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Investigation of Sediment Suspension Technology

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16. Abstract
The goal of the project was to critically review existing literature to access currently available devices, the identification of areas of improvement for future designs, and the outline of a new-generation cohesive sediment erosion measuring device. The results of this investigation shows that several devices exist for the measurement of cohesive sediment erosion upon which there are great opportunities for improvement. Most significantly, the availability of technologies such as laser Doppler velocimeters and bed mapping systems would allow for the noninvasive measurement of key parameters directly in the field. The introduction of such instruments to the framework of existing flume devices would allow for greater accuracy in determining a relationship between bed shear stress and suspended sediment concentration. Direct measurement of the flow profile by the LDV would erase the potential for error where flows were previously estimated. Acoustic bed mapping technology has already been successfully utilized in the NIWA-II flume to noninvasively measure the erosion process (Aberle et al. 2004, Debnath et al. 2007). However, the integration of more advanced technologies, whether laserbased or acoustic, has the potential to improve accuracy and resolution in measurements. The development of the proposed device is realistic and achievable, and would enhance the understanding of cohesive sediment erosion.

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Investigation of Sediment Suspension Technology

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Introduction

The study of cohesive sediment erosion is important for decisions regarding the maintenance of harbor systems and their infrastructure. Cohesive sediments are defined as sediments that form flocs whose characteristics differ from those of individual particles. This cohesion may result from chemical properties of the sediment and eroding fluid (Berlamont 1993) or biogenic stabilization (Grant and Darborn 1994). Unlike the erosion of larger, non-cohesive sediment particles, for which critical shear can be predicted using Shield's Diagram, the erosion of cohesive sediments is often difficult to predict. Understanding bed sediments' potential for erosion is important for the prediction of scour and the filling in of channels. It is also valuable for situations in which contaminants are found within the sediment bed, as the fate and transport of contaminants correlate with those of the sediment.

Recent advancements in understanding the suspension of cohesive sediments have resulted in a shift from laboratory experiments to in-situ techniques. Measurements taken in the environment rather than in the laboratory are less susceptible to errors related to the coring or sampling of sediments. In addition, in-situ techniques allow for site-specific device applications. For example, opportunities to predict scour around bridges, the transport of contaminants, or the filling in of dredged channels make the study of cohesive sediment erosion especially relevant to New York Harbor and other waterways around the world. Many devices have been designed to study the erosion of cohesive sediments in environmental systems, varying significantly in design, scale, and driving theory. However, there exist opportunities for the improvement of these devices due to advancements in modern technology.

This proposal includes the results of a literature review conducted to assess currently available devices, the identification of areas of improvement for future designs, and the outline of a new-generation cohesive sediment erosion measuring device. The goal of the new design is to improve upon established in-situ flumes to accurately determine the relationship between bottom shear stress and the potential for erosion.

Literature Review

The study of cohesive sediment suspension has seen significant advancements in technology and understanding over recent years. The past two decades of progress have produced a shift from laboratory experiments using field samples to in-situ techniques for measuring sediments' potential for erosion. Such techniques have been improved through the introduction of sensor technologies and unique system designs. A number of in-situ devices have been developed that attempt to representatively predict sediments' potential for erosion. These devices include the cohesive strength meter (Patterson 1989, Grabowski 2010), Sea Carousel (Amos et al. 1992), SEDflume (McNeil et." al. 1996), In-Situ Erosion Flume (Houwing and van

Rijn 1997), Plymouth Marine Laboratory annular flume (Widdows et al. 1997), ASSET flume (Roberts et al. 2003), Mobile Recirculating Flume (Black and Cramp 1995), NIWA in situ flume (Aberle et al. 2003), NIWA-II (Aberle et al. 2004, Debnath et al. 2007), Mini Annular Flume (Bale 2006) and VIMS Sea Carousel (Maa 1993, 2008), among others. A literature review was conducted for this project to determine the ideal scale, configuration, and technology required to produce representative cohesive sediment erosion measurements. The literature review, in its entirety, is attached to this proposal as Appendix A.

1. Scale required for representative sediment suspension measurements

Existing technologies for the in-situ measurement of cohesive sediment suspension vary significantly in scale, with test area footprints ranging from square centimeters to square meters. Smaller devices may be more easily deployable and transportable, however their results are often dependent on irregularities in bottom shear stress distributions (Houwing and van Rijn 1998). Larger devices provide more integrated results, with the disadvantage of limited spatial and temporal variability in measurements (Widdows et al. 1997). Ultimately, it was determined that ideal in-situ cohesive sediment testing instrument is light and small, thus easily deployable, but with a relatively large test surface of at least 0.1 m^2 (Houwing and van Rijn 1998).

2. Ideal configuration of suspension measuring devices

The majority of existing devices fall under the category of benthic flumes, and can be further classified as either recirculating or flow-through. Flow-through flumes are rectangular in geometry and produce a unidirectional flow across the sediment to induce erosion. Recirculating flumes may be of circular or raceway geometry, with parallel inner and outer channel walls.

Circular flumes produce a fully developed boundary layer above the test bed, which is important in the case of shear stress derivation (Black and Paterson 1997). However, the design of circular flumes requires the consideration of techniques that limit secondary radial flows and flow differences between inner and outer parts that occur due to curvature. In addition, since recirculating flumes are closed systems, suspended cohesive sediment accumulates over the test area during the period of measurement. Raceway or flow-through flumes may avoid the complications of underdeveloped boundary layers by measuring shear stress directly (Black and Paterson 1997). In the case of flow-through flumes, sediment that erodes into suspension is lost out of the end of the flume (Black and Paterson 1997).

Overall, the simplest and most representative configuration was identified as a benthic, flow-through flume with direct shear stress measurement techniques.

3. Technology required to quantify shear and suspended load

The simultaneous collection of water flow rate and suspended sediment concentration measurements is necessary for the quantification of the suspended load and erosion rate. Existing devices utilize electromagnetic flow meters, impellor current meters, and paddlewheel flowmeters to measure flow. However, more advanced flow measuring technologies, such as acoustic Doppler velocimeters and laser Doppler velocimeters, should be considered for improved accuracy in measurements. Turbidity probes and optical backscatter sensors are utilized in most devices to take measurements regarding the suspended sediment concentration.

Most early devices did not directly measure shear stress, instead estimating shear stress as a function of average velocity, pressure difference, or other parameters. Though the estimates were found to be representative in certain circumstances, it is recommended that both flow speed and shear stress are directly measured in situ.

Additional instrument recommendations include a water sampling system near the optical backscatter sensors that allows for subsequent laboratory calibration of suspended sediment concentration measurements (Widdows et al. 1997), cameras to visualize the process (Black and Paterson 1997), and an ultrasonic ranging system to noninvasively measure bed sediment elevations (Debnath et al. 2007).

Potential for Improvement

The proposed design includes a benthic, flow-through, rectangular flume modeled closely after the NIWA and NIWA II flumes (Aberle et al. 2003, Aberle et al. 2004, Debnath et al. 2007). The new design adopts concepts from the NIWA flumes, such as the noninvasive measurement of bed elevation and calibration of suspended sediment concentration measurements against periodic water samples. However, the use of a laser Doppler velocimeter (LDV) will enable the onsite measurement of the actual flow profile, resulting in more accurate calculations of bottom shear stress. In addition, the project team will explore the use of more advanced bed-mapping technologies, such as laser displacement sensors. Unfortunately, the first laser displacement sensor found and tested in the lab was inapplicable for submerged, nonzero flow systems. Other options will be pursued, and if laser technologies are incapable of producing accurate results, more advanced acoustic systems will be considered.

The new design will be lighter and more compact than many of the existing flumes. This will allow for greater portability and improve the potential for variability in field applications.

Proposed Flume Design

The recommended flume design is a benthic, flow-through, rectangular flume with a total length of approximately 1.5 m. The cross section of the flume's entrance will be 0.3 x 0.15 m (WxH). The entrance section will be 0.3 m long, contracting to a 0.5 m long erosion test section with a cross section of 0.2 x 0.1 m (WxH). The erosion section will be followed by a 0.7 m long fixed-bed section with the same cross section, leading to the pump that draws water through the flume. The fixed-bed section serves to reduce abnormalities in erosion due to pump influence. The flume structure will consist of acrylic plastic material. Flanges and wings imbedded into the sediment will minimize the suction of water near the edges of the system.

Once the flume has been deployed into an environmental system, water will be pulled through it by a pump. The flow will be increased according to timed intervals, or steps, to ensure that the critical shear stress is reached during each step. To most closely model the water bodies of interest, the velocity of water pulled through the flume will range between 0 - 1.0 m/s. Near the entrance of the flume, a turbidity probe will take readings of background suspended sediment concentration. Another turbidity probe, located just after the test section, will measure suspended sediment concentration and establish the change in suspended sediment due to erosion. Water samples will be taken near the second turbidity probe and analyzed in the lab to calibrate the turbidity probes' measurements with actual suspended sediment values.

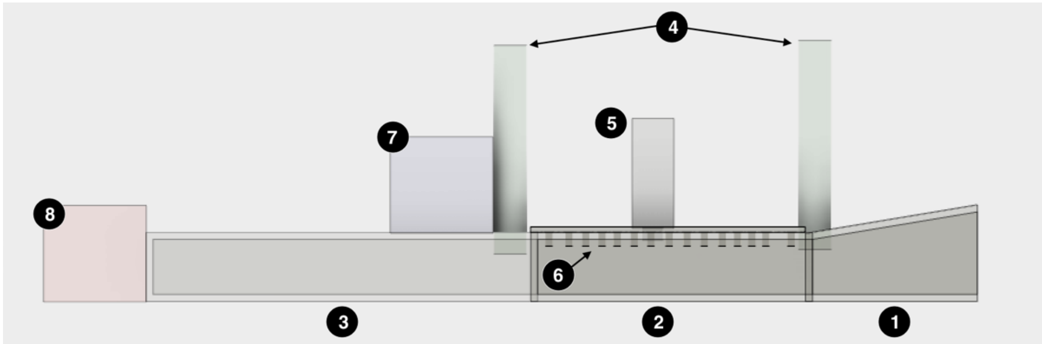

Figure 1. Side-view depiction of proposed flume and components, including: 1. Entrance section, 2. Erosion test section, 3. Fixed-bed section, 4. Turbidity/Suspended sediment concentration probes, 5. LDV, 6. Bed-mapping sensors, 7. Water sampling system, 8. Pump

The LDV, located above the test section to avoid flow disruption, will be used to measure the full velocity profile in the flume. It is anticipated that the deployable, full-scale version of the flume will include a motorized system to allow systematic measurements by the LDV at all heights above the bed within the flume. However, for the purpose of cost-efficiency in the prototype, movement of the LDV above the bed will be done manually. The velocity profile recorded by the LDV will provide longitudinal and vertical velocity components for the calculation of the near-bed Reynolds stress. This value will be used to determine the relationship between bed shear and suspended load. Also located within the test section will be sensors designed to map bed elevation. Changes in bed elevation will be compared with changes in suspended sediment concentration in order to better understand the erosion process taking place within the flume.

Materials Required

The following table lists key elements of the prototype flume and their respective cost estimates. Selected technologies are subject to change due to issues with performance, availability, or cost fluctuation.

Table 1. Key Materials and Cost Estimates

Material	Purpose	Available Option(s)	Estimated Cost
Pump or Impeller	Drive flow through flume	(Already in possession)	-
Bed-mapping Sensors	Noninvasively measure changes in sediment bed elevation	Seatek Ultrasonic Ranging System	$23,000
Turbidity/Suspended Sediment Concentration Probes	Measure changes in suspended sediment concentration	Sequoia Scientific LISST-200X	$37,250 (x 2)
		Campbell Scientific OBS-5+	$5,650 (x 2)
Water Sampling System	Ensure accuracy of measured changes in suspended sediment concentration	Clog-resistant Portable Dispensing Pump – McMaster-Carr	$591.22
Laser Doppler Velocimeter	Noninvasively measure full velocity profile of flow through test section	MSE 2D miniLDV	$114,000
Plexiglass Structure	Establish experimental boundaries while maximizing visibility and ease of transport	Optically Clear Acrylic – McMaster-Carr	$600

Proposed Schedule

- Approval of proposal
- Acquisition of materials
- Construction of flume structure
- Installation and calibration of instruments
- Laboratory test
- Field test
- Final report

Conclusion

Several devices exist for the measurement of cohesive sediment erosion upon which there are great opportunities for improvement. Most significantly, the availability of technologies such as laser Doppler velocimeters and bed mapping systems would allow for the noninvasive measurement of key parameters directly in the field. The introduction of such instruments to the framework of existing flume devices would allow for greater accuracy in determining a relationship between bed shear stress and suspended sediment concentration. Direct measurement of the flow profile by the LDV would erase the potential for error where flows were previously estimated. Acoustic bed mapping technology has already been successfully utilized in the NIWA-II flume to noninvasively measure the erosion process (Aberle et al. 2004, Debnath et al. 2007). However, the integration of more advanced technologies, whether laser-based or acoustic, has the potential to improve accuracy and resolution in measurements. The development of the proposed device is realistic and achievable, and would enhance the understanding of cohesive sediment erosion.

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Appendix A – Literature Review

Assessment of Technologies for the Measurement of Cohesive Sediment Erosion

March 2016

Introduction

The field of study regarding cohesive sediment suspension has seen significant advancements in technology and understanding over recent years. The past two decades of progress have produced a shift from laboratory experiments using field samples to in-situ techniques for erodability measurements. Such techniques have been improved through the introduction of sensor technologies and unique system designs. A number of in-situ devices have been developed that attempt to representatively predict erodability, with differing approaches to design, scale, and driving theory. These devices include the cohesive strength meter (Patterson 1989, Grabowski 2010), Sea Carousel (Amos et al. 1992), SEDflume (McNeil et." al. 1996), In-Situ Erosion Flume (Houwing and van Rijn 1997), Plymouth Marine Laboratory annular flume (Widdows et al. 1997), ASSET flume (Roberts et al. 2003), Mobile Recirculating Flume (Black and Cramp 1995), NIWA in situ flume (Aberle et al. 2003), NIWA-II (Aberle et al. 2004, Debnath et al. 2007), Mini Annular Flume (Bale 2006) and VIMS Sea Carousel (Maa 1993, 2008), among others. This report consists of a review of existing literature on the suspension of cohesive sediments. It is designed to determine the ideal configuration, scale, and technology required to produce representative cohesive sediment erosion measurements.

1. Scale required for representative sediment suspension measurements

Existing technologies for the in-situ measurement of cohesive sediment suspension vary significantly in scale, from footprint areas of square centimeters to those of square meters. This variation in size affects the nature and scale of physical and biological processes to be studied. Larger flumes, defined in this report as devices whose test sections are on the order of 0.1 – 1.0 m^2, constitute the majority of modern instruments. They may be designed to ensure a logarithmic distribution of velocity within the device, which is advantageous in the calculation of shear stress and is particularly important for devices that estimate values for shear stress rather than measuring it directly (Houwing and van Rijn 1998). Though affected by changes in sediment topography, such as ridges and gullies, larger flumes have been found to provide a more integrated response, masking localized small-scale erosion (Widdows et al. 1997). Larger flumes have the disadvantage of reduced field-portability, resulting in the decreased potential for temporal and spatial variation in measurements. They may be expensive or time-consuming to deploy, but can be useful for deployment in several areas or daily use throughout tidal cycles (Black and Paterson 1997).

Conversely, smaller instruments allow for significant temporal and spatial variation in field measurements due to improved portability and ease of use. They are able to provide detailed information on small-scale properties such as benthic community structure and spatial sediment variation (Widdows et al. 1997). However, small devices, defined as having test surfaces on the order of 0.01 m^2 or smaller, produce results that are highly dependent on irregularities in bottom-shear stress distributions (Houwing and van Rijn 1998). Consequently, results may not be fully representative of the cohesive sediment's erodability. The ideal in-situ cohesive sediment testing instrument is light and small, thus easily deployable, but with a relatively large test surface, greater than 0.1 m^2 (Houwing and van Rijn 1998).

2. Ideal configuration of suspension measuring devices

Benthic flumes designed to measure cohesive sediment suspension may be categorized as either flow-through or recirculating flumes. Flow-through flumes are rectangular in geometry and produce a unidirectional flow across the sediment to induce erosion. In the case of flow-through flumes, sediment that erodes into suspension is lost out of the end of the flume (Black and Paterson 1997). Recirculating flumes may be of circular or raceway geometry, with parallel inner and outer channel walls.

Unlike flow-through flumes, which utilize a gradual increase in flow to induce erosion, flow speed in recirculating flumes is increased step-wise over time, eroding sediment by layer and recording an erosion profile (Black and Paterson 1997). Annular flumes produce a fully developed boundary layer above the test bed, which is important in the case of shear stress derivation (Black and Paterson 1997). However, raceway or flow-through flumes may avoid the complications of an underdeveloped boundary layer by measuring shear stress directly (Black and Paterson 1997). Since recirculating flumes are closed systems, suspended cohesive sediment accumulates over the test area during the period of measurement, potentially resulting in lower erosion rates than anticipated at higher flow rates (Black and Paterson 1997). For sites where local accumulation of suspended sediment occurs naturally, recirculating flumes may produce more representative measurements than flow-through flumes (Black and Paterson 1997).

In the case of the Plymouth Marine Laboratory annular flume, the absence of pumps, which contribute to the breakdown of suspended biota and flocculated sediment, was identified as a factor favoring the design of an annular flume (Widdows et al. 1997). Additional advantages included the containment of the entire flow volume over the cohesive sediment bed, as well as the ease of field deployment, enabling observation of the undisturbed sediment and biological community (Widdows et al. 1997). Resuspension in annular flumes, however, can be limited to surficial sediment layers, consisting only of the top few millimeters of sediment (McNeil et al. 1996).

The occurrence of secondary radial flows and flow differences between inner and outer parts due to curvature are also potential consequences of the annular configuration. Both may be minimized via reductions in the channel width (Fukada and Lick 1980). Raceway geometry was introduced as an alternative to annular design, intended to reduce the magnitude of secondary flows (Black and Paterson 1997). Parallel plate flow deflectors were utilized in the Mobile Recirculating Flume (MORF) to also reduce secondary flow (Black and Cramp 1995). Finally, the In Situ Erosion Flume (ISEF) was a vertically-oriented flume designed to reduce cross-stream variability and produce secondary fluid motions in the same direction as the primary flow, resulting in fewer problems associated with secondary flows (Houwing and van Rijn 1997).

3. Technology required to quantify shear and suspended load

Though existing devices for the measurement of cohesive sediment erosion vary greatly in their designs, some technological attributes remain consistent. Most early devices did not directly measure shear stress (Black and Paterson 1997). Crowley et al.

(2012) conducted an assessment of estimation methods for the measurement of shear stress in erosion rate testing devices. The methods analyzed included the computation of shear stress as a function of average velocity and as an approximation of the pressure difference across the flume (Crowley et al. 2012). Though the estimates were found to be representative in certain circumstances, it is recommended that both flow speed and shear stress are directly measured in situ. Capable measurement technologies utilized in existing systems include flush mounted shear stress sensors (Gust and Morris 1989), electromagnetic current meters (Hawley 1991, Houwing and van Rijn 1997, Nikora et al. 2007, Widdows et al. 1997), and impellor current meters (Black and Cramp 1995). Modern technologies include hot film probes, acoustic Doppler velocimeters (ADV), laser Doppler velocimeters (LDV), and particle tracking systems. These will be further discussed in a following section of this report.

The simultaneous collection of water flow rate and suspended sediment concentration measurements is necessary for the quantification of erosion rate. Optical backscatter sensors were utilized in the VIMS Sea Carousel, Plymouth Marine Laboratory annular flume, Mobile Recirculating Flume (MORF), and NIWA-II for the purpose of measuring suspended sediment concentration (Maa et al. 1993, Widdows et al. 1997, Black and Cramp 1995, Debnath et al. 2007). Erosion rate is determined by the difference between inflow and outflow suspended sediment concentrations (Black and Paterson 1997). Tolhurst (2000b) developed a method for normalizing suspended particulate matter with respect to device volume, then to surface area, to allow the comparison of suspended sediment measurements between devices. Electromagnetic current flowmeters were utilized in the Plymouth Marine Laboratory annular flume, In Situ Erosion Flume (ISEF), and NIWA-II to measure the current velocity in the flume (Widdows et al. 1997, Houwing and van Rijn 1997, Debnath et al. 2007). Alternative measurement technologies included the impellor current meter (Black and Cramp 1995) and paddlewheel flowmeter (Roberts et al. 2003, McNeil et al. 1996). Additional instrument recommendations include a water sampling system near the optical backscatter sensors that allows for subsequent laboratory calibration of suspended sediment concentration measurements (Widdows et al. 1997) and cameras to visualize the process (Black and Paterson 1997).

4. Impact of flume flow on the spatial distribution of erosion

A primary concern regarding annular flumes involves the spatial variation of erosion due to radial increases in bed stress from the inner wall to the outer wall of the flume (Black and Paterson 1997). This is a consequence of secondary flow patterns developed within annular flumes. Non-uniform distribution of shear stress across the sediment being studied is problematic for erosion studies.

5. Important aspects of erosion that are not currently addressed

Several aspects of the fate of sediments are not fully addressed by current cohesive sediment erosion measurement technologies. The impact of important biological processes on the stability and erodability of sediments, for example, may be studied more comprehensively with the development of more field-portable in-situ flumes (Widdows et al. 1997, Tolhurst 2000b). Sediment disturbance during instrument deployment via resuspension or vertical shearing and the non-uniform distribution of bed shear strength require additional observation (Black and Paterson 1997). The definition of erosion threshold appears to differ among studies as well, posing challenges to the comparison of data between devices (Tolhurst 2000b).

6. Potential for improvement via advanced measurement and sensing technology

One complex cohesive sediment erosion measurement system developed in recent years is the NIWA-II. Designed to allow fully automated measurement of streambed or stream bank sediments, the NIWA-II includes the sampling of water near optical backscatter sensors for subsequent laboratory calibration, considers both bed-load and resuspension in the measurement of overall erosion, and, most uniquely, noninvasively measures bed sediment elevations via an ultrasonic ranging system (Debnath et al. 2007). The incorporation of the ultrasonic ranging system, in particular, indicates the existence of significant potential for the improvement of in-situ cohesive sediment erosion measurements via the advancement of noninvasive sensing technologies.

As was briefly discussed earlier in this report, systems would also be improvement by the inclusion of modern instruments that measure velocity, shear stress, and turbulence. Such instruments include hot film anemometers, ADVs, LDVs, and particle tracking systems. Hot film probes, while commonly used to measure fluid flow, can be difficult to maintain and require precise calibration. Particle tracking velocimetry may be impractical in the case of studying cohesive sediment erosion, as high concentrations of suspended sediment may impede the system's ability to take measurements. ADVs produce highly precise 3D velocity measurements but would require intrusive placement within the system in order to obtain measurements from within the boundary-layer. LDVs also produce precise measurements with high spatial and temporal resolution, with the additional advantage of non-intrusive location within the system.

Conclusion

Unique circumstances enable certain instrument designs to be more advantageous than others in measuring the erodability of cohesive sediments. If small-scale variation in erosion rate (on the scale of 0.01 m) is of primary importance, devices with smaller footprints are most desirable. In most other cases, instruments with larger footprints (test section area of 0.1-1.0 m^2) are ideal. The size of cohesive sediment erosion measurement instruments often limits the potential for spatial and temporal variability in field measurements and should be carefully considered. For regions of interest in which localized suspended sediment accumulation is typical, recirculating flumes may produce more representative results than flow-through flumes. In this case, methods for minimizing secondary flow patterns should be considered and applied. Conversely, flow-through flumes are ideal for regions in which suspended sediment accumulation is atypical, or where the breakdown of suspended flocculated sediment or biota through pumping mechanisms is deemed unimportant. In all cases, instruments should be included to directly and simultaneously measure flow rate, suspended sediment concentration, and bed shear stress. A water sampling mechanism for post-measurement laboratory calibration of suspended sediment readings is advised. Emerging technology that would allow the noninvasive measurement of bed sediment elevations should also be considered and applied where possible. Finally, the device should be designed to operate remotely, with all necessary datalogging and power-supply components.

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