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Measurement Techniques for the Estimation of Cohesive Sediment Erosion

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Abstract

This paper provides an overview on measurement techniques related to cohesive sediment erosion. Important hydraulic parameters governing the erosion potential of cohesive sediments are defined and methods for the determination of these parameters in field studies are discussed. An overview over the available in situ technology is given. For this purpose, the in situ instruments are classified in recirculating flumes, straight flow-through flumes, and miscellaneous devices. Hydraulic working principles, advantages and disadvantages of the devices are described. Results of recent comparative studies are summarized.

1. Introduction

The dynamical behavior of cohesive sediments is an important issue for many hydraulic engineering applications such as the estimation of erosion and sedimentation in aquatic environments and artificial water bodies. This issue is also important for ecological and environmental applications, since cohesive sediments may affect the health of aquatic ecosystems by degrading water clarity, smothering benthic communities, and acting as a secondary source of pollution. For example, during floods or other natural or artificial re-suspension events, contaminated sediment particles may be mobilized and released into the water phase, affecting water quality and the ecosystem. Thus, the understanding of cohesive sediment erodibility is a prerequisite for the development of sustainable management strategies for both fresh- and saltwater environments.

The erosive potential of cohesive sediments is governed by the interaction between the cohesive strength of the sediment bed and the acting fluid force. Thus, compared to sand dynamics, cohesive sediment dynamics are much more complicated due to the complexity of relevant physical, chemical, and biological processes and their spatial and temporal variability. For example, Berlamont *et al*. (1993) proposed a list of 28 parameters for the characterization of cohesive sediments. A significant proportion of the current knowledge on the erosion potential of mud has been gained from laboratory studies (Black and Paterson 1997). However, laboratory studies have the significant shortcoming that physical, chemical, and biological/microbiological sediment properties cannot be simulated accurately (e.g., Young and Southard 1978, Amos *et al*. 1992a, Widdows *et al*. 1998, Paterson and Black 1999, Black *et al*. 2002). Testing field sediment samples in laboratory experiments is also not a complete solution to the problem as during sampling and transportation from the field to the laboratory the properties of the samples may be significantly changed. Thus, the application of laboratory results for field assessments, computer modeling, and/or theoretical developments is often not appropriate. In contrast, the data required for such tasks should be collected directly in the field over undisturbed beds (Black and Paterson 1997).

The objective of this paper is to provide an overview on measurement techniques and hydraulic instrumentation related to cohesive sediment erosion. In a first step, important hydraulic parameters governing the erosion potential of cohesive sediments are defined and methods for the determination of these parameters in field studies are discussed. Then, the state-of-the-art in situ technology is broadly reviewed and results from comparative studies found in the literature are presented. Finally, limitations and needs for further studies are discussed. It is worth mentioning that it is not the scope to provide detailed comments on the influence of biological and chemical parameters on cohesive sediment erosion – a review on this topic can be found in Paterson and Black (1999) and Black *et al*. (2002).

2. Background

The main purpose of investigations related to cohesive sediment erosion is the determination of the critical erosive shear stress and erosion rates. The physical processes governing cohesive sediment erosion provide the basis for the development and application of adequate methods and instruments.

2.1 Erosion rate

The surface erosion rate E is defined as the mass of sediment eroded per unit bed area per unit time and it is related to the temporal change in bed elevation, dz/dt, as:

$$E = -\rho_d(z)\frac{dz}{dt} \tag{1}$$

where z = bed elevation with an arbitrary origin (positive upwards), t = time, and ρ_d = dry bulk density of bed material (e.g., Mehta and Partheniades 1982). Alternatively, E can be estimated considering the sediment flux from a defined bed section. The sediment flux consists of two components, resuspension rate E_R and bed load rate E_B. The first component, E_R, refers to sediments which are directly transported in suspension after being eroded and the second component, E_B, refers to sediments (or aggregates) which move as bed load. Thus, for open systems (i.e., eroded sediments are washed out of the flume and are not accumulated in the erosion channel), the continuity equation for the solid phase can be written according to (Debnath *et al*. 2007):

$$\underbrace{\frac{\partial(HC)}{\partial t}+q\frac{\partial C}{\partial x}}_{E_R}+\underbrace{\frac{\partial q_B}{\partial x}}_{E_B}=\underbrace{-\rho_d(z)\frac{dz}{dt}}_{E} \qquad (2)$$

where C = suspended sediment concentration (SSC), H = channel height or flow depth, q = specific water discharge, q_B = specific bed load, and x = longitudinal coordinate along the flow direction positive with an arbitrary origin.

According to Eq. (2), erosion rate can be measured by two independent methods. The first method, related to the right-hand side of Eq. (2), is monitoring the evolution of bed elevation with time. This method requires information on $\rho_d(z)$ which may be obtained from bed samples. A drawback of this method is the limited accuracy of bed monitoring techniques when being applied in muddy environments. Optical systems are influenced by turbidity and acoustic systems need, in general, a sufficient amount of sand in the bed mixture for adequate signal strength, i.e., their applicability in pure muddy environments without any sand in the bed material is restricted. Nonetheless, recent studies showed that such measurements provide new insights into the erosion process of mud-sand mixtures (e.g., Debnath *et al*. 2007, Plew *et al*. 2007).

An alternative approach for the determination of dz/dt in laboratory investigations is the use of special flumes with an open-bottomed test section, through which a coring tube containing the sediment sample can be inserted (e.g., Jepsen *et al*. 1997, Kern *et al*. 1999, Roberts *et al*. 2003). The shear caused by the flow causes sediment erosion in the core and, therefore, the sediments are continually moved upwards during the measurements by an operator so that the sediment-water interface remains level with the flume bottom. Erosion rate is recorded as the upward movement of the sediments in the coring tube. However, a disadvantage of this method is the abrupt change in roughness of the boundary between the flume floor and the sediment core (Roberts *et al*. 2003).

The second method to estimate erosion rate is related to the left hand side of Eq. (2) and consists of sediment flux measurements, i.e., SSC and bed load. So far, the bed load component has been neglected in most cohesive sediment studies as it has often been assumed that fine grained sediments are entrained directly into suspension under most flow conditions. However, recent studies showed that bed load may, in principle, contribute significantly to total erosion (Mitchener and Torfs 1996, Aberle *et al*. 2004, Debnath *et al*. 2007). For example, Mitchener and Torfs (1996) found for mud-sand mixtures that muddy layers are eroded predominantly directly into suspension, whereas sand layers are eroded into bed load. Moreover, for pure cohesive and consolidated beds, large aggregates or lumps of bed material may be transported as bed load. However, direct field measurements of E_B over cohesive beds (in terms of eroded mass) are sophisticated and a satisfying measurement system is not yet available. Therefore, Debnath *et al*. (2007) and Plew *et al*. (2007) used Eq. (2) to estimate the bed load component E_B from measurements of E and E_R.

The erosion rate due to resuspension, E_R, is generally estimated from turbidity measurements using turbidimeters (e.g., Optical Backscatters (OBS) or photodetectors). The corresponding readings are calibrated against SSC, where SSC is usually determined from water samples. Thus, knowing the suspended sediment concentration, flow depth, and flow rate, the resuspension rate E_R can be calculated.

2.2 Experimental procedure and data interpretation

Both in situ and laboratory measurements of cohesive sediment erosion are often based on an experimental procedure in which shear stress is increased stepwise to constant levels during fixed time steps or intervals, usually 10 to 20 min (e.g., Parchure and Mehta 1985, Amos *et al.* 1992a, Aberle *et al*. 2003). During these time intervals, erosion rates are estimated using the aforementioned methods. A typical time series of flow velocity and SSC is displayed in Fig. 1. The figure shows that at the beginning of each experimental step (interval) with an increased flow velocity (and hence bed shear stress), erosion rate is often initially high and then decreases with time. In the literature, such a behavior has been associated with two potential mechanisms: (1) the structure of the (consolidated) bed; and (2) transient hydrodynamic effects. Aberle *et al*. (2006) investigated the significance of transient hydrodynamic effects analyzing velocity data obtained by Acoustic Doppler Velocimeter (ADV) measurements and concluded that these effects can be neglected. Thus, the erosion pattern shown in Fig. 1 is most likely solely due to the structure of the bed (see also Zreik *et al*. 1998, Krone 1999). This becomes also obvious from Eq. (1), in which $\rho_d(z)$ is a significant parameter.

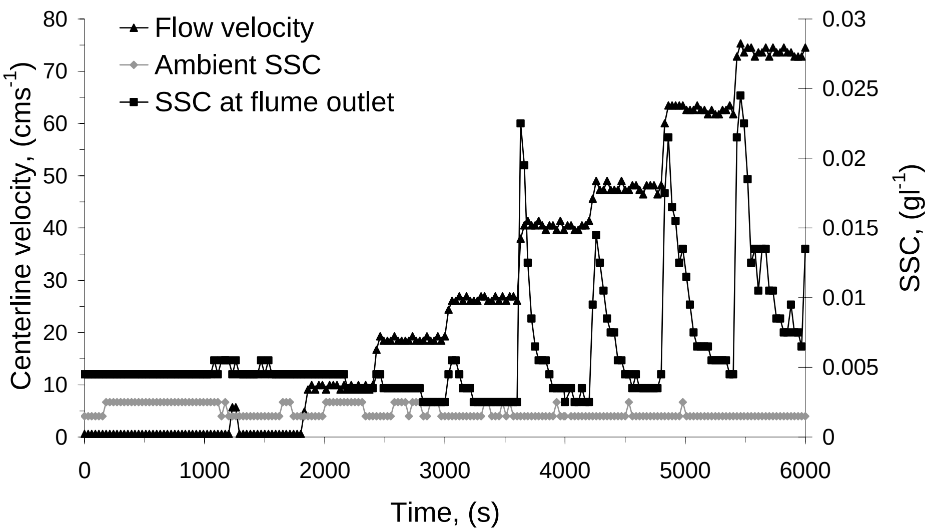

Fig. 1. Time series of the centreline flow velocity in an erosion channel (measured by an Ott-flow meter; triangles), ambient SSC (diamonds), and SSC at the end of the erosion channel (squares) for an experiment carried out in the Styx River near Christchurch, New Zealand. Once the critical threshold for erosion is exceeded, erosion increases sharply at the onset of each velocity level and then decreases.

The erosion process of cohesive beds is often classified using two erosion types (e.g., Paterson and Black 1999). Depth-limited (type I) erosion occurs due to a large vertical gradient in the bed shear strength, which depends on a number of factors such as sediment characteristics, deposition history, and consolidation. In this case, erosion ceases when the bed erodes down to the level where the bed shear strength τ_s within the consolidated bed is in equilibrium with the applied bed shear stress (e.g., erosion event at 3500 s in Fig. 1). After erosion of the upper sediment layer, the initial erosion rate may still be high in further experimental steps, but then erosion rate may reduce and reach a constant value (e.g., erosion event at 4300 s in Fig. 1). In this case the erosion process can be described as sharing features from two erosion types, depth-limited erosion (type I) and steady-state (i.e., constant) erosion, defined as type II erosion. Steady-state erosion (type II) is characterized by a constant erosion rate and is expected for uniform beds when the bed shear strength does not change with sediment depth (e.g., Mehta and Partheniades 1982, Parchure and Mehta 1985, Zreik *et al.* 1998). It is worth mentioning that the shared erosion type shown in Fig. 1 may be an artefact of the experimental procedure, as one may infer that the time duration for each velocity step of 10 min in Fig. 1 is insufficient for the condition $\tau_B = \tau_s$ to be attained (Aberle *et al.* 2006).

The erosion types and associated formulas describing the erosion mechanisms have been introduced to support interpretation of experimental data and to calculate erosion rates from such data. Several formulations have been derived in which erosion rate is described in terms of the excess bed shears stress concept, i.e., erosion occurs as long as bed shear stress is larger than the critical stress at the bed. Using a power law function, this concept can be formulated as:

$$E = M(z)\left(\tau_b - \tau_c(z)\right)^n \tag{3}$$

where $M(z)$ is an empirical erosion constant with its dimension depending on the exponent n, τ_b is the bed shear stress, and $\tau_c(z)$ is the critical bed shear stress for erosion which may vary with depth z (Maa *et al.* 1998, Ravens and Gschwend 1999, Mehta and Parchure 2000).

However, the use of Eq. (3) for determination of erosion rate is not straightforward because both $M(z)$ and τ_c, and a variety of physical, chemical and biological factors influencing them, are unknown functions of sediment depth (Aberle *et al.* 2004). Furthermore, erosion is a highly dynamical process (see Fig. 1) and there is a lack of consistency in the way the various parameters from field deployments are interpreted. For example, in some investigations E is defined as the initial erosion rate after application of a new bed shear stress (e.g., Amos *et al.* 1992a, Maa *et al.* 1998, Houwing 1999), Ravens and Gschwend (1999) define erosion rate as the rate of sediment resuspension after some initial response has passed, while other investigators averaged erosion rates over each velocity step (e.g., Andersen *et al.* 2002). Obviously, such diverse definitions can result in different values for erosion rate from the same experimental data set, aggravating a direct comparison of the experimental results. Sanford and Maa (2001) developed a time dependent solution for Eq. (3) for $n = 1$ and the special case of a step-wise increase of bed shear stress that incorporates both types of erosion. This solution was used by Aberle *et al.* (2004, 2006) to develop a method for data interpretation from field studies taking into account the time dependency of the erosion process.

2.3 Bed shear stress estimation

Equation (3) shows that bed shear stress is a key parameter in cohesive sediment studies, since it determines erosion rates and erosion rate parameters. However, estimation of bed shear stress during bed erosion is difficult and, therefore, bed shear stress is generally estimated from calibration curves. These curves are obtained under controlled conditions by determining bed shear stress in the erosion channel using hydrodynamic measurements and relating these estimates to bulk properties of the flow such as mean flow velocity or flow rate. Flow velocity in the erosion channel is usually measured by current meters and/or velocimeters or estimated using the equation of continuity (given the flow rate is known). Methods to determine bed shear stress used in cohesive sediment studies range from direct measurements with skin friction probes to indirect estimates using pipe flow laws (e.g., Moody-Diagram), analyses of the vertical velocity profile and/or near bed turbulence properties, and testing quartz sediment samples with a known critical shear stress for incipient motion (i.e., once the particles start moving, the corresponding critical shear stress is related to the applied forcing mechanism of the apparatus). A detailed description of these methods is beyond the scope of this paper and a review on this topic can be found in Rowiński *et al.* (2005).

So far there is no standard procedure available for bed shear stress calibration of in situ devices. Thus, discrepancies in bed shear stress estimates due to these different methods may be interpreted as an important factor which prevents a rigorous comparison of erosion rates. Another important issue is the influence of roughness, turbulence properties, and flow structure on bed shear stress. The use of calibration curves (which were often obtained over well defined surfaces such as wooden beds or sandpaper; e.g., Aberle *et al.* 2003) implies that the roughness of natural cohesive beds is similar to the roughness used during instrument calibration. However, this is not necessarily the case as the roughness of cohesive beds can be quite variable (e.g., Black and Paterson 1997). Besides, Debnath *et al.* (2007) showed that bed roughness may change significantly during erosion and, therefore, τ_b does not necessarily follow calibration curves.

The influence of turbulence properties on bed shear stress is related to the fact, that most erosion devices are closed conduits and, therefore, the size of the turbulent eddies is not comparable to the eddy-sizes observed under natural flow conditions (Rowiński *et al.* 2005). Furthermore, in environments with high SSC, fluid properties may be altered due to large amounts of particles in the fluid (e.g., Wang and Larsen 1994). Another issue is related to the general flow structure. For example, in estuarine or coastal environments oscillatory wave activity may be the key erosion process instead of shear stress imposed by unidirectional flow (Jepsen *et al.* 2004). Last but not least it must be mentioned that secondary currents in flumes may result in a non-uniform shear stress distribution across the erosion channel (e.g., Gust and Müller 1997). Consequences of all these factors on the estimation of erosion rates have not been investigated in depth yet in cohesive sediment erosion studies, showing that adequate bed shear stress estimation is still an open question.

3. In situ devices

Various in situ instruments have been built since the 1970's to investigate cohesive sediment dynamics. The design of these instruments has been a compromise between various factors, such as costs, portability, number of required operators, duration of erosion tests, required water supply, fluid flow in the instrument, objective of the investigation, required data, etc. (Black and Paterson 1997). In general, the instruments are operated in either submerged or sub-aerial conditions (i.e., open to the air). When being operated in sub-aerial conditions, additional water supply is often required which may limit the use dependent on the deployment site.

A detailed review on in situ technology available until 1997 can be found in Black and Paterson (1997). Since then, various new devices have been developed and it is the scope of this section to provide an updated overview on the existing in situ technology. For this purpose, the existing instruments are subdivided into two groups: (1) benthic flumes; and (2) miscellaneous devices. Benthic flumes, in turn, are subdivided into recirculating and flow-through types. In the following, the basic principles of the instruments are briefly outlined. For detailed information on each device as well as the deployment protocol, the reader is directed to the corresponding source.

3.1 Recirculating in situ flumes

Recirculating in situ flumes are parallel-walled rectangular channels with either an annular or race-way plan view (see Table 1). When deployed, a skirt or flange around the outer walls prevents penetration of the flume into the bed. Recirculating flumes are closed systems and as erosion proceeds the water inside the flume gradually becomes saturated with suspended sediments. Therefore, the change of concentration C with time t is always non-negative ($dC/dt > 0$) unless sediment deposition occurs or water infiltrates from outside the device.

Table 1

Recirculating in situ flumes

Source	Shape	Instrument name	Use
Peirce *et al*. (1970)	annular	–	sub-aerial
Nowell *et al*. (1985)	race-way	SEADUCT	submerged
Amos *et al*. (1992b)	annular	Sea Carousel	submerged
Houwing and van Rijn (1992)	race-way	ISEF	sub-aerial
Maa *et al*. (1993, 1995)	annular	VIMS Sea Carousel	submerged
Black and Cramp (1995)	race-way	–	sub-aerial
Widdows *et al*. (1998)	annular	PML in situ AF	sub-aerial
Thompson and Amos (2002)	annular	AMF	sub-aerial
Bale *et al*. (2006)	annular	PML MAF	sub-aerial

In annular devices, the channel floor is formed by the natural sediment and the eroding flow is driven by different methods, such as a rotating lid (e.g., Maa *et al.* 1993, Widdows *et al.* 1998), a rotating lid with paddles (e.g., Amos *et al.* 1992, Thompson and Amos 2002, Bale *et al.* 2006), or by paddles (e.g., Peirce *et al.* 1970). An advantage of the annular shape is that the "infinite" flow length results in a fully developed boundary layer. Hence, bed shear stress can be estimated from measured velocity profiles using the logarithmic formula. However, this advantage is offset by inherent secondary currents causing a non-uniform shear stress distribution across the channel. It is worth mentioning that, in laboratory investigations, the effect of secondary currents can be minimized by counter-rotating the outer channel-wall (e.g., Krishnappan 1993, Schweim 2005).

In contrast to the annular geometry, race-way shaped flumes have a relatively long straight open-bottomed test section connected to short high-curvature sections leading to and from a return flow channel with a fixed bed. Race-way flumes are oriented horizontally (Black and Cramp 1995) or vertically (Nowell *et al.* 1985, Houwing and van Rijn 1998) and the flow is driven by a propeller (Black and Cramp 1995), paddles (Houwing and van Rijn 1998), or a pump (Nowell *et al.* 1985). Hence, unlike in annular flumes, suspended flocs in the water column may be broken by the flow driving system. Although it is assumed that the racetrack shape reduces the magnitude of the secondary currents, the boundary layer may not be fully developed in the test section (Houwing and van Rijn 1998).

3.2 Straight benthic flow through flumes

Flow-through flumes, summarized in Table 2, are designed as straight canals or conduits with an open bottom. Most devices consist of a contracting, open-mouthed entrance section, a straight erosion section, and a straight fixed-bed section. They are enclosed by an upper lid or open to the air when used in submerged or sub-aerial conditions, respectively. Similar to recirculating flumes, a skirt or flange around the outer walls prevents penetration of the flume into the bed. Flow-through flumes are open systems and the eroded sediment is lost at the flume outlet. Thus, when erosion ceases SSC decreases and in contrast to recirculating flumes, both $dC/dt < 0$ and $dC/dt > 0$ are possible.

The flow in straight flumes is driven by propellers (Scoffin 1968, Hawley 1991, Aberle *et al.* 2003, Debnath *et al.* 2007, Plew *et al.* 2007), pumps (Young 1977, Manzenrieder 1983, Gust and Morris 1989, Ravens and Gschwend 1999, Krishnappan and Droppo 2006) or by gravity (sub-aerial devices of Grissinger *et al.* 1981, Cowgill 1994). In flumes where water is sucked through the channel, the entrance section is usually designed to be similar to that of a wind tunnel to smooth out entrance effects. As an example for a straight flow-through flume the NIWA in situ flume I, described in detail by Aberle *et al.* (2003), is shown in Fig. 2.

Due to the straight erosion section, effects of secondary currents are assumed to be minimal in straight flumes. On the other hand, straight flow-through flumes are often criticized because the boundary layer may not be fully developed in the test section, which may introduce significant uncertainties in bed shear stress estimates using the logarithmic formula. However, Young and Southard (1978) and Ravens and

Gschwend (1999) pointed out that this effect was not crucial in their studies. The requirement of a fully developed logarithmic profile for estimating the bed shear stresses can be avoided either by using stress probes (Gust and Morris 1989) or by measuring near-bed turbulence parameters (e.g., Aberle *et al*. 2003, Debnath *et al*. 2007).

Table 2

Straight flow through flumes

Source	Name	Use
Scoffin (1968) Neumann *et al*. (1970)	Underwater flume	submerged
Young (1977) Young and Southard (1978)	SEAFLUME	submerged
Grissinger *et al*. (1981)[1]	Portable flume	sub-aerial
Manzenrieder (1983)	Strömungskanal	sub-aerial
Gust and Morris (1989)	SEAFLUME	submerged
Hawley (1991)	–	submerged
Cowgill (1994)[1]	–	sub-aerial
Ravens and Gschwend (1999)	FLUME	submerged
Westrich and Schmid (2003)	EROMOB	submerged
Aberle *et al*. (2003)	NIWA in situ flume I	submerged
Krishnappan and Droppo (2006)		submerged
Debnath *et al*. (2007)	NIWA in situ flume II	submerged
Plew *et al*. (2007)	NIWA in situ flume III	submerged

[1] described in Black and Paterson (1997)

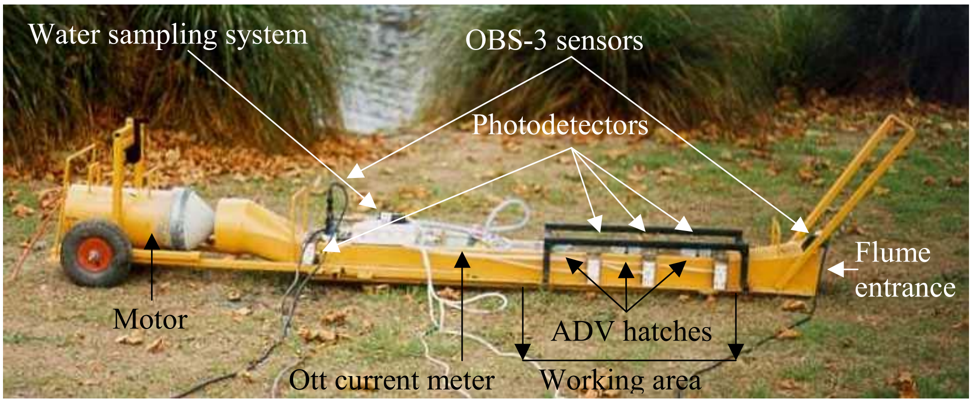

Fig. 2. The NIWA in situ flume I. The flume has been designed as a straight benthic flow-through flume and is equipped with OBS-3 sensors, photodetectors, an Ott current meter, and a water sampling system. Special ADV-hatches allow for ADV calibration measurements inside of the flume. Note that the wheels are uplifted during operation; handles and frames attached to the flume are removable. For a description of the operation of the flume refer to Aberle *et al*. (2003).

3.3 Miscellaneous devices

Miscellaneous devices, summarized in Table 3, are mostly based on alternative methods of assessing the potential for erosion of cohesive beds rather than erosion caused by flowing water. The used methods comprise erosion due to vertical jets (Paterson 1989), vertically oscillating grids (Tsai and Lick 1986, PES), rotating flows in small cylinders (Gust 1991, Schünemann and Kühl 1991), shear strength testing using a shear pad (which is a field-modification of a standard uniaxial shear test instrument; Faas *et al*. 1992), or an erosion bell (Williamson and Ockenden 1996, and SedErode), and shear vane testing (Bassoullet and Le Hir 2007). The footprint of these devices is generally much smaller than the footprint of benthic flumes.

Table 3

Miscellaneous devices

Source	Name	Method
Faas *et al*. (1992)	INSIST	shear pad
Tsai and Lick (1986)	Shaker	oscillating grid
Paterson (1989); Vardy *et al*. (2007) Tolhurst *et al*. (1999)	CSM	vertical jet
Schünemann and Kühl (1991)	EROMES	rotating flow
Gust (1991)	Microcosm	rotating flow
Williamson and Ockenden (1996)	ISIS	erosion bell
Delft Hydraulics[1]	PES	oscillating grid
HR Wallingford[2]	SedErode	erosion bell
Bassoullet and Le Hir (2007)	–	shear vane

[1] described in Cornelisse *et al*. (1997); [2] described in Tolhurst *et al.* (2000)

4. Comparative studies

The listed in situ technology in Tables 1-3 reveals that an abundance of unique instruments has been developed with different operation principles, geometries, and test-section sizes. Bearing in mind the known limitations related to data acquisition and interpretation as well as the problems faced in the field during deployments, surprisingly few comparative studies have been carried out until today. Relevant comparisons, where different instruments have been applied simultaneously over the same sediment, are described by Cornelisse *et al*. (1997), Tolhurst *et al*. (2000) and Widdows *et al.* (2007).

Cornelisse *et al*. (1997) used a kaolinite bed over which PES, EROMES, ISIS, and ISEF were tested (see Table 1 and 3). The results of the tests with these devices were also compared to data obtained in an annular laboratory flume. This comparison showed that all instruments were able to establish an accurate and reproducible value for critical shear stress but that estimates of erosion rate parameters varied significantly, which was partly associated with spatial and temporal variations of bed shear stress and bed strength. Therefore, Cornelisse *et al.* (1997) concluded that the error in measured erosion rate is mainly related to footprint size of the instruments.

Tolhurst *et al.* (2000) compared Microcosm, ISEF, SedErode, and CSM (see Table 1 and 3) in a natural environment and found that erosion threshold was relatively comparable between these devices. On the other hand, Tolhurst *et al.* (2000) found that erosion rate estimates were not comparable between the different devices, confirming the findings of Cornelisse *et al.* (1997). This fact was attributed to fundamental differences between the erosion devices (e.g., flow structure, bed-shear stress calibration, etc.) as well as to deployment time, and instrument size.

Widdows *et al.* (2007) compared five erosion devices (PML in situ AF, PML MAF, AMF, CSM, and EROMES; see Table 1 and 3) and found good agreement between similar erosion devices (e.g., annular flumes). On the other hand, they identified significant differences comparing the three investigated basic types of erosion devices, confirming again the studies of Cornelisse *et al.* (1997) and Tolhurst *et al.* (2000). Widdows *et al.* (2007) concluded that the main cause of the observed differences is the manner in which the shear stress is applied to the bed. In this context, Debnath *et al.* (2007) found that data obtained from two similar straight flumes deployed at identical locations were comparable, although a time period of three years separated the two measurement series.

5. Summary and conclusions

This paper presents an overview of measurement techniques for the estimation of cohesive sediment erosion. Based on the definition of the surface erosion rate *E*, relevant physical parameters were identified and methods for their determination briefly described. As several studies have shown that the application of laboratory results for field assessments, computer modeling, and/or theoretical developments is often not appropriate, the main focus was set on a review and summary of existing in situ erosion devices. The influence of biological and chemical parameters on cohesive sediment erosion was not addressed specifically, since the scope of the paper was related to hydraulic instrumentation.

The review of the existing in situ instruments revealed that an abundance of devices exists (thirty of them are listed in this paper) which can be broadly subdivided into benthic flumes and miscellaneous devices. Each device is a unique piece of equipment which was developed according to specific needs and boundary conditions. This means that each individual instrument has its specific advantages and disadvantages and, hence, it is not possible to evaluate which instrument is best. Nonetheless, within the last years the instruments have been steadily improved on the basis of experiences from previous investigations. One such example is the development of the NIWA in situ flumes (see Table 2). The latest prototype, described in Plew *et al.* (2007), may now be used in deeper waters, is lighter, better equipped, and easier to handle than its antecessors.

Comparative studies between different instruments revealed that instruments based on the same principle of operation yield similar results for critical shear stresses and erosion rates. On the other hand, erosion rates obtained with devices based on different working principles are not directly comparable. In the literature, this has been associated with different factors such as footprint size, mode of bed shear stress application, bed shear stress calibration, etc. It is interesting to note that a direct comparison of a straight in situ flow-through flume with recirculating flumes and/or miscellaneous devices has not yet been carried out under field conditions. This is somewhat surprising, as several types of straight flow-through flumes exist. Thus, to gain more insight into the performance of such instruments and to explore the comparability of the results of the abundance of studies related to cohesive sediment erosion found in the literature, such a comparison would be desirable. Last but not least, it would also be desirable to compare the results of in situ devices with data from specifically designed large scale field experiments in canals or rivers, where hydraulic parameters and erosion are directly assessed during a flood event. Although this is a challenging task, such data should provide further insight into the erosion processes of cohesive beds.

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