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## **Development for the Optional Use of Circular Core Tubes with the High Shear Stress Flume**

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### **Abstract**

In this study, the erosion rates of four reconstituted sediments in both rectangular and circular sample tubes have been determined as a function of density and shear stress by means of a high shear stress sediment erosion flume at Sandia National Laboratories. This was done to determine if circular cores used in field sampling would provide the same results found using the existing technology of rectangular cores. Two samples were natural, cohesive sediments retrieved from different sites in the Boson Harbor identified as Open Cell and Mid Channel. The other two sediments were medium and coarse grain, non-cohesive quartz sediments. For each sediment type, erosion tests were performed with both rectangular and circular core tubes. For all cores, bulk density was determined as a function of depth and consolidation time. Sediments were eroded to determine erosion rates as a function of density and shear stress for both types of core tubes used. No measurable difference was found between the two core types.

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# 1. Introduction

The original design of the High Shear Stress Flume was for use of 10 by 15 cm rectangular sediment cores to be inserted into the false bottom of the flume (McNeil et al, 1996). Justification for the shape of the core was based on the argument that the leading edge of the sample should be perpendicular to the flow in case flow variations due to the sediment caused irregular erosion patterns and results. There is no other published evidence or reasoning to use a rectangular core and the use of a circular core has never been tested.

The optional use in the field of circular cores would greatly alleviate some of the operational difficulties in retrieving in-situ samples. Sample recovery and core length would increase and the coring device would be much easier to push into coarse-grained or densely compacted sediments. Many devices and methods that have proven to be successful in retrieving core samples use circular coring tubes. Using a similar coring device for the flume would create the opportunity to use and interchange parts that are already available rather than having to use new coring designs for each specific project. Finally, circular cores create a much better seal with the plunger that is used to raise the sediments into the flume test section.

In the following section, descriptions of the high shear stress sediment erosion flume and experimental procedures are given. The results of laboratory studies for the reconstituted sediments are presented in section 3, while the fourth section discusses the laboratory results. The summary and concluding remarks are given in the final section.

## 2. Experimental Procedures

### 2.1 Description of the High Shear Stress Sediment Erosion Flume

The High Shear Stress Sediment Erosion Flume is shown in Figure 1 and is essentially a straight flume, which has a test section with an open bottom through which a rectangular cross-section coring tube containing sediment can be inserted. More recently, an attachment has been made that will allow the use of a circular cross-section coring tube. The main components of the flume are the coring tube; the test section; an inlet section for uniform, fully-developed, turbulent flow; a flow exit section; a water storage tank; and a pump to force water through the system. The coring tube, test section, inlet section, and exit section are made of clear acrylic or polycarbonate so that the sediment-water interactions can be observed. The rectangular coring tube has 10 cm by 15 cm cross-section, the circular coring tube has a 10 cm diameter and both can be up to 1 m in length.

Water is pumped through the system from a 120 gallon storage tank, through a 5 cm diameter pipe, and then through a flow converter into the rectangular duct shown. The flow converter changes the shape of the cross-section from circular to the rectangular duct. This duct is 5 cm in height, 10 cm in width, and 200 cm in length; it connects to the test section which has the same cross-sectional area and is 15 cm long to match the rectangular core tubes. When the circular core attachment is fastened in place the test section has a 10 cm diameter. The flow is regulated by a three-way valve so that part of the flow goes into the duct while the remainder returns to the tank. Also, there is a small valve in the duct immediately downstream from the test section which is opened at higher

flow rates to keep the pressure in the duct and over the test section at atmospheric conditions.

At the start of each test, the coring tube is filled with reconstructed sediments. The procedure for preparing the reconstructed sediments in the laboratory is described later in section 2.3. The coring tube and the sediment it contains are then inserted into the bottom of the test section. When using the circular core tubes, the circular core attachment must be in place before beginning the experiments. An operator moves the sediment upward using a piston inside the coring tube, that is connected to a mechanical jack and driven by a variable-speed controller. By this means, the sediments can be raised and sediment surface kept level with the bottom of the test section. The speed of the piston movement can be controlled at a variable rate in measurable increments as small as 0.25 mm.

Water is forced through the duct and the test section over the surface of the sediments. The shear produced by this flow causes the sediments to erode. As the sediments in the core erode, they are continually moved upwards by the operator so that the sediment-water interface remains level with the bottom of the test and inlet sections. The erosion rate is recorded as the upward movement of the sediments in the coring tube over time.

## **2.2 Hydrodynamics**

### **2.2.1 Flume Channel**

For the flow rates of interest, it can be shown that fully developed turbulent flow exists in the test section. Turbulent flow through pipes has been studied extensively, and

empirical functions have been developed which relate the mean flow rate to the wall shear stress. In general, flow in circular cross-section pipes has been investigated. However, the relations developed for flow through circular pipes can be extended to non-circular cross-sections by means of a shape factor. An implicit formula relating the wall shear stress to the mean flow in a pipe of arbitrary cross-section can be obtained from Prandtl's Universal Law of Friction (Schlichting, 1979). For a pipe with a smooth surface, this formula is

$$\frac{1}{\sqrt{\lambda}} = 2.0 \log \left| \frac{UD\sqrt{\lambda}}{\nu} \right| - 0.8 \quad (2.1)$$

where  $U$  is the mean flow speed,  $\nu$  is the kinematic viscosity,  $\lambda$  is the friction factor, and  $D$  is the hydraulic diameter defined as the ratio of four times the cross-sectional area to the wetted perimeter. For a pipe with a rectangular cross-section, or duct, the hydraulic diameter is

$$D = 2hw/(h + w) \quad (2.2)$$

where  $w$  is the duct width and  $h$  is the duct height. The friction factor is defined by

$$\lambda = \frac{8\tau}{\rho U^2} \quad (2.3)$$

where  $\rho$  is the density of water and  $\tau$  is the wall shear stress. Inserting Eqs. (2.2) and (2.3) into Eq. (2.1) then gives the wall shear stress  $\tau$  as an implicit function of the mean flow speed  $U$ .

For shear stresses in the range of 0.1 to 10 N/m<sup>2</sup>, the Reynolds numbers,  $UD/\nu$ , are on the order of  $10^4$  to  $10^5$ . These values are sufficient for turbulent flow to exist for over the range of interest in this study. For flow in a circular pipe, turbulent flow theory suggests that the transition from laminar to turbulent flow occurs within 25 to 40 diameters from the entrance to the pipe. Since the hydraulic diameter of the duct pipe is 6.8 cm, this suggests an entry length of approximately 170 to 270 cm. The length of the duct leading to the test section is 180 cm and is preceded by a 20 cm flow converter and several meters of inlet pipe. These arguments along with direct observations indicate that the flow is fully turbulent in the test section.

### **2.2.2 Sediment Surface and Core Shape**

The shear stresses calculated for the sediment surface are based on the use of hydraulically smooth turbulent flow. If the sediment surface is assumed to be approximately hydraulically smooth (McNeil et al, 1996), then the shape of the leading edge where the smooth channel bottom transitions to the sediment surface should be irrelevant. In addition, extensive observations have shown that the flume operator must take the average of the whole surface into account since the surface can become uneven due to pits formed from aggregate erosion (McNeil et al, 1996, Jepsen et al, 1997a and b, and Roberts et al, 1998). In this case, the leading edge and its shape also become irrelevant.

## 2.3 Core Preparation

For each sediment type, the rectangular and circular cores were prepared in exactly the same way. To obtain different bulk densities for the sediments taken at the Open Cell and Mid Channel sites from the Boston Harbor for the erosion tests, sediment cores were prepared as follows. Approximately 30 gallons of wet sediments were placed in 35 gallon cylindrical tanks and mixed until the sediment-water mixture was homogeneous. The sediment mixtures were then poured in the coring tubes to a depth of 30 cm. The rectangular and circular cores were allowed to consolidate until a broad density range with depth was achieved for the erosion tests. For the Open cell and Mid Channel sediments the consolidation time was determined to be 5 days.

The quartz sediments used in these experiments were relatively coarse grained, non-cohesive, settled quickly and could not be mixed in the manner described above. Therefore, to obtain different bulk densities for the two quartz sediments for the erosion tests, sediment cores were prepared as follows. Water was poured directly into the core and dry quartz was added until the sediment-water interface reached 30 cm. Since these quartz sediments were non-cohesive, density does not change appreciably with consolidation time or depth (Roberts et al, 1998). Both the rectangular and circular erosion cores and analysis cores were allowed to consolidate for 1 day.

## 2.4 Measurements of Sediment Erosion Rates

The procedure for measuring the erosion rates of the sediments as a function of shear stress and depth was as follows. The sediment cores were prepared as described above and then moved upward into the test section until the sediment surface was even with the bottom of the test section. A measurement was made of the depth to the bottom of the sediment in the core. The flume was then run at a specific flow rate corresponding to a particular shear stress. Erosion rates were obtained by measuring the remaining core length at different time intervals, taking the difference between each successive measurement, and dividing by the time interval.

In order to measure erosion rates at several different shear stresses using only one core, the following procedure was generally used. Starting at a low shear stress, the flume was run sequentially at higher shear stresses with each succeeding shear stress being twice the previous one. Generally about three shear stresses were run sequentially. Each shear stress was run until at least 2 to 3 mm but no more than 2 cm were eroded. The time interval was recorded for each run with a stop watch. The flow was then increased to the next shear stress, and so on until the highest shear stress was run. This cycle was repeated until all of the sediment had eroded from the core. If after three cycles a particular shear stress showed a rate of erosion less than  $10^{-4}$  cm/s, it was dropped from the cycle; if after many cycles the erosion rates decreased significantly, a higher shear stress was included in the cycle.

## 2.5 Measurements of Sediment Bulk Properties

The sediment bulk properties were determined from duplicate cores that were prepared in a similar manner as the rectangular and circular erosion cores. The core sleeves of these analysis cores were made from 7.6 cm inner diameter thin acrylic tubes of the same length as the erosion cores.

In order to determine the bulk density of the sediments at a particular depth and consolidation time, the sediment analysis cores were frozen, sliced into 2.5 cm sections, and then weighed (wet weight). They were then dried in the oven at approximately 75°C for 2 days and weighed again (dry weight). The water content  $W$  is then given by

$$W = \left| \frac{m_w - m_d}{m_w} \right| \quad (2.4)$$

where  $m_w$  and  $m_d$  are the wet and dry weights respectively. A volume of sediment,  $V$ , consists of both solid particles and water, and can be written as

$$V = V_s + V_w \quad (2.5)$$

where  $V_s$  is the volume of solid particles and  $V_w$  is the volume of water. If the sediment particles and water have densities  $\rho_s$  and  $\rho_w$  respectively, the water content of the sediment can be written as

$$W = \frac{\rho_w V_w}{\rho V} \quad (2.6)$$

where  $\rho$  is the bulk density of the sediments. A mass balance of the volume of sediment gives

$$\rho V = \rho_s V_s + \rho_w V_w \quad (2.7)$$

By combining Eqs. (2.5), (2.6), and (2.7), an explicit expression can be determined for the bulk density of the sediment,  $\rho$ , as a function of the water content,  $W$ , and the densities of the sediment particles and water. This equation is

$$\rho = \frac{\rho_s \rho_w}{\rho_w + (\rho_s - \rho_w)W} \quad (2.8)$$

For the purpose of these calculations, it has been assumed that  $\rho_s = 2.6 \text{ gm/cm}^3$  and  $\rho_w = 1.0 \text{ gm/cm}^3$ .

Particle sizes and particle size distributions were determined by use of a Malvern Mastersizer S particle sizing package for particle diameters between 0.05 and 900  $\mu\text{m}$ . The two natural sediments and the fine-grained quartz sediment samples had particle sizes less than 900  $\mu\text{m}$ . Approximately 5 to 10 grams of sediment was placed in a beaker containing about 500 mL of water and mixed by means of a magnetic stir bar/plate combination. Approximately 1 mL of this solution was then inserted into the particle sizer sampling system and further disaggregated as it was re-circulated through the

sampling system by means of a centrifugal pump. The sample was allowed to disaggregate for five minutes on the stir plate and an additional five minutes in the recirculating pump sampling system before analysis. To ensure complete disaggregation and sample uniformity, the sediment samples were analyzed multiple times and repeated in triplicate. From these measurements, the distribution of grain sizes and mean grain sizes as a function of depth were obtained. For the large grained quartz sediment, which had a mean size greater than 900  $\mu\text{m}$ , sieve analysis was used to determine particle size and particle size distribution.

The dry sediment was crushed into powder and then weighed. Approximately 5 mL of 10% hydrochloric acid was added to every 1 gram of dry sediment (Tye et al, 1996). The sample was again dried in the oven at 75°C, and analyzed in an UIC, Inc. Model CM5014 CO<sub>2</sub> Coulometer to determine the total organic carbon content of the sediment.

The mineralogies of the sediments were approximately determined by means of X-ray powder diffraction using a Bruker, AXS Model D8 Advance X-ray Diffractometer. Samples were crushed to a size of less than 100  $\mu\text{m}$  before being measured by X-ray diffraction.

## 3. Results for Laboratory Consolidation and Erosion

### Tests

Tests were done to determine erosion properties for four sediments with respect to consolidation and bulk density, using both round and rectangular coring tubes. The measurements of the consolidation and the erosion tests using the rectangular cores with the Boston Harbor sediments were developed for the Boston Harbor Sediment Study (Roberts et al, 2000a). The erosion constants (to be discussed) were developed by using data derived only from the rectangular cores. The data from the round cores are displayed for comparison only. The other two sediments are medium and course-grained quartz that were purchased in dry 50 lbs. bags. Both quartz sediments were mixed directly in the erosion core prior to testing. For each sediment type, the rectangular and round cores were prepared in the same way.

#### 3.1 Bulk Properties

Particle size, bulk density, organic content, and mineralogy of each of the four composite sediment mixtures were measured. The size distributions for each composite are shown in Figure 2. The mean particle size was 99.8, 35.7, 145 and 1250  $\mu\text{m}$  for the Open Cell, Mid Channel, medium-grained quartz and course-grained quartz sediments, respectively. The organic content for the composite mixture was 3.02 % for Open Cell, 2.23 % for Mid Channel and 0.00% for both quartz sediments. The mineralogy of each composite and a summary of all sediment properties are shown in Table 1. Particle size,

organic content, and mineralogy were constant with depth for each composite core. Bulk density was the only variable parameter in each core.

Bulk density was determined as a function of depth for 30 cm core lengths. Consolidation times were between 2 and 120 days for the Open Cell and Mid Channel rectangular cores developed for the Boston Harbor Sediment Study (Roberts et al, 2000a), were 5 days for the Open Cell and Mid Channel Circular cores, and were one day for the quartz sediments. Densities were determined by measuring the water content of each core in 2.5 cm increments. Sediment bulk densities are shown in Figure 3a for Open Cell, Figure 3b for Mid Channel, Figure 3c for medium grained quartz and Figure 3d for large grained quartz. For the Open Cell and Mid Channel cores, the bulk density generally increases with depth and consolidation time. The bulk density for the Open Cell sediments ranged between  $1.45 \text{ g/cm}^3$  and  $1.58 \text{ g/cm}^3$  for up to a 120 day consolidation time. The Mid Channel sediments had a bulk density range of 1.38 to  $1.51 \text{ g/cm}^3$ . For the medium and coarse-grained quartz cores, the consolidation was relatively rapid within seconds to minutes. Previous work has shown that the density of coarse-grained quartz sediments does not change appreciably with time (Roberts et al, 1998). The medium-grained quartz sediment had a bulk density range of 1.88 to  $1.93 \text{ g/cm}^3$ . The coarse-grained quartz sediment had a bulk density range of 1.90 to  $1.96 \text{ g/cm}^3$ .

### **3.2 Erosion Rates**

Erosion rates as a function of shear stress and depth were obtained for rectangular cores at consolidation times ranging from 2 and 120 days for the Open Cell and Mid Channel sediments. Erosion rates as a function of shear stress and depth were obtained

for circular cores at a consolidation time of 5 days for the same sediments. Erosion rates were measured for shear stresses of 0.5, 1.0, 2.0, and 4.0 N/m<sup>2</sup>. The erosion rates for the lower shear stress of 0.5 N/m<sup>2</sup> could only be reasonably measured for the upper portion of the cores and for short consolidation times. This is because erosion either does not occur or is so slow that it would take hours to days to erode a measurable amount of sediment. Likewise, the 4.0 N/m<sup>2</sup> shear could not be tested at all depths because it eroded low bulk density areas too fast for the operator to accurately measure erosion rates.

All of the data for erosion rates as a function of bulk density for shear stresses of 0.5, 1.0, 2.0, and 4.0 N/m<sup>2</sup> are shown for each core in Figures 4a and 4b for site composites Open Cell and Mid Channel, respectively. In general, there is good agreement between the erosion data from the rectangular cores and the circular cores. A large decrease in erosion rate as the bulk density increases can be seen at all shear stresses. This has also been observed in previous experiments by Jepsen et al (1997a, 1997b, and 1998) and Roberts et al, (1998 and 2000a) for other natural and pure quartz sediments in similar laboratory tests. In general, the data can be approximated by an equation of the form

$$E = A\tau^n\rho^m \quad (3.1)$$

where E is the erosion rate (cm/s),  $\tau$  is the shear stress (N/m<sup>2</sup>),  $\rho$  is the bulk density (g/cm<sup>3</sup>), and n, m, and A are constants. The constants are shown in Table 2 for each composite. For each shear stress, the erosion rate as a function of bulk density is shown

as a straight line which demonstrates that the above equation represents the data quite well and also that the erosion rate is a unique function of shear stress and bulk density. This relationship (with different constants) has been shown to successfully describe seven other natural and many synthetic sediments (Jepsen et al, 1997a, 1997b and 1998, Roberts et al, 1998 and 2000a).

Erosion rates as a function of shear stress and depth were obtained for the 1 day consolidation time for the medium and coarse grain quartz sediments using both the rectangular and circular core tubes. Erosion rates were measured for shear stresses of 0.5 and 1.0 N/m<sup>2</sup>. The erosion rates for the higher shear stresses could not be tested at any depth because the erosion was too fast for the operator to accurately measure erosion rates. This is similar to observations in Roberts et al (1998) for these particle sizes.

All of the data for erosion rates as a function of bulk density for shear stresses of 0.5 and 1.0 N/m<sup>2</sup> are shown for each core in Figures 4c and 4d for the medium and coarse-grained quartz sediments. In general, there is good agreement between the erosion data from the rectangular cores and the circular cores. As seen in Figures 4c and 4d, the erosion rates are independent of bulk density and  $m$  from Equation 3.1 is therefore zero. For each shear stress, the erosion rate as a function of bulk density can be approximated by a straight line shown in Figures 4c and 4d and can be represented by Equation 3.1.

## 4. Discussion of Results

The following compares erosion rates measured from use of the rectangular and circular erosion core tubes for the four composite sediments.

The Open Cell and Mid Channel sediments are both cohesive sediments, in which, erosion has strong dependence on bulk density. The medium and coarse-grained quartz sediments are both non-cohesive sediments, and erosion was independent of density. The sediments had different mean particle sizes, particle size distributions and organic content and therefore, had different bulk density ranges. The erosion rate data measured from both the rectangular and circular cores for each distinctly different sediment type were indistinguishable as a function of density.

The rectangular cores have a greater erosion surface area than the circular cores and more of the erosion surface of the rectangular core is closer to the side of the channel. This allows for better observation of the erosion process, especially as the re-circulating water becomes turbid. For cohesive sediments, when aggregates erode from the surface of a sediment, pits or depressions are left behind. The operator of the flume must take into account the entire surface of the sediment sample when performing the erosion tests. When the aggregates become large during erosion, the depression formed becomes large as well. When the erosion is in the form of aggregates, it is easier to measure the erosion rate in the rectangular cores because of the larger observable erosion surface area. Ultimately, since the flume operator must take the whole surface into account during erosion tests, the visual inspection of the sediment surface by the operator during erosion

tests was easier for the rectangular cores than for the circular cores. However, careful measurement shows that the data is not affected by the change in shape of the core.

## Summary and Concluding Remarks

By means of the experiments described here, the effects of sediment bulk density on erosion rates were measured for four composite sediments by use of both rectangular and circular erosion core tubes. Two sediments were retrieved from locations in the Boston Harbor. The other two sediments were medium and coarse-grained, non-cohesive quartz sediments. From these experiments, the following was determined. (1) In general, there is good agreement between the erosion data from the rectangular core tubes and the circular core tubes for all sediments. (2) Visual inspection of the sediment surface by the operator during erosion tests was easier for the rectangular cores than for the circular cores.

These results demonstrate that the use of circular cores give the same results as measured with the rectangular cores. However, since rectangular cores provide a greater ease of use for the flume operator, it is recommended that issues regarding core retrieval in the field be considered in the decision to use either rectangular or circular cores. In the laboratory, it is recommended that rectangular cores be used.

## References

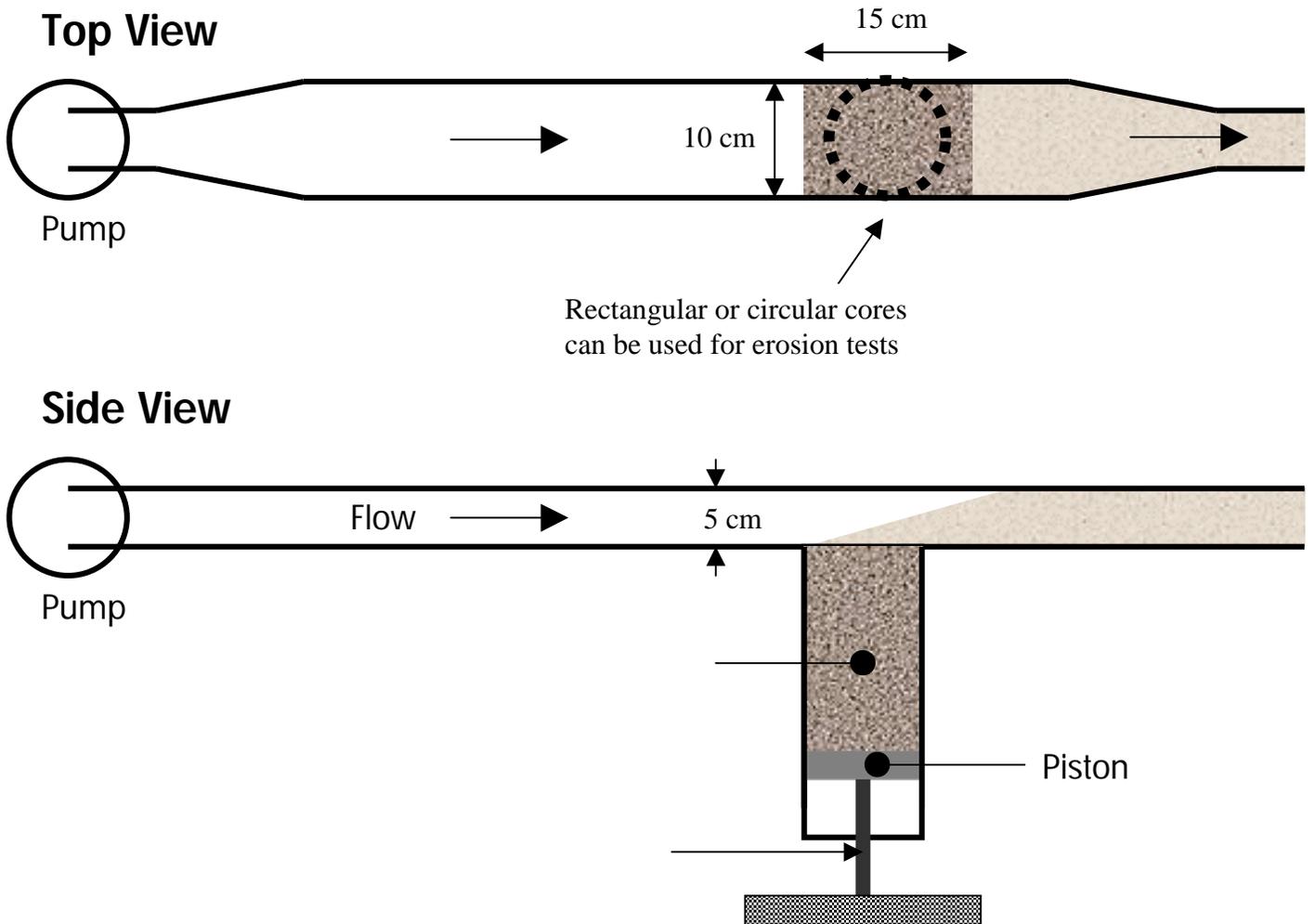
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Table 1 - Summary of all Sediment Bulk Properties

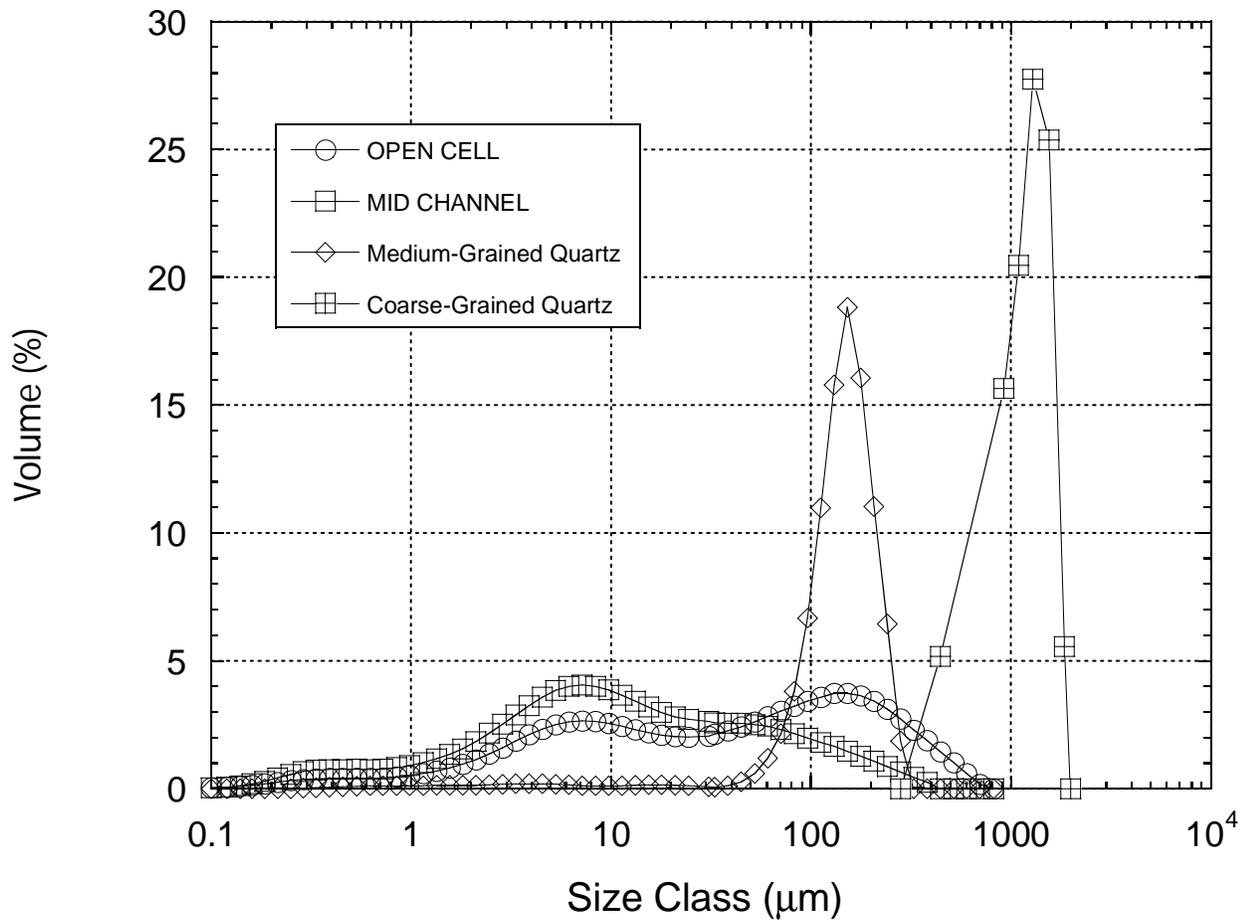
Sediment Name	Bulk Density Range (g/cm <sup>3</sup> )	Mean Particle Size (µm)	Mean Organic Content (% by mass)	Mineralogy (Minerals listed in descending amount)
Open Cell	1.45-1.58	99.8	3.02	1) Quartz, 2) Muscovite, 3) Albite, 4) Chlorite, 5) Microcline
Mid Channel	1.38-1.5	35.7	2.23	Same as above
Medium Grain Quartz	1.88-1.93	150	0	Quartz
Coarse Grain Quartz	1.90-1.96	1,250	0	Quartz

Table 2 - Constants for Equation 3.1 for the sediments from the Boston Harbor

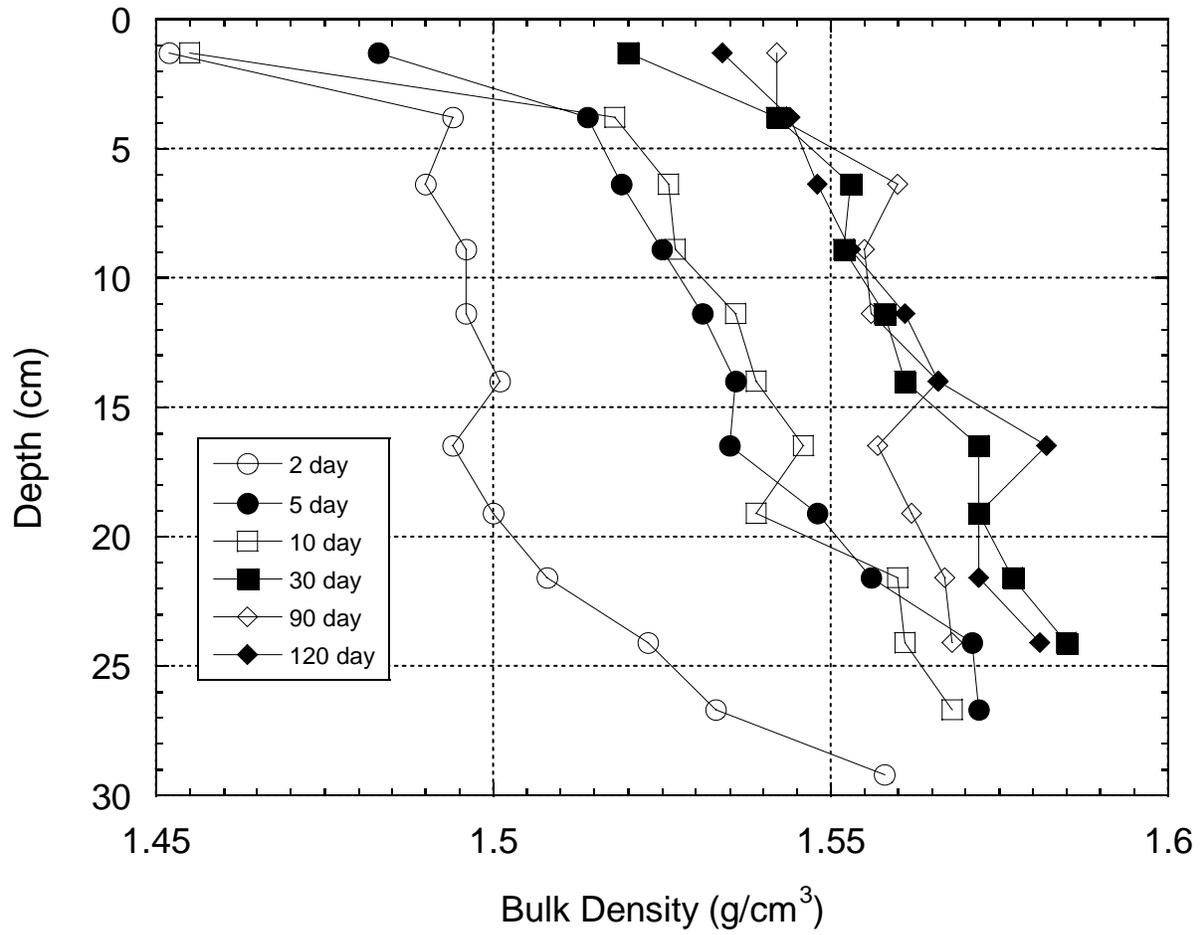
Sediment	n	m	A
Open Cell	3.25	-75	3.35 x 10 <sup>10</sup>
Mid Channel	3.55	-103	1.32 x 10 <sup>12</sup>



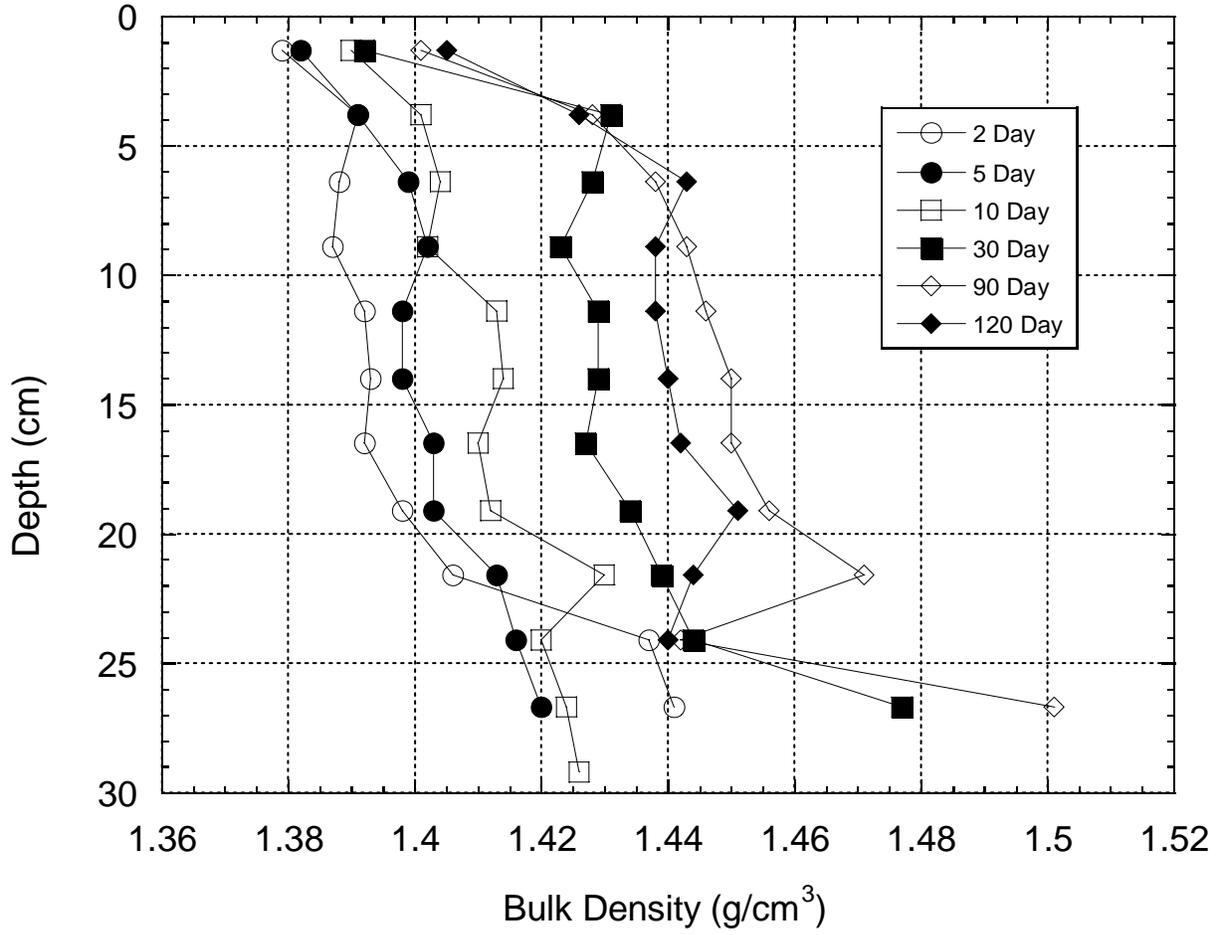
**Figure 1. High Shear Stress Sediment Erosion Flume schematic.**



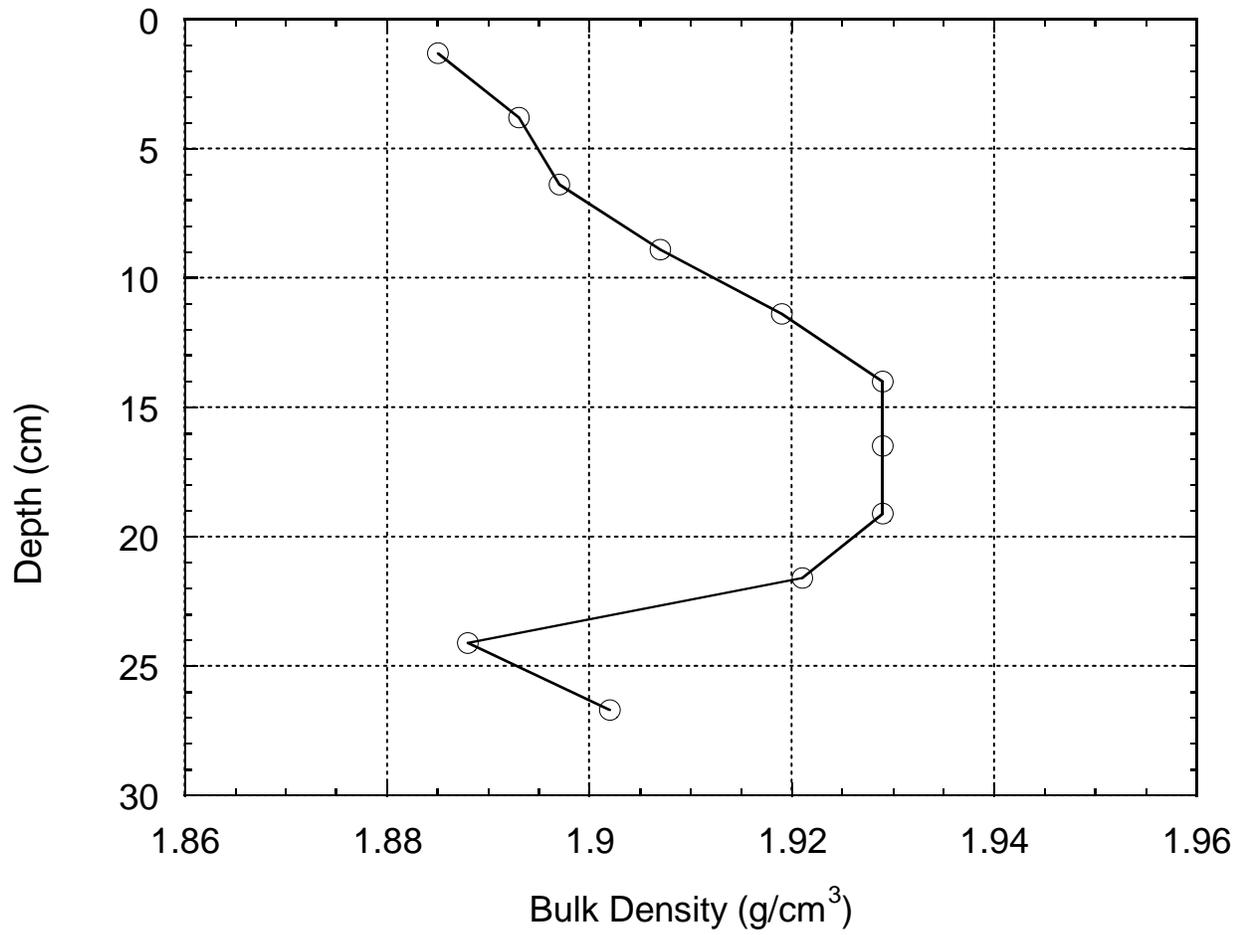
**Figure 2. Particle size distribution for all Sediments.**



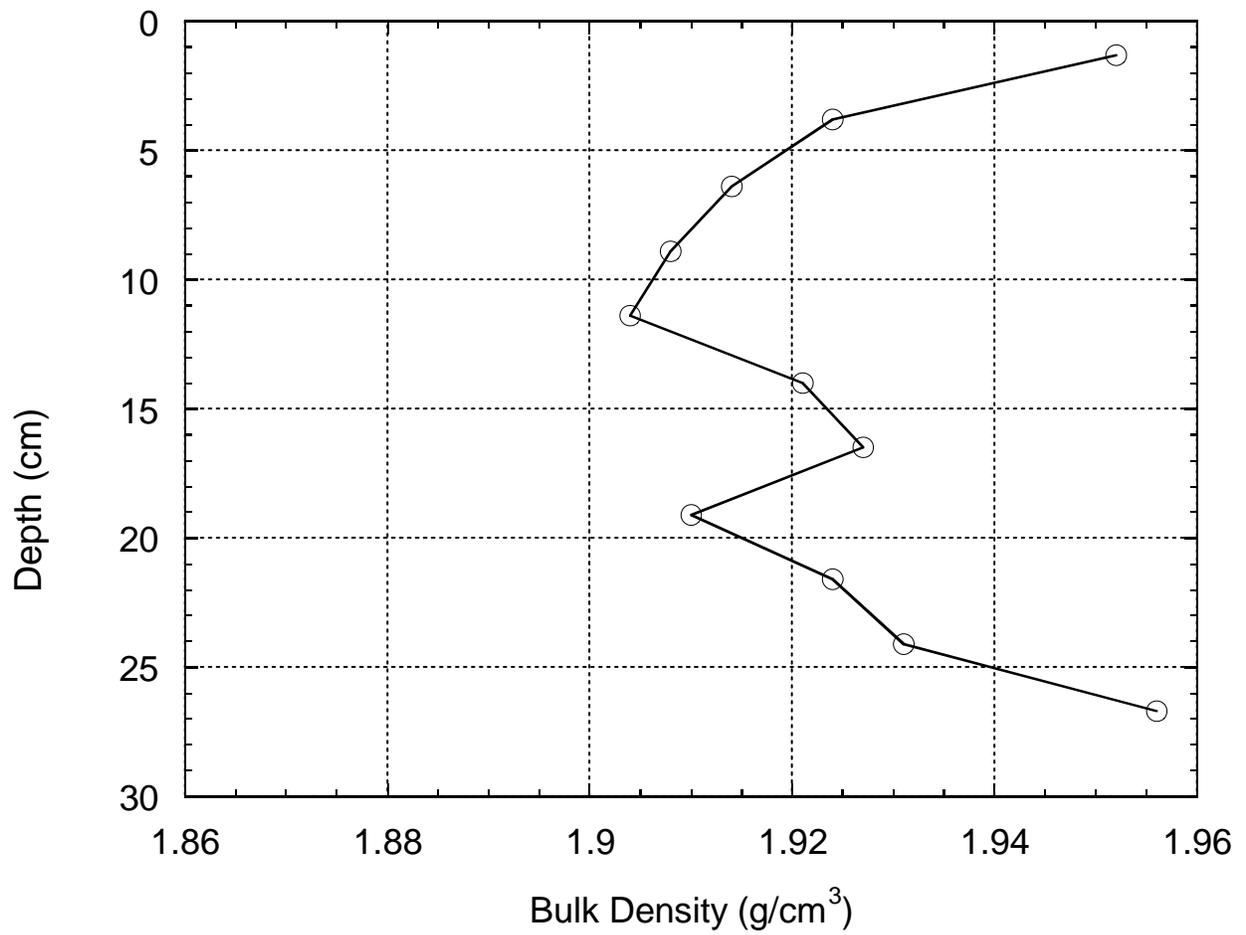
**Figure 3a. Bulk density as a function of depth and consolidation time for Open Cell composite.**



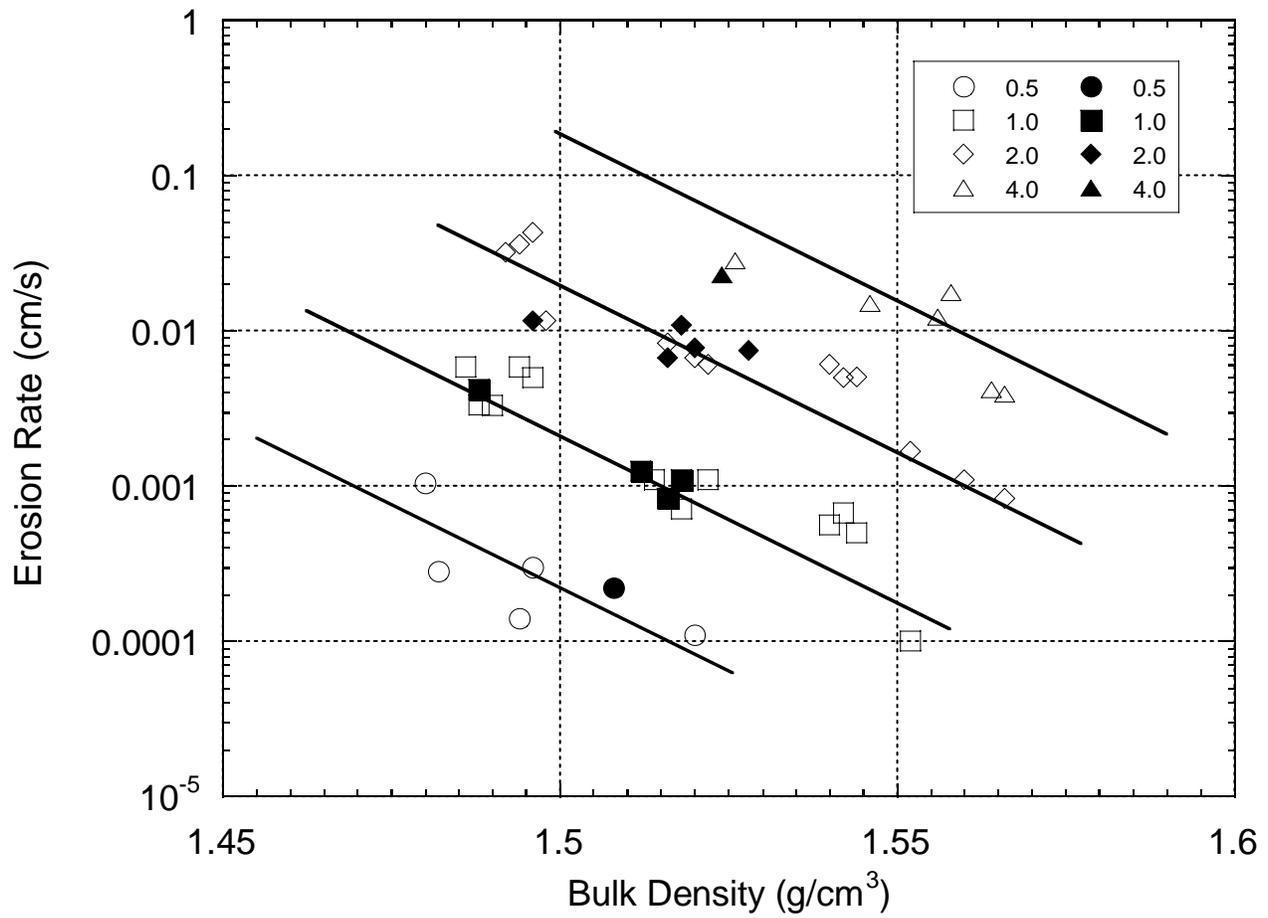
**Figure 3b. Bulk density as a function of depth and consolidation time for Mid Channel composite.**



**Figure 3c. Bulk density as a function of depth with a consolidation time of one day for the medium-grained quartz sediment.**

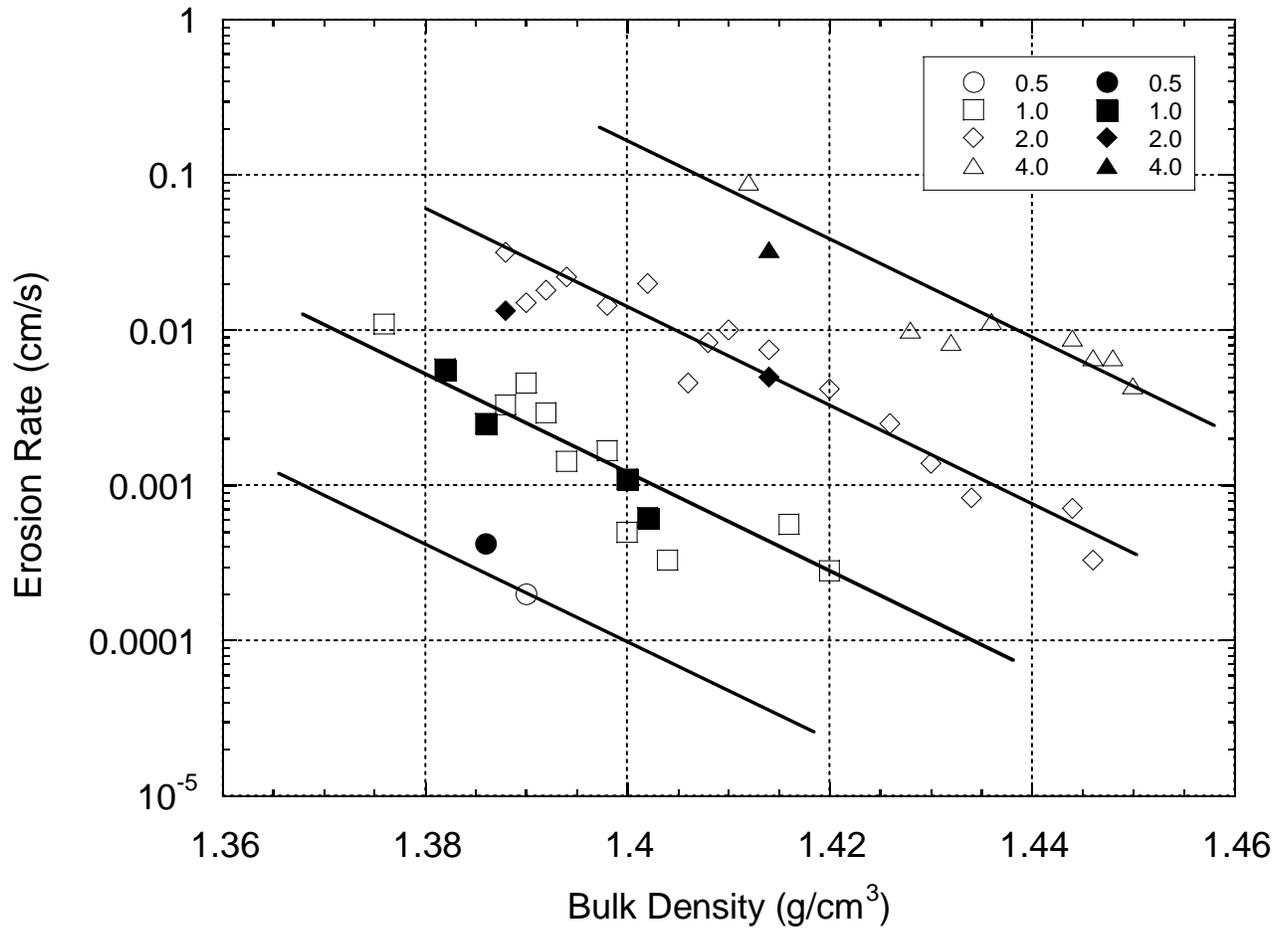


**Figure 3d. Bulk density as a function of depth with a consolidation time of one day for the coarse-grained quartz sediment.**



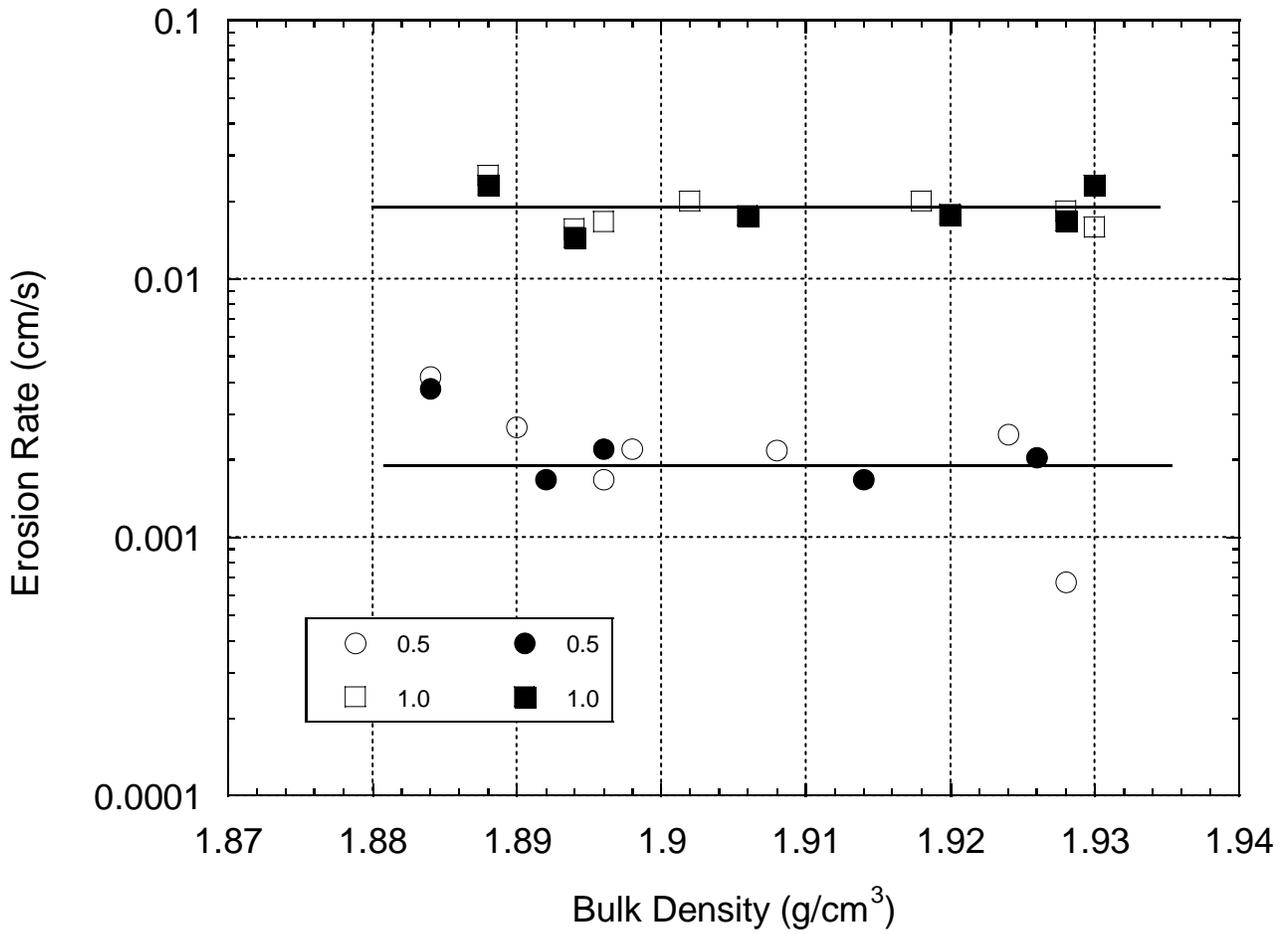
**Figure 4a. Erosion rate vs. bulk density and shear stress for Open Cell composite.**

Shear stresses of 0.5, 1.0, 2.0 and 4.0  $\text{N/m}^2$  are shown. Open symbols correspond to measurements with the rectangular cores and closed symbols correspond to measurements with the circular cores.



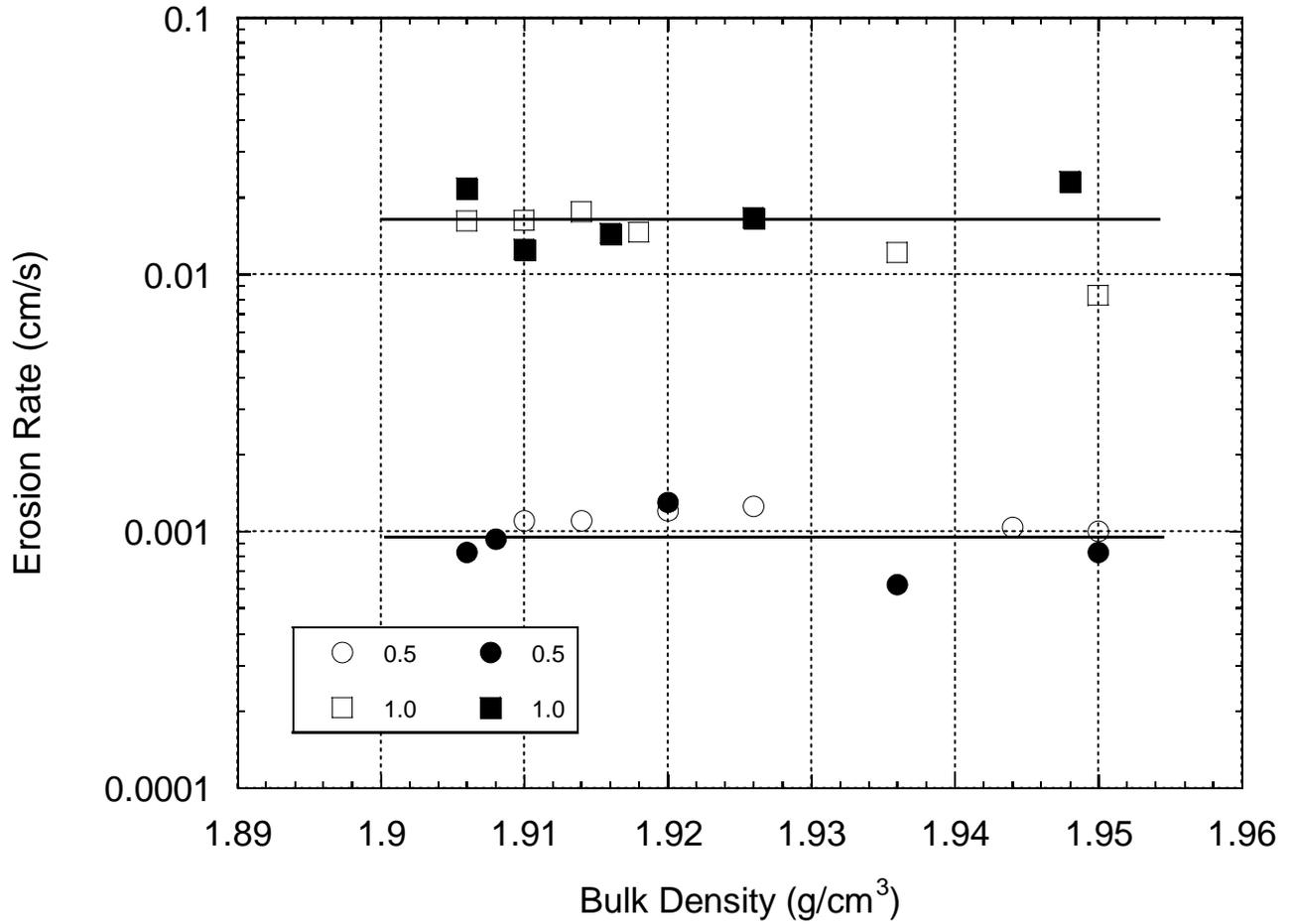
**Figure 4b. Erosion rate vs. bulk density and shear stress for Mid Channel composite.**

Shear stresses of 0.5, 1.0, 2.0 and 4.0 N/m<sup>2</sup> are shown. Open symbols correspond to measurements with the rectangular cores and closed symbols correspond to measurements with the circular cores.



**Figure 4c. Erosion rate vs. bulk density and shear stress for medium-grained quartz sediment.**

Shear stresses of 0.5 and 1.0 N/m<sup>2</sup> are shown. Open symbols correspond to measurements with the rectangular cores and closed symbols correspond to measurements with the circular cores.



**Figure 4d. Erosion rate vs. bulk density and shear stress for coarse-grained quartz sediment.**

Shear stresses of 0.5 and 1.0 N/m<sup>2</sup> are shown. Open symbols correspond to measurements with the rectangular cores and closed symbols correspond to measurements with the circular cores.

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