CHAPTER 149

In-Situ Determination of the Critical Bed-Shear Stress for Erosion of Cohesive Sediments

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Abstract

A new in-situ erosion meter has been developed to measure the in-situ bed-shear strength of cohesive beds. It is assumed that the current velocity, at initiation of motion of the toplayer of the bed, can be used to compute the critical bed-shear stress. This critical shear stress is the characteristic parameter which can define different types of sediment beds.
The in-situ measurements show that the test results are determined by the prevailing hydrodynamic conditions in the field (wave activity) and recent depositions rather than by physical and biological parameters.

Introduction

It is commonly accepted that the strength of the inter-tidal mud flats is strongly influenced by physical-, biological- and chemical- parameters (see Amos et al., 1992; Verreet at al., 1986). Until now it is not possible to measure these parameters separately and predict the resulting strength of the bed. The best way to handle this problem is to measure the critical shear stress for erosion of the top layer of the bed. By this, all shear strength related parameters are captured in one overall parameter: the critical shear stress corresponding to the erosion of the top layer of the bed (defining the maximum shear strength of the top layer of the bed). These tests can be performed in the laboratory either by using kaolinite beds or by samples of natural beds which have to be taken from the field. Both types of tests do not seem to reflect the natural conditions of in-situ beds properly. For this reason in-situ measurements have to be carried out in order to determine the erosive resistance of cohesive sediment. Several in-situ instruments have been developed already (Amos et al., 1992a; Williamson, 1994; Gust, 1994; Cornelisse

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et al., 1994). Until now, the techniques used are not accurately enough to determine the parameters controlling the entrainment of cohesive sediments. One of the major problems is that differences are found in the stresses generated by the instruments in comparison with the real values in nature (Gust, 1994). Furthermore, the measurement results are often biased and the measurement results of the available erosion instruments show significant differences. This is mainly caused by differences in the settings of the instruments (Cornelisse et al., 1994).

The in-situ Erosion Flume, presented herein, is developed to measure the shear resistance of the top layer of cohesive beds. Like most of the flume-systems the shear stress on the bed is exerted by an adjustable unidirectional flow. The shear stress exerted by the adjusted current velocity was calibrated in the laboratory. The results of the ISEF measurements will give the maximum shear strength of the top layer of the bed and is an overall representation of shear strength related parameters.

This article describes the development of the ISEF, the reproductivity tests in the laboratory and the field measurements on cohesive beds in the salt marsh region in the Netherlands Wadden Sea.

In-Situ Erosion Flume (ISEF)

The in-situ Erosion Flume is a circulating flow system in the vertical plane. It consists of a lower horizontal test section, two bend sections and an upper section where the flow is generated by a propeller (see figure 1).

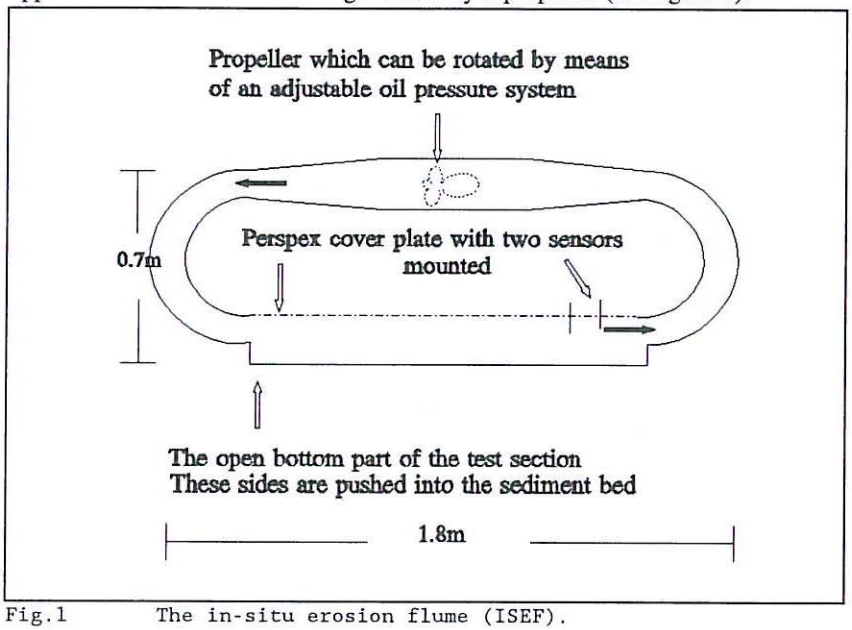

Fig.1 The in-situ erosion flume (ISEF).

The horizontal test section and the two bend sections have a rectangular cross-section with a height of 0.1 meter and a width of 0.2 meter. The bottom part of the horizontal test section is open over a length of 0.9 and a width of 0.2 meter. When the Erosion Flume is resting on the sediment bed properly, the surface of the bed will be in line with the steel bottom plates of the flume on both ends of the horizontal section. The total weight of the erosion flume is about 50 Kg. The total volume of water in the flume is 100 liter.
The propeller can be rotated at various speeds by means of an adjustable oil pressure system. The flow velocity in the horizontal section is measured with a small disc-type electro-magnetic flow meter (EMF) placed at 0.55 meter from the entrance of the horizontal test section. The measuring point is at 0.075 meter below the covering plate of the test section, which is 0.025 meter above the bed surface. The suspended sediment concentration is measured by means of an optical monitor.
The erosion process of sediment particles of the bed is related to the prevailing bed-shear stress.
The bed-shear stress can be determined from the measured velocity profile assuming a logarithmic distribution in vertical direction, which reads as:

$$u_z=\frac{u_*}{\kappa}\ln(\frac{z}{z_0}) \tag{1}$$

in which:
u_z = flow velocity at height z above the bed (m/s), $u_* = (\tau_b/\rho)^{0.5}$ = bed-shear velocity (m/s), τ_b = bed-shear stress (Pa), ρ = fluid density (kg/m^3), κ = constant of von Karman (0.4) (-), z = height above the sediment bed (m), z_0 = $0.033\ k_s + 0.11\nu/u_*$ = zero-velocity level (m), k_s = effective bed roughness height of Nikuradse (m), and ν = kinematic viscosity coefficient (m^2/s).
Based on Eq.(1) the bed-shear stress can be expressed as:

$$\tau_b=\rho\kappa^2 u_z^2[\ln(\frac{z}{z_0})]^{-2} \tag{2}$$

An equilibrium flow will not be established in the ISEF because of the short length of the test section. This means that the velocity distribution in the near-bed region of the horizontal section might deviate slightly from the logarithmic distribution. Introducing a calibration coefficient α (close to unity) to account for this effect, and using the maximum velocity u_m at the upper edge of the boundary layer (δ) above the bed, Equation (2) can be expressed as:

$$\tau_b=\rho\kappa^2(\alpha u_m)^2\left[\ln\left(\frac{\delta}{0.033k_s+0.11\nu\left(\frac{\tau_b}{\rho}\right)^{-0.5}}\right)\right]^{-2} \tag{3}$$

The α-coefficient was determined by measuring velocity profiles above a flat bed of moving (non-cohesive) sand and gravel particles at conditions just beyond the initiation of motion (Houwing and van Rijn, 1992). The α-coefficient varies from 0.9 to 0.74 as function of an increasing Reynolds number. The boundary layer thickness (δ) was found to be about 0.025 m. In field situations, the hydrodynamic conditions just above the cohesive bed lies within the hydraulic smooth regime. Therefore, an α-coefficient of 0.9 is recommended to determine the bed-shear stress. The velocity should be measured at a height of 0.025 meter above the bed.

Reproduction measurements

Reproduction tests are essential for a correct interpretation of data and to know whether the experimental results are reliable (see Cornelisse et al., 1994). Changes in test results should be due to changes in bed composition rather than to differences in the setting of the erosion meter. It is expected that, in case of the ISEF, erosion will appear more easily along the edges of the test section as here the bed might be slightly disturbed. Besides that, small undulations on top of the bed will lead to small velocity variations thus increasing erosion on that specific location.

Cornelisse et al. (1994) found that the areal size of the test section is crucial for the reproductivity of the erosion instruments. The spatial variations in the bed properties and the turbulent stresses are averaged out when the erodible area is larger. They found a linear relationship between the reproduction error and the areal surface which reads as: $R = 796*A^{-0.528}$, based on 13 tests carried out with four different erosion meters. The surface area of the test section of the ISEF measures 1800 cm^2 and the resulting error R is calculated to 15%.

In order to investigate the reproduction error of the ISEF three laboratory tests have been carried out similar to the tests performed with a laboratory carrousel (de Jong, 1991). For each test a new bed is constructed in the test section of the ISEF. The bed consists of kaolinite and is formed by sedimentation in still fresh water. The mean density of the kaolinite bed is in the order of 350 kg/m^3.

The current velocity in the ISEF is increased in steps of one hour during each experiment. The sediment concentrations are determined by means of the optical sensor. The output of the optical sensor is calibrated in situ based on pumped samples. The results of the tests show a good reproductivity (Fig. 2) and the error for the reproductivity tests is estimated to 20 % which is in agreement with the calculated 15%. The rate of erosion per exerted shear stress is up to 3 times higher for the ISEF in comparison with the test results performed by de Jong. This is probably due to a lower mean density of the initial bed used in the ISEF (350 vs 400 kg/m^3).

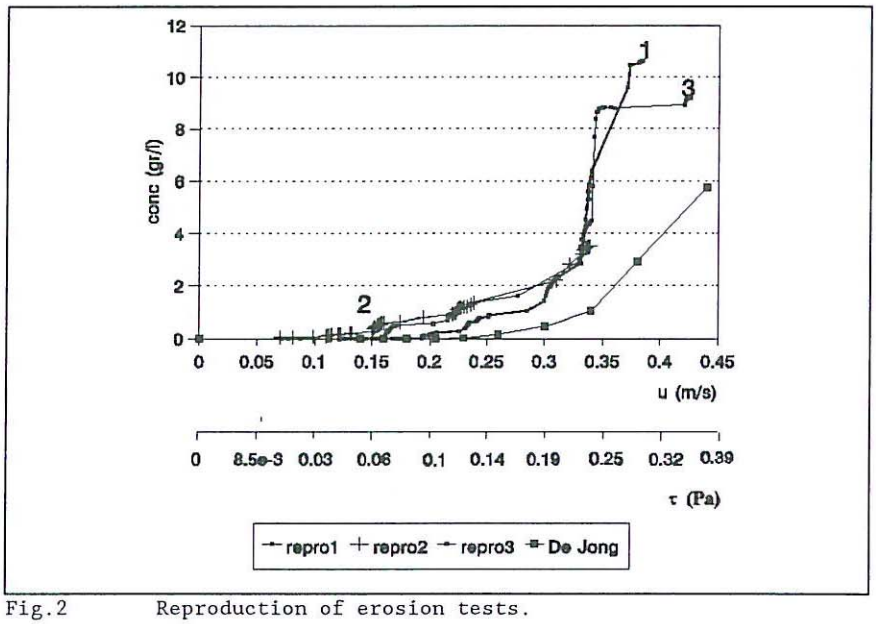

Fig.2 Reproduction of erosion tests.

Field measurements

The in-situ field measurements are carried out in one specific area in the salt marshes along the main coast of the Netherlands Wadden Sea. The field site is surrounded by brushwood groynes and measures 400 x 400 meter. The tide is diurnally and most of the time the field area is inundated during high water. Mean water depth lies in the order of 1 meter. The area develops into the salt marsh in landward direction and is bounded in seaward direction by low tidal flats. The bed sediment in this area can be classified as cohesive sediment. It consist of well sorted very fine sand ($d_{50}=80\mu m$; $d_{90}=100\mu m$; $d_{10}=65\mu m$) and contains between 20 to 30 % material smaller than $50\mu m$.

Small variations can be found within the field area ranging from $d_{50}\approx 75\mu m$ close to the groynes to $d_{50}\approx 90\mu m$ near the windward side of the groynes. The density of the top layer of the bed (first 5 mm) varies from 1050 kg/m^3 in less consolidated regions to 1300 kg/m^3 in the better consolidated regions. The increase in consolidation is found going towards the salt marsh and can be contributed to the decrease in frequency in tidal flooding and to a better dewatering of the bed. The bed density is measured with use of a cylinder of 2.5 cm in diameter. This cylinder is pushed into the bed and the sediment core is pushed out carefully and slices of 5 mm thick are cut accurately. The bed density is measured in this way till 3 cm beneath the surface with a 5 millimeter interval (figure 3).

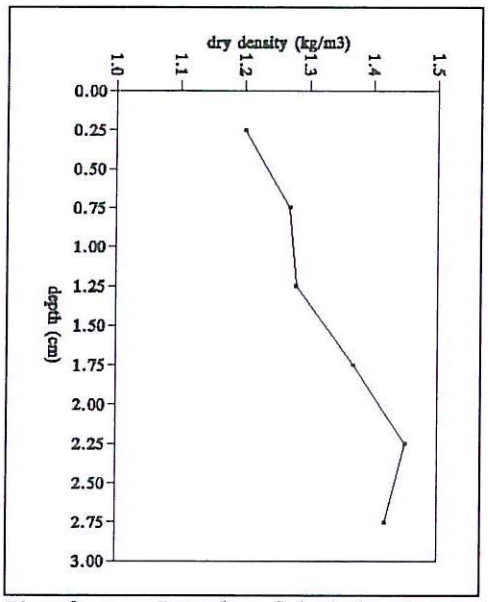

Fig. 3 Example of bed density as function of depth

The samples are weighted in order to obtain the wet bulk density, dry bulk density, moisture content and voids ratio.

The results from the ISEF-measurements will give the maximal shear strength of the top-layer of the bed for that specific location. Comparison with other ISEF-measurements will show how the erosion resistance of the bed will change both in time and in space.

Several in-situ field measurements distributed throughout the field area have been performed during the autumn and winter period of 1993 and the summer period of 1994. Five measurements are discussed here forming two identical groups where in each group the measurements are recorded for two consecutive days. Group 1 is formed by ISEF-1 and ISEF-3 and the tests are carried out during autumn on 13 and 14 october 1993. The second group is formed by ISEF-5, -6 and -7 and is carried out during summer on 7 and 8 june 1994.

ISEF-1 is carried out in the middle of the field area where the bed is inundated twice a day (mean water depth during high water is around 1 meter) and ISEF-3 is carried out close to the salt marsh where the bed is less frequently flooded (mean water depth is about 0.15 meter). The differences in bed density, grain size and mud content (d_{50} < 50 m) are given in Table 1.

Measurement ISEF-5 is carried out on the same spot as ISEF-1: in the middle of the field area. ISEF-6 and -7 are carried out more to the west in the field area where the bed is sheltered by the groynes. Here, the bed is less consolidated and contains a higher percentage of mud.

ISEF-6 and ISEF-7 are carried out close to each other on one day. The difference between both tests is that in case of ISEF-7 the fluffy top layer, of about 5 mm thickness, is removed by a scraper exposing the underlying undisturbed bed. The bed parameters are shown in Tabel 1.

The ISEF is placed carefully on the sediment bed. The current velocity in the ISEF is tuned accurately during the measurements until the top layer of the bed starts to erode. It is tried to follow the same procedure during each measurement. The first minutes of the test the velocity is adjusted to 0.05 m/s. The current velocity is than increased by steps of 0.05 m/s. Each step last as long as one hour or until at least the erosion of the bed is arrested (concentrations become constant in time). In the latter case the exerted shear stress equals the

strength of the bed at that particular depth (z): $\tau_b = \tau_{s(z)}$. With help of equation (3) the shear stress is computed. The results of the ISEF measurements are shown in figure 4 to 8.

Table 1. ISEF-measurements and bed parameters. The bed parameters are measured in the upper 5 millimeter of the bed. The grain size is computed from the fall velocity distribution from the sediment samples. The mud content is determined by filtering the sediment samples through a 50 μm filter. The standard deviation (STD) is the deviation around the mean (σ_{n-1}) calculated from five samples (n=5).

	d_{50} (μm)	d_{90}/d_{10} (-)	mud cont (%)	Bulkdens (kg/m^3)	STD	Drydens (kg/m^3)	STD
ISEF-1	80	1.85	15	1.74	0.15	1.15	0.14
ISEF-3	76	1.55	25	1.75	0.09	1.23	0.11
ISEF-5	80	1.86	15	1.82	0.02	1.20	0.07
ISEF-6	74	1.55	25	1.60	0.13	1.01	0.17
ISEF-7	76	1.98	25	1.77	0.13	1.17	0.19

All figures show an increase in erosion of the top layer of the bed at an increasing current velocity (increasing shear stress). At low velocities erosion of the bed is non linear and erosion is arrested after a while indicating that the exerted stress equals the bed shear strength at that level. At high current velocities erosion is linear (see figure 4). It is apparent that in all cases, except for ISEF-3, most linear erosion starts around an exerted velocity of 0.20 m/s (figures 4 to 8).

One of the major problems is to measure the bed density of the top mm's of the bed which is one of the basic parameters for the bed shear strength. The amount of erosion of the bed can be recalculated to erosion depth, assuming that the measured bed density of the first 5 mm of the bed is also characteristic for the top layer of the bed. If erosion occurred equally over the entire test section (1800 cm^2), the erosion depth is limited to 10^{-4} millimeter. This is not in agreement with visual observations after each test. Here it is found that at the end of the test the erosion depth can be as high as one centimetre. This difference can first of all be ascribed to the fact that the calculations are based on the mean bed density while it can be expected that the top millimeter of the bed measures a much lower density. Second, erosion of the bed will not always happen throughout the entire surface but will often be confined to patches in the test section where erosion resistance is lowest. This means that it is of major importance to measure the bed density with a much smaller interval and on a much more accurate way than in the present study.

The results of the tests show that the relationship between the exerted shear stress and the erosion rate is poor. This can be expected as in nature the composition of the bed and the density of the bed varies strongly in depth.

Conclusions and recommendations

The laboratory and the in-situ field measurements of the ISEF show realistic results in respect to the results of other researchers. The laboratory tests show that the reproducibility of the ISEF is reasonably good. The in-situ measurements based on the ISEF measures the minimum exerted shear stress at initiation of erosion of the bed leading to the maximum bed shear strength.
The ISEF measures erosion of the top-layer of the bed due to the uni directional current only. It is found that due to wave propagation mud-beds can weaken and the bed shear strength decreases as result (Mehta, 1988). The ISEF-measurements, in this respect, will overpredict the maximal bed shear strength.
It is expected that the moment of erosion of the top layer of the bed will strongly be determined by the composition of the bed, the bed density and biological activity in the top layer of the bed (for instance the presence of diatoms). The test results have shown that if variation in sand-mud composition, bed density, grainsize distribution and biologic activity in the top layer of the bed is relatively small, the strength of the top layer of cohesive beds at different locations tend to be constant.

The strength of the top layer of the bed of intertidal mudflats are determined by the governing (preceding) hydrodynamic conditions. Wave action, especially in very shallow water depth, remoulds the bed sediment. This effect is visual in the field to several cm beneath the bed surface, depending on the wave heights. The top layer of the bed was found to have approximately constant shear strength' on a small spatial scale. The strength of the top layer of intertidal mud flats, in this case, is determined rather by the prevailing hydrodynamic conditions (wave activity) and recent depositions than by physical and biological parameters.
Interdisciplinary research of physicist and biologists is needed in order to investigate the variation in shear strength of the top layer of intertidal mudflats properly. It is wise to choose research locations which differs in great extend in shear strength-related parameters. The ISEF is useful to characterize different types of cohesive sediment beds. More thorough investigation is possible if the bed density can be measured on a small vertical scale (millimeters). For this purpose the acoustic density meter which is developed by Delft Hydraulics can be recommended (Verbeek and Cornelisse, 1994).

More thorough investigation is possible if the in-situ pumped suction samples are analyzed with respect to grain size distribution during test procedure. In this way it is possible to separate the moment of resuspension of the fraction $d < 50\mu m$ from the moment the sand fraction $d > 50\mu m$ is resuspending.

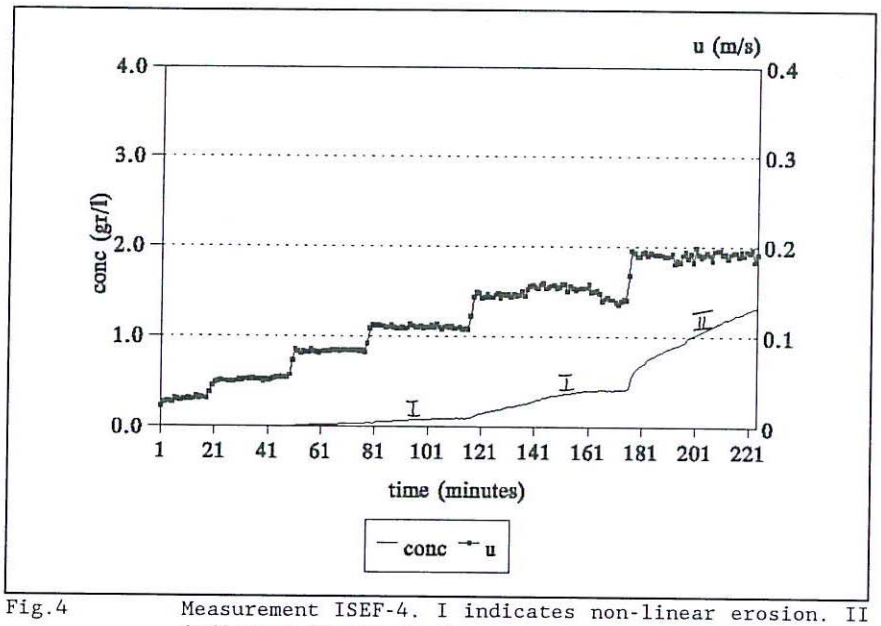

Fig.4 Measurement ISEF-4. I indicates non-linear erosion. II indicates linear erosion.

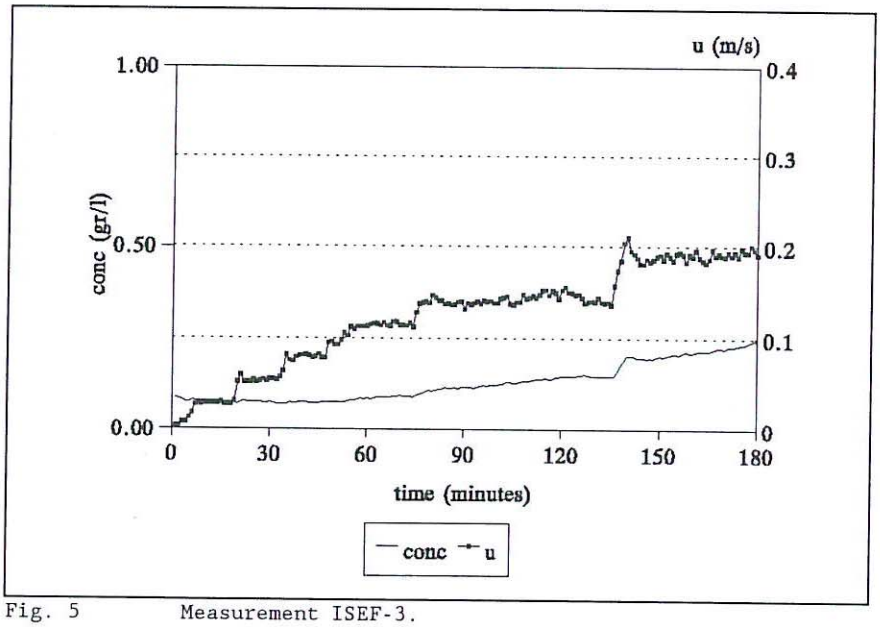

Fig. 5 Measurement ISEF-3.

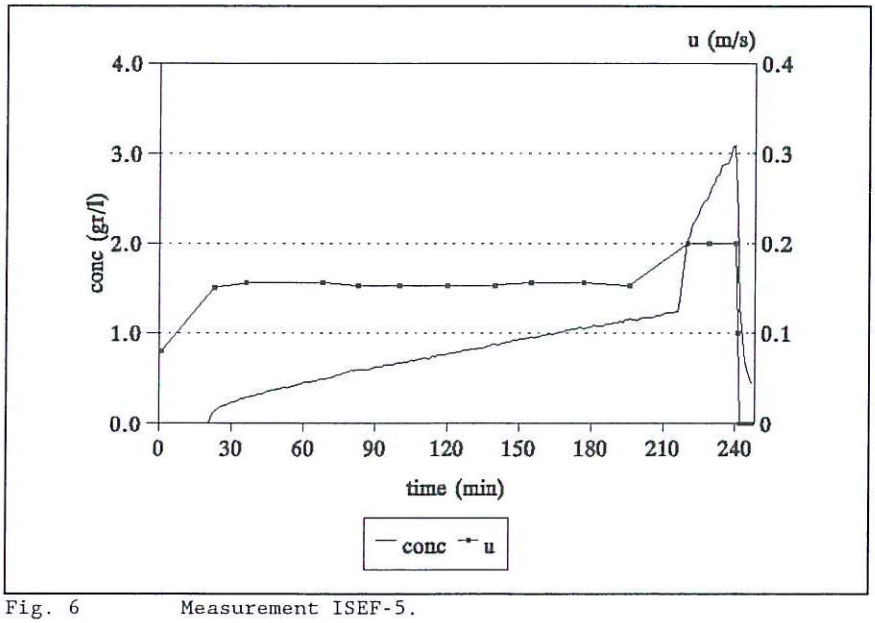

Fig. 6 Measurement ISEF-5.

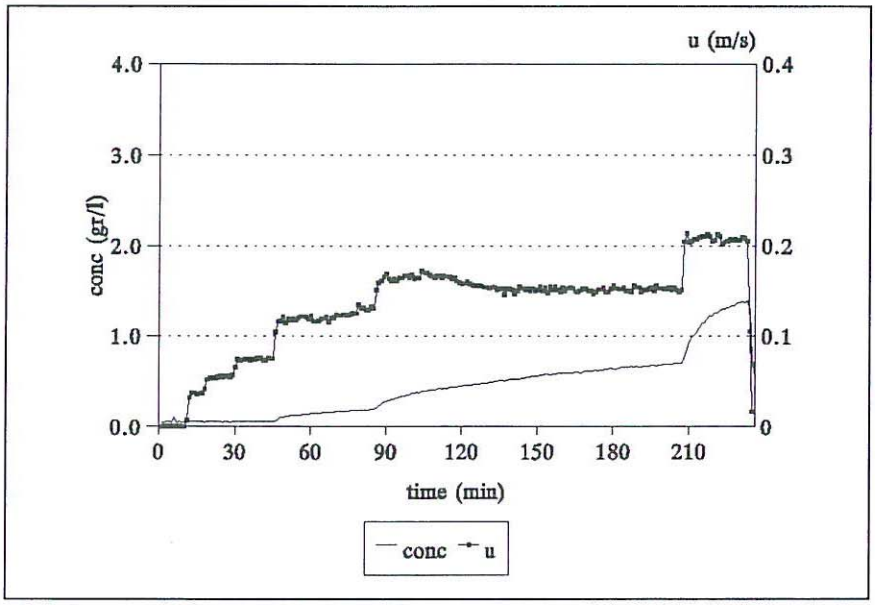

Fig. 7 Measurement ISEF-6.

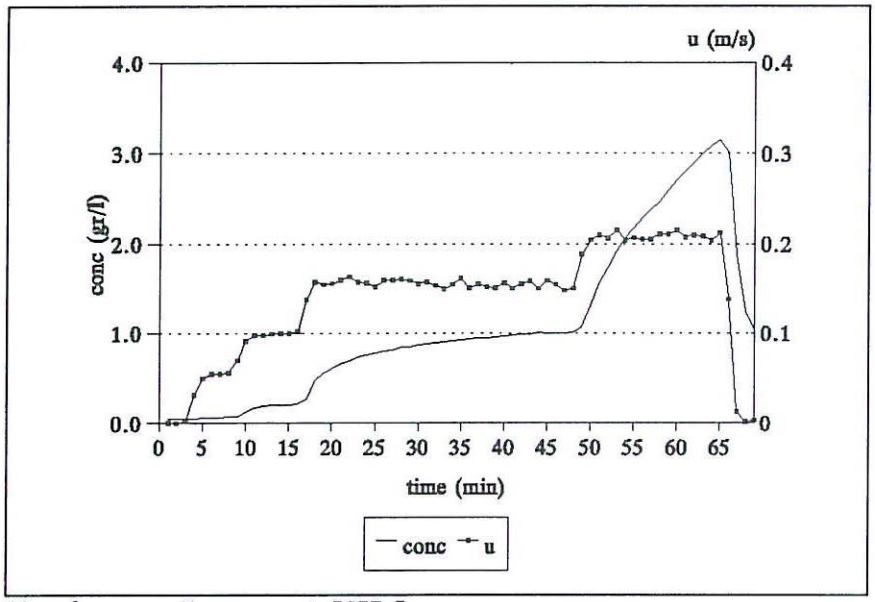

Fig. 8 Measurement ISEF-7.

References

Amos, C.L., G.R. Daborn and H.A. Christian (1992). In-situ erosion measurements on fine-grained sediments from the Bay of Fundy. Marine Geology, 108, 175-196.

Amos, C.L., J. Grant, G.R. Daborn and K. Black (1992a). Sea Carousel- A benthic, annular flume. Estuarine, Coastal and Shelf Science, 34, 557-577.

Cornelisse, J.M., H.P.J. Mulder, H. Williamson et al. (1994). On the development of instruments for in situ erosion measurements. 4th Nearshore and Estuarine Cohesive Sediment Transport Conference INTERCOH'94, Wallingford, England.

Houwing, E.J. and L.C. van Rijn (1992). In situ erosion Flume (EROSF): determination of bedshear stress and erosion of a kaolinite bed. Internal report, IMAU.

Jong, P. de (1991). Reproduction-research carrousel (in Dutch). Internal report Delft Hydraulics, note z161-94.

Mehta, A.J. and E. Partheniades (1982). Resuspension of deposited cohesive sediment beds. Proc. 18th ICCE, ASCE, 1569-1588.

Mehta, A.J. (1988). Laboratory studies in cohesive sediment deposition and erosion. In: Dronkers, J. and W. van Leussen (eds.). Physical processes in Estuaries. Springer Verlag, Berlin, 427-445.

Verbeek, H. and J.M. Cornelisse (accepted). Consolidation of dredged sludge, measured by an acoustic densitometer. Australian Journal of Marine and Freshwater Research.

Verreet, G., J. van Goethem, W. Viaene et al. (1986). Relations between physico-chemical and rheological properties of fine-grained muds. Proceedings of the Third International Symposium on River Sedimentation, River Sedimentation, volIII, 1637-1646.

Williamson, H.J. (1994). Recent Field Measurements of erosion shear stress using ISIS. 4th Nearshore and Estuarine Cohesive Sediment Transport Conference INTERCOH'94, Wallingford, England.