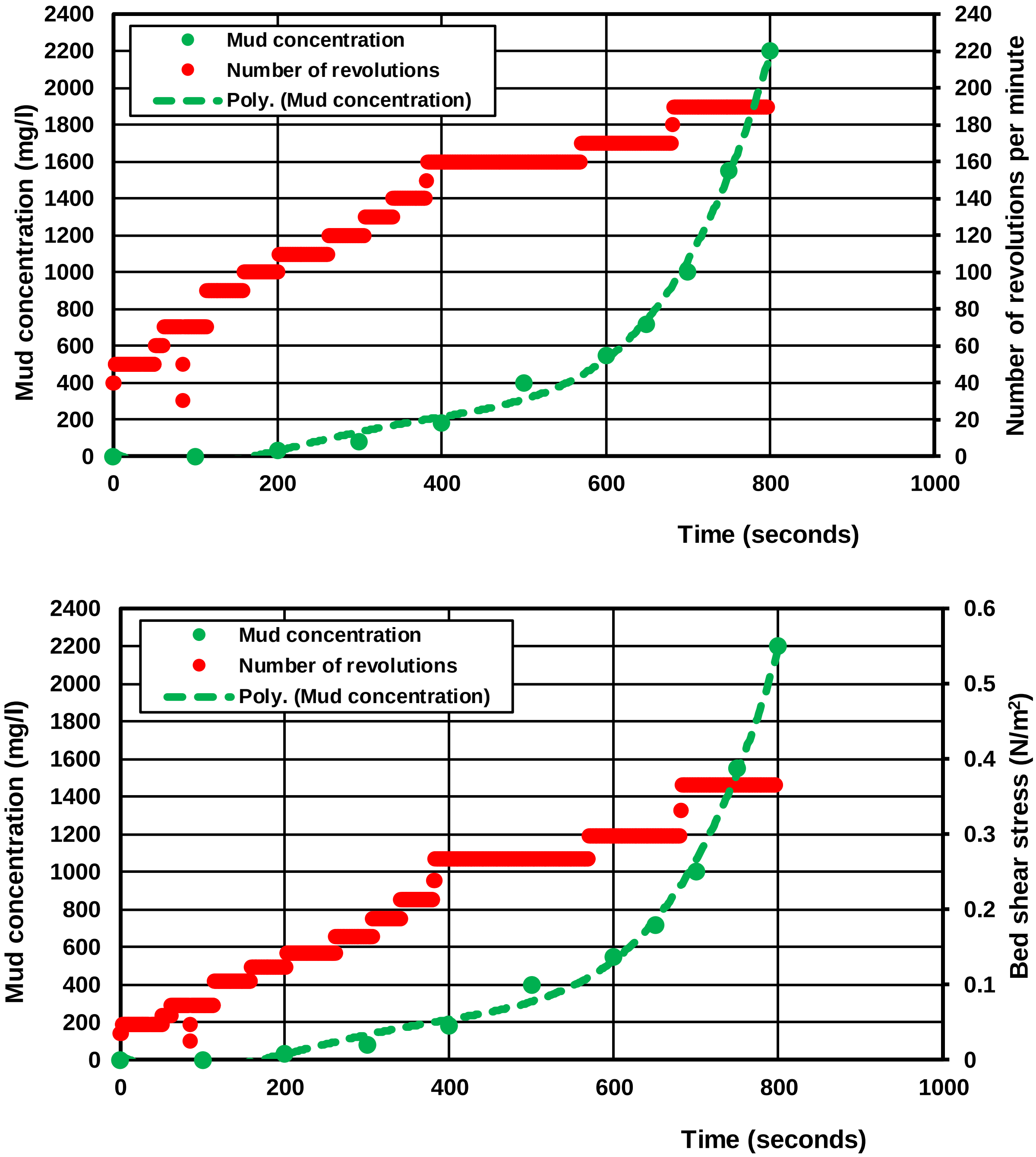


Figure 5.2.6 *Mud concentration of EROMES as function of time; Test E-N350-ps35%*
Upper= Number of revolutions on vertical scale right; Lower= bed-shear stress on vertical scale right

Time (s)	Number of revolutions (N_P) per minute	Mud concen tration (mg/l)	Estimated bed-shear stress (N/m^2)	Estimated erosion rate cumulative ($gram/m^2/s$)	Erosion of bed surface
100-150	50-70	< 10	< 0.1	<<0.01	clear water; no mud erosion of surface; no flakes rolling and suspended particles (silt-sand 30-100 μm) eroded from top surface layer
150-220	70-100	50-100	0.10 ±0.05	<0.1	similar; flakes/flocs of eroded from grey film layer and suspended
220-380	100-120	100-200	0.15 ±0.06	0.08	water less clear; suspended flakes, flocs, particles; propeller is clearly visible
380-620	120-140	200-400	0.20 ±0.07	0.1	similar; grey film is eroded in middle;
620-820	140-160	400-1000	0.25 ±0.08	0.15	propeller hardly visible; erosion of upper 1 mm
820-1200	160-180	>1000	0.30 ±0.10	0.2	propeller not visible

Table 5.2.5 *Erosion results of EROMES test E400-ps35%; dry bulk density= 400 kg/m³ (seawater)*

Time (s)	Number of revolutions (N_P) per minute	Mud concen tration (mg/l)	Estimated bed-shear stress (N/m^2)	Estimated erosion rate cumulative ($gram/m^2/s$)	Erosion of bed surface
80-120	50-70	< 10	< 0.1	<<0.01	clear water; no mud erosion of surface; rolling and suspended particles (silt-sand 30-100 μm) eroded from top surface layer; mud flakes (< 5 mm) from grey top film are dislodged and suspended
120-200	70-100	10-50	0.10 ±0.05	<0.05	similar; mud flakes are broken into smaller flakes
200-300	100-120	50-150	0.15 ±0.06	0.06	clear water with suspended mud flakes
300-400	120-140	150-200	0.20 ±0.07	0.08	almost clear water with suspended mud flakes
400-600	140-160	200-400	0.25 ±0.08	0.1	surface layer (1 mm) breaks locally, small grooves; flakes; propeller remains visible
600-700	160-180	400-1000	0.30 ±0.10	0.15	similar; erosion of upper 1 mm; propeller hardly visible
700-800	180-200	> 1000	0.35 ±0.12	0.2	similar; propeller not visible

Table 5.2.6 *Erosion results of EROMES test E-N350-ps35%; dry bulk density 350 kg/m³ (seawater)*

Based on the results of this test, the critical bed-shear stresses for a mud bed with dry density of about 350 to 400 kg/m^{3}are estimated to be about:

- initiation of minor surface erosion of sand: $\tau_{b,cr,e}$ = 0.2-0.3 N/m^2;
- initiation of minor surfac erosion of mud (local erosion rate of < 0.1 gr/m^2/s): $\tau_{b,cr,e}$ = 0.25-0.35 N/m^2.

5.2.3 Noordpolderzijl mud; initial dry mud density of 435 kg/m^3 (March-June 2017)

Flume test F-N435-ps30%

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m^3; ρ_{wet}= 1275 kg/m^3; p_{sand}=30%) was mixed first. A mud layer with a height of 0.06 m was made in the mud compartment (maximum depth of 0.05 m in the middle) of the flume which was enclosed by temporary woorden walls on both sides. After a consolidation period of 43 hours the mud layer thickness was about 0.055 m above the surrounding flume bottom resulting in a dry bulk density of about 435 kg/m^3 (layer-averaged). Two surface samples (at about 10-20 mm below the mud surface) were taken using a syringe of 25 ml resulting in wet bulk densities of 1260 to 1270 kg/m^3 (dry densities of 390 to 400 kg/m^3).

The excess mud layer of 5 mm was removed by scraping horizontally in downstream direction using a window wiper. This resulted in a flat horizontal mud surface flush with the flume bottom, see **Figure 5.2.7**.

The time between the preparation of the mud surface and the start of the test was about 2 hours.

Initially, the mud surface was black, but a very thin (0.1 mm) grey film layer of mud was formed at the bed surface. No thin fluffy surface layer was present, as often observed at field sites.

The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section.

The OBS3+ sensor was installed above the rigid flume bottom at about 1 m downstream of the mud section.

The velocity of the fresh water flow was raised in steps from 0.2 to 0.65 m/s to observe the behaviour of the mud bed surface, see **Table 5.2.7**. Small water surface undulations (about 3 cm high)s were generated at the flume entrance section during consitions with relatively high velocites (0.65 m/s; Froude$\cong$0.5).

Long and narrow grooves were generated (mass erosion) in the mud bed surface at a mean velocity of about 0.6-0.7 m/s, see **Figure 5.2.8**. These grooves extended gradually in length and in width. About 80% of the mud surface was eroded at the end of the test. Mud clouds were eroded from the grooves.

The total eroded mass at the end of the test (**Figure 5.2.9**) was about 3 liters or 3x435=1300 grams of dry mud over an area of 0.14 m^2 during a period of about 12 minutes resulting in a mass erosion rate of 13 grams/m^2/s.

The erosion rate from the grooves is much less (<0.1 gr/m^2/s) at a mean velocity of 0.4. The erosion rate (mass erosion) increases to about 5 to 10 gr/m^2/s at a mean velocity of 0.5 m/s

Based on the results of this test, the critical bed-shear stresses for a mud bed with dry density of about 435 kg/m^{3}are estimated to be about:

- initiation of minor surface erosion of sand: $\tau_{b,cr,e}$ = 0.25-0.35 N/m^2;
- initiation of minor surfac erosion of mud (local erosion rate of < 0.1 gr/m^2/s): $\tau_{b,cr,e}$ = 0.4-0.6 N/m^2;
- initiation of mass erosion of mud (local erosion rate of 10-15 gr/m^2/s): $\tau_{b,cr,fail}$ = 0.8-1.0 N/m^2.

Figure 5.2.7 *Mud bed before the test F-N435-ps30%*

Time (hrs)	Mean velocity at 8 cm above bed (m/s)	Bed-shear stress (N/m^2)	Mud concentration OBS3+ at 1 m downstream of mud section (mg/l)		Erosion of bed surface	Bed rough ness; Chezy (mm) ($m^{0.5}/s$)	Bed load fine sand (g/m/s)
			counts (counts-offset)	mg/l			
12.25	0	0	50 (offset) (0)	≅ 0	-	-	-
12.27	0.21	0.05	150 (100)	< 10	minor movement of individual particles	<0.1; 80-90	n.m.
12.37	0.27	0.11	200 (150)	20	minor movement of individual particles	<0.1; 80-90	n.m.
12.39	0.32	0.14	220 (170)	25	minor movement of individual particles	<0.1; 80-90	n.m.
12.45	0.39	0.25	240 (190)	25	minor groove generation	<0.3; 70-80	n.m
13.10	0.46	0.40	350 (300)	30	minor groove generation	<0.3; 70-80	n.m
13.16	0.52	0.50	400 (350)	35	minor groove generation	<0.3; 70-80	n.m
13.22	0.56	0.60	550 (500)	50	minor groove generation	<0.3; 70-80	n.m
13.29-13.41	0.63-0.68	0.80	750-1550 (700-1500)	100-250 (150-200 mg/l based on water sample)	mass erosion; generation of large scour hole (length=470 mm; width=300 mm; maximum depth=30 mm); mass erosion rate= 13 $gr/m^2/s$; OBS not visible	<0.3; 70-80	n.m.

n.m.= not measured; water depth=0.2 m; water temperature≅ 15° C

Table 5.2.7 *Erosion flume tests with mud bed (dry mud density= 435 kg/m³); fresh water*

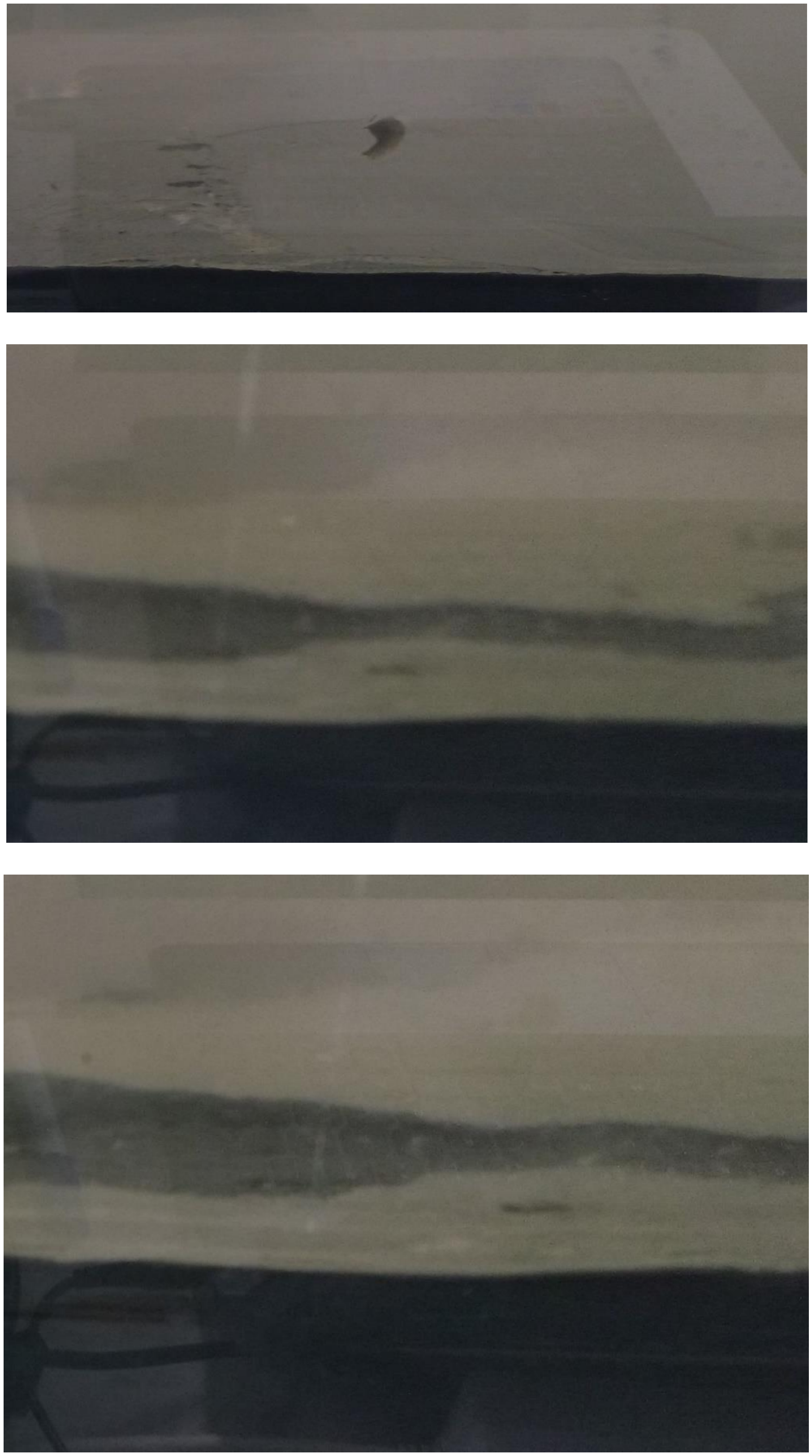


Figure 5.2.8 *Generation of long groove at mud bed during flume test F-N435-ps30%; mean velocity=0.65 m/s*

Figure 5.2.9 *Mud bed after test F435-ps30%; scour hole length=47 cm; width=30 cm; maximum depth=30 mm*

EROMES-test E-N435-ps30%

The Noordpolderzijl mud of the base container with dry mud density of about ρ_{dry}= 425 kg/m^3 and p_{sand}=30% is mixed first and a bucket of mud is taken to fill a small wooden frame with mud (the frame is covered with plastic sheet; frame surface area of 15x15 cm^2; thickness of frame =50 mm, see **Figure 5.2.10**). The mud surface is scraped horizontal by moving a wooden stick over the frame. The perspex tube is pushed vertically into the mud surface of the frame. Then, the frame is taken away (dismantled) and the excess mud is removed from the plastic sheet. After that, the plastic sheet is cut circular and taped (ductape) around the perspex tube to prevent any leakage through the mud layer in the EROMES-tube (**Figure 5.2.10**). The tube is partly filled by spraying seawater over a height of about 1 to 2 cm above the mud surface.

The consolidation between the preparation of the mud bed in the tube and the start of the test was about 43 hours resulting in a dry buk density of about 435 kg/m^3 (averaged over layer thickness of about 50 mm). Initially, the mud surface was black, but a very thin (0.1 mm) grey film layer of mud was formed at the bed surface. No thin fluffy surface layer was present, as often observed at field sites. The height of the water column was filled to about 150 mm. The water temperature was 19^o C.

Just before the test, the tube was carefully filled with seawater (about 1.2 liter) The height of the water column was about 150 mm.

The propeller was installed at the prescribed 30 mm above the mud surface. The OBS3+ optical sensor was mounted in the tube (at about 80 mm from the mud surface).

The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 50 to the maximum value of 350 to observe the behaviour of the mud bed surface.

The total test duration was about 1 hours.

At the end of test a smal mud sample was taken at the bottom of the mud layer using a small syringe resulting in a dry density of 325 kg/m^3. The maximum erosion layer at the end of the test was about 1 to 2 mm. Mass erosion cannot be generated in the EROMES-tube.

The mud layer with a layer thickness of about 50 mm was so soft that the thermometer tube (diameter of about 5 mm) sank to the bottom of the tube through the mud by its own weight (load of about 0.1 to 0.2 kg/cm^2). The water is dark grey at the end of the test (**Figure 5.2.10**).

The number of propeller revolutions (N_P) was raised in steps (10 to 20) from 50 onwards to observe the behaviour of the mud bed surface, see **Table 5.2.8**.

The cumulative erosion rate (gram/m^2/s) can be computed as: e_{mud}= h_w $\Delta c_{mud}/\Delta t$, with h_w=0.15 m, c=concentration (1 mg/l= 1 gr/m^3), Δt = total time from start (t=0), Δc_{mud}= total concentration increase with respect to start t=0; see **Table 5.2.8.**

The erosion rate is about 0.03 to 0.05 $gr/m^2/s$ for a shear stress of 0.45± 0.05 N/m^2 (see **Table 5.2.8**).
The critical bed-shear stress of surface erosion is assumed to be about 0.45 N/m^2 for a mud bed with a layer-averaged dry density of 435 kg/m^3 (mud concentration of 400 to 500 mg/l).
The total erosion layer at the end of the EROMES-tests is approximately:
$\delta_e = (c_{mud,end}/\rho_{dry})\ h_w = [(2.5\ kg/m^3)/435\ (kg/m^3)] \times 0.15\ (m) = 0.0009\ m \cong 1\ mm$ after about 45 min.

Time (s)	**Number of revolutions (N_P) per minute**	**Mud concentration** counts (counts-offset)	mg/l	**Estimated bed-shear stress (N/m^2)**	**Estimated erosion rate ($gram/m^2/s$)**	**Erosion of bed surface**
0-400	50-70	2200 (offset) (0)	< 10	< 0.1	<<0.1	clear water; no mud erosion of surface; rolling and suspended particles (silt-sand 30-100 μm) eroded from top surface layer; mud flakes (< 5 mm) from grey top film are dislodged and suspended
400-600	90-110	2400 (200)	30	0.12	<0.01	similar; mud flakes are broken into smaller flakes
600-1000	120-130	2500 (300)	50	0.18	<0.01	clear water with suspended mud flakes
1000-1300	150-160	3000 (800)	120	0.25	0.012	almost clear water with suspended mud flakes; propeller visible
1300-1600	170-180	3500 (1300)	200	0.3	0.01	propeller just visible; mud surface hardly visible
1600-2000	190-210	5500 (3300)	500	0.4	0.035	propeller just visible; mud surface hardly visible
2000-2200	230	7500 (5300)	800	0.5	0.05	propeller not visible; mud surface not visible
2200-2300	240	8000 (5800)	1000	0.55	0.07	propeller not visible; mud surface not visible
2300-2400	250	9000 (6800)	1300	0.6		propeller not visible; mud surface not visible
2400-2500	280	10000 (7800)	1500	0.8		propeller not visible; mud surface not visible; dark grey colour
2500-2600	300	11000 (8800)	1800	0.9		propeller not visible; mud surface not visible; dark grey colour
2600-2700	320	13000 (10800)	2300	1.05		propeller not visible; mud surface not visible; dark grey colour
2700-2800	350	14000 (11800)	2500	1.25	0.15	propeller not visible; mud surface not visible; dark grey colour; maximum erosion ≅ 1 mm

Table 5.2.8 *Erosion results of EROMES test E-N435-ps30%; dry bulk density 425 kg/m^3 (seawater)*

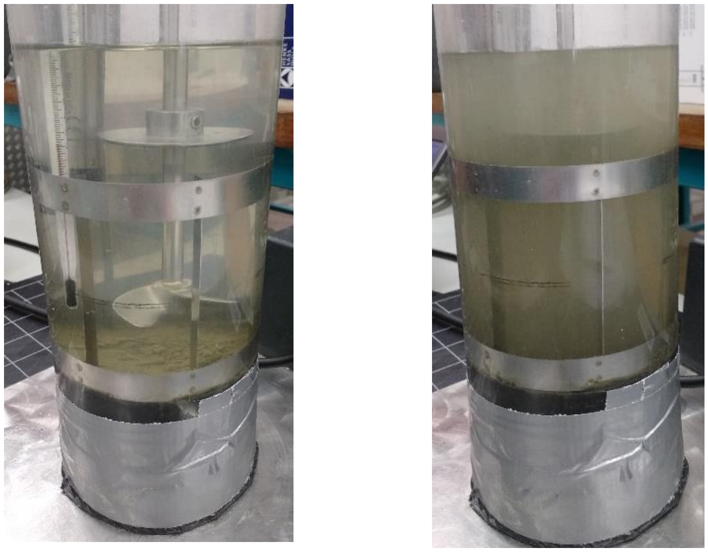


Figure 5.2.10 *EROMES-test E-N435-ps30%; before test (left) and after test (Right)*

5.2.4 Noordpolderzijl mud; initial dry mud density of 530 kg/m³ (March-June 2017)

Flume test F-N530-ps30%

The Noordpolderzijl mud mixture was made by taking mud from the base containers of November 2016 (about ρ_{dry}= 685 kg/m^3; p_{sand}=35%) and march 2017 (about ρ_{dry}= 425 kg/m^3; p_{sand}= 30%). A mass of 5 kg was taken from each container and mixed thoroughly yielding a bulk density of about (685+425)/2 $\cong$ 550 kg/m^3, see **Figure 5.2.11**. The mud after consolidation of 24 hours has a soft buttery-type of texture with a thin grey cover layer. A mud layer with a height of 0.06 m was made in the mud compartment (maximum depth of 0.05 m in the middle) of the flume which was enclosed by temporary woorden walls on both sides. After a consolidation period of 24 hours, the excess mud layer was removed by scraping horizontally in downstream direction using a window wiper. This resulted in a flat horizontal mud surface flush with the flume bottom, see **Figure 5.2.11**. Two surface samples (at about 10-20 mm below the mud surface) were taken using a syringe of 25 ml resulting in wet bulk densities of 1340 kg/m^3 (dry density of 530 kg/m^3).
Initially, the mud surface was black, but a very thin (0.1 mm) grey film layer of mud was formed at the bed surface. No thin fluffy surface layer was present, as often observed at field sites.
The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section.
The OBS3+ sensor was installed above the rigid flume bottom at about 1 m downstream of the mud section.
The velocity of the fresh water flow was raised in steps from 0.2 to 0.8 m/s to observe the behaviour of the mud bed surface, see **Table 5.2.9**.
The mud bed surface showed to be very stable, even at relatively high velocities. Very minor erosion was observed at a mean velocity of about 0.7 m/s.
Sudden bed failure was observed at a depth-mean velocity of about 0.78 m/s. The mud section (layer of 0.05 m) was removed almost completely in about 1 to 2 minutes. The total eroded mass at the end of the test was about 10 liters or 10x530= 5300 grams of dry mud over an area of 0.24 m^2 during a period of about 1.5 minutes resulting in a mass erosion rate of about 250 grams/m^2/s.

Based on the results of this test, the critical bed-shear stresses for a mud bed with dry density of about 530 kg/m^{3}are estimated to be about:

- initiation of minor surface erosion of sand : $\tau_{b,cr,e}$ = 0.35-0.5 N/m^2;
- initiation of minor surface erosion of mud : $\tau_{b,cr,e}$ = 0.6-0.8 N/m^2;
- initiation of mass erosion of mud: $\tau_{b,cr,fail}$ = 1-1.2 N/m^2.

Time **(hrs)**	**Water depth** **(m)**	**Mean velocity at 8 cm above bed (m/s)**	**Bed-shear stress** **(N/m^2)**	**Mud concentration OBS3+ at 1 m downstream of mud section (mg/l)**		**Erosion of bed surface**	**Bed roughness; Chezy (mm) (m$^{0.5}$/s)**	**Bed load fine sand** **(g/m/s)**
				counts (counts-offset)	mg/l			
14.54-15.12	0.2	0.2-0.34	0.06-0.18	300 (offset)	≅ 0	no erosion (turbid water due to dust pollution)	<0.1; 80	-
15.12-15.30	0.2	0.4	0.25	420 (100)	10	no erosion (turbid water)	<0.1; 80-90	0.006
15.30-15.37	0.15	0.5	0.45	500 (200)	10	no erosion (turbid water)	<0.1; 75	n.m.
15.37-15.51	0.13	0.7	0.85	500 (200)	10	very minor erosion, very small craters locally (turbid water; upstream mud concentration ≅ 40 mg/l based on water sample)	<0.1; 75	0.022
15.51-15.55	0.12-0.13	0.78	1.05	500-6000 (200-5700)	10-1000 cws=200	sudden bed failure initiated at upstream transition zone; bed removed in a bout 1 to 2 minutes	<0.1; 75	n.m.

n.m.= not measured; cws= concentration based on water-sediment sample of 50 ml; Temperature= 14^o C

Table 5.2.9 *Erosion flume tests with mud bed (dry mud density= 530 kg/m^3); fresh water*

Figure 5.2.11 *Mud in container (upper) and mud bed before the test F-N530-ps30% (lower)*

EROMES-test E-N530-ps30%

Similar Noordpolderzijl mud as used in the flume test F-N530-ps30% was used to fill a small wooden frame with mud (the frame is covered with plastic sheet; frame surface area of 15x15 cm^2; thickness of frame =50 mm, see **Figure 5.2.2**). The mud surface is scraped horizontal by moving a wooden stick over the frame. The perspex tube is pushed vertically into the mud surface of the frame. Then, the frame is taken away (dismantled) and the excess mud is removed from the plastic sheet. After that, the plastic sheet is cut circular and taped (ductape) around the perspex tube to prevent any leakage through the mud layer in the EROMES-tube. The tube is slowly filled by spraying seawater.
The consolidation between the preparation of the mud bed in the tube and the start of the test was about 20 hours. Initially, the mud surface was black, but a very thin (0.1 mm) grey film layer of mud was formed at the bed surface. No thin fluffy surface layer was present, as often observed at field sites. The height of the water column was about 170 mm. The water temperature was 18^o C.
The propeller was installed at the prescribed 30 mm above the mud surface. The OBS3+ optical sensor was mounted in the tube (at about 80 mm from the mud surface).
The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 50 to the maximum value of 350 to observe the behaviour of the mud bed surface. The total test duration was about 1 hours.
No erosion was observed in the EROMES-tube, not even at the highest propeller speed of 350 revolutions per minute. The mud concentration at the end of the test was about 70 mg/l based on a water-mud sample of 50 ml. This means that the critical bed-shear stress for erosion is higher than 1 N/m^2.

5.2.5 Delfzijl mud; initial dry density of 500 kg/m^3 (February 2018)

Mud from Delfzijl-harbour (test E-D300-ps20%) with initial dry density of about 500 kg/m^3 and ps=20% was used to fill a small wooden frame with mud (the frame is covered with plastic sheet; frame surface area of 15x15 cm^2; thickness of frame =100 mm, see **Figure 5.2.2**). The mud surface is scraped horizontal by moving a wooden stick over the frame. The perspex tube is pushed vertically into the mud surface of the frame. Then, the frame is taken away (dismantled) and the excess mud is removed from the plastic sheet. After that, the plastic sheet is cut circular and taped (ductape) around the perspex tube to prevent any leakage through the mud layer in the EROMES-tube. The tube is slowly filled by spraying seawater.
The consolidation between the preparation of the mud bed in the tube and the start of the test was about 24 hours. Initially, the mud surface was black, but a very thin (<0.5 mm) grey film layer of mud was formed at the bed surface. Various cracks were visible at the grey mud surface, see also **Figure 5.2.12**. No thin fluffy surface layer was present. The height of the water column was about 140 mm. The water temperature was 13^o C. The propeller was installed at the prescribed 30 mm above the mud surface.
The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 50 to the maximum value of 350 to observe the behaviour of the mud bed surface. The total test duration was about 15 minutes.
At the end of the test, the propeller was set at 10 mm above the bed surface with N_p=350-370 resulting in mass erosion with black clouds of mud being suspended. Estimated bed-shear stress is about 1-1.5 N/m^2.

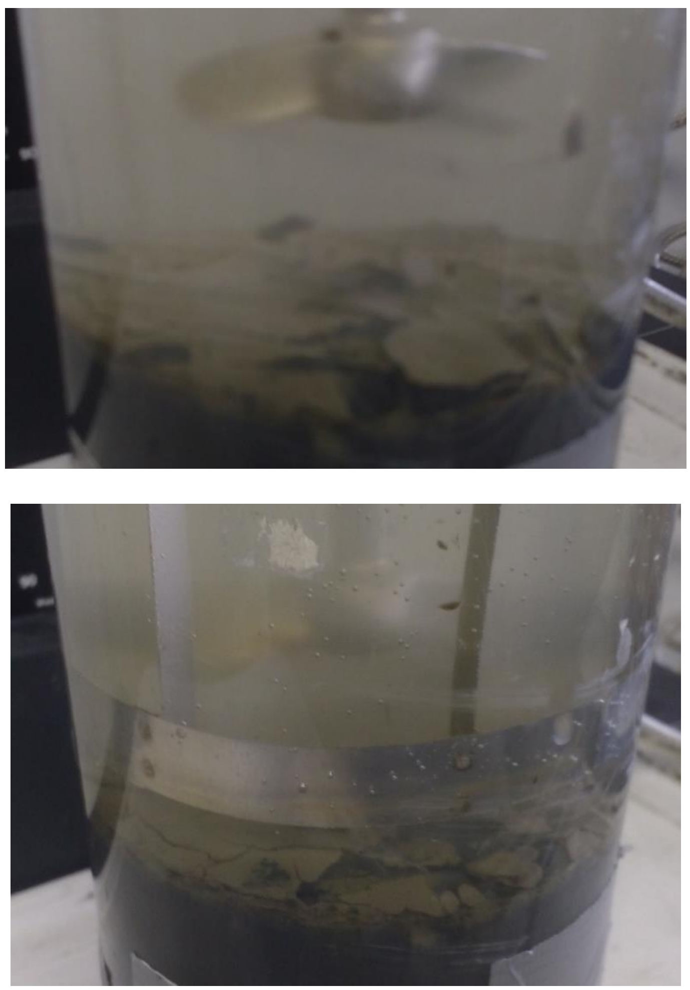


Figure 5.2.12 *EROMES-test E-D500-ps20%; large flakes with cracks at mud surface during test*

The EROMES-results can be used to determine the critical bed-shear stress for particle erosion and for surface erosion, as follows:

- particle erosion (particles and flocs suspended): revolutions per minute = 150-200; critical bed-shear stress= 0.3-0.4 N/m^2;
- surface erosion (propeller and bed hardly visible): revolutions per minute= 250-300; critical bed-shear stress= 0.6-0.9 N/m^2;
- mass erosion at bed-shear stress of 1.0-1.5 N/m^2.

Time (s)	Number of revolutions (N_P) per minute	Mud concentration		Estimated bed-shear stress (N/m^2)	Estimated erosion rate (gram/m^2/s)	Erosion of bed surface
		counts	mg/l			
0-120	100		< 50	< 0.1		clear water; no mud erosion of surface; some mud flakes (< 5 mm) from grey top film are dislodged and suspended
120-240	150		50-100	0.25		mud flakes are eroded; propeller is clearly visible
240-420	200		100-300	0.4		many mud flakes are eroded and are broken by vortices; mud surface is black under grey flakes and remains stable; propeller is visible
420-540	250		330-500	0.6		mud flakes are eroded and moving everywhere; propeller is visible (Figure 5.2.12)
540-780	300		500-700 mg/l	0.9		Mud flakes eroded everywhere; propeller just visible
780-1020	350		700-1000	1.2		Propeller not visible; mud surface not visible; maximum erosion=1 mm

Table 5.2.10 *Erosion results of EROMES test E-D-500-ps20%; dry bulk density 500 kg/m^3 (seawater)*

5.2.6 Delfzijl mud; initial dry density of 300 kg/m^3 (February 2018)

Mud from Delfzijl-harbour (test E-D300-ps20%) was used to fill a small wooden frame with mud (the frame is covered with plastic sheet; frame surface area of 15x15 cm^2; thickness of frame =100 mm, see **Figure 5.2.2**). The mud surface is scraped horizontal by moving a wooden stick over the frame. The intial concentration was 250 kg/m^3, which increased to about 300 kg/m^3 due to consolidation over 24 hours (water layer of about 20 mm on top of mud surface). The percentage of sand was ps=20%. The perspex tube is pushed vertically into the mud surface of the frame. Then, the frame is taken away (dismantled) and the excess mud is removed from the plastic sheet. After that, the plastic sheet is cut circular and taped (ductape) around the perspex tube to prevent any leakage through the mud layer in the EROMES-tube. The tube is slowly filled by spraying seawater.
The consolidation between the preparation of the mud bed in the tube and the start of the test was about 24 hours. Initially, the mud surface was black, but a very thin (<0.5 mm) grey film layer of mud was formed at the bed surface. No thin fluffy surface layer was present. The height of the water column was about 140 mm. The water temperature was 16^o C. The propeller was installed at the prescribed 30 mm above the mud surface.
The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 50 to the maximum value of 350 to observe the behaviour of the mud bed surface. The total test duration was about 10 minutes.

The EROMES-results can be used to determine the critical bed-shear stress for particle erosion and for surface erosion, as follows (see **Table 5.2.11**):

- particle erosion (particles and flocs suspended): revolutions per minute = 100-130; critical bed-shear stress= 0.15 - 0.2 N/m^2;
- surface erosion (propeller and bed hardly visible): revolutions per minute= 140-150; critical bed-shear stress= 0.2 - 0.3 N/m^2;
- mass erosion at bed-shear stress >0.6 N/m^2.

Time **(s)**	**Number of revolutions (N_P) per minute**	**Mud concentration**		**Estimated bed-shear stress (N/m^2)**	**Estimated erosion rate** **(gram/m^2/s)**	**Erosion of bed surface**
		counts	**mg/l**			
0-60	90		< 10	< 0.1		clear water; single particles/flocs are suspended
60-120	100		50	0.13		larger flocs are suspended
120-180	110			0.15		larger flocs are suspended
180-240	130		200-300	0.20		water becomes turbid; propeller is clearly visible
240-360	140		500	0.21		Particle erosion; propeller is just visible
360-480	150		500-1000	0.25		Propeller is not visible; larger flocs/flames are eroded from mud surface
480-540	200		>1000	0.4		Mud surface vibrates slowly
540-600	250		>1000	0.6		Black mud is eroded everywhere

Table 5.2.11 *Erosion results of EROMES test E-D300-ps20%; dry bulk density 300 kg/m^3 (seawater)*

5.2.7 Payra mud; initial dry mud density of 1280 kg/m^3 (April 2018)

EROMES test Payra mud E-P1280-ps20%

Payra mud is a very pure mud with almost no calcareous and organic materials; the bed surface is very smooth without any protrusions.

The Payra mud from Bangladesh offshore with dry mud density of about ρ_{dry}= 1280 kg/m^3 and p_{sand}=20% is poured into the perspex tube and the tube is partly filled by spraying seawater.

The consolidation between the preparation of the mud bed in the tube and the start of the test was about 1 hour.

The propeller was installed at the prescribed 30 mm above the mud surface. The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 50 to the maximum value of 370 to observe the behaviour of the mud bed surface. The mud surface is very smooth at the start of the test. **Figure 5.2.13** shows the EROMES-tube with mud before, during and after the test.

The test with the propeller at 30 mm above the bed surface did not show any appreciable erosion of the mud surface for the highest possible propeller speed equivalent to a bed-shear stress of 1.5 N/m^2, see **Table 5.2.12**. After lowering the propeller to 10 mm above the bed surface, erosion was generated at the highest propeller speed, which is equivalent with a bed -shear stress of about 2 N/m^2.

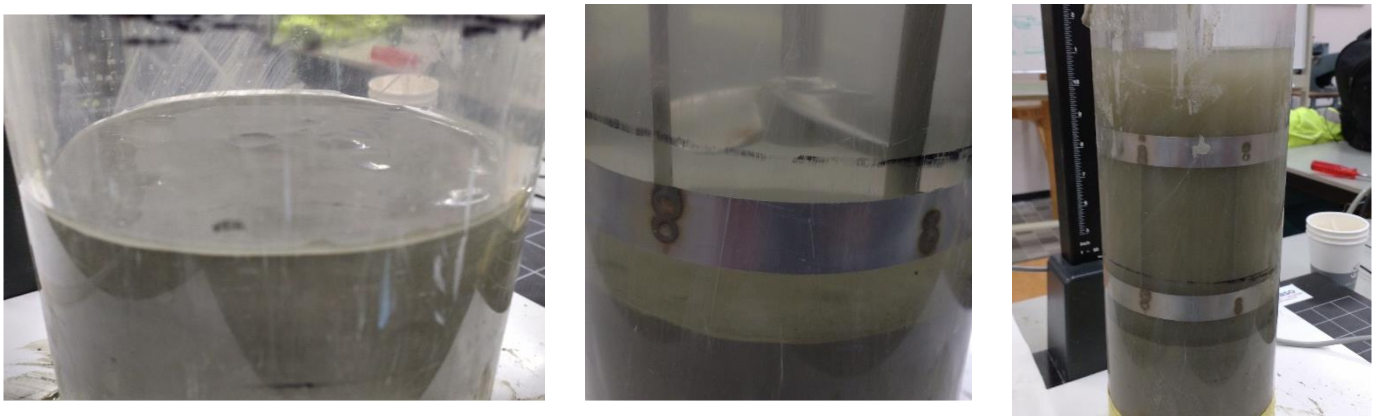


Figure 5.2.13 *EROMES-tube after filling with Payra mud (left), with water and propeller (middle) and at end of test (right)*

Sample	**Wet and dry bulk density (kg/m³)**	**Propeller height above bed (m)**	**Number revolu tions (-/min)**	**Bed-shear stress (N/m²)**	**Turbidity in water column**	**Erosion description**
Payra mud	1800; 1280	0.03	30-230	0-0.5	low	very smooth initial bed surface; no movement except some loos individual particles; water becomes slowly more turbid
		0.03	230-370	0.5-1.5	medium to high (max 1000 g/l)	similar; very fine silt/clay particles are eroded; bed surface is intact; no surface erosion; water very turbid, but propeller is visible
		0.01	370	2	very high (1000-5000 mg/l)	very turbid (dark grey colour) ; propeller is not visible; severe surface/mass erosion near tube wall

Testing: 2 hours after preparation of sample; native saline water; water temperature= 20 °C; h_w= water depth ≅0.15 m; ps= percentage of sand;
$c_{mud}=\rho_{dry}\,\delta_e/h_w \cong$ 0.5-1.0 for $\delta_e \cong$0.001 m and $\rho_{dry} \cong$ 500 kg/m³; high turbidity≅ 0.5-1 kg/m³ (=500-1000 mg/l)
pjv= propeller in middle just visible (500-700 mg/l); pnv=propeller in middle not visible (700-1000 mg/l);
Cohesionless sand of 150 to 200 μm has onset value of about 80-100 rev's per minute (10% of bed is moving)

Table 5.2.12 *Critical bed-shear stress of Payra mud based on EROMES-test*

<u>EROMES test Payra sand</u>

The Payra sand sample consist of 93% sand (> 63 μm) and 7% fines (< 63 μm).

The sand surface is very smooth at the start of the test. **Figure 5.2.14** shows the EROMES-tube before, during and after the test.

The test with the propeller at 30 mm above the bed showed initiation of rolling particles at a bed-shear stress of about 0.2 N/m^2; initiation of suspension was observed at a bed-shear stress of 0.4 N/m^2, see **Table 5.2.13**.

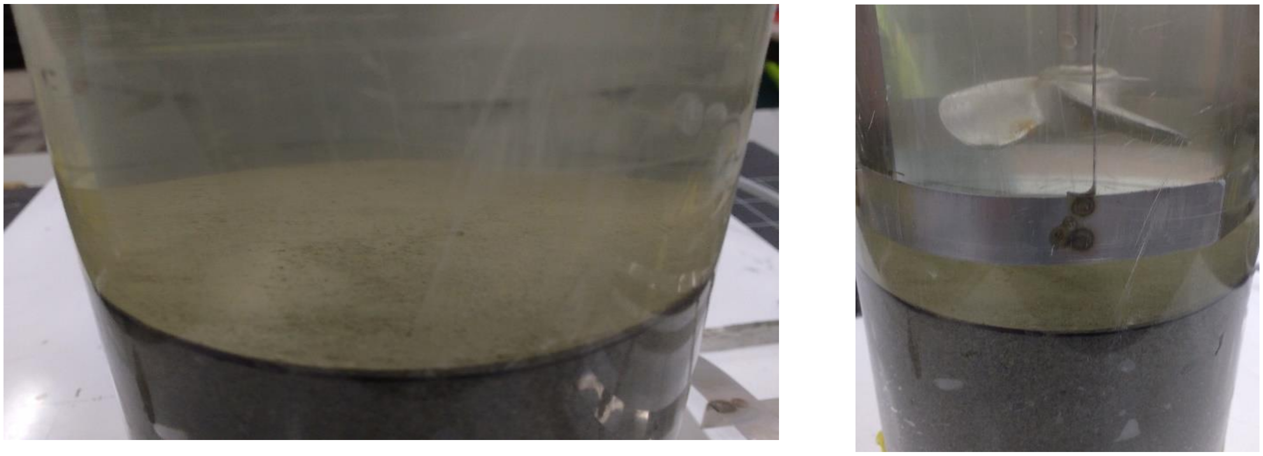


Figure 5.2.14 *EROMES-tube after filling with Payra sand (left), with water and propeller (right)*

Sample	Wet and dry bulk density (kg/m^3)	Propeller height above bed (m)	Number revolu tions (-/min)	Bed-shear stress (N/m^2)	Turbidity in water column	Erosion description
Payra silty sand (ps= …)	1925; 1480	0.03	30-140	0-0.2	low	very smooth initial bed surface; no movement except some loose individual particles; no suspension; water becomes slowly more turbid
		0.03	140-200	0.2-0.4	medium	rolling of particles; initiation of suspension; propeller is visible; 10%-50% of bed surface is moving
		0.03	200-240	0.4-0.6	high (1000 mg/l)	turbid water; 50% -100% of bed surface is movingsuspension everywhere; propeller is just visible

Testing: 2 hours after preparation of sample; saline water; water temperature= 20 °C; h_w= water depth ≅0.15 m; ps= percentage of sand;
$c_{mud}=\rho_{dry}\,\delta_e/h_w \cong$ 0.5-1.0 for $\delta_e \cong$0.001 m and $\rho_{dry} \cong$ 500 kg/m^3; high turbidity≅ 0.5-1 kg/m^3 (=500-1000 mg/l)

Table 5.2.13 *Critical bed-shear stress of Payra sand based on EROMES-test*

<u>Flume tests Payra mud; F-P1280-ps20%</u>

The test was done with Payra mud having a dry bulk density of about 1280 kg/m^3 and a percentage of sand of about ps=20%.

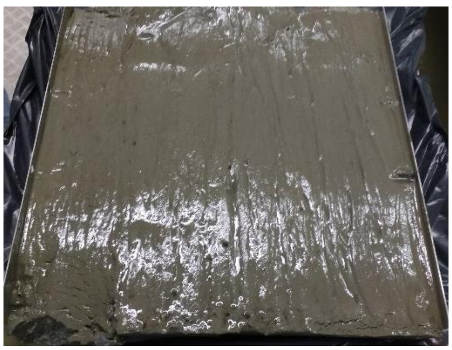
The Payra mud was poured slowly in the metal tray of measurement section. The dry density of the mud bed was about 1280 kg/m^3. The mud sample had a soft muddy texture with a very smooth surface. Some irregularities of the smoothing procedure are visible at the bed surface, see **Figure 5.2.15.** The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section and the flume was filled with fresh water. The water depth was 0.2 m. The time period between bed preparation and flume test was about 1 hour.

The velocity of the fresh water flow was raised in steps from 0.2 to 1 m/s to observe the behaviour of the mud surface, see **Table 5.2.14.** Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocities (> 0.7 m/s).

Figure 5.2.16 shows the bed surface at the end of the test with maximum velocity of about 1 m/s. The bed is almost fully in tact. Minor erosion with small erosion grooves is visible. The total erosion during the test is about

1 to 2 mm over the complete area of the tray (40x40 cm^2). The bed surface is very soft. A finger tip can be very easily pushed into the bed surface.

Figure 5.2.15 *Bed surface of Payra mud in flume after filling of tray (left) and after filling of flume (right)*



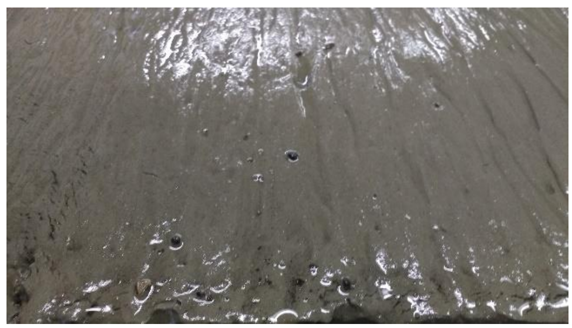


Figure 5.2.16 *Bed surface at end of test; tray with mud (left); detail of surface (middle); small pit with depth of 5 cm made in surface (right)*

Time (hrs)	Water depth (m)	Mean velocity at 8 cm above bed (m/s)	Bed-shear stress (N/m²)	Erosion of bed surface	Bed roughness; Chezy (mm) ($m^{0.5}$/s)	Bed load fine sand (g/m/s)
13.55-14.00	0.2	0.27	0.1	very smooth surface; no movement; water turbid	<0.1 80-90	n.m.
14.00-14.06	0.2	0.39	0.21	similar; no movement at surface	<0.1 80-90	n.m.
14.06-14.24	0.2	0,57	0.44	similar; mud patches (remainings from filling procedure) at dowmstream flume bottom are eroded away	<0.1 80-90	22 gram; 10 min 0.1 gram/m/s
14.24-14.40	0.2	0.65	0.58	no movement at bed surface; water very turbid	<0.1 80-90	38 gram; 15 min 0.1 gram/m/s
14.40-14.48	0.2	0.77	0.8	local pit erosion at bed surface; no general movement; water very turbid	<0.1 80-90	
14.48-14.50	0.16	1.0	1.5	minor local erosion at bed surface; no general movement; water very turbid	<0.1 80	
14.50-15.00	0.15	1.03	1.65	minor local erosion at bed surface; no general movement; water very turbid	<0.1 80	22 gram; 12 min 0.08 gram/m/s

n.m.= not measured; water temperature≅ 18-20° C

Table 5.2.14 *Erosion flume tests with Payra mud; fresh water*

Based on the results of this test, the critical bed-shear stresses for the Payra mud bed ($p_{sand} \cong 20\%$) with dry density of about 1280 ± 50 kg/m^{3}are estimated to be about:

- initiation of minor sand erosion: $\tau_{b,cr,sand}$=0.35-0.45N/m^2; $u_{cr,sand}$= 0.55 m/s;
- initiation of minor mud erosion (erosion rate < 1 gr/m^2/s): $\tau_{b,cr,e}$=0.7-1.5 N/m^2; $u_{cr,mud}$= 0.95 m/s;
- initiation of mass erosion (local erosion rate > 10 gr/m^2/s): $\tau_{b,cr,mass}$ > 2 N/m^2; $u_{cr,mass}$= 1.3 m/s.

The depth-mean critical velocities are computed as : u_{cr}= C $[\tau_{b,cr/}(\rho g)]^{0.5}$ with C=Chézy-coefficient= 90 m$^{0.5}$/s (water depth= 8m; bed roughness = 0.001 m), ρ=fluid density = 1020 kg/m^3 and g=9.81 m/s^2.
Given these results, the bed surface of the sandy areas in the coastal zone at Payra will be stable up to velocities of about 0.4 m/s. Inititiation of sand suspension is estimated to start at velocities of about 0.55 m/s.

5.3 Erosion tests of artificial, moulded mud-sand beds

5.3.1 General

Most natural mud beds are mixtures of clay/lutum (<2 μm), silt (2-63 μm) and fine sand (> 63 μm).
The mud from the harbour area of Noordpolderzijl contains about 30% to 35%% of fine sand.
To study the effect of the percentage of fine sand on the erosive properties of a mud bed, various mixtures of mud and sand have been prepared artificially. The percentage of sand was varied in the range of 25% to 95%. Fine sand was added and mixed with the base mud to obtain the desired mud-sand mixture (see Section 5.3.1). Two types of fine sand have been used (see Table 3.1): very fine sand of about 95 μm (percentage of fines < 63 μm of about 15%) and fine sand of 180 μm (percentage fines < 63 μm of about 1%).

5.3.2 Preparation of mud-sand mixtures

The mud-sand mixtures have been prepared by the adding/mixing of dry fine sand (with mass $M_{total,added}$) into a given volume of mud (V_o) from the base mud container with known wet/dy density ($\rho_{wet,o}$; $\rho_{dry,o}$) and known percentage of sand ($p_{sand,o}$). The volume V_o is about 10 to 15 liter to fill the deepened section of the flume bottom, see **Figure 2.1**.

Mass of mud and sand in volume V_o is:	$M_{mud+sand,o}= \rho_{dry,o} V_o$
Mass of sand in volume V_o is:	$M_{sand,o}= (p_{sand}/100) \rho_{dry,o} V_o$
Mass of mud in volume V_o is:	$M_{mud,o}= (1-p_{sand}/100) \rho_{dry,o} V_o$
Mass of added sand	$M_{sand,added}= p_{sand,added} M_{total,added}$
New mass of sand is:	$M_{sand,new} =M_{sand,o} + M_{sand,added}$
New mass of mud and sand is:	$M_{mud+sand,new}= \rho_{dry,o} V_o + M_{total,added}$
New volume of mud and sand is:	$V_{new}= V_o + M_{total,added}/\rho_s$
New percentage of sand is:	$p_{sand,new} = (M_{sand,new}/M_{mud+sand,new})x100\%$
New dry density of mud-sand mixture is:	$\rho_{dry,new} = (M_{mud+sand,new}/V_{new}) =$
	$= (\rho_{dry,o}V_o+M_{total,added})/(V+ M_{total,added}/\rho_s)$

<u>Example</u>

Given: V_o =15 liter mud+sand = 0.015 m^3; $p_{sand,o}$ = 25%; $\rho_{wet,o}$= 1400 kg/m^3;
Total mass added $M_{total,added}$= 2.5 kg; $p_{sand,added}$= 90%, $p_{mud,added}$=100%-90%=10%

Question: What is percentage of sand, and dry bulk density of new mud-sand mixture?

Solution:

$\rho_{dry,o}$= 611 kg/m^3

$M_{mud+sand,o}= \rho_{dry,o} V_o = 9.16$ kg

$M_{sand,o}= p_{sand} \rho_{dry,o} V_o = 2.29$ kg and $M_{mud,o}= (1-p_{sand}) \rho_{dry,o} V_o= 6.87$ kg/m^3

$M_{sand,new} =M_{sand,o} + p_{sand,added} xM_{total,add} = 2.29+0,9x2.5 = 4.29 +2.25=4.54$ kg

$M_{mud+sand,new}= \rho_{dry,o} V_o + M_{total,added} = 9.16+2.5 = 11.66$ kg

$V_{new}= V_o + M_{total,added}/\rho_s = 0.015 + 2.5/2650 = 0.01594$ m^3

$p_{sand,new} = (M_{sand,new}/M_{mud+sand,new})x100\%= (4.54/11.66)x100 = 39\%$

$\rho_{dry,new}= (\rho_{dry,o}V_o+M_{total,added})/(V+ M_{total,added}/\rho_s) =11.66/0.01594 = 732$ kg/m^3

5.3.3 Noordpolderzijl mud; initial dry mud density of 530 kg/m^3; $p_{sand} \cong$ 45% (March-June 2017)

Flume test F-N530-ps45%

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m^3) was mixed first and fine sand (d_{50}≅0.095 mm, see **Table 3.1**) was added to obtain a mixture with a sand content of 45% (based on sample analysis). The dry bulk density was about 530 kg/m^3 (wet density of 1345 kg/m^3) based on samples taken by a syringe (50 ml). The mud-sand mixture had a very soft muddy texture after mixing, see **Figure 5.3.1**.
A mud layer with a height of 0.06 m was made in the mud compartment (maximum depth of 0.05 m in the middle) of the flume which was enclosed by temporary woorden walls on both sides. After a consolidation period of about 22 hours, the excess mud about of 5 mm high was removed by scraping horizontally in downstream direction using a window wiper. This resulted in a flat horizontal mud surface flush with the flume bottom. The time between the preparation of the mud surface and the start of the test was about 1 hour. The top surface of the bed showed light grey stripes indicating the presence of fine sand, see **Figure 5.3.2**.
The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section. The OBS3+ sensor was installed above the rigid flume bottom at about 1 m downstream of the mud section.
The velocity of the fresh water flow was raised in steps from 0.2 to 0.9 m/s to observe the behaviour of the mud bed surface, see **Table 5.3.1**. Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocites.
Long and narrow grooves were generated (mass erosion) in the mud bed surface at a mean velocity of about 0.6-0.7 m/s. These grooves extended gradually in length and in width. About 60% of the mud section was eroded at the end of the test.
The total eroded mass at the end of the test was about 6 liters or 6x530=3120 grams of dry mud over an area of 0.4x0.6=0.24 m^2 during a period of about 10 minutes resulting in a mass erosion rate of 20 grams/m^2/s at a velocity of about 0.75 to 0.9 m/s.
The erosion rate from the grooves is much less (<0.1 gr/m^2/s) at a mean velocity of 0.4. The erosion rate (mass erosion) increases to about 5 gr/m^2/s at a mean velocity of 0.6 m/s

Based on the results of this test, the critical bed-shear stresses for a mud bed ($p_{sand} \cong$ 50%) with dry density of about 530 kg/m^{3}are estimated to be about:

- initiation of minor surface eroison of sand: $\tau_{b,cr,e}$ = 0.3-0.4 N/m^2;
- initiation of minor surface erosion of mud (local erosion rate of < 0.1 gr/m^2/s): $\tau_{b,cr,e}$ = 0.6-0.7 N/m^2;
- initiation of mass erosion of mud (local erosion rate of 10-20 gr/m^2/s): $\tau_{b,cr,fail}$ = 1.0-1.2 N/m^2.

Time **(hrs)**	**Water depth** **(m)**	**Mean velocity at 8 cm above bed** **(m/s)**	**Bed-shear stress** **(N/m²)**	**Mud concentration OBS3+ at 1 m downstream of mud section (mg/l)**		**Erosion of bed surface**	**Bed rough ness; Chezy (mm) ($m^{0.5}$/s)**	**Bed load fine sand** **(g/m/s)**
				counts (counts-offset)	mg/l			
11.31	0.2	0.17	0.04	350 (offset) (0)	≅ 0	bed surface is very smooth	-	-
11.34	0.2	0.32	0.14	425 (75)	<10	minor movement of individual particles mud	<0.1; 80-90	n.m.
11.41	0.2	0.43	0.25	575 (225)	<20	minor movement of individual particles; rolling sand particles depositing in small depressions	<0.1; 80-90	0.007
12.06	0.2	0.52	0.40	600 (250)	<30	minor movement of individual particles; rolling sand particles depositing in small depressions	<0.1; 80-90	n.m.
12.17	0.2	0.63	0.6	900 (550)	80	generation of small grooves and mud clouds; grooves grow slowly bigger (length=250 mm, width=50 to 100 mm; depth= 5 mm); minor vibration of bed surface	<0.3; 70-80	0.04
12.32	0.2	0.66	0.65	1100 (750)	100	slow growth of grooves	<0.3; 70-80	n.m
12.34	0.2	0.72	0.75	1550 (1200)	200 cws=140	mud clouds eroded from grooves; OBS is not visible	<0.3; 70-80	n.m
12.39	0.2	0.75	0.85	1700 (1350)	200	mud clouds eroded from grooves	<0.3; 70-80	n.m
12.41-12.45 end	0.15	0.9	1.2-1.4	3200 (2850)	500 cws= 1900	Mass erosion of mud; bed collapses; 60% of bed is eroded; mud layer is middle is 20 mm high	<0.3; 70-80	n.m

n.m.= not measured; water temperature≅ 14° C

cws= concentration based on water-sediment sample of 50 ml

Table 5.3.1 *Erosion flume tests with mud bed (dry mud density= 530 kg/m³; 45% sand); fresh water*

Figure 5.3.1 *Mud in container before the test F-N530-ps45%*

Figure 5.3.2 *Mud bed before the test F-N530-ps45%*

<u>EROMES test E-N530-ps45%</u>

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m^3) was mixed first and fine sand (d_{50}≅0.095 mm) was added and mixed again resulting in a dry buk density of about 530 kg/m^3 (similar to that used in the flume test). The mud was used to fill a small wooden frame, see **Section 5.2.1** and **Figure 5.2.2**).

The consolidation between the preparation of the mud bed in the tube and the start of the test was about 19 hours. Just before the test, the tube was carefully filled with seawater (about 1.2 liter) The height of the water column was about 150 mm. The water temperature was 20^o C.

The propeller was installed at the prescribed 30 mm above the mud surface. The OBS3+ optical sensor was mounted in the tube (at about 80 mm from the mud surface).

The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 50 to the maximum value of 350 to observe the behaviour of the mud bed surface. The total test duration was about 1 hours.

The maximum erosion layer at the end of the test was < 1 mm. Mass erosion cannot be generated in the EROMES-tube.

The number of propeller revolutions (N_P) was raised in steps (10 to 20) from 50 onwards to observe the behaviour of the mud bed surface, see **Table 5.3.2**.

The erosion rate is about 0.03 to 0.05 gr/m^2/s for a shear stress of 1$\pm$ 0.2 N/m^2 (see **Table 5.3.2**).
The critical bed-shear stress of surface erosion is assumed to be about 1 N/m^2 for a mud bed with a layer-averaged dry density of 530 kg/m^3 and 45% sand.
The total erosion layer at the end of the EROMES-tests is approximately:
δ_e= ($c_{mud,end}$/ρ_{dry}) h_w = [(0.3 kg/m^3)/530(kg/m^3)] x 0.17 (m) = 0.00009 m $\cong$ 0.1 mm after about 30 min.

Time (s)	**Number of revolutions (N_P) per minute**	**Mud concentration**		**Estimated bed-shear stress (N/m^2)**	**Estimated erosion rate (gram/m^2/s)**	**Erosion of bed surface**
		counts (counts-offset)	**mg/l**			
0-500	70-140	900 (offset) (0)	< 10	< 0.1	<<0.01	clear water; no mud erosion of surface; rolling and suspended particles (silt-sand 30-100 μm) eroded from top surface layer; mud flakes (< 5 mm) are suspended
500-900	140-230	1600 (700)	100	0.25-0.5	<0.01	similar; mud flakes are broken into smaller flakes
900-1200	230-310	2400 (1500)	180	0.5-0.9	<0.01	clear water with suspended mud flakes
1200-1500	310-350	2600 (1700)	200	0.9-1.2	<0.03	turbid water with suspended mud flakes; propeller visible; generation of small groove
1500-1800	350-380	2800 (1900)	220 (cws= 160)	1.2-1.4	<0.05	turbid water with suspended mud flakes; propeller visible; generation of small groove (length=20 mm; width=5 mm)

cws= concentration based on water-sediment sample (50 ml) at end of test

Table 5.3.2 *Erosion results of EROMES test E-N530-ps45%; dry bulk density 530 kg/m^3 (seawater);*

5.3.4 Noordpolderzijl mud; initial dry mud density of 700 kg/m^3; $p_{sand} \cong 55\%$ (March-June 2017)

Flume test F-N700-ps55%

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m^3) was mixed first and fine sand ($d_{50}\cong0.095$ mm, see **Table 3.1**) was added to obtain a mixture with a sand content of 55% (based on sample analysis). The dry bulk density was about 700 kg/m^3 (wet density of 1450-1465 kg/m^3) based on samples taken by a syringe (50 ml). The mud-sand mixture had a soft muddy texture after mixing, see **Figure 5.3.3**. A mud layer with a height of 0.05 m and a flat horizontal surface was made in the mud compartment which was as flush as possible with the adjacent bottom of the flume. The time between the preparation of the mud surface and the start of the test was about 20 hours. The top surface of the bed showed light grey stripes indicating the presence of fine sand and some grooves with depth of 1 mm were visible.
The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section.
The OBS3+ sensor was installed above the rigid flume bottom at about 1 m downstream of the mud section.
The velocity of the fresh water flow was raised in steps from 0.2 to 0.95 m/s to observe the behaviour of the mud bed surface, see **Table 5.3.3**. Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocites.
The erosion rate from the grooves is minor (<0.1 gr/m^2/s) at a mean velocity of 0.4.
The erosion rate (mass erosion) increases to about 5 gr/m^2/s at a mean velocity of 0.7 m/s
Long and wide grooves are generated (mass erosion) in the mud bed surface at a mean velocity of about 0.5-0.95 m/s. These grooves extended gradually in length and in width, see **Figure 5.3.3**. About 70% of the mud section was eroded at the end of the test. The total eroded mass at the end of the test was about 7 liters or 7x700 ≅ 5000 grams of dry mud over an area of 0.4x0.6=0.24 m^2 during a period of about 3 minutes resulting in a mass erosion rate of 100 grams/m^2/s at a velocity of about 0.9 m/s.

Based on the results of this test, the critical bed-shear stresses for a mud bed ($p_{sand} \cong 55\%$) with dry density of about 520 kg/m^{3}are estimated to be about:

- initiation of minor surface erosion of sand: $\tau_{b,cr,e}$ = 0.3 - 0.4 N/m^2;
- initiation of minor surface erosion of mud (initiation of grooves): $\tau_{b,cr,e}$ = 0.5 - 0.7 N/m^2;
- initiation of mass erosion (local erosion rate > 10 gr/m^2/s): $\tau_{b,cr,fail}$ = 1.0 - 1.2 N/m^2.

Figure 5.3.3 *Left: Mud in container before the test F-N700-ps55%*
Right: Erosion of grooves in mud surface

Time (hrs)	Water depth (m)	Mean velocity at 8 cm above bed (m/s)	Bed-shear stress (N/m²)	Mud concentration OBS3+ at 1 m downstream of mud section; 0.04-0.08 m above bottom		Erosion of bed surface	Bed roughness; Chezy (mm) ($m^{0.5}$/s)	Bed load fine sand (g/m/s)
				counts (counts-offset)	mg/l			
11.12	0.2	0	-	500 (offset) (0)	≅ 0	bed surface is very smooth; water turbid	-	-
11.19	0.2	0.14	-	500 (0)	<10	minor movement of individual particles mud	<0.1; 80-90	n.m.
11.21	0.2	0.23	0.07	650 (150)	<10	minor movement of individual particles mud;	<0.1; 80-90	n.m
11.28	0.2	0.27	0.1	650 (150)	<10	minor movement of particles; rolling sand	<0.1; 80-90	0.001
11.33	0.2	0.29	0.12	650 (150)	< 10	similar	<0.1; 80-90	n.m.
11.56	0.2	0.33	0.15	650 (150)	<10	similar	<0.1; 80-90	n.m
12.04	0.2	0.36	0.18	650 (150)	<10	similar	<0.1; 80-90	n.m
12.09	0.2	0.38	0.2	650 (150)	<10	turbid water; erosion of mud/sand from grooves	<0.1; 80-90	0.006
12.19	0.2	0.42	0.25	650 (150)	<10	similar; flakes break loose from surface layer; initiation of grooves	<0.1; 80-90	n.m.
12.23	0.2	0.47	0.35	700 (200)	30	mud clouds from grooves; long groove of 150 mm; 40 mm wide; 10% grooves on surface; 90% flat surface	<0.3; 70-80	0.018
12.35	0.2	0.53-0.57	0.5	750 (250)	50	similar; slow growth of grooves	<0.3; 70-80	n.m.
12.43	0.2	0.60-0.64	0.65	850 (350)	60	similar; slow growth of grooves	<0.3; 70-80	n.m.
12.48	0.2	0.67	0.8	1000 (500)	70	mud clouds from grooves; 20% grooves; 80% smooth	<0.3; 70-80	0.02
12.58	0.2	0.73	1.0	1050 (550)	80	similar	<0.3; 70-80	n.m.
13.00	0.15	0.95	1.6	1100 (600)	cws= 70 mg/l	more grooves	<0.3; 70	n.m.
13.11-13.14	0.15	0.95	1.8	1500 (1000)	200	mass erosion from grooves; 60% grooves; 40% flat, smooth without erosion (mostly upstream)	<0.3; 70	n.m
13.14-13.16	0.15	0.95	1.8	n.m. (black turbid water)	cws= 860 mg/l	stick used to make small hole upstream; mass erosion of bed in 2 min.; black clouds; erosion depth in middle=35 mm;		n.m.

n.m.= not measured; water temperature≅ 15° C

cws= concentration based on water-sediment sample of 50 ml

Table 5.3.3 *Erosion flume tests with mud bed (dry mud density= 700 kg/m³; 55% sand); fresh water*

EROMES test E-N700-ps55%

The Noordpolderzijl mud mixture with 55% sand was used to fill a small wooden frame, see **Section 5.2.1** and **Figure 5.2.2**).

The consolidation between the preparation of the mud bed in the tube and the start of the test was about 18 hours. Just before the test, the tube was carefully filled with seawater (about 1.2 liter) The height of the water column was about 180 mm. The water temperature was 20^o C.

The propeller was installed at the prescribed 30 mm above the mud surface. The OBS3+ optical sensor was mounted in the tube (at about 80 mm above the mud surface).

The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 70 to the maximum value of 350 to observe the behaviour of the mud bed surface. The total test duration was about 40 minutes. The basic data are given in **Table 5.3.4**.

The maximum erosion layer at the end of the test was < 1 mm. Mass erosion cannot be generated in the EROMES-tube.

At end of test, the propeller was lowered to a level of 10 mm above the bed (in stead of 30 mm). Even at the highest speed of N_p=350, the OBS-concentration did not increase (no additionsal erosion of mud from the mud surface).

The total erosion layer at the end of the EROMES-tests is approximately:

δ_e= ($c_{mud,end}/\rho_{dry}$) h_w = [(1 kg/m^3)/700 (kg/m^3)] x 0.18 (m) = 0.0003 m $\cong$ 0.3 mm after about 36 min.

The erosion layer is about 0.1 mm at a mud concentration of cmud= 0.0001x700/0.18=0.4 kg/m^3, which occurs at a shear stress of anout 0.3-0.4 N/m^2 which is defined as initiation of mud erosion.

The critical bed-shear stress of surface erosion is assumed to be about 0.3-0.4 N/m^2 for a mud bed with a layer-averaged dry density of 700 kg/m^3 and 55% sand.

Time (s)	Number of revolutions (N_P) per minute	Mud concentration		Estimated bed-shear stress (N/m^2)	Erosion of bed surface
		counts (counts-offset)	mg/l		
0	0	1200 (offset) (0)	< 10	< 0.1	clear water
0-60	80	1200 (0)	<10	0.1	clear water; individual suspended particles
60-300	100	2000 (800)	80	0.13	clear water; individual suspended particles
300-540	110	3100 (1900)	200	0.14	turbid water; propeller clearly visible
540-660	130	3500 (2300)	250	0.19	similar
660-840	140	3900 (2700)	300	0.22	turbid water; propeller visible
840-1020	170	4500 (3300)	350	0.3	turbid water; propeller visible
1020-1260	190	4700 (3500)	400 cws= 160 mg/l	0.35	turbid water; propeller visible
1260-1380	200	5200 (4000)	450	0.4	turbid water; propeller visible; bottom not visible
1380-1500	210	5700 (4500)	500	0.45	very turbid water; propeller visible
1500-1620	230	5900 (4700)	650	0.5	propeller not visible
1620-1680	250	6000 (4800)	700	0.6	propeller not visible
1680-1840	270	6500 (5300)	7500	0.75	propeller not visible
1840-1960	300	6800 (5600)	800	0.9	propeller not visible
1960-2020	330	6900 (5700)	850	1.1	propeller not visible
2020-2080	350	7100 (5900)	900 cws= 850 mg/l	1.2	propeller not visible

cws= concentration based on water-sediment sample (50 ml) at end of test

Table 5.3.4 *Erosion results of EROMES test E-N700-ps55%; dry bulk density 700 kg/m^3 (seawater);*

5.3.5 Noordpolderzijl mud; initial dry mud density of 1100 kg/m^3; $p_{sand} \cong 80\%$ (March-June 2017)

Flume test F-N1100-ps70%

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m^3) was mixed first and fine sand ($d_{50} \cong 0.095$ mm, see **Table 3.1**) was added to obtain a mixture with a sand content of 70% (based on sample analysis). The dry bulk density was about 1100 kg/m^3 (wet density of 1650-1700 kg/m^3) based on small subsamples. The mud-sand mixture had a soft-firm muddy texture after mixing, see **Figure 5.3.4**. A mud layer with a height of 0.05 m and a flat horizontal surface was made in the mud compartment which was as flush as possible with the adjacent bottom of the flume. The time between the preparation of the mud surface and the start of the test was about 20 hours.
The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section.
The OBS3+ sensor was installed above the rigid flume bottom at about 1 m downstream of the mud section.
The velocity of the fresh water flow was raised in steps from 0.2 to 0.95 m/s to observe the behaviour of the mud bed surface, see **Table 5.3.5**. Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocites.

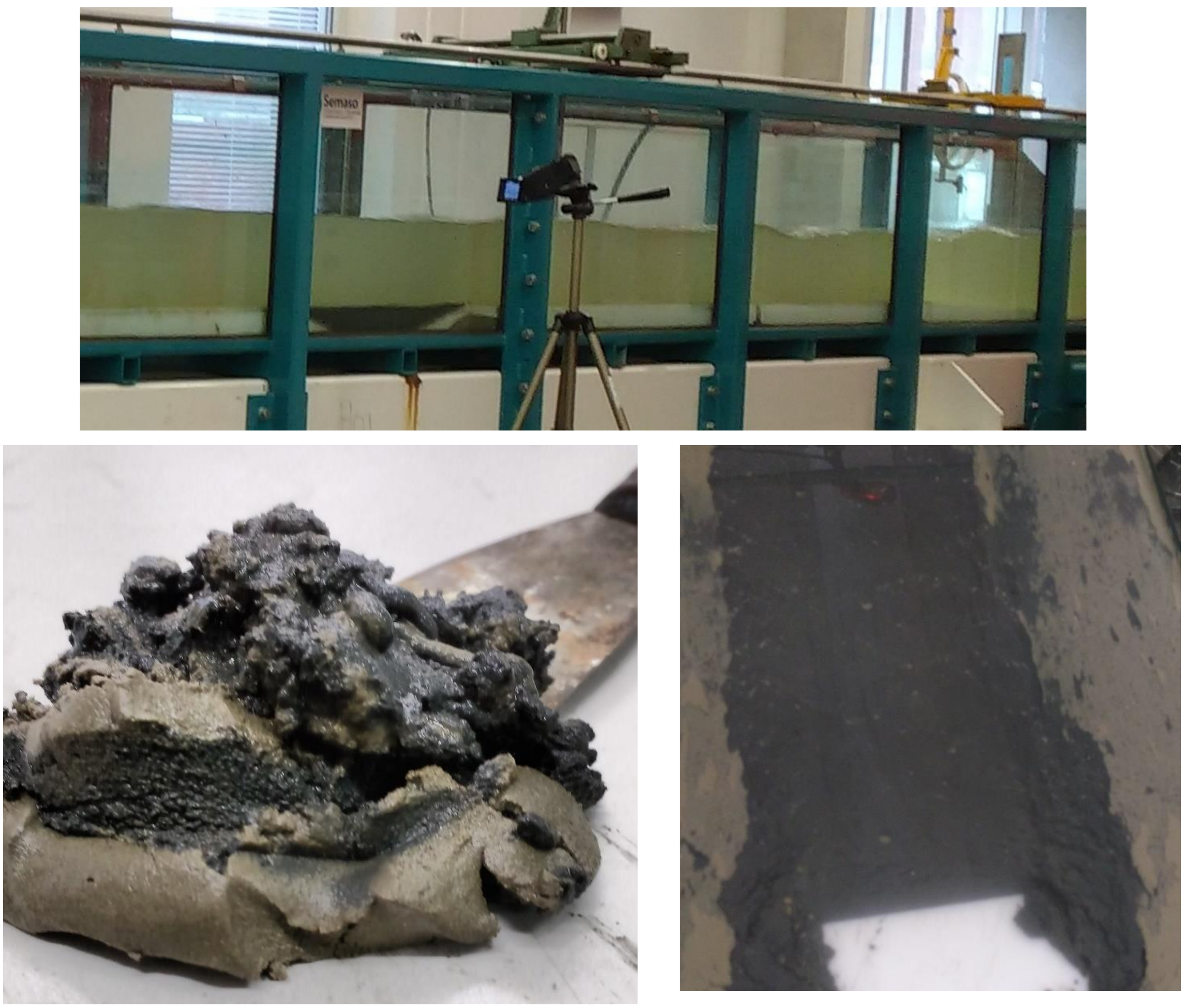


Figure 5.3.4 *Upper: flume set-up*
Lower-Left: Sand-mud before the test F-N1100-ps70%;Lower-Right: Bed surface after the test

The erosion rate from the grooves is minor (<0.1 gr/m^2/s) at a mean velocity of 0.5.
Long and wide grooves are generated (mass erosion) in the mud bed surface at a mean velocity of about 0.8-0.95 m/s. The total eroded mass (local) at the end of the test is estimated to be about 100 grams/m^2/s at a velocity of about 0.95 m/s.
Based on the results of this test, the critical bed-shear stresses for a mud bed ($p_{sand} \cong$ 80%) with dry density of about 1100 kg/m^{3}are estimated to be about:

- initiation of minor sand erosion: $\tau_{b,cr,e}$= 0.3-0.4 N/m^2;
- initiation of minor mud erosion; initiation of grooves (erosion rate < 0.1 gr/m^2/s): $\tau_{b,cr,e}$= 0.4-0.6 N/m^2;
- initiation of mass erosion (local erosion rate > 10 gr/m^2/s): $\tau_{b,cr,fail}$ =1.2-1.4 N/m^2.

Time (hrs)	**Water depth** (m)	**Mean velocity at 8 cm above bed** (m/s)	**Bed-shear stress** (N/m^2)	**Mud concentration OBS3+ at 1 m downstream of mud section; 0.04-0.08 m above bottom (mg/l)**		**Erosion of bed surface**	**Bed rough ness; Chezy (mm) (m$^{0.5}$/s)**	**Bed load fine sand (g/m/s)**
				counts (counts-offset)	mg/l			
11.17	0.2	0.2	0.055	400 (offset) (0)	≅ 0	bed surface is very smooth; water turbid	<0.1 80-90	-
11.25	0.2	0.4	0.22	600 (200)	30	bed surface is very smooth; water turbid	<0.1 80-90	0.0083 (10 minutes)
11.46	0.2	0.51	0.40	750 (350)	50	small craters and grooves locally (max 40 mm long; 1 mm deep)	<0.1 80-90	0.025 (10 min)
11.59	0.2	0.65	0.60	900 (500)	70	more grooves (1-2 mm deep); ott-propeller visible	<0.3 70-80	0.05 (10 min)
12.13	0.2	0.71	0.8	950 (550)	80	similar	<0.3 80-90	-
12.17	0.2	0.77	0.9	1050 (650)	90	similar	<0.3 70-80	-
12.21	0.17	0.90	1.3	1150 (750)	100	long grooves (max 400 mm)	<0.3 70-80	0.05 (10 min)
12.32	0.15	0.95	1.6	-	-	similar; mass erosion at small local disturbances	<0.3 70-80	-

n.m.= not measured; water temperature≅ 15° C

Table 5.3.5 *Erosion flume tests with mud bed (dry mud density= 1100 kg/m^3; 70% sand); fresh water*

EROMES test E-N1100-ps70%

The Noordpolderzijl mud mixture with 70% sand was used to fill a small wooden frame, see **Section 5.2.1** and **Figure 5.2.2**).
The consolidation between the preparation of the mud bed in the tube and the start of the test was about 18 hours. Just before the test, the tube was carefully filled with seawater (about 1.2 liter) The height of the water column was about 170 mm. The water temperature was 20° C.
The propeller was installed at the prescribed 30 mm above the mud surface. The OBS3+ optical sensor was mounted in the tube (at about 80 mm above the mud surface).
The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 70 to the maximum value of 380 to observe the behaviour of the mud bed surface. The total test duration was about 35 minutes. The basic data are given in **Table 5.3.6**. At end of test, the propeller was lowered to a level of 10 mm above the bed (in stead of 30 mm). Small depressions are visible at the end of the test (propeller at 10 mm above bed), see **Figure 5.3.5**.

Based on the test results, the critical bed-shear stresses of surface erosion for a mud bed with a layer-averaged dry density of 1100 kg/m^3 and 70% sand are assumed to be about:

- initiation of surface erosion of mud: $\tau_{b,cr,e}$ = 0.5-0.8 N/m^2
- initiation of mass erosion: $\tau_{b,cr,e}$ = 2-2.2 N/m^2.

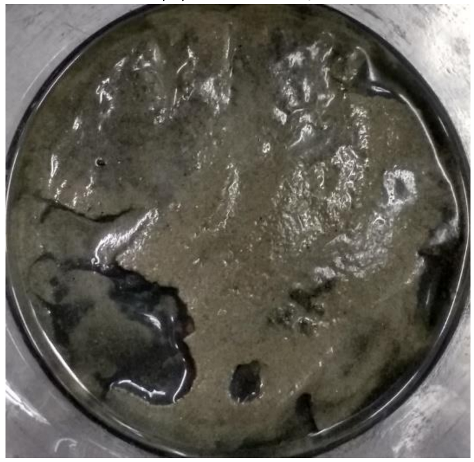


Figure 5.3.5 *Bed surface after EROMES-test E-N1100-ps70%*

Time (s)	Number of revolutions (N_P) per minute	Mud concentration counts (counts-offset)	mg/l	Estimated bed-shear stress (N/m^2)	Erosion of bed surface
0	0	700 (offset) (0)	< 10	< 0.1	clear water
0-120	70	850 (150)	20		clear water; individual suspended particles
120-300	110	1200 (500)	70		clear water; individual suspended particles
300-420	130	1350 (650)	80		clear water; individual suspended particles
420-540	150	1500 (800)	90	0.25	sand particles rolling over surface
540-600	170	1650 (950)	100		similar
600-720	190	1800 (1100)	120		similar
720-840	210	1900 (1200)	130		similar
840-900	230	2100 (1400)	150	0.5	similar; propeller visible
900-1020	250	2300 (1600)	170		similar
1020-1200	270	2400 (1700)	190		similar
1200-1380	290	2500 (1800)	200	0.8	small crater (5 mm); propeller visible; clouds of fine sand
1380-1500	310	2600 (1900)	230	0.95	slow growth of crater
1500-1680	330	2700 (2000)	250	1.1	similar
16801800	350	2900 (2200)	300	1.3	similar
1800-2040	370	3400 (2700)	400	1.5	small grooves; propeller visible
Propeller at 10 mm 2040-2100	380	>10000	1000	2.0-2.2	initiation of mass erosion

cws= concentration based on water-sediment sample (50 ml)

Table 5.3.6 *Erosion results of EROMES test E-N1100-ps70%; dry bulk density 1100 kg/m^3 (seawater)*

5.3.6 Noordpolderzijl mud; initial dry mud density of 1450 kg/m^3; $p_{sand} \cong 75\%$ (March-June 2017)

Flume test F-N1450-ps75%

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m^3) was mixed first and very fine sand ($d_{50}\cong$0.095 mm, see **Table 3.1**) was added to obtain a mixture with a sand content of 75% (based on sample analysis). The dry bulk density was about 1450 kg/m^3 (wet density of 1850-1950 kg/m^3) based on small subsamples. The mud-sand mixture had a lumpy texture after mixing, see **Figure 5.3.6**. A mud layer with a height of 0.05 m and a flat horizontal surface was made in the mud compartment which was as flush as possible with the adjacent bottom of the flume. The time between the preparation of the mud surface and the start of the test was about 1 hour.
The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section. The OBS3+ sensor was installed above the rigid flume bottom at about 1 m downstream of the mud section.
The velocity of the fresh water flow was raised in steps from 0.2 to 0.95 m/s to observe the behaviour of the mud bed surface, see **Table 5.3.7**. Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocities. **Figure 5.3.7** shows the bed at the end of the flume test.

Figure 5.3.6 *Sand-mud mixture with 75% fine sand (lumpy texture)*

Small craters and small grooves are generated (mass erosion) in the mud bed surface at a mean velocity of about 0.8-0.95 m/s. The total eroded mass (local) at the end of the test is estimated to be about 10-100 grams/m^2/s at a velocity of about 0.9 m/s.
Based on the results of this test, the critical bed-shear stresses for a sand-mud bed ($p_{sand} \cong 75\%$) with dry density of about 1450 kg/m^{3}are estimated to be about:

- initiation of minor surface erosion of sand: $\tau_{b,cr,e}$ = 0.25 - 0.35 N/m^2;
- initiation of minor surface erosion of mud (initiation of grooves): $\tau_{b,cr,e}$ = 0.6 - 0.8 N/m^2;
- initiation of mass erosion (local erosion rate > 100 gr/m^2/s): $\tau_{b,cr,fail}$ = 1.4 - 1.6 N/m^2.

Figure 5.3.7 *Bed suraface at end of flume test (75% sand)*

Time (hrs)	Water depth (m)	Mean velocity at 8 cm above bed (m/s)	Bed-shear stress (N/m^2)	Mud concentration OBS3+ at 1 m downstream of mud section; 0.04-0.08 m above bottom (mg/l)		Erosion of bed surface	Bed rough ness; Chezy (mm) (m$^{0.5}$/s)	Bed load fine sand (g/m/s)
				counts (counts-offset)	mg/l			
14.00	0.2	0.28	0.11	1300 (offset) (0)	≅ 0	bed surface is very smooth; water turbid	<0.1 80-90	-
14.02	0.2	0.34	0.16	1350 (50)	<10	similar	<0.1 80-90	
14.04	0.2	0.4	0.22	1375 (75)	<10	similar; erosion of top layer ; rolling particles od mud/sand	<0.1 80-90	BLT1 0.025
14.17	0.2	0.45	0.28	1400 (100)	10	similar	<0.1 80-90	
14.22	0.2	0.52	0.37	1450 (150)	20	similar	<0.1 80-90	BLT2 0.055
14.36	0.2	0.66	0.6	1600 (300)	50	similar	<0.1 80-90	BLT3 0.027
14.49	0.2	0.76	0.8	1750 (450)	70	small craters (5 mm)	<0.1 80-90	BLT1 0.015
15.03	0.17	0.88	1.3	1800 (500)	80	similar	<0.3 70-80	-
15.05	0.15	0.95	1.6	2000 (700)	100	growth of crater; small grooves (30 mm; 1-2 mm deep); erosion from craters; initiation of mass erosion at disturbances	<0.3 70-80	-

n.m.= not measured; water temperature≅ 15° C

Table 5.3.7 *Erosion flume test with mud bed (dry mud density= 1450 kg/m^3; 75% sand); fresh water*

EROMES test E-N1450-ps75%

The Noordpolderzijl mud mixture with 75% sand was used to fill a small wooden frame, see **Section 5.2.1** and **Figure 5.2.2**).

The consolidation between the preparation of the mud bed in the tube and the start of the test was about 1 hours. Just before the test, the tube was carefully filled with seawater (about 1.2 liter) The height of the water column was about 170 mm. The water temperature was 20° C.

The propeller was installed at the prescribed 30 mm above the mud surface. The OBS3+ optical sensor was mounted in the tube (at about 80 mm above the mud surface).

The number of propeller revolutions (N_p) was raised in steps (10 to 20) from 70 to the maximum value of 380 to observe the behaviour of the mud bed surface. The total test duration was about 35 minutes. The basic data are given in **Table 5.3.8**. At end of test, the propeller was lowered to a level of 10 mm above the bed (in stead of 30 mm). Small depressions are visible at the end of the test (propeller at 10 mm above bed), see **Figure 5.3.8**.

Based on the results of this test, the critical bed-shear stresses are estimated to be about:

- initiation of minor surface erosion of mud: $\tau_{b,cr,e}$ = 0.6-0.8 N/m^2;
- initiation of mass erosion of mud: $\tau_{b,cr,fail}$ =1.4-1.6 N/m^2.

Figure 5.3.8 *Bed surface after EROMES-test E-N1450-ps75%*

Time (s)	Number of revolutions (N$_P$) per minute	Mud concentration		Estimated bed-shear stress (N/m^2)	Erosion of bed surface
		counts (counts-offset)	mg/l		
0	0	800 (offset) (0)	< 10	< 0.1	clear water; very smooth surface
0-120	70	1000 (200)	20	<0.1	similar
120-240	90	1000 (200)		0.1	similar
240-300	110	1000 (200)			similar
300-420	120	1000 (200)			similar
420-540	140	1000 (200)			similar
540-600	160	1000 (200)			similar
600-720	170	1000 (200)	20	0.35	similar
720-840	190	1050 (250)		0.4	fine sand is accumulated in middle under propeller
840-900	210	1100(300)	40	0.45	clouds of fine sand visible
900-960	220	1150 (350)	40		similar
960-1080	240	1200 (400)	50		similar
1080-1200	270	1250 (450)	70	0.6	small craters (3 mm); propeller very visible; many clouds of fine sand
1200-1320	290	1250 (450)	70	0.85	similar
1320-1440	310	1250 (450)	70	0.95	similar
1440-1500	330	1250 (450)	70	1.1	similar
1500-1620	360	1350 (550)	80	1.4	similar
1620-1740	380	1400 (600)	90	1.7	growth of craters (5 mm); dark flocs (3 mm) are suspended
Propeller at 10 mm 1740-2220	350-360	1400-4500 (600-3700)	400 cws= 250 mg/l	2.2-2.5	growth of craters to 20 mm; bed not visible; initiation of mass erosion

cws= concentration based on water-sediment sample (50 ml) at end of test

Table 5.3.8 *Erosion results of EROMES test E-N1450-ps75%; dry bulk density 1450 kg/m^3 (seawater)*

5.3.7 Noordpolderzijl mud; initial dry mud density of 1450 kg/m^3; $p_{sand} \cong 85\%$ (March-June 2017)

Flume test F-N1450-ps85%

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m^3) was mixed first and fine sand ($d_{50} \cong$ 0.18 mm, **Figure 5.3.12**) was added to obtain a mixture with a sand content of 85% (based on sample analysis). The dry bulk density was about 1450 kg/m^3 (wet density of 1850-1950 kg/m^3) based on small subsamples. The mud-sand mixture had a lumpy texture after mixing and a cohesive appearance, see **Figure 5.3.9**. A sediment layer with a height of 0.05 m and a flat horizontal surface was made in the mud compartment which was as flush as possible with the adjacent bottom of the flume. The time between the preparation of the mud surface and the start of the test was about 15 hours.

The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section. The velocity of the fresh water flow was raised in steps from 0.2 to 0.6 m/s to observe the behaviour of the sediment bed surface, see **Table 5.3.9**. The mud concentrations were very small and estimated visually. Small isolated sand ripples were generated at a depth-mean velocity of about 0.45-0.5 m/s and trapped in the downstream slot.

Based on the results of this test, the critical bed-shear stresses for a sand-mud bed ($p_{sand} \cong 85\%$) with dry density of about 1450 kg/m^{3}are estimated to be about:

- initiation of minor surface erosion of sand: $\tau_{b,cr,e}$ = 0.2 - 0.3 N/m^2;
- initiation of generation of small isolated sand ripples $\tau_{b,cr,e}$ = 0.4 -0.5 N/m^2;
- initiation of minor surface erosion of mud: $\tau_{b,cr,e}$ = 0.25-0.3 N/m^2.

Figure 5.3.9 *Sand-mud mixture with 85% fine sand (lumpy texture)*
Upper: before the test; Lower: after the test during removal of sediment bed

Figure 5.3.10 *Sand-mud mixture with 85% fine sand (lumpy texture); lighter spots are sand spots where mud film is removed due to erosion*

Time (hrs)	Water depth (m)	Mean velocity at 8 cm above bed (m/s)	Bed-shear stress (N/m²)	Mud concentration OBS3+ at 1 m downstream of mud section (mg/l)	Erosion of bed surface	Bed rough ness; Chezy (mm) ($m^{0.5}$/s)	Bed load fine sand (g/m/s)
10.40	0.2	0.23	0.11	≅ 0	bed surface is very smooth with a thin mud film as top layer; water is clear; no movement	<0.3; 70	-
10.43	0.2	0.30	0.18	<5	movement of individual sand/mud particles	<0.3 70	
10.45-11.02	0.2	0.35	0.25	<10	mud film is removed locally and white sandy spots are visible; movement at 5% of bed	<0.3 70	BLT1 0.009
11.05	0.2	0.41	0.33	≅10	similar; no ripples	<0.3 70	n.m.
11.12-11.27	0.2	0.49	0.48	≅20	small isolated ripples (height=1 mm; length=20-30 mm) move over sediment bed and rigid downstream bottom	<0.3 70	BLT2 0.043
11.28-11.43	0.2	0.6	0.7	< 30	small craters are eroded locally; sand enters suspension immediately; no isolated ripples	<0.3 70	BLT3 0.022

n.m.= not measured; water temperature≅ 16° C

Table 5.3.9 *Erosion flume test with mud bed (dry mud density= 1450 kg/m³; 85% sand); fresh water*

5.3.8 Noordpolderzijl mud; initial dry mud density of 1450 kg/m³; $p_{sand} \cong 90\%$ (March-June 2017)

Flume test F-N1450-ps90%

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m³) was mixed first and fine sand ($d_{50} \cong$ 0.18 mm, **Figure 5.3.12**) was added to obtain a mixture with a sand content of 90% (based on sample analysis). The dry bulk density was about 1450 kg/m³ (wet density of 1850-1950 kg/m³) based on small subsamples. The mud-sand mixture had a lumpy texture after mixing and a cohesive appearance, see **Figure 5.3.11**. A sediment layer with a height of 0.05 m and a flat horizontal surface was made in the mud compartment which was as flush as possible with the adjacent bottom of the flume. The time between the preparation of the mud surface and the start of the test was about 1 hour.

The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section. The velocity of the fresh water flow was raised in steps from 0.2 to 0.55 m/s to observe the behaviour of the sediment bed surface, see **Table 5.3.10**. The mud concentrations were very small and estimated visually. Small isolated sand ripples were generated at a depth-mean velocity of about 0.4-0.45 m/s and trapped in the downstream slot.

Based on the results of this test, the critical bed-shear stresses for a sand-mud bed ($p_{sand} \cong 90\%$) with dry density of about 1400 kg/m³are estimated to be about:

- initiation of minor surface erosion of sand: $\tau_{b,cr,e}$ = 0.2-0.25 N/m²;
- initiation of generation of small isolated sand ripples $\tau_{b,cr,e}$ = 0.4-0.45 N/m²;
- initiation of minor surface erosion of mud: $\tau_{b,cr,e}$ = 0.2-0.25 N/m².

Figure 5.3.11 *Sand-mud mixture with 90% fine sand (lumpy texture)*
Upper: before the test; Lower: after the test during removal of sediment bed

Time (hrs)	Water depth (m)	Mean velocity at 8 cm above bed (m/s)	Bed-shear stress (N/m^2)	Mud concentration OBS3+ at 1 m downstream of mud section (mg/l)	Erosion of bed surface	Bed rough ness; Chezy (mm) ($m^{0.5}/s$)	Bed load fine sand (g/m/s)
12.25	0.2	0.23	0.11	≅ 10	bed surface is very smooth with a thin mud film as top layer; water is slightly turbid; no movement	<0.3; 70	-
12.30	0.2	0.25	0.13	<20	movement of individual sand/mud particles	<0.3 70	
12.32-12.47	0.2	0.3	0.18	<20	mud film is removed locally and white sandy spots are visible; movement at 5% of bed	<0.3 70	BLT1 0.004
12.48-13.06	0.2	0.35	0.25	≅20	similar; no ripples	<0.3 70	BLT2 0.013
13.08-13.23	0.2	0.44	0.4	≅20	small isolated ripples (height 1=mm; length=20-30 mm; v=0.15 m per minute) move over sediment bed and rigid downstream bottom	<0.3 70	BLT3 0.048
13.27-13.42	0.2	0.54	0.6	< 30	about 10% of surface is moving; no ripples; sand goes into suspension	<0.3 70	BLT3 0.24

n.m.= not measured; water temperature≅ 16° C

Table 5.3.10 *Erosion flume test with mud bed (dry mud density= 1450 kg/m³; 90% sand); fresh water*

5.3.9 Noordpolderzijl mud; initial dry mud density of 1450 kg/m³; p_{sand} ≅ 95% (March-June 2017)

Flume test F-N1450-ps95%

The Noordpolderzijl mud of the base container (about ρ_{dry}= 425 kg/m³) was mixed first and fine sand (d_{50}≅ 0.18 mm, **Figure 5.3.12**) was added to obtain a mixture with a sand content of 95% (based on sample analysis). The dry bulk density was about 1450 kg/m³ (wet density of 1850-1950 kg/m³) based on small subsamples. The mud-sand mixture had a slighty dy and lumpy texture after mixing, see **Figure 5.3.13**. A sediment layer with a height of 0.05 m and a flat horizontal surface was made in the mud compartment which was as flush as possible with the adjacent bottom of the flume. The time between the preparation of the mud surface and the start of the test was 1 hour. The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section. The velocity of the fresh water flow was raised in steps from 0.2 to 0.55 m/s to observe the behaviour of the sediment bed surface, see **Table 5.3.11.** The mud concentrations were very small and estimated visually. Turbid water was present due to gradual loading of flume water with fine sediments. Three tests with 85%, 90% and 95% sand were done successively on one day.

Three-dimensional sand ripples are generated at a depth-mean velocity of about 0.4-0.45 m/s; isolated sand ripples moved over the rigid bottom surface downstream of the bed (**Figures 5.3.14** and **5.3.15**).

Based on the results of this test, the critical bed-shear stresses for a sand-mud bed (p_{sand}≅ 95%) with dry density of about 1450 kg/m³are estimated to be about:

- initiation of minor surface erosion of sand: $\tau_{b,cr,e}$ = 0.15-0.2 N/m²;
- initiation of generation of sand ripples $\tau_{b,cr,e}$ = 0.3-0.5 N/m²;
- initiation of minor surface erosion of mud: $\tau_{b,cr,e}$ = 0.15-0.2 N/m².

Figure 5.3.12 *Sand of 180 μm without mud*

Figure 5.3.13 *Sand-mud mixture with 95% fine sand (slightly lumpy texture)*

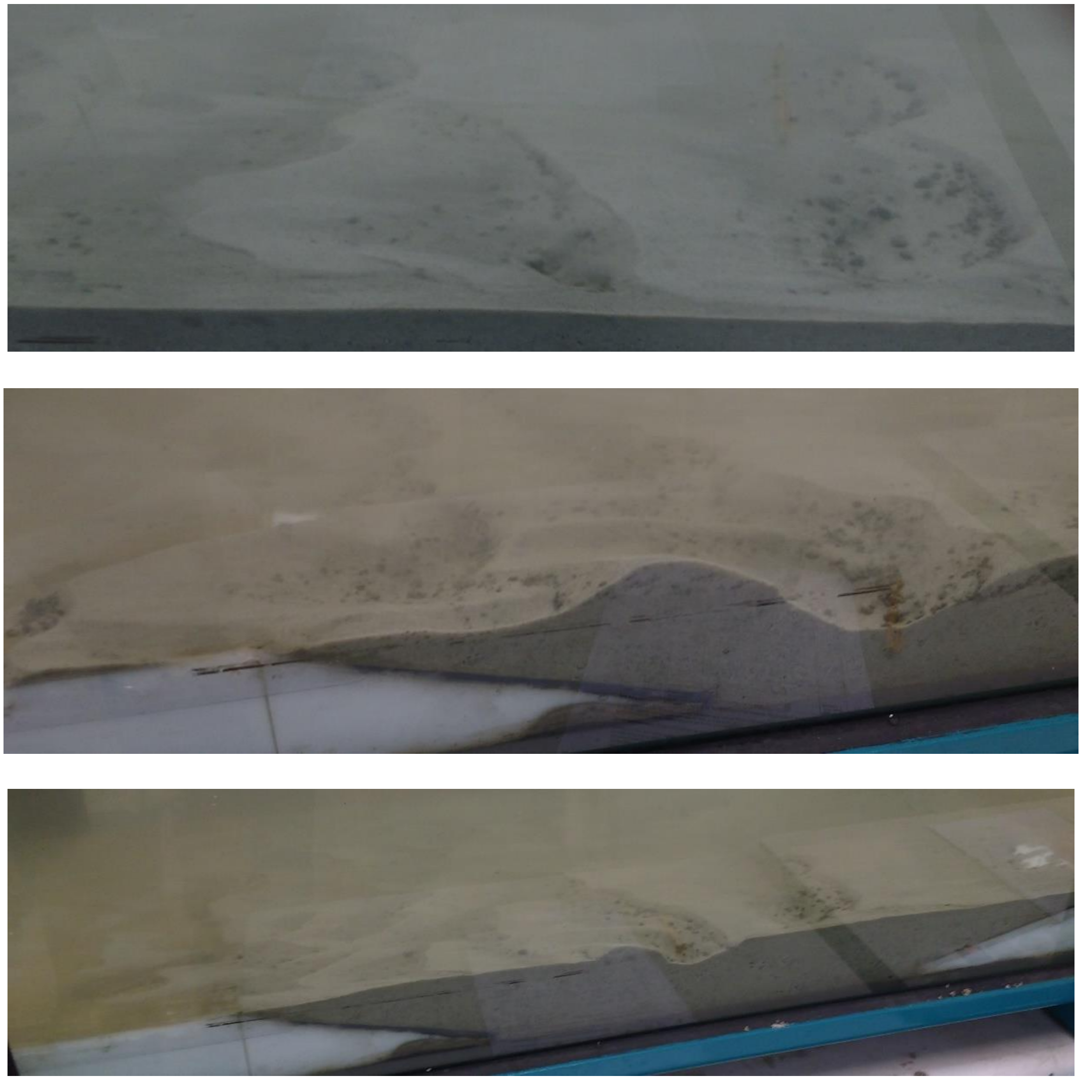


Figure 5.3.14 *Generation of sand ripples at sediment bed; 95% sand*

Figure 5.3.15 *Movement of isolated sand ripples over rigid bottom downstream of bed; 95% fine sand*

Time (hrs)	Water depth (m)	Mean velocity at 8 cm above bed (m/s)	Bed-shear stress (N/m^2)	Mud concentration OBS3+ at 1 m downstream of mud section (mg/l)	Erosion of bed surface	Bed rough ness; Chezy (mm) ($m^{0.5}/s$)	Bed load fine sand (g/m/s)
14.32	0.2	0.20	0.08	≅ 20	bed surface is very smooth with a thin mud film as top layer; water is turbid; no movement	<0.3; 70	0
14.40- 14.55	0.2	0.29	0.17	≅ 30	movement of individual sand/mud particles as rolling transport; thin transport layer; 5% moving	<0.3 70	BLT1 0.02
14.58- 15.13	0.2	0.38	0.29	≅ 40	30% of surface is moving (sandy spots); no clear ripples at bed; isolated ripples moving over rigid bed	<0.3 70	BLT1 0.084
15.16- 15.26	0.2	0.44	0.50	≅ 50	3D ripples are generated; length=0.1-0.2 m; height=20-30 mm; transport layer of about 50 mm high with suspended sediment	<5 60	BLT2 0.42

n.m.= not measured; water temperature≅ 16° C

Table 5.3.11 *Erosion flume test with mud bed (dry mud density= 1450 kg/m^3; 95% sand); fresh water*

5.4 Erosion tests of unmoulded, in situ mud-sand beds Noordpolderzijl (2017 and 2018)

5.4.1 General

In June 2017 and in March-April 2018, various mud surface samples were taken at the ocations B5 to B16 in Noordpolderzijl using the EROMES-tubes, see **Figure 3.2.** Small samples were taken to determine the wet bulk density. EROMES-tube samples were taken at the same time to be tested in a local field laboratory, which was setup in the building of the pumping station. The EROMES-tube is pressed into the dry bed, the surrounding mud is removed and the tube is closed by using a bottom plate. Four locations could be sampled in one walk at low tide; the tubes were placed in a small sledge which was towed to the field laboratory.
The dry bulk density and the percentage of sand (> 63 μm) have been determined in the laboratory, see **Table 5.4.4** and **Figure 3.3**.

In April 2018, four (undisturbed) in-situ samples were taken at locations B5, B7, B9 and B15 (**Figure 3.2**) using a small metal tray (length=0.4 m; width=0.4 m; height=0.05 m), see **Figure 5.4.3** The tray is open at two sides and can be pushed horizontally through the bed to sample a slice of mud. The tray with mud is placed into another tray with closed sides and returned to the flume, where it is placed into the measurement section of the flume, see **Figure 5.4.3**. To allow the sample to come to rest, the in-situ sample was tested the next day (resting/consolidation time of 15 hours).

5.4.2 Noordpolderzijl mud; Eromes tests of in situ samples (June 2017; March 2018)

EROMES tests June 2017; E-N400-ps30% (IS)
In-situ EROMES tests have been done using mud samples from three locations (M03, M04 and M05; June 2017) in the harbour basin area (**Figure 3.2**). At each location the perspex tube (without bottom plate) of the EROMES was pushed into the bed surface over a height of about 100 mm. The mud around the tube was removed and the bottom plate of the tube was carefully put in place to close the tube at the bottom side. After that, the tube was removed from the bed in vertical position and returned to the local field laboratory and immediately tested by installing and using the propeller. At each location, the wet bulk density of the mud surface was determined by taking a small sample with a steel ring of 100 ml. **Figures 5.4.1** and **5.4.2** show typical mud samples from the field site (after sampling and before testing).

The test results are presented in **Tables 5.4.1**, **5.4.2** and **5.4.3**.
The wet bulk density of the three field samples (thickness of about 0.03 m) vary in the range of 1330 to 1465 kg/m^3 resulting in a mean value of 1400$\pm$70 kg/m^3. Based on this, the dry bulk density is 600$\pm$100 kg/m^3. The very wet soft top layer (say 3 to 5 mm) of the bed is assumed to have dry bulk density of about 400 kg/m^3. The percentage of sand is about p_{sand}=30%.
The EROMES-results can be used to determine the critical bed-shear stress for particle erosion and for surface erosion, as follows:

- particle erosion (particles and flocs suspended): revolutions per minute = 80-100; critical bed-shear stress= 0.13 N/m^2;
- surface erosion (propeller and bed hardly visible): revolutions per minute= 160-180; critical bed-shear stress= 0.3 N/m^2.

The critical stress at mass erosion (bed failure) cannot be determined from the EROMES-results.

Figure 5.4.1 *EROMES tube after in-situ sampling; 13 June 2017*

Time **(minutes)**	**Number of revolutions (N_P) per minute**	**Mud concentration (mg/l)**	**Erosion of bed surface**
0	0	≅10-50	Irregular bed surface, water slightly turbid
0-1	30		Similar
1-3	50		Fine particles move/roll along the bed
3-5	70		Fine particles and flocs are suspended
5-7	90		Water becomes turbid
7-9	110		Relatively large flocs are suspended
9-10	130		Similar
10-12	140	≅ 200-400	Water very turbid
12-15	160	≅ 500-700	Continuous erosion of bed surface; water very turbid; propeller hardly visible
15-17	170		Bed surface hardly visible
17-19	190		Similar
19-21	220		Similar
21-23	240	≅ 1000-2000	Water almost black

mud layer thickness= 88 mm; water height in column=175 mm; propeller height above bed surface= 30 mm
water temperature= 18 ^oC; wet bulk density= 1465 kg/m^3

Table 5.4.1 *In-situ EROMES test of mud sample from location M03; 13 June 2017*

Time (minutes)	Number of revolutions (N_P) per minute	Mud concentration (mg/l)	Erosion of bed surface
0		≅ 10-50	Irregular bed surface, water slightly turbid
0-1	40		Fine particles move/roll along the bed
1-3	60		Similar
3-5	80		Larger flocs move along bed surface; small particles are suspended
5-7	100		Water is more turbid
7-9	130		Flocs are eroded from the bed surface
9-11	150	≅ 200-400	Bed surface is smooth due to erosion
11-13	160	≅ 500-700	Water very turbid; propeller hardly visible
13-15	190		Continuous erosion
15-17	220	≅ 1000-2000	Water is black; propeller not visible

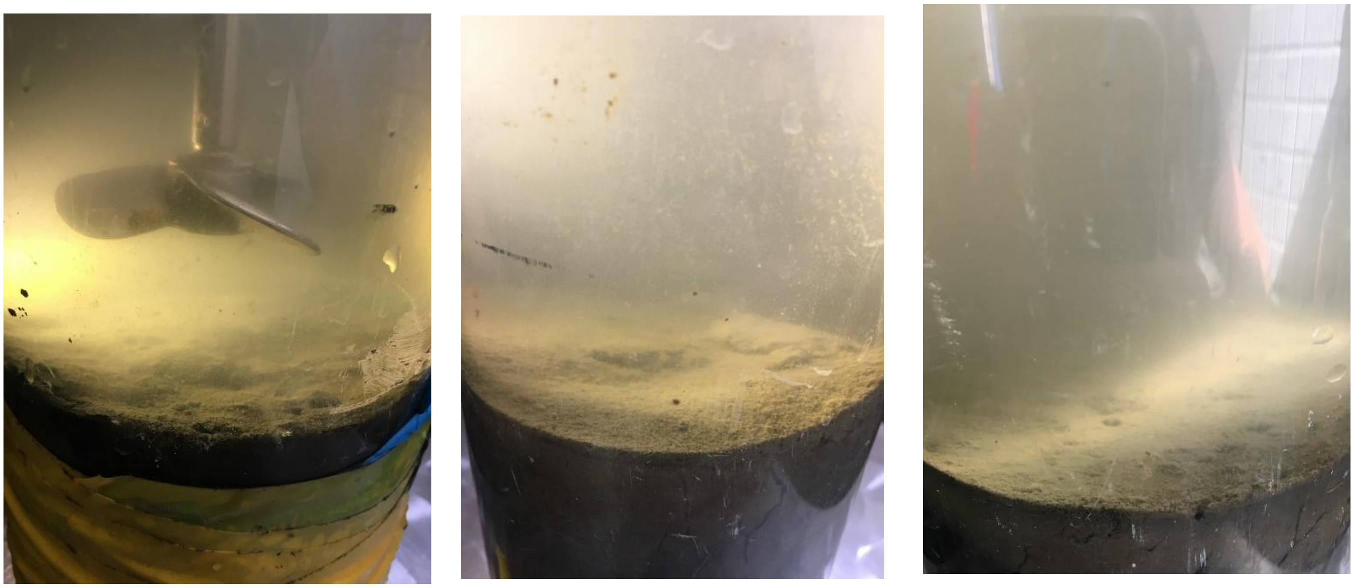
mud layer thickness= 125 mm; water height in column=160 mm; propeller height above bed surface= 30 mm
water temperature= 18 ^{o}C; wet bulk density= 1330 kg/m^3

Table 5.4.2 *In-situ EROMES test of mud sample from location M04; 13 June 2017*

Time (minutes)	Number of revolutions (N_P) per minute	Mud concentration (mg/l)	Erosion of bed surface
0		≅ 10-50	Smooth bed surface
0-2	30		-
2-4	60		Fine particles move/roll along the bed
4-6	80-90		Similar
6-8	110		Larger flocs move along bed surface; small particles are suspended
8-10	130-140		water is turbid; propeller is visible
10-12	150	≅ 200-400	Larger flocs are eroded from the bed surface
12-14	180	≅ 500-700	Water very turbid; propeller hardly visible
14-16	200		Continuous erosion; water very turbid
16-18	220		Similar
18-20	240	≅ 1000-2000	Propeller not visible; water almost black

mud layer thickness= 125 mm; water height in column=170 mm; propeller height above bed surface= 30 mm
water temperature= 18 ^{o}C; wet bulk density= 1350 kg/m^3

Table 5.4.3 *In-situ EROMES test of mud sample from location M05; 13 June 2017*



M03 M04 M05

Figure 5.4.2 *Mud surface before in-situ tests*

<u>EROMES tests March 2018</u>

In all, 12 samples from locations B5-B16 have been tested, see **Table 5.4.4**.

Eromes tests show very variable results, as only a very small surface sample with diameter of 0.1 m is used. Visual observation and analyis of the Eromes-results shows that the presence of a very smooth surface without protrusions consisting of cohesive materials leads to relatively high critical bed-shear stresses. In some tests it was not possible to generate surface erosion at all (tests B9 and B15-1) for bed-shear stresses < 1.5 N/m^2. In other tests with a more irregular sandy surface the critical shear stress for surface erosion was much lower.

Overall, the critical bed-shear stress for surface erosion based on the EROMES-tests can be represented by:

- dry density= 600-1000 kg/m³ and ps=50%-70%: $\tau_{b,cr,e}$= 0.9 $\pm$ 0.3 N/m^2;
- dry density= 1000-1450 kg/m³ and ps=70%-90%: $\tau_{b,cr,e}$= 0.6 $\pm$ 0.2 N/m^2;
- dry density > 1450 kg/m³ and ps > 90%: $\tau_{b,cr,e}$= 0.3 $\pm$ 0.1 N/m^2.

Sample	Wet and dry bulk density (kg/m³)	Number revolu tions (-/min)	Bed-shear stress (N/m²)	Turbidity in water column	Erosion description
B5 (ps=57%) E-N670-ps57%	1450 (670)	300	0.9	low	organic materials are fully suspended
		330	1.1	medium (pjv)	more organic material is suspended
		370	1.4	high (pnv)	very turbid water; propeller not visible
		end	0	high	remains turbid; propeller not visible after 2 min.
B6 (ps=71% E-N1020-ps71%	1648 (1020)	170	0.3	low	minor particle movement
		200	0.4	medium (pjv)	particle movement mud and sand
		250	0.6	high (pnv)	intensive particle movement sand and mud
B7 (ps=66% E-N950-ps66%	1603 (950)	200	0.4	low	minor particle movement
		260	0.7	medium (pjv)	particle movement mud and sand
		280	0.8	high (pnv)	intensive particle movement sand and mud
B8 (ps=58% E-N800-ps58%	1512 (800)	220	0.5	low	particle erosion mud
		260	0.7	medium (pjv)	particle movement mud and sand
		310	0.95	high (pnv)	intensive particle movement sand and mud
B9 (ps=78% E0N990-ps78%	1635 (990)	370	1.5	clear	very smooth surface; no irregularities; no movement at surface
B10 near middle (ps=74%) E-N970-ps74%	1618 (970)	220	0.5	low	particle erosion
		260	0.7	medium (pjv)	particle movement mud and sand; turbidity in lower part of column
		280	0.8	high (pnv)	intensive particle movement sand and mud
B10 side (ps=74%) E-N1400-ps74%	1884 (1400)	280	0.8	low	particle erosion mud
		320	1.0	medium (pjv)	particle movement mud and sand
		350	1.3	high (pnv)	intensive particle movement sand and mud
B11 (ps=78%) E-N1025-ps78%	1658 (1025)	170	0.3	low	particle erosion mud
		210	0.45	medium (pjv)	particle movement mud and sand
		240	0.55	high (pnv)	intensive particle movement sand and mud
B12 (ps=95%) E-N1545-ps95%	1970 (1545)	170	0.3	low	particle erosion mud
		210	0.45	medium (pjv)	particle movement mud and sand
		260	0.7	high (pnv)	intensive particle movement sand and mud
B13 (muddy sand (ps=90%) E-N1450-ps90%	1917 (1450)	200	0.4	minor	particle erosion of mud and sand
		260	0.7	medium (pjv)	particle erosion of mud and sand at most places; water relatively clear near surface
		300	0.9	high (pnv)	intensive particle movement; sand concentrations dominant; water relatively clear near surface
		end	0	high-clear	settling of sand particles; water clear after 30 sec
B14 (ps=85%) E0N1220-ps85%	1770 (1220)	170	0.3	medium (pjv)	mud is washed out; particle erosion of sand
		200	0.4	high (pnv)	particle erosion of mud and sand everywhere
B15-1 first sample (ps=90%) E-N1410-ps90%	1893 (1410)	370	1.5	clear	very smooth surface; no irregularities; no movement at surface
		370	1.5	medium (pjv)	bed is disturbed artificially; small pit (20 mm long; 2 mm deep); growth of pit; erosion
B15-2 second sample (ps= 77%) E-N1310-ps77%	1830 (1310)	300	0.9	low	very smooth surface; limited particle erosion
		340	1.2	medium (pjv)	particle erosion and suspension
		380	1.5	high (pnv)	particle erosion of mud and sand everywhere; propeller visible within30 sec at end of test
B15-3 (ps=79%) top layer removed E-N1280-ps79%	1810 (1280)	300	0.9	low	very smooth surface; limited particle erosion
		330	1.1	medium (pjv)	particle erosion and suspension of mud/sand
		370	1.4	high (pnv)	particle erosion of mud and sand everywhere; propeller visible within 30 sec at end of test
B16 (ps=90%) E-N1280-ps90%	1808 (1280)	170	0.3	medium (pjv)	particle erosion and suspension of mud; water turbid in lower part; upper part clear
		200	0.4	high (pnv)	particle erosion of mud and sand everywhere
		end	0	medium (pjv)	propeller visible after 2 minutes; settling of flocs and mud

Testing: within 24 hours after sampling; native saline water; water temperature= 12-14 ^oC; h_w= water depth ≅0.15 m; ps= percentage of sand;
$c_{mud}=\rho_{dry}\,\delta_e/h_w \cong$ 0.5-1.0 for $\delta_e \cong$0.001 m and $\rho_{dry} \cong$ 500 kg/m³; high turbidity≅ 0.5-1 kg/m³ (=500-1000 mg/l)
pjv= propeller in middle just visible (500-700 mg/l); pnv=propeller in middle not visible (700-1000 mg/l);
Samples B13 to B16 were taken at seward end of channel; feet sank into bed over 10 to 20 cm during sampling
Cohesionless sand of 150 to 200 μm has onset value of about 80-100 rev's per minute (10% of bed is moving)

Table 5.4.4 *Critical bed-shear stress of field samples Noordpolderzijl (N-mud) based on EROMES-tests (March 2018)*

5.4.3 Noordpolderzijl mud; Flume/Eromes-tests of in situ samples (April 2018)

In April 2018, four (undisturbed) in-situ samples were taken at locations B5, B7, B9 and B15 using a small metal tray (length=0.4 m; width=0.4 m; height=0.05 m), see **Figure 5.4.3**. The tray is open at two sides and can be pushed horizontally throough the bed to sample a slice of mud. At the same locations various samples were taken and mixed into a bucket.
The tray with mud is placed into another tray and returned to the flume, where it is placed into the measurement section of the flume, see **Figure 5.4.4**. To allow the sample to come to rest, the in-situ sample was tested the next day (resting/consolidation time of 15 hours).
The bucket samples were used to perform EROMES-tests (saline water) in the laboratory at the same day of the flume tests.

Table 5.4.5 shows the EROMES test results.

Tables 5.4.6-5.4.9 show the results of the flume tests.

Sample	Wet and dry bulk density (kg/m^3)			Number revolu tions (-/min)	Bed-shear stress (N/m^2)	Turbidity in water column	Erosion description
	in-situ bed	from tray at end flume test	in-situ samples mixed in bucket				
B5 soft muddy sample (ps=55%) (pf=45%) (pc=20%) d_{50}=70μm E-N800-ps55% (IS)	1500 (800)	1490 (760)	1550 (850)	200	0.4	low	individual particles are eroded
				250	0.6	medium (pjv)	grey surface layer is eroded
				290	0.8	high (pnv)	erosion of surface layer; very turbid water; propeller not visible
B7 soft muddy sample (ps=70%) (pf=30%) (pc=10%) d_{50}=80 μm E-N1290-ps70% (IS)	1810 (1290)	1850 (1350)	1670 (1070)	130	0.18	low	minor movement of indicidual particles
				190	0.4	medium (pjv)	many particles in suspension; black aggregates in suspension
				270	0.7	high (pnv)	severe surface erosion; very turbid; propeller not visible
B9 soft part from tray sample (ps=80%) (pf=20%) (pc<10%) d_{50}=95 μm E-N1350-ps80% (IS)	1855 (1350)	1695 (1090)	1615 (950)	200	0.4	low	individual particles are eroded
				250	0.6	medium (pjv)	grey surface layer is eroded
				380	1.5	high (pnv)	severe sand erosion of surface layer; very turbid water; propeller not visible
				360 (p=0.01m)	2.0	high (pnv)	mass erosion; water very black
B9 hard cohesive part from tray sample (ps=80%) (pf=20%) (pc<10%) d_{50}=95 μm E-N1350-ps80% (IS)	1855 (1350)	1815 (1290)	1615 (950)	150	0.25	low	individual mud particles/film are eroded; no sand movement
				380	1.4	medium (pjv)	no sand movement
				320 (p=0.01m)	1.5	medium (pjv)	sand movement near wall
				360 (p=0.01m)	2	high (pnv)	mass erosion
B15 very sandy sample; many shells (ps=90%) (pf=10%) (pc<5%) d_{50}=110 μm E-N1450-ps90% (IS)	1905 (1450)	1880 (1415)	1865 (1380)	150	0.25	low	minor movement of loose particles
				210	0.45	medium (pjv)	rolling sand particles; mud in suspension; propleer just visible
				290	0.8	high (pnv)	severe surface erosion; erosion around bed protusions; propeller not visible

Testing: within 24 hours after sampling; native saline water; water temperature= 17-20 °C; h_w= water depth ≅0.15 m;
ps= percentage of sand> 63 μm; pf=percentage fines < 63 μm; pc= percentage clay < 8 μm
$c_{mud}=\rho_{dry}\,\delta_e/h_w \cong$ 0.5-1.0 for $\delta_e \cong$0.001 m and $\rho_{dry} \cong$ 500 kg/m³; high turbidity≅ 0.5-1 kg/m³ (=500-1000 mg/l)
pjv= propeller in middle just visible (500-700 mg/l); pnv=propeller in middle not visible (700-1000 mg/l);

Table 5.4.5 *Critical bed-shear stress of field samples Noordpolderzijl (N-mud) based on EROMES-tests (April 2018)*

Flume test Sample B5 17-18 April 2018; dry bulk density 800 $\pm$ 50 kg/m³; ps=55%; F-N800-ps55% (IS)

Sediment sampling was done at location B5 of the Noordpoldzijl-channel, see **Figure 5.4.3**. A small pit is made in which the empty tray is placed. The empty tray is moved horizontally to extract a mud slice with a thickness of about 0.05 m.

The in-situ tray sample of Noordpolderzijl mud was placed into the measuremnt section of the flume. The dry bulk density was about 800 $\pm$50 kg/m^3 (wet density of about 1500 kg/m^3) based on small subsamples taken at the silte. The mud-sand mixture had a soft muddy texture, see **Figure 5.4.4**. The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section.

Figure 5.4.3 *Sampling at location B5 (left); tray with sediment sample (right)*

Figure 5.4.4 *Upper: bed sample (soft) surface B5 at end of test (light grey film layer at surface)*
Lower: bed sample (soft) surface B5 at end of test (dark grey layer below surface)

The velocity of the fresh water flow was raised in steps from 0.2 to 0.9 m/s to observe the behaviour of the mud-sand bed surface, see **Table 5.4.6.** Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocities.

During the last 30 minutes, about the erosion layer is estimated to be about 1.5 m over the tray area, which is equivalent to an erosion rate of about 1 gram/m²/s (surface erosion).

Sand was transported in very small quantities along the bottom. The bed load transport was smaller than 0.1 gr/m/s.

Based on the results of this test, the critical bed-shear stresses for a mud bed ($p_{sand} \cong 55\%$) with dry density of about 800 kg/m³are estimated to be about:

- initiation of minor sand erosion: $\tau_{b,cr,e}$= 0.3-0.4 N/m²;
- initiation of minor mud erosion; initiation of grooves (erosion rate < 1 gr/m²/s): $\tau_{b,cr,e}$= 0.5-0.8 N/m²;
- initiation of mass erosion (local erosion rate > 10 gr/m²/s): $\tau_{b,cr,fail}$ > 2 N/m².

Time **(hrs)**	**Water depth** **(m)**	**Mean velocity at 8 cm above bed (m/s)**	**Bed-shear stress** **(N/m²)**	**Erosion of bed surface**	**Bed rough ness; Chezy (mm) ($m^{0.5}/s$)**	**Bed load fine sand** **(g/m/s)**
10.00	0.2	0.1	-	no movement; water turbid	<0.1 80-90	-
10.57	0.2	0.3	-	movement of some individual particles; water turbid	<0.1 80-90	-
11.13	0.2	0.45	0.28	small grassy protrusions from the bed were visible; not much movement	<0.1 80-90	2 gr; 20 min 0.005 gr/m/s
11.55	0.2	0.56	0.43	slight surface erosion between grassy materials	<0.3 70-80	14; 30 min 0.02 gr/m/s
12.21	0.2	0.64	0.56	similar	<0.3 70-80	10; 15 min 0.03 gr/m/s
12.45	0.2	0.67	0.65	similar; water very turbid, middle of bed not visible	<0.3 70-80	-
13.03	0.18	0.76	1.0	erosion of grooves near glass wall	<0.3 70-80	-
13.11	0.16	0.88	1.35	severe surface erosion (about 1 gram/m²/s)	<0.3 70-80	-
13.30	0.13	0.95	1.55	severe surface erosion (about 1 gram/m²/s)	<0.3 70-80	10; 25 min 0.03 gr/m/s

n.m.= not measured; water temperature≅ 17° C

Table 5.4.6 *Erosion flume tests with in-situ mud-sand bed from location B5 (dry mud density= 800 kg/m³; 55% sand); fresh water*

Flume test Sample B7 25-26 April 2018; dry bulk density 1070-1360 kg/m³; ps=70%; F-N1200-ps70% (IS)

Sediment sampling was done at location B7 of the Noordpoldzijl-channel, see **Figure 5.4.5**. The empty tray is moved horizontally to extract a mud slice with a thickness of about 0.05 m.

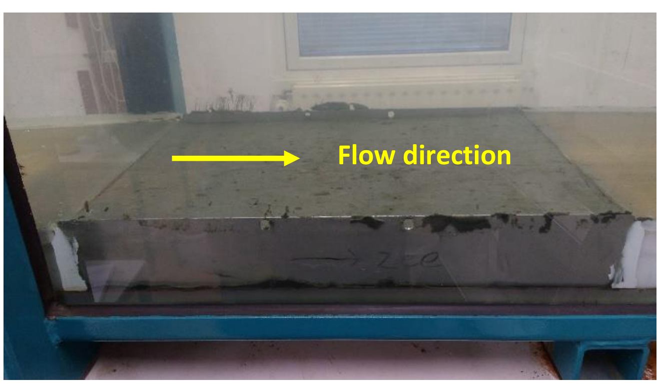
The in-situ tray sample of Noordpolderzijl mud was placed into the measurement section of the flume and the bed surface was slighty smoothed to get a horizpntal bed surface without iregularities (generated during sampling). The dry bulk density based on small subsamples was variable in the range of 1070 to 1360 kg/m³ (wet density of about 1670-1850 kg/m^3) based on small subsamples.

The in-situ mud-sand sample in the tray consisted of sandy mud (very few shells), see **Figure 5.4.5**.

Figure 5.4.5 *Sampling at location B7*

The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section. The velocity of the fresh water flow was raised in steps from 0.2 to 0.9 m/s to observe the behaviour of the mud-sand bed surface, see **Table 5.4.7**. Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocites.

Figure 5.4.6 shows the tray sample surface at the beginning and at the end of the test. The total erosion layer is about 3 mm over the tray area (40x40 cm^2) or about 0.6 kg. The erosion rate is estimated to be about about 1 to 2 gram/m²/s over a period of about 30 to 40 minitutes with velocities in the range of 0.6 to 1 m/s.



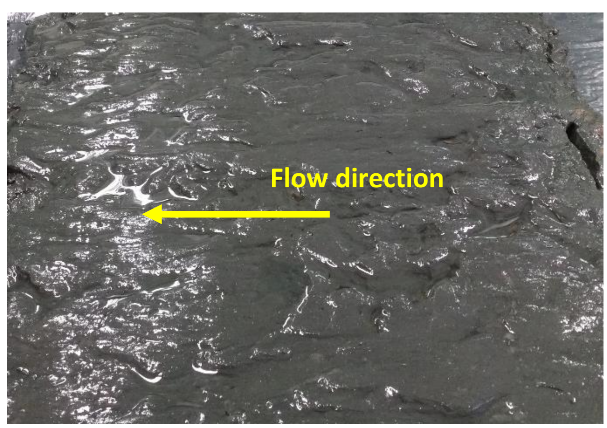


Figure 5.4.6 *Left: metal tray with sample placed in flume before start of test*
Right: bed sample surface at end of test (pit and groove erosion; soft surface)

Based on the results of this test, the critical bed-shear stresses for a mud bed ($p_{sand} \cong 70\%$) with dry density of about 1200 kg/m^{3}are estimated to be about:

- initiation of minor sand erosion: $\tau_{b,cr,e}$= 0.3-0.4 N/m^2;
- initiation of minor mud erosion; initiation of grooves (erosion rate < 1 gr/m^2/s): $\tau_{b,cr,e}$= 0.5-0.8 N/m^2;
- initiation of mass erosion (local erosion rate > 10 gr/m^2/s): $\tau_{b,cr,fail}$ > 2 N/m^2.

Time (hrs)	**Water depth (m)**	**Mean velocity at 8 cm above bed (m/s)**	**Bed-shear stress (N/m^2)**	**Erosion of bed surface**	**Bed rough ness; Chezy (mm) (m$^{0.5}$/s)**	**Bed load fine sand (g/m/s)**
10.23-10.25	0.2	0.1	<0.1	very smooth bed surface; water turbid from mud in water supply system; no movement	<0.1 80-90	-
10.25-10.28	0.2	0.32	0.14	no movement	<0.1 80-90	
10.28-10.32	0.2	0.40	0.22	some rolling particlesof sand and mud	<0.1 80-90	
10.32-10.51	0.2	0.57	0.45	movement of sand particles at bed surface; local pit erosion; no isolated ripple downstream; water very turbid	<0.1 80-90	19 gram; 15 min. 0.05 gram/m/s
10.51-11.14	0.2	0.65	0.58	some groove and pit erosion locally; no isolated ripples downstream	<0.1 80-90	23 gram; 15 min. 0.06 gram/m/s
11.14-11.16	0.19	0.72	0.9	surface erosion locally; no isolated ripples downstream	<0.3 70-80	
11.16-11.25	0.16	0.87	1.35	severe surface erosion; no isolated ripples	<0.3 70-80	
11.25-11.27	0.14	1.01	1.8	severe surface erosion; no black clouds; total erosion of about 3 mm over complete bed area (soft surface after test)	<0.3 70-80	12 gram; 13 min. 0.04 gram/m/s

n.m.= not measured; water temperature≅ 17° C

Table 5.4.7 *Erosion flume tests with in-situ mud-sand bed from location B7 (dry mud density= 1200 kg/m^3; 70% sand); fresh water*

Flume test Sample B9 19-20 April 2018; dry bulk density 1350±100 kg/m³; ps=80%; F-N1350-ps80% (IS)

Sediment sampling was done at location B9 of the Noordpoldzijl-channel, see **Figure 5.4.7**. A small pit is made in which the empty tray is placed. The empty tray is moved horizontally to extract a mud slice with a thickness of about 0.05 m.

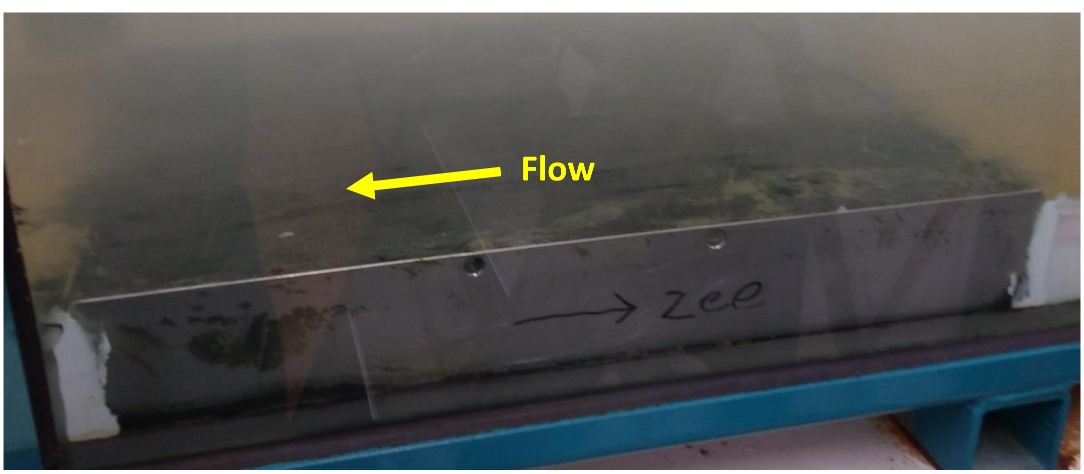
The in-situ tray sample of Noordpolderzijl mud was placed into the measurement section of the flume and the bed surface was slighty smoothed to get a horizpntal bed surface without iregularities (generated during sampling). The dry bulk density based on small subsamples was variable in the range of 1350±100 kg/m³ based on small subsamples.

The in-situ mud-sand sample in the tray consisted of soft cohesive parts (light grey colour; about 30% of area) and an hard sandy parts (dark grey colour; about 70% of area) with small and large shells, see **Figure 5.4.8.**

The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section. The velocity of the fresh water flow was raised in steps from 0.2 to 0.9 m/s to observe the behaviour of the mud-sand bed surface, see **Table 5.4.8**. Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocites.

Figure 5.4.8 shows the tray sample surface at the end of the test; shells, soft and hard spots can be observed. The total erosion layer is about 15 mm over the tray area (40x40 cm^2) or about 3 kg. The erosion rate in the end phase (about 20 min) is estimated to be about about 10 to 20 $gram/m^2/s$

Figure 5.4.7 *Sampling at location B9*



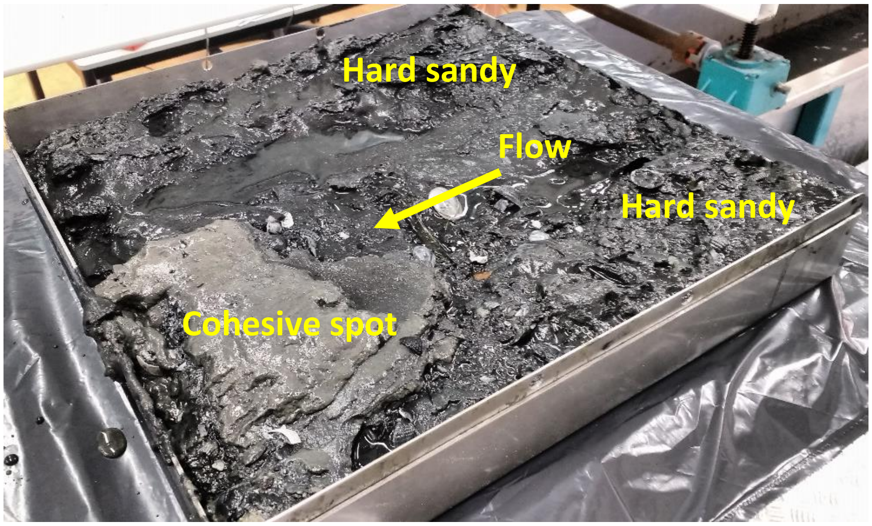


Figure 5.4.8 *Upper: metal tray with sample B9 placed in flume (light colour= cohesive; dark colour=sandy)*
Lower: bed sample B9 surface at end of test (cohesive and sandy spots; shells at many places)

Based on the results of this test, the critical bed-shear stresses for a mud bed ($p_{sand} \cong 80\%$) with dry density of about 1350 ± 100 kg/m^{3}are estimated to be about:

- initiation of minor sand erosion: $\tau_{b,cr,e}$= 0.2-0.3 N/m^2;
- initiation of minor mud erosion; initiation of grooves (erosion rate < 1 gr/m^2/s): $\tau_{b,cr,e}$= 0.4-0.7 N/m^2;
- initiation of mass erosion (local erosion rate > 10 gr/m^2/s): $\tau_{b,cr,fail}$ = 1.0-1.4 N/m^2.

Time (hrs)	Water depth (m)	Mean velocity at 8 cm above bed (m/s)	Bed-shear stress (N/m^2)	Erosion of bed surface	Bed rough ness; Chezy (mm) (m$^{0.5}$/s)	Bed load fine sand (g/m/s)
10.10	0.2	0.27	0.1	no movement; water turbid	<0.1 80-90	-
10.16-10.30	0.2	0.39	0.21	many individual sand partiles are moving at sandy spots; no movement at cohesive spots; isolated sand ripples are generated at downstream flume bed	<0.1 80-90	1.3 gram; 14 min; 0.004 gram/m/s (14 minutes)
10.38-11.00	0.2	0.49	0.33	similar; larger black cohesive aggregates are moving (surface erosion mud)	<0.1 80-90	23 gram; 22 min; 0.045 gram/m/s
11.00-11.21	0.18	0.63	0.70	surface erosion with clouds of mud	<0.3 70-80	130 gram; 21 min 0.25 gram/m/s
11.23-11.30	0.16	0.72	0.90	mass erosion; black clouds of mud	<0.3 70-80	
11.30-11.40	0.14	0.90	1.40	mass erosion (aggregates of 3 to 5 cm); black clouds of mud; total erosion is about 2.5 litre of mud and sand (1.5 cm of tray area); erosion rate of about 10-20 gram/m^2/s	<0.3 70-80	122 gram; 13 min.; 0.4 gram/m/s

n.m.= not measured; water temperature≅ 17^o C

Table 5.4.8 *Erosion flume tests with in-situ mud-sand bed from location B9*
(dry mud density= 1350 kg/m^3; 80% sand); fresh water

Flume test Sample B15 23-24 April 2018; dry bulk density 1425±75 kg/m³; ps=90%; F-N1425-ps90% (IS)

Sediment sampling (in-situ IS) was done at location B15 of the Noordpoldzijl-channel, see **Figure 5.4.9**. A small pit is made in which the empty tray is placed. The empty tray is moved horizontally to extract a mud slice with a thickness of about 0.05 m.

The in-situ tray sample of Noordpolderzijl mud was placed into the measurement section of the flume and the bed surface was slighty smoothed to get a horizpntal bed surface without iregularities (generated during sampling). The dry bulk density based on small subsamples was variable in the range of 1425±75 kg/m³ based on small subsamples.

The in-situ mud-sand sample in the tray consisted of muddy sand and many shells, see **Figure 5.4.9** and **5.4.10**.


Figure 5.4.9 *Sampling at location B15 (left); tray with sediment sample (right)*

The Ott-propeller sensor was installed above the rigid flume bottom at about 1 m upstream of the mud section. The velocity of the fresh water flow was raised in steps from 0.2 to 0.9 m/s to observe the behaviour of the mud-sand bed surface, see **Table 5.4.9**. Small water surface undulations (about 2 cm high) were generated at the flume entrance section during consitions with relatively high velocites.

Figure 5.4.8 shows the tray sample surface at the beginning and at the end of the test; may shells are visible. The total erosion layer is about 20 mm over the tray area (40x40 cm^2) or about 4 to 4.5 kg. The erosion rate is estimated to be about about 10 to 20 gram/m²/s over period of about 30 to 40 minutes


Figure 5.4.10 *Left: metal tray with sample placed in flume before start of test*
Right: bed sample surface at end of test (many shells are visible)

Based on the results of this test, the critical bed-shear stresses for a mud bed ($p_{sand} \cong 90\%$) with dry density of about 1425 $\pm$ 75 kg/m^{3}are estimated to be about:

- initiation of minor sand erosion: $\tau_{b,cr,e}$= 0.2-0.3 N/m^2;
- initiation of minor mud erosion; initiation of grooves (erosion rate < 1 gr/m^2/s): $\tau_{b,cr,e}$= 0.4-0.7 N/m^2;
- initiation of mass erosion (local erosion rate > 10 gr/m^2/s): $\tau_{b,cr,fail}$ > 2 N/m^2.

Time **(hrs)**	**Water depth** **(m)**	**Mean velocity at 8 cm above bed** **(m/s)**	**Bed-shear stress** **(N/m^2)**	**Erosion of bed surface**	**Bed roughness; Chezy (mm)** **(m$^{0.5}$/s)**	**Bed load fine sand** **(g/m/s)**
10.45-10.51	0.2	0.1	0.015	very smooth bed surface; water turbid from mud in water supply system; no movement	<0.1 80-90	-
10.51-10.57	0.2	0.33	0.15	onset of rolling sand particles; some isolated ripples at downstream section	<0.1 80-90	
10.57-11.14	0.2	0.38	0.2	rolling sand particles; some isolated ripples at downstream section	<0.1 80-90	4 gram; 15 min. 0.01 gram/m/s
11.14-11.39	0.2	0.5	0.35	movement of sand particles at bed surface; some erosion around protruding shells; isolated ripple downstream; water very turbid	<0.1 80-90	57 gram; 20 min. 0.1 gram/m/s
11.39-12.03	0.2	0.61	0.5	some groove and pit erosion locally; no isolated ripples downstream	<0.1 80-90	175 gram; 15 min. 0.5 gram/m/s
12.03-12.06	0.16	0.77	1.4	severe surface erosion; no isolated ripples downstream	<1 60-70	
12.06-12.09	0.14	0.9	1.5-2	mass erosion with black clouds; total erosion of about 20 mm over complete bed area	<3 55-60	330 gram; 7 min. 2 gram/m/s

n.m.= not measured; water temperature≅ 17^o C

Table 5.4.9 *Erosion flume tests with in-situ mud-sand bed from location B15 (dry mud density= 1425 kg/m^3; 90% sand); fresh water*

5.4.4 Summary

The EROMES-tests show very variable result, as only a very small surface sample is used. Visual observation and analyis of the EROMES-results show that the presence of a very smooth surface without protrusions consisting of cohesive materials leads to relatively high critical bed-shear stresses. In some tests it was not possible to generate surface erosion at all (tests B9 and B15-1) for bed-shear stresses < 1.5 N/m^2.

Flume tests show less variable results, as the tray samples (40x40 cm^2) contain a mixture of soft muddy and harder sandy materials, while sometimes many shells are present.

All results of the flume tests using in-situ samples are given in in **Table 5.4.10**.

Sample	Dry density (kg/m³); Percentage sand (%)	Particle erosion sand		Surface erosion of fines < 63 μm				Mass erosion		
		Depth-mean velocity (m/s)	Bed-shear stress (N/m²)	Depth-mean velocity (m/s)	Bed-shear stress (N/m²)	Bed load transport sand (g/m/s)	Erosion rate (g/m²/s)	Depth-mean velocity (m/s)	Bed-shear stress (N/m²)	Erosion rate (g/m²/s)
B5 silty mud F-N800-ps55%	800; 55	0.4-0.55	0.3-0.4	0.6-0.7	0.5-0.8	<0.03	<1	>1.2	>2	>10
B7 silty mud F-N1200-ps70%	1200;70	0.4-0.55	0.3-0.4	0.6-0.7	0.5-0.8	<0.1	<1	>1.2	>2	>10
B9 muddy sand F-N1350-ps80%	1350;80	0.4-0.45	0.2-0.3	0.55-0.65	0.4-0.7	<0.2	<1	0.8-0.9	1-1.4	10-20
B15 muddy sand F-N1425-ps90%	1425;90	0.4-0.45	0.2-0.3	0.55-0.65	0.4-0.7	<0.2	<1	0.9-1.0	2-3	10-20

Depth-mean velocitiy is related to the flume water depth of 0.2 m

Table 5.4.10 *Summary of erosion data of unmoulded, in situ samples*

5.5 Critical bed shear stress of mud-sand mixtures; synthesis

5.5.1 Basic data

All test results with soft and firm mud-sand beds based on mud from Noordpolderzijl and Delfzijl are summarized in **Table 5.5.1**. The most influencial parameters are the percentage of fines (<63 μm) and the dry bulk density of the mud-sand mixture. It is noted that test samples with a percentage of sand > 45% are artificially made mixtures. Three types of critical bed-shear stress (at increasing strength) are distinguished herein: particle erosion; surface erosion and mass erosion.

Particle erosion is the (lowest) flow stage at which individual fine mud particles/flocs are eroded from the sediment surface. This critical stage was identified by visual observation. The critical shear stress for mud particle erosion is assumed to somewhat lower than that of the sand particles, which were rolling as bed load and trapped in the slot downstream of the bed.

Surface erosion of the mud fraction is herein defined as the flow stage in the flume at which small craters and grooves (visually observed) are generated at the bed surface (visually observed) and eroded locally in the form of small clouds of mud particles and flocs. Often, these small-scale bed features were generated at initial disturbances created during bed surface preparation. Craters and grooves were mostly generated at the mud bed in the flume and and were only very sparsely (mostly small craters) generated in the EROMES-tube. This type of groove and crater erosion is herein referred to as surface erosion. Particle erosion in the EROMES-tube is defined as the stage at which the mud concentration in the tube is about 400 to 500 mg/l (propeller and bed under the propeller hardly vissible) which is equivalent to an erosion layer of less than 0.3 mm and erosion rates < 0.1 gram/m^2/s.

During all tests, the mud surface in the EROMES-tube with diameter of 0.1 m was much more stabile (yielding higher critical shear stress values; about 10% to 15%) than the mud surface of 0.4x0.6 m^2 in the flume. Large-scale turbulence and near-bed pressure fluctations were present in the flume flow due to minor water surface oscillations at higher Froude-numbers (Fr= 0.5-0.7). The rotary flow in the EROMES-tube is not representative for natural flows in tidal channels.

Mass erosion is defined as the flow stage with local bed failure. Two types of mass erosion with erosion rates > 10 gram/m^2/s have been observed in the present tests:

- low-density mud mixtures (weakly consolidated < 400 kg/m^3); total collapse of the top layer of the bed over 10 to 30 mm resulting in a large-scale black cloud of mud;
- high-density mud (firmly consolidated > 800 kg/m^3); local grooves and craters show a sudden increase in size and depth (up to 10 mm) with large clouds of mud escaping from the grooves and craters.

Test	Dry/wet bulk density of layer (kg/m³)	Dry bulk density of top layer (kg/m³)	Percentage (%) > 63 μm	Critical bed-shear stress for particle erosion of fine and sand fraction > 63 μm (Pa)	Critical bed-shear stress for surface erosion of fine fraction < 63 μm (Pa)	Bed shear stress at bed failure (mass erosion) (Pa)
F-S1590-ps95% (na)	1590 (2000)	1590	95	0.15; 0.2	0.15-0.2	0.15-0.2
F-N325-ps35% (na) E-N325-ps35% (na)	≅325 (1220)	≅ 200-300	35	0.2; 0.25	0.25-0.35 local craters, grooves	0.5-0.7 top layer 10-30 mm
E-N350-ps35% (na)	≅350 (1235)	≅ 300	35	0.2; 0.3	0.25-0.35 local crates, grooves	did not occur
E-N400-ps30% (IS)	≅ 600 (1390)	≅ 400	30	0.2; 0.3	0.25-0.35 (bed hardly visible)	did not occur
E-N400-ps35% (na)	≅400 (1265)	≅ 350	35	0.2; 0.3	0.25-0.35 local craters, grooves	did not occur
F-N435-ps30% (na) E-N435-ps30% (na)	≅435 (1285)	≅ 350-400	30	0.25; 0.35	0.4-0.6 local craters, grooves	0.8-1.0 top layer 10-30 mm
F-N530-ps30% (na) E-N530-ps30% (na)	≅530 (1345)	≅ 450-500	30	0.35; 0.5	0.6-0.8 local craters/grooves	1-1.2 top layer 10-30 mm
F-N685-ps35% (na) E-N685-ps35% (na)	≅685 (1440)	≅ 600	35	0.5; 0.8	1-1.5; slight erosion at local disturbances	2-2.5; estimated not measured
E-D500-ps20% (na)	≅500 (1325)	≅500	15	0.3; 0.4	0.6-0.9; flakes are disrupted from surface	1.0-1.5
E-D300-ps20% (na)	≅300 (1205)	≅300	15	0.15; 0.2	0.2-0.3; flakes are disrupted from surface	>0.6
E-N400-ps30% (IS)	≅600 (1390)	≅400	30	0.2; 0.3	0.25-0.35 general surface erosion	did not occur
F-N530-ps45% (a) E-N530-ps45% (a)	530 (1345)	500	45	0.3; 0.4	0.6-0.7 local craters/grooves	1-1.2 top layer 10-30 mm
F-N700-ps55% (a) E-N700-ps55% (a)	700 (1450)	700	55	0.3; 0.4	0.5-0.7 local craters/grooves	1-1.2 local grooves 10 mm
F-N1100-ps70% (a) E-N1100-ps70% (a)	1100 (1695)	1100	70	0.3; 0.4	0.6-0.7 generation/ erosion of local craters/grooves	1.2-1.4 mass erosion of local grooves 1-3 mm
F-N1450-ps75% (a) E-N1450-ps75% (a)	1450 (1910)	1450	75	0.25; 0.35	0.6-0.8 local craters/grooves	1.4-1.6 local grooves 1-2 mm
F-N1450-ps85% (a)	1450 (1910)	1450	85	0.2; 0.3	0.25-0.35	did not occur
F-N1450-ps90% (a)	1450 (1910)	1450	90	0.2; 0.25	0.25-0.35	did not occur
F-N1450-ps95% (a)	1450 (1910)	1450	95	0.15; 0.2	0.2-0.25	did not occur
F-N800-ps55% (IS)	800 (1510)	800	55	0.3; 0.4	0.5-0.8	>2
F-N1200-ps70% (IS)	1200 (1760)	1200	70	0.3; 0.4	0.5-0.8	>2
F-N1350-ps80% (IS) (many shells)	1350 (1850)	1350	80	0.2; 0.3	0.4-0.7	1-1.4
F-N1425-ps90% (IS)	1425 (1895)	1425	90	0.2; 0.3	0.3-0.7	>2

Test code: F-N325-ps35%: F=Flume; N=Noorpolderzijl-mud; dry density=325 kg/m³; na= natural sample; a= artificial sample; ps=percentage sand >63 μm=35%; E=Eromes-tube; D=Delfzijl-mud; IS=in situ sample tested in flume or Eromes; wet bulk density for saline water 1020 kg/m³

Table 5.5.1 *Critical bed-shear stresses of present data set (Hanze Technical School HTS 2016-2017)*

5.5.2 Particle erosion of sand and mud fraction

Three modes of erosion have been observed in this study:

- particle/floc erosion; erosion of of particles/flocs of the (fluffy) top layer; pick-up rates of 0.1 to 1 g/m^2/s;
- surface erosion; simultaneous mobilization of several layers of particles/flocs (failure of local networks, drained process); generation of pits, craters and grooves; pickup rates of 1 to 10 g/m^2/s;
- mass erosion; erosion of lumps of bed material,when the applied fluid stresses are larger than the undrained (remoulded) soil strength of the bed; pickup rates of 10 to 100 g/m^2/s.

All test results with soft and firm mud-sand beds (from Noordpolderzijl en Delfzijl field sites) are summarized in **Table 5.5.1**. Results of moulded natural (na), moulded artifical (a) and unmoulded in situ (IS) samples are given. The most influencial parameters are the percentage of clay/silt (< 8 μm), the percentage of fines (<63 μm), and the dry bulk density of the mud-sand mixture. It is noted that p_{fines}+p_{sand}=1. Column 5 gives the critical bed shear stresses for particle erosion of the fine and sand fractions. The critical stress of the fine fraction is found to be smaller (10% to 50%) than that of the sand fraction, depending on the percentage of fines and the bed density. Mud was always suspended first before sand was observed to roll into the bed load slot in the flume.
During all tests, the mud surface in the EROMES-tube with diameter of 0.1 m was much more stable (yielding higher critical shear stress values; about 10% to 15%) than the mud surface of 0.4x0.6 m^2 in the flume. Most likely, these differences are caused by differences of the bed state and the type of forcing in the tube and in the flume. In some Eromes-tests with samples containing a high percentage of fines > 70%, the bed surface was very smooth without any irrregularity resulting in very high critical bed shear stresses (> 1 Pa). Once a small artificial irregularity was created (small pit) at the bed in the Eromes-tube, the erosion process started immediately. In the flume, bed irregularities were always present, particularly when small shells were present. Large-scale turbulence and near-bed pressure fluctations were also present due to minor water surface oscillations.

The critical stress for particle erosion of the sand fraction ($\cong$ 100 μm) can be determined by analyzing the results of the bed load trap (small slot) at about 1 m downstream of the sediment section in the flume. Mud was not trapped in the slot, not even during mass erosion conditions. The measured bed load transport rates are used to determine the proper bed shear stress (flow stage) for critical erosion of the sand particles and to get an indication of the effect of the fine fraction on the bed load transport process. It was not possible to simultaneously measure the suspended sand transport.
Separate tests with an almost pure sand bed have been done to determine the critical bed-shear stress of the sand fraction. Two types of sand (d_{50} $\cong$ 100 μm and 180 μm) with small amounts (< 5%) of fines < 63 μm were tested. The critical bed-shear stress of these two sands was found to be in the range of 0.15-0.2 N/m^2 in agreement with the Shields-curve values for these types of sands. Thus, fine sand with 5% fines < 63 μm behaves almost as as pure sand.

Figure 5.5.1 shows the observed bed load transport rates of the sand fraction as function of the depth-averaged velocity in the range of 0.25-0.9 m/s for a series of experiments with p_{fines} in the range of 5% to 70%. The two upper curves represent measured bed load transport rates for an almost pure sand bed with d_{50}= 100 μm and 180 μm. During the tests with mixed beds of mud and sand, the fines were visible as stripes and spots with a different colour. Ripples were largely suppressed. Small isolated ripples (maximum height of 1 to 2 mm) were present locally in the tests with p_{fines}< 30%. Ripple generation was not observed in any of the tests with p_{fines} > 30%. If the percentage of fines < 63 μm is larger than 30%, the bed load transport of the sand fraction is strongly reduced, mainly due to the suppression of ripple generation. The suppression of sand ripples (and thus less generation of turbulent vortices near the bed) will also reduce the suspended load transport. The largest reduction of bed load transport (almost factor 100) is obtained in test F685-ps35%-pf65% (dry density of 685 kg/m^3; 35% sand>63 μm; 65% fines < 63 μm). Bed load transport of the sand fraction is initiated at a depth-averaged velocity in the range of 0.3 to 0.5 m/s (depending on the percentage of fines and the dry bulk density) which is equivalent to a critical bed shear stress of about 0.2 to 0.5 Pa. Bed shear stresses involved are the grain-related bed shear stress values.

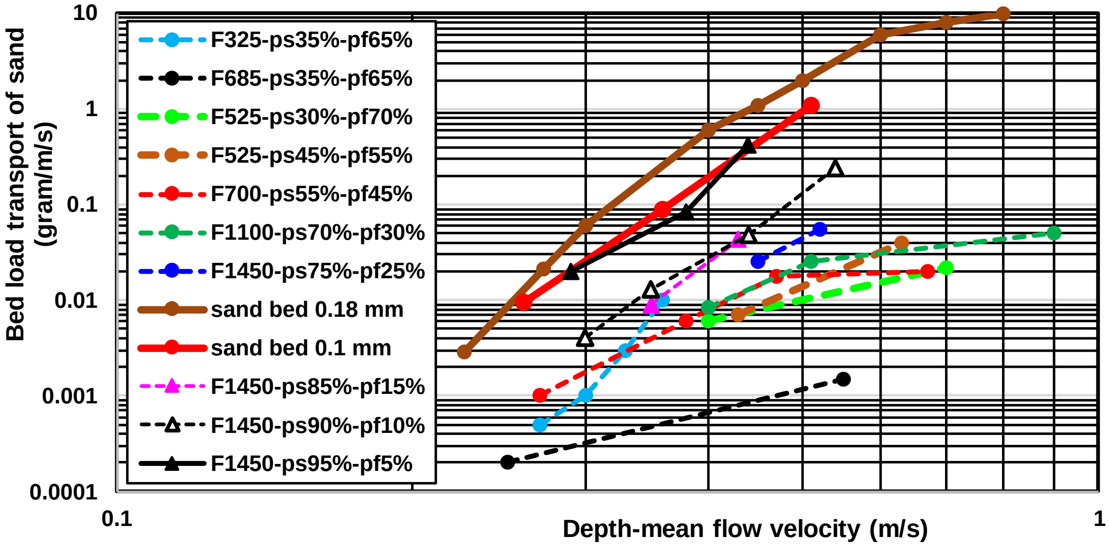
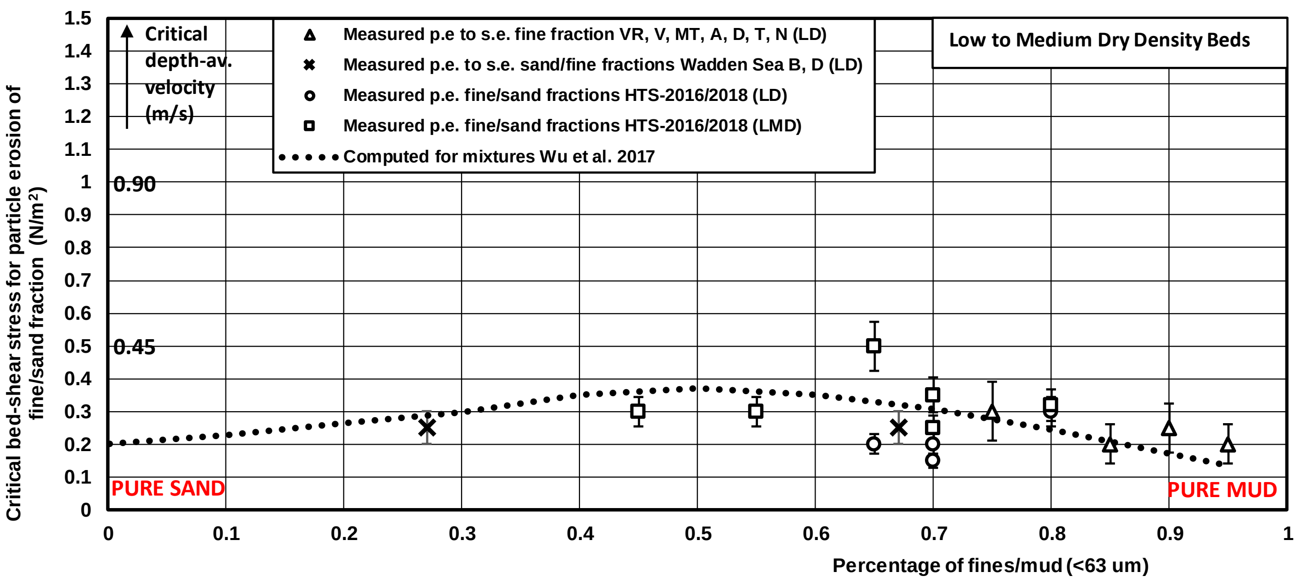


Figure 5.5.1 *Bed-load transport of sand fraction as function of depth-mean velocity (ps=percentage sand > 63 μm; pf=percentage fines < 63 μm; dry density=325 to 1450 kg/m³)*

The critical bed shear stress related to particle erosion of the fine fraction is shown in **Figure 5.5.2A,B** for four bed density ranges: (1) low dry density < 400 kg/m³ (LD); (2) low to medium dry density 400 to 800 kg/m³ (LMD); (3) medium to high dry density 800-1200 kg/m³ (MHD) and (4) high dry density 1200 to 1600 kg/m³ (HD).
The critical bed shear stress is shown on the outside of the vertical axis, whereas the critical depth-averaged flow velocity is shown on the inside of the vertical axis. The critical velocity is derived from the Chézy-equation: $\tau_{cr}=\rho g\, u_{cr}^2/C_{gr}^2$ or $u_{cr} = C_{gr}\,(\tau_{cr}/(\rho g))^{0.5}$, with u_{cr}= depth-averaged velocity at critical conditions, C_{gr}= grain-related Chézy-coefficient (about 80 to 100 $m^{0.5}$/s for muddy field sites with depths of 1 to 5 m). High Chézy values in the range of 80 to 100 $m^{0.5}$/s are very typical for muddy field sites. The precise mode (p.e. or s.e) of erosion is unkown for most of the Literature data. The symbols of the HTS-data in **Figures 5.5.2A,B** represent the critical stress of the fine fraction. The critical stresses of the sand fraction are somewhat higher (not shown in **Figure 5.5.2A,B**; see column 5 of **Table 5.5.1**). The individual particles/flocs of the fine fraction are more easily set into motion, which may also be the result of the presence of a very thin mud film layer (< 1 mm) of very low density on top of the bed surface in the flume. The particles/flocs of this low density layer are always first dislodged and immediately suspended. Most of the critical stress values are in the range of 0.15 to 0.4 Pa for LD and LMD-beds (**Figure 5.5.2A**). The particle erosion of fines for soft, almost pure mud beds (p_{fines} > 80%) occurs at relatively low bed shear stresses in the range of 0.15 to 0.25 Pa (open circles, triangles). Righetti and Lucarelli (2007) have found the same critical shear stress range of 0.15-0.35 Pa (based on flume tests) for benthic muds (< 10 μm) in water depths of 10 to 50 m in several lakes in Italy. Field data for low density beds in the River Elbe and River Saale in Germany (Noack et al. 2015) show similar values:
-River Elbe: p_{fines}>85%; ρ_{wet}=1100-1150 kg/m³ (ρ_{dry}= 125-200 kg/m³); $\tau_{cr,fine}$= 0.15-0.35 Pa;
-River Saale: p_{fines}>90%; ρ_{wet}=1150-1200 kg/m³ (ρ_{dry}= 200-300 kg/m³); $\tau_{cr,fine}$=0.3-0.35 Pa.

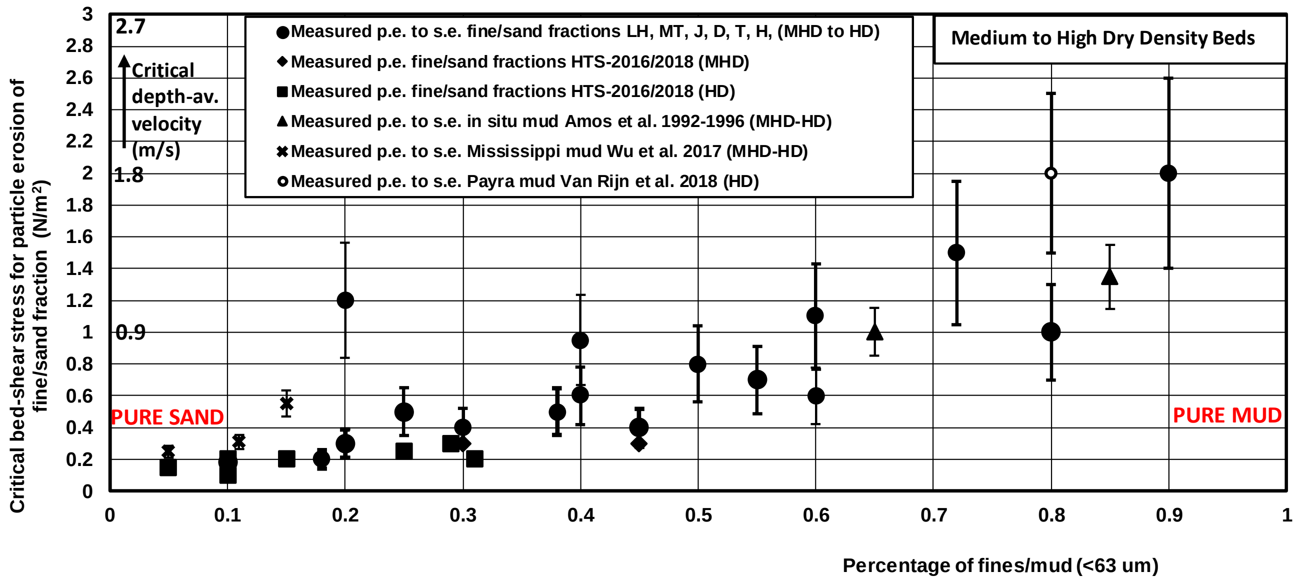
Noack et al. (2015) observed that the silt and clay particles/flocs lying on the top bed surface as a thin fluffy layer are eroded at very low velocities and bed shear stresses in the case of a low density top layer. In practice, this thin fluffy top layer of a low density bed is not of much importance as it will lead to very low mud concentrations

in the water column (in the range of 1 to 10 mg/l). In the case of medium to high density beds, the critical stresses are larger and clearly increase for increasing percentages of fines. (**Figure 5.5.2B**). The maximum critical bed shear stress is of the order of 2 Pa for a HD-bed of pure mud with p_{fines} > 80%. Smith et al. (2015) and Wu et al. (2017) have tested HD-mixtures of Mississippi-mud (M-mud) and sand. The samples were tested in an erosion flume after 30 days of consolidation, when the dry density values were 750 to 1200 kg/m³ (initial dry density of 700 to 950 kg/m³). The critical shear stresses, defined as the shear stress in conditions with an erosion rate of 10^{-4}cm/s (surface erosion), are shown in **Figure 5.5.2B**). The data are in good agreement with the other data. Data of Payra mud (p_{fines}≅80%) from the offshore Bangladesh coast is also shown in **Figure 5.5.2B**. This is a very pure mud with almost no calcareous and organic materials, which consolidates within one or two days to a dry density of 1200 to 1300 kg/m³. The texture is that of a soft buttery mud, but the critical bed shear stress for particle to surface erosion (sudden generation of small grooves) is found to be rather high (≅ 1.5 to 2 Pa). The critical bed shear stresses (surface/pit erosion) based on the flume tests of Kothyari and Jain (2008) for high density beds are in the range of 1 to 2.5 Pa, whereas the present HTS-data are in the range of 0.5 to 1 Pa (surface erosion) and 1 to 1.5 Pa (mass erosion) for high density beds. Most likely, this discrepancy is caused by the relatively high percentage of clay used by Kothyari and Jain (2008). The results of Desnath et al. (2007) also point to the importance of the clay content. Discrepancies between various data sets are most likely related to the sediment composition of the mixtures (percentage of clay; percentage organic materials) and the various definitions of particle/surface/mass erosion.
The results for artificial mud-sand beds and in situ mud-sand beds (IS) show no major differences. The critical bed shear stress for particle/surface erosion is in the range of 0.2 to 0.8 Pa for both type of beds, see **Table 5.5.1** (lower 10 rows).



An= Andersen 2001; B= Bauamt 1987; De= Deltares 1989, 1991, 2016; D= Dou 2000, J= Jacobs 2011; H= Houwing 2000, LH= Le Hir et al. 2008; MT= Mitchener and Torfs 1996; N= Noack et al. 2015; T= Thorn 1981; To=Tolhurst et al. 2000; V= Van et al. 2012; VR= Van Rijn 1993
p.e.= particle erosion; s.e.= surface erosion
LD= low dry density beds < 400 kg/m³; LMD= low to medium dry density beds 400-800 kg/m³;
MHD= medium to high dry density beds 800-1200 kg/m³; HD= high dry density beds > 1200 kg/m³

Figure 5.5.2A *Critical bed shear stress for particle erosion; low to medium dry density beds*



An= Andersen 2001; B= Bauamt 1987; De= Deltares 1989, 1991, 2016; D= Dou 2000, J= Jacobs 2011; H= Houwing 2000, LH= Le Hir et al. 2008; MT= Mitchener and Torfs 1996; N= Noack et al. 2015; T= Thorn 1981; To=Tolhurst et al. 2000; V= Van et al. 2012; VR= Van Rijn 1993

p.e.= particle erosion; s.e.= surface erosion

LD= low dry density beds < 400 kg/m³; LMD= low to medium dry density beds 400-800 kg/m³;

MHD= medium to high dry density beds 800-1200 kg/m³; HD= high dry density beds > 1200 kg/m³

Figure 5.5.2B *Critical bed shear stress for particle erosion; medium to high dry density beds*

Summarizing, the following phenomena can be derived from the data:

- p_{fines}<15%: the mixture has a sandy texture with dry bulk density of 1200 to 1600 kg/m^3; the critical bed-shear stress for particle erosion of sand and mud is found to be in the range of 0.15 to 0.25 N/m^2, which is slightly larger than the Shields values of 0.15-0.2 N/m^2 for fine sand. A minor percentage of fines has a minor effect on the critical bed-shear stress of the sand fraction. The mud fraction is washed out at the moment of sand particle movement. Sand ripples are generated.
- p_{fines}=15%-30%; the mixture has a lumpy cohesive texture with dry bulk density of 800 to 1600 kg/m^3; the critical bed-shear stress for particle erosion of sand and mud is found to be in the range of 0.2 to 0.5 N/m^2 increasing slightly with increasing bed density. The erosive behaviour of the sand fraction and the mud fraction of the top layer are highly interrelated. The bed surface is mostly flat; sand ripples donot occur. The critical stress for mud particle erosion is smaller than the critical stress of the sand particle erosion.
- p_{fines}=30%-60%; weak and medium consolidated mud-sand bed (dry density of 400 to 800 kg/m^3). The critical bed-shear stress for particle erosion of sand and mud is found to be in the range of 0.3 to 1 N/m^2, increasing slightly with increasing dry density of about 400 kg/m^3 to about 800 kg/m^3 (weak to medium consolidated).
- p_{fines}=60%-90%; mostly weakly consolidated mud beds < 600 kg/m^3 in tidal channels with relatively low critical stress of 0.2 to 0.3 N/m^2.

5.5.3 Surface and mass erosion of mud fraction

Surface and mass erosion are most important for the engineering practice, as these processes create relatively high mud concentrations in the water column. The transition from particle erosion to surface erosion is reasonably continuous for low to medium density beds (compare closed and open circles of HTS-data; LD and LMD), but discontinuous for higher density beds (MHD and HD), as shown in **Figure 5.5.3**. Both the measured data points and the trend lines are shown.
For p_{fines} between 0.1 and 0.5, the bed dry density is mostly > 800 kg/m³ (MHD to HD) and the critical stress for surface erosion gradually increases from 0.2 to 1 Pa. For p_{fines}> 0.5, the bed dry density is generally much smaller (LD to LMD) and the critical stress for surface erosion is gradually decreasing to about 0.2 Pa for p_{fines}=0.9. The critical shear stress of particle and surface erosion tend to approach a value of about 0.15 to 0.2 Pa for LD-beds with p_{fines} > 0.9 (close to gelling point of sediment; dry density of 100 to 150 kg/m³). The critical stress for surface erosion of LD to LMD-beds can be crudely related to the critical stress for particle erosion: $\tau_{cr,se}$ = 1.1 to 1.5 $\tau_{cr,pef}$. The trend lines for surface erosion of LD, LMD and MHD beds are reasonably reliable as many data points are available. The trend line for surface erosion of HD-beds shows a fairly strong increase of the critical stress for increasing values of p_{fines}, which is mainly based on the relatively high critical stress of Payra mud. The data of Le Hir et al. (2005) and Jacobs (2011) also show this increasing trend for HD beds.

Mass erosion of LD, LMD, MHD and HD-beds occur at critical stresses of in the range of 0.7 to 2 Pa. An estimate of the critical mass erosion velocity of a cohesionless silt bed (50 μm; bed density of 1500 kg/m³) can be obtained from the work of Bisshop (2018), who studied the pickup of fine silt in a recirculating pipeline system. Mass erosion was observed for a depth-averaged velocity of about 1.7 m/s in a depth of about 0.2 m (≅ 2 to 2.5 m/s for a depth of 1 m). The critical stress for mass erosion of LD to LMD-beds can be crudely related to the critical stress for particle erosion: $\tau_{cr,me}$ = 2 to 3 $\tau_{cr,pef}$. The trend line for mass erosion of LD beds is fairly reliable, but the trendlines for LMD, MHD and HD beds are less reliable (lack of data). It is assumed that there is an increase of the critical stress for increasing values of p_{fines}.

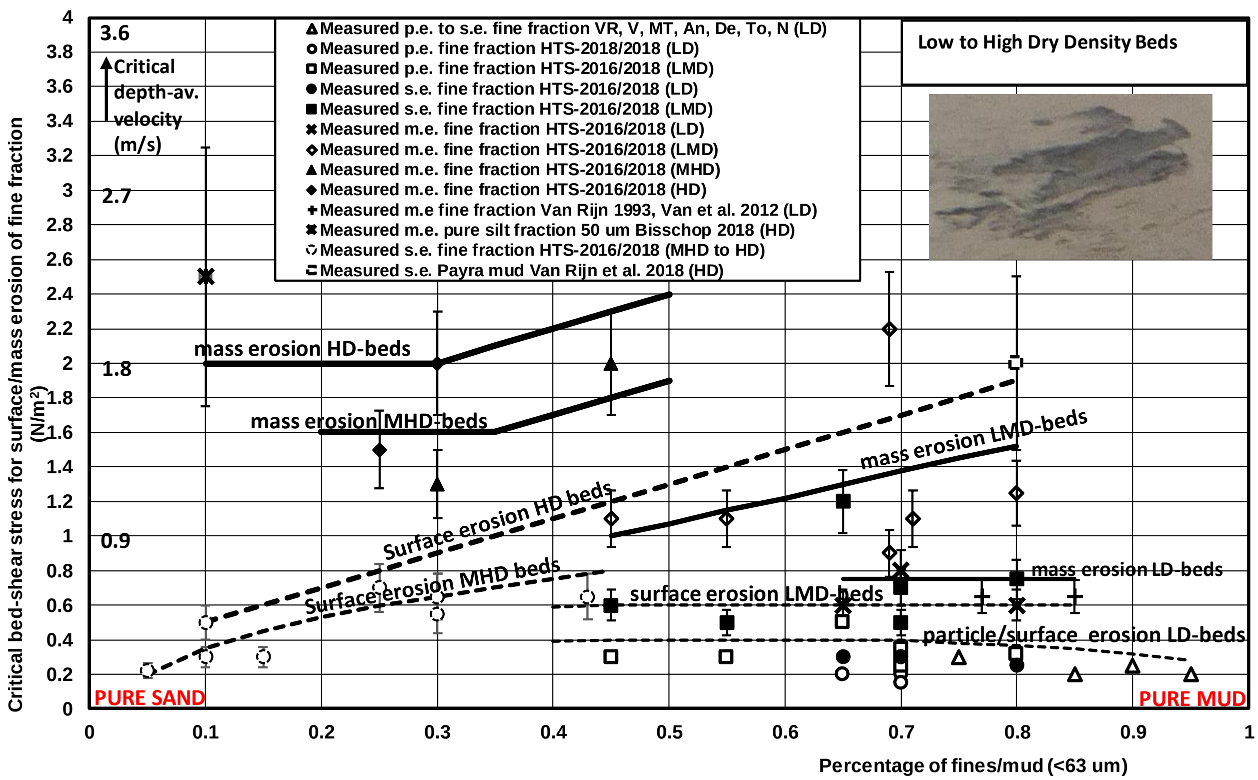


Figure 5.5.3 *Critical bed shear stress for surface and mass erosion; low to high dry density beds*

Figure 5.5.4 shows the critical bed-shear stress for surface erosion of the fine fractions as function of the dry density of the top layer; four ranges related to the percentage of fines (< 63 μm) are distinguished: <15%, 15%-30%, 30%-60% and 60%-90%. The critical bed-shear stress at the moment of bed failure (mass erosion) is also shown.
It is noted that the critical bed-shear stress for surface erosion of the mud fraction (generation of grooves) is much larger (factor 2) than the critical stress for particle/floc erosion of mud fraction.
Many data from other sites with low-density mud beds in the range of 200 to 400 kg/m^3 (Thorn 1981; Van Rijn 1993; Mitchener and Torfs, 1996; Dou 2000, Van et al. 2012) are in the same range as the present HTS-data. Some data from other sites are shown in **Figure 5.4.4**; other data are left out for clearness. Discrepancies are most likely related to the various definitions of surface/mass erosion applied. Furthermore, particle, surface and mass erosion are relatively close together in the low-density range (soft mud beds).

The following phenomena can be observed:

- p_{fines}<15%; the bed consists of very firmly consolidated sediment materials; dry densities are > 1200 kg/m^3; the mud particles are washed out when the sand particles are eroded; critical shear stress is in the range of 0.15-0.25 N/m^2;
- p_{fines}=15%-30%; the bed consists of firmly consolidated sediment materials; dry densities are > 800 kg/m^3; the critical shear stress increases weakly with the dry bulk density; the critical shear stress for mass erosion (small grooves and craters) is much higher (factor 2 to 2.5) than that for surface erosion;
- p_{fines}=30%-60%; the bed consists of soft muddy materials (400-800 kg/m^3) with clear traces of fine sand; the critical shear stress increases moderately with the dry bulk density; the critical shear stress for mass erosion is much higher (factor 2) than that for surface erosion;
- p_{fines}=60%-90%: the bed consists of very soft muddy materials; the critical shear stress increases strongly with the dry bulk density; the critical shear stress for mass erosion is higher (factor 1.5 to 2) than that for surface erosion.

Figure 5.5.5 shows the critical depth-mean velocity for surface erosion and mass erosion of the mud fraction based on the data of Figure 5.5.4 and C=90 m$^{0.5}$/s and is valid for depths between 1 and 5 m.
The critical depth-mean velocity for surface and mass erosion can be determined from the Chézy-equation. Using: $\tau_{cr}=\rho g U_{cr}^2/C^2$, it follows that $U_{cr} \cong C\ (\tau_{cr}/(\rho g))^{0.5}$, with U_{cr}= depth-mean velocity at critical conditions, C= Chézy-coefficient (about 80 to 100 m$^{0.5}$/s for muddy field sites).
The critical velocities are in the range of 0.5 to 1.5 m/s depending on the percentage of fines < 63 μm and the dry bulk density. The cohesive effects are largest for p_{fines} > 60%. Bisshop (2018) has studied the pickup of fine sediments in a recirculating pipeline system. The finest sediment was silt with a mean size of about 50 μm ($p_{fines}\cong$70%; very firmly consolidated bed of about 1500 kg/m^3). Mass erosion with a pickup rate of about 1000 gr/m^2/s did occur for a mean velocity of about 1.7 m/s and a depth of about 0.2 m. The equivalent mean velocity for a depth of > 1 m is about 2 m/s.

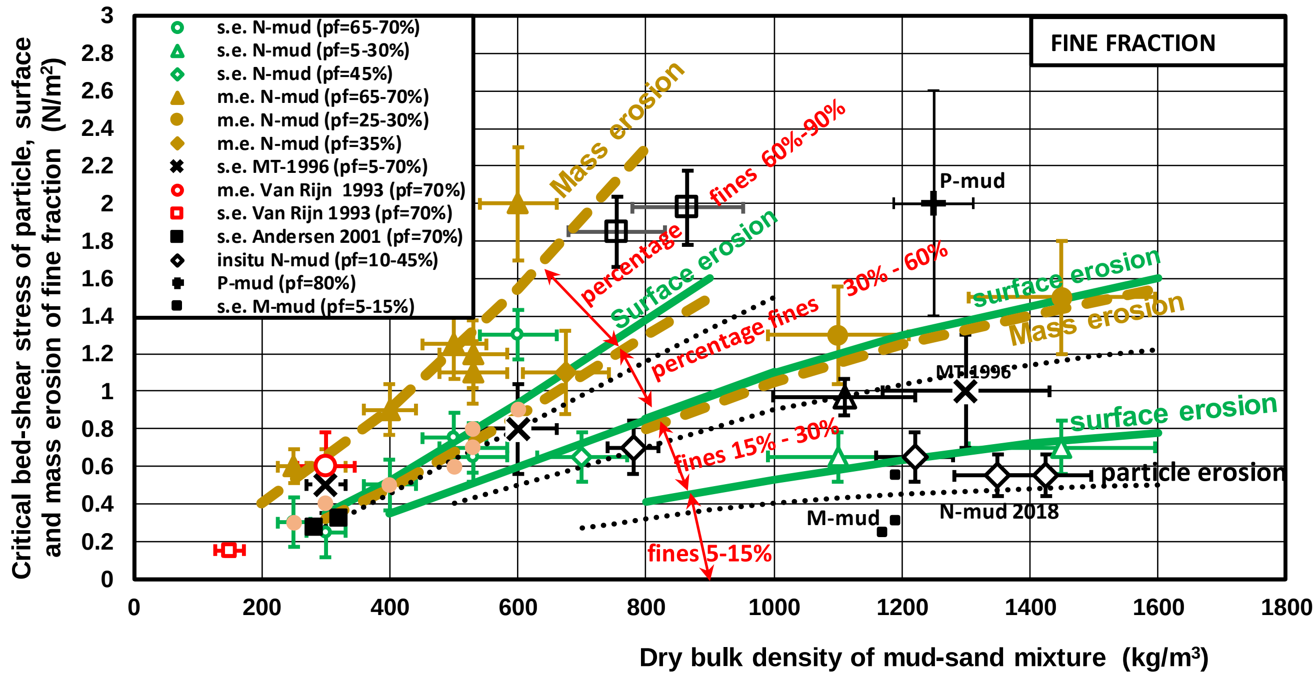


Figure 5.5.4 *Critical bed-shear stress for surface and mass erosion of the fine fractions (MT= Mitchener and Torfs; p.e=particle erosion; s.e=surface erosion; m.e= mass erosion)*

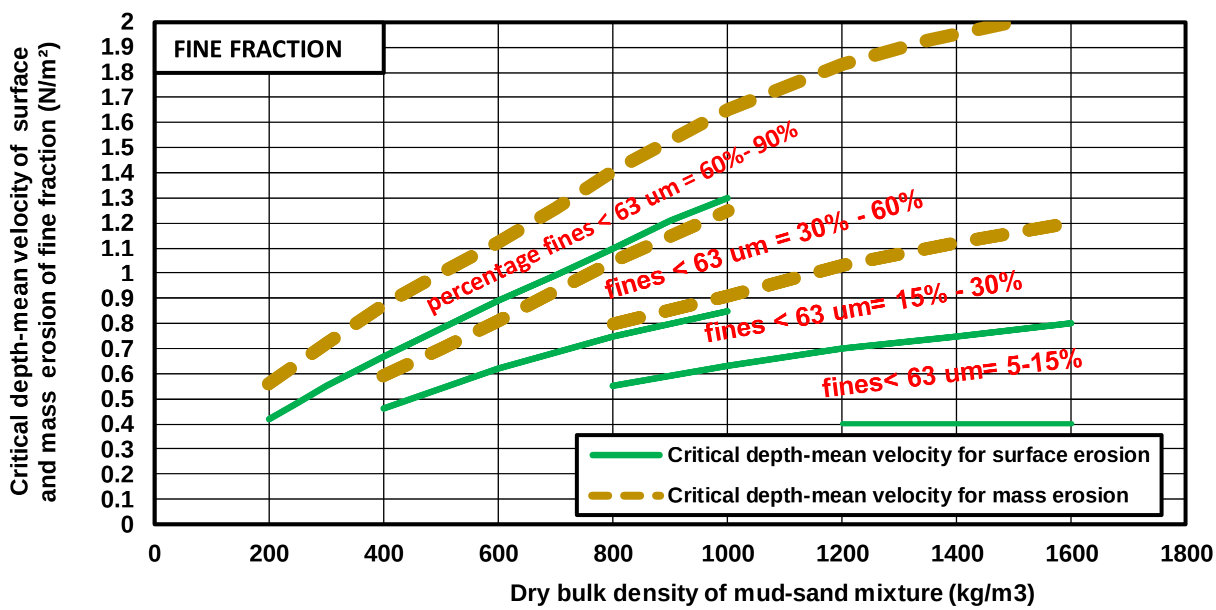


Figure 5.5.5 *Critical depth-mean velocity for surface and mass erosion of the fine fractions; water depths of 1 to 5 m; C= 90 $m^{0.5}$/s*

Figures 5.5.4 and **5.5.5** can be used to better understand the erosive behaviour of tidal channels with mud-sand bed mixtures.Three cases are considered:

- Tidal channels with a dynamic bed consisting of low-density mud (weakly consolidated; p_{fines}> 0.7; dry density < 400 kg/m^3) mostly occur in a regime with relatively high velocities (>0.7 m/s) resulting in significant reworking of the bed surface. The critical bed-shear for surface erosion for this type of conditions is about 0.2 to 0.4 N/m^2 (Figure 5.5.4).
- Tidal channels with a bed consisting of high-density mud (firmly consolidated; p_{fines}> 0.7; dry density > 800 kg/m^3) are present mostly in quiescent tidal environments with relatively low velocities (< 0.3 m/s) where the fine sediments can deposit and consolidate. The critical bed-shear for surface erosion for this type of conditions is about 0.8 N/m^2 or larger (Figure 5.5.4).
- Tidal channel beds with intermediate bulk densities (dry density of 400-800 kg/m^3) generally occur along the banks in the transition zones to the intertidal mud-sand flats. The sand particles are scattered throughout the mud fraction and are surrounded by many layers of mud particles. The critical bed-shear stress of the mud fraction is in the range of 0.4 to 0.8 N/m^2 (Figure 5.5.4).

5.6 Measured erosion rates

The flume test results have been used to estimate the erosion rates, see **Section 5.1**.

Figure 5.6.1 shows the measured erosion rates (flume test F325-ps35) as function of the bed-shear stress.

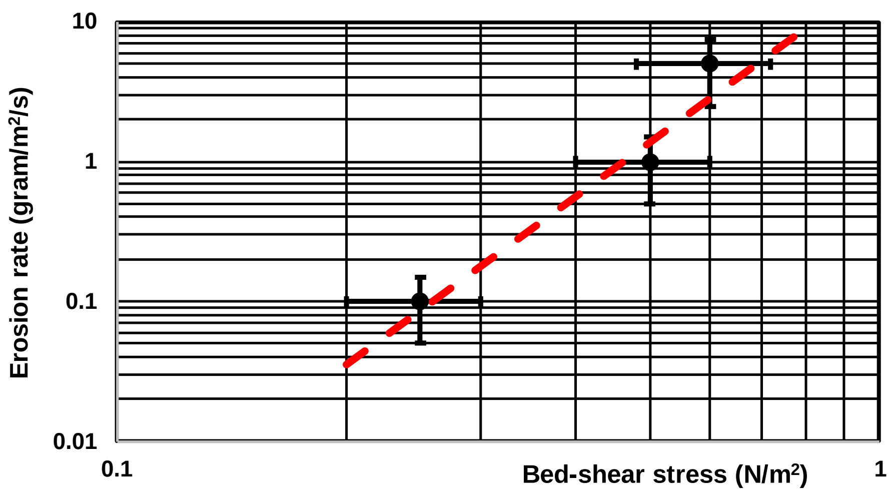


Figure 5.6.1 *Erosion rate as function of bed-shear stress; test F325-ps35*

Figure 5.6.2 shows the dimensionless erosion rate as function of the dimensionless bed-shear stress based on Equations (5.1.2) and (5.1.3) and using $w_{mud,max}$= 0.0015 m/s (Figure 3.17), ρ_{dry}= 350 kg/m^3 and $\tau_{b,cre}$= 0.25 N/m^2.

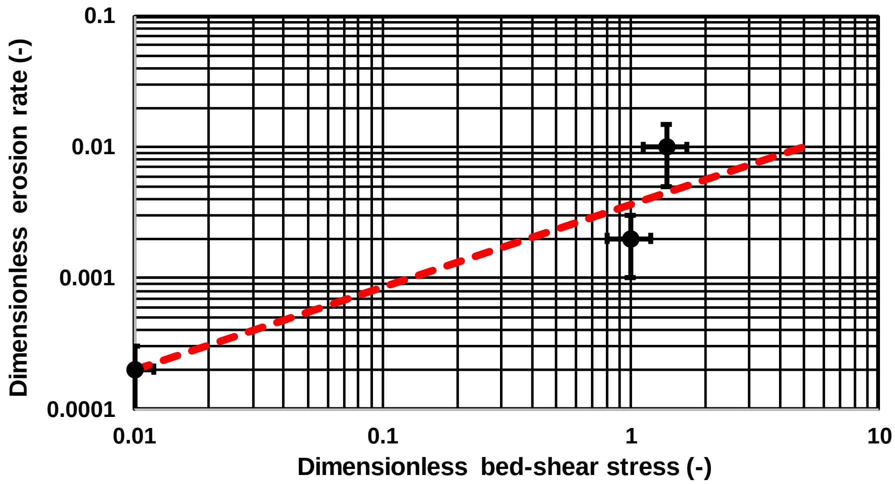


Figure 5.6.2 *Dimensionless erosion rate as function of dimensionless bed-shear stress; test F325-ps35*

A rough indication of the erosion rates of mud-sand mixtures observed in all tests is given in **Figure 5.6.3**. The erosion rates were determined from the estimates of the eroded sediment mass and the time elapsed (flume test results; accuracy $\pm$ factor 2). For clearness the measured values (only crude estimates) are omitted. In stead the trend lines are given resulting in a type of conceptual plot identifying the influence of the most basic parameters. The erosion rate increases for increasing bed shear stress ($E \sim \tau_b^2$) and decreases strongly for increasing dry density (400, 600, 700, 800 and > 1000 kg/m³). The erosion rate of fine cohesionless sand of 63 μm measured in a high-velocity pipeline circuit is also shown (Van Rijn et al. 2019). Strong damping of turbulence at high bed shear stress was observed for cohesionless fine sand resulting in a less steep increase of the erosion rate of fine sand. The erosion rate of mixtures of clay-silt-sand is smaller than that of fine cohesionless sand due to the cohesive effects of the very fine clay fraction reducing the erosion rate of cohesive mixtures.
The deposition flux is defined as: $D=c_b\, w_s$ with c_b= near-bed concentration of fines (range of 10 to 100 kg/m^3) and w_s= settling velocity near the bed (range of 0.1 to 1 mm/s). Using these values, an estimate of the deposition flux is 1 to 100 g/m²/s, which is of the same order of magnitude as the erosion rate. Hence, fairly stable channel beds are possible in very muddy conditions (soft mud beds, fluid mud beds).

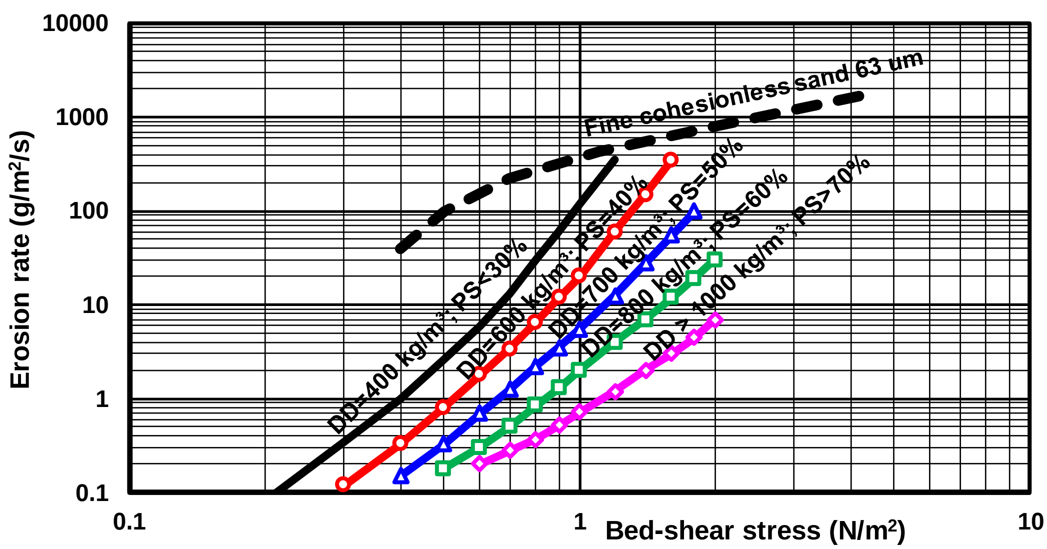


Figure 5.6.3 *Erosion rates of mud-sand mixtures derived from measured data*
(DD=dry density; PS= percentage of sand)

The thickness of eroded mud layers in tidal flow conditions can be estimated using (Eq. 5.1.1): $\delta_e = e_{mud}\, \Delta t/\rho_{dry}$ with: e_{mud}= erosion rate of mud (kg/m^2/s), Δt= time period considered, ρ_{dry}= dry density of mud top layer.

Surface erosion: Using: e_{mud}= 1 gram/m^2/s = 0.001 kg/m^2/s, Δt= 10000 s (3 hours of tidal flow), ρ_{dry}= 300 kg/m^3, it follows that δ_e =0.033 m after 3 hours.

Mass erosion: Using: e_{mud}= 10 gram/m^2/s = 0.01 kg/m^2/s, Δt= 10000 s (3 hours of tidal flow), ρ_{dry}= 300 kg/m^3, it follows that δ_e =0.33 m after 3 hours (assuming a homogeneous bed with the same bulk density).

The maximum thickness of a mud layer that can be eroded in tidal flow is of the order of 0.3 to 0.5 m (upper limit) if the flow velocity and associated bed-shear stress during 3 hours is so large that mass erosion occurs. This means that the dry density of the mud layers of a tidal channel should be known (measured) over a thickness of about 0.3 to 0.5 m with a vertical resolution of about 0.03 m.
A mass erosion rate of 100 kg/m^2 over 3 hours and a water depth of 5 m would mean a mud concentration of 20 kg/m^3 (or 20 gr/l), which is exceptionally high. At most places , the mud concentrations are smaller than about 1 gr/l (1000 mg/l).
In reality, the dry soil density will increase with depth below the bed surface and thus the critical bed-shear stress and the erosion rate will decrease with depth.

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