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PRELIMINARY OBSERVATIONS OF SEDIMENT EROSION FROM A BOTTOM RESTING FLUME

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ABSTRACT. A small portable flume was designed and constructed to measure in situ *erosion velocities. Preliminary results from deployments in Lake Michigan, Lake Superior, and Lake Ontario show that the flume can produce and measure the velocities required to erode fine-grained material from the lake bottom. Shear stresses required for erosion (calculated from the measured velocities) varied from 0.03 to 1.34 dynes/cm^2. As the flow velocity increases, erosion appears to occur as discrete episodes rather than continuously. Before flume results can be used to predict a sediment's resistance to erosion, both extensive measurements of sediment properties and comparisons of flume results to naturally-occurring erosion events are needed.*
INDEX WORDS: Sediment erosion, erosion rates, flumes, shear stress.

INTRODUCTION

Predicting the erosion threshold for natural cohesive sediments is difficult since the resistance to erosion exhibited by a cohesive bed may depend not only on particle size, but also on particle composition, pore water content, the degree of bioturbation, and depositional history. Erosion criteria can be empirically determined by examining time series records of water transparency and current velocity recorded by instrument packages deployed on the bottom, but there are two major drawbacks to this method. First, these investigations rely on natural occurrences to produce the shear stress (this is usually calculated from the velocity measurements, rather than measured directly) required to resuspend the sediment. Unless the deployment is in an area where large variations in current velocity occur regularly (as in tidal channels for instance), few or no resuspension events may occur during the deployment. Second, since resuspension is not measured directly, the investigator must be able to distinguish between resuspension episodes and other causes of high turbidity, such as lateral advection. Laboratory investigations can circumvent these difficulties, but the results are often of limited use because the physical disturbances inherent in collecting, storing, transporting, and then redepositing sediment in a flume significantly alter the shear strength of the sediment. Another approach is to measure *in situ* the stress or velocity required to erode bottom material. Tsai and Lick (1986) described a shaker device which resuspends material by vertical agitation of the overlying water and related these results to those obtained in an annular laboratory flume. Young (1977) described a bottom-resting flume that Young and Southard (1978) used to determine the critical shear stress necessary to resuspend sediments in Buzzard's Bay, Massachusetts. They found that although the critical shear stresses from their seaflume were considerably less than those calculated from laboratory flume experiments, the seaflume data were in rough agreement with the shear stresses calculated from an array of current meters deployed near the flume sites. The purpose of this paper is to describe a small bottom-resting flume based on Young's (1977) design, and to report some initial results from deployments made in Lake Michigan, Lake Ontario, and Lake Superior.

EQUIPMENT AND METHODS

The flume (Fig. 1) is a bottomless rectangular duct 4.88 m long and 0.3 m wide. To ensure that any erosion occurs first in the test section, the flume height decreases from 0.3 m at the entrance to 0.15

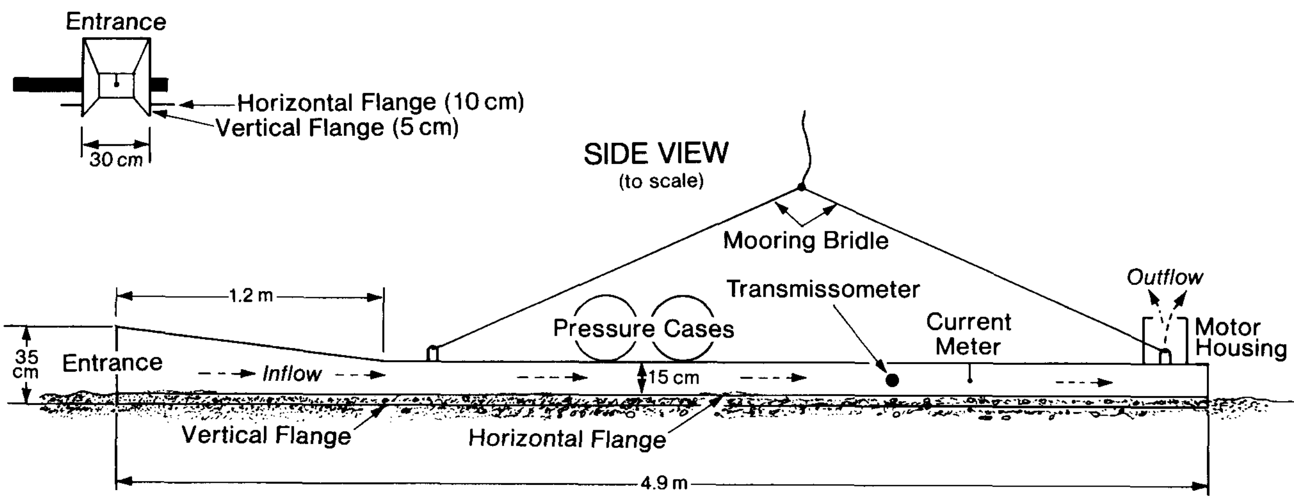

FIG. 1. Schematic side and front views of the flume. The sail (not shown) is mounted on the housing which contains the emitting end of the transparency meter. One pressure case contains the battery, the other contains the data acquisition and control unit.

m in the test section. The height of the flume walls is measured from a horizontal flange which runs the length of the flume on either side. This flange is designed to prevent the flume from sinking too deeply into the bottom. However, since the flume walls actually extend 5 cm below the flange, the actual channel height could be up to 0.20 m. Water is pulled through the flume at a controlled rate by a motor and prop located on top of the flume at its downstream end. This motor is merely a standard trolling motor whose housing has been filled with oil. Current velocity is measured in the center of the channel with a Marsh-McBirney 512 electromagnetic current meter located 3.94 m downstream from the flume entrance. Water transparency is measured with a Seatech transmissometer located in the sidewalls of the flume 3.51 m from the entrance.

Both the sensors and the motor are controlled by a data acquisition and control unit located in one of two pressure cases mounted on top of the flume. Power is supplied by a storage battery housed in the other pressure case. The data acquisition and control unit consists of three parts: a small portable computer, an analog-to-digital converter, and a motor speed control box. The computer program controls both the sampling of the current meter and transmissometer and the speed of the motor. This program has options for the user to specify: a) the time delay prior to starting the motor, b) up to four motor speeds, and c) the length of time (in half-minute intervals) that the motor is to run at each speed. In order to monitor ambient conditions, the user can also specify that transparency readings be made before the motor starts. Readings from both axes of the current meter and from the transmissometer are made every two seconds. Since there was not enough memory in the computer to record each individual observation for more than a few minutes, after every 15 readings (30 seconds) the average and standard deviation of each parameter was computed and recorded. In addition, during all but the Lake Michigan deployments, we recorded the values of the first 15 individual observations at each speed. The user determines the length of time the motor is to operate at each speed by specifying the number of sample values to be recorded.

Four variable potentiometers set by the user prior to deployment control the motor speed. During the deployment a stepping switch shifts from one potentiometer to the next at the appropriate time, thus altering the voltage. Measurements of the currrent velocity at different voltages were made so that the approximate velocity could be selected prior to deployment. These calibrations showed a linear relationship between motor voltage and measured speed (linear regression analysis gave an r^2 value of 0.95 based on 76 samples). Depending upon which of two different props is used, velocities between 2 and 12 cm/s can be obtained.

Because the flume has a great deal of drag (particularly when it is being lowered), two lead weights, each weighing about 36 kg, are mounted on top of the flume to facilitate its deployment and anchor it on the bottom. During the initial deployments we found that the flume generally oriented itself transverse to the ambient flow; apparently the transmissometer acts as a sail. However, if the flume was initially oriented with the motor upstream, it stayed in that configuration. Since this would allow material eroded by the flume to be transported back to the flume intake and recycled, a sail was added above the transmissometer to ensure that the flume orients itself transverse to the flow regardless of its initial orientation.

Deployment of the flume is straightforward, and similar to the procedure used by Young (1977). The flume is lowered slowly to the bottom on a steel cable connected to a bridle held above the flume by several small floats. A subsurface float is also attached near the upper end of the cable to prevent it from fouling the flume. Once the flume is on the bottom, a few extra meters of cable are payed out and attached to a surface marker. The entire assembly is then released so that the flume is totally independent of the ship.

The flume was first deployed in 1986 near Grand Haven, Michigan (Fig. 2). These deployments were exploratory in nature and were designed to test the various components of the flume. However during one deployment (M26-2, discussed below) we did observe bottom erosion. It was during these deployments that we discovered the need for the weights and the sail. We also found that material suspended by the flume when it reached the bottom was still in suspension inside the flume unless the flume sat on the bottom for at least an hour prior to starting the motor.

No deployments were made during 1987, but in 1988 deployments were made in Lake Superior (near Copper Harbor and in Whitefish Bay) and Lake Ontario (near Oswego, NY). The deployments in Lake Superior were made from the R/V *Seward Johnson*, the tender for the research submersible *Johnson Sealink* II. During the two deployments off of Copper Harbor, observations of the flume from the submersible showed that deployment of the flume did not visibly disturb the sediment surface, although the uppermost sediment layer was undoubtedly resuspended. This is the material that requires the delay prior to starting the runs. Unfortunately, there appears to be no way to avoid resuspending this "fluff" layer. The flume remained stationary during operation and appeared to be oriented across the flow, although the currents were very small. There were no small-scale topographic features at the deployment site.

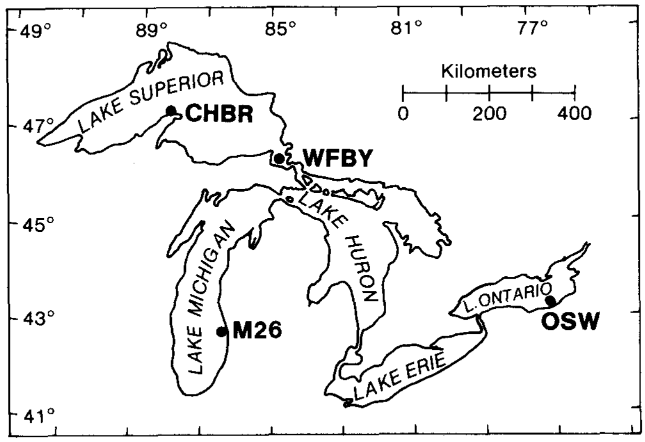

FIG. 2. Locations of the deployments. In Lake Michigan one run was made near Grand Haven, Michigan (M26); in Lake Superior two runs were made near Copper Harbor (CHBR), and one in Whitefish Bay (WFBY); and in Lake Ontario four runs were made near Oswego, NY (OSW). Details of the stations are given in Table 1.

Bottom sediments were collected at each site. A Ponar grab sampler was used in Lake Michigan, a gravity corer in Lake Ontario, and a punch corer mounted on the submarine in Lake Superior. Size analyses were done in triplicate by wet sieving the samples to remove the sand fraction and then analyzing the fine material using a Coulter Counter with 50 and 200 micron aperature tubes. Unfortunately we do not yet have the resources needed for a complete characterization of the sediment.

RESULTS

Young (1977) used a camera to record his observations and identified erosion by noting changes in the appearance of the bottom. In many areas of the Great Lakes however, and particularly in those areas which have a muddy bottom, a bottom nepheloid layer from 5 to 25 m thick exists during the stratified season. Since this nepheloid layer seriously reduces visibility, we decided to use a transmissometer to monitor changes in water transparency, which should decrease when erosion occurs. By allowing the flume to sit on the bottom for at least an hour after deployment, and by making transparency readings before turning on the motor, we can measure the ambient water transparency (these measurements were checked several times by comparing them to those measured with another transparency meter deployed separately). We consider any reduction from this ambient value as an indication that erosion occurred and call the velocity recorded at this time (a thirty second average) the critical erosion velocity. We also observed a simultaneous increase in the standard deviation of the transparency. These changes usually, but not always, occurred immediately after the speed was increased. We also found that after some time interval (whose length varied from location to location), the transparency usually increased to near the original value, suggesting that no more material could be eroded at that velocity.

It is important to recognize that although we measured the centerline velocity, it is actually the bottom shear stress that causes erosion. Calculation of the shear stress is required in almost all field investigations, since in very few is the shear stress actually measured. Young and Southard (1978) used an equation given by Prandtl and Tietjens (1934) to calculate the bottom shear stress (τ_0) from their velocity data (u)

$$\tau_0 = .0228\ \rho(u^7\nu/z)^{.25} \qquad (1)$$

where ρ is the density of water, ν the viscosity, and z the distance from the wall. Since this equation was derived for fully developed turbulent flow in cylindrical pipes, its use here is somewhat questionable. However, duct experiments by Melling and Whitelaw (1976) showed that although fully-developed flow did not occur at distances from the entrance less than $25{*}D_H$ (D_H is the hydraulic diameter and is equal to 4* cross-sectional area/wetted perimeter), τ_0 was constant when the distance to the entrance was greater than 5.6 D_H. In Young's flume the test section was about $12D_H$ from the entrance while in ours the distance is almost $20D_H$, so the shear stress should be constant in both. The non-circular geometry of the flume could be a more serious problem, but in Melling and Whitelaw's experiments (Re = 42,000), the calculated value of τ_0 (23.5 dynes/cm^2) compares quite well with the measured value of 24.01 dynes/cm^2. Other problems associated with the use of equation 1, including the distribution of the total stress between the bottom and the other walls of the flume, and the effect of a transitional or hydrodynamically rough boundary layer, are discussed by Young and Southard (1978). An additional error may result from the uncertainty of the exact value of z, the flume depth. For our flume z may vary between 7 and 10 cm. This translates to an uncertainty in τ_0 of about 10%. This is the same order of magnitude as the other errors discussed by Young and Southard.

Although the use of equation 1 cannot be justified on theoretical grounds, it seems to give fairly accurate results. In the absence of anything better, we have used it to calculate the shear stresses, but we are aware that its use introduces some error. In addition, since the flow velocity increased in discrete steps, we cannot be sure that the velocity at which we observed erosion is the minimum velocity required. All that we can be sure of is that the critical velocity is bounded by the previous velocity and the one at which we observed erosion.

Shear stress values calculated from the critical erosion velocities are listed in Table 1. They range from 0.03 dynes/cm^2 (for a velocity of 3 cm/s) to 1.34 dynes/cm^2 (for u = 26.4 cm/s). This range of shear stresses is approximately the same as Young and Southard reported. Although there are no laboratory results from material from any of these sites, tests on material from the bottom of Lake Erie (Fukuda and Lick 1980, and Lee *et al.* 1981) show that erosion began when the stress was on the order of 1–2 dynes/cm^2. Tsai and Lick (1986) reported sediment entrainment of Lake St. Clair sediments at 2.5 dynes/cm^2. Thus, our results are in the same range or lower than previous estimates.

Details of the eight successful deployments are given in Table 1. We observed bottom erosion in all of the deployments except CHBR1, although sometimes the change in transparency was quite small. Note that the mean velocities given in Table 1 are averaged over the total time period that a particular voltage was applied, while the critical erosion velocities and shear stresses are values for a single half-minute interval.

During some of the runs (M26-2, OSW3, and OSW4) water leaked into the motor housing. This caused the motor speeds to become elevated (for instance the velocities measured during run M26-2 are much higher than the applied voltages should have produced) and erratic (runs OSW3 and OSW4, as well as run M26-2). We have not used any results where this problem was severe enough to hinder the data interpretation.

Results from run M26-2 are shown in Figure 3.

TABLE 1. Details of the eight successful deployments.

Run #	Location	Depth (m)	Mean Velocities (Standard dev.) (cm/s)	Critical Velocities (Standard dev.) (cm/s)	Critical Shear Stress (Standard dev.) (dynes/cm²)	Clay Content %	Sand Content %
M26-2	40°03.43'N 86°18.30'W	65	7.7(.44), 9.6(.50), 15.2(.44), 26.2(.79)	5.6(.96) 26.4(1.22)	0.09(.0041) 1.34(.0073)	9.99	20.10
CHBR1	47°28.98'N 87°51.39'W	93	1.8(.14), 3.0(.37), 4.6(.75), 6.3(.75)*	–	–	14.90	18.40
CHBR2	47°28.98'N 87°51.39'W	93	4.1(.36), 6.6(.14), 9.1(.48), 11.6(.52)*	11.6*	0.32*	14.90	18.40
WFBY	46°42.73'N 84°45.90'W	99	1.6(.35), 2.4(.35), 4.0(.36), 6.4(.44)	4.2(.53) 6.4(.50)	0.11(.0044)	45.59	0.50
OSW1	43°30.13'N 76°35.62'W	108	2.8(.28), 3.9(.36), 8.0(1.22), 13.9(1.46)	3.0(.29)	0.03(.0004)	4.48	80.00
OSW2	43°29.78'N 76°35.16'W	86	3.7(.30), 5.2(.28), 3.7(.27), 4.9(.28)**	3.4(.53)	0.04(.0002)	2.28	83.20
OSW3	43°29.85'N 76°35.06'W	87	3.1(.24), 6.7(.35), 11.4(.45), 14.4(.61)	3.3(.21)	0.04(.0004)	2.28	12.90
OSW4	43°35.26'N 76°25.25'W	84	5.1(.95)***	5.3(.27)	0.08(.0004)	11.10	8.40

*During these runs, the current meter did not work. The velocities were calculated from motor voltages. No standard deviation can be calculated for the critical velocity in run CHBR2.

**During this run, the motor speed control did not work properly. So, rather than four different speeds, two speeds were repeated.

***During this run, water in the motor housing caused the motor to run erratically. No meaningful average velocities can be calculated for the three higher motor voltages.

As noted above, a small amount of water in the motor housing caused both erratic changes and somewhat higher speeds than were expected. Two very well-defined events can be identified: the first just after the motor was turned on, and the second when the maximum speed was begun. Both of these transparency reductions occur simultaneously with a peak in the standard deviation of the transparency. After each of these events the transparency increases but does not reach its previous value. This indicates that erosion was still occurring, although at a reduced rate. Two other, smaller, peaks in the standard deviation record (both of which also occur simultaneously with changes in the speed), are probably due to erosion, but the changes in mean transparency are much smaller.

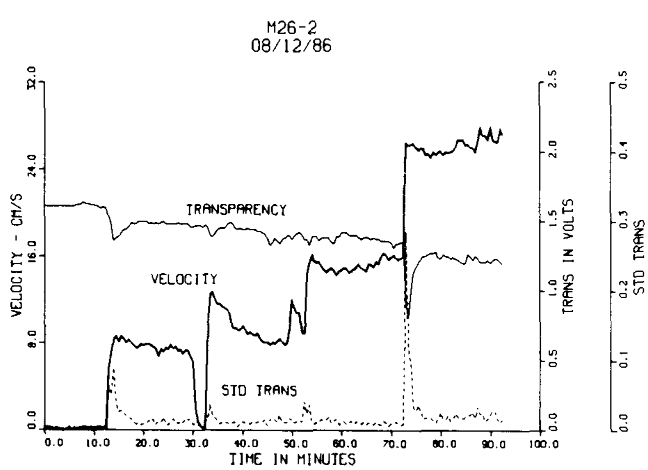

FIG. 3. Flume results from the deployment at M26. Both erosion events coincide with changes in current velocity. STD Trans is the standard deviation of the transparency.

The results from the second deployment at Copper Harbor (Fig. 4) also show a well-defined erosion event, but his one occurs 2 minutes after the maximum velocity began. There are also two smaller peaks in the standard deviation of the transparency, one when the motor was first turned on and the other when the fourth speed was started, but neither of them is correlated with a pronounced dip in the mean transparency values. The transparency readings do decrease slightly during both these times so some erosion may have

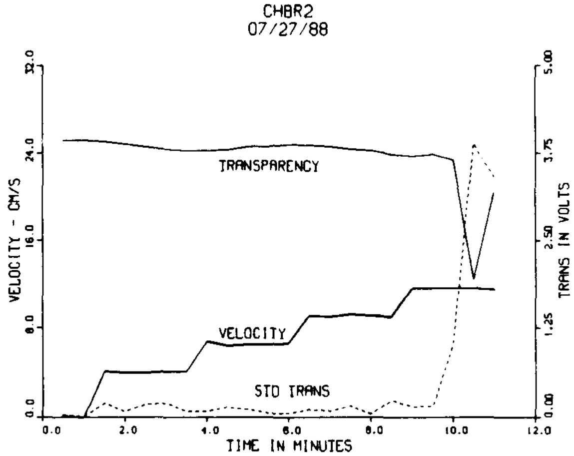

FIG. 4. Flume results from the second deployment near Copper Harbor. There was a slight decrease in transparency when the flume was first turned on and a second, much more pronounced erosion event about 1 minute after the highest velocity was reached. The velocity values were calculated from the applied voltages. STD Trans is the standard deviation of the transparency.

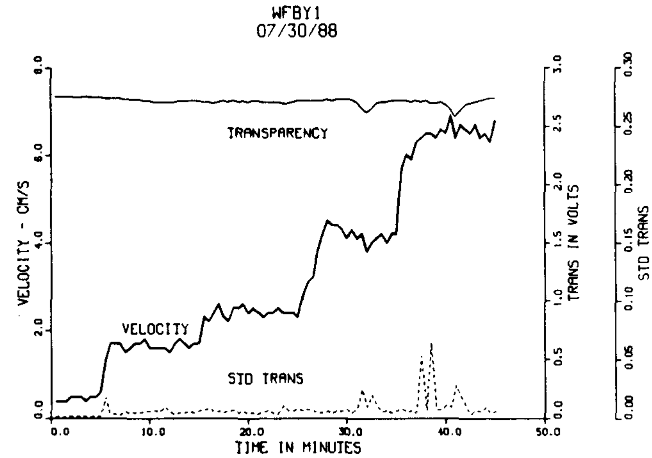

FIG. 5. Flume results from the deployment in Whitefish Bay. Two erosion events are evident, although the change in transparency is less than at the other sites. Note that the maximum velocity is somewhat less than in Figures 3 and 4. STD Trans is the standard deviation of the transparency.

occurred, but since the results from the first deployment (which covered the same range of velocities but showed no erosion) do not confirm this, we used 11.6 cm/s as the critical erosion velocity.

The Whitefish Bay results (Fig. 5) show two dips in the mean transparency. One occurs 5 minutes after the third speed began, and the other 6 minutes after the fourth speed started. This thixotropy (a time-dependence of shear stress at a constant shear rate) is not uncommon in cohesive materials (Williams 1985). Both these dips are correlated with increases in the standard deviation values, but there are two other peaks in the transparency standard deviation that are not associated with a change in the mean transparency. One of these occurs when the motor was first turned on, and the other when the fourth speed started. Although some minor erosion may have occurred during these periods, we used 4.6 cm/s as the critical velocity for erosion.

In the first three deployments in Lake Ontario (OSW1, OSW2, and OSW3) erosion began between 3 and 3.5 cm/s. This is intriguing since the percent sand in the sediments varied widely. The results of runs OSW1 and OSW2, where the sediment sizes were similar, indicate that the flume results are reproducible. Erosion did not begin as soon as the flume was turned on, but 2 minutes later in OSW1, 7 minutes later in OSW2, and about half a minute later in OSW3. The higher speeds during OSW4 were so erratic that no meaningful data were obtained, although we did get a definite erosion event at the lowest speed.

DISCUSSION

The results from Lake Michigan and Whitefish Bay seem to indicate that erosion does not occur continuously as velocity increases, but rather as a series of discrete episodes. This suggests that the bottom sediment may consist of discrete layers with marked discontinuities of sediment shear strength, rather than a single mass with steadily increasing shear strength with depth. Unfortunately, since we do not know how much sediment was eroded, we cannot correlate these discontinuities with any vertical changes in sediment properties. Several of the results also exhibit thixotropy, so the sediments can probably best be described as non-Newtonian fluids.

It is also possible that erosion was caused by the impulsive shear generated by the changes in velocity, rather than the increased shear due to higher steady velocities. If this is the case, then the changes in velocity and transparency should coincide and the transparency should increase after the eroded material has been transported out of the flume. However, as noted above, in many instances the changes in transparency lag the velocity changes by up to several minutes. Calculations also show that the decreases in transparency persist longer than the time required to clear the flume of a pulse of sediment. In addition, examination of the individual velocities recorded in the first 30 seconds after each speed change showed that it took 10–15 seconds for the velocity to increase to its new value. We conclude that—except possibly during run M26-2 when the velocity changes were large—erosion was most likely caused by an increase in the shear due to increased steady flow, rather than due to an impulse shear generated by an abrupt change in velocity.

Since our results are only preliminary, we did not fully characterize the bottom material, but all of the samples consisted of varying amounts of quartz and clay minerals with a small amount of feldspar. It is impossible from the data available to develop any meaningful relationship between the flume results and the sediment properties. To do this it will be necessary in the future to measure the vertical distribution of sediment parameters, including pore water content, Atterberg limits, grain size, and mineralogic composition, and to reduce the intervals between the different velocities tested as much as possible. It will also be necessary to deploy the flume at locations where naturally occurring erosion events have been monitored so that the flume results can be compared to them.

CONCLUSIONS

An operating bottom-resting flume has been constructed and deployed in several areas in the Great Lakes. The initial results show that the onset of erosion can be measured and that it does vary from site to site. The flume gives reproducible results and is a useful way to quickly collect data from a large number of sites.

In two of the deployments, two distinct episodes of erosion occurred. This suggest that the shear strength of the bottom material may not increase smoothly with depth, but rather in a series of discrete steps. Future work will require better knowledge of both the sediment parameters and a better determination of the minimum velocity required to produce erosion. It will also be necessary to compare flume results with those from naturally occurring episodes of erosion before flume results can be used to predict a sediment's resistance to erosion.

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