The LABEREX chamber for studying the critical shear stress for fine-grained sediment

Lars Chresten Lund-Hansen, Christian Christiansen, Ole Jensen & Mario Laima

Abstract

A new portable instrument, the Laberex chamber - LABoratory ERosional EXperiments - for studies of the "fluff layer" and sediment critical shear stress is described. The chamber consists of a cylindric plexiglass tube with an inner diameter of 84 mm. A four-bladed impeller connected to a motor is placed in the centre of the chamber. Rotation of the impeller induces resuspension. Light attenuation is measured across the centre line in the chamber at a wave length of 633 nm (red light). A PC automatically controls both the stirring voltage that is increased at predetermined time-intervals and collects data from the light attenuation meter every second. Velocity distributions in the chamber and the relation between stirring voltages and critical shear stress are known from laser-doppler measurements in the chamber.

Keywords

Chamber hydrodynamics, shear stress, resuspension, sediment, fluff layer.

Lars Chresten Lund-Hansen: Marine Ecology, Biological Institute, Aarhus University, Finlandsgade 14, 8200 Århus N, Denmark.
Email: lund-hansen@biology.au.dk
Christian Christiansen: Institute of Geography, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark.
Email: cc@geogr.ku.dk
Ole Jensen and Mario Laima: Department of Earth Sciences, Aarhus University, Ny Munkegade, Build. 520, 8000 Århus C, Denmark.

Geografisk Tidsskrift, Danish Journal of Geography 99: 1-7, 1999.

Resuspension of fine-grained sediments with a high content of nutrients may fertilize the water column (Simon, 1989), enhance phytoplankton growth since cells are periodically carried back into the euphotic layer (Garcia-Soto et al., 1990) and change the sediment/water diffusive fluxes of nutrients (Christiansen et al., 1995). Therefore, a knowledge on critical shear stresses for resuspension is important both from a basic science point of view and in environmental monitoring programs.

Instruments used for studies of critical shear stress and entrainment rates of sediments can be organized into two sets. One set comprises the rotating annuli for laboratory studies. The sediments are placed in the rotating annuli for variable periods to study consolidation effects prior to further experiments (Sheng, 1989). Recently instruments have been developed for *in situ* studies on intertidal mudflats (Williamson & Ockenden, 1996). The second set comprises instruments designed for *in situ* erosional studies of sediment deposited in non-tidal environments. The SEAFLUME (Young & Southard, 1978) was used for studies in the shallow Buzzards Bay. The principle of the instrument is a duct through which water is transported at variable speeds. This instrument was further developed and improved by Gust & Morris (1989) and deployed at water depths up to 190 m in Puget Sound. Another instrument for erosional *in situ* studies in shallow water areas is the VIMS Sea Carousel (Maa et al., 1995), an annular flume similar to the Sea Carousel (Amos et al., 1992). Besides these two major groups, smaller instruments have been developed and used for erosional studies of sediments from different depositional environments. For instance, "EROMES", a cylindric 100 mm diameter chamber with a central stirrer has been used for erosional studies of muddy sediments (Schönemann & Kühl, 1991). A combination of stirrer and suction is used in the "Microcosm" which is a circular chamber with a diameter of 300 mm (Gust & Müller, 1997). Gust & Müller (1997) make an intercomparison of hydrodynamic conditions in some smaller devices designed for erosion studies.

These instruments and devices operate on the assumption of a vertically homogenous sediment. However, the sediment-water interface in the coastal zone is often covered with a loosely aggregated material, the so-called "fluff layer" (Stolzenbach et al., 1992). The fluff layer has a high porosity and low density in comparison with the consolidated sediment below (Rhoads & Boyer, 1982). Recent studies in Baltimore Harbor showed that the critical shear stress was 0.05 N m^{-2} when a fluff layer was present, and 0.1 N m^{-2} when the fluff layer was absent (Maa et al., 1998). The present paper has two aims. 1) To describe a new, portable instrument for laboratory determinations of the critical shear stress for the fluff layer and fine-grained sediments. 2) To show that when fluff layers are present, there are no longer direct relation between sediment grain-size and critical shear stress.

Instrument and procedures

The instrument's main body is a fully transparent cylindrical plexiglass chamber with an inner diameter of 84 mm and wall thickness of 3 mm. A four-bladed impeller is placed in the centre of the chamber (Figure 1). The impeller is constructed of plexiglass and has a width of 65 mm, a height of 30 mm and 3 mm thick blades. The impeller is connected to an electric motor via a stainless steel rod. The gear-ratio of the motor is 18:1. A light emitter and receiver are placed outside the chamber but in such a way that the light beam passes through the centre of the chamber. The wave length of the light is 633 nm (red light) to avoid interference with both living phytoplankton that has two maxima of absorbency at wave lengths of 440 and 680 nm and with yellow substances which have a strong absorbency in the short-wave length region (Jerlov, 1976).

Instruments and devices used to measure suspended sediment concentrations use either optical back scatter (Amos et al., 1992; Maa et al., 1995), light attenuation (Gust & Morris, 1989; Williamson & Ockenden, 1996) or water sampling (Kusuda et al., 1984). Light attenuation is used in the Laberex chamber in order to compare the laboratory experiments with *in situ* measurements of light attenuation obtained by deployments of tripods (Lund-Hansen & Christiansen, 1998). In contrast to water sampling, light attenuation gives a continuous, high resolution signal, that by calibration, can be converted into concentrations (Wells & Kim, 1991). The light attenuation of the water itself - C_w in equation [1] - is assumed to be constant during a Laberex experiment. The emitted light is pulsed to suppress any unwanted light components such as daylight

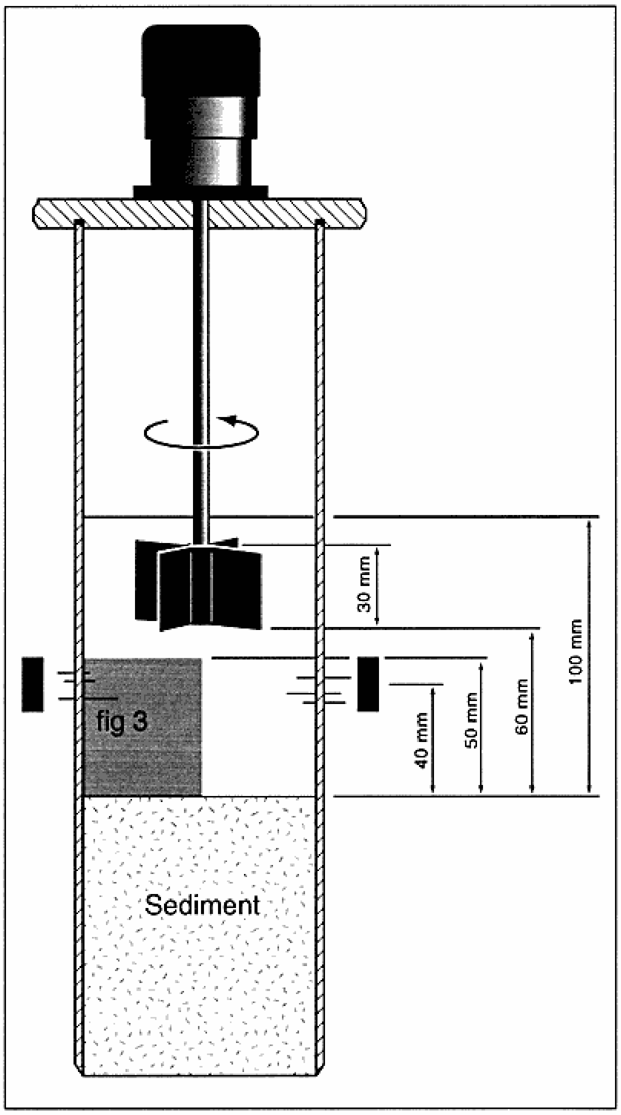

Figure 1: The Laberex chamber.

(DC-light) and any other artificial light sources (AC 50 Hz light). The electric motor, light emitter and receiver are connected to a 12 bit A/D converter (CIO-DAS08AOH Bipolar ± 5 Volt) although the emitter-receiver signal is only 10 bit giving a resolution of 0.1%. The converter is operated through the LABTECH® software that allows for real time monitoring (digital and graphically) of stirring voltage and light attenuation. The latter sampled at frequency of 1 Hz.

Light attenuation in water is expressed as a light attenuation coefficient ($C-C_w$):

$$C - C_w = (\ln (F/F_0))/r \qquad (1)$$

where C_w is the light attenuation of the water (m^{-1}), F the measured, F_0 the initial light intensity (volts), and r is the distance (m) between the light emitter and receiver (Wells & Kim, 1991). F_0 is adjusted to the same initial level (4.0 volts) before any experiment is started to compensate for scratches in the plexiglass and any potential minor impurities on the inside of the chamber. The light beam is placed 40 mm above the sediment surface and the distance between the lowermost impeller edge and surface of the sediment is 60 mm (Figure 1). The height of the water column above the sediment surface in the chamber is adjusted to 100 mm giving a volume of 554.2 cm^3. Figure 2 illustrates the Laberex chamber, peripherals, and PC placed in a flight case.

In order to collect fully undisturbed sediment surfaces with an intact fluff layer (if present) sediment cores are collected with the chamber either by divers or as subsamples from a specially designed hydraulic damped box-

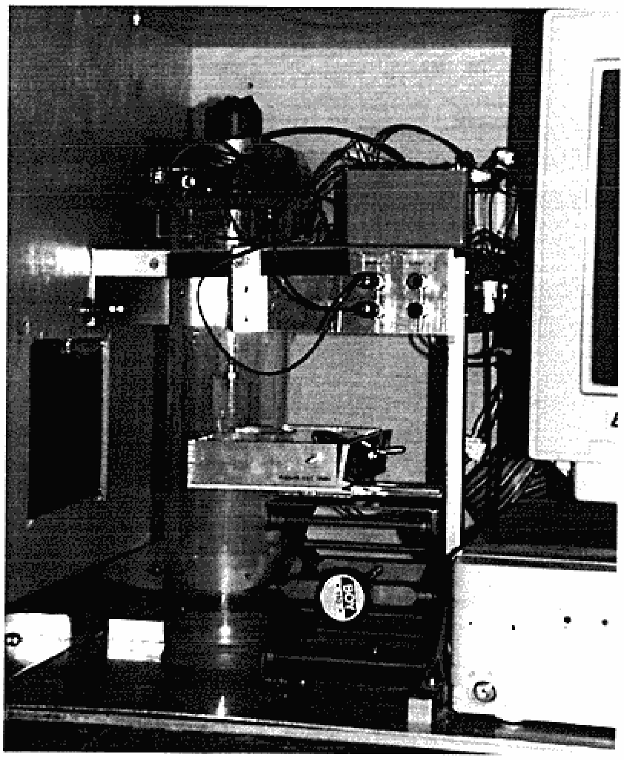

Figure 2: A photograph that shows the Laberex chamber with peripherals and a PC placed in a flight case.

corer (Lund-Hansen and Christiansen, 1999). The chamber is stored in the dark for at least 12 hours before experiments are started. This allows settling of suspended matter in the chamber. Applying Stoke's law, a period of 8.2 hours is required for a clay-sized particle with a diameter of 2 μm to settle 100 mm and, similarly, 8 hours is required for a spherical phytoplankton cell with a diameter of 10 μm (Jackson, 1990).

Chamber hydrodynamics

Different methods have been applied to study the hydrodynamic conditions in benthic chambers, *e.g.* skin friction probes (Gust, 1988), modelling of near bottom velocities (Williamson & Ockenden, 1996).

Laser-doppler techniques (Dantec 50H48) were applied in the present study to measure the tangential velocities in the chamber. This technique is often used for flow velocity measurements in confined spaces *(e.g.* Cardoso et al., 1989; Wu & Patterson, 1989; Winardi & Nagase, 1991) as the technique is non-intrusive. The elliptic measuring volume in this study was 80 μm by 680 μm. A false plexiglass bottom was placed inside the chamber and sediment were glued onto the bottom prior to the measurements in order to simulate a real bed. The lower edge of the impeller was placed 60 mm above the sediment surface similar to the planned experimental conditions (Figure 1). The chamber was placed in a rectangular glass basin filled with tap water to avoid any optical distortion from reflected laser beams during the measurements (Wu & Patterson, 1989). In order to increase the sample rate, water in the chamber was seeded using 10 μm latex particles, which has a density close to water (Coulter Techniques). Tangential velocities were measured at 1.0, 2.0, 3.0, 4.0, 8.0, 12.0, 16.0, 20.0, 24.0, 32.0, 36.0, and 40.0 mm above the sand surface. Tangential velocities were also measured at 1.36, 2.72, 5.44, 8.16, 10.88, 13.6, 16.32, 19.04, 21.76, 24.48, 27.2, 29.92, 32.64, 35.36, 38.08, and 40.8 mm from the inner chamber wall towards the centre line. Positioning of the measuring tube was carried out using a x-y mechanical board with a precision of 0.05 mm. The total grid comprised 192 single measurement points covering a rectangle (40.0x40.8 mm) placed between the inner chamber wall and the centre line. Each observation was the average of 40 to 50 measurements. The laser velocity measurements were carried out for seven different stirring voltages: 0.5, 0.75, 1.0, 1.25, 1.50, 1.75, and 2.0 volt. Measured velocities were contoured (SURFER®) for lines of equal velocities.

Figure 3 illustrates the spatial distribution of the tangential velocities in the chamber at 1.0 volt; this was very similar to the distributions obtained at other stirring voltages. The velocity distribution is quite uniform in the vertical. The isolines of equal velocity > 3.0 cm s^{-1} cover about 50 percent of the bottom area in the chamber at 1.0 volt.

Supplementary velocity measurements at 1.0 mm above the sediment surface were obtained at the same horizontal positions as above and at the same stirring voltages: 0.5, 0.75, 1.0, 1.25, 1.50, 1.75, and 2.0 volts. The mean velocity and standard deviation at each position and stirring voltage were determined from 500 measurements. Figure 4 illustrates the tangential velocities between the inner chamber wall and the centre line with standard deviations at 1.0 mm above the sediment surface for the stirring voltages: 0.5, 1.0, 1.5, and 2.0 volts. The velocities are generally uniform on the major part of the sediment surface. However, steep velocity gradients occur near the chamber wall and centre line.

Figure 4 also shows that the velocity gradients between positions in the chamber increases with increased stirring voltage. For instance, the velocity at 1.5 volt is 6.3 cm s^{-1} at 30 mm from the chamber wall and 3.8 cm s^{-1} at 13.6 mm. Standard deviations increase expectedly as the stirring voltage is increased and they are comparatively high on both sides of 30 mm from the chamber wall at 2.0 volt. However, critical shear stress in fine-grained and fluff layer as in the present examples (see later) is reached at stirring voltages between 0.9 and 1.4 volt. Standard deviations at these stirring voltages are comparatively low (Figure 4). A clear maximum in velocity for each stirring voltage is found at about 30 mm from the chamber wall and initial erosion of the sediment always occur in this region of maximum velocities. This was also shown by video recordings of the experiments. The relation between stirring voltage and shear stress applied to the sediment surface in the chamber was calculated from velocity profiles based on the Laser-Doppler measurements. Velocity profiles were selected for different stirring voltages and they were located in the area of maximum velocities about 30 mm from the chamber wall (Figure 4).

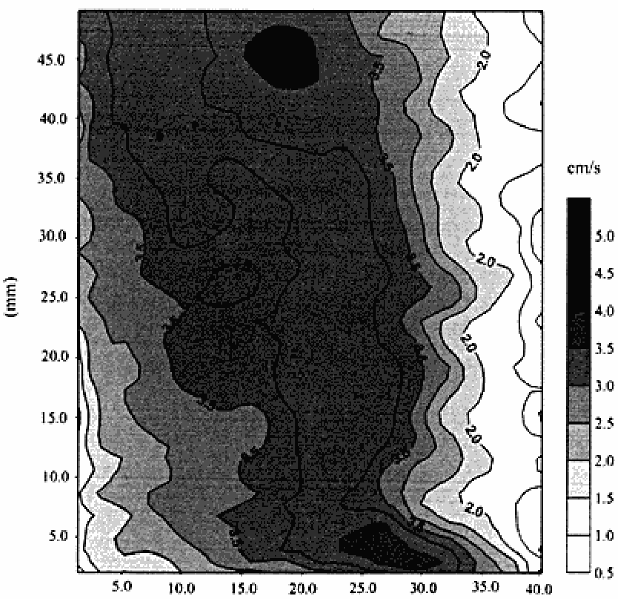

Figure 3: Distribution of tangential velocities (cm s^{-1}) at 1.0 volt. The area covers the hatched area shown in the lower left corner of the chamber (Figure 1).

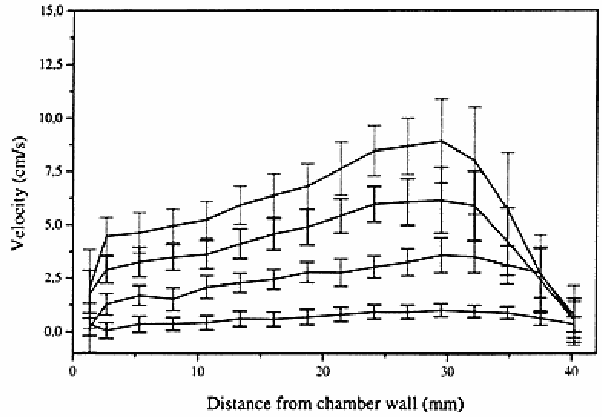

Figure 4: Tangential velocities measured 1.0 mm above the sediment surface as a function of distance from the chamber wall (to the left). Standard deviations are indicated by the vertical bars for stirring voltages: 0.5, 1.0, 1.5, and 2.0 volts.

Results and discussion

The results of Laberex experiments using three sediment cores collected from different locations are illustrated in Figure 5A-C. One core was collected in the Arkona Basin (54° 45 N, 14° 05 E) southwest of Bornholm in the southwest part of the Baltic Sea on 25 June 1998. The second core was collected from Tromper Wiek (54⁰ 45 N, 14⁰ 05 E) in the western part of the Pomeranian Bay south of the Arkona Basin on 24 June 1998. The third core was collected in Århus Bay (54⁰ 45 N, 14⁰ 05 E) on the east coast of Denmark on 24 August 1998. The water depths at the three locations were 45 m in the Arkona Basin, 26 m in Tromper Wiek, and 15 m in Århus Bay. Further details concerning the sediment characteristics of the top 1 cm of

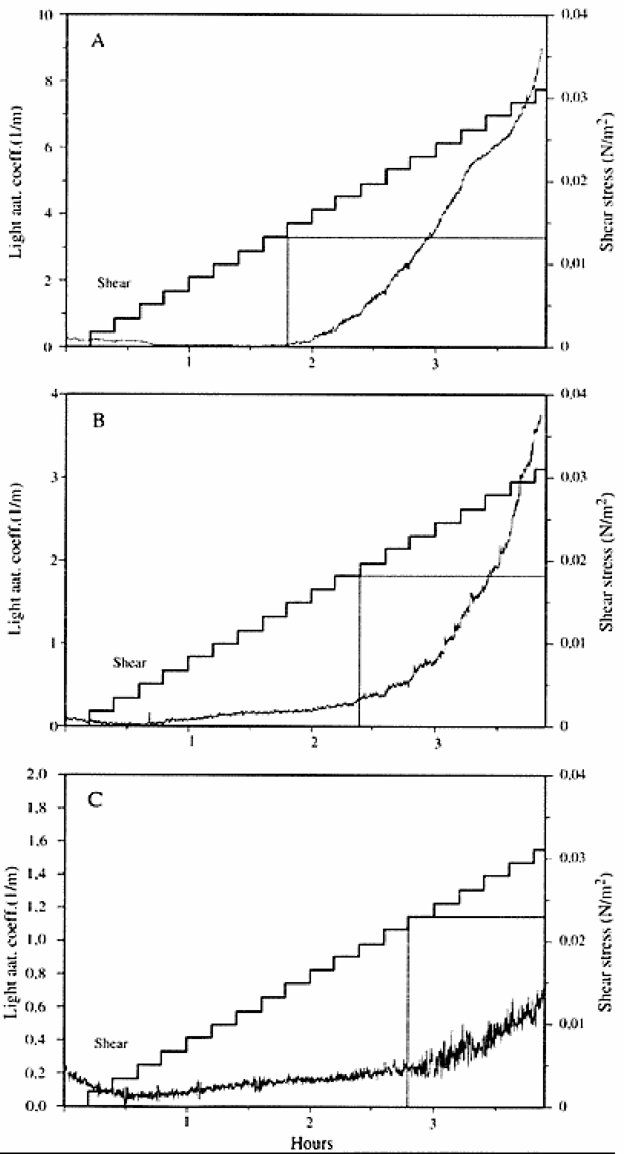

Figure 5: Shear stress (N m⁻²) and light attenuation coefficient (m⁻¹) during three Laberex experiments: A) Arkona Basin, B) Pomeranian Bay, and C) Århus Bay.

sediment at the sampling positions are summarized in Table 1. Grain size distributions were obtained using the Malvern® laser diffractometer (Agrawal et al., 1991) for the Arkona and Tromper Wiek samples, whereas conventional sieving and settling analyses were performed on the Århus Bay samples. Organic matter content was determined as loss on ignition after 3 hours of burning at 550 °C.

The shear stress was increased by 0.0014 N m^{-2} every 12 minutes and each experiment was run for 4 hours. This allows for both non-linear and linear entrainments rate to occur (Mehta and Partheniades, 1982). Each data point in the light attenuation time-series is the average of 10 measurements. All three experiments exhibit a decrease in light attenuation coefficient (LAC) during the first 0.5 hour of the experiment (Figure 5A-C). This LAC decrease is related to flocculation processes in the chamber. After collection, the sediment samples are stored at *in situ* temperatures for a period of 12 hours prior to the experiment being started. About 8 hours are required for both a clay particle (ϕ = 2 µm) and a spherical phytoplankton cell (ϕ = 100 µm) to settle 10 cm. The experimental results show that even after 8-10 hours with quiescent water, there are still some particles in the water. However, the effects of the initial flocculation on the determination of the critical shear stress are thought to be negligible. The LAC increases slightly after having reached a minimum during the initial part of the experiment (Figure 5A-C). Note the difference in vertical scale on the y-axes, which especially enhances the Århus Bay LAC time-series. Resuspension of the surface sediment is initiated when changes in the LAC time-series per time reaches a maximum and increased variation in the LAC time-series are observed (Figure 5C). This increased variation reflects the fact that particles have been resuspended into the water and that particles of various sizes pass through the light beam producing a larger variation in the signal. Accordingly, the critical shear stress is 0.015 N m^{-2} in the Arkona Basin, 0.018 N m^{-2} in Tromper Wiek, and 0.023 N m^{-2} in Århus Bay (Figure 5A-C). A shear stress of 0.015 N m^{-2} and 0.023 N m^{-2} (Table 1) relates to maximum velocities of 3.2 cm s^{-1} and 5.9 cm s^{-1} respectively at 1.0 mm above the sediment surface (Figure 4).

The three samples represent a wide range of depositional environments. The Tromper Wiek sediment (Pomeranian Bay) shows a quite coarse grained, sandy sediment, which is related to a strong wave exposure as the fetch varies between 190 and 500 km with wind directions between

Experiment	*Depth (m)*	*Sand (%)*	*Silt (%)*	*Clay (%)*	*Org. (%)*	*Shear N m⁻²*
Arkona Basin	*45*	*0.5*	*63.7*	*35.8*	*15.1*	*0.015*
Pomeranian Bay	*26*	*53.3*	*41.9*	*4.8*	*5.4*	*0.018*
Århus Bay	*15*	*21*	*24*	*55*	*9.5*	*0.023*

Table 1: *Water depth, sand, silt, clay, organic matter content, and critical shear stress of the surface samples.*

east and northeast. The shallow water Århus Bay shows a high percentage of silt (Table 1). The bay is semi-enclosed and protected from all wind directions except from the southeast which can cause strong wave-induced resuspension in the bay (Lund-Hansen et al., 1997). However, there is no clear relation between grain size parameters of the surface sediments and critical shear stress (Table 1) For instance, the critical shear stress is only 0.003 N m^{-2} higher for the Tromper Wiek sample, which contains 53.3 percent sand compared to the Arkona Basin sample which contains only 0.5 percent sand (Table 1). Underwater video inspections were conducted at the Tromper Wiek location using the HYBALL® which revealed that the surface of the sediment was covered by a "fluff" layer with an average thickness of about 0.5 cm. A fluff layer consists of low density material, with a relatively high organic content, which is temporarily deposited on top of the more strongly consolidated sediment (Stolzenbach et al., 1992). Underwater video inspections in Århus Bay also revealed the presence of a few millimeters thick fluff layer. Video inspections were not carried out at the Arkona position, but the sediment at this position is relatively soft with no consolidated sediment in the vicinity of the sediment surface.

Values of the critical shear stress for resuspension cited in the literature vary between 0.1 and 0.2 N m^{-2} for mud flats (Williamson & Ockenden, 1996), and between 0.1 and 0.025 N m^{-2} at a shallow water (< 5.0 m) position in Chesapeake Bay (Sanford, 1994). A critical shear stress of 0.13 N m^{-2} was obtained by *in situ* experiments also in Chesapeake Bay at a water depth of about 11 m (Maa et al., 1991). On the other hand, Young & Southard's (1978) *in situ* experiments in Bussards Bay at a water depth of 16 m showed an average critical shear stress of 0.023 N m^{-2} similar to the results obtained in the present study (Table 1). The low critical shear stress obtained at all three positions in this study were related to the presence of either a fluff layer (Tromper Wiek, Århus Bay) or fine-grained unconsolidated sediments (Arkona Basin).

Figure 4 showed that the standard deviation of velocity (1.0 mm above the sediment surface) increases with increased stirring rate, and also that the change in velocity with distance from the chamber wall increases with increased stirring rate. This emphasizes that the Laberex chamber can only be used for determination of critical - shear stress of fine-grained sediments or fluff layers at comparatively low stirring rates or critical shear stress as the standard deviation of the velocity increases with increasing stirring rate.

Acknowledgments

This work was supported by financial support from the Danish Environmental Research Programme 1992-1996, the Danish Natural Science Research Council, and BASYS EU-MAST III project contract number MAS3-CT96-0058). We acknowledge the very valuable comments and suggestions given to the manuscript by Prof. Brian Greenwood and an anonymous referee.

References

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

Agrawal, Y.C., McCave, I.N. & Riley, J.B. (1991): Laser diffraction size analysis. Pp 119-128 in: Syvitski, J.P.M. (Ed.): Principles, methods, and application of particle size analysis. Cambridge University Press.

Cardoso, A.H., Graf, W.H., & Gust, G. (1989): Uniform flow in a smooth open channel. Journal of Hydraulic Research, 27: 603-616.

Christiansen, C., Gertz, F., Laima, M.J.C., Lund-Hansen, L.C., Vang, T. & Jürgensen, C. (1995): Nutrient (P,N) dynamics in the southwestern Kattegat, Scandinavia: sedimentation and resuspension effects. Environmental Geology, 29: 66-77.

Garcia-Soto, C., de Madariaga, I., Villate, F. & Orive, E. (1990): Day-to-day variability in the plankton community of a coastal shallow embayment in response to changes in river runoff and water turbulence. Estuarine, Coastal and Shelf Science, 31: 217-229.

Experiment	*Depth (m)*	*Sand (%)*	*Silt (%)*	*Clay (%)*	*Org. (%)*	*Shear N m⁻²*
Arkona Basin	*45*	*0.5*	*63.7*	*35.8*	*15.1*	*0.015*
Pomeranian Bay	*26*	*53.3*	*41.9*	*4.8*	*5.4*	*0.018*
Århus Bay	*15*	*21*	*24*	*55*	*9.5*	*0.023*

Table 1: *Water depth, sand, silt, clay, organic matter content, and critical shear stress of the surface samples.*

east and northeast. The shallow water Århus Bay shows a high percentage of silt (Table 1). The bay is semi-enclosed and protected from all wind directions except from the southeast which can cause strong wave-induced resuspension in the bay (Lund-Hansen et al., 1997). However, there is no clear relation between grain size parameters of the surface sediments and critical shear stress (Table 1) For instance, the critical shear stress is only 0.003 N m^{-2} higher for the Tromper Wiek sample, which contains 53.3 percent sand compared to the Arkona Basin sample which contains only 0.5 percent sand (Table 1). Underwater video inspections were conducted at the Tromper Wiek location using the HYBALL® which revealed that the surface of the sediment was covered by a "fluff" layer with an average thickness of about 0.5 cm. A fluff layer consists of low density material, with a relatively high organic content, which is temporarily deposited on top of the more strongly consolidated sediment (Stolzenbach et al., 1992). Underwater video inspections in Århus Bay also revealed the presence of a few millimeters thick fluff layer. Video inspections were not carried out at the Arkona position, but the sediment at this position is relatively soft with no consolidated sediment in the vicinity of the sediment surface.

Values of the critical shear stress for resuspension cited in the literature vary between 0.1 and 0.2 N m^{-2} for mud flats (Williamson & Ockenden, 1996), and between 0.1 and 0.025 N m^{-2} at a shallow water (< 5.0 m) position in Chesapeake Bay (Sanford, 1994). A critical shear stress of 0.13 N m^{-2} was obtained by *in situ* experiments also in Chesapeake Bay at a water depth of about 11 m (Maa et al., 1991). On the other hand, Young & Southard's (1978) *in situ* experiments in Bussards Bay at a water depth of 16 m showed an average critical shear stress of 0.023 N m^{-2} similar to the results obtained in the present study (Table 1). The low critical shear stress obtained at all three positions in this study were related to the presence of either a fluff layer (Tromper Wiek, Århus Bay) or fine-grained unconsolidated sediments (Arkona Basin).

Figure 4 showed that the standard deviation of velocity (1.0 mm above the sediment surface) increases with increased stirring rate, and also that the change in velocity with distance from the chamber wall increases with increased stirring rate. This emphasizes that the Laberex chamber can only be used for determination of critical - shear stress of fine-grained sediments or fluff layers at comparatively low stirring rates or critical shear stress as the standard deviation of the velocity increases with increasing stirring rate.

Acknowledgments

This work was supported by financial support from the Danish Environmental Research Programme 1992-1996, the Danish Natural Science Research Council, and BASYS EU-MAST III project contract number MAS3-CT96-0058). We acknowledge the very valuable comments and suggestions given to the manuscript by Prof. Brian Greenwood and an anonymous referee.

References

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

Agrawal, Y.C., McCave, I.N. & Riley, J.B. (1991): Laser diffraction size analysis. Pp 119-128 in: Syvitski, J.P.M. (Ed.): Principles, methods, and application of particle size analysis. Cambridge University Press.

Cardoso, A.H., Graf, W.H., & Gust, G. (1989): Uniform flow in a smooth open channel. Journal of Hydraulic Research, 27: 603-616.

Christiansen, C., Gertz, F., Laima, M.J.C., Lund-Hansen, L.C., Vang, T. & Jürgensen, C. (1995): Nutrient (P,N) dynamics in the southwestern Kattegat, Scandinavia: sedimentation and resuspension effects. Environmental Geology, 29: 66-77.

Garcia-Soto, C., de Madariaga, I., Villate, F. & Orive, E. (1990): Day-to-day variability in the plankton community of a coastal shallow embayment in response to changes in river runoff and water turbulence. Estuarine, Coastal and Shelf Science, 31: 217-229.

Gust, G. (1988): Skin friction probes for field applications. Journal of Geophysical Research, 93: 121-132.

Gust, G. & Morris, M.J. (1989): Erosion thresholds and entrainment rates of undisturbed *in situ* sediments. Journal of Coastal Research, 5: 87-99.

Gust, G. & Müller, V. (1997): Interfacial hydrodynamics and entrainment functions of currently used erosion devices. In: Burt, N., Parker, R. and Watts, J. (Eds.): Cohesive Sediments. John Wiley, Chichester, U.K.

Jackson, G.A. (1990): A model of the formation of marine algal flocs by physical coagulation processes. Deep-Sea Research, 37: 1197-1211.

Jerlov, N.G. (1976): Amsterdam, Marine optics. Elsevier Scientific Publishing Company.

Kusuda, T., Umita, K.K., Futawatari, T. & Awaya, Y. (1984): Erosional process of cohesive sediments. Water Science Technology, 17: 891-901.

Lund-Hansen, L.C. & Christiansen, C. (1998): Resuspension, sediment fluxes, and suspended sediment diffusion coefficients under wave and current forcing in two coastal environments. Danish Journal of Geography, 98: 10-19.

Lund-Hansen, L.C. & Christiansen, C. (1999): Presentation of the new video equipped Århus box-corer for collecting fully undisturbed sediments. Abstract, 2nd Nordic Marine Science Meeting, Hirtshals.

Lund-Hansen, L.C., Valeur, J. M., Pejrup, M. & Jensen, A. (1997): Sediment fluxes, resuspension and mixing at two exposed coastal sites and in a sheltered bay. Estuarine, Coastal and Shelf Science, 44: 521-531.

Maa, P.-Y.J., Shannon, W.T., Li, C. & Lee, C.-H. (1991). In-situ measurements of the critical bed shear stress for erosion. Pp. 123-133 in Lee, C.-H. & Cheung, Y. K. (Eds.): Environmental Hydraulics. Rotterdam, Balkema.

Maa, J. P.-Y., Lee, C.-H. & Chen, F.J. (1995): Bed shear stress measurements for VIMS Sea Carousel. Marine Geology, 129: 129-136.

Maa, J. P.-Y., Sanford, L. & Halka, J.P. (1998): Sediment resuspension characteristics in Baltimore Harbor, Maryland. Marine Geology, 146: 137-145.

Mehta, A.J. & Partheniades, E. (1982): Resuspension of deposited cohesive sediment beds. 18th Conference on Coastal Engineering. 1569-1588.

Rhoads, D.C. & Boyer, L.F. (1982): The effect of marine benthos on physical properties of sediments: A successional perspective. Pp 51-65 in: McCall, P.L. & Tevesz, M.J.S. (Eds.): Animal-Sediment Relations. New York, Plenum Books.

Sanford, L. (1994): Wave-forced resuspension of upper Chesapeake Bay muds. Estuaries, 17: 148-165.

Schönemann. M., & Kühl, H. (1991): A device for erosion-measurements on naturally formed, muddy sediments: the EROMES-System. GKKS Report 91/E/18. GKSS-Forshungscentrum Geesthacht.

Sheng, P. (1989): Consideration of flow in rotating annuli for sediment erosion and deposition studies. Journal of Coastal Research, 5: 207-216.

Simon, N.S. (1989): Nitrogen cycling between sediment and the shallow-water columnn in the transition zone of the Pontomac River and estuary. II. The role of wind-driven resuspension and adsorbed ammonium. Estuarine, Coastal and Shelf Science, 28: 531-547.

Stolzenbach, K.D., Newman, K.A. & Wong, S.H. (1992): Aggregation of fine particles at the sediment-water interface. Journal of Geophysical Research, 97: 17889-17898.

Wells, J.T. & Kim, S.Y. (1991): The relationship between transmission and concentration of suspended particulate matter in the Neuse River estuary, North Carolina. Estuaries, 14: 395-403.

Williamson, H.J. & Ockenden, M.C. (1996): ISIS: An istrument for measuring erosion shear stress *in situ*. Estuarine, Coastal and Shelf Science, 42: 1-18.

Winardi, S. & Nagase, Y. (1991): Unstable phenomenon of flow in a mixing vessel with a marine propeller. Journal of Chemical Engineering of Japan, 24: 243-249

Wu, H. & Patterson, G.K. (1989): Laser-doppler measurements of turbulent-flow parameters in a stirred mixer. Chemical Engineering Science, 44: 2207-2221.

Young, R.N. & Southard, J.B. (1978): Erosion of fine-grained marine sediments: sea floor and laboratory experiments. Bulletin of the American Geological Society, 89: 663-672.