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# The characterisation of cohesive sediment properties

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ABSTRACT

This paper describes apparatus, techniques and methods used by participants in MAST G6M project 4 (Cohesive Sediments) for determining cohesive sediment properties. This comparison of methods aims to stimulate a more general discussion on standardisation of techniques which will lead to characterisation of muds in terms of physical parameters. Such characterisation would allow intercomparison of muds from different sources. Methods are given for sediment properties of grain size distribution, settling velocity and rheological parameters and for water–bed exchange properties of permeability, effective stress and critical shear stress for erosion and deposition. Accuracy and repeatability are discussed. A typical range of values is indicated for each of these parameters.

## INTRODUCTION

Unlike sand, which can be fully characterised by its grain size distribution, cohesive coastal and estuarine sediments, generally referred to as *mud*, are much more difficult to characterise. Indeed, mud is a quite complex mixture of (saline or brackish) water, cohesive sediments (different clay minerals, mainly illite, montmorillonite and kaolinite), organic matter of diverse origin and nature, and usually, small amounts of sand and silt.

Mud should be characterised for two main engineering purposes: (1) to allow an intercomparison of different muds; (2) to introduce a few comprehensive parameters in the mathematical models, which aim at predicting morphological changes of estuaries, lagoons and sea beds, access channels and harbours, or to design dredged mud deposit basins. Therefore erosion, resuspension, sedimentation, deposition, consolidation and fluid mud flow must be simulated.

Problems arise due to the diversity and large number of parameters to be included, the diversity of measuring techniques, sampling techniques and sample preparation procedures. Measurements can be made either in the field

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or in the laboratory. There is a diversity of purposes for which mud is characterised by researchers of different disciplines, such as geologists, engineers, modellers, ecologists, etc., who all have their own definitions, methodologies and even literature references (e.g., a parameter which is useless for an engineer, may be vital for a geologist).

Therefore, from the start of the MAST-1 G6M project on cohesive sediments, much attention has been paid to identify the relevant parameters and the procedures and methodologies to determine them. A comprehensive list of mud parameters used by Delft Hydraulics (Winterwerp et al., 1990) has been discussed within the framework of the MAST G6M project. The resulting list of 28 parameters (or parameter sets) is presented in the Appendix.

It became obvious that a parameter found in literature did not always mean the same thing to everyone, or could not be compared to other values found in literature or measured. Therefore an inventory was made of all techniques being used in the different laboratories involved in MAST G6M (1992) to measure the parameters listed in the Appendix.

The present paper aims at stimulating the discussion to bring about standardisation of the procedures and techniques. It focuses on the parameters controlling the mechanical behaviour of mud as can be found from the study of the different morphological and bed exchange processes (Teisson et al., 1993), i.e.:

- the settling velocity, which is an "integrated" parameter of the flocs;
- the consolidation, controlled by permeability and effective stresses;
- the rheological behaviour of the fluid mud;
- the erosion and sedimentation mechanisms.

For each item relevant parameters and the methodology to determine them are discussed. Attention is paid to the repeatability, accuracy and interpretation of the results.

## SETTLING VELOCITY AND GRAIN SIZE DISTRIBUTION

The settling velocity is a salient parameter for sediment particles in suspension, governing the transport processes, but may also be used to characterise the sediment found in the bed by analysing bed samples in the laboratory. However, it is not directly related to the grain size of the particles (through Stokes' law or similar) due to flocculation effects, affecting the shape, size and density of the particle aggregates. Moreover, these effects may vary in space and time as a result of stress history (turbulence levels, affecting aggregation and break-up of flocs), sediment concentration, organic compounds, chemical environment (e.g. salinity), etc. Therefore, it is recommended that the settling velocity be measured in-situ, whenever that is possible.

*Settling velocity*

Settling velocities of cohesive particle aggregates in a natural suspension are of the order of 0.01–10 mm/s. The value increases with concentration due to aggregation to reach a maximum at a concentration of 2–10 g/l. At higher concentrations flocs are broken again and the settling velocity decreases rapidly with concentration due to mutual hindrance.

Presently, two techniques are available for suspended sediment: the bottom and pipette withdrawal tube and in-situ video systems. The bottom withdrawal tube was developed by Owen (1976) (Owen tube). It is essentially a cylindrical sampling device of about 1 m length with a diameter of about 0.05 m, which is lowered into the water and brought into a horizontal position. Two valves at both ends of the tube can be closed remotely, after which the tube is retrieved. It is then brought into a vertical position and samples are withdrawn from the lower valve at specific time intervals, from which the sediment concentration is measured in the laboratory. From its variation, the settling velocity distribution of the sediment in the tube can be assessed by applying the mass balance equation. A slightly modified system is the Field Pipette Withdrawal Tube, which enables the samples to be taken with a pipette from the tube (Van Rijn, 1986). Major advantages of these devices are that they are fairly cheap, and can be operated under "natural conditions". However, the method can only yield accurate results for concentrations of about 0.1 $kg/m^3$ or larger. Other disadvantages are possible floc break-up during sampling, secondary currents in the tube (due to density currents and/or return flow) and the long measuring time (of the order of one hour or more) during which additional flocculation may occur.

The in-situ video system was developed in the Netherlands (Van Leussen, 1992, 1993). Presently similar techniques are being used at various institutes all over the world. Sediment is trapped in a settling column, part of which is illuminated with a thin sheet of light. A video camera is focused on this sheet, monitoring the falling sediment particles. The video tape can then be digitised and analysed with digital image processing techniques, yielding the distribution of particle size, shape and settling velocity. A major advantage of this technique is that the actual measurement can be observed directly on a monitor, enabling a direct assessment of the quality of the data. Particles that can be observed are larger than a few to 20 microns, depending on the lens system applied. A disadvantage is the possibility of secondary currents within the settling column due to return flow and/or density currents. Fig. 1 shows a comparison of the settling velocity of sediment from the Thames Estuary as obtained with the Owen tube and a video system. The graph shows that for the video system considerably higher settling velocities are measured during the first 5 minutes. The settling velocity then reduces, probably due to the influence of the walls of the enclosing column which is increasingly felt. For

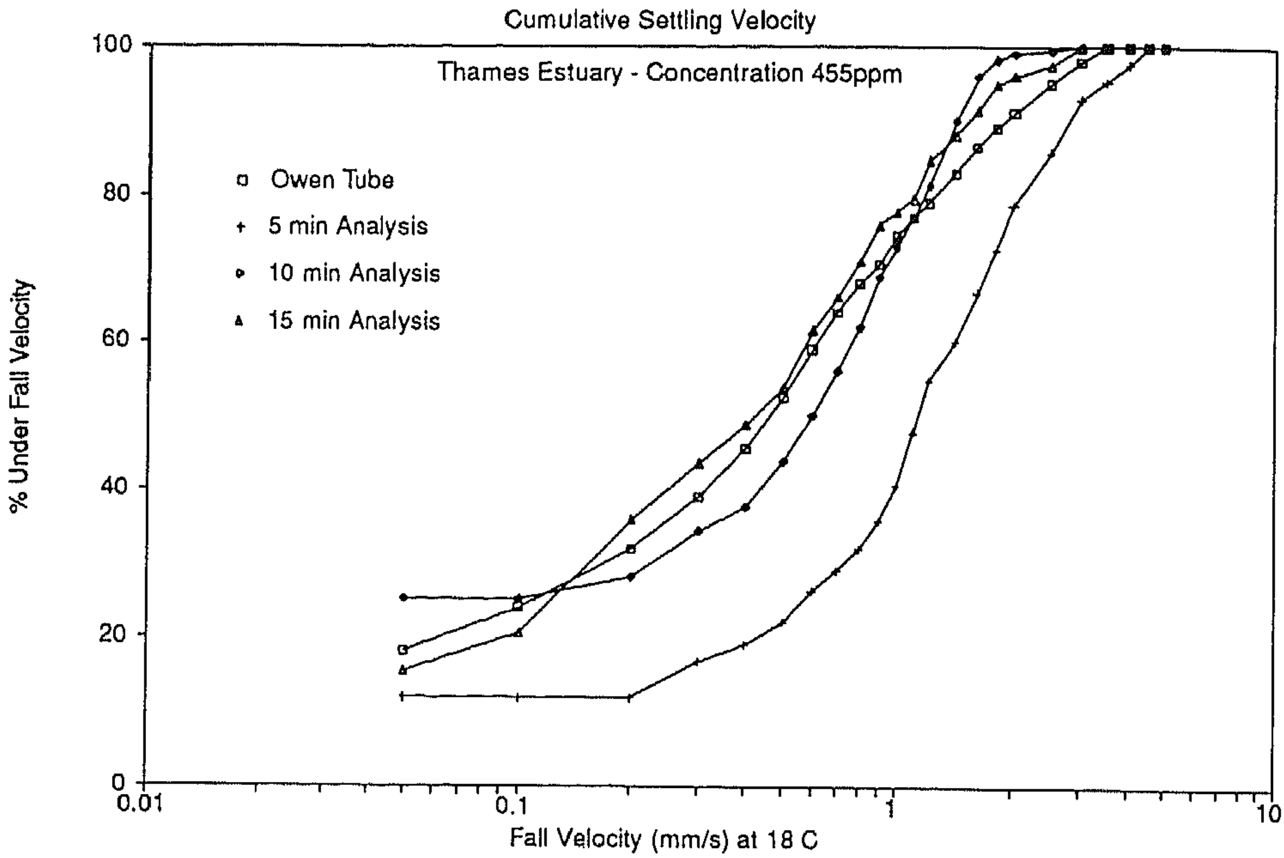


Fig. 1. Comparison of settling velocity from Owen tube measurements (□) and video image analysis (+,♦,△) (*HR Wallingford*).

the latter reason the Owen tube results, based on measurements over 60 minutes, similarly give lower settling velocities. In both techniques the natural turbulence levels are eliminated, which may alter the aggregate dynamics, introducing an other possible source of error.

For bed samples, apart from the techniques described above, which also can be applied in the laboratory, two other instruments are often used to measure the distribution of settling velocity of bed samples. The sedigraph is a settling tube which measures the attenuation of an X-ray beam, due to the presence of falling particles, as a function of time and height. The suspension should be dispersed, i.e. deflocculated (see below) and the sediment concentration should be fairly high, i.e. about 30 kg/m$^3$.

The sedimentation balance is a small settling tube (typically a few dm long) with a balance at its bottom enabling the weighing of the accumulated sediments. Because of its limited length it can only be used for sediment with a settling velocity of about 1 mm/s or lower and the initial concentration should be of the order of 0.3 to 1 kg/m$^3$. The settling velocity follows from the accumulated weight on the balance using Oden's equation. This was elaborated by Kranenburg (1992). He determined the required filter time of the experimental data to account for random errors during the measurement, allowing the empirical curve to be smoothed as a function of the measuring and sampling time to obtain a required accuracy.

*Grain size distribution*

The grain size distribution of bed samples can also be measured directly with either a Coulter Counter or laser-diffraction techniques (Peters Rit et al., 1987). In a Coulter Counter, particles dispersed in an electrolyte are entrained through a calibrated orifice, resulting in local changes in the resistivity of the suspension. It is obvious that the aggregate structure of the sediment is severely affected in a non-controlled way; this method is therefore not recommended to be used for cohesive sediments.

Various instruments are available that are based on laser-diffraction techniques, such as the Malvern, Fritsch and Cilas-Alcatel Particle Sizers and can be used for particle sizes ranging from 1 to 800 $\mu$m. This technique is based on the principle that light diffraction increases with decreasing particle size. A laser beam passes through the suspension to be studied and the diffracted light passes through a lens and is monitored with semi-circular photo-diodes. The deconvolution of the measured diffraction pattern is done with the Fraunhofer or the Lorenz–Mie model (for small particles). These kind of instruments are expensive, but a major advantage is that they are easily operated. However, several severe limitations exist: the particles are assumed to be spherical, their accuracy for smaller particles (say below 5 to 15 $\mu$m) is poor and problems arise with well sorted sediments containing clay (particle size $d<2$ $\mu$m), silt ($2<d<63$ $\mu$m) and sand ($d>63$ $\mu$m). During experiments with fine grained sediment with a known grain size distribution, the amount of particles $<2$ $\mu$m was underestimated by more than 80 %, and the amount of particles $<16$ $\mu$m was under-estimated by about 40 %. Also for coarser sediment the accuracy of the instrument is limited. Another parameter that affects the results is the so-called obscuration parameter, a measure of the turbidity of the sample, which can be related to the sediment concentration. This is shown in Fig. 2 for natural sediments from the Eems–Dollard. More information and comparison with other instruments is given by Singer et al. (1988) and McCave et al. (1986). In spite of all its limitations, this measuring technique is still very valuable, and it is especially recommended to be used for intercomparison and to study changes in grain size distribution. A well documented standard procedure is essential to obtain meaningful and reproducible results.

An important item is the treatment of the sample. Various procedures are described in literature (e.g. Singer et al., 1988; Stein, 1985). The purpose of such treatment is to disperse the sample, i.e. to break up the aggregates of the sediment and to remove the organic compounds. Removal of organic compounds from wet samples can be done by oxidation with hydrogen peroxide

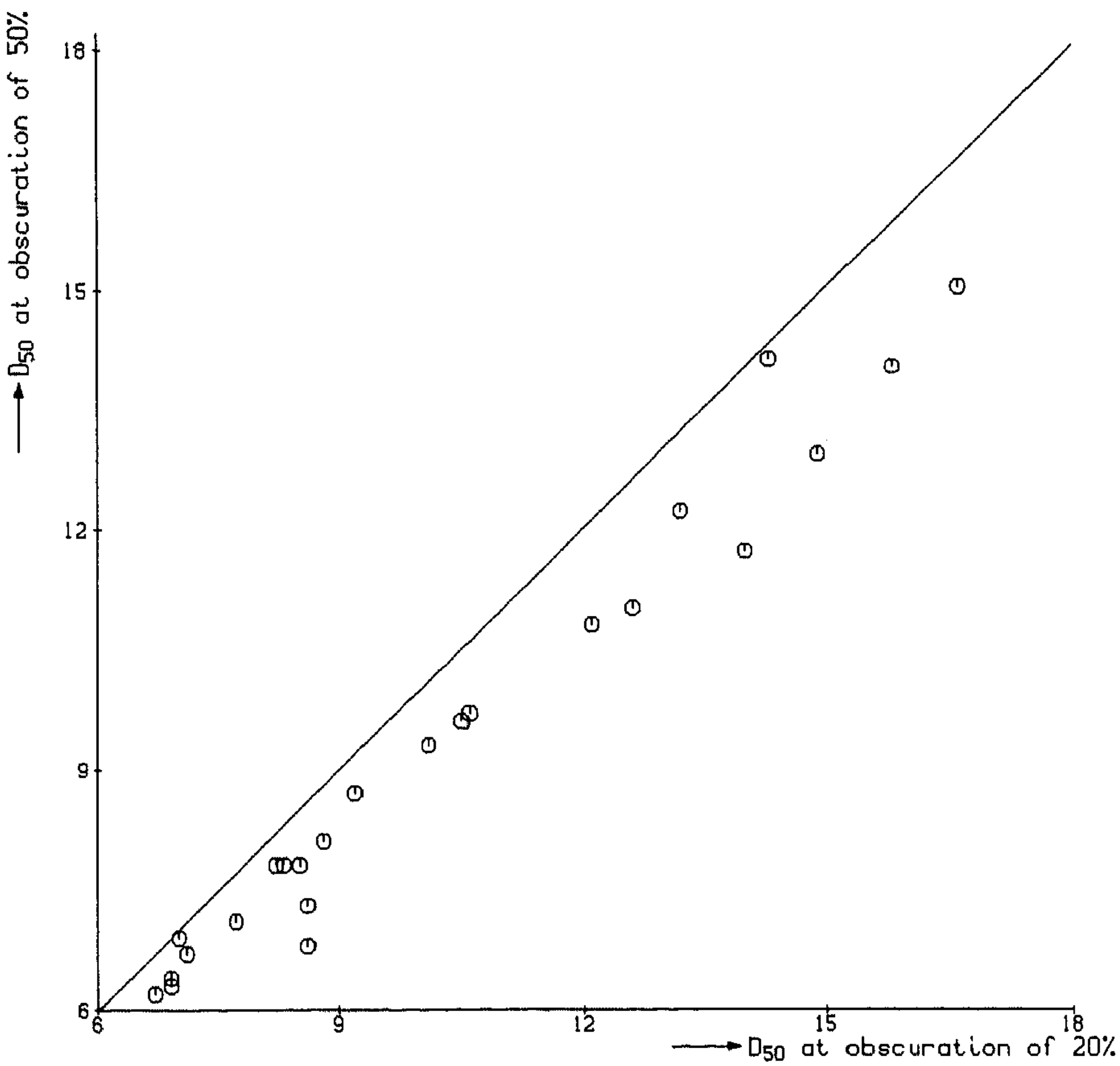


Fig. 2. Malvern particle size measurements: effect of sediment concentration on the median particle diameter $D_{50}$ (in $\mu$m) for Eems–Dollard mud (Kuijper et al., 1991).

($H_2O_2$); this is a common procedure. The break-up of aggregates can be done mechanically with an ultrasonic stirrer. The sample should be stirred for about 5 to 15 minutes. Often a deflocculant is added to the sample (e.g. sodiumpyrophosphate and EDTA, the latter to prevent the reaction between calcium ions and the phosphate). However, this procedure is likely to bias the results (Fig. 3).

A final remark concerns the way a sample is put into an instrument. For instance the measuring chamber of the Malvern particle sizer is very small and only little sediment is added. If a pipette is used to take the sample from a larger sample, probably only the finer fraction will be taken. That procedure should also be standardised.

Clearly all methods described have some drawback and it can be concluded that none of these methods give the actual particle (aggregate) size for cohesive sediments. Standardisation of the techniques however can give useful results for the characterisation of the sediment and/or intercomparison. The

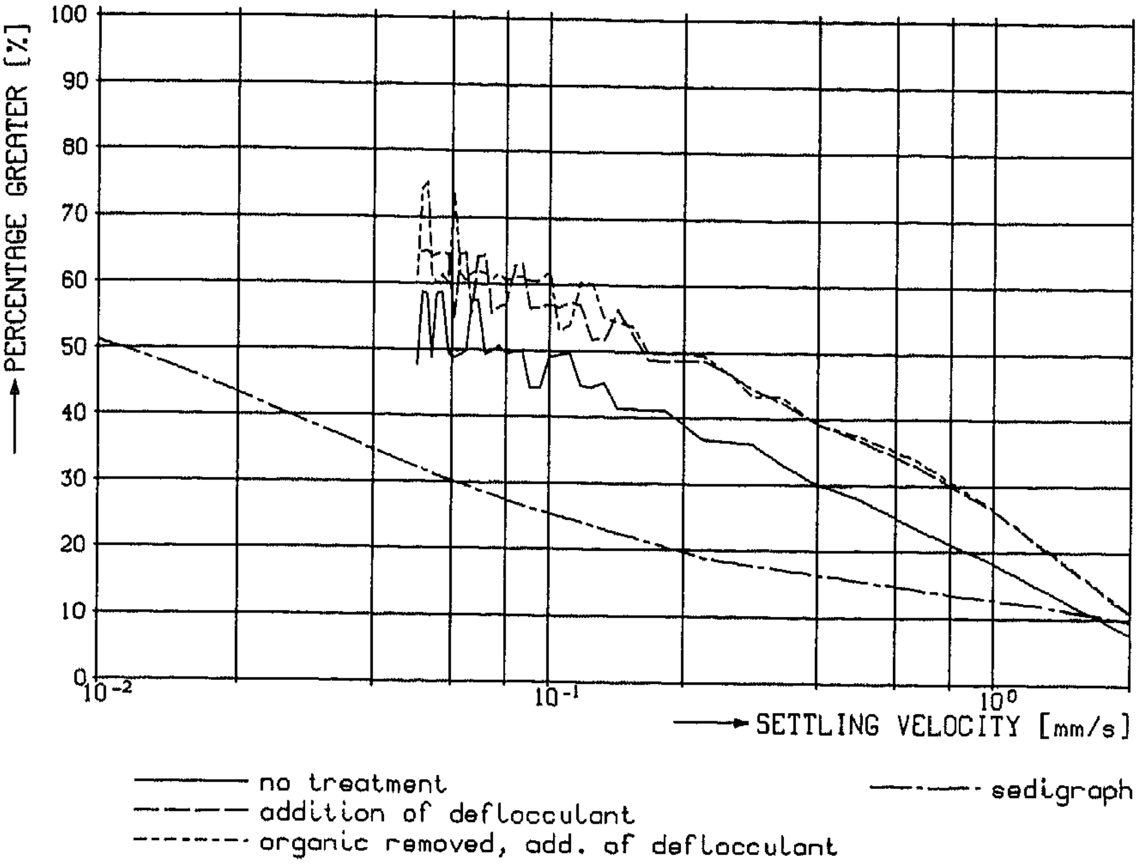


Fig. 3. Sedimentation balance: effect of deflocculant (4 g/l sodium pyrophosphate + 30 mg/l EDTA) and organic matter on Eems–Dollard mud (1 g/l). Note the increase of settling velocity after treatment, while a decrease is expected. Comparison with sedigraph measurements (Kuijper et al., 1991).

actual particle (aggregate) size distribution can only be measured using (in-situ) photographic and/or video systems, as described in the previous section.

## CONSOLIDATION PARAMETERS

When modelling morphological changes of a river or a sea bed, the degree of consolidation of the bed must be predicted since it controls the bed level variations and the initiation and rate of erosion (Teisson et al., 1993). Consolidation rates can be predicted if the variation of **permeability** (the water flux through a unit gross cross sectional area) and **effective stress** (the part of the normal stress supported by the solid particles, i.e. total stress minus pore water pressure) with time are known. None of these parameters is a simple function of the mud composition or density since they are affected by the history of the bed. Therefore these characteristics should be determined empirically.

The consolidation of mud deposits can be monitored in the field by measuring vertical density profiles at regular intervals, with either a nuclear transmission, a backscatter, an acoustic or a conductivity probe. Nevertheless, the consolidation behaviour of a cohesive sediment is usually studied in the laboratory where the environmental conditions are much better under control.

*Settling column experiments*

Consolidation tests are carried out in a settling or consolidation column, the general set-up of which is shown in Fig. 4. It basically consists of a vertically mounted cylinder, made of transparent material (glass, PVC or plexiglass), provided with an X-ray- (Been, 1981) or a gamma-densimeter (Crickmore et al., 1990) to monitor density profiles, and with pressure taps to measure pore pressure with piezometers or pressure gauges.

The column is filled with the sediment either by pumping or by introducing the sediment from the top into a column filled with (saline) water. Depending on the initial bulk density $\rho_o$, either settling and consolidation ($\rho_o$ < critical gel density, i.e. the density where a continuous structure is formed, $\rho_g = \pm 1090$ kg/m$^3$) or only consolidation ($\rho_o > \rho_g$) is studied.

During the consolidation test, which may last for a few weeks or even

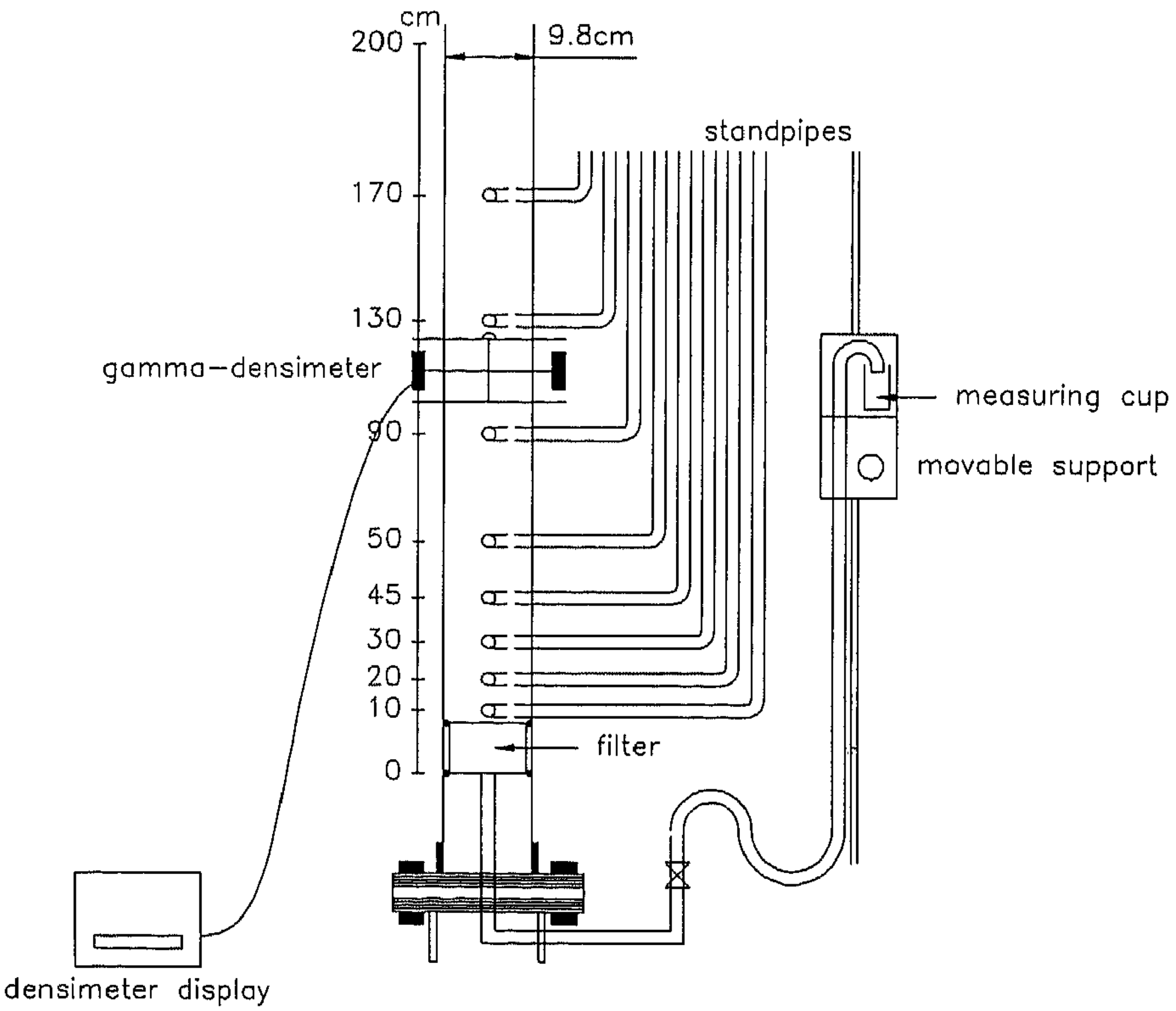


Fig. 4. Settling column experimental set-up (Berlamont et al., 1992).

months, the following features are recorded: (1) the mud–water interface level as a function of time (Fig. 5); (2) density profiles; and (3) pore pressure profiles (Fig. 6). The total stress can be calculated by integrating the density profiles from the interface to the required depth. At the base of the column the total stress can also be measured by a pressure transducer.

The results of the tests (and thus their repeatability) are very much influenced by the sample treatment and by the actual test conditions. The sediment must be adequately homogenised before being introduced into the column. In some laboratories the sand fraction is removed from the sample before

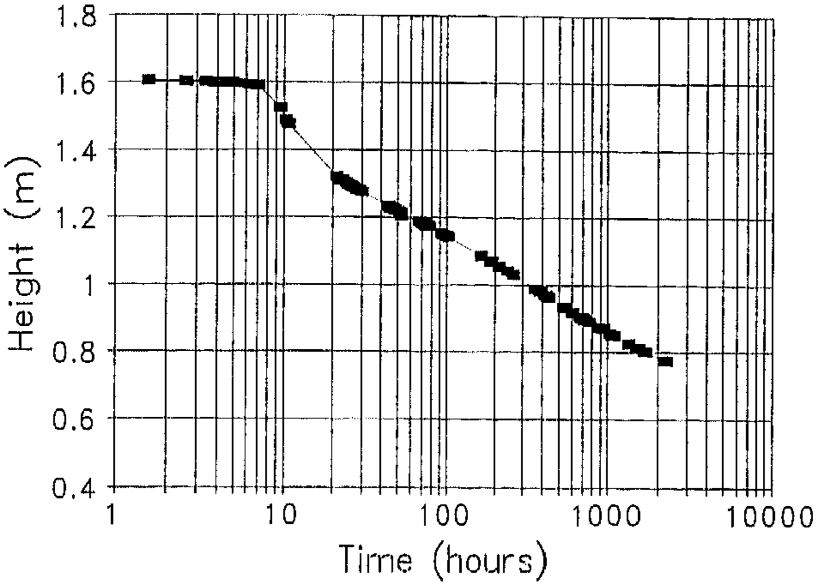


Fig. 5. Consolidation curve of River Scheldt mud. Initial density = 1095 kg/m$^3$; initial height = 1.602 m (Hydraulics Laboratory, K.U. Leuven).

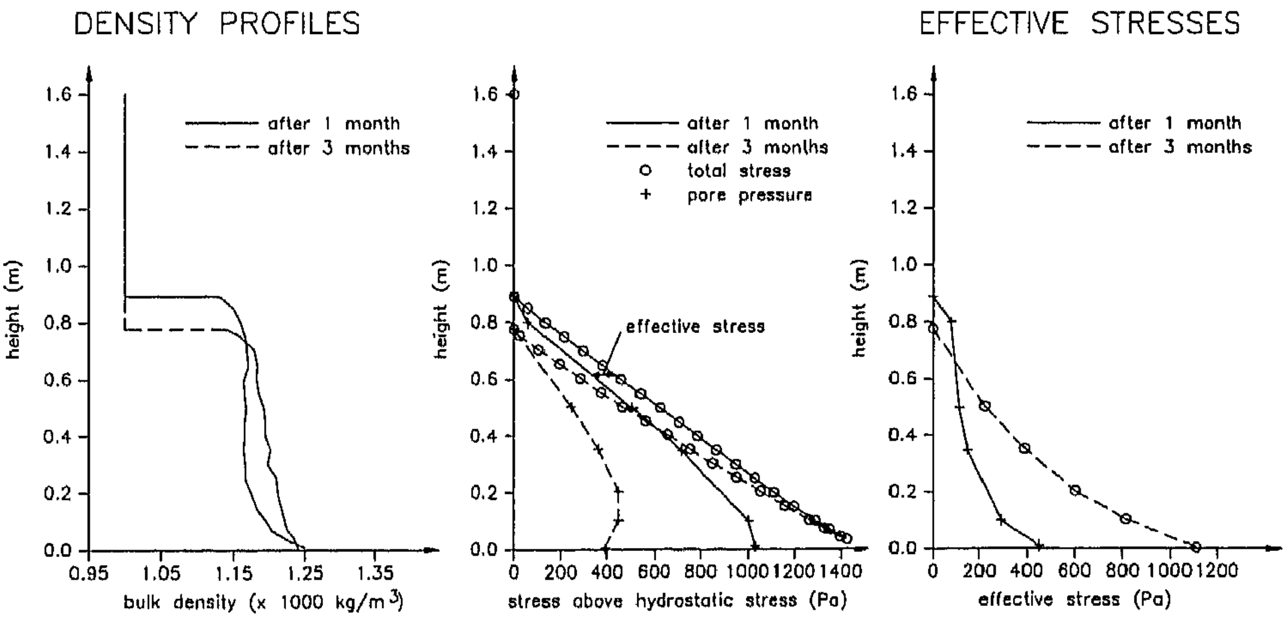


Fig. 6. Density and effective stress distribution in a settling column. Same experiment as Fig. 5 (Hydraulics Laboratory, K.U. Leuven).

the test. The filling technique may influence the results. The salinity of the sample and the water into which it is poured must be correctly adjusted (and identical to the expected field conditions). The temperature should be kept constant. The set-up can be located in a dark room to avoid possible effects of light on the organic material which might bias the test results. Whether the column diameter and the initial height of the mud sample influence the results is less clear. Most often an internal diameter of about 100 mm is chosen but apparently it can be reduced to 50 mm without affecting the results (Bowden, 1988; Migniot and Hamm, 1990). The initial height of the sediment is usually between 0.25 and 3.00 m. A height of 1 to 2 m is common, but 0.18 m and 10 m have also been used. It is advisable to de-aerate the mud sample before the test by applying a moderate vacuum.

*Permeability and effective stress*

The measurement of the permeability ($k$) of mud is done by assuming the validity of Darcy's law (Bowles, 1979). When the sample has approximately a uniform density, time history and structure, the water flow rate can be estimated by observing the lowering of the mud water interface and an average permeability can be calculated. When the local discharge is to be measured, it has to be derived from the solids mass flow through the given cross section by comparing successive density profiles. Sometimes columns drained at the bottom have been used in order to obtain higher densities and corresponding values of the permeability (Berlamont et al., 1992). However, the large pressure gradients, particularly at the beginning of the drainage process, may result in a different structure of the bottom layers.

Permeability measurements are subject to some reservations. In the procedure sketched above, it is assumed that there is a unique relationship between permeability and density. There is some indication however that the permeability of a mud deposit depends on the structure of the mud layer, and thus its time history, i.e. how a mud with a given density has been obtained (e.g. after a settling process and consequently a slow consolidation, or after a shorter consolidation of an initially denser mud) (Toorman, 1992). The accuracy of measuring the local slope of the piezometric line ($\mathrm{d}h/\mathrm{d}x$, which is of the order of 10 mm per 10 cm at the start of an experiment with $\rho = 1100$ kg/m$^3$) depends on the accuracy of the measurement of a very small difference of two piezometric heads ($\pm 2$ mm on $\mathrm{d}h$). In addition, the measurement of the very small mass flux is limited by the accuracy of the gamma-densimeter used (1 to 3 %, 10 to 30 kg/m$^3$). Typical values of permeability range from $10^{-4}$ to $10^{-10}$ m/s, depending on concentration, sediment composition and structural history (Teisson et al., 1993).

The effective stress $\sigma'$ is obtained as the difference of the total stresses $\sigma$ (obtained from the density profiles with an accuracy of 1%) and the pore water pressure (Fig. 6). The value of $\sigma'$ is of the order of 1 to 5% of the total stress $\sigma$ (depending on consolidation time and density) which is of the same magnitude as the accuracy on $\sigma$. In the case of drained columns $\sigma'$ is 1 to 50% of $\sigma$. Therefore, the error on $\sigma'$ may be large, even up to 100%.

## RHEOLOGICAL PROPERTIES

The rheological properties of mud characterise its resistance to flow, deformation and structural changes. They are important for the estimation of sensitivity to fluidisation and erodibility, damping of turbulence and the prediction of density currents and fluid mud flow.

Because of the direct relationship between rheology and structure of mud the same parameters which influence the strength of the aggregation bonds also affect the rheological parameters. These parameters are (Verreet and Berlamont, 1989): sediment concentration, salinity, mineralogical composition, organic matter content, pH and redox potential.

Rheometry for dense cohesive suspensions is extremely difficult and no standardisation exists at present. The lack of reliable data for high concentration suspensions, particularly at low shear rates, has stimulated the use of computer simulations of flow problems in order to find the proper rheological model and to calibrate it (e.g. Toorman, 1992). However, currently this method too is limited by a lack of experimental data to verify the model, because the measurement of velocities in highly concentrated suspensions, necessary for validation and calibration of the model and its parameters, is still difficult.

### *Rheometry for mud*

The flow behaviour of mud is studied in 1D shear flow experiments. The flow curves can be obtained using rotational or capillary viscometers. The most commonly used rheometrical device is the concentric cylinder (or Couette) viscometer. The torque on the inner cylinder, which is proportional to the shear stress ($\tau$) at the cylinder wall, is measured as a function of the rotation speed, which is assumed to be proportional to the shear rate. A typical experimental flow curve is shown in Fig. 7. The apparent dynamic viscosity ($\mu$) is obtained as the ratio of shear stress to shear rate intensity (which for 1D shear flow equals the velocity gradient). The experimental data show that mud is a **visco-plastic** (i.e. **shear thinning**) fluid, which is typical for a flocculated suspension. When a gel is formed (at a volume fraction $\phi_g$=3–7%), a **true yield stress** is observed, which is a measure of the strength of the structure. Below the gel point it behaves as a dilute suspension. As a consolidated soil it has visco-elastic properties.

The rheometrical techniques for yield stress fluids suffer from several seri-

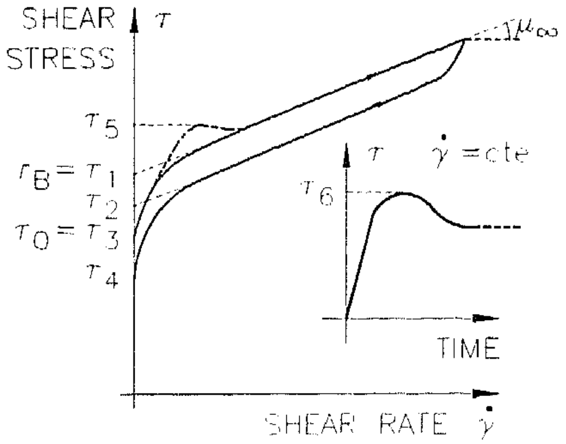


Fig. 7. Typical flow curve of mud. Different possible definitions of yield stress: Extrapolation of the up- or down-curve (upper or Bingham yield: $\tau_1$ and $\tau_2$; lower yield: $\tau_3$ and $\tau_4$). Stress peak values: dynamic ($\tau_5$ — Kuijper et al., 1991) or static, at the lowest shear rate ($\tau_6$ — Migniot, 1968; Migniot and Hamm, 1990).

ous problems (Nguyen and Boger, 1992). The determination of the true shear rate requires the knowledge of the exact velocity profile, which can only be calculated having the correct rheological model. Since the best model is not yet known, the rheological data are presented assuming a certain velocity profile. Consequently, data from different rheometrical configurations cannot be compared quantitatively.

For low concentration suspensions inaccuracy may result from sedimentation and, at high rotation speeds, turbulence or Taylor vortices. With increasing sediment concentration and decreasing shear rate slip occurs at the wall, making the reading totally erroneous. Moreover, the accuracy for low shear rates is poor, even for Newtonian fluids (error $>30\%$). Consequently, the data for cohesive suspensions at shear rates $<1\ s^{-1}$ are unreliable for this equipment. As a result of these problems the narrow gap Couette viscometer cannot be used at low shear rates for high concentrations ($C>160\ kg/m^3$).

The problem of wall slip can be overcome by replacing the inner cylinder by a vane (Gularte et al., 1979; Nguyen and Boger, 1983). Another important advantage of the vane is the much smaller disruption of the sample structure during insertion of the vane.

Since shearing of the material results in the break-up of the original structure (liquefaction), the flow resistance decreases. Once at rest, the structure will slowly recover. This is called **thixotropy**. Consequently the magnitude of the rheological parameters changes. For different cycles of increasing and subsequent decreasing shear rate the consecutive flow curves lie below the previous ones. The first up-curve is of the highest interest because it gives the best information concerning the initiation of flow. However, because the initial structure is often unknown and disturbed or remoulded prior to the experiment, the obtained rheological parameters are often lower than the values, expected from in-situ tests or computer simulations. Hence, as a result of thixotropy the interpretation of data is complicated, repeatability is difficult, and standardisation of rheometry for mud, including sample preparation, is required.

Useful data for comparisons of different methods can only be obtained when the sample is continuously sheared until the structure has reached its equilibrium state. The obtained equilibrium flow curve can be parameterised. To take into account the structural break-up the rheological model must be extended with a time-dependent function which contains an additional structural parameter (e.g. Cheng and Evans, 1965). Until now few studies (mainly experimental) have been carried out on the effects of thixotropy of dense cohesive sediment suspensions (e.g. Jones and Golden, 1990) mostly without taking into account its implications on e.g. the rheometry of mud (Toorman, 1992).

New techniques are now being used. The **controlled stress rheometer** deforms the material by applying a constant stress without imposing a shear rate or deformation. Low shear rates (down to 0.005 $s^{-1}$) can be obtained, but few results have been published so far (James et al., 1987; Jones and Golden, 1990). Oscillatory and shear wave propagation tests provide information on elastic properties of a mud bed, which is of importance for the study of wave forcing in shallow waters (Williams and Williams, 1989).

### *Rheological parameters*

Several classical rheological models have been proposed to approximate the flow curves. The oldest and most popular model is the Bingham model, because it requires only two parameters: the Bingham yield stress $\tau_B$ and the Bingham (differential) viscosity $\mu_\infty$.

For sedimentological applications the rheological behaviour should be studied in the shear rate range $\dot{\gamma} < 100$ $s^{-1}$. In this range, the value of $\tau_B$ increases and of $\mu_\infty$ decreases when the maximum applied or measured shear rate is increased. Other models have been used to allow better agreement in the low shear rate range, introducing 1 to 3 additional parameters (for a review, see Toorman, 1992).

For engineering purposes efforts have been restricted mainly to the determination of the Bingham parameters, $\tau_B$ and $\mu_\infty$, and the true yield stress $\tau_o$. These rheological parameters decrease with increasing sand content and increase with sediment concentration according to a power law or as an exponential function (Fig. 8). $\mu_\infty$ is of the order of 0.003 Pa.s for a concentration $C = 100$ kg/m$^3$, roughly doubling for each additional 100 kg/m$^3$. $\tau_B$ varies from approximately 0.1 to 1 Pa, corresponding to concentrations ranging from 50 to 160 kg/m$^3$ and is usually 2 to 10 times higher than the yield stress.

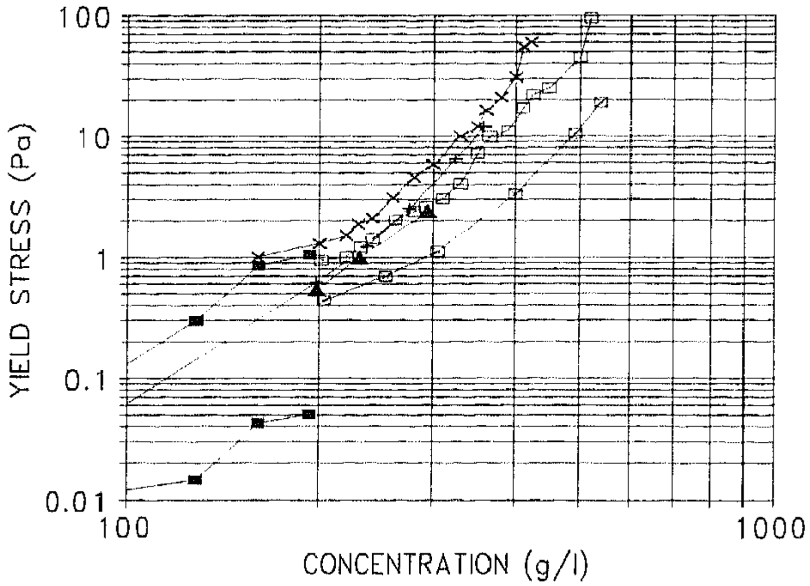


Fig. 8. Measured yield stresses for different muds. (■) Parrett: upper or Bingham and lower yield stress from Jones and Golden (1990); static peak values from Berlamont and Van Goethem (1984): (▲) Zeebrugge and (+) Kallo, and Migniot (1989): (□) Marne, (×) Dunkerque and (⊠) Gironde.

## *Yield stress measurement*

The measurement of the yield stress $\tau_0$ has received much attention, because of the expected correlation with the critical shear stress for erosion, since both are directly related to the strength of the mud layer (Gularte et al., 1979).

However, the thixotropic behaviour makes the determination and even the definition of the yield stress difficult. The concept and value of the yield stress depend on the time scale: the material will always flow, but needs time to adapt to a change in flow regime. At an infinitely small shear rate there ultimately may be no yield stress, only an extremely high viscosity. Different methods are used to determine a measure for the yield stress (James et al., 1987; Nguyen and Boger, 1992), some of which are shown in Fig. 7. Other methods are: (1) calculation of the apparent yield stress from a least squares fitting of a rheological model (Nguyen and Boger, 1983, 1992); (2) stress relaxation: extrapolation of the residual yield stress (after equilibrium has been reached) for different shear rates (James et al., 1987); (3) controlled stress rheometer (James et al., 1987).

Few comparative studies have been carried out until now (e.g. Nguyen and Boger, 1983; James et al., 1987). They reveal that consistent results can only be obtained when the sample has and maintains the same structure, which is very difficult to achieve. As a result of thixotropy the acceleration and deceleration for the continuous recording of a flow curve plays a significant role in the determination of the yield stress (Kuijper et al., 1991).

Field measurements in undisturbed mud are performed using vane testers or a motor driven rotating body, which is calibrated with a Couette viscometer on samples (Galichon et al., 1990). These generally give significantly higher values. Therefore, efforts should be made in the future in order to obtain more in-situ data.

## WATER–BED EXCHANGE PROPERTIES

In order to predict sediment transport, it is necessary to parameterise the source and sink terms for sediment exchange from the bed into and out of the water column. These engineering parameters are the critical shear stress for erosion, erosion rate and critical shear stress for deposition and the previously discussed settling velocity. In general, the more consolidated the bed, the higher the shear stress needed to erode it, and the slower it will erode.

### *Critical shear stress for erosion*

For a mud bed, the critical shear stress for erosion, $\tau_e$, is defined as the value at which sediment begins to be eroded from the bed. This has generally been found to be related to the density of the material. Most laboratory erosion tests are carried out on beds which have been deposited or placed from a suspension or remoulded slurry — the tests are to simulate erosion of recent deposits. It is difficult to reproduce sediment beds in the laboratory without significantly changing the physical, chemical or biological characteristics. Some laboratory tests are carried out on "undisturbed" samples, i.e. surface samples brought back and placed in a flume. However, it is difficult to collect and transport such samples without affecting some of the important properties. Therefore it has been recognised that it is also important to develop techniques for measuring erosion and deposition in-situ in order to complement laboratory studies.

Several instruments for measuring the in-situ erosion of sediment have recently been developed, or are under development. This includes SEAFLUME (Young, 1977; Young and Southard, 1978) and its later modifications (Gust and Morris, 1989), a straight flow-through flume which must be deployed under water. The Sea Carousel (Daborn, 1991) is an annular flume with an open base which sits on the sea bed. The operation is very similar to the operation of an annular flume in the laboratory, except that sealing the flume at the rotating roof becomes important. Smaller instruments have also been tried (Wilkinson and Jones, 1989). It is recognised that this is an area where more research is needed, as the biological influences which affect the erodibility of the mud can be a very important factor in the change of the erosion characteristics.

In the laboratory, erosion tests can be run in a straight flume which is not recirculating, a straight flume with recirculating flow, or an annular flume.

Descriptions of the flumes and test procedures are given in detail in the MAST report (MAST G6M, 1992).

With straight flumes, the mud beds can be deposited from suspension, placed as slurries or brought "undisturbed" from the field. If the discharge is increased in steps, the determination of incipient motion can be rather arbitrary (often by visual observation) and depends on the rate of increasing the discharge and on the interpretation of the person doing the experiments. Because the volume of these flumes tends to be very large it is more difficult to determine erosion rates from the rise in suspended sediment concentration, because of the length of time for complete mixing of the sediment and because of the small changes in the overall suspended concentration.

Erosion roughens the sediment surface and the position of the surface is no longer exactly known. This causes uncertainties in methods for calculating bed shear stress, either in calculating a reference level where the velocity is zero (for use in a velocity profile), or in calculation of the hydraulic radius. Sensitivity analyses were carried out at KUL (Kabir and Torfs, 1992) on a whole range of experiments with fixed and movable beds, both hydraulically rough and smooth. Two methods of calculating the bed shear stress were compared: (1) from the velocity profile ($\rho u_*^2$, $u_*$=shear stress velocity) and (2) as $\rho gRS$ ($R$=hydraulic radius corrected for wall effects and $S$=slope). Changing the bed level by 2 mm induced 50% of error in method (1) but only 4% in method (2). The latter seemed thus less sensitive to changes or uncertainties in the bed level.

Annular flumes can be used to measure the erosion properties of a deposited mud bed under uni-directional currents. Because of the circular nature of the flume, secondary flows are set up within the flume. This is reduced by having a large diameter or by rotating the roof and channel in opposite directions. The optimal ratio of the angular velocities of the upper lid and the channel is also a function of the water depth. Suspended sediment concentrations are measured continuously by pumping a sample through a densimeter and by drawing off discrete samples. The shear stresses in annular flumes are inferred from the roof (and channel) rotational speeds, as a result of previous measurements using lasers, velocity profiles, shear stress probes or numerical modelling (Karelse, 1989; Graham, 1989). All these measurements of shear stress have been made in clear water. Suspended sediment may have a damping effect on the shear stress, and this is being studied further (see Teisson et al., 1993). However, the effect is thought to be small for low concentrations ($< 2$ kg/m$^3$).

The end effects of a short test section are eliminated in an annular flume. Suspended sediment concentrations in the flume become well mixed very quickly, and hence reflect the amount of erosion.

A test consists of several runs, increasing the shear stress in steps, then holding until no further erosion is observed. At this point, the mud has eroded down to a level where the shear strength of the mud is equal to the applied shear stress. The density of the material eroded can be calculated from the concentration in suspension and the depth of erosion, resulting in an empirical relationship between shear strength and density (Fig. 9).

Typical values for critical shear stress for erosion of soft estuarine muds measured in laboratory tests are in the range 0.1–2 Pa. Kuijper et al. (1989) noted that erosion of mud beds in a straight flume appeared to be more severe than in an annular flume with similar mud beds and velocities. This emphasises the difficulty in using laboratory experiments to simulate field processes.

## *Erosion rate*

The erosion rate of a bed determines the local suspended sediment concentration, and thus how much sediment is available for tranport and deposition elsewhere. Erosion rate is usually calculated from the increase in sediment in suspension during an erosion test, and is generally related in some way to the excess shear stress (Teisson et al., 1993).

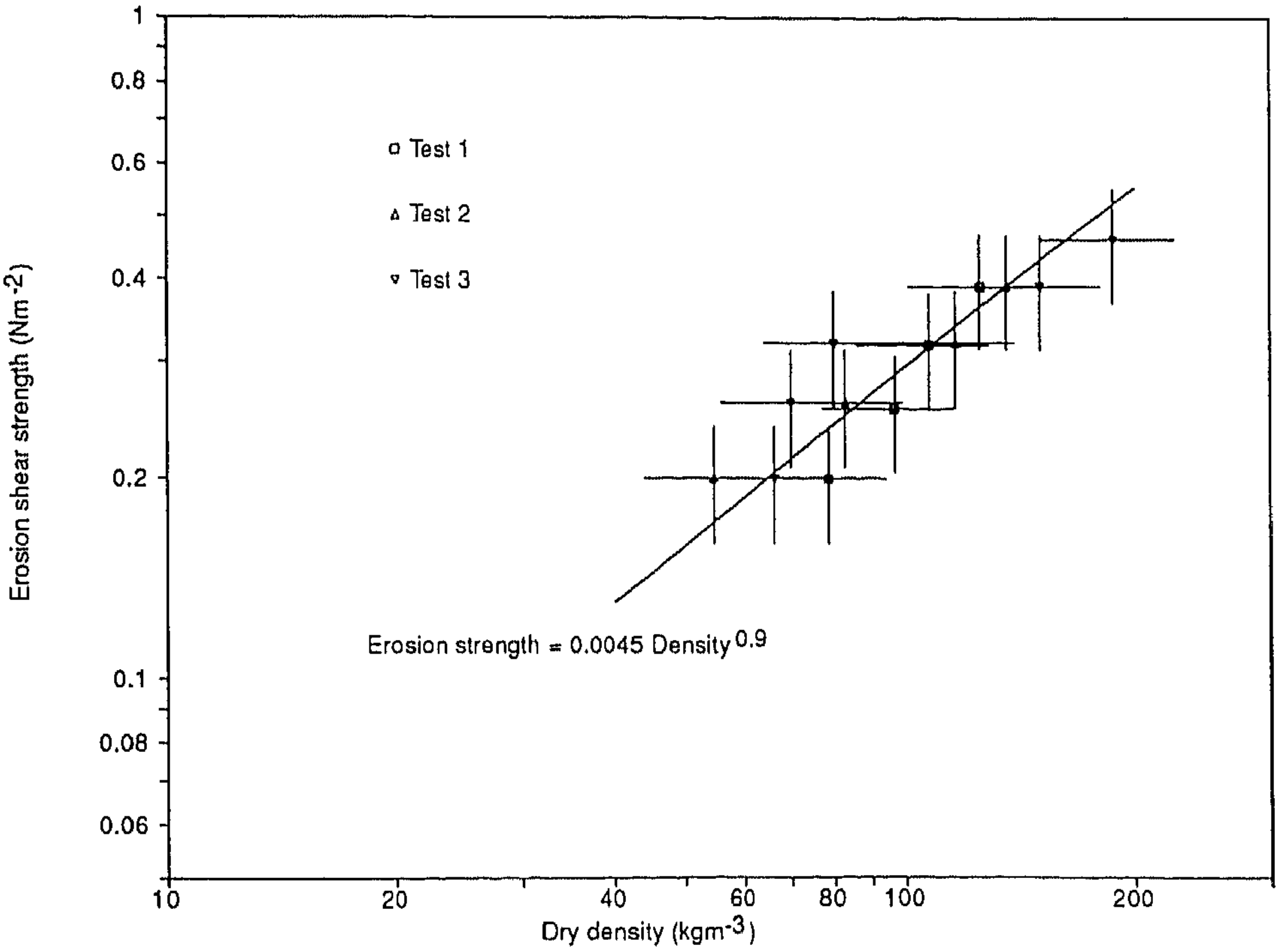


Fig. 9. Erosion shear strength as a function of the density of the eroded layer. Mud from Grangemouth, Scotland (HR Wallingford).

*Critical shear stress for deposition*

For cohesive sediment suspended in flowing water, there exists a certain low value of the bed shear stress, $\tau_d$, below which all sediment will eventually deposit from suspension. For a uniform sediment, all sediment will remain in suspension above this critical shear stress, but for a distributed sediment some particles (the larger or heavier flocs) will deposit at shear stresses above the critical shear stress.

In order to avoid the break-up of flocs by a pump in a recirculating flume, deposition tests are generally run in annular flumes where the flow is generated by rotation of the roof or rotation of the roof and channel. For a deposition test, the concentration in suspension in the flume is in the range likely to be found in the field, typically less than 2 kg/m$^3$.

A typical deposition test consists of running the Carousel at high speed, to mix all the mud into suspension, and then dropping the roof rotation speed (or relative roof/channel speeds) very quickly to a lower value (and hence lower shear stress), which is then held constant for around 24 hours. The shear stress may then be reduced by further discrete steps. At each step, material deposits quickly at first, then more slowly, eventually reaching an equi-

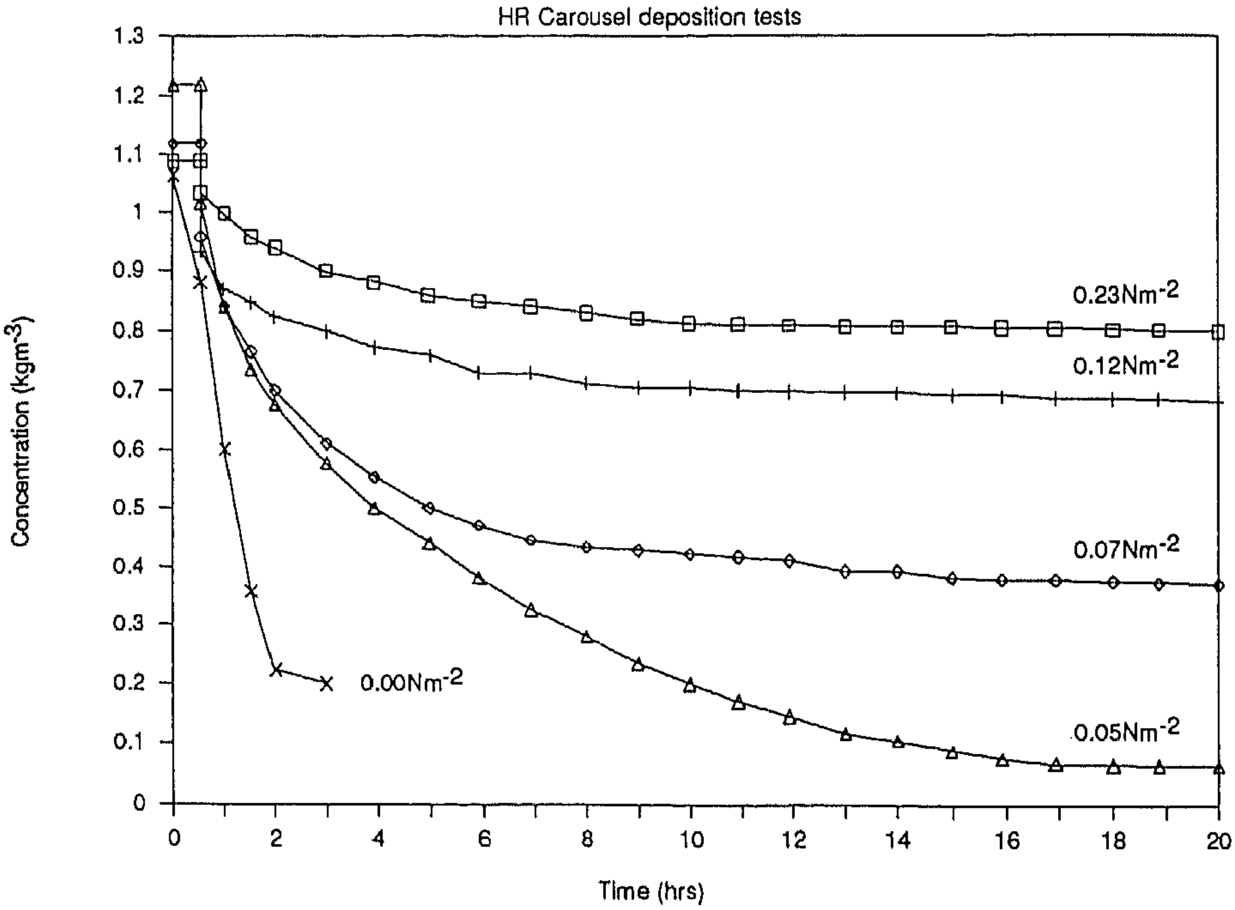


Fig. 10. Concentration of suspended sediment as a function of time for different bottom shear stresses (HR Wallingford).

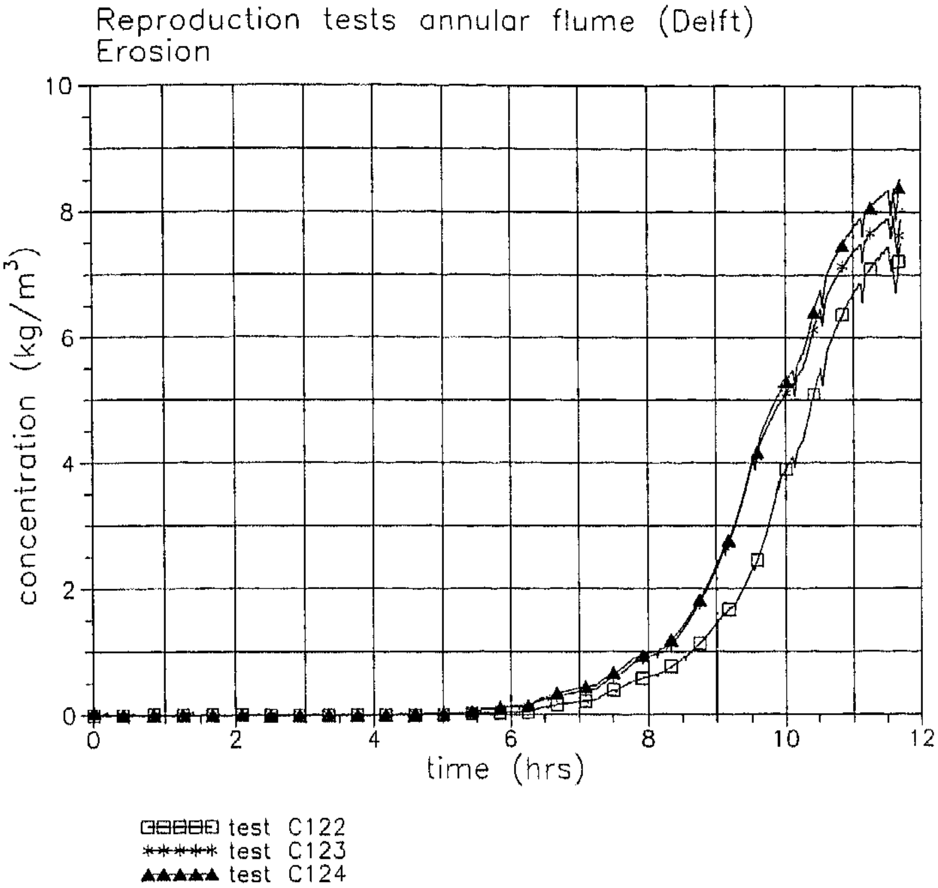


Fig. 11. Measured concentration evolution during a reproducibility test for erosion in an annular flume (Jong, 1991).

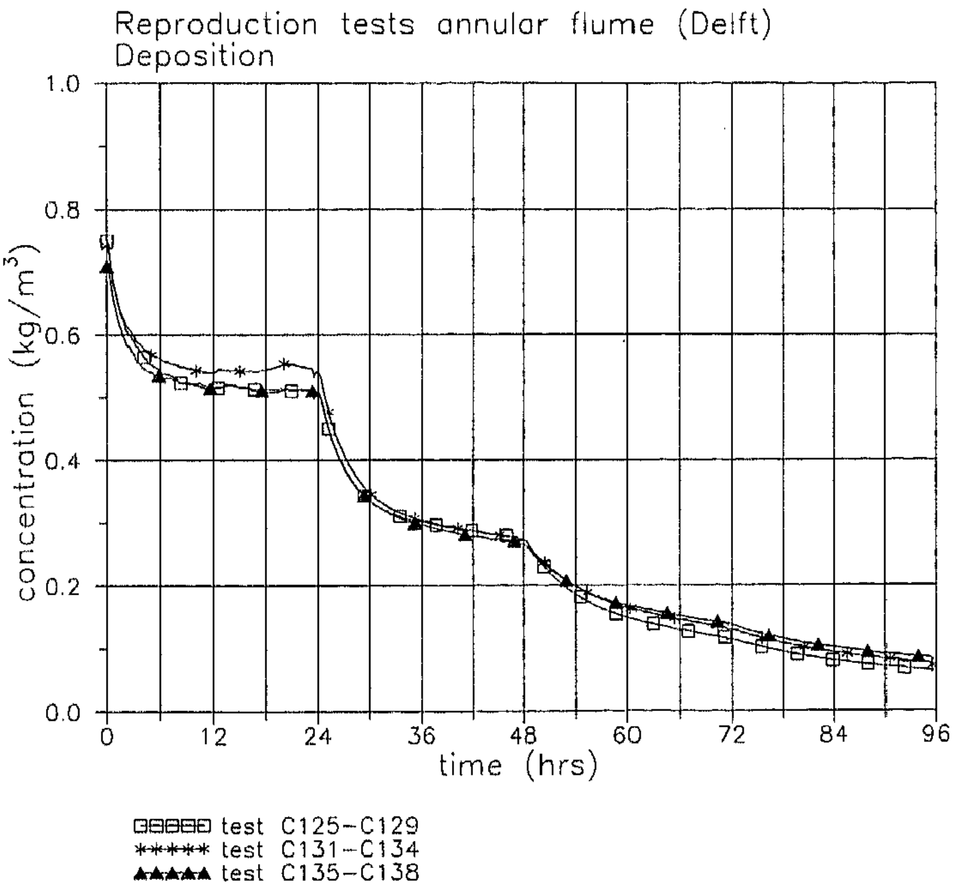


Fig. 12. Measured concentration evolution during a reproducibility test for deposition in an annular flume (Jong, 1991).

librium. It has been found (e.g. Mehta and Partheniades, 1973) that the ratio of the initial concentration to the final concentration is independent of the initial concentration, and is a function of the bed shear stress.

Fig. 10 shows the concentration in suspension during a series of deposition tests starting from approximately the same concentration, but reducing the shear stress to different values. A minimum critical shear stress for deposition of around 0.05 Pa is indicated for this mud. The critical shear stress for deposition of the whole sediment is usually in the range 0.05–0.2 Pa. For a distributed sediment, some larger aggregates will generally begin to deposit at higher shear stresses of 0.2–1 Pa.

The reproducibility of the annular flume and the methodology of working was tested at Delft Hydraulics in erosion and deposition tests using China Clay (kaolinite), starting from the same initial conditions. The results are shown in Figs. 11 and 12. Though some small differences are observed, the general conclusion is that the annular flume and the methodology of working produce repeatable results. Secondary flows may have an important role in the deposition process. However the annular flume has proved to be a useful apparatus for giving a quantitative feeling for the erosion and deposition properties of fine grained sediments.

## CONCLUSIONS

In order to predict sediment transport for engineering purposes, mud needs to be characterised by a few comprehensive parameters which can be used in numerical models. Because of the complex nature of cohesive sediment, many physical, chemical and biological factors affect its behaviour. Discussion within the MAST G6M Project 4 has highlighted the difficulty in choosing the most important parameters, and in measuring them in a way which allows comparison with measurements made elsewhere. Methods for measuring any one parameter are very diverse, and, where comparisons exist, may yield quite different results.

An initial list of 28 parameters has been identified, and methodology, repeatability and accuracy have been discussed. A detailed report (MAST G6M, 1992) contains descriptions and comparisons for all these parameters. Wherever possible, parameters should be measured in-situ, as transport of the sediment to the laboratory significantly changes some properties. Succesful methods are being developed for measuring the settling velocity of the flocculated sediment in the field. The need for measuring the shear strength of the sediment in-situ has been recognised, although laboratory measurements have given a qualitative understanding of the behaviour. Annular flumes have shown reasonably repeatable tests for erosion and deposition. It is hoped that this paper and the report will be a starting point for discussion to bring about standardisation of the procedures and techniques.

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## APPENDIX. LIST OF PARAMETERS USED IN THE MAST-1 G6M PROJECT TO CHARACTERISE MUD

*Physico-chemical properties of the overflowing fluid*
1 chlorinity
2 temperature
3 oxygen content
4 redox potential
5 pH
6 Na-, K-, Mg-, Ca-, Fe-, Al-ions
7 sodium adsorption ratio
8 suspended sediment concentration
*Physico-chemical properties of the mud*
9 chlorinity
10 temperature
11 oxygen content
12 redox potential
13 pH
14 gas content
15 organic content
16 Na-, K-, Mg-, Ca-, Fe-, Al-ions
17 cation exchange capacity (CEC)
18 bulk density (density profile)
19 specific surface area
20 mineralogical composition
21 grain size distribution and sand content
*Characteristics of bed structure*
22 consolidation:
(a) consolidation curve and density profile
(b) permeability

(c) pore pressure and effective stress
23 rheological parameters:
(a) upper and lower yield stress
(b) Bingham viscosity
(c) equilibrium slope of mud deposits
24 Atterberg limits (liquid and plastic limit)
*Water–bed exchange processes*
25 settling velocity (in laboratory and field):
(a) as a function of sediment concentration and floc density
(b) as a function of salinity
26 critical shear stress for deposition
27 critical shear stress for erosion
28 erosion rate

This is a tentative list, resulting from the combination of the different lists used by the participants to the MAST G6M Cohesive Sediment Project. Some parameters are interdependent.

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