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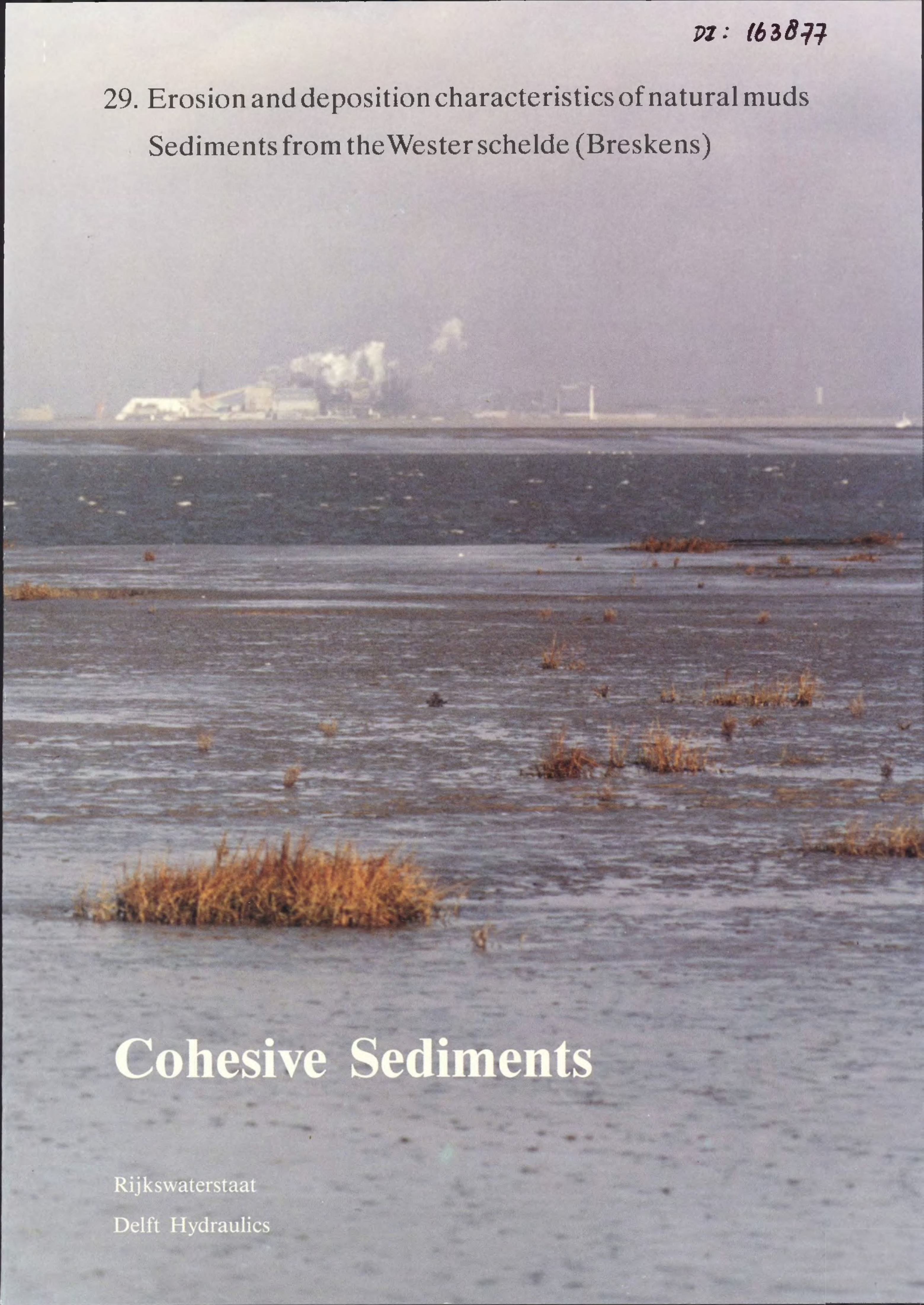
29. Erosion and deposition characteristics of natural muds

Sediments from the Wester schelde (Breskens)



Cohesive Sediments

Rijkswaterstaat

Delft Hydraulics

Report 29. Erosion and deposition characteristics of natural muds
Sediments from the Westerschelde (near Breskens)

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CONTENTS

Nomenclature

a, b	- non-dimensionless constants in equation (1)	
c	- suspension concentration of the sediment	[kg/m^3]
c_o	- initial sediment concentration (of the subtest)	[kg/m^3]
c_{eq}	- equilibrium sediment concentration (of the subtest)	[kg/m^3]
D	- particle diameter	[m]
h	- water depth	[m]
M	- erosion parameter in equation (5)	[$kg/m^2/s$]
r	- radius of the annular flume	[m]
t	- time	[s],[min]
V_l	- longitudinal velocity	[m/s]
ε	- erosion rate	[$kg/m^2/s$]
ε_f	- floc erosion rate	[$kg/m^2/s$]
τ_b	- bed shear stress	[Pa]
τ_d	- critical shear stress for deposition	[Pa]
τ_e	- critical shear stress for erosion	[Pa]
$\tau_s(z)$	- bed strength profile	[Pa]
ω_1	- angular velocity of the annular ring	[rad/s]
ω_2	- angular velocity of the channel	[rad/s]
ρ_b	- bulk density of the sediment	[kg/m^3]
ρ_s	- density of sediment particles	[kg/m^3]
ρ_w	- density of the water	[kg/m^3]
σ_2	- model parameter (eq. 2)	[-]
t_{50}	- model parameter (eq. 2)	[min]
$(\tau_b/\tau_d-1)_{50}$	- model parameter (eq. 3)	[-]
σ_1	- model parameter (eq. 3)	[-]
α	- model parameter (eq. 6)	[$Pa^{-\beta}$]
β	- model parameter (eq. 6)	[-]

Note:

Most quantities are given in SI-units, e.g.: "mass" in "kg", "time" in "s" and "length" in "m". However, because of practical reasons some exceptions occur in the text:

- CEC:	[meq/100 g]
- conductivity:	[mS/cm]
- SAR:	[$(meq/l)^{1/2}$]
- settling velocity:	[mm/s]
- specific surface:	[m^2/g]

List of figures

ABSTRACT

A sediment sample from the Western Scheldt (harbour of Breskens) is investigated with respect to its behaviour on deposition and erosion. An annular flume is used to quantify the parameters governing these processes. Parallel to these tests various physico-chemical properties of the sediment are determined.

The sediment mainly consists of quartz, feldspar and illite and in less quantities calcite, chlorite, kaolinite, dolomite and smectite. The cohesiveness of the sediment is indicated with a value of 10 for the Cation Exchange Capacity. The sediment is further characterised by a specific surface of 111.5 m^2/g and an organic content of 5%. The fraction smaller than 16 µm amounts 54%. Two different samples show a sand fraction (>63 µm) of 12% and 27% respectively. The fluid is saline with a Sodium Adsorption Ratio varying during the experiments between 35 and 38.

The critical shear stress for deposition is 0.06 ± 0.01 Pa. Below this value complete deposition occurs as for higher values partial deposition takes place. The concentration-time curves are approximated by the equation according to Mehta and Partheniades. The parameters $(\tau_b/\tau_d-1)_{50}$ and σ_1 are in the range of 1.3-2.4 and 0.5-0.8 respectively. The median settling velocity of the sediment in the flocculated state is estimated as 0.23 mm/s (at an initial concentration of 0.84 kg/m^3). When deflocculated a median settling velocity of 0.12 mm/s is measured.

In the annular flume as well as in a separate column a sediment bed with a consolidation period of 1 day is placed. The layer is formed by settling in still water with a depth of 0.3 m. One day after the start of consolidation the dry density near the surface amounts 110 kg/m^3. After 3 days the dry density near the surface is increased to 140 kg/m^3. The dry density profile shows values up to 700 kg/m^3 near the bottom. The water over pressure is largely dissipated during the first day.

At the start of the erosion experiment (consolidation period: 1 day) a top layer of a few mm is present. Erosion takes place at a small rate for a bed shear stress of 0.2 Pa and is enhanced for a bed shear stress of 0.4 Pa. The critical bed shear stress is therefore estimated as 0.2-0.3 Pa. Erosion rates are 0.6 10^{-3} $kg/m^2/s$ or less depending upon the magnitude of the bed shear stress. The parameter M in the erosion rate equation as suggested by Kandiah is in the order of 0.05 10^{-3} - 0.2 10^{-3} $kg/m^2/s$. When the erosion rates are approximated with the erosion rate

expression according to Parchure and Mehta (β = 0.5) an erosion parameter α with a value of 10.4 is found.

In addition to the deposition and erosion experiment two modeltests under <u>tidal conditions</u> are performed. During the tidal experiments the maximum bed shear stress is 0.2 Pa and 0.4 Pa respectively. For both tests the consolidation period of the sediment layer amounts 6 hours. The maximum sediment concentration during the first tidal experiment is less than 0.35 kg/m^3. Erosion and deposition is initiated at a bed shear stress of 0.1 Pa. The type of erosion can be described as surface erosion. The second tidal experiment displays a different erosion behaviour. Due to the high maximum bed shear stress a large amount of sediment is eroded resulting in a maximum sediment concentration of 10 kg/m^3. During the decelerating phase no or little deposition takes place when the bed shear stress is in the range of 0.1 - 0.4 Pa. A rapid decrease of the sediment concentration results when the bed shear stress drops below 0.1 Pa. Around slack water a fluid mud layer is formed with a thickness of 60 mm. When the bed shear stress is increased, internal waves at the interface of the fluid mud layer and the water are originated. The breaking of these waves results in erosion rates in the order of $1.5\ 10^{-3}$ $kg/m^2/s$ (bed shear stresses between 0.1 and 0.2 Pa). This is followed by a period with surface erosion and much lower erosion rates.

1. INTRODUCTION

In order to improve the understanding of the physical processes related to the transport of cohesive sediments, a long-term research program has been started by the Rijkswaterstaat (Ministry of Transport and Public Works of The Netherlands). The program includes physical experiments at Delft Hydraulics.

In 1989 a standard approach was defined to determine the depositional and erosive properties of natural muds in The Netherlands (appendix A). The objectives are:

- to derive the properties for muds of specific sites (lakes, rivers, estuaries, coastal waters),
- to compare the outcomes of the experiments on the various muds and get insight in the ranges of the parameters,
- to establish a data base for further analysis on erosion and deposition and their relations with bulk parameters.

The ultimate goal is to arrive at reliable physical and mathematical descriptions of the transport processes on erosion and deposition and to incorporate the results in numerical models.

The research as described in this report mainly consists of experiments in an annular flume. Additional measurements with a roto-viscometer, a sedimentation balance and a consolidation column are used to determine various properties of the sediment. Furthermore, a number of physico-chemical quantities of the sediment and the fluid are measured: mineralogical composition, Cation Exchange Capacity, conductivity, pH, redox-potential, chlorinity, oxygen and organic content, Sodium Adsorption Ratio and specific area.

The experiments relate to a sediment obtained from the Western Scheldt (taken from the harbour of Breskens) (figure 1). The sampling in the field and the meteorological as well as the hydraulic conditions are described in chapter 2. In chapter 3 a description is given of the annular flume. Attention is paid to the experimental procedure as well as the measurements in the flume. Some of the physico-chemical parameters characterising the sediment are determined by Delft Geotechnics. The results of these analyses are given in chapter 4. Also the measurements at Delft Hydraulics with the roto-viscometer, the sedimentation balance and the consolidation column are presented in this chapter. Subsequently, in chapter 5, 6 and 7 the results of the model tests on deposition, consolidation and erosion in the annular flume are discussed. Finally the experimental results of two experiments under tidal conditions are described in chapter 8.

2. FIELD SAMPLING

The sediment sample was collected on October 4 1989 at 13:00 hrs (MET) with the Rijkswaterstaat motorvessel "Delta". The sampling was done in the harbour of Breskens as indicated in figure 1 (x: 27289, y: 380881). The weather conditions on that day can be described as: sunny, wind direction 30°, wind velocity 5 m/s (Bft. 2) and a temperature of 19 °C.

During the sampling vertical profiles of the conductivity, temperature, pH and oxygen content were measured. The results are shown in table 1. Because no stratification was present only the depth-averaged values are presented. The local water depth during the measurements was 6.4 m. All parameters in table 1 are measured with instruments from Rijkswaterstaat.

conductivity	[mS/cm]	39.04
chlorinity	[kg/m³]	17.13
temperature	[°C]	16.6
oxygen content	[kg/m³]	$6.8\ 10^{-3}$
oxygen content	[% by weight]	81.9
redox-potential	[mV]:	
- fluid		-
- sediment		-
pH (fluid)	[-]	8.09

table 1 - Conditions during sampling

The sediment was collected with a small "van Veen" grab and was sampled from the upper 0.15 m of the sediment layer. The water was pumped from middepth. The sediment and the fluid were transported to the laboratory at a temperature of 4° C with a refrigerator car. At the laboratory the sediment was stored in refrigerators at a temperature varying between 4 °C and 8 °C. The water was kept in a climate controlled room with a constant temperature of 20 °C. Before using the mud for the tests, the sediment was sieved on a screen with a 1 mm lattice.

3. EXPERIMENTAL PROCEDURE AND MEASUREMENTS

3.1 The annular flume

The annular flume (or carousel) (figure 2) consists of a circular channel with a mean diameter of 2.1 m and a channel width of 0.2 m. The water depth is 0.3 m. A circular lid at the surface drives the water. In order to minimize the effect of secondary currents near the bottom the channel itself is rotated in the opposite direction. The operational speeds of the lid and the channel are experimentally determined using small spheres with a density slightly larger than that of the water. Furthermore, velocities above the bottom were measured with an electromagnetic current meter [1]. The proportion of rotational speeds is found to vary between 2.8 and 2.9, which is almost the same as the value of 3.1 derived by Mehta and Partheniades [2] in a somewhat smaller flume. For the experiments described in this report a value of 2.8 is used. The optimal ratio of the angular velocities of the upper lid and the channel is also a function of the water depth ([1] and [2]). In the case of erosion experiments when a sediment layer is present the water depth in the annular flume is less than 0.30 m and changes during erosion. The operational speeds of the upper lid and the channel are slightly corrected to account for this effect.

The bed shear stresses in the annular flume are calculated with an expression as derived by Mehta and Partheniades [2]:

$$\tau_b = a\, V_1^{\,b}, \qquad (1)$$

with,
- τ_b - bed shear stress [Pa],
- $V_1 = |\omega_1 - \omega_2|\, r$ [m/s],
- ω_1 - angular velocity of the annular ring [rad/s],
- ω_2 - angular velocity of the channel [rad/s],
- r - radius of the annular flume [m],
- $a = 0.275$,
- $b = 1.37$.

The sediment suspension is pumped from the flume at middepth (0.14 m above the channel bottom) and led through a small cell with a diameter of 5 mm in which the light adsorption is measured. The suspension is returned to the flume at an elevation of 0.24 m. At regular time intervals samples are taken from the flume to calibrate the optical probe.

The sampling as well as the rotational speeds of the lid and the channel are controlled by a personal computer. A sampling frequency of 1/30 Hz is chosen for the experiments on deposition and erosion. During the tidal experiments the optical sensor is sampled each minute. Data are transmitted between the rotating flume and the personal computer with the aid of an infra-red transmitter and receiver.

The annular flume is located inside a climate controlled room. A temperature of 20 °C and a humidity of 80% guarantee almost constant test conditions.

3.2 Preparations

After the sediment is sieved on a 1 mm mesh (a small amount of water is added), five samples are taken to determine the dry density of the sediment. The dry density is defined as the ratio of the "dry weight" and the "wet volume" and is determined by weighting the sediment sample before and after drying at a temperature of 105 °C. It is assumed that the density of the sediment is 2600 kg/m^3 (not corrected for the organic content). The density of the fluid at a chlorinity of 17.1 kg/m^3 and a temperature of 20 °C is 1021.5 kg/m^3. From this a dry density of 567 ± 7 kg/m^3 is found. The value is used further on to calculate the amount of sediment to be added to the annular flume for the various tests. Furthermore, a bulk density of 1364 kg/m^3 is derived from the measurements (the bulk density is defined as the ratio of the "wet weight" and the "wet volume").

3.3 Tests on deposition

One test with an initial concentration of 0.76 kg/m^3 is performed. The test consists of a mixing period of approximately 0.5 day followed by successive subtests in which the bed shear stress is lowered in small steps. Each subtest is continued until an equilibrium concentration is achieved. With the sediment used in the study this situation is reached after approximately one day or less.

Samples for the calibration of the optical instrument are also used to determine the variations in the grain size distribution as well as the pH, the redox potential and the organic content during the test. During the mixing period preceding the experiment a sample of 1000 ml is taken and analysed at Delft Geotechnics with respect to conductivity, pH, redox-potential, chlorinity, oxygen and organic content and cations.

3.4 Tests on erosion

One erosion test is carried out in order to determine the erosional characteristics of the sediment. The experiment is performed on a sediment layer with a consolidation period of one day with a layer thickness of 0.055 m. The sediment bed is formed by deposition in still water after a mixing period of approximately 12 hours. The concentration of the initial suspension is 55 kg/m³.

The erosional behaviour of each sediment layer is determined by increasing the bed shear stress in successive steps of 1-2 hours. Samples are withdrawn from the flume for analyses on the grain size, the sediment concentration (for the calibration of the optical probe), pH, redox-potential, oxygen and organic content, chlorinity and cations.

The dry density profile within the bed is deduced from measurements in a separate column. At the end of the mixing period the column is filled to a height of 0.3 m with a sediment suspension from the annular flume. Apart from the height of the sediment-water interface the water pressure at the bottom of the cylinder is measured. The results of the measurements in the consolidation column are described in chapter 6.

3.5 Tidal experiments

Two experiments under tidal conditions are performed. The tidal period is taken as 12 hours. The angular velocity of upper lid and channel vary according to a sine function. During the first experiment the maximum bed shear stress is 0.2 Pa. For the second experiment the maximum bed shear stress is taken as 0.4 Pa. The sediment bed is formed by deposition in still water after a mixing period of approximately 12 hours. The initial concentration of the suspension is 54 kg/m³ for the first experiment and 50 kg/m³ for the second experiment. After a consolidation period of 6 hours the thickness of the sediment bed is 0.07 m.

4. SEDIMENT PROPERTIES

4.1 Physico-chemical analyses

The physico-chemical properties and the mineralogical composition of the sediment, as determined by Delft Geotechnics, are presented in table 2 and table 3. The samples of the (wet) sediment are taken after sieving (see chapter 2).

conductivity	[mS/cm]	7.8
chlorinity	[mg/kg]	6500
oxygen content	[kg/m³]	2.5 10^{-3}
oxygen content	[%]	30
redox-potential	[mV]	-310
pH	[-]	7.63
organic content	[% by weight]	5.3
Na	[meq/100 gds]	2.8
K	,,	1.3
Mg	,,	8.4
Ca	,,	14
Fe	[g/kg]	18
C.E.C.		10
dry content [1])	[%]	41
specific area	[m²/g]	111.5

table 2 - Physico-chemical properties of the sediment
[1]) dry weight/total weight
100 gds - 100 grams dry sediment

The mineralogical composition of the sediment is examined by means of X-ray diffraction. Some properties of the clay minerals as density, CEC and specific area are also mentioned in table 3.

	% by weight	ρ_sed.[1] [kg/m³]	CEC[1]	sp.area[1] [m²/g]
smectite	≈ 3			
chlorite	7	2600-2900		
illite	20	2600-2860	40	80
kaolinite	< 3	2610-2640	3 - 8	13 - 26
montmorillonite	-	2350-2700	80	768 -847
quartz	33	2650		
feldspar	20			
calcite	12	2720		
dolomite	3	2850		

table 3 - Mineralogical composition and properties
[1] additional data from: Lambe [9], Taylor [10] and Committee on Tidal Hydraulics [11].

In figure 3 some pictures of the sediment are shown made with a CCD camera connected to a microscope.

4.2 Grain size distribution

A Malvern particle sizer is used to find the particle size distribution of the sediment. The instrument is based on the principle of diffraction of a laser beam around particles (according to Fraunhofer). Size distributions down to a (equivalent) diameter of 1.2 µm can be measured, although it is suspected that measurements of particles smaller than five microns are unreliable. With a small stirrer the sediment is kept in suspension during the measurements. The samples are not deflocculated by means of an ultrasonic treatment or application of a deflocculant. The 10%, 50% and 90% particle diameters as well as the Stokes settling velocity are given in table 4 (ρ_s = 2600 kg/m³, ρ_w = 1022 kg/m³, ν = 10^{-6} m²/s). The presented values are obtained after averaging over 5 different samples (initial samples at the start of the deposition, erosion and tidal experiments). All measurements are done with the 100 mm lens, suited for particles up to 188 µm. Some samples are measured twice, i.e. with a different sample concentration ('obscuration'). It is remarked here that some measurements with the 300 mm lens (up to 564 µm) result in much larger values for the d_{50} and d_{90} particle sizes. For reasons of consistency with the preceding experimental programs with natural muds only the results obtained with the 100 mm lens are presented.

%<	particle diameter	settling velocity
10	4 µm	0.01 mm/s
50	11 µm	0.10 mm/s
90	53 µm	2.36 mm/s

table 4 - Malvern measurements

4.3 Settling velocity

The grain size and the settling velocity can be related according to Stokes' law assuming spherical particles. In a settling column however the fall velocity is measured more directly. A sedimentation balance (type: Sartorius) is used with a fall height of 0.2 m and a volume of 550 ml. At the start of the test the wet sediment is added to the settling column and the suspension with a concentration of approximately 1 kg/m³ is mixed uniformly over the height of the column. This is achieved with a number of vertical strokes with the balance. The mixing is followed by a deposition period of three hours during which the cumulative mass on the balance is recorded. Data are sampled at a rate of 1 Hz and processed on a personal computer. The temperature during the test is kept constant at 20 °C. The total mass on the balance is determined 1 day after the start of the experiment, when it is assumed that the sediment is completely settled. From this value the initial concentration is estimated as 0.84 kg/m³ (assuming a sediment density of 2600 kg/m³). The resulting settling distribution curve is given in figure 4. From this curve a median settling velocity of 0.23 mm/s is derived (equivalent particle diameter: 16 μm). Addition of Na_3PO_4 causes flocculation (!), possibly due to a chemical reaction between the calcium and phosphate ions. Therefore these results are not presented in figure 4.

At Delft Geotechnics a Sedigraph Particle Sizer is used to determine the particle size distribution. The settling velocity is measured and using Stokes´ law an equivalent particle diameter is calculated (ρ_s = 2600 kg/m³, ρ_w = 1022 kg/m³, $\nu = 10^{-6}$ m²/s). A deflocculant ($Na_4P_2O_7.6H_2O$) is added to disperse the sediment. The results of two different samples are shown in table 5.

eq. part. diameter	settling velocity [mm/s]	%< by wgt.	%< by wgt.	eq. part. diameter	settling velocity [mm/s]	%< by wgt.	%< by wgt.
2 μm	0.003	28	24	16 μm	0.22	54	55
4 μm	0.01	38	35	30 μm	0.76	67	65
6 μm	0.03	42	42	38 μm	1.22	72	68
8 μm	0.05	45	46	53 μm [1])	2.36	85	70
10 μm	0.08	48	49	63 μm [1])	3.34	88	73

table 5 - Sedigraph measurements (2 samples)
[1]) obtained by sieving

4.4 Rheological properties

The rheological properties govern the deformation of a fluidum when subjected to a force. From a flow curve, i.e. the shear stress as a function of the shear rate, the yield stress and the dynamic viscosity can be derived.

Two Haake roto-viscometers (CV100 and RV100) with two different sensors (DA45 and MVII) are used for the rheological experiments. The yield stress and the viscosity are determined for suspensions with concentrations varying between 50 kg/m³ and the "natural" concentration obtained after sieving (see 3.2). At the end of a 1 minute acceleration period a maximum shear rate of 150 s^{-1} is achieved. This phase is followed by a deceleration period with the same length. During the tests a constant temperature of 20 °C is maintained. The sampling is done with a personal computer with a frequency of 4 Hz.

In the present study the properties are derived from the flow curve with a decreasing shear rate. The viscosity is taken from the linear part of the 'decelerating' flow curve (mostly shear rates between 30 and 150 s^{-1}). The yield stress is determined as the intercept of the flow curve with the vertical axes. The flow curves of the sediment for both viscometers and various concentrations are given in figure 5. In figure 6 the dynamic viscosity as a function of the concentration is shown on a log-linear scale. The result indicates an exponential relationship as can also be found in literature [3].

A similar graph, relating the yield stress with the sediment concentration, is presented in figure 7. In this case a power law seems to hold for the higher concentrations, which is also in agreement with measurements reported in literature [4]. It will be a point of further research whether the rheological properties can be related to parameters describing the deposition and erosion of a cohesive sediment.

5. RESULTS ON DEPOSITION

5.1 Critical bed shear stress for deposition

The critical bed shear stress for deposition is defined as the value below which complete deposition occurs. For bed shear stresses higher than the critical value *partial deposition* takes place. In this chapter no attention will be paid to the well-known equation according to Krone [12]. This equation predicts a constant sediment concentration when the bed shear stress is higher than the critical value. The resulting equilibrium concentration is estimated from the concentration-time curves with the use of a log-normal fit. Examples of this relationship are given by Cornelisse et al [5] and Kuijper et al [6].

$$\frac{c_0 - c}{c_0 - c_{eq}} = \frac{1}{\sqrt{(2\pi)}} \int_{-\infty}^{T} \exp(-w^2/2)\, dw \qquad (2a)$$

with,

$$T = \frac{1}{\sigma_2}\, {}^{10}\log\left(\frac{t}{t_{50}}\right) \qquad (2b)$$

and,
- c - sediment concentration [kg/m³]
- c_0 - initial concentration (of the subtest) [kg/m³]
- c_{eq} - equilibrium concentration (of the subtest) [kg/m³]
- t - time [s]
- σ_2 - model parameter [-]
- t_{50} - model parameter [s]

The measurements as well as the log-normal fits are given in figure 8 (initial concentration: 0.76 kg/m³).

	initial conc.: 0.76 kg/m³				
τ_b [Pa]	c_0 [kg/m³]	c_{eq} [kg/m³]	t_{50} [min]	σ_2 [-]	
0.4	0.745	0.640	5	0.218	
0.3	0.654	0.518	8	1.262	
0.2	0.516	0.335	75	0.753	
0.15	0.360	0.341	246	0.759	
0.125	0.344	0.309	68	1.252	
0.1	0.306	0.222	106	0.636	
0.075	0.224	0.050	152	0.597	
0.05	0.057	-0.002	459	0.547	
0.1	0.785	0.177	20	1.094	(resuspended)
0.075	0.730	0.011	38	0.896	(resuspended)

table 6 - Model parameters for concentration - time functions

Values for t_{50} and σ_2 for each subtest are given in table 6, together with the initial and equilibrium concentration.

The calculated equilibrium concentration is normalized with the initial value and is given in figure 9 as a function of the bed shear stress. From figure 9 the critical bed shear stress is estimated as 0.06 ± 0.01 Pa. A functional relationship can be derived between the normalized equilibrium concentration (c_{eq}/c_0) and the bed shear stress parameter $(\tau_b/\tau_d - 1)$, see e.g. Mehta and Partheniades [2] and [6].

$$\frac{c_{eq}}{c_0} = \frac{1}{\sqrt{(2\pi)}} \int_{-\infty}^{Y} \exp(-w^2/2)\, dw \qquad (3a)$$

with,
$$Y = \frac{{}^{10}\log[(\tau_b/\tau_d - 1)/(\tau_b/\tau_d - 1)_{50}]}{\sigma_1} \qquad (3b)$$

and, τ_b - bed shear stress [Pa]
τ_d - critical bed shear stress for deposition [Pa]
$(\tau_b/\tau_d - 1)_{50}$ - model parameter [-]
σ_1 - model parameter [-]

Estimates of the parameters are given in table 7 for three values of the critical shear stress .

	$(\tau_b/\tau_d-1)_{50}$	σ_1	number of datapoints
τ_d = 0.05 Pa	2.41	0.57	9
τ_d = 0.06 Pa	1.78	0.65	9
τ_d = 0.07 Pa	1.32	0.78	9

table 7 - Deposition parameters for equilibrium concentration

5.2 Grain size, pH and redox-potential in the suspension

During the deposition experiment the grain size (D_{50} and D_{90}) decreases with decreasing bed shear stress, indicating a loss of the larger particles from the suspension (figure 10). This especially holds for D_{90} which becomes approximately half of the initial value.

The pH measurents are presented in figure 11 showing a slowly decreasing value from 7.8 to 7.65. This is somewhat lower than the value of 7.9 as analysed by Delft Geotechnics (at the start of the test). It is also less than the value measured during the field sampling (8.1). The redox-potential presented in figure 12 varies between 150 mV and 240 mV which is completely different from the value obtained by Delft Geotechnics (-60 mV, see table 8).

5.3 Physico-chemical properties of the suspension

A sample, taken during the mixing period preceding the deposition experiment, is analysed with respect to conductivity, oxygen and organic content, chlorinity, pH, redox-potential and cations. The results are shown in table 8.

Property of suspension		C_0 =0.76 kg/m³
conductivity	[mS/cm]	34.3
chlorinity	[kg/m³]	18
oxygen content	[kg/m³]	$3.4\ 10^{-3}$
oxygen content	[% by weight]	40
redox-potential	[mV]	-60
pH	[-]	7.90
organic content	[% by weight]	9.8
Na	[kg/m³]	5.600
K	,,	0.340
Mg	,,	0.950
Ca	,,	0.130
Sod. Ads. Ratio	$[(meq/l)^{1/2}]$	37.56

table 8 - Physico-chemical properties of the suspension during the deposition experiment (Delft Geotechnics)

6. RESULTS ON CONSOLIDATION

6.1 Consolidation curves

Because of practical considerations the consolidation of the sediment layer is studied in a separate column. After severe mixing in the annular flume 4.6 10^{-3} m^3 of the sediment suspension is brought into the consolidation column. The height of the sediment-water interface, as determined by visual observation, is given in figure 13 as a function of time. The curves are measured in the annular flume as well as in the settling column. The interface changes 0.007 m in the period between 1 day and 7 days after the start of consolidation, which is less than 3% of the total variation (= water depth - bed thickness).

6.2 Pore water pressure

The pore water pressure is measured with a transducer attached to the bottom of the settling column. A filter in front of the transducer prevents direct contact between the transducer and the sediment particles. In figure 14 the water pressure during consolidation is given. The initial pressure is also calculated from the bulk density of the suspension (c_0 = 56 kg/m^3, ρ_b = 1053.8 kg/m^3) assuming a hydrostatic pressure distribution. The ultimate pressure also follows from the hydrostatic pressure (ρ_w = 1020 kg/m^3). From figure 14 it follows that during the first day the water over pressure is largely dissipated. After three days the water over pressure has reached a constant value.

It must be kept in mind that the consolidation period strongly depends upon the layer thickness.

6.3 Dry density profiles

The dry density is measured with a probe that detects the attenuation of an acoustic signal due to the presence of the sediment mass. The measuring technique is recently made operational at Delft Hydraulics. The transducers are shaped according to small cylinders with a diameter of 10 mm and a length of 8.5 mm. The vertical resolution is in the order of 3 mm. The profile is measured by lowering the transmitter and receiver down into the sediment layer. During the successive measurements a lowering of the sediment-water interface is observed at the location of the measurements. This affects mainly the concentration in the top layer. A detailed description of the instrument is given in [7]. The measurements are performed during a consolidation period of 7 days. From figure 15 it is derived that after 1 day the dry density near the surface is approximately 110 kg/m^3. After a consolidation period of

3 days the dry density near the sediment-water interface is increased to 140 kg/m^3. The dry density profile shows relatively high values, up to 700 kg/m^3, near the bottom of the column. Because of the size of the transducers the measurements in the upper few millimetres of the layer are unreliable.

7. RESULTS ON EROSION

7.1 Critical bed shear stress for erosion

The concentration-time curves during erosion are given in figure 16. At the start of the test a background concentration of 0.1 kg/m³ is present. The erosion rates are calculated according:

$$\varepsilon = h \frac{dc}{dt}, \qquad (4)$$

with, ε - erosion rate [kg/m²/s],
h - water depth [m],
c - suspension concentration (depth-averaged) [kg/m³],
t - time [s].

The results are presented in figure 17.

During the erosion experiment no or little erosion occurs for a bed shear stress up to 0.2 Pa. More severe erosion is initiated at a bed shear stress of 0.3 Pa. First a small top layer with a thickness of 2 - 3 mm is eroded. At the end of the subtest with a bed shear stress of 0.4 Pa the top layer is completely eroded (as seen from the outside of the annular flume). The maximum erosion rates are in the order of 0.35 10^{-3} - 0.6 10^{-3} kg/m²/s. From the description given above a critical shear stress of 0.2 - 0.3 Pa can be deduced.

7.2 Erosion parameters

First, the results of the erosion experiments are interpreted according to the widely used equation:

$$\varepsilon = M \left(\frac{\tau_b}{\tau_e} - 1\right) \qquad (5)$$

Equation 5 results in a invariable erosion rate when a constant bed shear stress is applied. For each sub test the erosion rate is averaged and the erosion parameter M is calculated. The erosion rates and the results of the calculations are given in table 9. It appears that the values for the erosion parameter (M) are highly affected by the choice for the critical shear stress.

τ_b [Pa]	$\varepsilon_{max} * 10^3$ [kg/m²/s]	$\varepsilon_f * 10^3$ [kg/m²/s]	$\varepsilon_{avg} * 10^3$ [kg/m²/s]	duration [min]	M * 10³ [kg/m²/s] τ_e=0.20 Pa	M * 10³ [kg/m²/s] τ_e=0.30 Pa
0.10	0.007	0.000	0.001	82		
0.16	0.011	0.002	0.003	100		
0.20	0.052	0.002	0.006	94		
0.30	0.363	0.009	0.028	91	0.056	
0.40	0.537	0.023	0.066	88	0.066	0.198
0.50	0.615	0.037	0.088	95	0.059	0.132
0.60	0.514	0.048	0.090	91	0.045	0.090

table 9 - Erosion rates and erosion parameter M
consolidation period: 1 day
ε_{max} - maximum erosion rate during sub test
ε_f - floc erosion rate (averaged over ≈ 30 min)
ε_{avg} - erosion rate averaged during sub test

As mentioned before the suspension concentration shows a non-linear increase in time when a constant bed shear stress is applied. Consequently, also the erosion rate equation as formulated by Parchure and Mehta is used [8]:

$$\ln \left(\frac{\varepsilon}{\varepsilon_f}\right) = \alpha \, [\tau_b - \tau_s(z)]^{\beta} \tag{6a}$$

with, ε_f - floc erosion rate [kg/m²/s],
$\tau_s(z)$ - bed strength profile [Pa],
α - model parameter [$Pa^{-\beta}$],
β = 0.5.

The erosion depth can be calculated from the erosion rate provided that the dry density profile is known. Subsequently the bed strength is interpolated from the bed strength profile. In this way a multi-layer approach for the bed is followed. The state with floc erosion is reached when the erosion has proceeded to the depth where the bed shear stress is equal to the strength of the bed. At that stage occasionally flocs are removed from the bed surface resulting in floc erosion.

The model parameters α is estimated from the measurements as follows. At the start of subtest (i) the strength of the bed at the surface is equal to the bed shear stress from the preceding subtest (i-1). When the erosion rate at the initial state is known (ε_0) and the floc erosion rate is taken from the ´tail´ of the curve of subtest (i) eq. 6a changes into:

$$\ln\left(\frac{\varepsilon_a}{\varepsilon_f}\right) = \alpha\,[\tau_b^{(i)} - \tau_b^{(i-1)}]^{\beta} \qquad (6b)$$

The results of the calculations are given in table 10.

cons.: 1 day (7 subtests)	
β	α [$Pa^{-\beta}$]
0.50	10.42

table 10 - Erosion parameters (eq. 6a)

So far, no calculations with eq. 6a and parameters from table 10 are made. This will be the subject of research in 1990.

7.3 Grain size, pH and redox-potential in the suspension

The particle sizes as measured with the Malvern particle sizer are given in figure 18. It follows that the grain size of the sediment during the erosion experiment differs from the grain size of the original suspension (during mixing). This especially holds for the D_{90}, which is approximately half of the initial value.

The acidity (pH) during the erosion test is almost constant and is presented in figure 19. The measured value (pH = 7.6) is considerably larger than the value obtained by Delft Geotechnics. The redox-potential is not measured because no redox probe was available at the time.

7.4 Physico-chemical properties of the suspension

Two samples from the annular flume are also analysed with respect to conductivity, oxygen and organic content, chlorinity, pH, redox potential and cations (see table 11). The first sample is taken during the mixing period preceding the erosion test. The second sample is taken during the mixing period following the test.

Property of suspension		sample 1	sample 2
conductivity	[mS/cm]	35.4	36.1
chlorinity	[kg/m³]	18	17
oxygen content	[kg/m³]	0.0048	0.0057
oxygen content	[%]	55	65
redox-potential	[mV]	+210	+174
pH	[-]	7.43	7.04
organic content	[%]	5.2	4.7
Na	[kg/m³]	5.4	5.4
K	,,	0.33	0.34
Mg	,,	1.00	0.96
Ca	,,	0.13	0.14
Sod. Ads. Ratio	[(meq/l)$^{1/2}$]	35.4	35.9

table 11 - Physico-chemical properties of the suspension during the erosion experiment.

8. TIDAL EXPERIMENTS

The concentration-time curve of the first tidal experiment (τ_b = 0.2 Pa) is given in figure 21 (tidal period 11). The erosion depth is small resulting in maximum suspension concentrations of 0.34 kg/m³. The erosion and deposition rates are presented in figure 22. The maximum erosion and deposition rates are in the order of 0.015 10^{-3} kg/m²/s. The graph with the sediment concentration as a function of the bed shear stress (figure 23) shows that a critical value exists for the bed shear stress. When the bed shear stress is larger than 0.1 Pa erosion commences. A bed shear stress lower than this critical value results in deposition.

The particle size during the tidal experiment is given in figure 24. In comparison with the original suspension the D_{50} is much smaller (≈ 30%). The particle size does not exhibit a 'tidal fluctuation'.

During the second tidal experiment (τ_b = 0.4 Pa) the maximum suspension concentration is 10 kg/m³ (figure 25, tidal period 11). No or little erosion takes place for bed shear stresses lower than approximately 0.1 Pa. Below this value the sediment concentration decreases rapidly. Around slack water a fluid mud layer is formed with a thickness of 60 mm. The mean sediment concentration in the mud layer follows from continuity considerations and is in the order of 45 - 50 kg/m³. Waves originate on the interface between the fluid mud layer and the water when the bed shear stress gradually increases after slack water. At a bed shear stress of approximately 0.06 Pa the internal waves break and cause an upward sediment flux. This does not immediately show as an increase of the suspension concentration (mixing time). The maximum erosion rate is 1.5 10^{-3} kg/m²/s (figure 26). During this phase with erosion due to internal waves the thickness of the fluid mud layer decreases from 40 mm towards 10-20 mm and internal waves gradually disappear. The sediment layer is more and more resuspended by surface erosion, which is accompanied by a reduced erosion rate (≈ 0.2 10^{-3} kg/m²/s). In figure 27 the sediment concentration is plotted against the bed shear stress.

Acknowledgements

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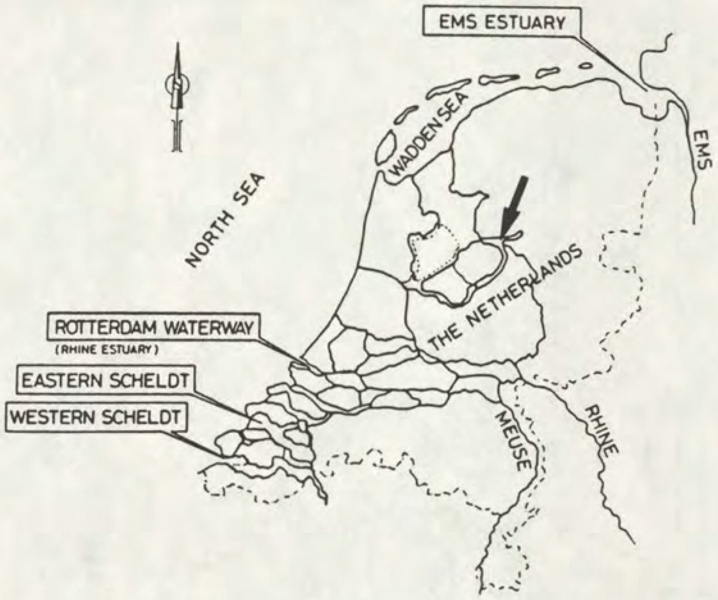
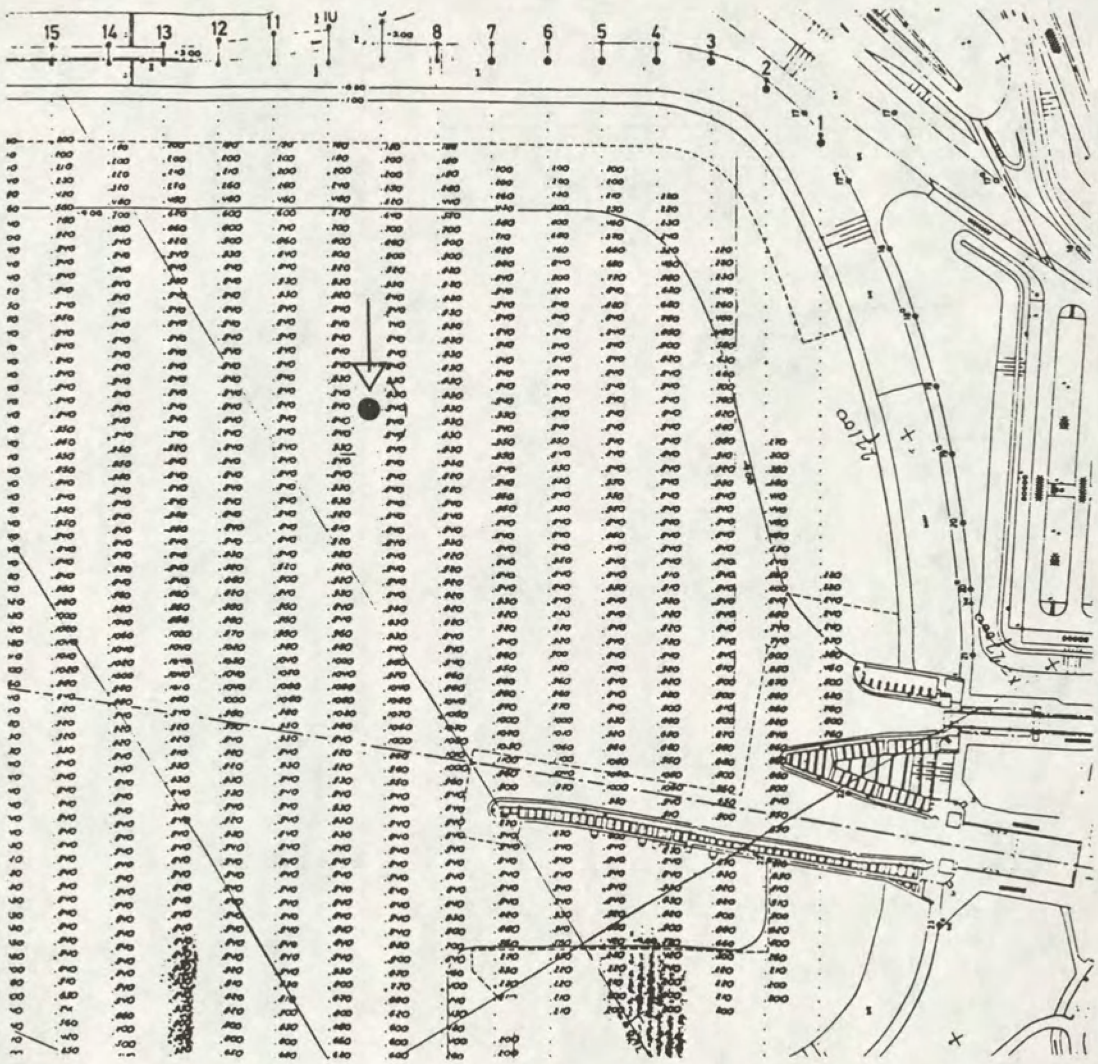
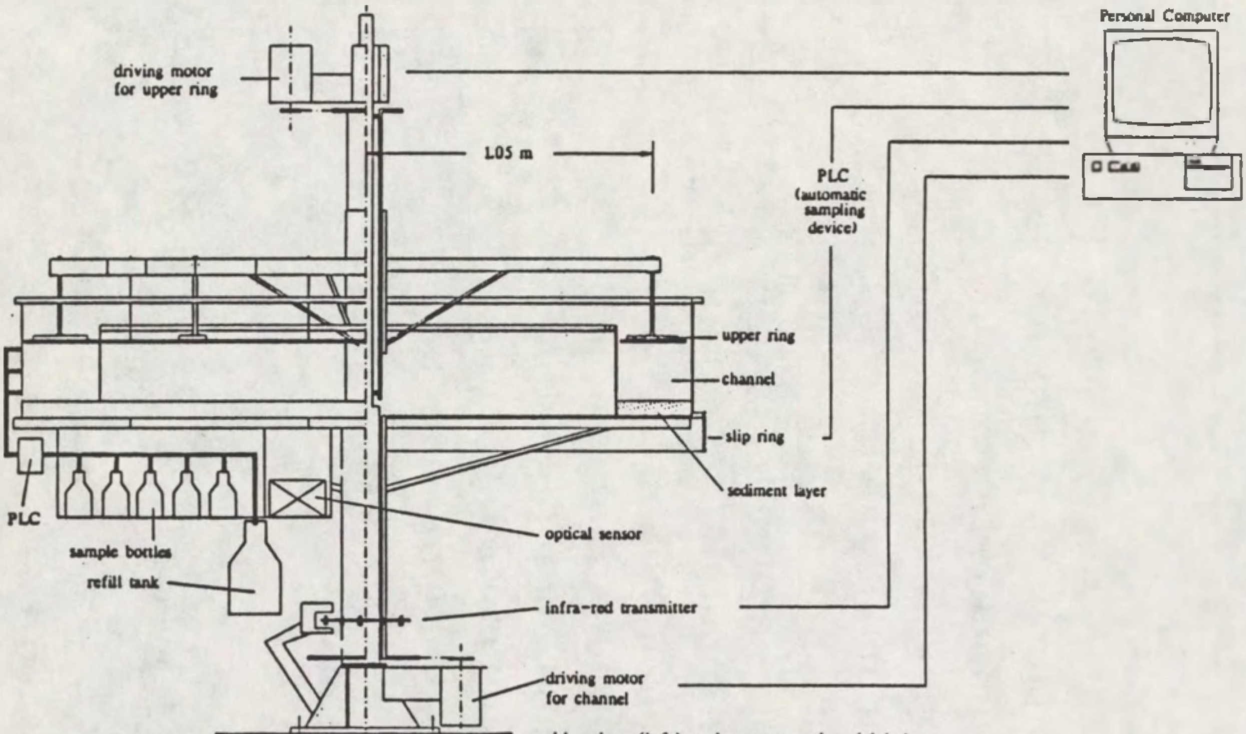




Sampling location.

DELFT HYDRAULICS		A4
		Fig 1



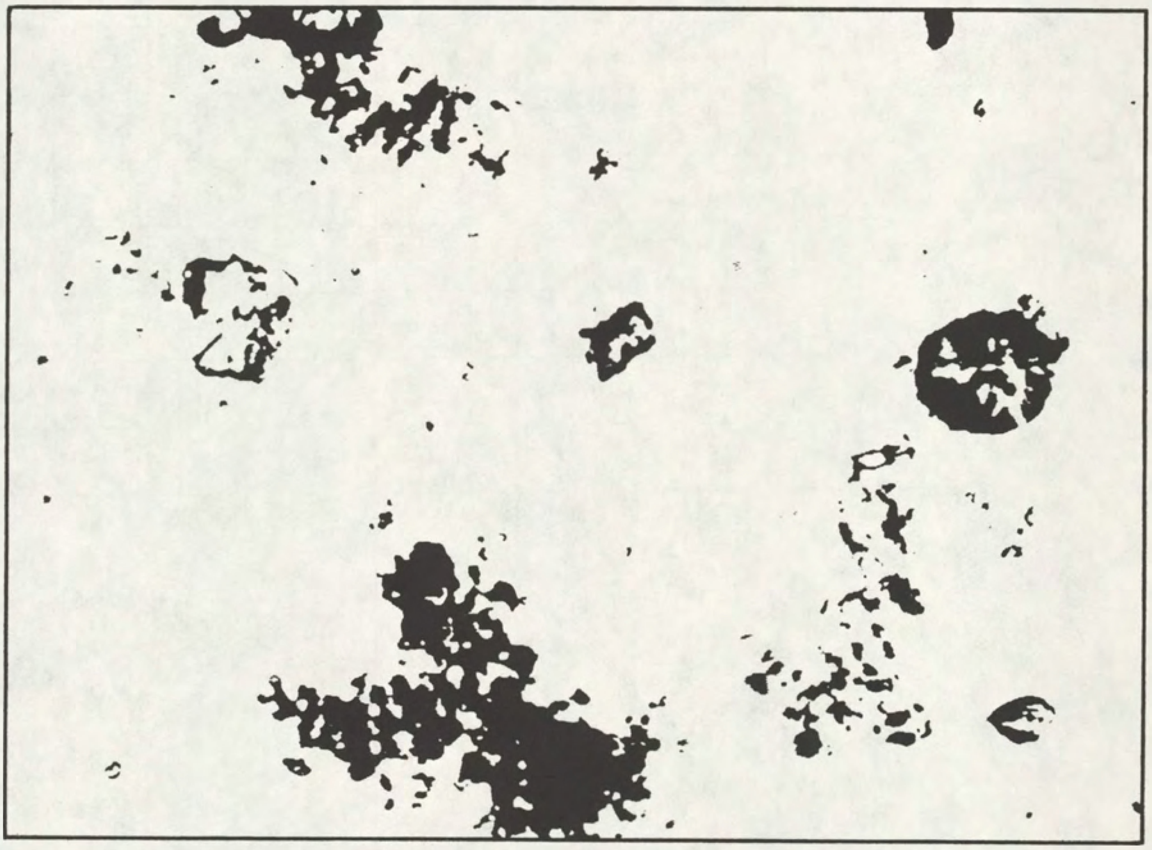
side view (left) and cross-section (right)

Annular flume.

A4

DELFT HYDRAULICS

Fig 2



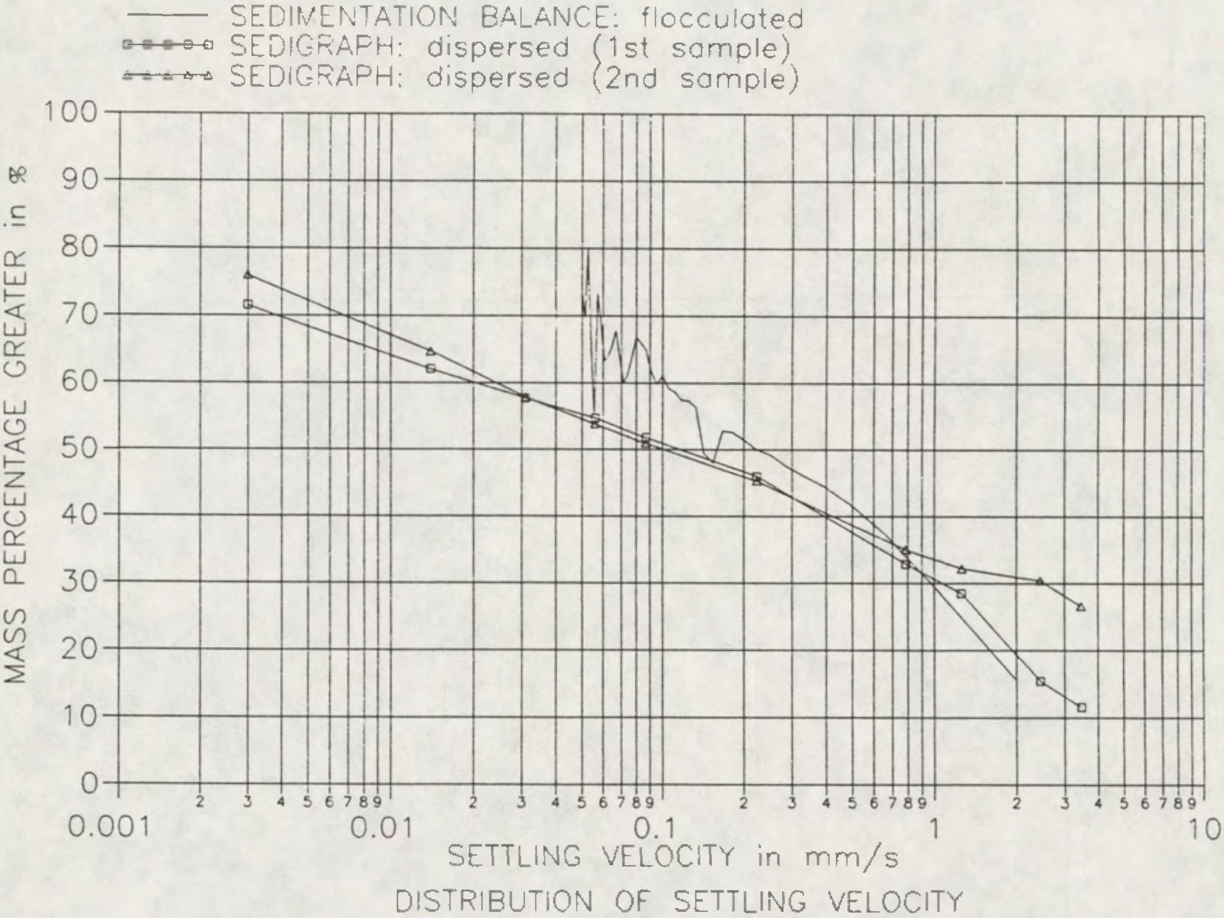
290 μm

Photographs of sediment and sediment particles.

A4

DELFT HYDRAULICS

Fig 3

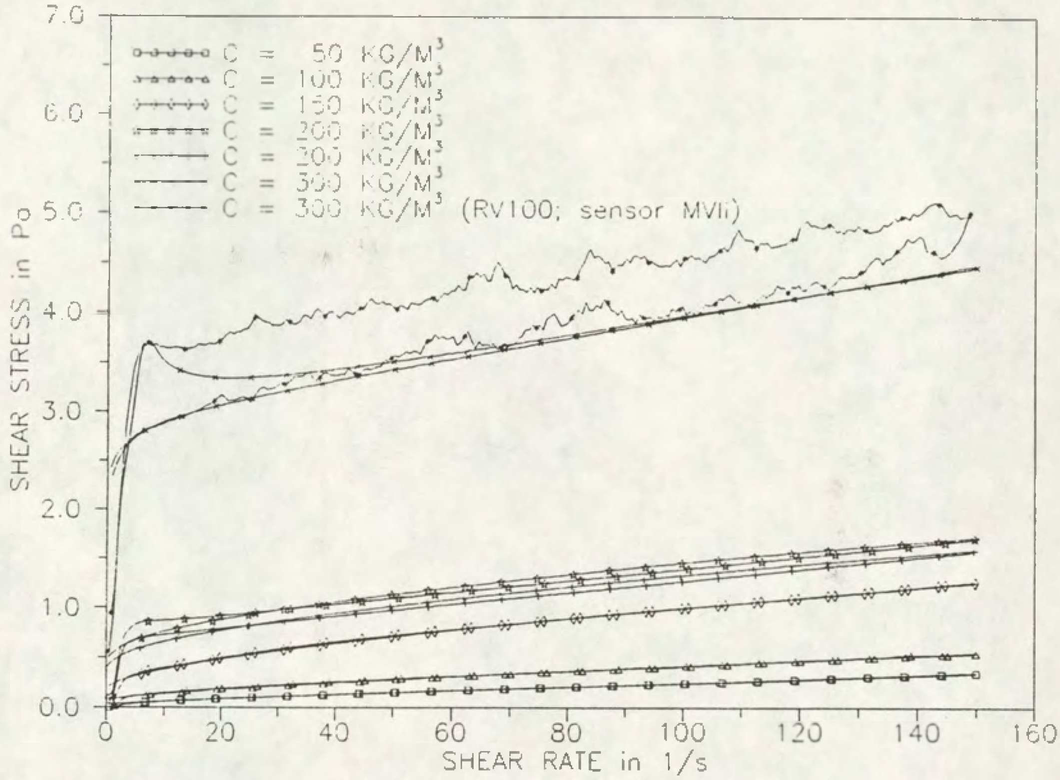


Distribution of settling velocity.

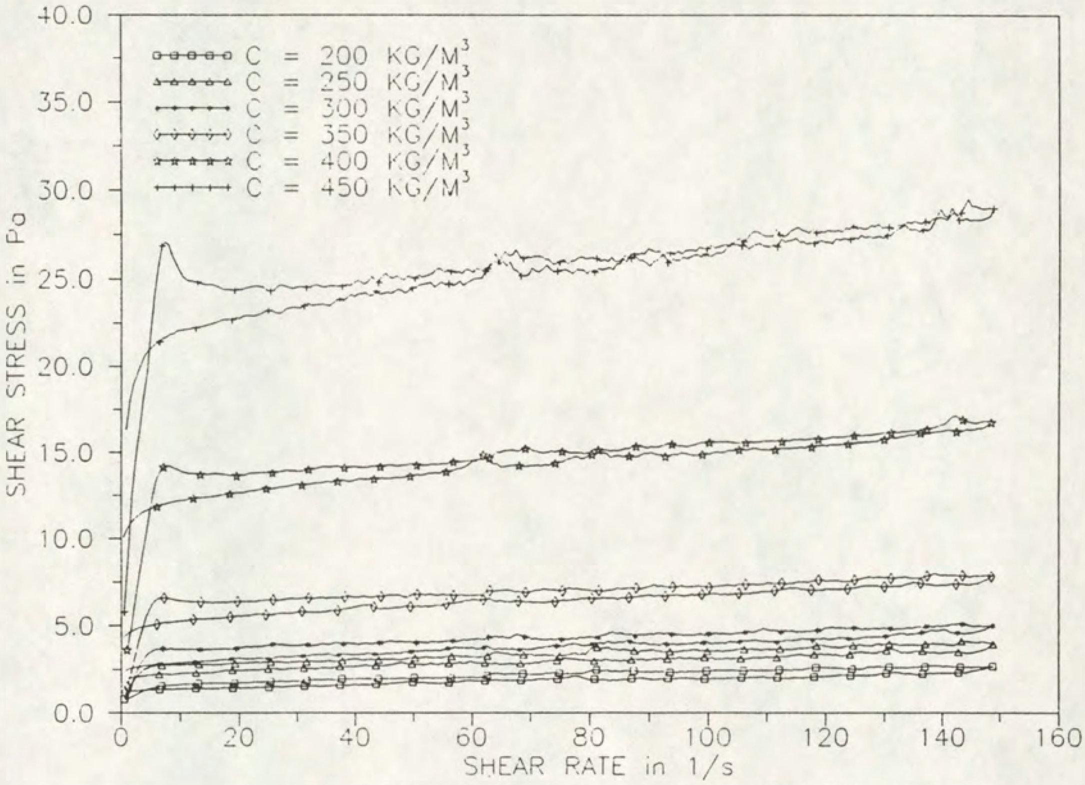
A4

DELFT HYDRAULICS

Fig 4

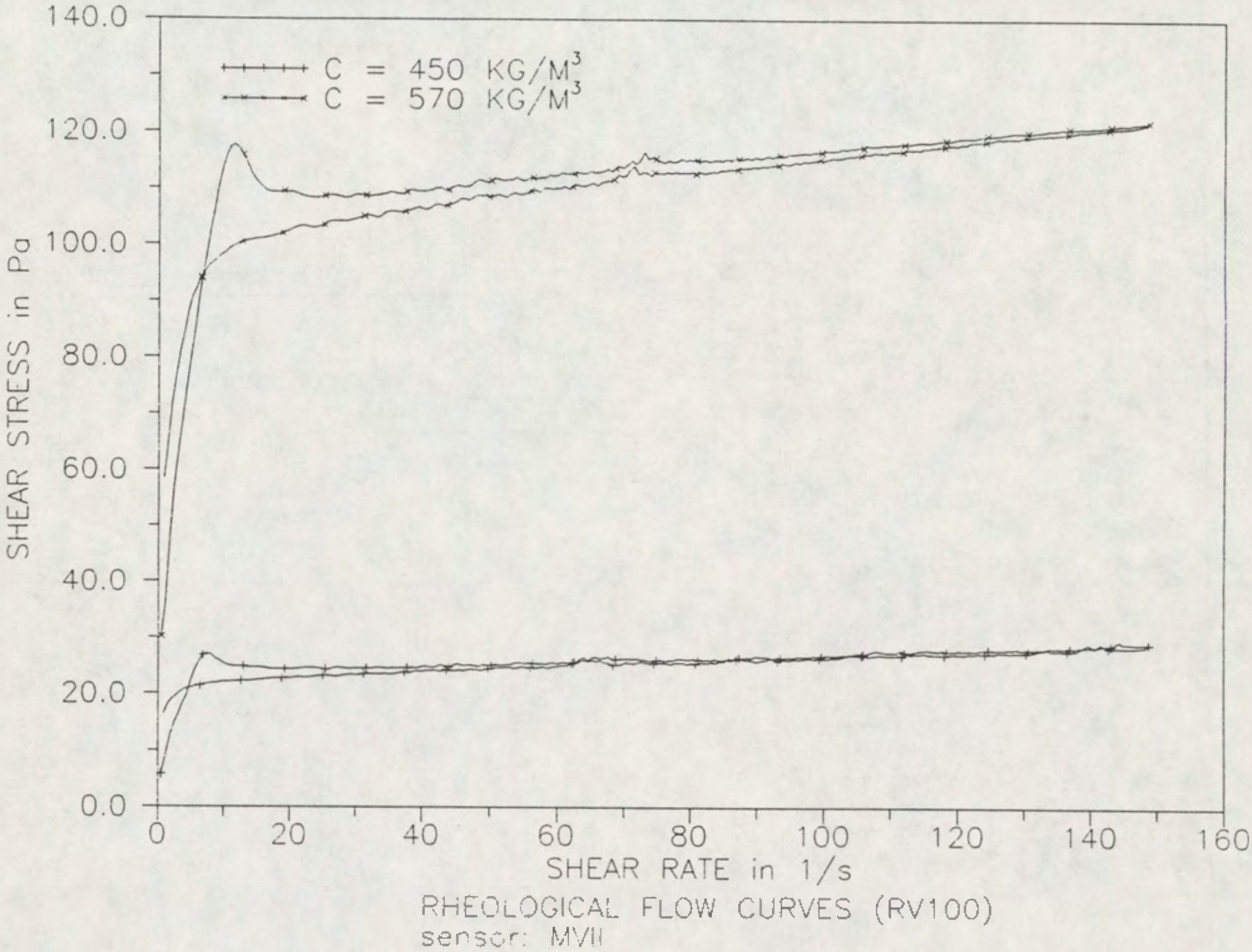


RHEOLOGICAL FLOW CURVES (CV100)
sensor: DA45



RHEOLOGICAL FLOW CURVES (RV100)
sensor: MVII

Rheological flow-curves.		
		A4
DELFT HYDRAULICS		Fig 5[a]

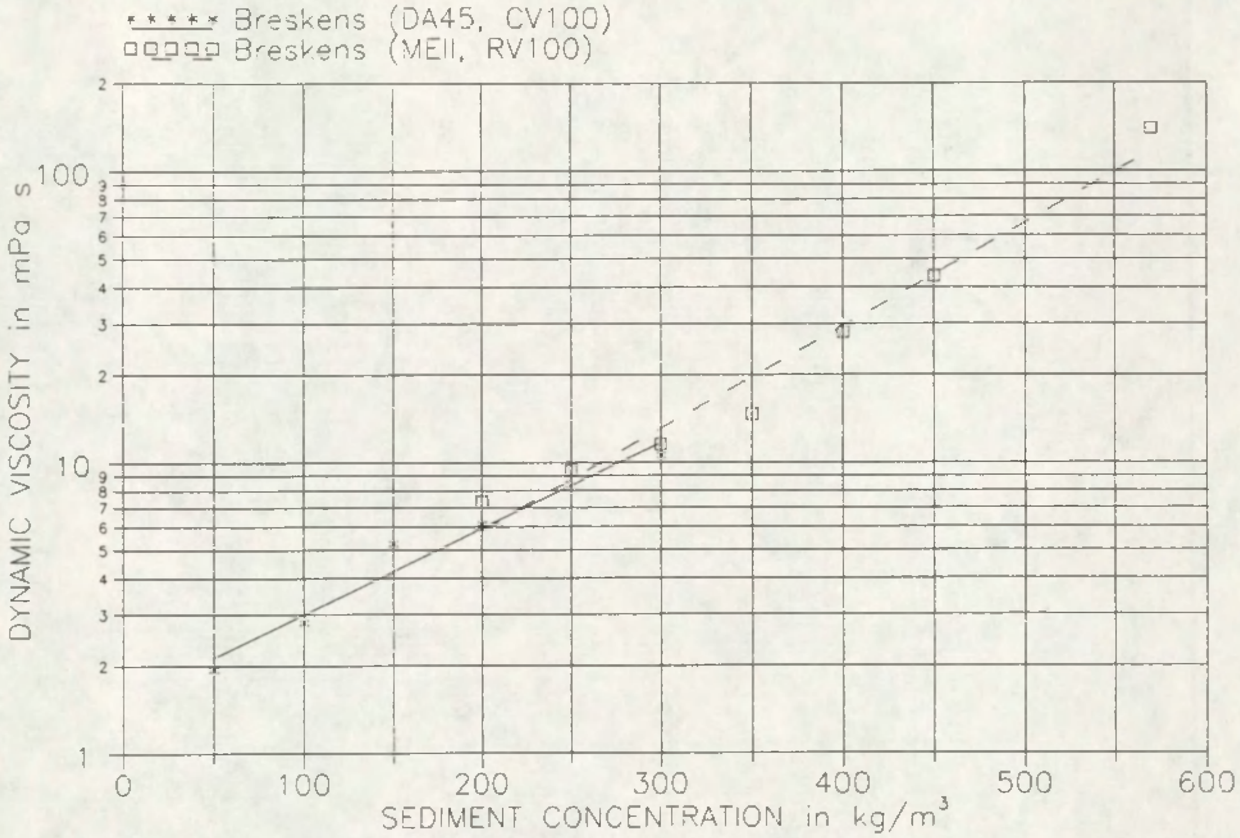


Rheological flow-curves.

A4

DELFT HYDRAULICS

Fig 5[6]



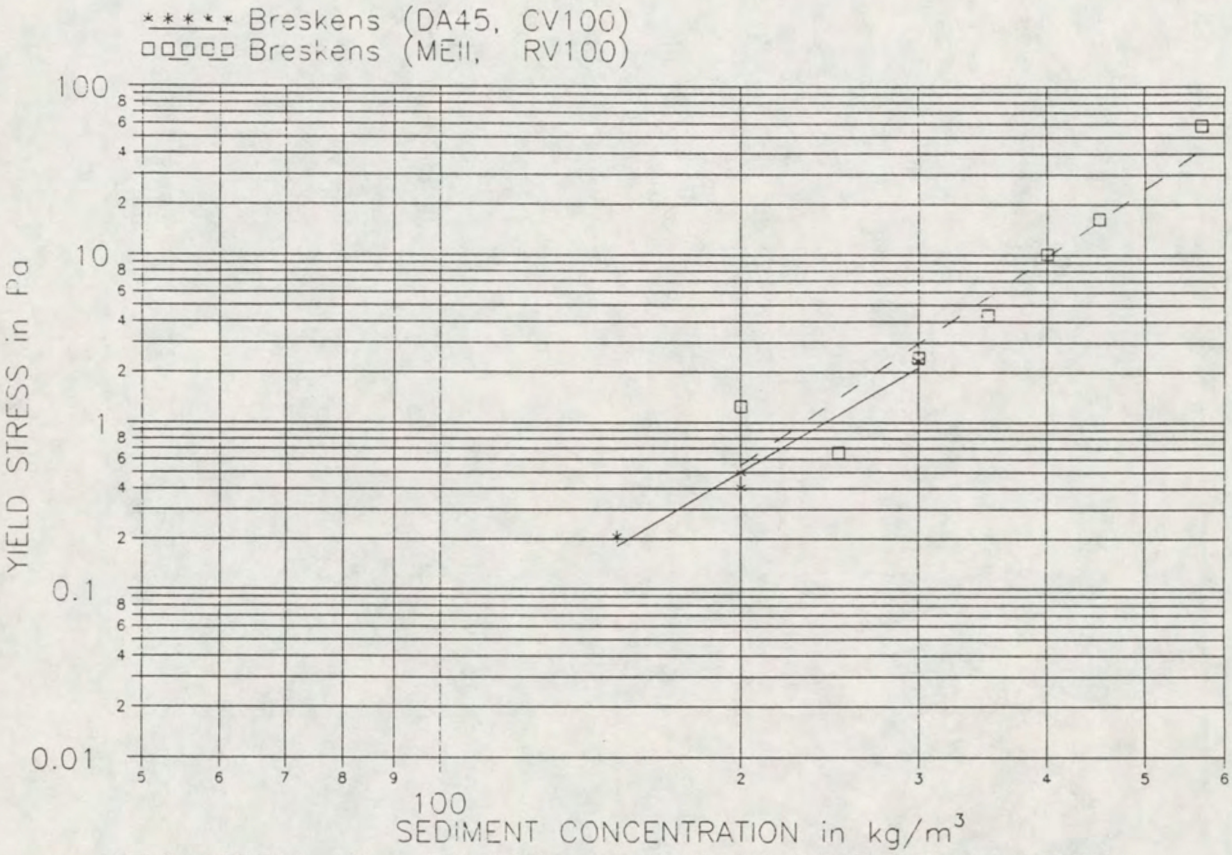
DYNAMIC VISCOSITY AS A FUNCTION OF THE SEDIMENT CONCENTRATION ('downcurve')

Dynamic viscosity of the sediment.

A4

DELFT HYDRAULICS

Fig 6



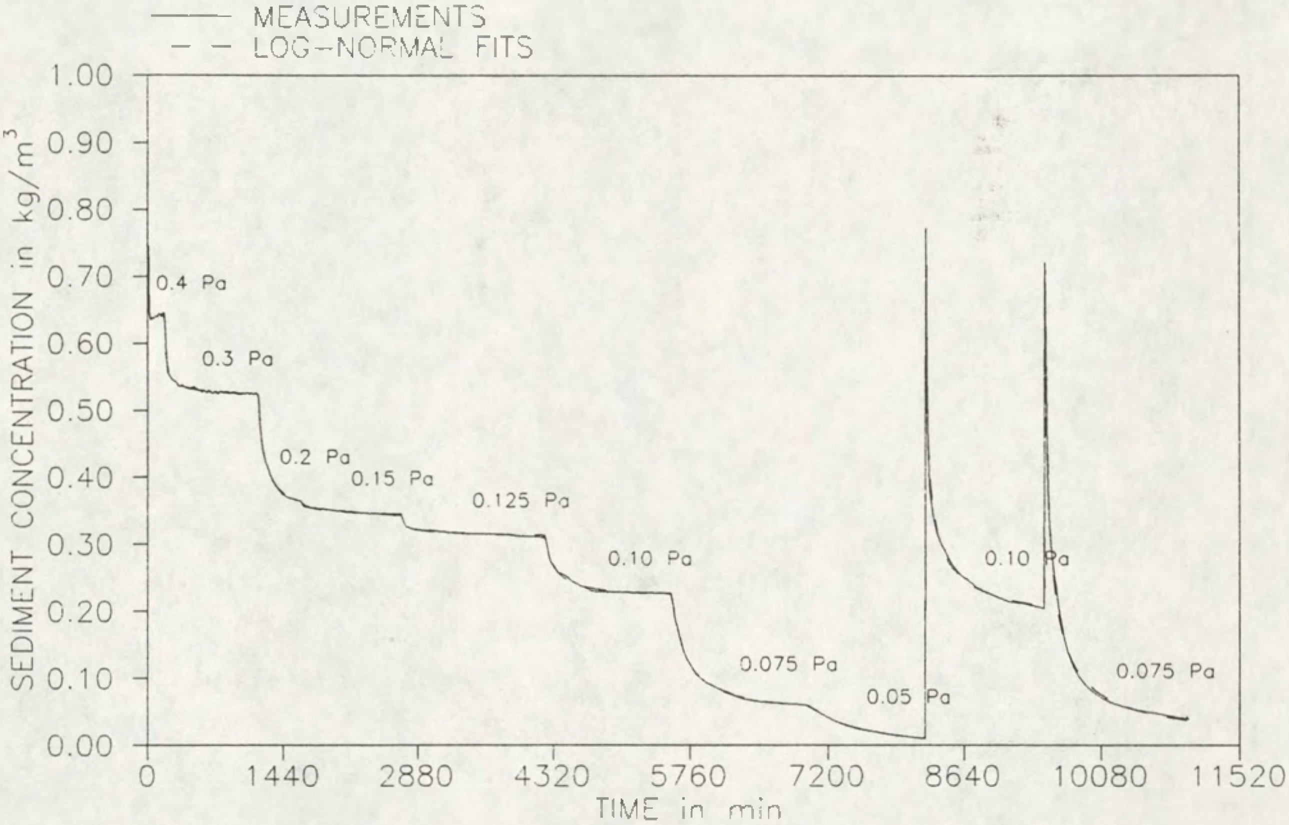
YIELD STRESS AS A FUNCTION OF THE SEDIMENT CONCENTRATION
('down curve': intersection of flow curve with vertical axis)

Yield stress of the sediment.

A4

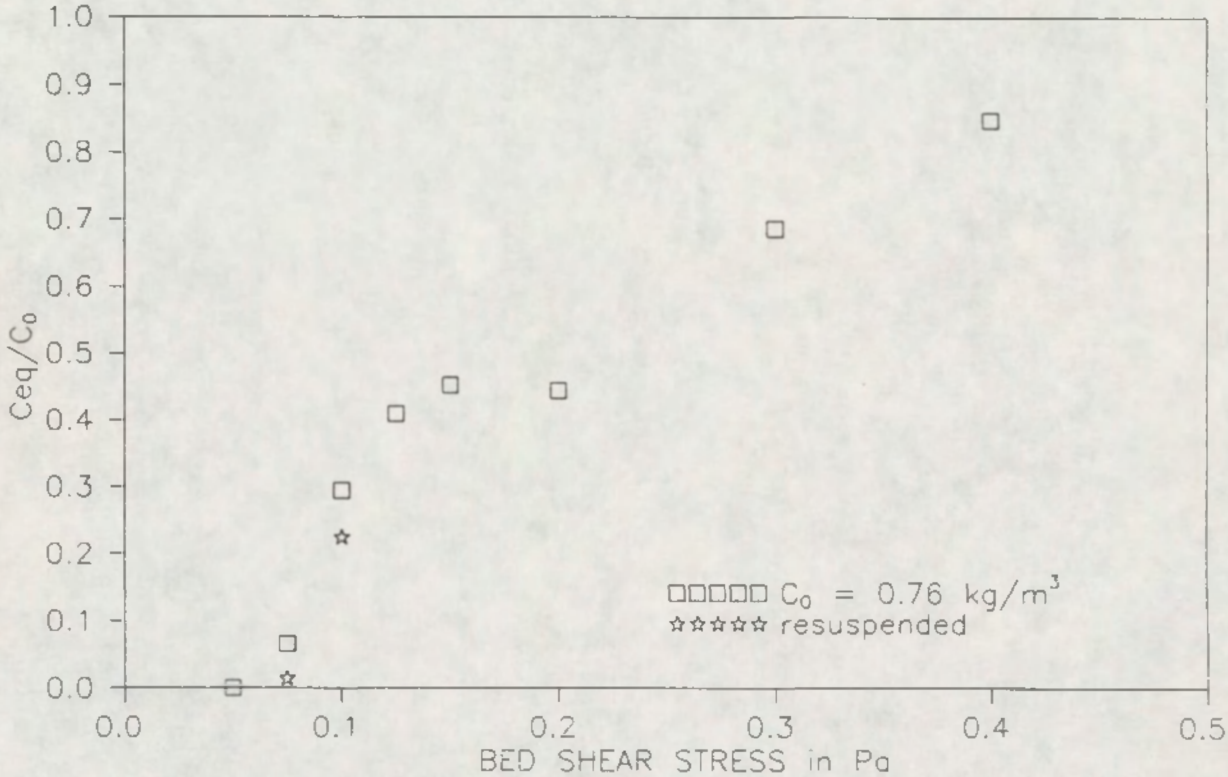
DELFT HYDRAULICS

Fig 7



CONCENTRATION-TIME CURVES DURING DEPOSITION AND LOG-NORMAL FITS
initial concentration: 0.76 kg/m^3

Concentration-time curves during deposition and log-normal fits.		A4
DELFT HYDRAULICS		Fig 8



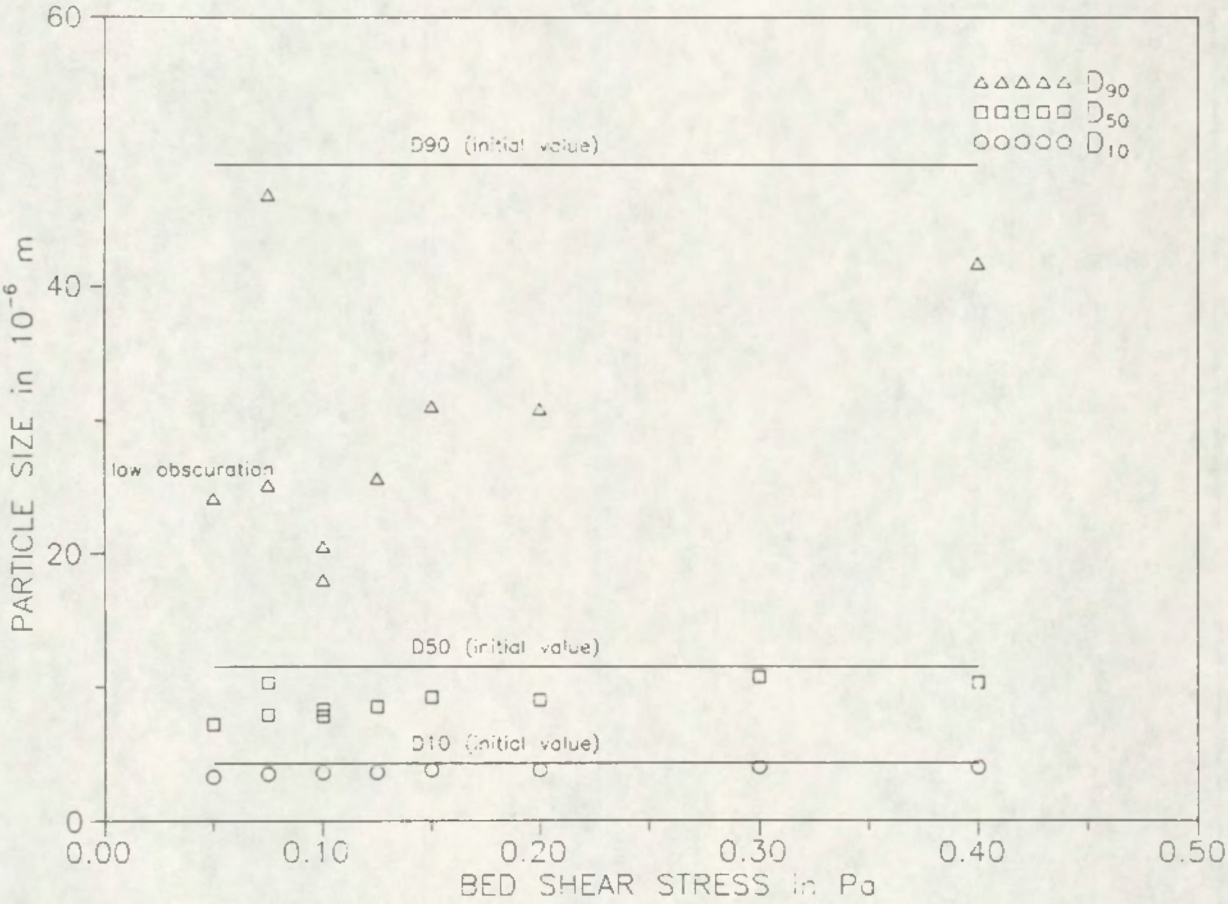
EQUILIBRIUM CONCENTRATION FROM LOG-NORMAL FIT
normalized with initial concentration

Concentration-time curves during deposition and log-normal fit.

A4

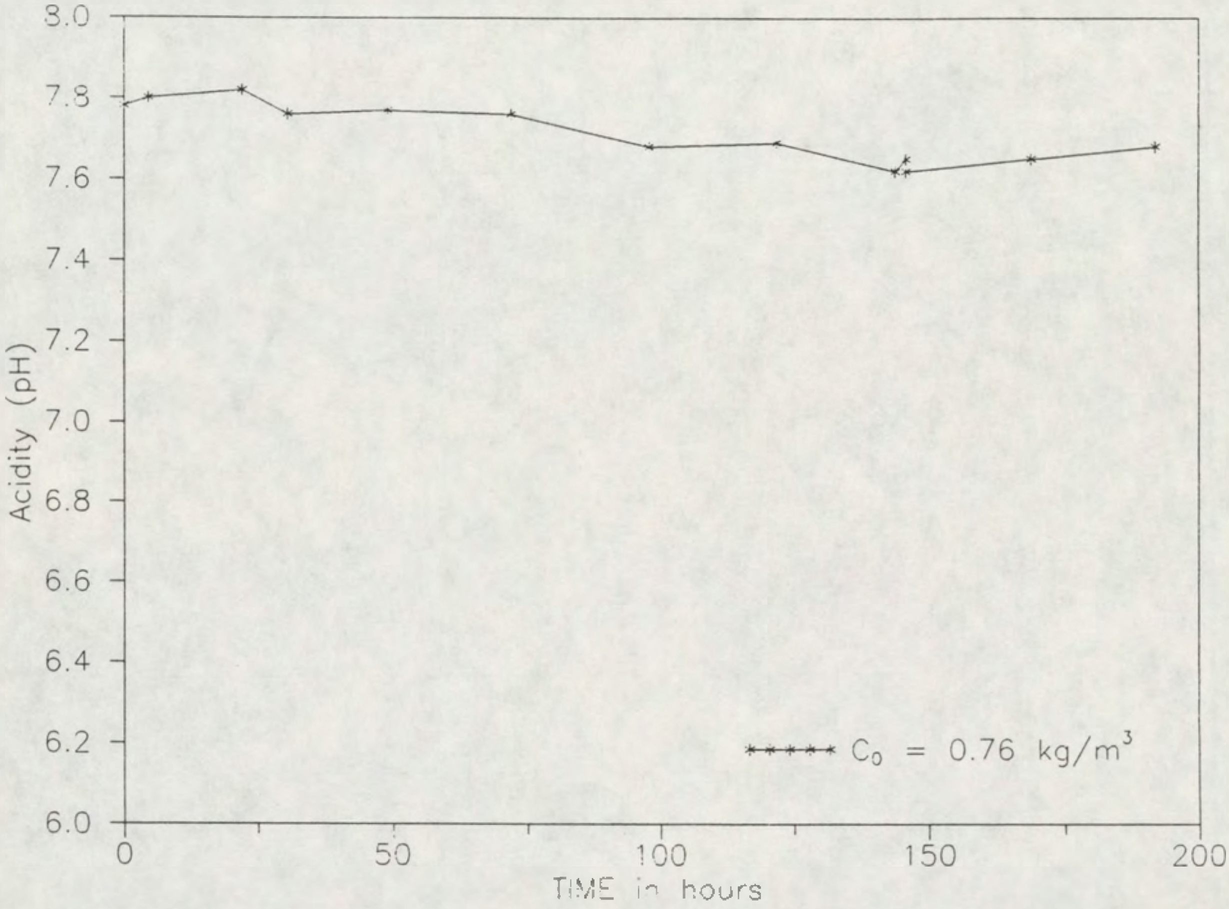
DELFT HYDRAULICS

Fig 9



PARTICLE SIZE DURING EXPERIMENT ON DEPOSITION (C_0 = 0.76 kg/m^3)

Particle size during experiments on deposition.		
		A4
DELFT HYDRAULICS		Fig 10



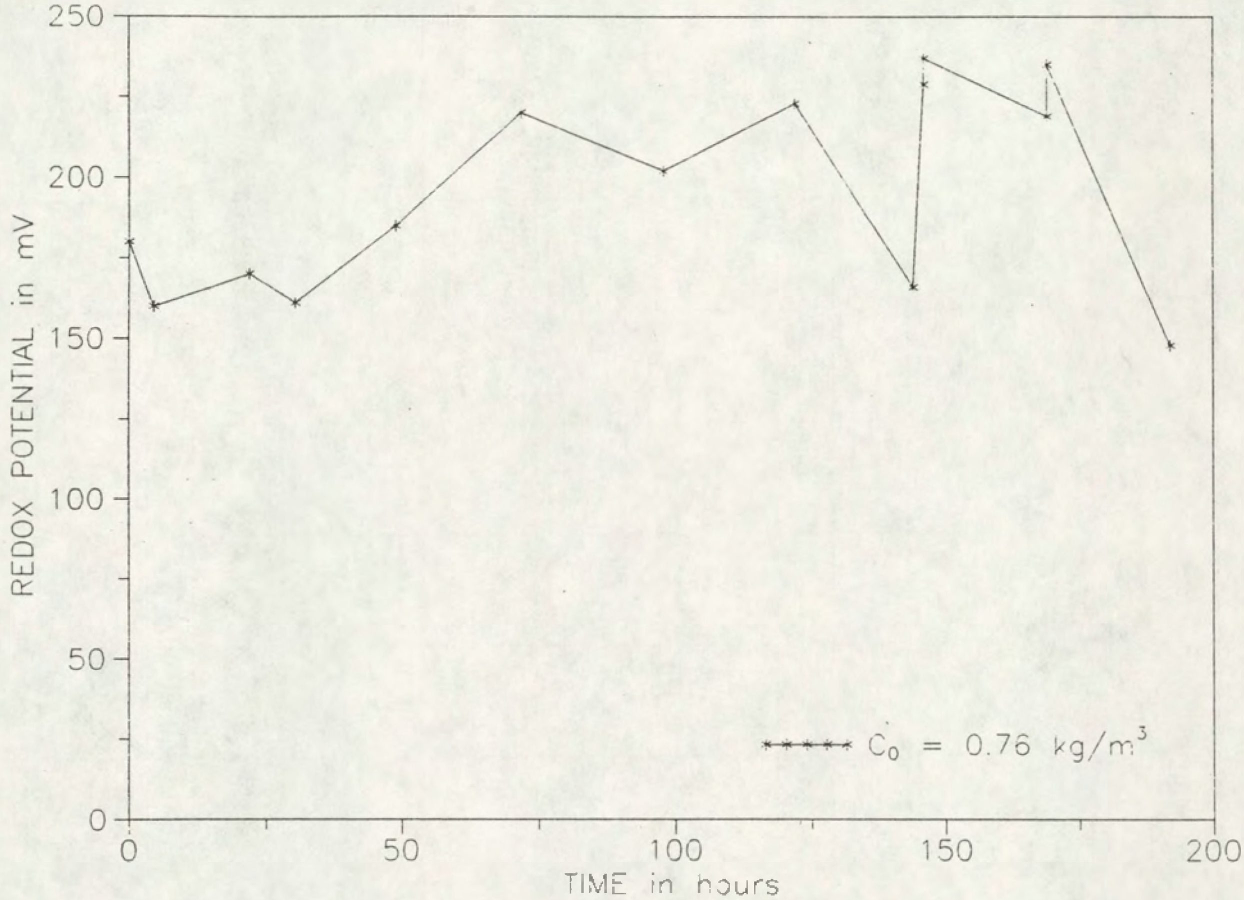
pH DURING EXPERIMENT ON DEPOSITION

pH during experiments on deposition.

A4

DELFT HYDRAULICS

Fig 11



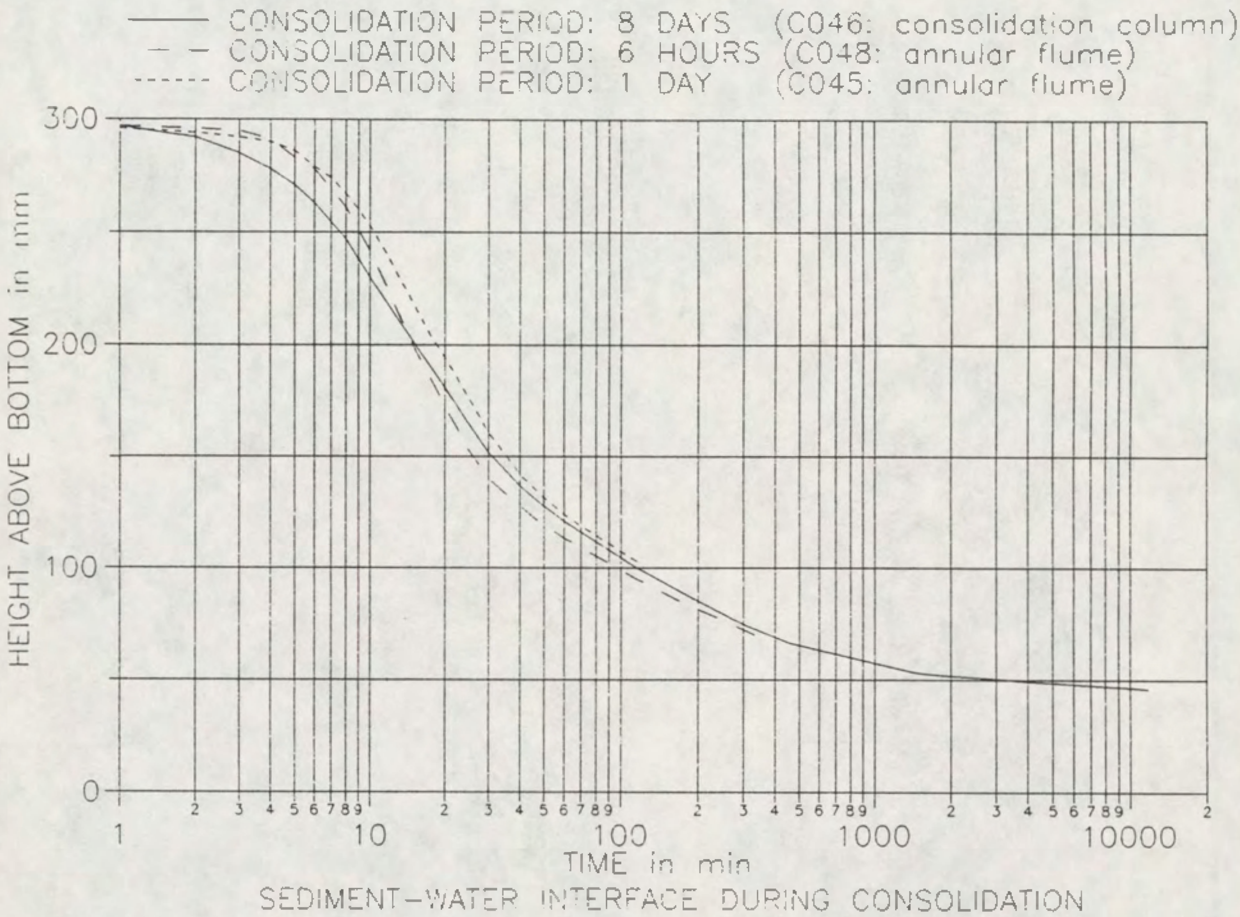
REDOX POTENTIAL DURING EXPERIMENT ON DEPOSITION

Redox potential during experiments on deposition.

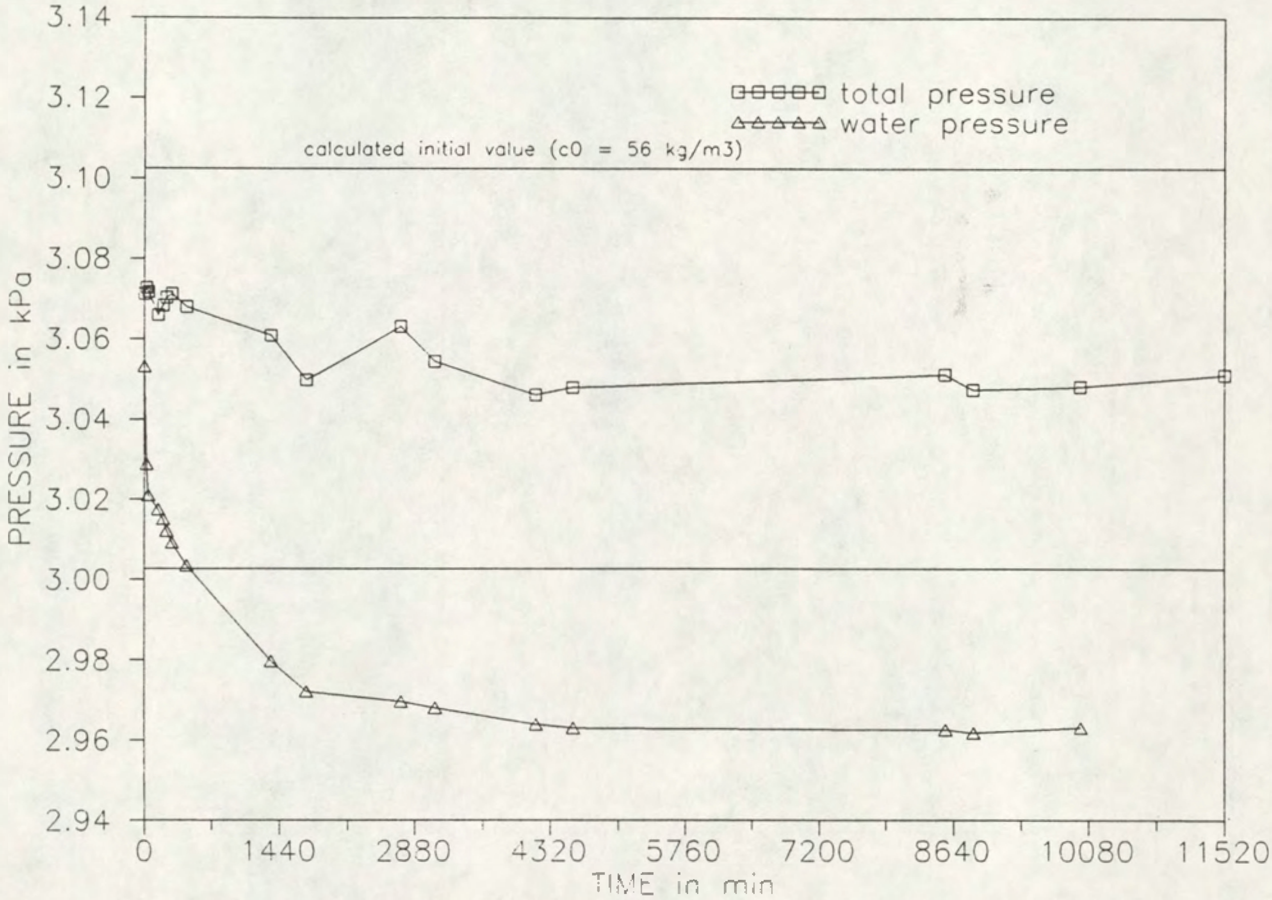
A4

DELFT HYDRAULICS

Fig 12

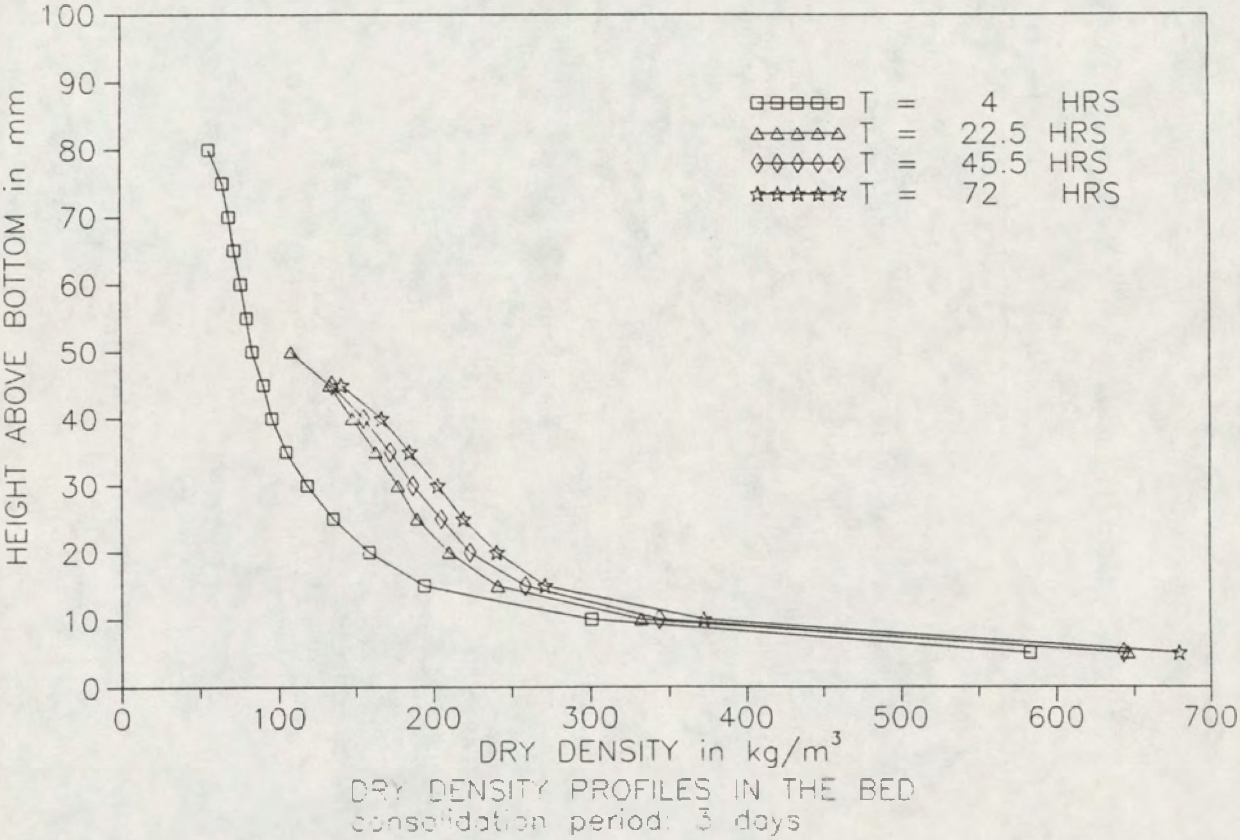


Sediment-water interface during consolidation.		
		A4
DELFT HYDRAULICS		Fig 13



PORE WATER PRESSURE AND TOTAL PRESSURE DURING CONSOLIDATION

Pore water pressure during consolidation.		
		A4
DELFT HYDRAULICS		Fig 14

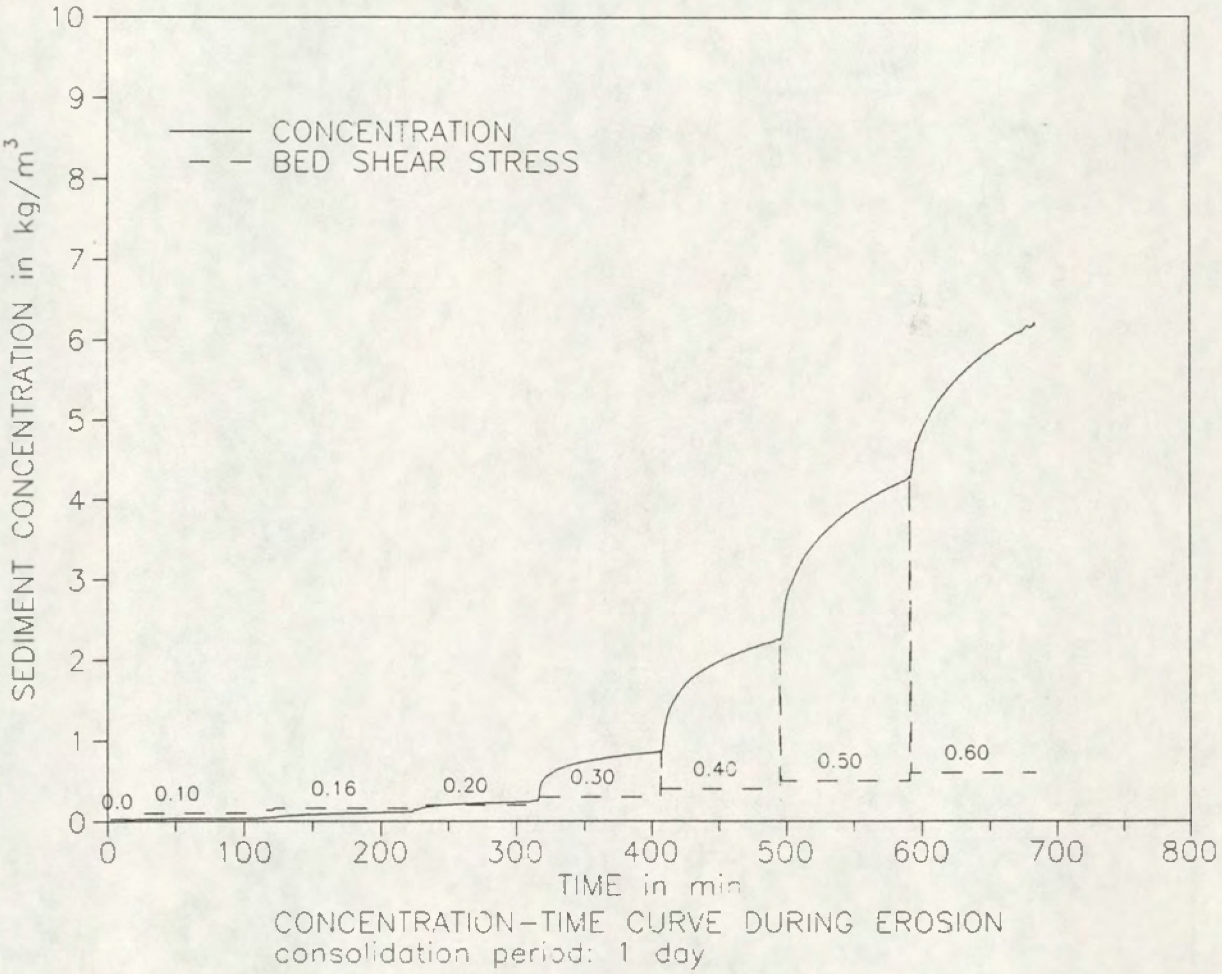


Dry density profiles during consolidation
(consolidation period: 3 days)

A4

DELFT HYDRAULICS

Fig 15

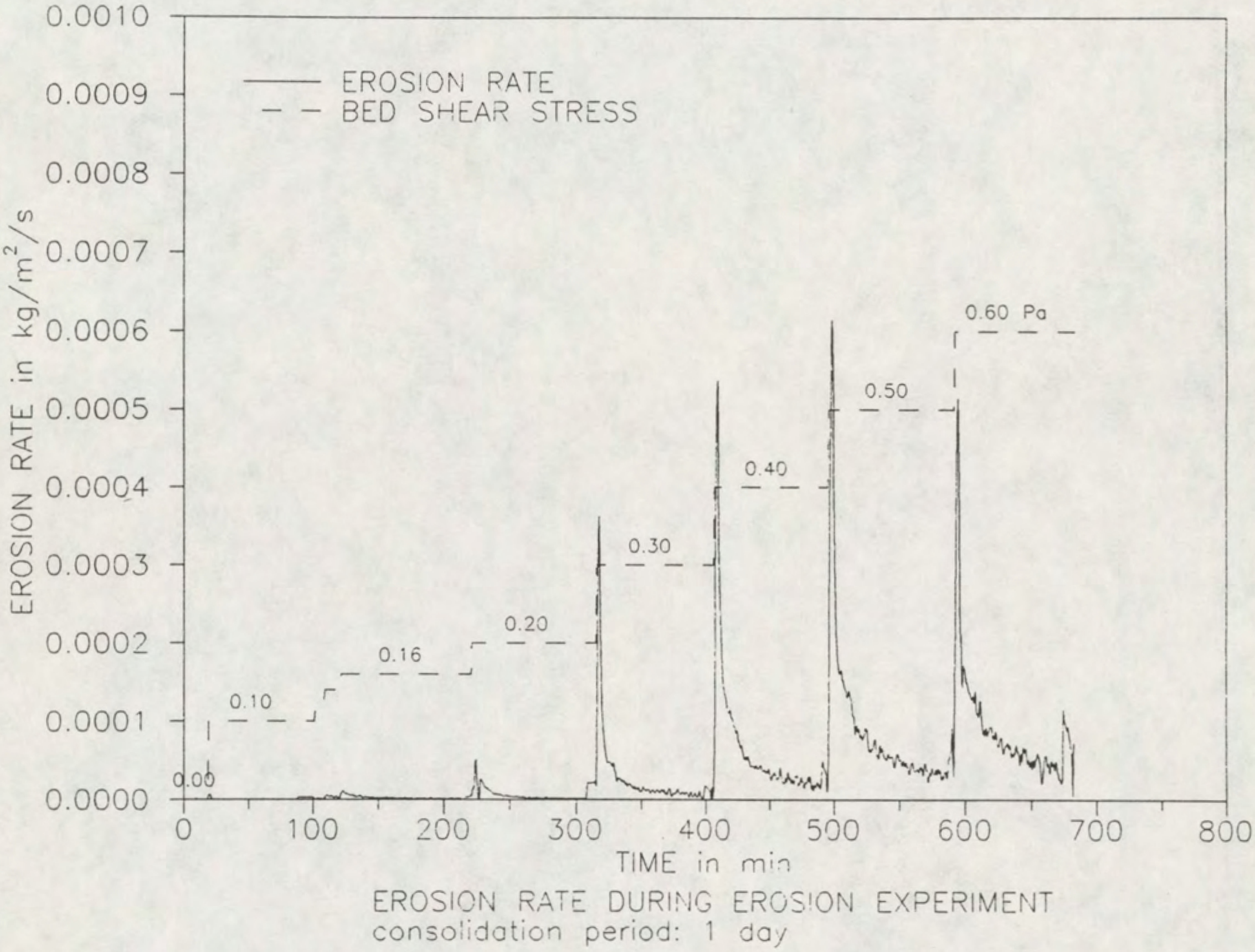


Concentration-time curves during erosion
(consolidation period: 1 day).

A4

DELFT HYDRAULICS

Fig 16

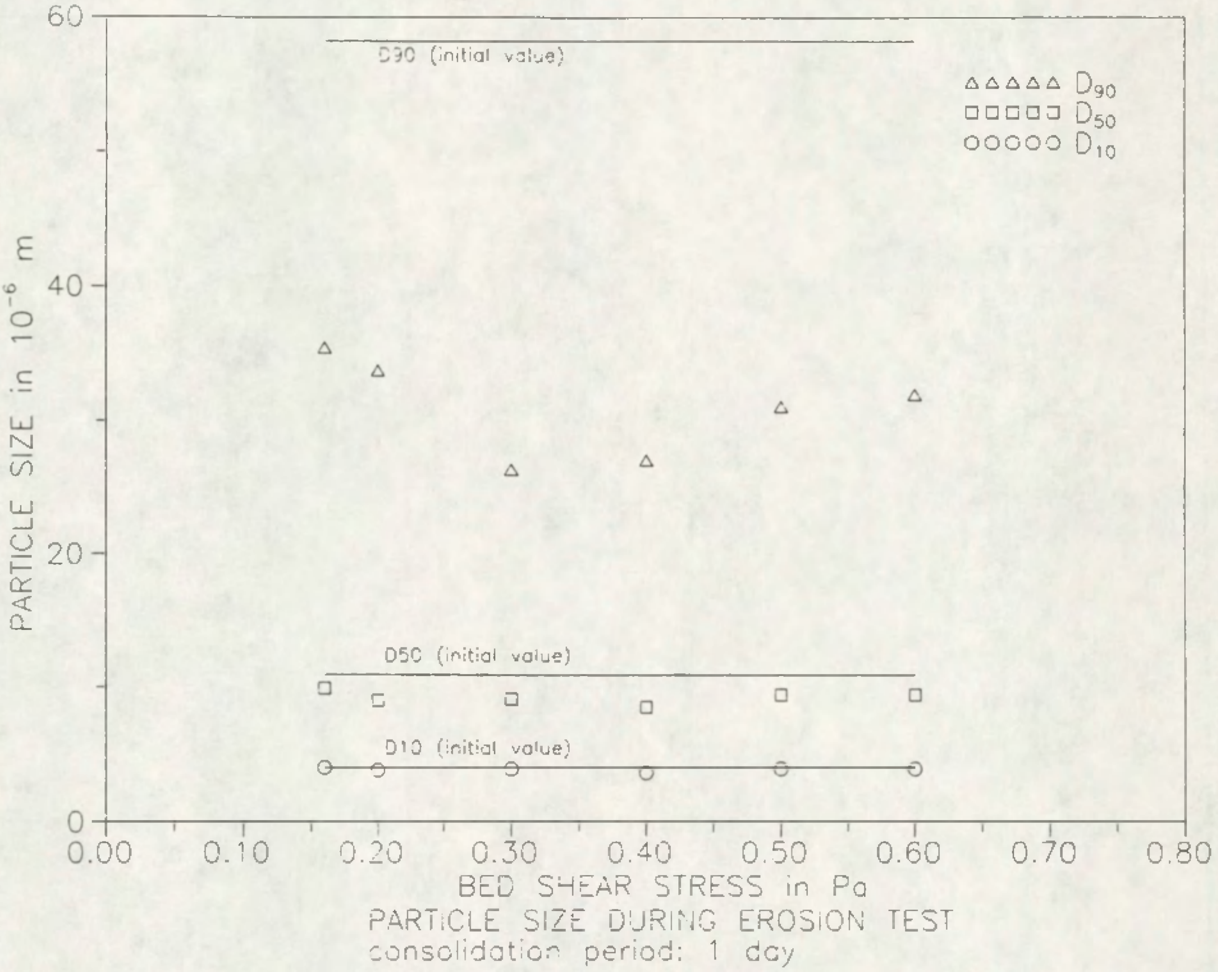


Erosion rate (consolidation period: 1 day).

A4

DELFT HYDRAULICS

Fig 17

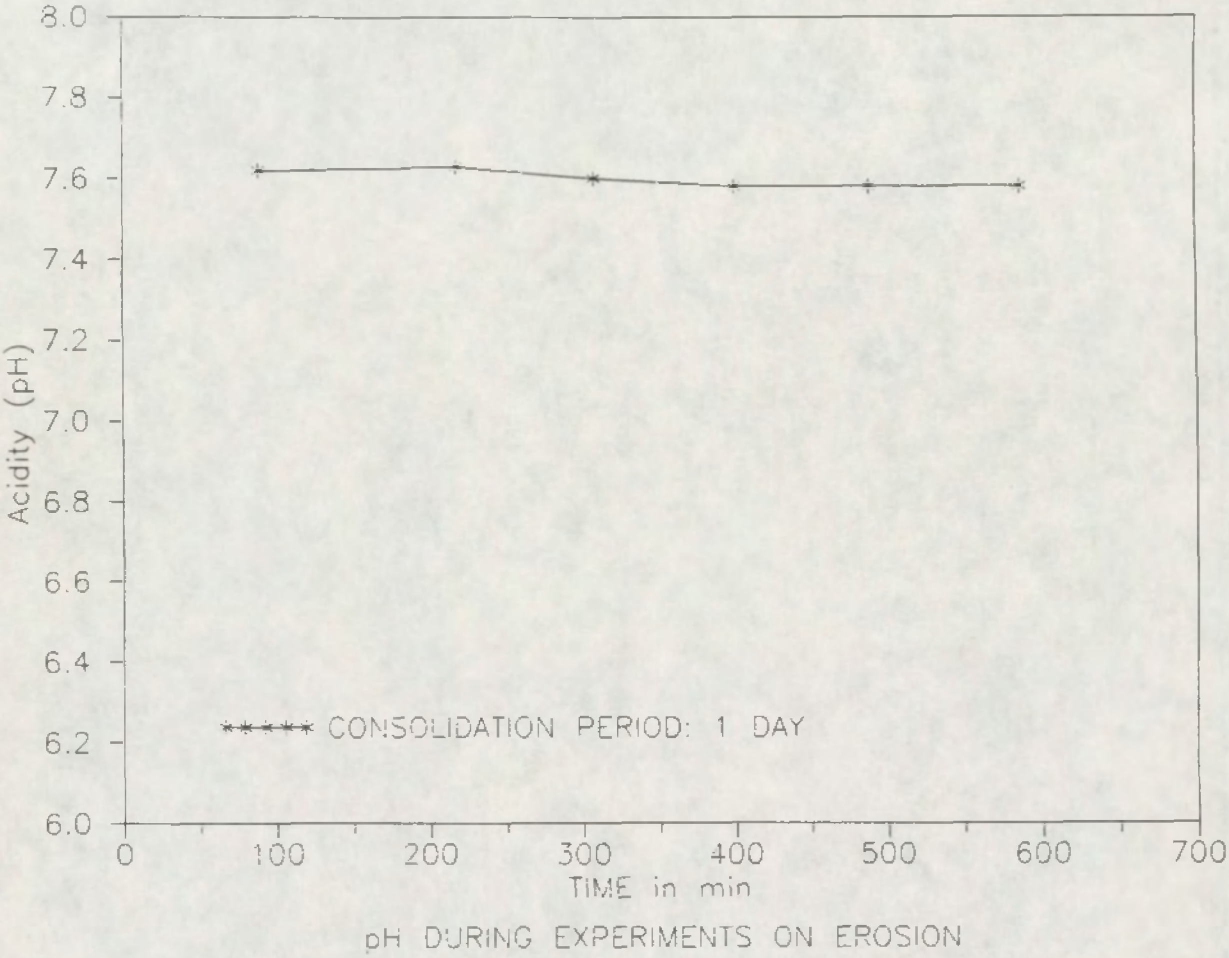


Particle size during erosion (consolidation period: 1 day).

A4

DELFT HYDRAULICS

Fig 18

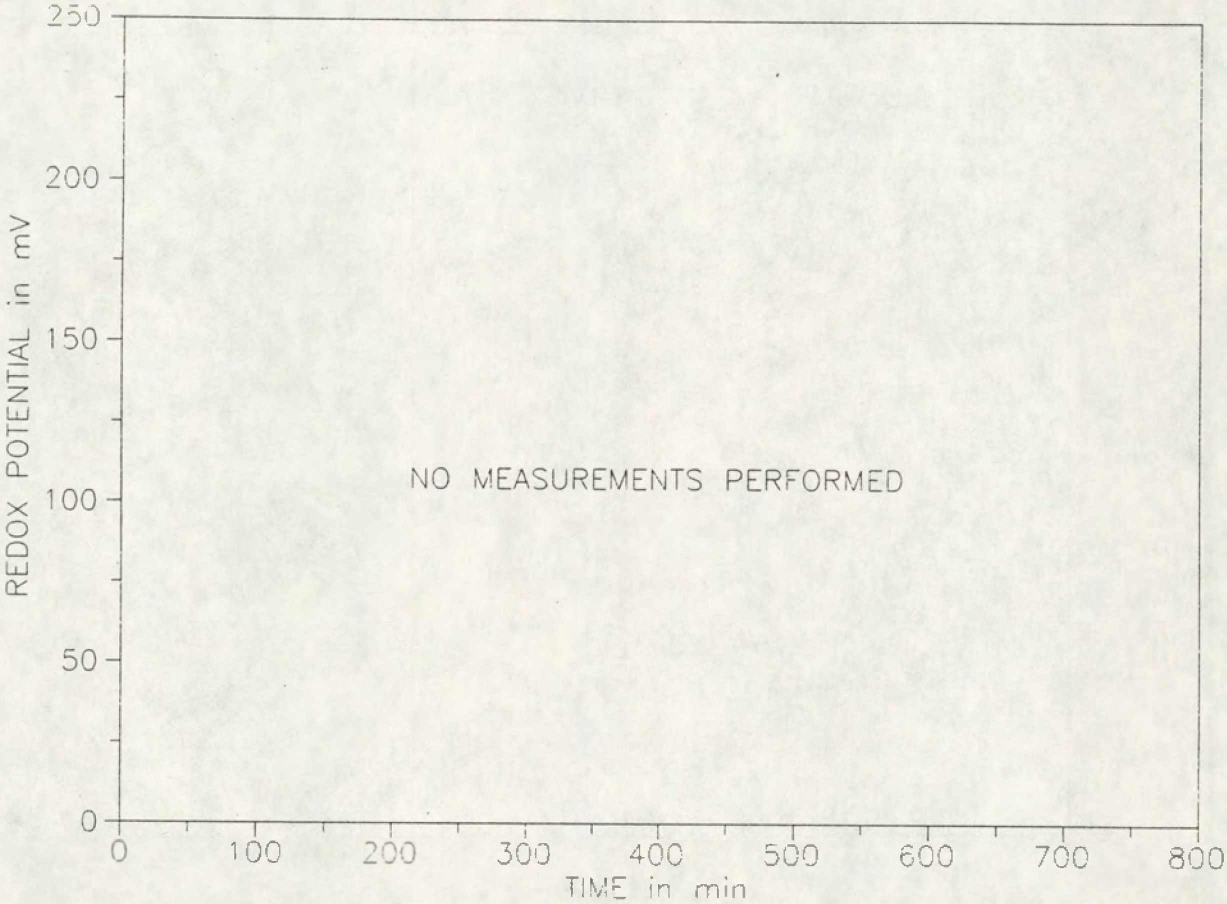


pH during erosion tests.

A4

DELFT HYDRAULICS

Fig 19



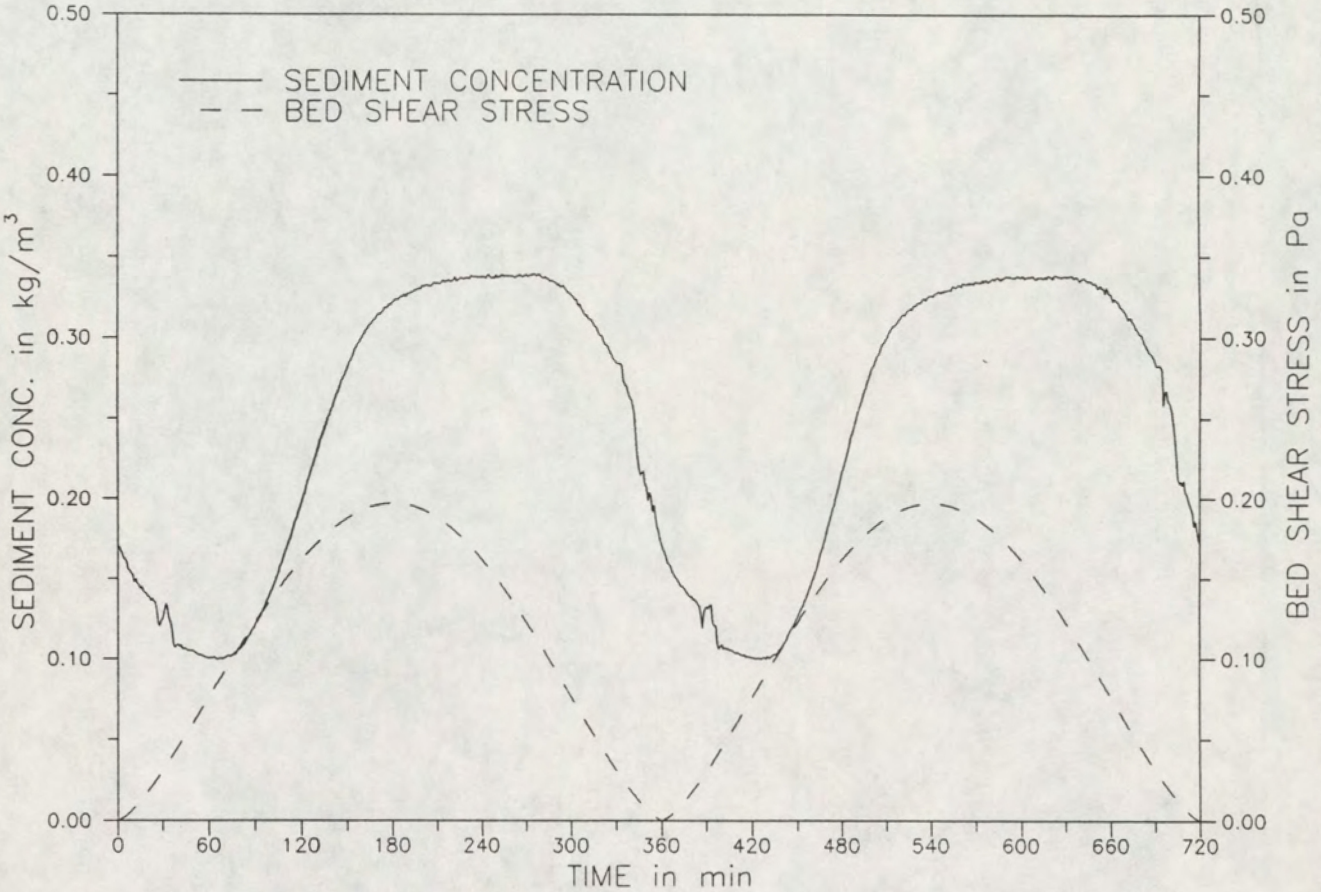
REDOX POTENTIAL DURING EXPERIMENTS ON EROSION

Redox potential during erosion tests.

A4

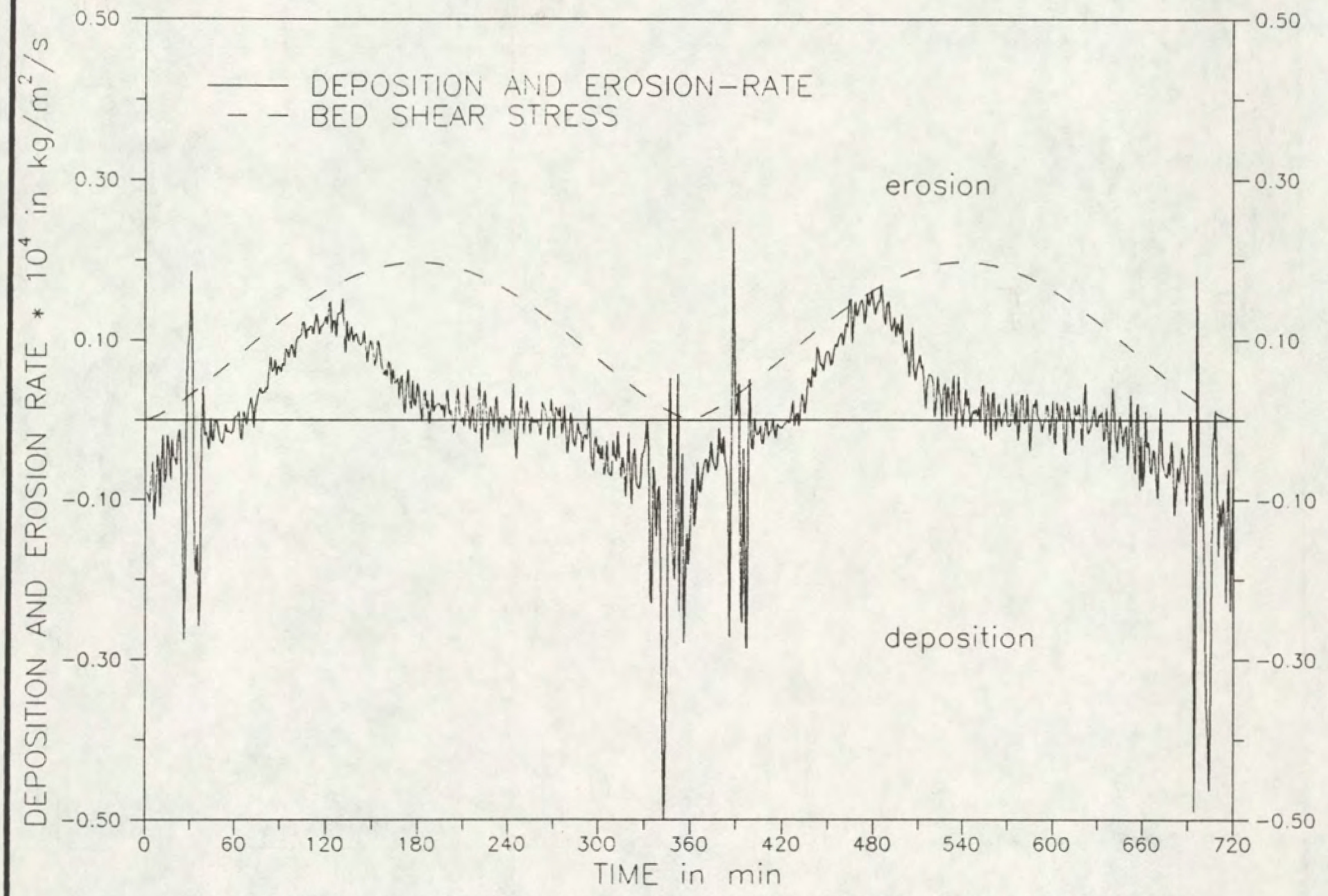
DELFT HYDRAULICS

Fig 20



DEPOSITION AND EROSION UNDER TIDAL CONDITIONS
maximum bed shear stress: 0.2 Pa

Deposition and erosion under tidal conditions (0.2 Pa)		A4
DELFT HYDRAULICS		Fig 21



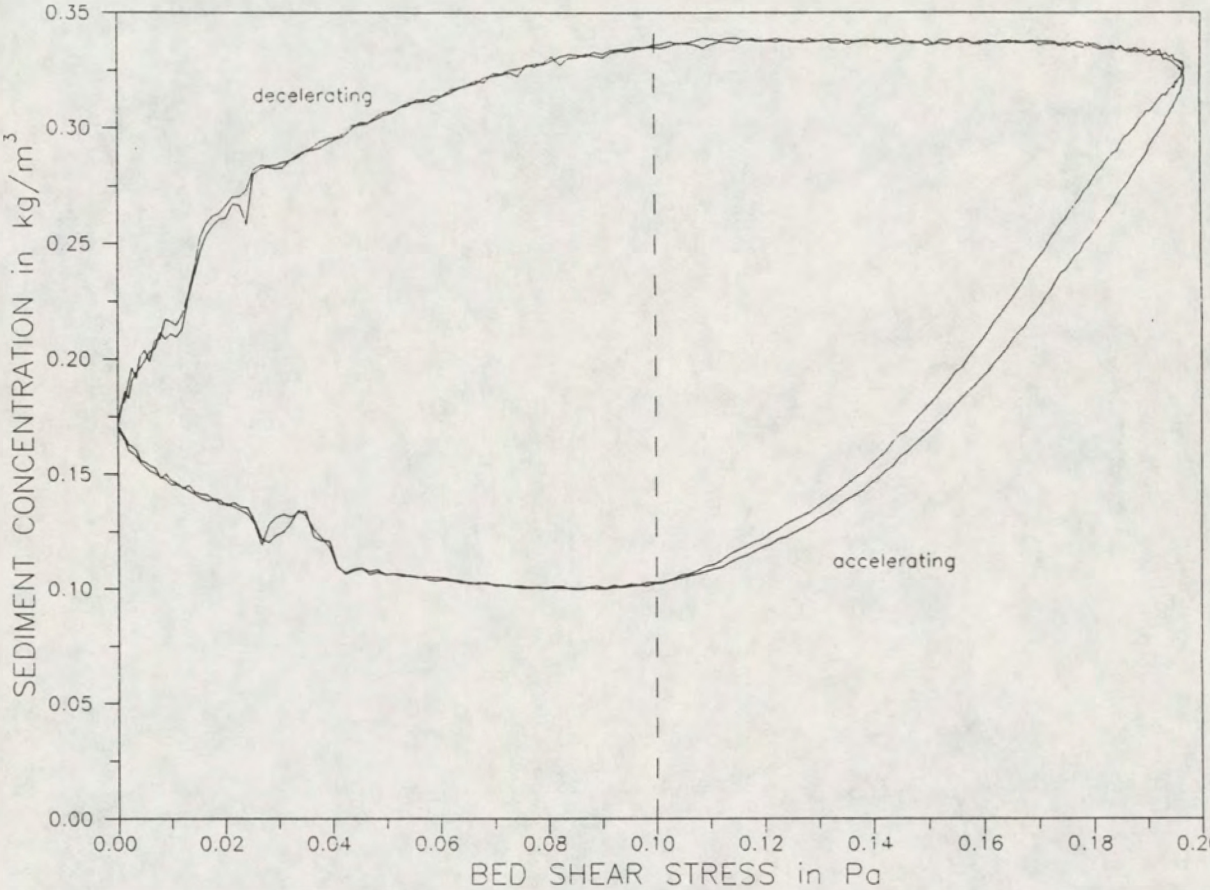
DEPOSITION-RATE AND EROSION-RATE UNDER TIDAL CONDITIONS
maximum bed shear stress: 0.2 Pa

Deposition and erosion rate under tidal conditions (0.2 Pa)

A4

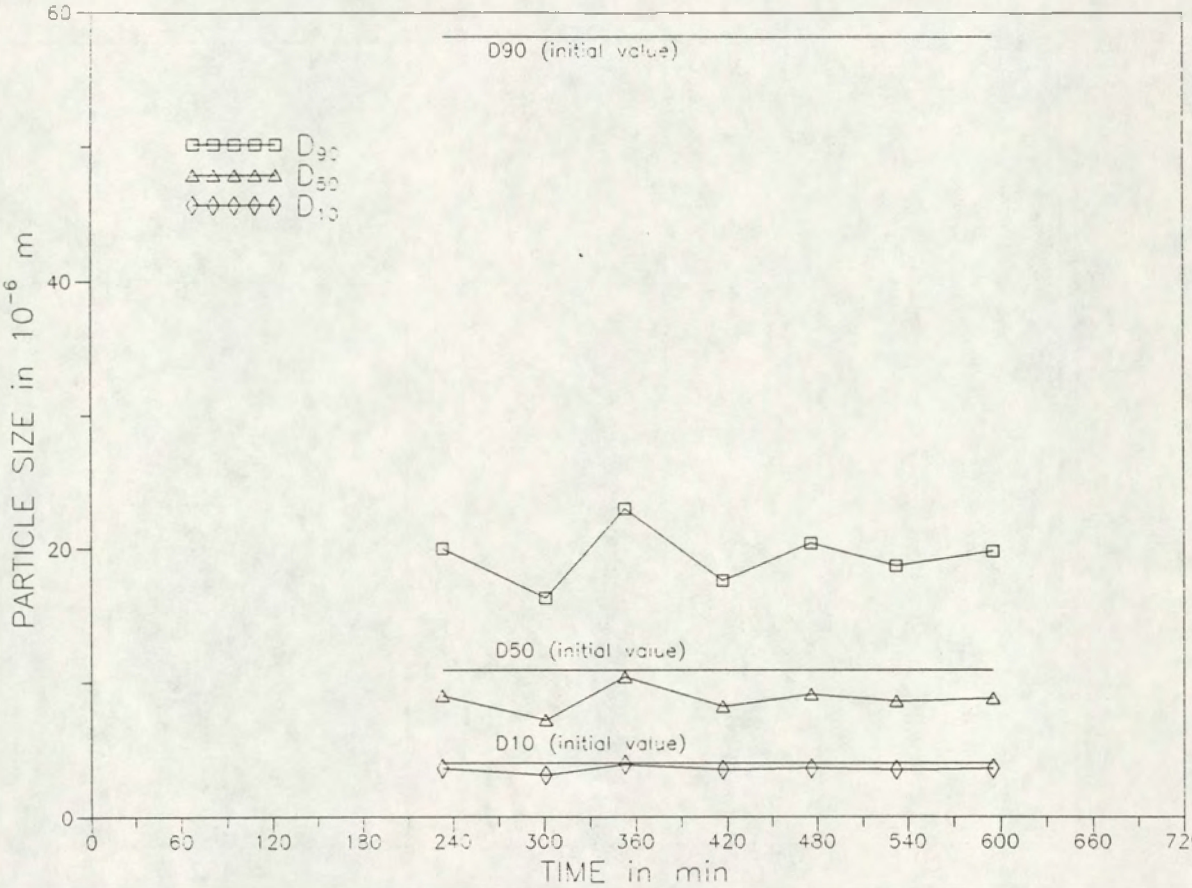
DELFT HYDRAULICS

Fig 22



SEDIMENT CONCENTRATION AS A FUNCTION OF THE BED SHEAR STRESS
consolidation period: 6 hours

Sediment concentration vs. bed shear stress (0.2 Pa)		
		A4
DELFT HYDRAULICS		Fig 23



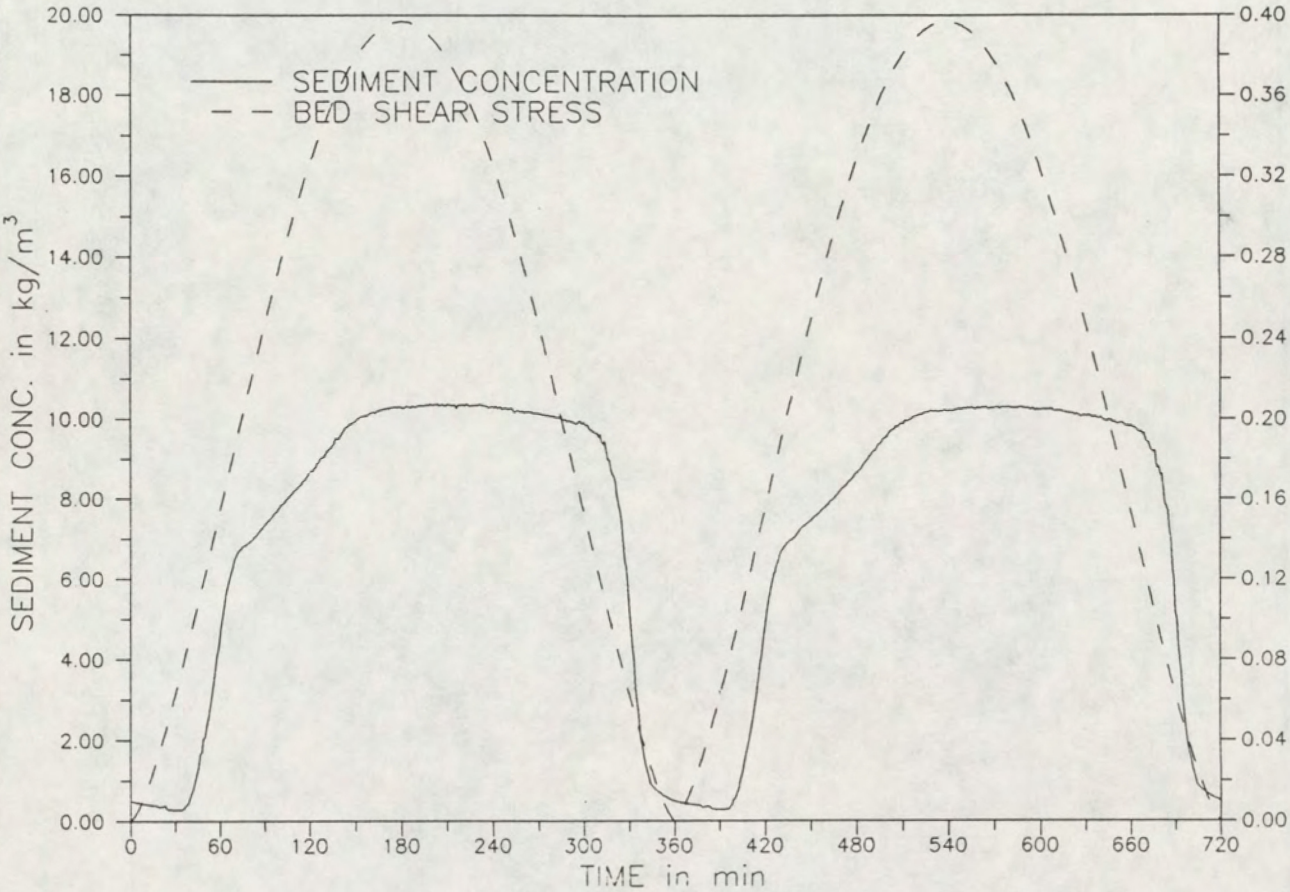
PARTICLE SIZE DURING TIDAL EXPERIMENT
maximum bed shear stress: 0.2 Pa

Particle size during tidal experiment (0.2 Pa)

A4

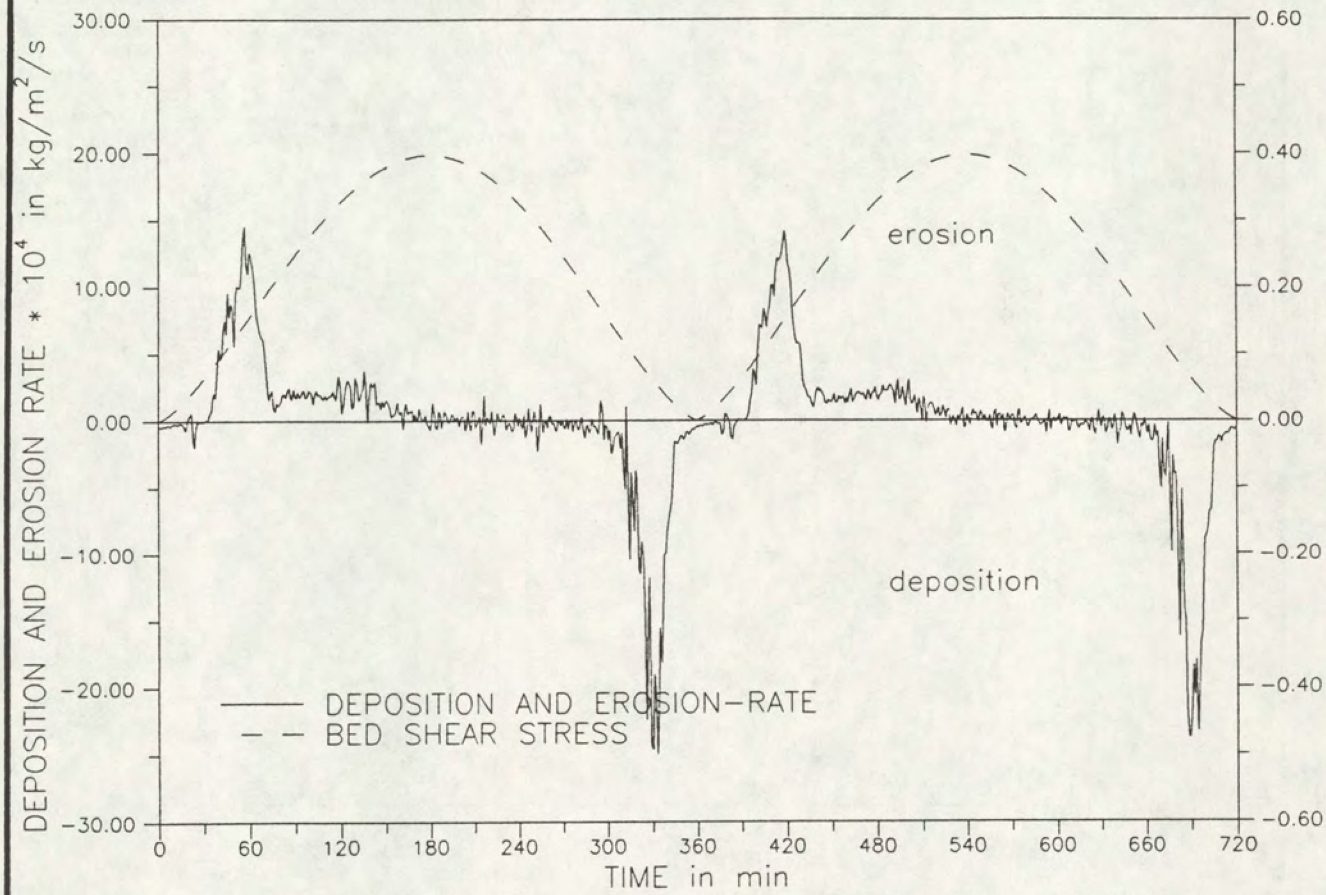
DELFT HYDRAULICS

Fig 24



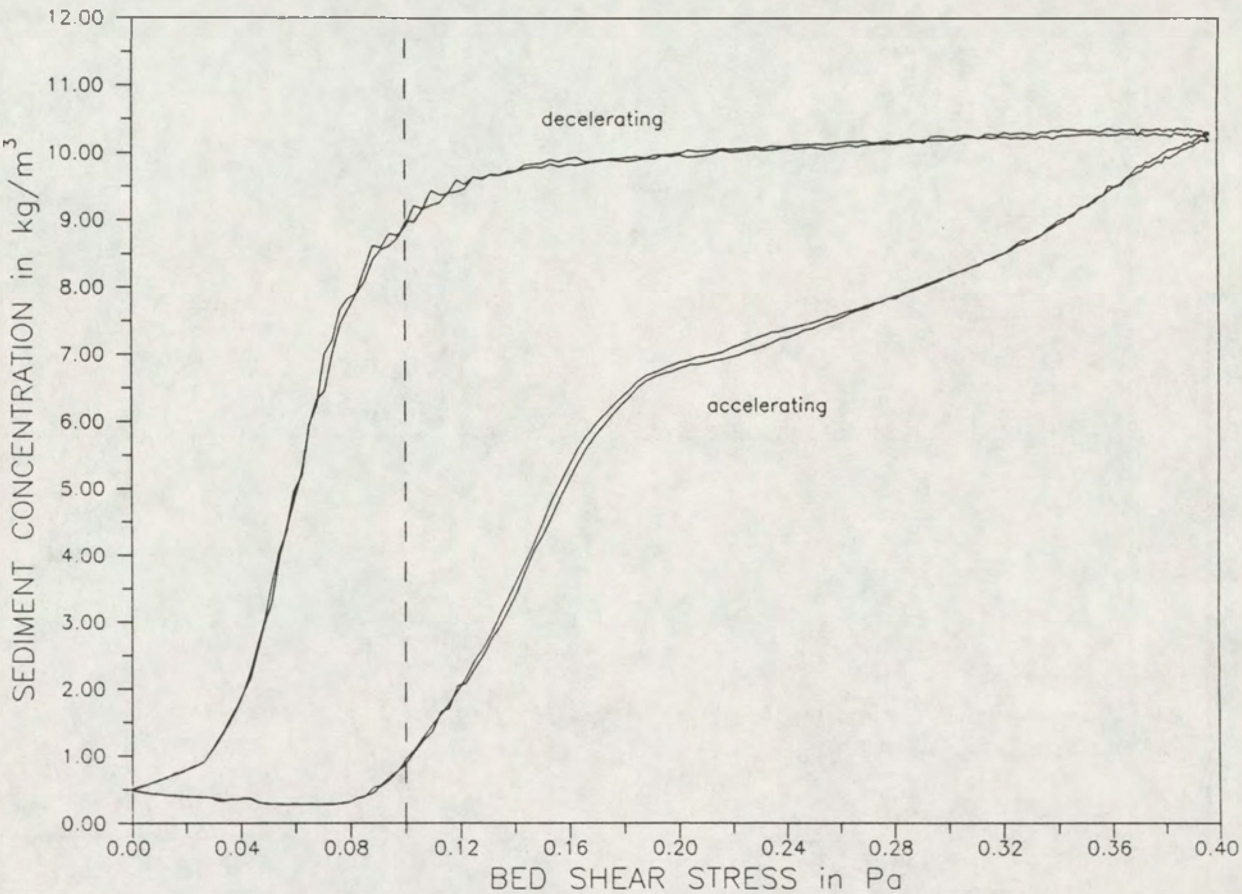
DEPOSITION AND EROSION UNDER TIDAL CONDITIONS
maximum bed shear stress: 0.4 Pa

Deposition and erosion under tidal conditions (0.4 Pa)	A4
DELFT HYDRAULICS	Fig 25



DEPOSITION-RATE AND EROSION-RATE UNDER TIDAL CONDITIONS
maximum bed shear stress: 0.4 Pa

Deposition and erosion rate under tidal conditions (0.4 Pa)		A4
DELFT HYDRAULICS		Fig 26



SEDIMENT CONCENTRATION AS A FUNCTION OF THE BED SHEAR STRESS
consolidation period: 6 hours

Sediment concentration vs. bed shear stress (0.4 Pa)		A4
DELFT HYDRAULICS		Fig 27

APPENDIX A - DESCRIPTION OF TEST PROGRAM

A1. Sampling.

a. Selection and description of the location.

b. Sample about 30 kg dry bed material (e.g. about 100 kg wet material) from a sedimentation area with a small "Van Veen" grab sampler; probably the sediments in a sedimentation area are representative for the sediments in the selected location, whereas in an eroding area, the finer particles may have been washed out.
The sampler should be small to obtain mainly sediments from the surface layer, i.e. not from one deep pit. The sediment should be brought ashore as fast as possible and transported and stored in a cooling box.
Sample simultaneously also 500 ltr water under quiet weather conditions; this water can be transported and stored in 25 l jerrycans.

c. Describe the area and the local conditions, take photographs at the site and of the mud. Measure the temperature, salinity (if relevant) and oxygen content of the water, and the redox potential of the water and the mud.

A2. Determine the physical-chemical properties.

a. The composition of the mud:
- Deflocculate the mud and determine the grain size distribution with the MALVERN and with the sedimentation balance.
- Determine the specific surface of the mud (by Delft Geotechnics).
- Determine the mineralogical composition of the mud (Delft Geotechnics).
- Determine the organic content, the O_2 content, and the redox potential.
- Determine the pH, temperature and salinity.
- Measure the SAR and CEC (Delft Geotechnics).
- Make some photographs of the sediments with the microscope.

b. The properties of the mud:

-Determine the distribution of the settling velocity of the mud in the sedimentation balance (without de-flocculent).

-Determine the up-going and down-going flow curve (viscosity and yield strength) with the Haake-viscometer at concentrations of 0 (50) $c_{natural}$ kg/m³ up to a shear rate of 150 s^{-1} and a temperature of 20° C. Use the natural water.

-Determine the consolidation behaviour in a column by measuring the height of the interface and the water over pressure. Measure the vertical dry density profile within the consolidation column with a conductivity and/or acoustic probe (and measure the vane shear strength at the end of the test at various depths).

<u>A3. Determine the erosion and sedimentation behaviour in the carousel.</u>

a. General tests for all samples:

-Perform a sedimentation test at an initial concentration of 1 kg/m³ by lowering the bed shear stress from about 0.40 to about 0.05 Pa in small steps of about 0.02 to 0.10 Pa. Each sub-test will be continued until equilibrium is attained. During the tests, the variations in suspended sediment concentration will will be measured continuously with the OSLIM (optical concentration measuring probe); samples will be taken at regular intervals to calibrate the OSLIM recordings and to determine the organic content and grain size distribution.

-Carry out an erosion test. A so-called deposited bed will be formed in still water from the deposition of a homogeneous suspension of c_0 = 60 kg/m³. A consolidation time of 24 hours (after stopping the annular flume) is used. The dry density profile within this bed will be deduced from the consolidation test described above. The erosional behaviour is determined by increasing the bed shear stress from 0 to about 0.7 Pa in steps of 0.02 to 0.1 Pa.; each sub-test is continued for about one hour. During the tests, the variations in suspended sediment concentration will be measured continuously with the OSLIM; samples will be taken at regular intervals to calibrate the OSLIM recordings and to determine the organic content and grain size distribution.

b. Sediments from non-tidal locations;

Next to the tests mentioned under A3.a. the following tests will be performed:

-A sedimentation test as described above with an initial concentration of $c_0 = 0.2\ kg/m^3$.

-An erosion test as described above with a consolidation time of 7 days.

c. Sediments from tidal locations:

Next to the tests mentioned under A3.a. the following tests will be performed:

-A test with a sinusoidal varying bed shear stress on a deposited bed (see A3.a), with a consolidation time of 6 hours. The tidal period will amount to 12 hours, and the amplitude of the bed shear stress to 0.4 Pa. The test will be continued until equilibrium is achieved. During the tests, the variations in suspended sediment concentration will will be measured continuously with the OSLIM; samples will be taken at regular intervals to calibrate the OSLIM recordings and to determine the organic content and grain size distribution.

-A similar tidal test with a shear stress amplitude of 0.2 Pa.

A4. Reporting.

The results and experimental data of the composition, properties and tests will be summarized in a report. These results will be used to determine the critical shear strength for erosion and sedimentation of the mud and its erosion rate.

A5. Determination of the flocculation properties in the settling column (p.m.)

Determine the distribution of the settling velocity and flocculation properties at a grid frequency of 0.05 Hz (amplitude = 0.075 m) and initial concentrations of $c_0 = 0.1$ and $0.5\ kg/m^3$. Samples will be taken from 13 locations over the entire height of the column at regular time intervals. The settling mud flocs will be monitored with a CCD-camera at the bottom of the column.

APPENDIX B - CALIBRATION CURVES

Optical instrument ('OSLIM')

The calibration curve for the optical instrument for the experiment on deposition is given in figure B1. During the subtests samples are taken (volume: 150 - 200 ml) at various time-steps: t = 15 and 30 min, 1, 2 and 4 hours after the start of the experiment as well as at the end of each subtest. During the experiment on deposition the optical instrument is set in position 1 (low concentration range).

In figure B2 the calibration curve for the erosion test is shown. Because of the increase in sediment concentration during the test the optical instrument is set in two different positions (2 and 10). The calibration curves for the tidal experiments are given in figure B3.

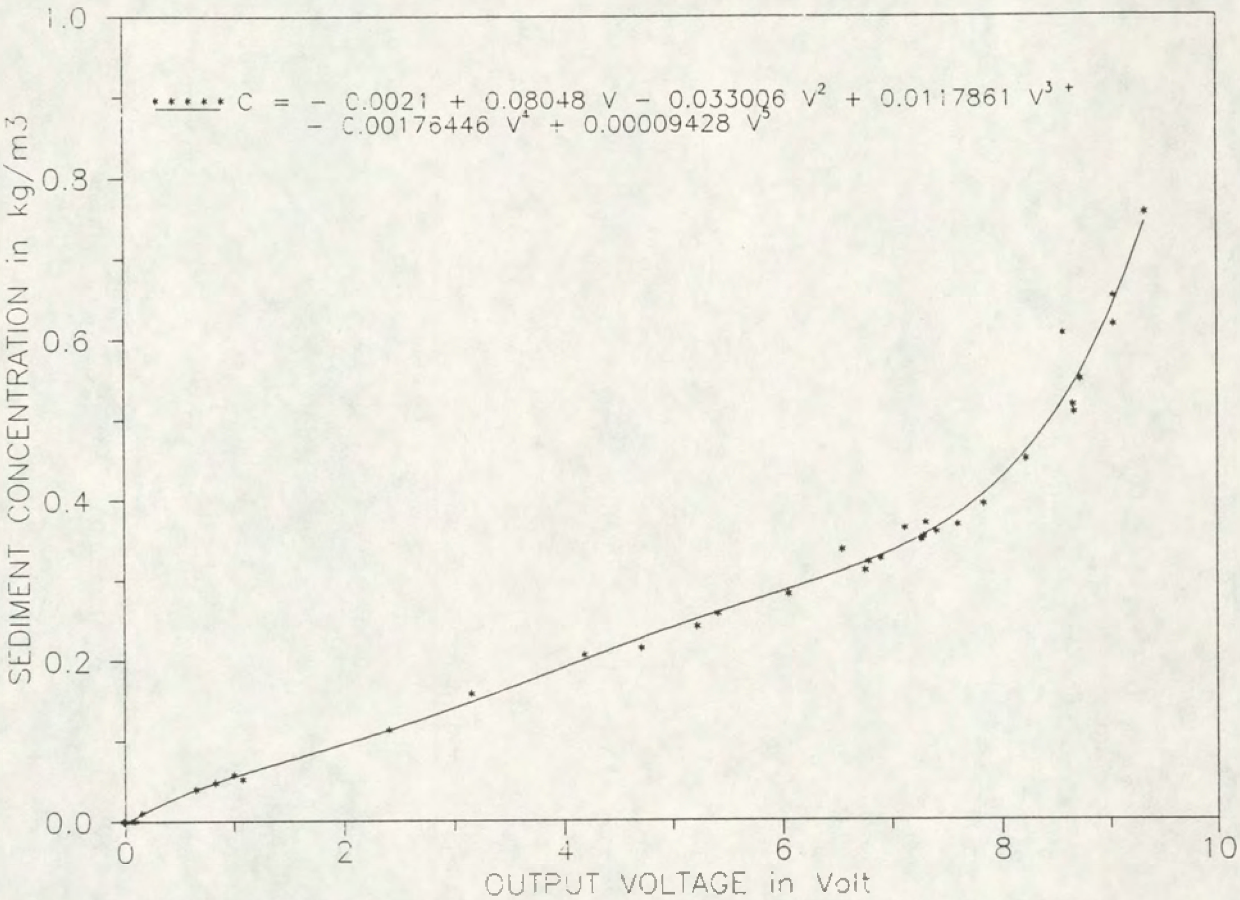
All calibration curves are related to the 'OSLIM' with a 5 mm cell.

Acoustic instrument

The calibration curve for the acoustic instrument is given in figure B4. The calibration curve is derived from measurements in samples which are mixed thoroughly with a mechanical stirrer for some minutes. Calibration is performed after the measurements in the consolidation column are carried out. The calibration curve follows the semi-logarithmic relationship as can be derived from theoretical considerations [7]:

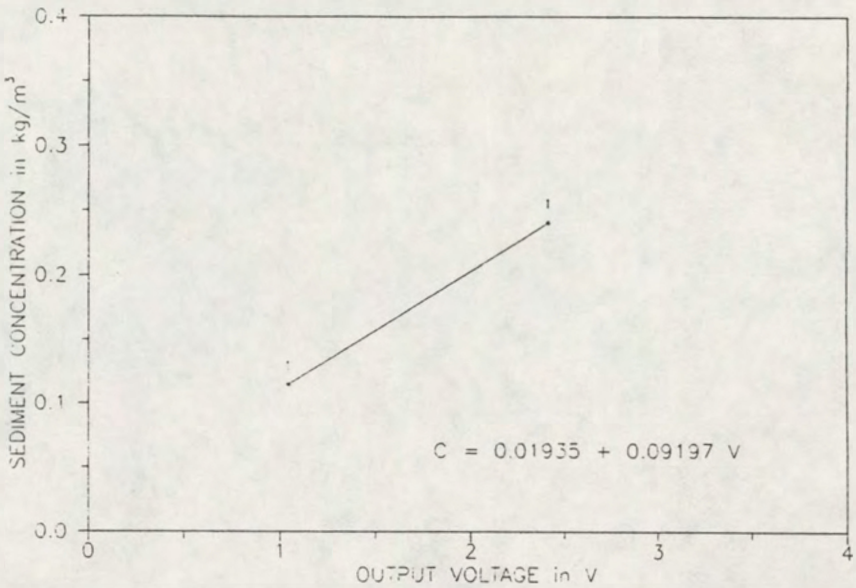
$$\ln \left(\frac{U_c}{U_0}\right) = \delta C, \qquad \text{(B1)}$$

with,
- U_c - output voltage [Volt],
- U_0 - output voltage in clear water [Volt]
- δ - constant [m^3/kg],
- C - dry density [kg/m^3].

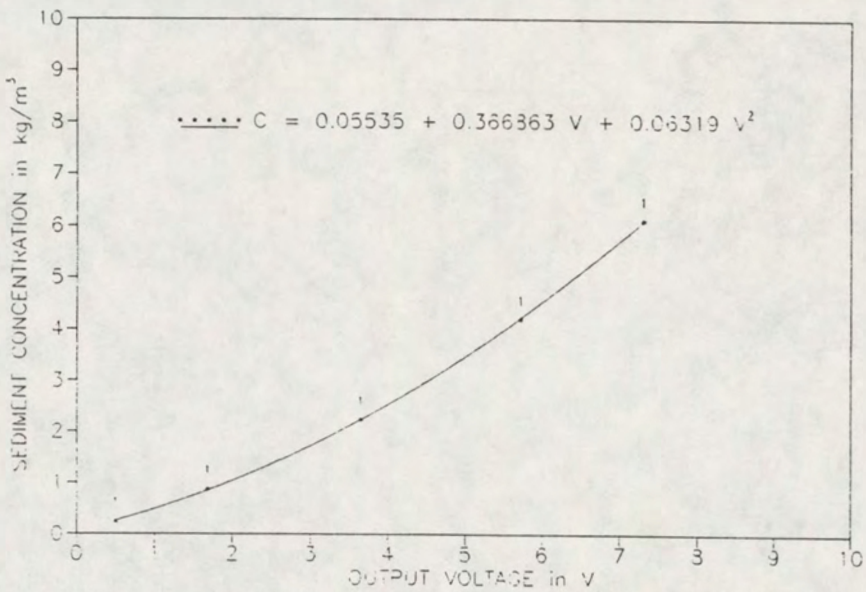


CALIBRATION OPTICAL INSTRUMENT (5 MM 'OSLIM')
experiment on deposition
sediment: Western Scheldt (Breskens); October 1989

Calibration curves optical instrument for experiment on deposition.		A4
DELFT HYDRAULICS		Fig B1



CALIBRATION CURVE OPTICAL INSTRUMENT (5 mm 'OSLIM' POSITION 2)
experiments on erosion
1: consolidation period: 1 day (C045)



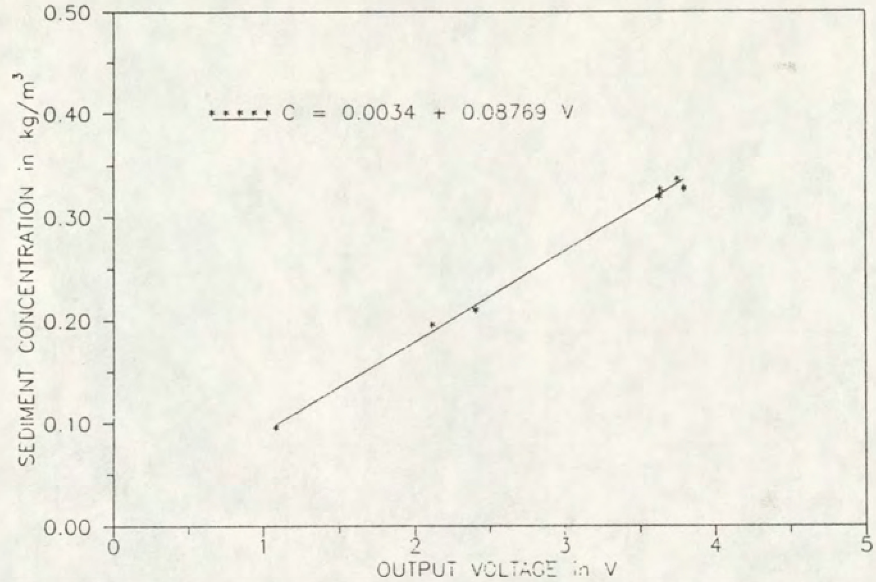
CALIBRATION CURVE OPTICAL INSTRUMENT (5 mm 'OSLIM' POSITION 10)
experiments on erosion
1: consolidation period: 1 day (C045)

Calibration curves optical instrument for tests on erosion.

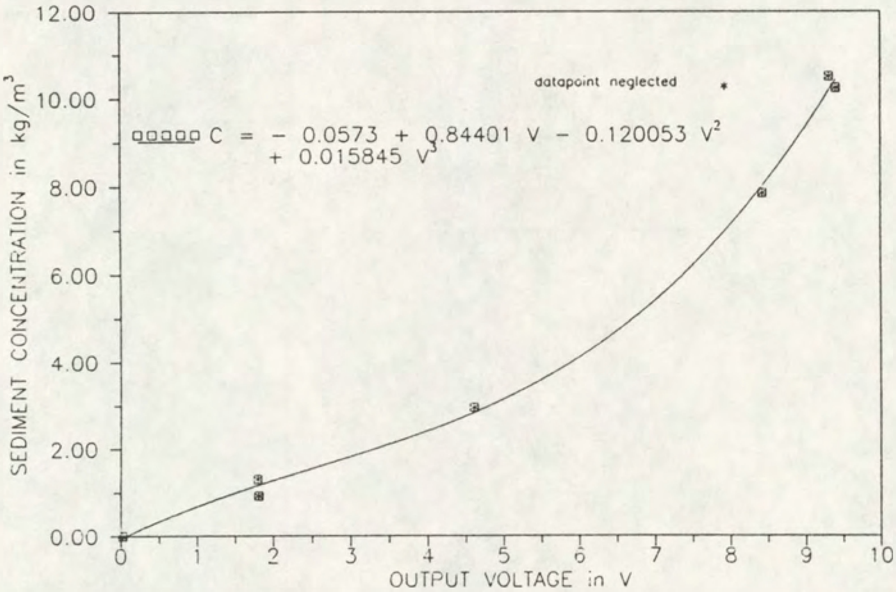
A4

DELFT HYDRAULICS

Fig B2



CALIBRATION CURVE OPTICAL INSTRUMENT (5 mm 'OSLIM': POSITION 2)
tidal experiment (max. bed shear stress: 0.2 Pa)
consolidation period: 6 hours



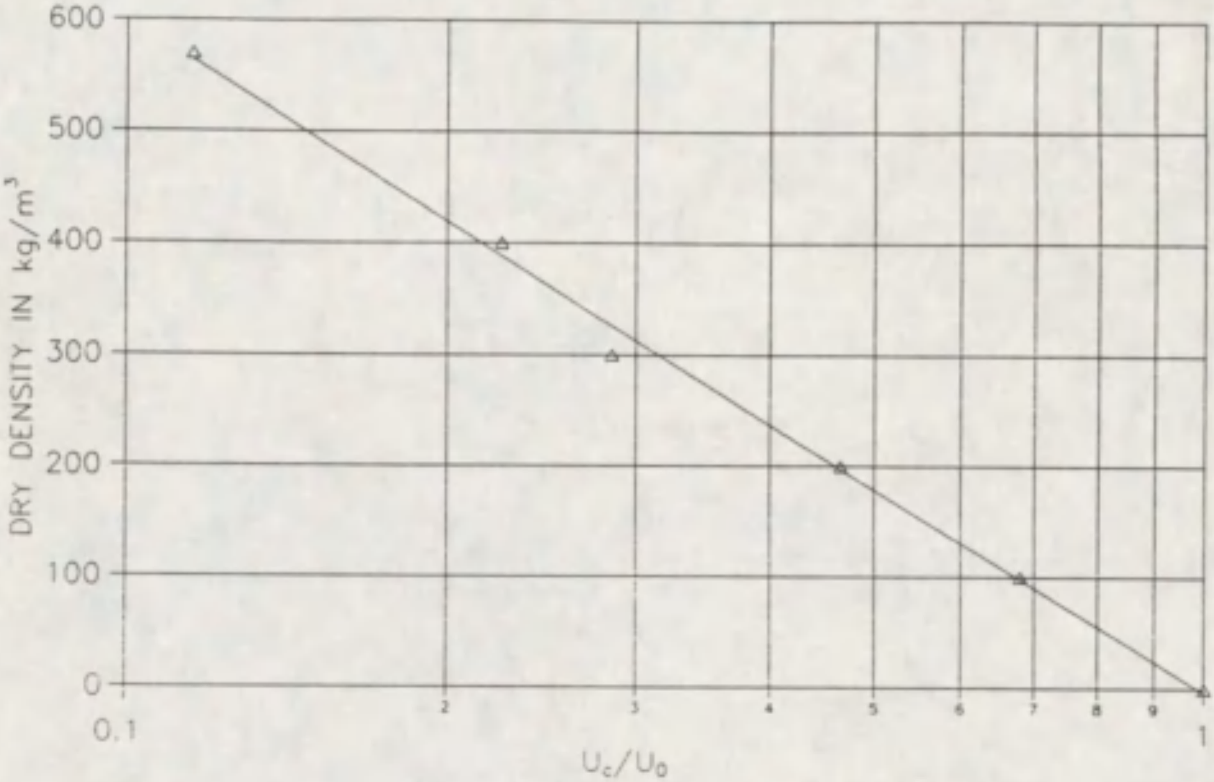
CALIBRATION CURVE OPTICAL INSTRUMENT (5 mm 'OSLIM': POSITION 10)
tidal experiment (max. bed shear stress: 0.4 Pa)
consolidation period: 6 hours

Calibration curves optical instrument for tidal experiments.

A4

DELFT HYDRAULICS

Fig B3



CALIBRATION CURVES ACOUSTIC TRANSMISSION

△△△△△ Breskens: $C = -262.6\ LN(U_c/U_0) - 3.7$ (U_0 = 1000 mV)

Calibration curves acoustic instrument.		
		A4
DELFT HYDRAULICS		Fig B4