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Devices to measure settling velocities of cohesive sediment aggregates: A review of the in situ technology

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Abstract

Suspended cohesive sediments in coastal water bodies occur mainly as amorphous aggregates of single particles and microflocs. The fragile nature of these aggregates demands that their settling velocities be measured under field conditions to minimise their disruption. This review presents the main devices available to measure settling velocities of cohesive sediments in situ. These include hand-operated settling tubes and automated settling columns equipped with video systems, optical and laser instruments and an underwater balance. Additionally, non-intrusive techniques can be used, such as holographic and acoustic backscatter sensors. Regarding their operational principle, these in situ devices can apply direct or indirect methods for computing the settling velocity distribution in terms of particle size, mass or concentration. These devices are briefly described emphasising some important logistical and scientific issues that arise when these instruments are used in the field, in order to facilitate the selection of an appropriate technique for a particular research application. Due to the complexity involved in the in situ settling velocity measurements, a simultaneous application of different types of instruments seems to be the more appropriate approach to understand the aggregate dynamics.

Keywords: Settling velocity; In situ devices; Measurements in the field; Review

1. Introduction

Settling velocity corresponds to the constant velocity at which a particle settles through a static fluid when the resistance of the fluid exactly equals the downward force of gravity acting on the particle. The settling velocity depends on the particle density, shape, size, roundness and surface texture, and on the density and viscosity of the fluid (Krumbein and Pettijohn, 1938; Dietrich, 1982).

For low concentration suspensions of cohesionless particles not subjected to aggregation, the settling velocity of particles can be calculated by theoretically derived expressions, such as the well-known Stokes Law (Stokes, 1851). This equation describes the settling velocity (W_s, m s^{-1}) of small spheres (diameter <0.1 mm) of uniform density settling in the viscous Reynolds number (Re) regime under constant temperature, i.e. when:

$$\mathrm{Re} = W_s d \rho_w / \mu < 1, \tag{1}$$

$$W_s = \frac{g d^2 \rho_e}{18\mu} \tag{2}$$

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where g is the gravitational field strength (m s^{-2}), d is the equivalent spherical diameter of a particle (m), μ is the dynamic molecular viscosity of water (kg m^{-1} s^{-1}) and ρ_e is the excess density (or effective density) equivalent to $\rho_e = \rho_f - \rho_w$ with ρ_f and ρ_w being the sphere/floc and fluid densities (kg m^{-3}), respectively (Stokes, 1851; Krumbein and Pettijohn, 1938; Dyer, 1986).

Assumptions implicit within Stokes Law are rarely met in nature, or even under laboratory conditions, since sediment particles are seldom homogeneous in terms of grain size, shape and density. In addition, cohesive sediments in coastal environments form amorphous aggregates of organic and inorganic particles bound by microbiological activity and electrochemical forces when the particles are brought together by turbulence, differential settling and Brownian motion (Eisma, 1986; Van Leussen, 1988; Eisma et al., 1991). Within marine systems, temporal changes of the turbulence level promote a continuous process of aggregation and disaggregation of flocs (Van Leussen, 1988). Therefore, the settling behaviour of cohesive sediment in coastal waters is complex, depending on a large number of factors and on the interactions between them. These factors are: floc size, shape, roundness, texture, density and organic content as well as the degree of aggregation, inter-particle interactions, the properties of the ambient fluid (viscosity, density and turbulence), and particularly, the suspended particulate matter (SPM) concentration (Owen, 1976; Dietrich, 1982; Burt, 1986; Kranck, 1986; Hamm and Migniot, 1994; Mehta, 1994). The settling velocity of aggregates in coastal systems typically ranges from 10^{-4} to 10 mm s^{-1} for SPM concentrations of 10 to 1000 mg l^{-1} (Berlamont et al., 1993; Dyer et al., 1996).

Flocs generally have a higher settling velocity than their constituent particles (Migniot, 1968). In addition, the presence of large settling particles, such as organic macroscopic aggregates (composed of plankton, detritus and fine inorganic particles) and faecal pellets, has been claimed as important mechanisms for sediment removal from the water column (Van Leussen, 1988; Ayukai and Wolanski, 1997).

The settling velocity of cohesive sediments was first empirically determined in laboratory experiments using natural mud and synthetic aggregates (Owen, 1971; Gibbs, 1985). Over the past few decades, however, studies have shown that aggregate sizes and settling velocities measured in the laboratory can be one or two orders of magnitude smaller than values obtained by in situ techniques, as aggregates are easily damaged when sampled (e.g. by conventional sampling bottles or pumping) and manipulated (e.g. by dispensing suspensions), making it impossible to reproduce natural environmental conditions in the laboratory (Owen, 1971; Burt, 1986; Mehta et al., 1989; Kineke and Sternberg, 1989; McCave and Gross, 1991; Dearnaley, 1996; Manning, 2004). Therefore, an empirical quantification of aggregate settling velocities in situ is essential. As a result, great effort has been made in estuarine and coastal research to quantify the settling velocities of natural aggregates in situ, thus permitting the general behaviour of aggregate sedimentation to be better understood.

Settling velocity quantification has important applications to ecological studies, coastal engineering, navigation planning, water quality and prediction of short- and long-term sedimentation in coastal environments, etc. Moreover, the accurate determination of settling velocities and depositional fluxes is regarded as a top priority to improve cohesive sediment models for estuarine and coastal regions (McAnally and Mehta, 2001). Therefore, improving the empirical method of measuring cohesive sediment settling velocities in the field can increase simulation models reliability and prediction capability to assist management decisions.

1.1. Settling velocity measurements in situ

Devices for measuring settling velocities in situ can be broadly divided into manual and automated and can apply direct or indirect techniques for settling velocity quantification. These devices can also be classified as flow-intrusive or non-intrusive. The device is classified as a manual when most of the water collection and analysis is hand-operated. In contrast, automated devices have a water sampling mechanism, data acquisition system and storage, controlled by a built-in controller and data logger. These devices are significantly less labour-intensive in terms of sampling and water analysis, although they may require considerable effort in post-processing the data to calculate the settling velocity and size spectra. Devices are classified as direct when they do not need calibration to obtain SPM concentrations and the settling velocities or when the calibration is straightforward, while indirect devices require in situ calibration to translate the instrument's signal into SPM concentrations and often use complex algorithms to calculate settling velocities.

Direct manually operated devices include settling columns such as Owen tubes (Owen, 1971; Allersma, 1980; Van Rijn and Nienhuis, 1985; Cornelisse, 1996; Pejrup and Edelvang, 1996; Van Leussen, 1996; Jones and Jago, 1996). Alternatively, settling velocity can be directly measured by using automated settling columns equipped with in situ video cameras (Dearnaley, 1996; Eisma and Kalf, 1996; Sternberg et al., 1996), or more recently, an underwater mass balance (Mantovanelli, 2005). Similarly, indirect techniques include automated settling columns equipped with optical sensors (Murray et al., 1996) or laser beams (Bale, 1996; Agrawal and Pottsmith, 2000). The above devices are usually flow-intrusive since measurements are performed inside a closed settling column or in a confined volume of water. Non-intrusive instruments, however, take measurements in an unenclosed sampling field of several centimetres away from the sensors (e.g. direct holographic techniques) or a few metres away from the sensors (e.g. indirect acoustic backscatter).

Settling columns based on the bottom-withdrawal method were first applied in the laboratory to analyse the settling of small spheres and sediment grains from which the equivalent spherical particles size could be inferred (Office of Indian Affairs et al., 1943; Subcommittee on Sedimentation, 1953; Owen, 1976). In the late 1960s, two field versions of the laboratory settling columns were introduced, including the settling tube developed by Nedeco (1965) and the well-known Owen-tube developed at the Hydraulics Research in the United Kingdom (Owen, 1971, 1976). Such an apparatus, takes a large water sample from the environment by using a sampling tube that acts as a sedimentation column, from which subsamples are manually withdrawn at progressive time intervals to quantify their mass concentrations by gravimetry in the laboratory. These devices were built to collect a water sample in situ, and hence, they take into account the effect of the in situ turbulence in the formation of the flocs and in their settling velocity, as it is very difficult to reproduce the turbulent structure of the natural flow in the laboratory (Owen, 1971; Allersma, 1980). Owen (1971) found that settling velocities measured with field settling columns were up to an order of magnitude higher than those measured in the laboratory using bottom sediments or pumped water samples. Therefore, in situ settling columns represented a major improvement in relation to the laboratory version.

Subsequently, many different kinds of hand-operated settling tubes have been developed or improved (Van Rijn and Nienhuis, 1985; Van Leussen, 1988). Although settling tubes are considered in situ devices for measuring settling velocities, most of their analytical procedures happen in the laboratory or on the ship deck. Recently, a direct in situ quantification of the immersed weight of SPM under still conditions inside a settling tube was made possible through the development of an automated underwater mass balance (SEDVEL, Mantovanelli, 2005). Both the manually-operated settling tubes and the automated underwater balance determine the mass distribution of settling velocity based on the bulk deposition rate of the sediment under quiescent conditions inside a settling column. These instruments do not allow direct measurements of the floc size spectra.

Alternatively, devices equipped with optical sensors have been applied to measure the bulk clearance rate of sediment from the settling column and estimate the settling velocity of flocs (Kineke et al., 1989; Murray et al., 1996). In addition, laser diffraction instruments can provide both floc size and settling velocity spectra (Law et al., 1997; Agrawal and Pottsmith, 2000). Both optical and laser devices present high sampling autonomy (long-term deployments), but they suffer from calibration issues since the translation of the instrument's signal into SPM concentrations depends on many particle characteristics and on the adopted optical coefficients (Renagi, 1999; Agrawal and Pottsmith, 2000; Hatcher et al., 2000; Sutherland et al., 2000).

In the last few decades, video image systems have become very common, because they provide particle-specific information (e.g. size, shape) and allow simultaneous in situ measurements of floc size and settling velocity by imaging floc trajectory in successive time frames (Fennessy et al., 1994; Dearnaley, 1996; Syvitski and Hutton, 1996; Van Leussen and Cornelisse, 1993a, b; Manning, 2004; Manning et al., 2004). Dearnaley (1996) demonstrated that median settling velocities measured by video image analysis were significantly greater than those obtained using an Owen-tube. This fact was associated to floc break-up, reflocculation and water circulation during the sample withdrawal for gravimetric analysis of the Owen-tube method. Therefore, video image techniques represented a comparatively less disruptive system of measuring settling velocities in situ. However, video image techniques for particle size and settling velocity determination only sample a very small volume (in the order of a few millimetres from the optical window) (Dearnaley, 1996) and require complementary SPM mass quantification to obtain the total SPM concentration.

Overcoming the limitation of small sampling volume, holographic techniques are nowadays used in imaging and recording large volumes (up to 10^5 cm^3) of marine organisms and particles in a non-intrusive and non-destructive way. They provide information on particle distributions and motion over a large depth of field and on the three-dimensional particle morphology, with high resolution (Watson et al., 1999; Owen and Zozulya, 2000). Alternatively, multiple frequency acoustic sensors allow an indirect and non-intrusive quantification of floc sizes and settling velocities. Nevertheless, these sensors still require improvements to work accurately for cohesive suspensions (Thorne and Hanes, 2002).

The different techniques used to measure settling velocities in situ are not directly comparable, since each one applies different measurement principles (Dyer et al., 1996). Furthermore, none of the available instruments is completely free from error or limitations, and they are usually only suitable for a particular application. This paper reviews the main devices used to measure in situ settling velocities of cohesive sediments in coastal systems, briefly describing the different types of apparatus and adopted measurement principles, outlining the advantages and limitations of each technique, comparing their characteristics and concluding with an assessment of which factors should be taken into account when designing/building new devices for obtaining settling velocity measurements in the environment.

2. Direct measurements

2.1. Settling columns and their working principle

The basic operation of in situ settling tubes is to take a water sample at a given depth, bring it to the surface as quickly as possible, and keep it still in a vertical position, allowing particles to settle. Subsamples with volumes ranging from 10 to 550 ml, depending on the tube design, are manually taken close to the tube base at regular (or logarithmic) time intervals until the settling column is emptied. The last sample contains any residual sediment trapped within the tube. Subsequently, SPM mass concentrations ($M\ L^{-3}$)[1] of each subsample are gravimetrically quantified in the laboratory (Owen, 1976; Pejrup, 1988; Cornelisse, 1996; Jones and Jago, 1996; Pejrup and Edelvang, 1996). Usually there is a lag of 20 to 50 s between sampling and the beginning of analysis (when the tube is in its vertical position), with the first withdrawal occurring within 1–1.5 min after trapping the water sample; the total settling period usually lasts from 50 to 180 min (Dyer et al., 1996).

Settling tubes are usually cylindrical in shape, but their dimensions, sampling volumes, withdrawal and closure systems differ from one to the other. Subsamples can be withdrawn from the tube bottom (bottom withdrawal) (Owen, 1976) or through the sidewall close to the tube base by using a pipette (pipette withdrawal system) (Van Rijn and Nienhuis, 1985). Most devices are positioned horizontally at the sampling depth to take the water sample (i.e. horizontal tubes), then they can either be immediately brought to the vertical position after trapping a water sample, or be raised in the horizontal position and rotated to the vertical position at the surface. Some operators also rotate the tube (through its horizontal axis) before holding it in the vertical position in order to resuspend any particles that had settled onto the tube wall (Jones and Jago, 1996). Some tubes enclose a water volume whilst in the vertical position, but this procedure is not appropriate if SPM concentrations change over a stratum of the water column equivalent to the tube height (Puls and Kühl, 1996). Whatever the case, the sedimentation process starts when the tube is in a vertical position, and it is assumed that the SPM within the tube forms a homogeneously distributed suspension (Dyer et al., 1996; Eisma et al., 1997). Table 1 summarises the main characteristics of in situ settling tubes. A detailed description of these apparatuses can be found in Eisma et al. (1997).

Results obtained from settling tubes produce a curve relating the quantity of material settled out in discrete time intervals (the 'Odén curve', Fig. 1a), which can be also expressed in terms of the material left in suspension as time progresses (Fig. 1b). When computing the cumulative distribution of settling velocities expressed as percentage of mass or concentration, corrections are applied to the weights and times for the different depths of settling of each sample withdrawal (Owen, 1976; Bartz et al., 1985; Van Leussen, 1996). Settling velocities (W_i) at each instant of time (t_i) correspond to the fall height (H_i) divided by the elapsed time since the beginning of the experiment, i.e. $W_i = H_i/t_i$ (Cornelisse, 1996; Van Leussen, 1996). The settling velocity value obtained at 50% of the cumulative weight percentage curve of the settling velocity distribution corresponds to the median settling velocity (W_{50}) (Van Leussen, 1996). More elaborate methods for computing the mass frequency distribution of settling velocities, based on the Odén theory of sedimentation of polydisperse systems using graphic analysis of Odén curves as well as its mathematical validation, can be found in Fisher and Odén (1923–24), Krumbein and Pettijohn (1938) and Subcommittee on Sedimentation (1953).

[1] In the text, dimensions for diameter, width, length and height of each apparatus are indicated by D, W, L, H and given in cm. A (cm^2) and V (l) refers to area and volume, respectively. Generic units of mass and volume are indicated by M and L, respectively.

2.2. Advantages and constraints of settling columns

Owen-type settling columns have the advantage of being able to directly quantify the SPM mass concentration ($M\ L^{-3}$), not requiring further calibration. Such hand-operated devices are relatively simple and inexpensive, since they basically consist of a water sampler, with no further instrumentation. They are also unique devices that allow the user to determine the settling velocity distributions, not only of the entire SPM mass but also of each of its constituents (e.g. organic matter, POC, particulate nitrogen or bound lead), provided their masses are measured in each subsample (Puls and Kühl, 1996). They work over a wide range of concentrations, e.g. 2–50 to over 1000 mg l^{-1} (McCave and Gross, 1991).

Some matters associated with the original Owen-tube have been improved in later versions. One issue concerns the so-called 'wall effect', experienced by large flocs that settle across the horizontal tube before it is set upright and then cascade down the wall instead of settling through the fluid when the tube is placed in the vertical position (Jones and Jago, 1996; Wolfstein, 1996). Some workers have minimised this effect by rotating the tube 180 degrees after recovery and before placing it in the vertical position (Puls and Kühl, 1996), or by using vertical sampling tubes. The wall effect is bigger for small tube diameters.

In addition, settling tubes are outside the water during the subsample withdrawal (settling periods ranging from 1 to 3 h), and hence they can be subject to rapid temperature variations that can generate convection currents inside the tube and thus alter the settling velocities of aggregates. It has been shown in laboratory tests that temperature changes of 10 °C lead to statistically different median settling velocities (Puls and Kühl, 1996), and therefore these authors recommended that all Owen-type settling tubes have thermal insulation.

There are also two issues related to the subsample extraction: (i) contamination of one subsample by the previous one can take place if particles from the previous withdrawal were not completely removed (this can be particularly critical for the final subsample); and (ii) the break-up of flocs and change of the settling velocity of aggregates generated by turbulent-like currents within the tube during its closure and retrieval, as well as during subsample withdrawal (Pejrup, 1988; Dearnaley, 1996; Puls and Kühl, 1996). Fluid motion in the range 20–30 mm s^{-1} was observed within an Owen tube during subsample withdrawal (Dearnaley, 1997).

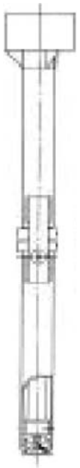
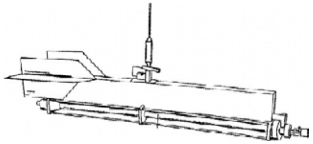
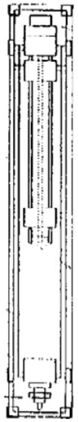
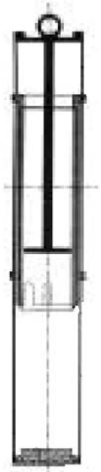
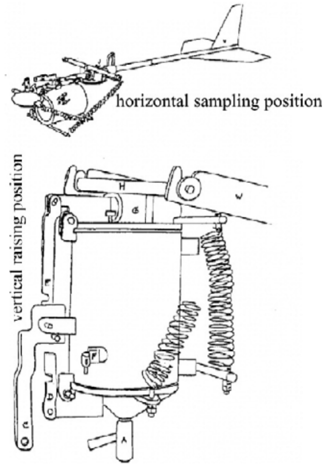
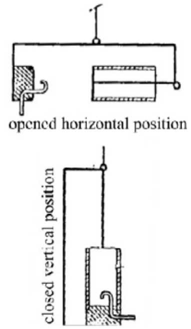
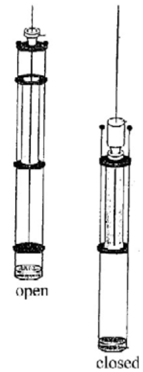
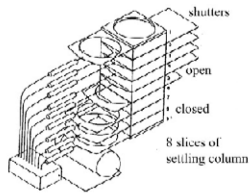
Improvements to earlier versions of the Owen tube have included: (i) the use of a steeper cone angle and rapid sample withdrawal to minimise the settlement of SPM onto the cone sides during analysis (as in the QUISSET tube, Table 1), although some contamination can still occur at high sediment concentrations (Jones and Jago, 1996); and (ii) the use of the pipette-withdrawal system that suppresses turbulent water movements inside the tube (Puls and Kühl, 1996). By comparing an old version of the Braystoke tube (with sealing cap ends, Table 1) with the improved pipette withdrawal system, it was observed that the sealing cap version led to a 30% reduction in the median settling velocity (Puls and Kühl, 1996). In addition, some authors have claimed that sampling tubes destroy large flocs, since much higher settling velocities are obtained by video systems than those measured with settling tubes (Van Leussen, 1988; Van Leussen and Cornelisse, 1993b; Dearnaley, 1996; Fennessy and Dyer, 1996).

Settling tubes entail a time-consuming procedure, since they require people to collect and analyse the water samples. They also have a low temporal resolution (one sample is taken in each time interval). According to Pejrup and Edelvang (1996), a major weakness of the method is its sensitivity to the individual operator carrying out the analysis. This is because large differences in median settling velocities may occur as a result of inaccuracies related to how fast the subsamples are withdrawn and how precisely their volumes are extracted. Also, the precision of the method is limited at low SPM concentrations (<50 mg l^{-1}) due to the small amount of material available for each subsample. Furthermore, the collection of water samples occurs over discrete time intervals and usually takes 20 to 30 s, while the sedimentation process is continuous. They measure neither size nor aggregate structure; they estimate the net settling velocity of material within the settling column.

2.2.1. Settling columns equipped with automated in situ video cameras

In situ devices equipped with video cameras use sequential images to directly follow the displacement of particles/aggregates in order to obtain their settling velocities between successive frames (Syvitski and Hutton, 1996). A grid or a millimetre scale is often used as a focusing target for image calibration (Van Leussen and Cornelisse, 1996; Sternberg et al., 1996). Most video systems apply a silhouette technique where particles appear dark on a light background or vice-versa (Fennessy et al., 1994; Milligan, 1996; Manning and Dyer, 2002a). Within video systems, the small effects of water circulation observed inside the settling columns are corrected by assuming that the motions of the smallest visible suspended particle are equivalent to

Table 1
Resume of the main characteristics of the in situ settling tubes

	Owen tube[1]	Baystoke 110 tube[2]	Quisset tube[3] (Quasi in situ settling velocity)	Allersma tube[4]	FIPIWITU[5] (Field pipette withdraw tube)	RWS tube[6]	Bigdan tube[7]	BEAST[8] (Benthic autonomous settling tube)
								
0	M. W. Owen Hydraulics Research, UK	Owen tube commercial version, Valeport Ltd.	I.N. McCave, Cambridge University and University of Wales	NEDECO (1965), The Netherlands	Van Rijn and Nienhuis (1985), Delft Hydraulics	Van Geldermalsen, Rijkswatertaat, The Netherlands	GKSS, Germany	Bartz et al. (1985)
1	5 × 100	5 × 100	9.5 × 100	8 × 32	12.5 × 30	10.4 × 21.1	19 × 100	30 × 82 (8 slices H = 10)
2	60 to 180	64	180	30 to 10 days	60	60	120	750
3	50 to 3000	>40	1–50 to 1123	na	20 to 2000	5 to 2000	2 to 6	0.1 to 100
4	0.02 to 8.0	0.03 to 4.9	0.0003 to 0.3–0.8	na	0.05–0.5 to 3.5	0.005–0.15 to 3.5	0.01 to 2.0	0.005
5	no	no	water jacket	no	double-insulated wall	double-insulated wall	gold-coated envelope	it works on the seabed
6	horizontal	horizontal	horizontal	horizontal	horizontal	horizontal	vertical	vertical
7	It is balanced to lie horizontally in water and to hang vertically in air.	It has a tail fin to line it up in the current direction.	It is mounted in a 2 m long frame and held opened at one end by stretched elastic cords.	The tube slides along a frame to which a plunger and a cork are attached.	It has a large tail fin to keep it horizontal. It is put in a vertical position as soon as it closes.	It immediately rotates to vertical position after sampling.	Both ends of the tube are opened; the lifted tube and its metal bottom are 1 m apart.	It sinks to the bed and it isolates 8 samples in a timed sequence from the bottom upwards while SPM is settling.

8	bottom (200–250)	bottom (200–250)	bottom (550)	pipette (10)	pipette (200)	pipette (200)	pipette (1000–3000)	closing 8 chambers (5000)
9	The inner tube rotates 3/4 of a turn relative to the outer and socks at both ends are twisted to seal.	It is closed by releasing a messenger that seals both ends at same time.	It traps a volume of water by moving the tube horizontally past a piston.	It is lowered in the horizontal position and the sample is taken by pulling a rope that causes the body and pipe to slide towards the cork, closing the tube in the vertical position.	It has valves at both ends connected to a spring system that are closed by releasing a messenger.	It is pulled down by an extra weight connecting to the tube bottom.	It cuts downward and encloses a volume of water when triggered by a messenger.	Chambers are closed by sliding flat sheets drove by hydraulically powered shutters.
10	Operable for currents greater than 0.4 m s^{-1}.		It can be automatically triggered 1 m above the bed.	It has exchangeable tubes.		It has exchangeable tubes.	Pipette is connected to a peristaltic pump with controlled flow intensity. Operable current range 0.1 to 0.5 m s^{-1}. Markdan is a smaller (5 l) version of Bigdan.	It is semi-automatic. After the settling period it sheds ballast and returns to the surface. Shutter relies on high deep sea pressures. Contamination among chambers occurred.
11	Owen (1971, 1976), Eisma et al. (1997)	Pejrup (1988), Pejrup and Edelvang (1996), Mikkelsen and Pejrup (1998)	Jones and Jago (1996), Jago and Jones (1998), Jones et al. (1998)	Allersma (1980), Van Leussen (1988), Eisma et al. (1997)	Van Rijn and Nienhuis (1985), Cornelisse (1996)	Van Leussen (1988, 1996), Van Leussen and Cornelisse (1993a,b)	Puls and Kühl (1996)	Bartz et al. (1985)

First row brings the tubes' picture. Pictures of the tubes were extracted from: [1]Fig. 5 of Owen (1976), [2]Fig. 3 of Eisma et al. (1997), [3]Fig. 1 of Jones and Jago (1996), [4]Fig. 14 of Allersma (1980), [5]Fig. 1 of Cornelisse (1996), [6]Fig. 1 of Van Leussen (1996), [7]Fig. 1 of Puls and Kühl (1996) and [8]Fig. 11 of Bartz et al. (1985). The subsequent rows are numbered and their contents are as follows: 0–Tube developer, 1–Tubes' dimensions for diameter and height (D × H, cm), 2–settling period (min), 3–range of measurable SPM concentrations (mg l^{-1}), 4–range of measurable settling velocities (mm s^{-1}), 5–thermal insulation system when present, 6–sampling position, 7–sampling set-up, 8–withdrawal system and volume (ml, unless otherwise specified) withdrawn in each subsample, 9–closure system, 10–particularities of each tube and 11–some references to obtain more information about tube description and field applications.

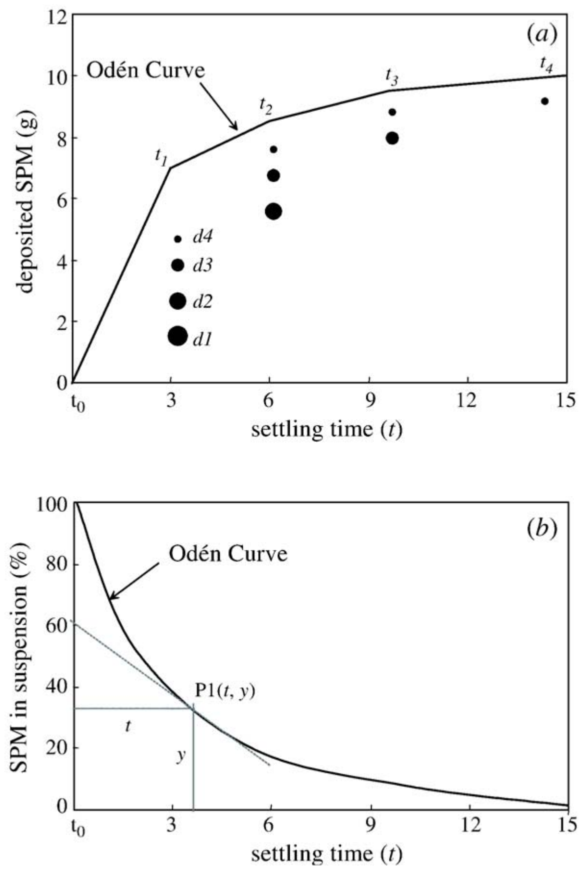


Fig. 1. (a) Odén Curve showing the temporal mass accumulation on the bottom of the settling tube for a SPM sample composed of four hypothetical discrete particle sizes (*d1* > *d2* > *d3* > *d4*). All particles are in suspension at $t = t_0$, when $t = t_1$ all particles d1 plus some *d2* and *d3* particles have settled out of suspension, and then successively as indicated by the circumferences on the picture; (b) representation of the Odén Curve in terms of percentage of material left in suspension. Figures adapted from Subcommittee on Sedimentation (1953).

water movements; hence the settling velocities of larger flocs are derived by calculating the difference in the vertical movements of the finest particles and the larger flocs (Van Leussen and Cornelisse, 1993a, 1996; Sanford et al., 2005).

Data analysis can be done on a manual basis by taking measurements from a video monitor (Fennessy et al., 1994; Manning and Dyer, 2002a) or by applying computer-based image processing techniques to the digitised images (Knowles and Wells, 1996). In addition, particle track computational methods have been developed to follow the particles over some time and distance in order to derive the settling velocity distribution (Van Leussen and Cornelisse, 1996). Sophisticated commercial software is also available for data analysis, which provides a large number of other parameters related to the aggregate dynamics (e.g. excess density, porosity, mass flux, mass concentration, number concentration) (Syvitski and Hutton, 1996; Sternberg et al., 1999). For instance, the excess density ($\rho_e = \rho_f - \rho_w$) is derived from the Stokes Law (Eq. (2)) or based on the drag coefficient (C_D), i.e. $\rho_e = C_D\, \rho W_s^2/(4/3gd)$, using the observed floc settling velocity and diameter; while the floc mass is determined by multiplying the floc excess density (ρ_e) by the floc volume (V_f) ($M = \rho_e\, V_f$), which is usually obtained by assuming a spherical or ellipsoidal shape and introducing the measured floc diameter (Syvitski and Hutton, 1996; Manning and Dyer, 1999; Van der Lee, 2000). Similarly, the dry mass can be obtained by $M = V_f\, \rho_e\, \rho_s/(\rho_s - \rho_w)$, where ρ_s is the mean dry density of the primary particles often estimated by making assumptions about the mineral (2600 kg m^{-3}) and organic (1030 kg m^{-3}) densities and applying generic inorganic to organic mass and volume ratios (Manning and Dyer, 1999). These parameters can be combined to estimate the volumetric concentration, mass flux and others, as described by Syvitski and Hutton (1996).

Imaging techniques comprise underwater photographic cameras, video systems and holographic techniques. Many in situ photographic cameras have been applied for measuring flocs size and shape, such as: the high resolution (4 μm) in situ camera NIOZ (Eisma et al., 1990; Eisma and Li, 1993; Chen et al., 1994; Eisma and Kalf, 1996), the ISSAC (Knowles and Wells, 1996), the Benthos 373 plankton silhouette (Milligan, 1996; Hill et al., 2000; Curran et al., 2002), the Benthos Plankton Camera (Eisma et al., 1991; Kranck et al., 1993), the Nikon N2000 camera system (Luettich et al., 1993), the Endoscopic photographic system (Maldiney and Mouchel, 1996), the VMSS (Pfeiffer, 1996), the camera system mounted in a pressure housing (Thomsen and Ritzrau, 1996), the UVP (Jackson et al., 1997; Gorsky et al., 2000; Fox et al., 2004). However, these devices will not be described here since they do not directly measure or do not furnish aggregate settling velocities. We present in major detail a few examples of underwater video and holographic systems, which measure both size and settling velocities of individual flocs.

2.2.2. Examples of the available video systems for settling velocity measurement

INSSEV (In situ Settling Velocity Instrument, Plymouth University) is a high-resolution monochrome video camera (35 mm, f/4, macro lens) with a shipborne control system that allows the determination of both flocs size (from 20 μm) and settling velocities, sampling a representative floc population every 10 to 20 min (Fennessy et al., 1994, 1997; Fennessy and Dyer, 1996;

Manning and Dyer, 2002a; Manning et al., 2004). It uses an integral low heat LED illumination that minimises heating and settling column instabilities due to temperature variations (Manning and Dyer, 2002a). This apparatus has two chambers separated by a slide door: (i) a decelerator chamber (D × H = 10 × 40 cm) that allows residual turbulence to decay after capturing a water sample; and (ii) a still settling column (D × H = 10 × 18 cm) filled with filtered water of known density. The amount of particles introduced into this column is set by an operator by controlling the time that the slide door is kept opened, based on the independently assessed SPM concentrations (Fennessy et al., 1994). Moreover, the decelerator chamber flap doors open and close at a speed proportional to the ambient current velocity (independently measured by a current meter). Operation of INSSEV requires the current direction to be less than 5–15° away from the decelerator axis to avoid sidewall turbulence. This is achieved by using a heavy tripod (180 kg), which has a fin that aligns the device with the main flow. Photos of low-density macroflocs (a few millimetres long) interlinked by fine strands suggest that the instrument has a low disruption effect on flocs (Fennessy et al., 1994; Manning and Dyer, 2002a,b).

VIS (Video in situ of Rijkswaterstaat and Delft Hydraulics, Netherlands) is composed of a funnel-shaped capture/stilling chamber (D × H = 10 × 15 cm) connected to a vertical settling tube (D = 3 cm) with two light sheet windows and a CCD video camera (HTH-MX-C) (Van Leussen and Cornelisse, 1993a, b; 1996, Fig. 2a). Both the capture/stilling chamber and the settling tube have their water removed by very gentle

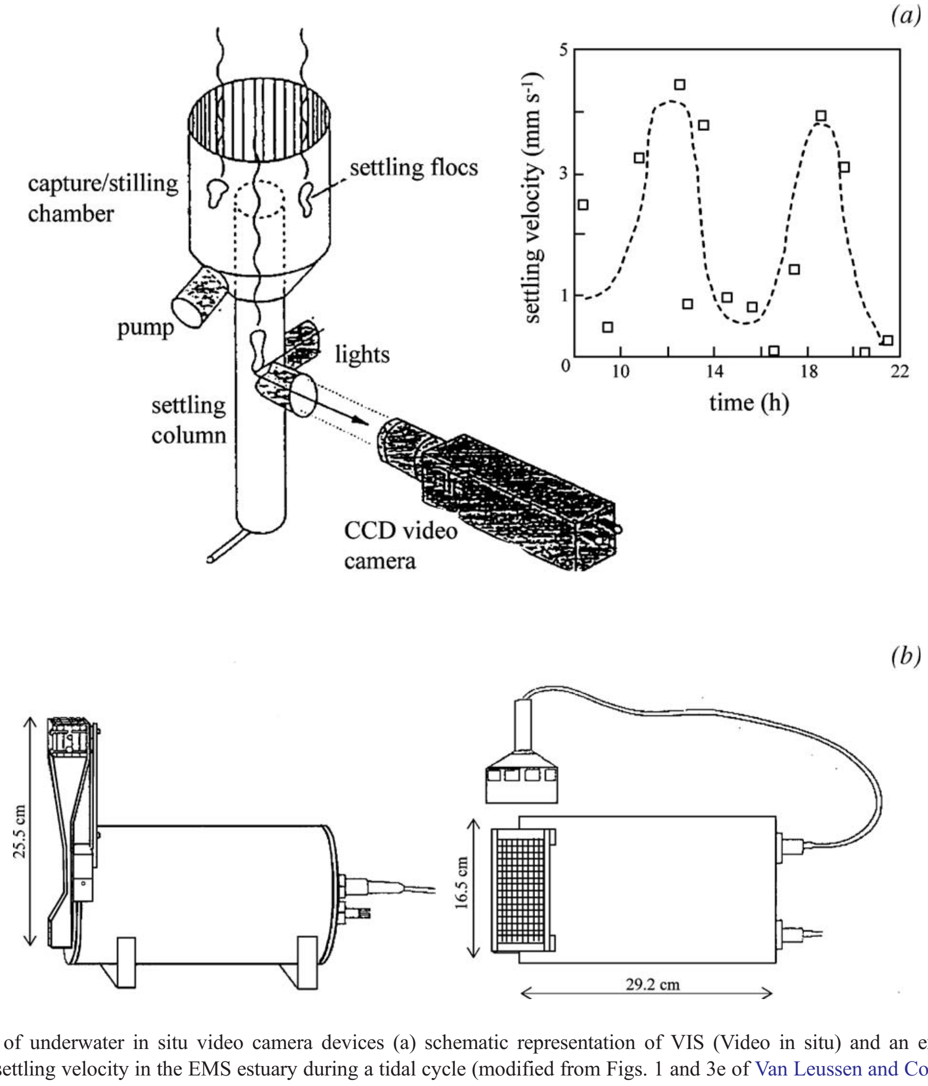


Fig. 2. Examples of underwater in situ video camera devices (a) schematic representation of VIS (Video in situ) and an example of floating measurements of settling velocity in the EMS estuary during a tidal cycle (modified from Figs. 1 and 3e of Van Leussen and Cornelisse, 1996); (b) side (left) and top (right) views of a compact benthic video system with a honey comb baffle (as presented in Fig. 1 of Sternberg et al., 1996).

pumping. The device is placed in a stainless steel housing (D × H = 30 × 60 cm) with a float, independently drifting during image recording. Therefore, it is a robust device, even in very high wind speeds (wind speeds of 8 Bft) and currents (up to 2 m s^{-1}), and under SPM concentrations up to 600 mg l^{-1}. The floating system also reduces shear around VIS that could cause floc break-up and the effect of horizontal advection on the measurement. The system is connected to a monitor so that the settling process can be directly observed on board (Van Leussen and Cornelisse, 1993a, b, 1996; Van der Lee, 2000, Fig. 2a). The video system has a resolution of 10 × 15 μm^2, total image size of 9 × 6 mm^2, a time step of 0.01 s and resolution of 50–85 μm. The error in settling velocity and size is within 10–20% for VIS measurements (Van der Lee, 2000). Fig. 2a shows settling velocities computed from VIS measurements during a tidal cycle; other examples of VIS applications are found in Van der Lee (1998, 2000).

Unlike the previous devices, a compact benthic video system (Sternberg et al., 1996) was designed to work moored on a tripod for 4 mo, logging for 7 s (30 frames s^{-1}) every 6 h, with a maximum recording time limited to 1 h. This video system is composed of a miniaturised sediment trap (L × W × H = 9.7 × 3.4 × 25.5 cm), a video camera (Sony TR600-Hi8) with controller board and an underwater light (Sternberg et al., 1996, 1999, Fig. 2b). It provides remote operation, independent control capability, low power consumption and a controller/data logger. The system size resolution ranges from 100 to 1000 μm, and it can operate at high concentrations (values not specified). The sediment trap has two particular features: a honeycomb baffle (W × H = 0.3 × 0.8 cm) at its top, and a double funnel shape (the top one collects water and the bottom one the settled sediment) divided by a narrow section 3 mm wide in front of a video camera viewing field that places all particles in focus (Sternberg et al., 1996, 1999, Fig. 2b).

The Floc Camera Assembly (FCA, Heffler et al., 1991) is composed of two stereo 50 mm lens cameras, one 200 mm lens camera, and a collimated plane of light (focal distance of 2.5 cm). For settling velocity measurements, the FCA is mounted on a frame with a stilling tank that lies on the seafloor. Photographs are taken through acrylic walls of the tank giving the position of sinking particles every 10 s. Usually a large number (concentration dependent) of particles is analysed (hundreds to a few thousand) (Syvitski and Hutton, 1996; Hill et al., 1998). Accuracies for size, shape factor and settling speed are within ±20 μm, ±0.05 and ±0.02 mm s^{-1} range, respectively, and its minimum size resolution is 50 μm. FCA can be used as a profiler for sampling floc size through the water column or deployed on the bottom to take sequential images for settling velocity determination (Syvitski and Hutton, 1996).

Sanford et al. (2005) applied the VISTA system (Video in situ Settling Tube Apparatus), composed of a settling tube and an underwater video camera (PULNIX CCD, field of view 8.3 × 11.2 mm; resolution of 30 μm), to measure in situ the size and settling velocity of aggregates. In this system, water is pumped to flush the tube, and then valves at the top and the bottom of the vertical section are triggered to trap a water sample and create a settling chamber. Due to a 90 degree turn at the tube's intake and rapid closure of the valves, some turbulence is generated inside the tube.

2.2.3. *Advantages and constraints of the in situ video cameras*

Video camera devices have the advantage of giving detailed information on the nature of sediment particles (shape and size), often ranging from 20–200 μm to up to a few millimetres, although a size resolution as fine as 4 μm can be achieved (Eisma et al., 1990). These image systems are also able to provide size and settling velocity spectra simultaneously by direct observation of particle tracks through time, from which the effective density can be calculated (Fennessy et al., 1994; Manning and Dyer, 2002a). Size and distance calibrations are straightforward using only a grid or a millimetre scale. They are generally less disruptive than other flow-intrusive devices in terms of sampling, preserving the large aggregates. Some video systems can work in relatively energetic environments (currents of 0.4 to 1–2.0 m s^{-1}) (Van Leussen and Cornelisse, 1996).

Video measurements do not depend on any particle or medium characteristic except for light quality (Eisma and Kalf, 1996), although some video systems can operate well even at high-suspended loads. For example, the INSSEV video system was found to be very effective at measuring floc characteristics even within concentrations up to 8 g l^{-1} (Manning and Dyer, 2002a). In addition, high-quality video image analysis provides comprehensive information about floc size, structure and characteristics and allows details about floc formation and temporal dynamics to be inferred (Manning and Dyer, 2002a,b; Manning, 2004; Manning et al., 2004).

However, as the focal distance of video systems is usually restricted to a distance of a few millimetres, they sample only a small number of flocs and a small portion of the settling flux. Hence, a large number of particles must be counted for appropriate statistical estimation and they also require a separate method to furnish the total SPM concentration (Dearnaley, 1996; Traykovski et al., 1999). Jackson et al. (1997) compared five different techniques for measuring particle sizes, and indicated that the sample volume was the most important factor in determining the maximum particle size. They concluded that the upper size limit is set by the rarity of large particles in the small sampling volumes of the image systems, thus compromising their full particle size capabilities.

Only a few comparisons are available between the SPM concentrations estimated from the video image analysis and those independently measured in the field in order to access the capability of the video techniques in representing the settling flux. For instance, Manning and Dyer (2002b) found a good agreement (around 100%) between the SPM concentration computed from the floc population measured by INSSEV and the SPM concentration estimated from a filtered gravimetric sample, except at high SPM loads when the video method underestimated the actual concentration by 20–30%.

Further, mass or volume concentration calculations derived from settling velocity and size measurements require assumptions on the 3D nature of particles based on a 'sphere equivalent diameter' or fractal analysis. This imposes uncertainties to the analysis, since particles are seldom regular in the environment and an irregular particle can have different 'diameters' (e.g. projected area diameter, Feret's diameter, sedimentation diameter) depending on where the cross-section chord is drawn and the adopted measurement technique (Skinner, 2000). Therefore, the projected particle cross-sections can change, depending on their orientation relative to the photographed angle of view. This again leads to the adoption of a statistical geometric diameter requiring a large number of measurements (Syvitski and Hutton, 1996).

Restrictions on the lower detection limit of video cameras (usually 20–100 μm) leave some of the small particles undetected, and can lead to an overestimation of the size of flocs. Also, if flocs are partially illuminated, out of focus or overexposed, their boundaries are not sharp and they may be digitised bigger or smaller than the actual size (Van der Lee, 2000). Corrections to the settling velocity, due to water movement inside the settling columns, can be complicated if the smallest observable floc, set by the instrument resolution, is already large (e.g. 85 μm, Van der Lee, 2000).

The post-processing image analysis is time-consuming, but with the advent of high speed computers and the development of sophisticated computer techniques, the time required to process an image has been drastically reduced. However, care must be taken to control the amount of pre-processing of images and to reduce the subjectivity of the analyses (Milligan, 1996). The analysis is not automated to the same extent as optical or laser diffraction techniques, as a result of the limitation in the maximum recording time. Some shear can be expected with the narrow camera sampling volume and mechanisms have been adopted to minimise the fluid flow relative to the path of measurement (e.g. floating devices, fins to align instruments to the flow).

2.3. Settling tube equipped with an underwater mass balance

Gravimetric analytical balances have been used in the laboratory for temporal monitoring of sand grains and silica particles settling inside a tall sedimentation tower ($D \times H = 20 \times 200$ cm). In the laboratory set-up, an electronic mass balance is placed at the cylinder top, while the weighing pan plate is located at its bottom held by an underhook suspension system. This balance is connected to a computer which allows continuous readings to be taken. These balances usually have a high accuracy and reproducibility (Rigler et al., 1981; Renagi, 1999; Ridd et al., 2001). Using a similar set-up, various commercial computerised sedimentation analysers are available for measuring size and settling velocity distributions of sand-sized material in the laboratory (e.g. MacroGranometer). Restrictions on the use of gravimetric quantifications for in situ applications include the difficulty of sealing electronic balances for underwater use, as well as their high power consumption. An alternative design of an underwater balance has recently been proposed for monitoring in situ the variation of SPM immersed weight with time as it settles on a plate located at the bottom of a settling tube (SEDVEL, Mantovanelli, 2005).

SEDVEL's basic measurement principle is a magnetic spring system driven by a pair of magnets: one located below the balance plate ($A = 79$ cm^2) that works immersed and another placed inside a sealed sensor case (Fig. 3a). The balance plate moves downwards as SPM particles/flocs deposit on it, and its micrometric changes (in relation to its equilibrium position) are detected by a high-sensitivity displacement sensor. These changes are proportional to the sediment immersed weight, and the actual sediment mass can be obtained by calibration with known masses (Mantovanelli, 2005). This instrument is fully automatic in terms of water sampling, measurement and data storage. It can operate in

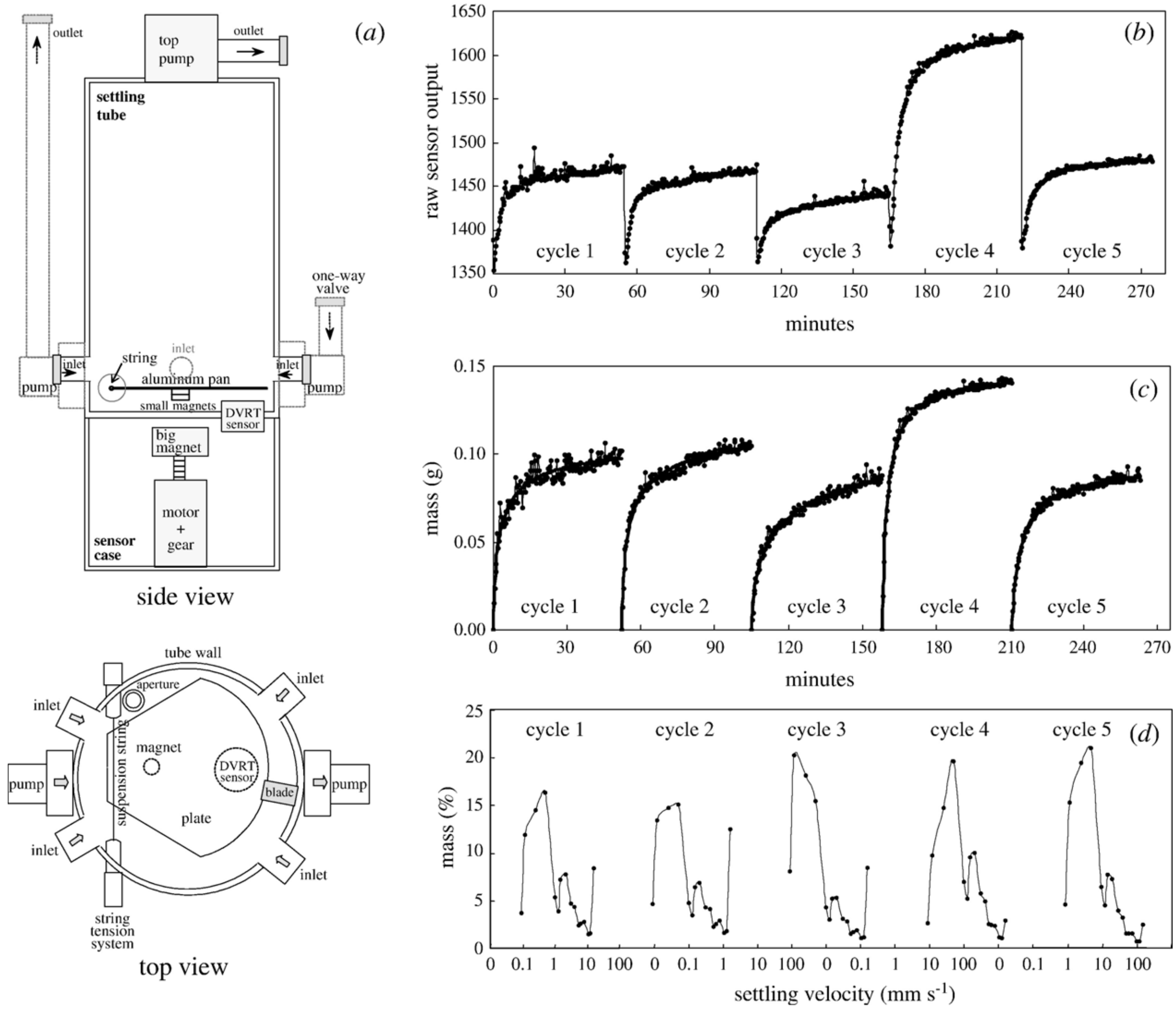


Fig. 3. (a) Side and top views of a schematic drawing of the underwater balance (SEDVEL) components (as presented in Fig. 3.9 of Mantovanelli, 2005), (b) examples of raw data, (c) estimated masses of particulate matter and, (d) estimated settling velocities during five consecutive cycles of measurement in Cleveland Bay (Mantovanelli, 2005). Settling velocities are shown on a log-scale and related to the percentage of mass in each settling class.

concentrations from 5 to about 500 mg l^{-1} (with a resolution better than 10 mg) and a sampling autonomy of 5 d; the settling period can be set as required from a few minutes to many hours, with a sampling rate of 20 s (Mantovanelli, 2005). The whole device includes a balance, sensor housing, acrylic tube, data logger, battery case, set of submersible pumps and tripod frame to be deployed on the bed (total weight of about 20 kg). Two opposite bottom pumps suck water in and out creating a jet that flushes the sediment accumulated on the pan out after each measurement. When these pumps are stopped, a pump located at the top of the tube sucks water out while a new sample enters at the bottom through four inlet openings fitted with one-way valves (Mantovanelli, 2005) (Fig. 3a). A typical raw output obtained from SEDVEL, its calibrated data, which is a curve relating the variation of SPM mass with time, and the calculated settling velocity distributions in terms of mass percentage in each settling class are shown in Fig. 3b, c and d, respectively. Data analysis employed in computing the aggregates settling velocities is similar to that applied to the settling columns results.

2.3.1. Advantages and constraints of the underwater mass balance

The SEDVEL instrument is unique in furnishing direct and automated in situ measurements of SPM mass concentration (M L^{-3}) and settling velocities.

Compared with other automated systems, SEDVEL presents a relatively simple working principle, calibration and data analysis procedure. Calibration assumes a medium density and therefore salinity and temperature changes are measured in order to apply the correct calibration curve (Mantovanelli, 2005). However, changes in the zero starting position (balance tare) with different cycles of measurements can make the calibration process demanding. Particle/floc properties do not influence instrument calibration or response. It records almost continuously (every 20 s) the floc settling, and it is flexible regarding the settling period. It does not require extraction of samples to obtain sediment mass, avoiding the break-up and settling velocity alteration observed in the Owen-type tubes due to the development of circulation inside the tube during subsamples withdrawal (Mantovanelli, 2005).

This instrument allows both the determination of SPM concentration and settling velocity, but not direct size measurements. The settling velocities of faster falling particles are extrapolated from curve fitting the data sets, since measurements cannot be performed within the first 1–1.5 min until the turbulence inside the settling column is damped.

The instrument has been tested in environments subjected to low currents (<0.2 m s^{-1}), and it would probably require a heavier tube and frame in order to be able to work under higher currents. It is possible that the system for water replacement causes some flocs' disruption, and it should ideally be replaced by a less disruptive system. Also, air bubbles introduced to the settling column when the instrument is filled up before deployment can bias the zero position and change the instrument's sensitivity; these bubbles are usually eliminated after a few cycles of measurement (Mantovanelli, 2005).

3. Indirect measurements

3.1. Settling columns equipped with optical instruments

The basic working principle of settling columns equipped with optical instruments (optical backscatter sensors (OBS) and transmissometers) is to indirectly monitor the depletion of SPM with time by measuring the rate of clearance (transmissometers) or decrease in the backscatter signal (nephelometers). Transmissometers measure the summed attenuation (due to the water, SPM and dissolved material) of a transmitted light beam along a fixed path length, while OBS sensors work by emitting a light beam (infrared or visible) and registering the amount scattered back to a light sensor (receiver) mounted adjacent to the transmitter (Ridd et al., 2001; Fugate and Friedrichs, 2002). Both sensors quantify turbidity by measuring total grain cross-sectional area per unit area (A) rather than mass concentration; the backscatter is proportional to A and transmission to 1-A, and A is directly proportional to the particle volume concentration (C_V) and inversely proportional to the particle diameter (d) integrated over n size classes, i.e. $A \propto \sum_n C_{Vn}/d_n$ (Fugate and Friedrichs, 2002).

3.1.1. Examples of in situ settling columns equipped with optical instruments

Kineke et al. (1989) proposed an in situ spring-loaded cylinder (D × L = 13 × 28.5 cm), which traps a parcel of fluid between two end plates, and is equipped with a vertical array of five miniature nephelometers used to monitor the decaying backscatter signal with time. This cylinder is mounted on a tripod that sits on the bed, and it is closed by an electrical signal sent from the ship through a cable. Records show a period of 10 to 50 s of high, rapid sensor output fluctuations due to turbulence inside the cylinder, and the swing of the ship limits the length of time that the tripod can remain on the bottom to 3–15 min (Kineke and Sternberg, 1989; Kineke et al., 1989). Maximum settling velocity resolutions are 13.3 and 66.7 mm s^{-1} for the top and lower sensors, respectively. Problems associated with the settling cylinder include: (i) a large mass of particles remained in suspension by the end of monitoring time; (ii) errors were introduced by calibration and cross-calibration of the optical sensors; (iii) residual turbulence during/after the cylinder closure may disrupt the flocs; and (iv) the particles may continue to aggregate after sampling (Kineke et al., 1989).

Remote Optical Settling Tube (ROST) (Zaneveld et al., 1982; Bartz et al., 1985) is a rectangular box (W × H = 10 × 25 cm) equipped with a trasmissometer (light beam 25 cm long, detection volume of 8.8 cm^3). The top and bottom of the box close at the same time, enclosing a volume of water for 22 h before opening again to allow a 2 h flushing period. It was designed to work in water depths of up to 5000 m for several months and to obtain particle settling velocity data with a resolution of 10 $\mu g\ l^{-1}$ and 0.1% accuracy, at sampling rates varying from 10 s to 5 min. Measurements can be taken 10 min after the closure of the lids, the time required for the residual turbulence to cease (Zaneveld et al., 1982; Bartz et al., 1985; McCave and Gross, 1991).

A successor of ROST was built which consists of a rectangular settling box (W × L × H = 25 × 13 ×

100 cm) equipped with a transmissometer (Sea Tech, 25 cm of path length and sampling rate of 1 Hz), opened and closed with end plates that pivot into position (Hill et al., 1994, Fig. 4a). Two problems were found with this box system: (i) imperfect sealing which promoted mixing and penetration of sediment-laden fluid within the box; and (ii) a relatively high interval of time (10 min) required for the damping of turbulence after closure (Hill et al., 1994).

An autonomous apparatus for long-term deployment (2 mo) has been developed at Cambridge University. Murray et al. (1996) constructed a cylindrical settling box (D × L = 25 × 30 cm) that traps water parcels (at specified time intervals) between two end lids and measures the decaying backscatter signal of four miniature sensors (MOBS, 3.5 × 1.7 cm, sample rate 1 Hz, infrared 850 nm) located at different heights inside the box. The settling box has an automatic system that slowly opens and closes the lids in order to minimise turbulence. When opened, the lids form a 45° angle relative to the body, so that the flushing is maximised (Fig. 4b). Turbulence induced by door closure usually takes 3 min to damp, and measurements during this period are discarded. Attempts to suspend the settling box (plus a lead weight) in the water column under high currents (1.5 m s^{-1}) did not succeed, and measurements were restricted to calm periods (Murray et al., 1996). The raw data obtained with this device is presented in Fig. 4b.

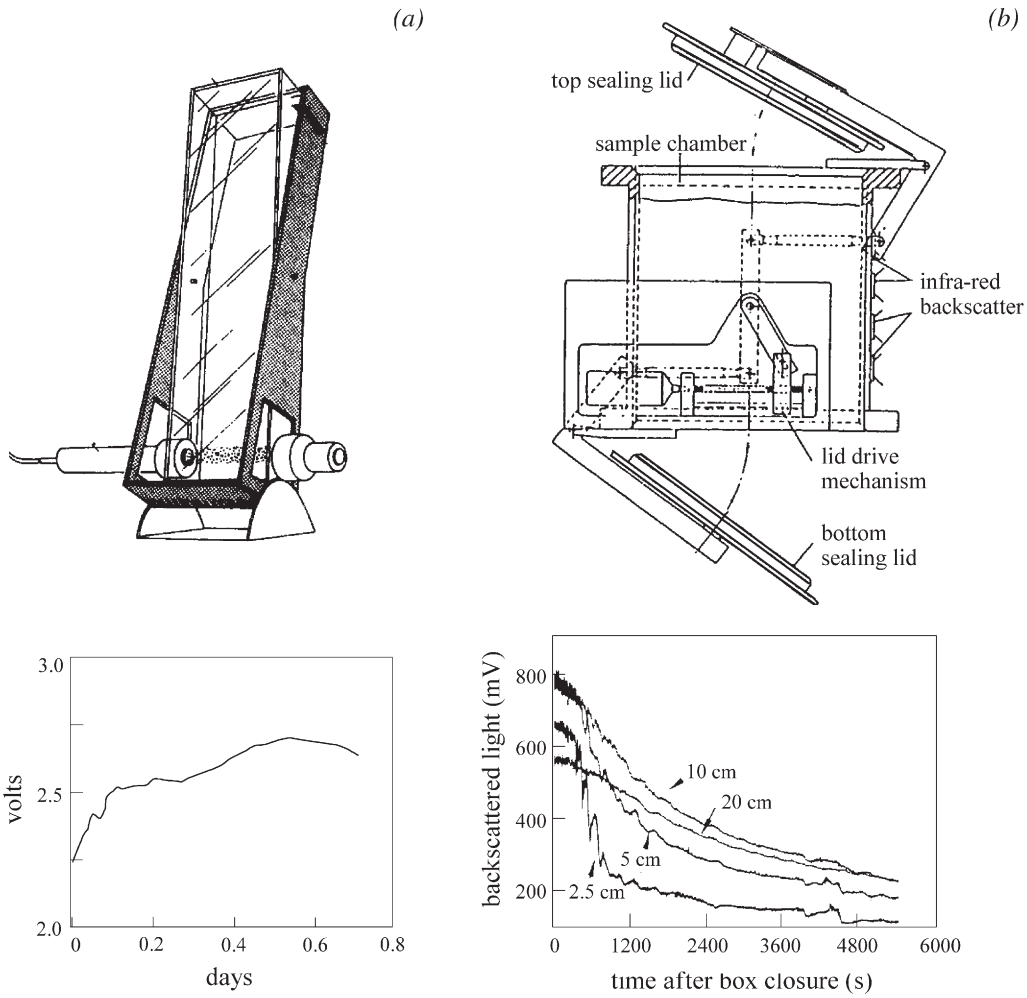


Fig. 4. (a) Remote optical settling box with pivotable doors and a sketch of a typical transmissometer output showing an increase in the transmissivity with time (modified from Figs. 2 and 3 of Hill et al., 1994); (b) schematic diagram of the in situ settling velocity box equipped with four miniature OBS sensors (MOBS) and an example of the raw data showing the decay of the backscatter signal with time at the four MOBS localised at 2.5, 5.0, 10.0 and 20.0 cm below the top lid (modified from Figs. 1a and 4 of Murray et al., 1996).

3.1.2. Advantages and constraints of settling columns equipped with optical instruments

Settling columns equipped with optical instruments are automatic in terms of sampling, data recording and storage, and they often have a great sampling autonomy (weeks to a few months). Single-frequency optical backscattering and transmission sensors have become very popular for producing data series with high temporal resolution over a wide range of concentrations, i.e., between 0.1 to 200 g l^{-1} (Sutherland et al., 2000), although multiple scattering effects and absorption usually occur at high concentrations (Fugate and Friedrichs, 2002).

All one-parameter sensors (e.g. OBS, transmissometers and single frequency acoustic sensors) give a weighed sum of the concentrations of underlying size classes; no size quantification is possible (Agrawal and Pottsmith, 2000). Although OBS response is primarily sensitive to SPM concentration, calibration curve constants and the backscatter signal depend upon a large number of particle characteristics, such as: shape, roughness, refractive index, density, mineralogy, degree of flocculation, colour, and particularly, the particle size (Renagi, 1999; Hatcher et al., 2000; Sutherland et al., 2000). Their sensitivity to SPM size has been widely demonstrated, and can result in poor calibration relationships between the output of optical instruments and the SPM mass concentrations, when size distribution varies over time or space, conditions that are common in estuaries (Fugate and Friedrichs, 2002; Murray et al., 1996; Mantovanelli et al., 1999; Agrawal and Pottsmith, 2000). Therefore, despite their sampling autonomy, to obtain reliable calibration curves they require extensive traditional bottle sampling to be taken in situ and filtered in the laboratory for SPM mass concentration ($M\ L^{-3}$) quantification. In addition, Murray et al. (1996) demonstrated the importance of adopting time-variable calibration curves to compute the effects of an increasing backscatter signal with decreasing particle size during the settling inside a settling column, and also the need to use site representative material to convert OBS response into SPM mass concentration.

Similarly, transmissometer attenuation coefficients for the particles are dependent on many factors, such as: floc diameter, spectral shape, density and organic content, number of particles per unit volume and the scattering efficiency factor. In addition, the calculation of these parameters involves several steps and the use of many conversion factors and assumptions regarding particle 3D fractal dimension, mass distribution and density, which are usually derived from relations between settling velocity and diameter (indirectly obtained by Stokes Law) (Zaneveld et al., 1982; McCave and Gross, 1991; Hill et al., 1994; Boss et al., 2001). Uncertainty regarding the ratio of particle mass to particle diameter degrades the transmissometers results; if particles are treated as uniform-density quartz spheres with constant scattering efficiency, the conversion from attenuation to mass is linear with particle diameter; if particle bulk density is a decreasing function of particle size, the conversion scales as diameter to a power less than unity. Therefore, "the sensitivity of the results to assumed geometry makes it imperative to better understand the fractal geometry of marine aggregates" (Hill et al., 1994).

3.2. Settling columns equipped with laser diffraction equipment

The working principle of laser diffraction instruments consists of emitting a laser beam (usually $\lambda \approx$ 670 nm) into a suspension of particles, creating a multi-angle scattering pattern that is detected by a series of concentric ring detectors of progressive diameters (Sequoia Scientific, application note L002; Wren et al., 2000, Fig. 5a). The recorded data is mathematically inverted to obtain the area distribution of particles, and the volume distribution is obtained by multiplying the area in any class by the median diameter in that class and using an empirically determined volume calibration constant. All classes are added to give the total volume concentration ($L^3\ L^{-3}$) of particles that is independent of particle density or size distribution (Agrawal and Pottsmith, 2000; Wren et al., 2000; Fugate and Friedrichs, 2002). The median diameter within each size class is calculated from knowledge of the scattering angle by applying Mie Theory for spheres and generally assuming a constant refraction index (Traykovski et al., 1999; Wren et al., 2000).

Laser diffraction techniques are primarily used to obtain particle size distribution. An automated in situ laser device (LISST-100, Laser in situ Scattering and Transmissometry), manufactured by Sequoia Scientific Inc., has been extensively applied for measuring volume concentrations ($L^3\ L^{-3}$) and size spectra (5 to 500 μm) using laser diffraction plus a beam transmission (Agrawal and Pottsmith, 2000; Mikkelsen and Pejrup, 2001; Fugate and Friedrichs, 2002; Serra et al., 2002; Ellis et al., 2004) as well as a similar laser diffraction sizer (Cilas 9250) (Van der Lee, 1998). An alternative laser technique that uses a focused beam reflectance is described elsewhere, and encompasses the commercially available laser reflectance particle-sizer

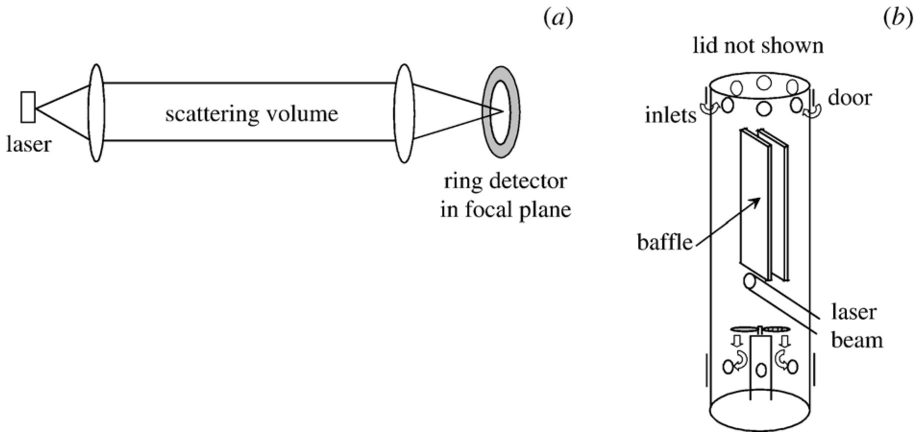


Fig. 5. (a) Configuration of the laser particle sizer instrument (LISST-100), and (b) and the LISST-ST settling column (Sequoia Scientific, Application note L002; Application note L007, www.sequoiasci.com).

instrument (Par-tec 100, Lasentec, Inc., Redmond, WA 98052) (Bale, 1996; Law et al., 1997; Law and Bale, 1998). In contrast with the laser diffraction method, the focused-beam reflectance devices are only based on the period of the backscattered pulse when the irradiated laser beam intersects a particle and not on pulse intensity (independent of particle nature). Therefore, they are able to measure broader particle size spectra (2 to 1000 μm) and concentrations (0.01 to 50 g l^{-1}) at high sampling rates (seconds to few minutes) and with minimal floc breakage (Law et al., 1997; Law and Bale, 1998). Both of these laser devices give volume concentrations (L^3 L^{-3}) of the size spectra, not mass concentration (M L^{-3}).

When using laser particle sizes to quantify particle size spectra, the settling velocity distribution can be indirectly obtained by using Stokes Law (Eq. (2)) and an estimated excess density of flocs (ρ_e) based on relationships between the flocs density and diameter (Krishnappan, 2000) or alternatively, derived from a division between the total SPM mass concentration (independently measured by taking water samples) and the total floc volume concentration obtained from a laser particle sizer (Mikkelsen and Pejrup, 2000, 2001).

Further, an in situ Laser Settling Tube (LISST-ST, Sequoia Scientific Inc.) was developed to obtain settling velocities of 8 size classes in the 5–500 μm range, with sampling autonomy of 83 scans d^{-1} in long-term deployments (up to 21 d) (Agrawal and Pottsmith, 2000). The LISST-ST is composed of a settling tube (D × H = 5 × 30 cm) with an enclosed settling column (W × L × H = 1 × 5 × 30 cm) and a laser beam near its bottom (identical to LISST-100). Samples enter at the top of the tube (through 1.3 cm holes) and a propeller at the bottom is used both to clean the tube and optics and to draw a new sample. A few seconds after the propeller has been turned off, the top and bottom doors are rapidly closed (Agrawal and Pottsmith, 2000, Fig. 5b). With LISST-ST, the settling velocity of any class size of particles settling through a column is obtained by dividing the column length by the time needed for the particles to reach the sensor. A particular feature of the LISST-ST is its automatic event-trigger that uses its built-in pressure and temperature sensors to program the logging schedule based on tides, waves, storms (pressure variance) or fronts (temperature gradients) (Agrawal and Pottsmith, 2000). Noise can be generated inside the settling column due to: (i) incomplete mixing of the initial sample at start; (ii) measurement noise; (iii) presence of particles of different densities; and (iv) the errors of inversion employed in estimating size distribution from the multi-angle scattering. These errors are minimised by estimating the settling times, using a fitting procedure that matches an ideal concentration history to the measured history in a least squares sense (Sequoia Scientific, application note L007).

3.2.1. Advantages and constraints of settling columns equipped with a laser beam

Laser devices can collect and process data quickly and they allow accurate particle sizing, because particle composition does not determine its scattering characteristics. They rely on the assumption that: (i) flocs are spheres; (ii) the laser beam scatters mainly from the cross-sectional area of a floc, rather than the primary particles that compose porous flocs; and (iii) the refraction index of natural flocs is uniform and it can be approximated to those of uniform spheres (Lynch et al., 1994; Agrawal and Pottsmith, 2000; Mikkelsen and

Pejrup, 2001). Results of several laboratory and field measurements have suggested that the second assumption is valid and that in situ laser instruments are able to measure flocs. They also indicate that at least for elliptical flocs, the spherical approximation has only a limited effect on size spectra, as reviewed by Mikkelsen and Pejrup (2001). However, errors become significant when the refractive index of natural particles is vastly different from that used in the computation of the scattering matrix (Lynch et al., 1994; Agrawal and Pottsmith, 2000). Although laser diffraction methods measure without contacting the sample, they require short optical paths (2.5–5.0 cm) that may cause shear-induced breakage of flocs (Law et al., 1997; Wren et al., 2000; Wren and Kuhnle, 2002).

Laser diffraction devices are also technologically complicated and expensive. Their use is limited at low concentrations, if there are not enough particles to measure the diffracted signal, as well as at high concentrations (200–500 mg l^{-1}) by light obscuration and multiple scattering effects. They also operate within a limited size range of between 5 and 560 μm (Bale, 1996; Agrawal and Pottsmith, 2000). However, Traykovski et al. (1999) showed through laboratory experiments that this upper size limit of 560 μm is restricted to 250 μm when measuring natural sediments. This is because the finite size of the detector limits the range of observable particles (Lynch et al., 1994). Furthermore, the presence of particles finer and coarser than the measured size range affects the estimated size distributions. Also, it is very complicated to estimate volume calibration constants for estuarine/coastal particles because of their size-density dependence and fragility (Fugate and Friedrichs, 2002). Finally, Fugate and Friedrichs (2002) pointed out that the inversion approach used to find particle diameters from the laser diffraction method is "an inherently underdetermined problem and the resulting size distribution is approximate", especially when considering multimodal distributions. In the case of LISST-100, the resolution of 32 size classes is only possible for a noise-free data set, because the inverse matrix amplifies any noise in the measurement and distorts the resulting estimated size spectra. In practice, only about 10–12 sizes can be resolved within the 200:1 observable size range (Sequoia Scientific, application note L008).

On the other hand, regardless of their broad concentration and size resolution, focused-beam devices work poorly for amorphous particles high in organic matter, which have little or no reflectance, and in situations when particle shapes vary drastically from spheres (Wren et al., 2000). The calibration procedure for multimodal size distributions is also complicated, and the reflectance method is less effective (Law et al., 1997), as the laser beam only focuses on a very small area (<2 μm^2) (Wren and Kuhnle, 2002).

3.3. Miscellaneous techniques

Different designs of sediment traps can be used for measuring particle sedimentation fluxes in the ocean, but the use of trapping mechanisms presents three main concerns: hydrodynamic bias; sample contamination; and particle degradation as discussed elsewhere (Asper, 1996; Thomas and Ridd, 2004). For instance, commercial versions of sediment traps (Model PPS4/3, Technicap, France) have been used in 36–48 h deployments to monitor in situ settling velocities of particles in wind-disturbed lakes. This trap (D × H = 25 × 100 cm) consists of a 12-bottle carousel with a programmable settling period interval (e.g. 3–4 h), and the sediment collected in each bottle is gravimetrically quantified on retrieval; sediment flux corresponds to the mass collected divided by the collecting area and sampling time (Douglas et al., 2003). This method gives an estimate of the total settling velocity integrated over the sampling period. More sophisticated free-floating sediment traps equipped with holographic cameras have also been used for measuring particle 3-D size and settling velocity (Carder et al., 1982; Costello et al., 1989) as described in Section 4.1.

A very complete device, called INSSECT (In situ size and Settling Column Tripod), has been developed for simultaneously measuring ambient floc size, settling floc size, settling velocity and Reynolds stress (turbulence) in situ (Mikkelsen et al., 2004). It is composed of several instruments including: a digital silhouette floc camera (DFC, resolution of 45 μm, minimum measurable size 135 μm); a digital silhouette video camera (DVC, with resolution of 66 μm, clips of 1 min) plus a settling column; a unique sediment trap; a laser sizer (LISST-100); an optical backscatter sensor (OBS); a compass and tilt meter; and a modular acoustic velocity sensor that measures turbulence (Mikkelsen et al., 2004). This instrument also includes a programmable sediment trap carousel (with 24 cups, L × W × H =9.5 × 5.0 × 2.5 cm). The equipment is attached to a rotating frame mounted on a tripod base, which has a fin to align it to the flow direction. This rotating frame ensures that the instruments, which have flow-through sensing zones (e.g. DFC and LISST-100), are kept perpendicular to the flow to minimise floc break-up. A critical point about INSSECT is its recovery, which has to be very careful to prevent loss of particles accumulated in the cups. It can be deployed in shallow waters for up to 2 weeks, be recovered, turned around and redeployed quickly (Mikkelsen et al., 2004).

Another technique under development (MOPAR, Moored Optical Particle, Dynamics Technology, California) includes: (i) a multi-aperture detector composed of several photodiodes; (ii) a dual-purpose imager that includes both a shadowgraph technique and laser diffraction instrument; and (iii) a sending device. This instrument will simultaneously provide three-dimensional trajectories of multiple particles and size-specific particle abundances. It is designed to be moored and to gently withdraw the water sample, aiming to minimise floc break-up (Asper, 1996).

4. Non-intrusive measurements of settling velocity in a turbulent field

Some methods allow a non-intrusive in situ determination of floc settling velocities without confining a water volume, and therefore they do not influence the ambient turbulence or the flocculation dynamics. Two examples are direct holographic techniques, and indirect acoustical sensors. Alternative in situ non-intrusive settling velocity evaluations can also be performed by: estimating the clearance rates of sediment from a plume (Hill et al., 2000), analysing the decay of SPM concentrations in consecutive profiles measured before and after a dredger (Wolanski and Gibbs, 1992); or monitoring over time the disappearance from the water column of fluorescent tracers to quantify the rate of paint/dye deposition (Adams et al., 1998).

4.1. Direct holographic technique

In the last few years, underwater optical holography has become increasingly feasible and its range of applications for oceanographic measurements has increased to include: in situ observation of living, motile, marine organisms (Chalvidan et al., 1998; Watson et al., 1999; Katz et al., 1999; Malkiel et al., 1999); inter-particle relationship, turbulence, local shear and relative motion (Katz et al., 1999); and as a particle velocimeter (Carder et al., 1982; Costello et al., 1989). We briefly describe here a few examples of holographic systems that have been directly applied to measure particle settling velocity in marine systems.

The hologram measurement principle consists of emitting a collimated and spatially filtered laser beam which traverses the ambient water between two windows. This light is diffracted by the particles in the sample volume and their interference pattern can be recorded on high-resolution film (Malkiel et al., 1999) or a charge-coupled device (CCD camera) (Owen and Zozulya, 2000, Fig. 6). They can work in one of two geometrical configurations, 'in-line' or 'off-axis', with the second method usually presenting a smaller size resolution but a larger sampling volume, i.e. a concentration of particles more than an order of magnitude larger (Malkiel et al., 1999).

One of the first contributions to in situ holography was due to Carder et al. (1982) who developed a free-floating sediment trap equipped with a submersible holographic particle velocimeter (HPV) for recording in situ size, shape, orientation and settling rate of microscopic particles. The HPV uses an in-line hologram to record the interference between the far field diffraction pattern scattered by the particles and the collinear background in the HeNe (2 mW) laser-illuminated sample volume (3.27 ml) (Carder et al., 1982). Measurements are taken in a settling chamber ($W \times L = 4.5 \times 50$ cm) opened only at the top and fitted with two sets of flow dampers ($L = 5$ and 10 cm) to minimise water motion in the sampling path. The HPV is controlled by a digital timer and programmed to trigger exposures at 7, 7.5, 9 and 13.5 s after starting the laser, with the system able to collect a total of 250 exposures (Carder et al., 1982). Data reduction was manually performed by reconstructing the holographic images onto a white screen (200× magnification) and measuring with a micrometer the dimensions and displacement between frames of 30 particles (Carder et al., 1982).

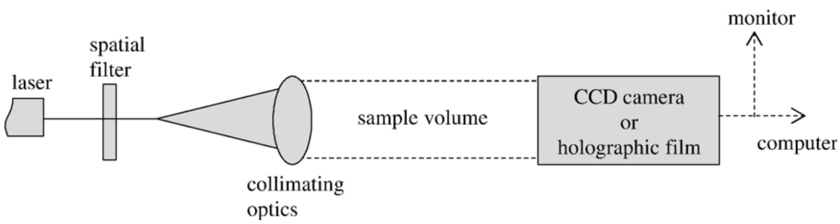


Fig. 6. Diagram of the holographic array composed of a laser light that is spatially filtered and collimated, a remote sample volume and a CCD camera or holographic film connected to a computer and a video monitor (modified from Costello et al., 1989; Owen and Zozulya, 2000).

A similar sediment trap system was used in 28 deployments in the North Pacific Ocean (depths of 37 to 907 m) that produced 4000 holograms with 10^8 observable data planes. This system integrates a free-drifting sediment trap with two independent holographic imaging systems, and a HeNe laser illumination to record sequential movement of particles through the collection cup from two orthogonal perspectives (Costello et al., 1989). The trap (H = 300 cm, 350 kg in air) has six conical cups ending in a small sampling volume ($V = 7\ cm^3$), where mass accumulation is monitored by an upward-looking holographic system. Six sequential samples of SPM can be collected over periods ranging from 3 h to 6 d, at a sampling rate varying from 15 s to 29 min. The maximum measurable fall velocity corresponds to that of a quartz sphere with a diameter of 76 μm. The sampling cups are filled either with a high-viscous fluid to observe the settling and shape of mineral particles, or high-salinity water to allow observations of light organic material and organisms (Costello et al., 1989).

The previous devices, although using holography, are flow intrusive since they measure the particle settling inside small chambers. Devices developed more recently are flow non-intrusive and utilise a bigger sample volume. For instance, a submersible holographic camera has been developed that records single or multiple exposure holograms (300 exposures per deployment) for measuring particle sizes (from 10 μm) or motions in the ocean. It is a battery-powered, modular, self-contained system remotely operated by a PC through fibre optic links. It also contains a buoyancy control system that allows deployment as a neutrally buoyant drifter or in a slow profiling mode. It consists of a pulsed ruby laser (694.3 nm light, power of 30 mJ and pulse of 30 ns) and two independent dual flash lamps. It can be configured both for in-line and off-axis holography of a sampling volume ranging from 732 to 1964 cm^3, in which typically 5000 to 20 000 identifiable particles are recorded (Katz et al., 1999; Malkiel et al., 1999).

Most recently, a commercial version of a digital in-line holographic sensor (DHS) has been developed (Owen and Zozulya, 2000). This device has two laser diodes (680 and 780 nm), with a field 25 cm deep and uses a CCD array to record the diffraction patterns formed by the particles. Over 200 sequential holograms can be recorded at a 30 Hz sampling rate and with a size resolution of 5 μm. A sophisticated software module (Holomaker) numerically reconstructs the particle images in two-dimensional slices taken through the 3D sample volume (Owen and Zozulya, 2000).

Recent holographic techniques provide a non-intrusive measurement of size and settling velocities of a large number of particles since they sample a much larger volume compared with video image systems. Data processing of hologram information is time consuming, but it has been facilitated by the use of advanced software for image reconstruction.

4.2. Indirect acoustic methods

Multiple-frequency acoustic backscatter can be used for measuring the size and concentration of particles, and current velocity by emitting very short pulses ($\approx 10\ \mu$s) of sound of high frequency ($\approx$1–10 MHz) through the water column, which are scattered back by the suspended particles and registered by a pressure sensor. Inversion methods are then applied to convert the backscatter pressure profiles as a function of z, the height above the bed, to particle diameter (62–2000 μm) and SPM concentration profiles (up to 30 g l^{-1}) (Kawanisi and Yokosi, 1997; Thorne et al., 1991; Rose and Thorne, 2001; Wren and Kuhnle, 2002). The acoustic backscatter signal can be empirically calibrated to mass concentration of SPM by collecting and analysing water samples taken in situ (Holdaway et al., 1999; Fugate and Friedrichs, 2003; Voulgaris and Meyers, 2004). Alternatively, the calibration can be performed in the laboratory using bottom sediment from the sampling site (Thorne et al., 1991; Kawanisi and Yokosi, 1997; Williams et al., 1999).

The equation used to compute the concentration profiles of suspended particles based on the backscatter pressure profiles depends on the backscatter pressure, density of sediment, the sediment backscattering form factor, attenuation coefficients due to water and suspended sediments as well as on other sensor specific parameters (e.g. acoustic power, gain, beam strength) (Vincent and Downing, 1994, Eq. (1)). In addition, temperature and to a lesser extent salinity can influence the total acoustic attenuation coefficient in seawater containing suspended particles (Richards, 1998). The intensity of the backscattered pressure due to suspended particles (I) is proportional to the particle concentration (C) multiplied by a form factor (f) and divided by the diameter of particles (d) integrated over the n size classes, i.e. $I \propto \sum_n C_n f_n^2/d_n$; where the form factor is a complex function of grain size, shape, elasticity and density (Lynch et al., 1994; Fugate and Friedrichs, 2002). The form factor (or f_n^2/d_n) is generally inferred by calibration in the laboratory by analysing the acoustic scattering properties of disaggregated sediments from the area of interest (Sheng and Hay, 1988; Lynch et al., 1994).

Through the acoustic method, settling velocities of near-bed suspended particles may be indirectly estimated by assuming a lowest-order sediment concentration balance between gravitational settling and upward turbulent diffusion, i.e. $-W_{sn}\,C_n = KdC_n/dz = -\langle w'C_n'\rangle$, where W_{sn}, C_n are the settling velocity and concentration of particle type n, respectively, K is the eddy diffusivity. Turbulent fluctuations in both vertical velocity (w') and backscatter (C') can be measured directly with the acoustic Doppler velocimeter (ADV) (Vincent and Downing, 1994; Fugate and Friedrichs, 2002, 2003). The above equation can be integrated under steady state conditions to produce the Rouse equation (Rouse, 1937), from which situ settling velocity can be computed based on vertical SPM concentrations and bed shear stresses (Dyer, 1986). Again, the wave-current bed shear stresses and SPM concentrations applied to the Rouse equation can be measured by acoustic backscatter sensors (Williams et al., 1999; Rose and Thorne, 2001; Williams et al., 2002). Alternatively, Kawanisi and Yokosi (1997) estimated temporal variations of SPM settling velocities using the non-steady form of the transport equation of suspended sediment and applying ADV data to estimate turbulent fluctuations of SPM concentration and flow velocity.

Acoustic backscatter offers a very high temporal ($\approx$0.1 s) and spatial ($\approx$1 cm) resolution and, additionally, the ability to measure SPM concentrations non-intrusively and to observe the behaviour of turbulent processes very close to the bed. The method also provides a temporal location of the bed and allows sampling of a large stratum (a few metres) of the water column (Thorne et al., 1991; Rose and Thorne, 2001). The acoustic method also allows estimating in situ settling velocities without affecting the ambient turbulence (Fugate and Friedrichs, 2002).

However, acoustical techniques require the use of complicated interactive-algorithms to translate the sensor response into SPM concentration and size distribution. These algorithms need to take into account several compensations for variations in water properties (e.g. temperature, salinity), instrument characteristics (e.g. power, frequency) and the dependency of the calibration on the size of sediment in suspension (Thorne et al., 1991; Vincent and Downing, 1994; Thorne and Hanes, 2002). Therefore, in order to calibrate the acoustic instruments it is necessary to know the size of material in suspension; changes in the in situ size distribution in relation to sediment sizes used to calibrate the sensor will increase uncertainty in the estimation of concentration values (Thorne et al., 1991). This fact is particularly critical when working with cohesive sediments, since the behaviour of the form factor (f_n^2/d_n) as a function of the particle size is unknown for naturally aggregated silts and clays (Fugate and Friedrichs, 2002). The acoustic backscattering characteristics of porous aggregates are still unexplored due to the difficulty in retrieving undamaged, unaltered samples of aggregates from the field (Lynch et al., 1994) and due to the non-existence of well-defined inversion algorithms for use with cohesive sediments, especially in high concentration environments, when attenuation is substantial (Thorne and Hanes, 2002). Further, Fugate and Friedrichs (2002) suggested that the acoustic form function depends mostly on the size and shape of the constituent grains rather than the size or shape of the aggregate as a whole.

In a review of acoustic methods, Thorne and Hanes (2002) pointed out that the use of sound to measure SPM concentration and particle size has been successful in non-cohesive environments; and therefore, there is a need to understand acoustic properties of more complex suspensions of combined cohesive and non-cohesive sediments, if the development of such instruments is to progress. However, the much larger sensitivity of acoustic sensors to sand-sized particles (tens to hundreds of microns) (Osborne et al., 1994; Gartner, 2002; Voulgaris and Meyers, 2004) complicates the interpretation of the acoustic signal in mixed non-cohesive/cohesive environments.

In addition, the translation of acoustic backscatter signal strength into SPM concentrations and size is very complicated due to the difficulty in creating apparatus in the laboratory that can maintain uniform sediment concentrations suitable for calibrating instruments; furthermore these laboratory facilities (e.g. large-scale flumes) may not be always available (Wren et al., 2000; Thorne and Hanes, 2002). Ultimately, the presence of biological material and bubbles can contaminate the acoustic backscatter signal (Thorne and Hanes, 2002).

5. General assessment and conclusion

The devices available to quantify settling velocities of cohesive sediments have demonstrated both the feasibility and the importance of in situ measurements. These in situ measurements have been performed using different devices and measurement principles over the last four decades.

Settling tubes have been used to measure the mass distribution of settling velocity in situ in different environments (Owen, 1971, 1976; Dearnaley, 1996; Van

Leussen, 1996). Laser diffraction and video techniques have been largely employed to describe settling velocities distributions in terms of particle size (Bale, 1996; Agrawal and Pottsmith, 2000; Dearnaley, 1996; Sternberg et al., 1996; Manning et al., 2004). Based on these in situ measurements in different estuaries and coastal systems, a relationship between settling velocity (W_s) and concentration (C) of the form $W_s = kC^n$ has been established for SPM concentrations ranging from 10 to 10000 mg l^{-1} (Van Leussen, 1988; Dyer et al., 1996; Eisma et al., 1997). In this equation, k and n are empirical constants, and n usually ranges from 0.6 to 3.6 depending upon the particle/floc characteristics (Burt, 1986; Jones and Jago, 1996; Van Leussen, 1996; Eisma et al., 1997; Agrawal and Pottsmith, 2000). Even though this relationship applies to different environments in a broad range of concentrations, the absolute values of settling velocity for a given concentration can vary by an order of magnitude between the different situations, since the k value changes as a function of SPM characteristics (Burt, 1986). In addition, although a positive relationship between settling velocity and aggregate size has been established in many studies (Fennessy et al., 1994; Fennessy and Dyer, 1996; Sternberg et al., 1996; Van Leussen and Cornelisse, 1996; Mikkelsen and Pejrup, 2001; Manning, 2004; Voulgaris and Meyers, 2004), these data also exhibit a large scatter. Further, most of the studies have demonstrated a reduction in the floc density (and excess density) as their size increases, once more large deviations in the data usually occurs (Gibbs, 1985; Fennessy et al., 1994; Mikkelsen and Pejrup, 2001; Manning, 2004).

This data variability may result from variations in the floc density and in the quantity and quality of organic polymers binding the aggregates as well as from differences in the turbulence regime during floc formation (Dyer, 1995). Moreover, this variability may partly result from differences in the instruments, field and analytical techniques used to compute settling velocities or from disturbance of aggregates during sampling (Dyer et al., 1996; Pejrup and Edelvang, 1996; Ten Brinke, 1997). The in situ measurement of both quantitative and qualitative floc characteristics (i.e. structure, composition and settling velocity) through video techniques, associated with simultaneous measurements of the turbulent shear stress, has provided new insights on the flocculation dynamics of cohesive sediments (Manning, 2004; Manning et al., 2004): settling velocity behaviour cannot be described by single parameter relationships, since a large number of factors are involved.

Even though many improvements and much technological sophistication have been achieved, there remain some issues to be resolved, mainly associated with difficulties in quantifying and predicting the complex properties of the aggregates and in finding mechanisms to perform undisruptive sampling. Although there is no ideal instrument, since each device was designed to meet a specific scientific purpose and a particular research application, it is valuable to put into perspective the different options available and the factors that should be taken into account when analysing results obtained with a particular device or comparing results between them. Moreover, some concerns are common to all or most of the instruments and they need to be considered in improving or building new devices.

The majority of the described devices confine or enclose a water volume to measure particle size and/or settling velocity and that eliminates or drastically reduces natural turbulence levels (Berlamont et al., 1993). Generating still conditions can induce diverse processes that alter aggregates' size and settling compared to their behaviour in the undisturbed environment. These include, for instance, differential settling, floc formation and/or break-up and modifications in the particle-fluid interactions within the settling columns.

When particles settle in a confined settling tube through a fluid of finite extent, the drag on particles is increased because when the fluid streamlines around the particle it hits the tube walls, and is reflected back on the particles. Also, as the fluid is stationary at a finite distance from the particle, there is a distortion of the flow pattern which reacts back on the particle (Allen, 1981). Interactions between particles in a polydisperse suspension can also change their terminal settling velocity compared to that of a single particle. For example, the entrapment of slower particles within the wakes and vortex rings of faster particles ('hydrodynamic wake capture') increases the settling velocity of the clustered particles (Lovell and Rose, 1991a,b). Therefore, settling column dimensions and flocs-fluid interactions can affect the measured settling velocities. A minimum internal tube diameter of 4.5 cm has been recommended to avoid wall and wake capture effects (Lovell and Rose, 1991b).

Some authors also claim that isolating particles inside the still-water environment of a closed settling column can enhance floc growth as turbulent-shear values decrease (Milligan, 1995; Fugate and Friedrichs, 2002). Curran et al. (2003) performed laboratory experiments with an invertible settling column using both sample withdrawal and video analysis, and concluded that there was a re-aggregation of the SPM after 15 min of settling that led to the growth of flocs with lower density than the initial floc population, and therefore, with lower settling velocity. Faster re-aggregation has also been reported, i.e. within the first 3 to 6 min after ceasing turbulence (Milligan, 1995; Dearnaley, 1996). In contrast, Mikkelsen et al. (2004) did not observe floc alteration inside a settling column when comparing data simultaneously obtained by a digital floc camera (outside the column) and a video camera mounted in a settling column, even in relatively energetic environments.

Differential settling promotes floc growth when a much faster settling aggregate (larger and denser) overtakes and collides with a particle of slower fall velocity (smaller or lighter) and they coalesce (Mehta, 1986). This process is enhanced with increasing SPM concentrations, and it may dominate the aggregation dynamics during times of reduced turbulent energy, when large porous flocs begin to form and settle out, due to an increase in the encounter frequency (Puls et al., 1988; Milligan, 1995; Fugate and Friedrichs, 2003). In addition, porous aggregates, with porosities typical of large marine flocs, have collision efficiencies one to two orders of magnitude higher than impermeable spheres. This is because there is sufficient flow across the sinking large aggregate surface to shift the trajectories of small particles so that they pass through the aggregate, making collisions possible that might otherwise not occur (Stolzenbach, 1993; Stolzenbach and Elimelech, 1994; Kim and Stolzenbach, 2004). Modelling of the differential settling inside settling tubes has shown that this process can lead to increases in the median settling velocities by a factor of 1.3 times for concentrations of 100 mg l^{-1}, and by a factor of 2–4.4 times for concentrations of 700–800 mg l^{-1} (Puls et al., 1988; Puls and Kühl, 1996). However, Stolzenbach and Elimelech (1994) showed that the probability of large, but less dense, rapidly falling particles colliding with small, but denser, slowly falling particles is very small, because the trajectory of the smaller particle is deflected around that of the larger one. They also pointed out that the effect of differential settling on aggregation in marine systems is probably significant only between very small and very large particles, for which the effect of particle porosity must be also considered.

Another point to consider is that most methods of measuring the settling of aggregates involve their capture in settling tubes or chambers by trapping or withdrawing a water volume in situ through sampling mechanisms, such as pumping, lids or valve closure systems, vertical/horizontal tube displacement, flow decelerators (e.g. baffles). These methods are all flow intrusive and can themselves alter the flow and aggregate characteristics. Although most authors agree that different devices can disturb fragile aggregates, the absolute quantification of the amount of disruption is very difficult because of the dissimilarity of the principle of measurement and design of these devices, the lack of well-controlled protocols for operating similar devices (such as the settling tubes) and the variability of aggregate characteristics between different environments. This makes comparisons of the results between them debatable.

As an example, Dearnaley (1996) observed an order of magnitude reduction in the settling velocities obtained with an Owen-tube (not thermally insulated) compared with those derived from image analysis. By contrast, Sanford et al. (2005) found reasonable agreement between the settling velocities obtained with a Valeport settling tube and those measured by an in situ video system. They attributed this to: (i) their sampling of break-up resistant resuspended flocs; (ii) sampling low enough SPM concentrations, so that interactions between particles were negligible; and (iii) careful insulation of the tube from external temperature fluctuations. An inter-comparison investigation testing ten devices (i.e. seven different settling tubes and three video image systems), used to quantify in situ the settling velocity of aggregates in the turbidity maximum of the Elbe estuary, showed differences of an order of magnitude between the results. These discrepancies were partially attributed to small-scale spatial and temporal SPM patchiness in the turbidity field, and also to differences in the setup/design/measurement principle of the devices, the experimental procedure and methods used to calculate median settling velocities, and the use of distinct starting times for computing settling velocities (Dyer et al., 1996).

Another issue common to all settling columns is the turbulence induced by the closure of the apparatus. The turbulence usually takes a few minutes to cease, which prevents the settling behaviour from being reliably measured during this period. All settling tubes exhibit this phenomenon to an extent that is dependent on the column dimensions and the closure system. If the influence of trapped turbulence is ignored there will be an underestimation of the settling velocities (Murray et al., 1996), since the settling velocities of the larger, faster aggregates are not well represented. This can be the case, not only for the Owen tubes, but also other devices. Although it would be very difficult to idealise a completely non-disruptive device in terms of water sample capture system and settling column closure, some design solutions can help minimise this influence. For instance, the feedback system used in the INSSEV instrument for closing the chamber flap door at a rate proportional to the ambient current speed potentially reduces the induced turbulence inside the tube (Fennessy et al., 1994). In addition, the rotating frame proposed by Mikkelsen et al. (2004), which orients itself with the flow, solves the problem for those instruments that need to be aligned to the flow, and diminishes the current shear on the devices under high currents.

None of the existing instrumentation can simultaneously measure the settling velocity, size and density of aggregates, all of which are crucial parameters for describing the dynamics of aggregates. According to Manning et al. (2004), a "true measure of flocculation can only be assessed by examining the combined factors (i.e. size, settling velocity and floc density) which effect the mass settling flux rates". These parameters change over time in coastal systems, as a function of variations in the balance between the forces of aggregation and disruption (Fennessy et al., 1994), mainly driven by the turbulence level within the water column. Therefore, researchers have become more aware over time of the need to combine diverse kinds of instruments to be able to measure the different aspects of cohesive sediment dynamics, and to join the various pieces of information together to delineate the whole picture. This approach has been adopted in recent studies, where compound instrumentation for simultaneous measurement of floc sizes and settling velocities (through multiple methods) as well as flow monitoring (3D velocity and density) has been applied using an instrumented platform (Mikkelsen et al., 2004) or simultaneous deployments (Sanford et al., 2005; Manning, 2004; Manning et al., 2004).

The use of multiple instruments in simultaneous deployments that follows a consistent sampling protocol to facilitate data comparison seems a more appropriate approach to investigate the cohesive aggregate dynamics. Further, the main parameters conditioning the aggregate dynamics, i.e. aggregates' settling velocity, size and density, should be ideally measured at the same time in a non-disruptive way. In addition, measurements of the physical characteristics of the settling medium (e.g. current speed, Reynolds regime, salinity and temperature) are very important, as are comparisons between the aggregate sizes and settling velocities measured inside and outside (turbulent-dependent) the settling columns. In order to perform these measurements, both flow intrusive and non-intrusive techniques need to be applied.

Additionally, the mass frequency distribution of settling velocities is needed for numerical modelling of SPM mass transport (Puls and Kühl, 1996). Direct devices used for this purpose have the advantage of reducing build-up errors that occur during data calibration and mathematical procedures for data analysis. Settling tubes (Owen-type tubes) and an underwater mass balance (SEDVEL) are the only direct devices available for SPM mass quantification. The SEDVEL is the unique autonomous device, which is also subject to less manoeuvring since measurements are made in place and it does not require subsample withdrawal. The integration of the underwater balance with video/holographic techniques would allow direct measurements of three main aggregates characteristics: mass, settling velocity and size. Care must be taken, however, because devices that measure mass give an integrated mass distribution for the whole aggregate population, while video image techniques analyse floc by floc within a size range depending on instrument resolution. Alternatively, optical methods can provide a relatively higher temporal and spatial resolution, but their calibration is dependent on many factors and their data analysis involves several theoretical approximations and assumptions. However, they are likely to be the most suitable techniques to use in very high sediment concentrations (up 100 g l^{-1}), because of the limitations of most of the other available methods.

Another source of error is inherent to all instruments and methods that apply the Stokes Law to indirectly estimate settling velocities from size measurements (or vice versa). "The estimate is very crude because of the unknown density" (Fennessy et al., 1994). The density is extremely important in determining the settling velocity of flocs, and to a lesser extent, the flow through and around a porous floc can also affect its fall speed (Lick and Huang, 1993). Van der Lee (2000) found a large scatter when plotting floc settling velocities as a function of their size and attributed this to differences in floc densities. It has been stated that the average density of aggregates decreases with increasing size and order of aggregation (Krone, 1986; Mikkelsen and Pejrup, 1998, 2001). A more accurate prediction of the floc effective density (or excess density) is obtained when Stokes Law is combined with both size and settling velocities, directly and simultaneously measured (Manning et al., 2004). And more robust mass flux estimates can be achieved by including assumptions about flocs' mean dry density based on their organic content (Manning and Dyer, 1999). However, it has been demonstrated in laboratory experiments that fractal permeable aggregates produced settling velocities 4 to 8.3 times higher than those predicted by using either an impermeable sphere model (Stokes Law) or a permeable sphere model that specified aggregate permeability for a homogeneous distribution of particles within an aggregate (Johnson et al., 1996). Therefore, Stokes Law underestimates floc settling velocities: porous, permeable aggregates have different drag relationships from those of spherical particles (Mikkelsen et al., 2004).

Estimates of aggregates' density are still more demanding, since density depends not only on the floc sizes, but also on their organic content and structure (Van der Lee, 2000). The aggregate density and effective density are required to calculate vertical settling fluxes, when measurements of aggregate mass are not available. Even a small number of macroflocs can account for a large portion of the vertical settling flux (Van Leussen and Cornelisse, 1993b; Manning et al., 2004). Even if the aggregates could be properly preserved after their collection in the field, the direct determination of the floc density in the laboratory is difficult. For instance, when measuring the density by settling flocs in sucrose solutions, the pore water of flocs is quickly replaced with the sucrose solution, thus altering the floc density (Gibbs, 1985). At present, there is no instrument available to directly measure the density of flocs in situ.

Alternatively, mass measurements together with the volume assumptions could be used to determine the floc density and excess density. Uncertainties remain on the assumptions about the three dimensional structure of aggregates. Advances in the indirect fractal analysis or direct techniques to measure the aggregates' volume (e.g. holographic and shadowgraph method) can improve these measurements in the future. Volume concentrations can also be obtained with laser diffraction techniques. Another approach that could be used to calculate the SPM volume is to use a sediment trap carousel to collect the material settled in a tube that contains an underwater balance. This set-up would permit the measurement of both the immersed (P_I) and dry (P_{spm}) weights of SPM, and the particle volume (V_{spm}) could be calculated by assuming that the V_{spm} is equal to the volume of water displaced by the particles (V_w) at a known water density (ρ_w) and gravitational field strength (g) through the relationship: $P_{spm} = P_I + \rho_w V_w g$.

Alternatively, a differential pressure transducer (DPT) may be used to determine differences in the specific weight of sediment bearing water versus water near surface, with lower concentration. This difference in pressure between two inlets of the DPT can be applied to calculate the average SPM concentration (Wren and Kuhnle, 2002). However, such measurements can be affected by changes in temperature gradient, turbulence and dissolved solid concentrations (Wren and Kuhnle, 2002).

One of the most challenging tasks is the design of non-intrusive sampling devices and settling chambers, since some turbulence is inevitably generated during sampling or water sample replacement. Most of the optical, laser and video techniques require a short scan path and focal window dimensions, and they usually use small sampling chambers that promote some instrumental shear-induced floc breakage. Although there is speculation about the potential of floc disruption during sampling, there are few systematic attempts to quantify this effect. Some effort should be directed to designing and testing different dimensions and shapes of settling columns as well as less disruptive ways to confine the water samples. Moreover, few devices can successfully work both as profilers and be deployed on the bottom. Higher flexibility in this direction could be sought by designing more robust devices to work while suspended in the water column under high current velocities. Increasing the portability of instruments (by reducing their weight and size) would also broaden their application to different environments (both shallow and deep coastal systems) and reduce the logistical and personal requirements for operating them.

Although great effort has been expended in finding simple relationships for describing settling velocity of aggregates, the settling behaviour is complex. It is usually explained by a combination of factors that change both spatially and temporally in coastal systems. Generalisations are also complicated because of the large range of instrumentation and methodologies applied, which demand careful comparisons between different studies. Simultaneous measurements of the characteristics of different aggregates (e.g. settling velocity, size, density, mass and organic content), and their reduction to inter-comparable quantities (despite methodological approaches), are still required in order to better understand the dynamics of cohesive aggregates.

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References

Adams, E.E., Stolzenbach, K.D., Lee, J.J., Caroli, J., Funk, D., 1998. Deposition of contaminated sediments in Boston Harbour studied using fluorescent dye and particles tracers. Est. Coast. Shelf Sci. 46, 371–382.

Agrawal, Y.C., Pottsmith, H.C., 2000. Instruments for particle size and settling velocity observations in sediment transport. Mar. Geol. 168, 89–114.

Allen, T., 1981. Particle Size Measurement, 3rd Ed. Chapman and Hall, London. 678 pp.

Allersma, E., 1980. Mud in estuaries and along coasts. Proc. Int. Symp. Riv. Sedim. Beijing, China, pp. 663–685.

Asper, V.L., 1996. Particle flux in the ocean: oceanographic tools. In: Ittekkot, V., Schafer, P., Depetris, P.J. (Eds.), Particle Flux in the Ocean. John Wiley and Sons Ltd, Chichester, pp. 71–84.

Ayukai, T., Wolanski, E., 1997. Importance of biologically mediated removal of fine sediments from the Fly River plume, Papua New Guinea. Est. Coast. Shelf Sci. 44, 629–639.

Bale, A.J., 1996. In situ laser optical particle sizing. J. Sea Res. 36, 31–36.

Bartz, R., Zaneveld, J.R.V., McCave, I.N., Hess, F.R., Nowell, A.R. M., 1985. Rost and Beast: devices for in-situ measurement of particle settling velocity. Mar. Geol. 66, 381–395.

Berlamont, J., Ockenden, M., Toorman, E., Winterwerp, J., 1993. The characterisation of cohesive sediment properties. Coast. Eng. 21, 105–128.

Boss, E., Pegau, W.S., Gardner, W.D., Zaneveld, J.R.V., Barnard, A. H., Twardowski, M.S., Chang, G.C., Dickey, T.D., 2001. Spectral particulate attenuation and particle size distribution in the bottom boundary layer of a continental shelf. J. Geophys. Res. 106 (C5), 9509–9516.

Burt, T.N., 1986. Field settling velocities of estuary muds. In: Mehta, A.J. (Ed.), Estuarine Cohesive Sediment Dynamics. Springer-Verlag, Berlin, pp. 126–150.

Carder, K.L., Steward, R.G., Betzer, P.R., 1982. In situ holographic measurements of the sizes and settling rates of oceanic particulates. J. Geophys. Res. 87 (C8), 5681–5685.

Chen, S., Eisma, D., Kalf, J., 1994. In situ size distribution of suspended matter during the tidal cycle in the Elbe estuary. Neth. J. Sea Res. 32, 37–48.

Chalvidan, V., Chambard, J.P., Craig, G., Diard, A., Foresti, G.L., Forre, B., Gentili, S., Hobson, P.R., Lampitt, R.S., Maine, P., Malmo, J.T., Nareid, H., Pescetto, A., Watson, J., 1998. High-resolution in situ holographic recording and analysis of marine organisms and particles (HOLOMAR). IEEE, Piscataway, NJ (USA), Ocean Engineering Soc. Oceans 98—Engineering for sustainable use of the oceans: Conference proceedings, 28 September to 1 October 1998, Nice (France), vol. 3, pp. 1599–1603.

Cornelisse, J.M., 1996. The field pipette withdrawal tube (FIPIWITU). J. Sea Res. 36, 37–39.

Costello, D.K., Carder, K.L., Betzer, P.R., Young, R.W., 1989. In situ holographic imaging of settling particles: applications for individual particle dynamics and oceanic flux measurements. Deep-Sea Res. 36, 1595–1605.

Curran, K.J., Hill, P.S., Milligan, T.G., 2002. Fine-grained suspended sediment dynamics in the Eel River flood plume. Cont. Shelf Res. 22, 2537–2550.

Curran, K.J., Hill, P.S., Milligan, T.G., 2003. Time variation of floc properties in a settling column. J. Sea Res. 49, 1–9.

Dearnaley, M.P., 1996. Direct measurements of settling velocities in the Owen tube: a comparison with gravimetric analysis. J. Sea Res. 36, 41–47.

Dearnaley, M.P., 1997. Direct measurements of settling velocities in the Owen tube: a comparison with gravimetric analysis. In: Burt, N., Parker, R., Watts, J. (Eds.), Cohesive Sediments. John Wiley and Sons Ltd., Chichester, pp. 75–85.

Dietrich, W.E., 1982. Settling velocity of natural particles. Wat. Resour. Res. 18, 1615–1626.

Douglas, R.W., Rippey, B., Gibson, C., 2003. Estimation of the in-situ settling velocity of particles in lakes using a time series sediment trap. Freshw. Biol. 48, 512–518.

Dyer, K.R., 1986. Coastal and Estuarine Sediment Dynamics. John Wiley and Sons Ltd., Toronto. 341 pp.

Dyer, K.R., 1995. Sediment transport processes in estuaries. In: Perillo, G.M.E. (Ed.), Geomorphology and Sedimentology of Estuaries. Developments in Sedimentology. Elsevier Science B.V., Amsterdam, pp. 423–449.

Dyer, K.R., Cornelisse, J., Dearnaley, M.P., Fennessy, M.J., Jones, S. E., Kappenberg, J., McCave, I.N., Pejrup, M., Puls, W., Van Leussen, W., Wolfstein, K., 1996. A comparison of in situ techniques for estuarine floc settling velocity measurements. J. Sea Res. 36, 15–29.

Eisma, D., 1986. Flocculation and de-flocculation of suspended matter in estuaries. Neth. J. Sea Res. 20, 183–199.

Eisma, D., Kalf, J., 1996. In situ particle (floc) size measurements with the NIOZ in situ camera system. J. Sea Res. 36, 49–53.

Eisma, D., Li, A., 1993. Changes in suspended-matter floc size during the tidal cycle in the Dollard estuary. Neth. J. Sea Res. 31, 107–117.

Eisma, D., Schuhmacher, T., Boekel, H., Van Heerwaarden, J., Franken, H., Laan, M., Vaars, A., Eijgenraam, F., Kalf, J., 1990. A camera and image-analysis system for in situ observations of flocs in natural waters. Neth. J. Sea Res. 27, 43–56.

Eisma, D., Bernard, P., Cadée, G.C., Ittekkot, V., Kalf, J., Laane, R., Martin, J.M., Mook, W.G., Van Put, A., Schuhmacher, T., 1991. Suspended-matter particle size in some West-European estuaries: Part I. Particle-size distribution. Neth. J. Sea Res. 28, 193–214.

Eisma, D., Dyer, K.R., Van Leussen, W., 1997. The in situ determination of the settling velocities of suspended fine-grained sediment—a review. In: Burt, N., Parker, R., Watts, J. (Eds.), Cohesive Sediments. John Wiley and Sons Ltd., Chichester, pp. 17–44.

Ellis, K.M., Bowers, D.G., Jones, S.E., 2004. A study of the temporal variability in particle size in a high-energy regime. Est. Coast. Shelf Sci. 61, 311–315.

Fennessy, M.J., Dyer, K.R., 1996. Floc population characteristics measured with INSSEV during the Elbe estuary intercalibration experiment. J. Sea Res. 36, 55–62.

Fennessy, M.J., Dyer, K.R., Huntley, D.A., 1994. INSSEV: an instrument to measure the size and settling velocity of flocs in situ. Mar. Geol. 117, 107–117.

Fennessy, M.J., Dyer, K.R., Huntley, A., 1997. Estimation of settling flux spectra in estuaries using INSSEV. In: Burt, N., Parker, R., Watts, J. (Eds.), Cohesive Sediments. John Wiley and Sons Ltd., Chichester, pp. 87–104.

Fisher, M.A., Odén, S., 1923–24. The theory of the mechanical analysis of sediments by means of the automatic balance. Proceedings of the Royal Society of Edinburgh, vol. 44, pp. 98–115. Edinburgh.

Fox, J.M., Hill, P.S., Milligan, T.G., Boldrin, A., 2004. Flocculation and sedimentation on the Po River Delta. Mar. Geol. 203, 95–107.

Fugate, D.C., Friedrichs, C.T., 2002. Determining concentration and fall velocity of estuarine particle populations using ADV, OBS and LISST. Cont. Shelf Res. 22, 1867–1886.

Fugate, D.C., Friedrichs, C.T., 2003. Controls on suspended aggregate size in partially mixed estuaries. Est. Coast. Shelf Sci. 58, 389–404.

Gartner, J.W., 2002. Estimation of suspended solids concentrations based on acoustic backscatter intensity: theoretical background. Turbidity and other sediment surrogates workshop. Reno, Nevada, US. http://water.usgs.gov/osw/techniques/TSS/listofabstracts.htm.

Gibbs, R.J., 1985. Estuarine flocs: their size, settling velocity and density. J. Geophys. Res. 90 (C2), 3249–3251.

Gorsky, G., Picheral, M., Stemmann, L., 2000. Use of the underwater profiler for the study of aggregate dynamics in the North Mediterranean. Est. Coast. Shelf Sci. 50, 121–128.

Hamm, L., Migniot, C., 1994. Elements of cohesive sediment deposition, consolidation and erosion. In: Abbott, M.B., Price, W.A. (Eds.), Coastal, Estuarial and Harbour Engineers' Reference Book. E and FN Spon, Melbourne, pp. 93–106.

Hatcher, A., Hill, P., Grant, J., Macpherson, P., 2000. Spectral optical backscatter of sand in suspension: effects of particle size, composition and color. Mar. Geol. 168, 115–128.

Heffler, D.E., Syvitski, J.P.M., Asprey, K.W., 1991. The floc camera. In: Syvitski, J.P.M. (Ed.), Principles, Methods and Application of Particle Size Analysis. Cambridge University Press, New York, pp. 209–221.

Hill, P.S., Sherwood, C.R., Sternberg, R.W., Nowell, A.R.M., 1994. In situ measurements of particle settling velocity on the northern California continental shelf. Cont. Shelf Res. 14, 1123–1137.

Hill, P.S., Syvitski, J.P., Cowan, E.A., Powell, R.D., 1998. In situ observations of floc settling velocities in Glacier Bay. Alaska. Mar. Geol. 145, 85–94.

Hill, P.S., Milligan, T.G., Geyer, W.R., 2000. Controls on effective settling velocity of suspended sediment in the Eel River flood plume. Cont. Shelf Res. 20, 2095–2111.

Holdaway, G.P., Thorne, P.D., Flatt, D., Jones, S.E., Prandle, D., 1999. Comparison between ADCP and transmissometer measurements of suspended sediment concentration. Cont. Shelf. Res. 19, 421–441.

Jackson, G.A., Maffione, R., Costello, D.K., Alldredge, A.L., Logan, B.E., Dam, H.G., 1997. Particle size spectra between 1 μm and 1 cm at Monterey Bay determined using multiple instruments. Deep-Sea Res. I 44, 1739–1767.

Jago, C.F., Jones, S.E., 1998. Observation and modelling of the dynamics of benthic fluff resuspended from a sandy bed in the southern North Sea. Cont. Shelf Res. 18, 1255–1282.

Johnson, C.P., Xiaoyan, L., Logan, B.E., 1996. Settling velocities of fractal aggregates. Environ. Sci. Technol. 30, 1911–1918.

Jones, S.E., Jago, C.F., 1996. Determination of settling velocity in Elbe estuary using QUISSET tubes. J. Sea Res. 36, 63–67.

Jones, S.E., Jago, C.F., Bale, A.J., Chapman, D., Howland, R.J.M., Jackson, J., 1998. Aggregation and resuspension of suspended particulate matter at a seasonally stratified site in the southern North Sea: physical and biological controls. Cont. Shelf Res. 18, 1283–1309.

Katz, J., Donaghay, P.L., Zhang, J., King, S., Russel, K., 1999. Submersible holocamera for detection of particle characteristics and motions in the ocean. Deep-Sea Res. Part I: Oceanogr. Res. Papers 46, 1455–1481.

Kawanisi, K., Yokosi, S., 1997. Characteristics of suspended sediment and turbulence in a tidal boundary layer. Cont. Shelf Res. 17, 859–875.

Kim, A.S., Stolzenbach, K.D., 2004. Aggregate formation and collision efficiency in differential settling. J. Coll. Interf. Sci. 271, 110–119.

Kineke, G.C., Sternberg, R.W., 1989. The effect of particle settling velocity on computed suspended sediment concentration profiles. Mar. Geol. 90, 159–174.

Kineke, G.C., Sternberg, R.W., Johnson, R., 1989. A new instrument for measuring settling velocities in situ. Mar. Geol. 90, 149–158.

Knowles, S.C., Wells, J.T., 1996. Suspended aggregate analyses using ISAAC, Elbe River, 9–10 June 1993. J. Sea Res. 36, 69–75.

Kranck, K., 1986. Settling behavior of cohesive sediment. In: Mehta, A.J. (Ed.), Estuarine Cohesive Sediment Dynamics. Springer-Verlag, Berlin, pp. 150–169.

Kranck, K., Petticrew, E., Milligan, T.G., Droppo, I.G., 1993. In situ particle size distributions resulting from flocculation of suspended sediment. In: Mehta, A.J. (Ed.), Coastal and Estuarine Studies. Nearshore and Estuarine Cohesive Sediment Transport. American Geophysical Union, Washington, DC, pp. 60–74.

Krishnappan, B.G., 2000. In situ size distribution of suspended particles in the Fraser River. J. Hydraul. Eng. 126, 561–569.

Krone, R.B., 1986. The significance of aggregate properties to transport processes. In: Mehta, A.J. (Ed.), Estuarine Cohesive Sediment Dynamics. Springer-Verlag, Berlin, pp. 67–84.

Krumbein, W.C., Pettijohn, F.J., 1938. Principles of mechanical analysis. Manual of Sedimentary Petrography. Appleton Century Crofts Inc., New York, pp. 91–134. Chap. 5.

Law, D.J., Bale, A.J., 1998. In situ characterization of suspended particles using focused-beam laser reflectance particle sizing. In: Black, K.S., Paterson, D.M., Cramp, A. (Eds.), Sedimentary Processes in the Intertidal Zone. Geol. Soc., Spec. Publ., vol. 139, pp. 57–68. London.

Law, D.J., Bale, A.J., Jones, S.E., 1997. Adaptation of focused beam reflectance measurement to in-situ particle sizing in estuaries and coastal waters. Mar. Geol. 140, 47–59.

Lick, W., Huang, H., 1993. Flocculation and the physical properties of flocs. In: Mehta, A.J. (Ed.), Nearshore and Estuarine Cohesive Sediment Transport. Coastal and Estuarine Studies, vol. 42. American Geophysical Union, Washington, DC, pp. 21–39.

Lovell, C.J., Rose, C.W., 1991a. Wake-capture effects observed in a comparison of methods to measure particle settling velocity beyond Stokes' range. J. Sed. Petrol. 61, 575–582.

Lovell, C.J., Rose, C.W., 1991b. The effects of sediment concentration and tube diameter on particle settling velocity measured beyond Stokes' range: experiment and theory. J. Sed. Petrol. 61, 583–589.

Luettich, R.A., Wells, J.T., Kim, S.Y., 1993. In situ variability of large aggregates: preliminary results on the effects of shear. In: Mehta, A.J. (Ed.), Nearshore and Estuarine Cohesive Sediment Transport. . Coastal and Estuarine Studies, vol. 42. American Geophysical Union, Washington, DC, pp. 447–466.

Lynch, J.F., Irish, J.D., Sherwood, C.R., Agrawal, Y.C., 1994. Determining suspended particle size information from acoustical and optical backscatter measurements. Cont. Shelf Res. 14, 1139–1165.

Maldiney, M.A., Mouchel, J.M., 1996. In situ video recording of suspended flocs. J. Sea Res. 36, 87–91.

Malkiel, E., Alquaddoomi, O., Katz, J., 1999. Measurements of plankton distribution in the ocean using submersible holography. Meas. Sci. Technol. 10, 1142–1152.

Manning, A.J., 2004. Observations of the properties of flocculated cohesive sediment in three Western European esturies. J. Coast. Res., Special Issue (41), 70–81.
Manning, A.J., Dyer, K.R., 1999. A laboratory examination of floc characteristics with regard to turbulent shearing. Mar. Geol. 160, 147–170.
Manning, A.J., Dyer, K.R., 2002a. The use of optics for the in situ determination of flocculated mud characteristics. J. Opt. A: Pure Appl. Opt. 4, S71–S81.
Manning, A.J., Dyer, K.R., 2002b. A comparison of floc properties observed during neap and spring tidal conditions. In: Winterwerp, J.C., Kranenburg, C. (Eds.), Fine Sediment Dynamics in the Marine Environment. Elsevier Science, Amsterdam, pp. 233–250.
Manning, A.J., Dyer, K.R., Lafite, R., Mikes, D., 2004. Flocculation measured by video based instruments in the Gironde estuary during the European Commission SWAMIEE Project. J. Coastal Res., Special Issue (41), 58–69.
Mantovanelli, A., 2005. A new approach for measuring in situ the concentration and settling velocity of suspended cohesive sediment. Ph.D. Thesis, James Cook University of North Queensland, Townsville, Australia. 190 pp.
Mantovanelli, A., Noernberg, M.A., Marone, E., Silva, E.T., 1999. Evaluation of turbidity sensor response in different concentrations and sizes of sediment and comparison with field measurements. Bol. Paranaense de Geociências 47, 101–109.
McAnally, W.H., Mehta, A.J. (Eds.), 2001. Coastal and estuarine fine sediment processes. Proceedings in Marine Science, vol. 3. Elsevier, Amsterdam. 507 pp.
McCave, I.N., Gross, T.F., 1991. In-situ measurements of particle settling velocity in the deep sea. Mar. Geol. 99, 403–411.
Mehta, A.J., 1986. Characterization of cohesive sediment properties and transport processes in estuaries. In: Mehta, A.J. (Ed.), Estuarine Cohesive Sediment Dynamics. Springer-Verlag, Berlin, pp. 290–325.
Mehta, A.J., 1994. Hydraulic behaviour of fine sediment. In: Abbott, M.B., Price, W.A. (Eds.), Coastal, Estuarial and Harbour Engineers' Reference Book. E and FN Spon, Melbourne, pp. 577–584.
Mehta, A., McAnally Jr., W.H., Hayter, E.J., Teeter, A.M., Schoellhamer, D., Heltzel, S.B., Carey, W.P., 1989. Cohesive sediment transport II: application. J. Hydraul. Eng. 115, 1094–1112.
Mikkelsen, O., Pejrup, M., 1998. Comparison of flocculated and dispersed suspended sediment in the Dollard estuary. In: Black, K. S., Paterson, D.M., Cramp, A. (Eds.), Sedimentary Processes in the Intertidal Zone. Geological Society, Special Publications, vol. 139, pp. 199–209. London.
Mikkelsen, O.A., Pejrup, M., 2000. In situ particle size spectra and density of particle aggregates in a dredging plume. Mar. Geol. 170, 443–459.
Mikkelsen, O.A., Pejrup, M., 2001. The use of a LISST-100 laser particle sizer for in-situ estimates of floc size, density and settling velocity. Geo-Mar. Lett. 20, 187–195.
Mikkelsen, O.A., Milligan, T.G., Hill, P.S., Moffatt, D., 2004. INSSECT-an instrument platform for investigating floc properties close to the seabed. Limnol. Oceanogr. Meth. 2, 226–236.
Migniot, C., 1968. Étude des proprietés physiques de differentes sediments trés fins et de leur comportment sous des actions hydrodynamiques. La Houille Blanche 7.
Milligan, T.G., 1995. An examination of the settling behaviour of a flocculated suspension. Neth. J. Sea Res. 33, 163–171.
Milligan, T.G., 1996. In situ particle (floc) size measurements with the benthos 373 plankton silhouette camera. J. Sea Res. 36, 93–100.
Murray, P.B., McCave, I.N., Owen, T.R.E., Mason, M., Green, M.O., 1996. A robust in situ settling velocity box for coastal seas. J. Sea Res. 36, 101–107.
Nedeco, 1965. A Study of the Siltation of the Bangkok Port Channel, vol. II: The Field Investigation. Netherlands Engineering Consultants, The Hague. 474 pp.
Office of Indian Affairs, Bureau of Reclamation Tennessee Valley Authority, Corps of Engineers Geological Survey, Department of Agriculture and Iowa Institute of Hydraulic Research. 1943. A study of new methods for size analysis of suspended sediment samples, Report 7, St. Paul, US. Engineer District Sub-Office, Hydraulic Laboratory, University of Iowa, Iowa, 101 pp.
Osborne, P.D., Vincent, C.E., Greenwood, B., 1994. Measurement of suspended sand concentrations in the nearshore: field intercomparison of optical and acoustic backscatter sensors. Cont. Shelf Res. 14, 159–174.
Owen, M.W., 1971. The effect of turbulence on the settling velocities of silt flocs. Proc. 14th Congres Of IAHR, Paris 4, pp. D4-1–D4-5.
Owen, M.W., 1976. Determination of the settling velocities of cohesive muds. Hydraulic Research Station, Wallingford, Report No. IT 161, pp. 1–8.
Owen, R.B., Zozulya, A.A., 2000. In-line digital holographic sensor for monitoring and characterizing marine particulates. Opt. Eng. 39, 2187–2197.
Pfeiffer, A., 1996. In situ measurements of flocculated suspended matter with a video multi sensor system. J. Sea Res. 36, 115–118.
Pejrup, M., 1988. Flocculated suspended sediment in a micro-tidal environment. Sed. Geol. 57, 249–256.
Pejrup, M., Edelvang, K., 1996. Measurements of in situ settling velocities in the Elbe estuary. J. Sea Res. 36, 109–113.
Puls, W., Kühl, H., 1996. Settling velocity determination using the BIGDAN settling tube and the Owen settling tube. J. Sea Res. 36, 119–125.
Puls, W., Kuehl, H., Heymann, K., 1988. Settling velocity of mud flocs: results of field measurements in the Elbe and Weser Estuary. In: Dronkers, J., Van Leussen, W. (Eds.), Physical Processes in Estuaries. Springer-Verlag, Berlin, pp. 405–425.
Renagi, O., 1999. Optical instrumentation for measuring sediment siltation rates. Master Thesis of Science in Department of Physics, James Cook University of North Queensland, Townsville, Australia. 90 pp.
Richards, S.D., 1998. The effect of temperature, pressure, and salinity on sound attenuation in turbid seawater. J. Acoust. Soc. Am. 103, 205–211.
Ridd, P., Day, G., Thomas, S., Harradence, J., Fox, D., Bunt, J., Renagi, O., Jago, C., 2001. Measurement of sediment deposition rates using an optical backscatter sensor. Est. Coast. Shelf Sci. 52, 155–163.
Rigler, J.K., Collins, M.B., Williams, S.J., 1981. A high precision, digital-recording sedimentation tower for sands. J. Sed. Petrol. 51, 642–644.
Rose, C.P., Thorne, P.D., 2001. Measurements of suspended sediment transport parameters in a tidal estuary. Cont. Shelf Res. 21, 1551–1575.
Rouse, H., 1937. Modern conceptions of the mechanics of fluid turbulence. Trans. Am. Soc. Civil Eng. 102, 463–541.
Sanford, L.P., Dickhudt, P.J., Rubiano-Gomez, L., Yates, M., Suttles, S.E., Friedrichs, C.T., Fugate, D.D., Romine, H., 2005. Variability of suspended particle concentratations, sizes and settling velocities in the Chesapeake Bay turbidity maximum. In: Droppo, I.G., Leppard, G.G., Liss, P., Milligan, T. (Eds.), Flocculation in Natural

and Engineered Environmental Systems. CRC Press, LLC, Boca Raton, Florida, pp. 211–236.

Sequoia Scientific, Application Note L002. Measuring the volume scattering function using Lisst-100. WWW Page, http://www.sequoiasci.com.

Sequoia Scientific, Application Note L007. The size resolution of the LISST series of instruments. WWW Page, http://www.sequoiasci.com.

Sequoia Scientific, Application Note L008. Estimating the size-dependent settling velocity of suspended particles using the LISST-ST. WWW Page, http://www.sequoiasci.com.

Serra, T., Casamitjana, X., Colomer, J., 2002. Observations of the particle size distribution and concentration in a coastal system using an in situ laser analyzer. Mar. Technol. Soc. J. 36, 59–69.

Sheng, J., Hay, A.E., 1988. An examination of the spherical scatterer approximation in aqueous suspensions of sand. J. Acous. Soc. Am. 83, 598–610.

Skinner, J., 2000. Pipet and x-ray grain-size analysers: comparison of methods and basic data. Federal interagency sedimentation project, Report 00, Vicksburg, WWW Page, http://fisp.wes.army.mil.

Sternberg, R.W., Ogston, A., Johnson, R., 1996. A video system for in situ measurement of size and settling velocity of suspended particulates. J. Sea Res. 36, 127–130.

Sternberg, R.W., Berhane, I., Ogston, A.S., 1999. Measurement of size and settling velocity of suspended aggregates on the northern California continental shelf. Mar. Geol. 154, 43–53.

Stolzenbach, K.D., 1993. Scavenging of small particles by fast-sinking porous aggregates. Deep-Sea Res. I 40, 359–369.

Stolzenbach, K.D., Elimelech, M., 1994. The effect of particle density on collisions between sinking particles: implications for particle aggregation in the ocean. Deep-Sea Res. I 41, 469–483.

Stokes, G.G., 1851. On the effect of the internal friction of fluids on the motion of pendulums. Transactions Cambridge Philosophical Society IX, 8–106 (Reprinted in Mathematical and Physical Papers, 2nd Ed., Vol. 3, Johnson Reprint Corp., New York, p1, 1966).

Subcommittee on Sedimentation, 1953. A study of methods used in measurement and analysis of sediment loads in streams. Accuracy of sediment size analysis made by the bottom withdrawal tube method, Report 10. Published by Project Offices of Cooperating Agencies, Iowa. 115 pp.

Sutherland, T.F., Lane, P.M., Amos, C.L., Dowing, J., 2000. The calibration of optical backscatter sensors for suspended sediment of varying darkness levels. Mar. Geol. 162, 587–597.

Syvitski, J.P.M., Hutton, E.W.H., 1996. In situ characteristics of suspended particles as determined by the floc camera assembly FCA. J. Sea Res. 36, 131–142.

Ten Brinke, W.B.M., 1997. Temporal variability in aggregate size and settling velocity in the Oosterschelde (The Netherlands). In: Burt, N., Parker, R., Watts, J. (Eds.), Cohesive Sediments. John Wiley and Sons Ltd., Chichester, pp. 63–73.

Thomas, S., Ridd, P.V., 2004. Review of methods to measure short time scale sediment accumulation. Mar. Geol. 207, 95–104.

Thomsen, L., Ritzrau, W., 1996. Aggregate studies in the benthic boundary layer at a continental margin. J. Sea Res. 36, 143–146.

Thorne, P.D., Hanes, D.M., 2002. A review of acoustic measurement of small-scale sediment processes. Cont. Shelf Res. 22, 603–632.

Thorne, P.D., Vicent, C.E., Hardcastle, P.J., Rehman, S., Pearson, N., 1991. Measuring suspended sediment concentrations using acoustic backscatter devices. Mar. Geol. 98, 7–16.

Traykovski, P., Latter, R.J., Irish, J.D., 1999. A laboratory evaluation of the laser in situ scattering and transmissometery instrument using natural sediments. Mar. Geol. 159, 355–367.

Van der Lee, W.T.B., 1998. The impact of fluid shear and suspended sediment concentration on the mud floc size variation in the Dollard estuary, The Netherlands. In: Black, K.S., Paterson, D.M., Cramp, A. (Eds.), Sedimentary Processes in the Intertidal Zone. Geological Society, London, Special Publications, vol. 139, pp. 187–198.

Van der Lee, W.T.B., 2000. Temporal variation of floc size and settling velocity in the Dollard estuary. Cont. Shelf Res. 20, 1495–1511.

Van Leussen, W., 1988. Aggregation of particles, settling velocity of mud flocs. A review. In: Dronkers, J., Van Leussen, W. (Eds.), Physical Processes in Estuaries. Springer-Verlag, Berlin, pp. 347–403.

Van Leussen, W., 1996. The RWS field settling tube. J. Sea Res. 36, 83–86.

Van Leussen, W.V., Cornelisse, J.M., 1993a. The determination of the sizes and settling velocities of estuarine flocs by an underwater video system. Neth. J. Sea Res. 31, 231–241.

Van Leussen, W., Cornelisse, J.M., 1993b. The role of large aggregates in estuarine fine-grained sediment dynamics. In: Mehta, A.J. (Ed.), Nearshore and Estuarine Cohesive Sediment Transport. Coastal and Estuarine Studies, vol. 42. American Geophysical Union, Washington, DC, pp. 75–91.

Van Leussen, W., Cornelisse, J.M., 1996. The underwater video system VIS. J. Sea Res. 36, 77–81.

Van Rijn, L.C., Nienhuis, L.E.A., 1985. In situ determination of fall velocity of suspended sediment. Proc. 21st Congress IAHR, Melbourne, Australia 4, 144–148.

Vincent, C.E., Downing, A., 1994. Variability of suspended sand concentrations, transport and eddy diffusivity under non-breaking waves on the shoreface. Cont. Shelf Res. 14, 223–250.

Voulgaris, G., Meyers, S.T., 2004. Temporal variability of hydrodynamics, sediment concentration and sediment settling velocity in a tidal creek. Cont. Shelf Res. 24, 1659–1683.

Watson, J., Craig, G., Chalvidan, V., Chambard, J.P., Diard, A., Foresti, G.L., Forre, B., Gentili, S., Hobson, P.R., Lampitt, R.S., Maine, J.T., Malmo, J.T., Nareid, H., Pieroni, G., 1999. High-resolution in situ holographic recording and analysis of marine organisms and particles. Third European Marine Science and Technology Conference (MAST conference), Lisbon, 23–27 May 1998: Conference Proceedings, pp. 104–105.

Williams, J.J., Rose, C.P., Thorne, P.D., O'Connor, B.A., Humphery, J.D., Hardcastle, P.J., Moores, S.P., Cooke, J.A., Wilson, D.J., 1999. Field observations and predictions of bed shear stresses and vertical suspended sediment concentration profiles in wave-current conditions. Cont. Shelf Res. 19, 507–536.

Williams, J.J., Rose, C.P., Thorne, P.D., 2002. Role of wave groups in resuspension of sandy sediments. Mar. Geol. 183, 17–29.

Wolanski, E., Gibbs, R., 1992. Resuspension and clearing of dredge spoils after dredging, Cleveland Bay, Australia. Wat. Environ. Res. 64, 910–914.

Wolfstein, K., 1996. Fractionation and measurements of settling velocities of suspended matter using Owen tube. J. Sea Res. 36, 147–152.

Wren, D.G., Kuhnle, R.A., 2002. Surrogate techniques for suspended-sediment measurement. In: Gray, J.R., Glysson, G.D. (Eds.), Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates, 30 April to 2 May, Reno, Nevada, US. http://water.usgs.gov/osw/techniques/TSS/listofabstracts.htm.

Wren, D.G., Barkdoll, B.D., Kuhnle, R.A., Derrow, R.W., 2000. Field techniques for suspended-sediment measurement. J. Hydraul. Eng. 126, 97–104.

Zaneveld, J.R., Spinrad, R.W., Bartz, R., 1982. An optical settling tube for the determination of particle-size distributions. Mar. Geol. 49, 357–376.