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## **Separations of BedLoad and Suspended Load with Modified High Shear Stress Flume**

Jesse Roberts and Rich Jepsen

Prepared by  
Sandia National Laboratories  
Albuquerque, New Mexico 87185 and Livermore, California 94550

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# **Separation of BedLoad and Suspended Load with Modified High Shear Stress Flume**

## **U.S. Army Corps of Engineers Waterways Experiment Station**

Jesse Roberts and Rich Jepsen  
Carlsbad Programs Group  
Soil and Sediment Transport Lab  
Sandia National Laboratories  
P.O. Box 5800  
Albuquerque, NM 87185-1395

### **Abstract**

A unique device that attaches to the downstream section of an existing High Shear Stress Sediment Erosion Flume (a modified SEDflume) has been designed, constructed and tested to measure bedload and suspended load properties for cohesive sediments. The device captures sediment grains transported as bedload in traps located on the channel bottom while suspended load is transported in the overlying water. The High Shear Stress Flume has been shown in several field and laboratory applications to be an extremely useful and accurate tool in determining sediment erosion properties with depth. However, it only measures the bulk erosion and cannot distinguish between suspended load and bedload. Since the transport of the sediments in an aquatic system are different for these two modes of erosion, it is very important to be able to separate the suspended load and the bedload from the currently measured bulk erosion. It has been observed and reported extensively that cohesive sediments erode, almost entirely, as aggregates or chunks and not by individual particles. The aggregates can vary in size from microns to centimeters, which generally do not suspend, and are made from very fine-grained particles that would suspend if

disaggregated. It has also been observed that these aggregates can maintain their integrity (size and shape) after being eroded from the sediment bed and subsequent tumbling down the channel bottom. Therefore, the commonly used assumption that fine-grained sediments will completely suspend, when eroded, may be invalid along with the predictions of subsequent particle deposition.

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# 1. Introduction

In this study, the measurements of erosion rates and subsequent bedload and suspended load transport properties of three pure quartz sediments has been determined as a function of shear stress by means of a modified High Shear Stress Sediment Erosion Flume at Sandia National Laboratories. One quartz sediment was fine grained ( $<30\ \mu\text{m}$ ), another was large grained ( $>1\text{mm}$ ) and the third was a known mixture of the coarse and fine grain quartz sediments. For this project, a unique device (Trap Channel) that attaches to the downstream section of the existing High Shear Stress Sediment Erosion Flume was designed, constructed, and tested to measure bed load and suspended load transport properties.

To characterize the movement of sediments in aquatic systems one must not only have an understanding of the bulk erosion rates of sediments but also be able to distinguish between the two modes of sediment transport, bedload and suspended load. Although it has been shown that the High Shear Stress Sediment Erosion Flume by itself is an extremely useful tool in determining sediment erosion properties, it only measures the bulk erosion and cannot give any information about the transport mode of the sediments after erosion (i.e. suspended load and bedload). Since the transport of the sediments in an aquatic system are different for these two modes of erosion, it is very important to be able to separate the suspended load and the bedload from the currently measured bulk erosion.

## 2. Background

There are three major modes of sediment transport generally considered in aquatic systems; they are suspension, saltation, and rolling or sliding of sediments, the latter generally considered as one mode. Suspension of a sediment grain (or aggregate) occurs when the vertical component of the turbulent velocity is approximately equal to or greater than the settling speed of the grain. Saltation occurs when a particle momentarily leaves the bed and rises no higher than a few grain diameters. Rolling and sliding are processes wherein the particle is transported along the bed by the force of the overlying flow of water.

Bagnold (1973) has argued that the major distinction in particle motion is between suspended and unsuspended transport, the latter term also known as bedload. Bedload, is a transport processes wherein saltation, rolling, and sliding of sediment grains and aggregates are combined (Dyer, 1986). This is because particles in unsuspended transport receive no upward impulses other than those due to successive contacts between the solid and the bed, the fluid impulses on the grains being essentially horizontal. It has been considered that in water it is relatively unimportant to distinguish saltation from rolling or sliding because saltation is restricted to only a few grain diameters in height (Dyer, 1986).

Van Rijn has done much careful work in the area of sediment transport. His series of articles on sediment transport, in which he discusses, at great length, the mechanisms of bedload, suspended load, and effects of wave forms, are some of the best information available for modeling sediment transport. Van Rijn has suggested techniques for determining bedload and suspended load transport rates, which may be

applicable to natural sediments. However, his work on bedload only considered the transport of large grained non-cohesive sediments, of uniform shape, size and density, ranging from 200  $\mu\text{m}$  to 2,000  $\mu\text{m}$  (van Rijn et al, 1984a) which erode in a particle by particle manner. Real sediments, especially those that harbor appreciable amounts of contaminants, are fine grained and cohesive, often eroding into aggregates or chunks. In particular, van Rijn's models assume that the bed particle size and transported particle size are the same, which is valid for the range of particle sizes that he considered. However, these assumptions may not be valid as the particle size decreases into the cohesive regime. In fact, the particles that make up the bed are generally much smaller than the aggregates that leave the bed. There has not been an in depth experimental investigation to quantify the transport modes of fine-grained, cohesive sediments.

In van Rijn's models (i.e. coarse-grained, non-cohesive particles) the mode and rate of that modes transport can be predicted, with fair accuracy, from knowledge of only the type and size of particles and the flow condition present. This is because the forces present, in that type of problem, are known. At present, the cohesive forces that bind fine-grained sediments together are not well understood. Because of this, transport modes and rates, for fine-grained sediments can not be predicted. Therefore, current contaminant and sediment transport models of systems containing natural, cohesive sediment are lacking the information necessary to accurately predict transport.

## 3. Experimental Procedures

### 3.1 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 or circular cross-section coring tube containing sediment can be inserted. 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. 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 converter changes the shape of the cross-section from circular to the rectangular duct. 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 will be described later. 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 that is inside the coring tube and is connected to a mechanical jack and then driven by a variable-speed controller. By this means, the sediments can be raised and made level with the bottom of the test section. The speed of the jack 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 sediment. The shear produced by this flow causes the sediment to erode. As the sediment 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.

### **3.2 Description of the Trap Channel**

Down stream from the test section, the channel will be extended for the placement of the sediment traps. An additional section of channel, three meters in length, will be attached to the end of the existing channel with the same cross-sectional dimensions.

This section of channel will be known as the Trap Channel and can be seen in Figure 2. In the bottom of the Trap Channel there are three trap test sections for capturing the bedload. The trap test sections will be as wide as the channel (10 cm) and 15 cm long. This gives an operational definition of bedload as the material that falls out of saltation, rolling, or sliding within 15 cm of travel downstream. The first trap test section is located 1 m from the center of the erosion test section and each successive trap test section is 1 m from the center of the one it precedes. Capture basins are fastened to the trap test section, have the same cross-sectional area and are 10 cm in length. A stainless steel flow converter attaches to the bottom of the capture basin which, in-turn is connected to a two inch ball valve.

As the sediment is eroded in the High Shear Stress Sediment Erosion Flume, some of the material will suspend and some will transport as bedload. The material transported as bedload will fall into the trap capture basins for collection at the end of the experiment.

### **3.3 Hydrodynamics**

#### **3.3.1 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

$$\frac{1}{\sqrt{\lambda}} = 2.0 \log \left[ \frac{UD\sqrt{\lambda}}{\nu} \right] - 0.8 \quad (3.1)$$

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

$$D = 2hw/(h + w) \quad (3.2)$$

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

$$\lambda = \frac{8\tau}{\rho U^2} \quad (3.3)$$

where  $\rho$  is the density of water and  $\tau$  is the wall shear stress. Inserting Eqs. (3.2) and (3.3) into Eq. (3.1) 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 the shear stresses 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.

### **3.3.2 Trap Channel**

For the flow rates of interest, it can be shown that: 1) the boundary layer produced in the channel is at least 90% of that found in the free stream for the same shear stresses, 2) that the channel can accommodate bedload particles up to 1 cm in size without experiencing the upper boundary layer near the channel lid, and 3) the trap dimensions are such that bedload will be captured for all sediment sizes and densities up to 1 cm in diameter.

In order to simulate free stream conditions, the channel height must be sufficiently tall. The channel height chosen for this work was 5 cm because it gives a boundary layer that is 90% or more of that found in the free stream for the same surface shear stress. The shear stress as a function of fluid velocity in the channel and for the free stream can be compared with varying channel heights. The following is the equation for the free stream case.

$$\tau = c_f \frac{1}{2} \rho U^2 \quad (3.4)$$

The friction factor,  $c_f \cong 0.004$  for smooth flow. Figure 3 shows the comparison for the internal case derived in section 3.3.1 and the free stream case from equation 3.4. This shows that the channel height must be equal to or greater than 5 cm in order to simulate flow conditions in the channel that are at least 90% of the free stream conditions.

From section 2, it was stated that bedload combines rolling, sliding and saltating grain or aggregates which are restricted to only a few grain diameters above the bed (Dyer, 1986). Therefore a 1 cm particle or aggregate would only reach the upper boundary of the channel if it suspended 5 times its diameter. This would define the particle or aggregate as suspended load and additional shear or disturbance near the upper lid would not affect the overall transport.

The trap test sections are as wide as the channel (10 cm) and 15 cm long. This gives an operational definition of bedload as the material that falls out of saltation, rolling, or sliding with 15 cm of downstream travel. This is comparable to the theoretical definition given by Dyer (1986) based on the fluid velocity and particle settling speeds.

### **3.4 Core Preparation**

For the purpose of the present experiments the rectangular erosion core tubes were used. The fine grained quartz sediment was prepared as follows. Approximately 100 lbs of dry quartz were placed in 12 gallon cylindrical tanks and mixed with approximately 3 gallons of water until the sediment-water mixture was homogeneous. The sediment mixture was then poured to a depth of 30 cm in a coring tube. The core was allowed to consolidate for 2 days.

The mixture of fine grained and coarse grained quartz sediment was prepared as follows. 6,911 grams of the pre-mixed fine grained quartz sediment (which is equivalent to 4713 grams of dry, fine grained quartz) was mixed with 2,791 grams of coarse grained quartz until the mixture was homogeneous. The resultant mixture was 37% coarse grained and 63% fine grained by mass. The sediment mixture was poured to a depth of 20 cm in a coring tube and allowed to consolidate for 2 days.

The coarse grained quartz sediment used in these experiments was non-cohesive, settled quickly and could not be mixed in the manner described above. Therefore, the coarse grained quartz sediment cores were prepared as follows. Water was poured directly into the core then dry quartz was placed into the water until the sediment water interface reached 30 cm. Since these quartz sediments were non-cohesive, density does not change appreciably with consolidation time (Roberts et al, 1998). The core was allowed to consolidate for 1 day.

### **3.5 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 a meaningful concentration of bedload and suspended load at 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. For the purposes of these experiments, only one shear stress was run at a time. Each shear stress was run until at least 1 cm was eroded. The time interval was recorded for each run with a stop watch. At the end of the erosion test for each shear stress, the bedload traps were emptied, the suspended load concentration was sampled, and the tank was emptied and filled with clean water. The flow was then increased to the next shear stress, and the process repeated.

### **3.6 Measurements of Bedload and Suspended Load**

The procedure for measuring the bedload and suspended load concentrations as a function of shear stress and depth was as follows. The erosion rates were measured as described above. In order to measure the suspended sediment concentration at the end of the erosion test approximately 150-300 ml of the overlying/re-circulating water was sampled before the pump was turned off. This sample was filtered with a 0.2  $\mu\text{m}$  filter paper and vacuum pump system. The sample was dried and weighed. The suspended load concentration,  $C$ , is given by

$$C = \frac{m_d}{V_s} \quad (3.5)$$

where  $m_d$  is the dry sediment weight and  $V_s$  is the volume sampled. After the suspended load concentration was sampled, the pump was turned off, the system was allowed to equilibrate and the total volume of water in the system was measured by the use of pre-calibrated markings on the side of the tank. The total suspended load,  $S$ , is then given by

$$S = CV_T \quad (3.6)$$

where,  $C$  is defined above and  $V_T$  is the total volume of water in the system after the erosion test (i.e. in the tank and all of the plumbing of the High Shear Stress Sediment Erosion Flume and Trap Channel).

After the suspended load concentration and total volume measurement in the system were sampled the bedload traps were drained of any overlying water. The contents of each trap were placed into individual containers, dried in an oven at approximately  $75^\circ\text{C}$  and weighed. This gives the dry sediment weight that was transported as bedload and captured in each sediment trap.

### **3.7 Measurements of Total Eroded Mass**

The total eroded mass is the amount of solid particles from the sediment that are eroded and transported downstream as both bedload and suspended load. The total volume of sediment eroded,  $V$ , is defined by

$$V = AD \quad (3.7)$$

where,  $A$  is the erosion surface area and  $D$  is the depth of sediment eroded. The total eroded mass is related to the bulk density, total volume and water content by

$$M_T = \rho V(1-W) \quad (3.8)$$

where,  $\rho$  and  $W$  are the bulk density and water content of the sediments respectively, both will be defined and described below.

### **3.8 Measurements of Sediment Bulk Properties**

For the analysis of the sediment bulk properties duplicate cores were prepared in the same manner as the rectangular 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 rectangular 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

$$W = \left( \frac{m_w - m_d}{m_w} \right) \quad (3.9)$$

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

$$V = V_s + V_w \quad (3.10)$$

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

$$W = \frac{\rho_w V_w}{\rho V} \quad (3.11)$$

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

$$\rho V = \rho_s V_s + \rho_w V_w \quad (3.12)$$

By combining Eqs. (3.10), (3.11), and (3.12), 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

$$\rho = \frac{\rho_s \rho_w}{\rho_w + (\rho_s - \rho_w)W} \quad (3.13)$$

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 sizers 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 by the sizer. To ensure complete disaggregation and sample uniformity the sediment samples were analyzed 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 coarse 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.

## 4. Results

Tests were done to determine the transport characteristics after erosion for three pure quartz sediments with respect to shear stress. One quartz sediment was fine grained ( $<30\ \mu\text{m}$ ), another was coarse grained ( $>1\text{mm}$ ) and the third was a known mixture of the coarse and fine grained quartz sediments. The mixture and fine grain sediments were individually mixed into a homogeneous composite prior to testing. The coarse grained quartz sediment was mixed directly into the erosion core prior to testing. For each sediment type, only the rectangular cores were used for the erosion tests.

### 4.1 Bulk Properties

Particle size and bulk density of each of the three quartz sediments were measured. The size distributions for the large and fine grain quartz sediments are shown in Figure 4. The mean particle size was 19.0, 474.5 and 1250  $\mu\text{m}$  for the fine grain, fine-coarse mixture, and coarse grained quartz sediments respectively. Particle size and distribution was 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 the fine and coarse grain quartz sediment at 30 cm core lengths and 20 cm core length for the fine-coarse mixture. Consolidation times were 2 days for the fine grained and fine-coarse mixture cores and was 1 day for the coarse grain quartz sediments. Densities were determined by measuring the water content of each core in 2.5 cm increments. The average bulk density for the fine grain quartz sediment was  $1.8\ \text{g}/\text{cm}^3$ . The fine-

coarse quartz mixture had an average of  $2.07 \text{ g/cm}^3$ . The average bulk density for the coarse grain quartz sediment was  $1.925 \text{ g/cm}^3$ .

## **4.2 Bedload and Suspended Load**

Shear stresses of 0.5, 1.0, and 2.0 Pa were run for each of the three quartz sediments. For the coarse grain quartz, the particles were observed to transport entirely as bedload and fell into the first trap for all shear stresses. For the mixture, it was observed that only the coarse fraction transported as bedload and fell into the first trap while the fine grained fraction eroded into suspension. The fine grained quartz sediment eroded into suspension for all shear stresses. The measured results for the bedload and suspended load are summarized in Tables 1, 2, and 3 for the fine grained, coarse grained, and fine-coarse mixture respectively.

### **4.2.1 Fine Grained Quartz**

The data shows that for the fine grained quartz, there was some material measured in each trap and at each shear stress. The amount was less than 1% for each trap. This material could have possibly been due to: (1) the small amount of quartz between 50 and 100  $\mu\text{m}$  in size that was associated with the fine grained quartz and traveled as bedload or (2) the settling of grains that were suspended in the 2 liters of water that the traps hold. The first explanation could not be directly supported because there was not enough sample ( $<1 \text{ g}$ ) to particle size the amount in the traps and determine if the material was due to bedload. The second explanation is supported by the data from the suspended load measurements because the amount

captured was very close to the amount that was suspended in the 2 liters of water in the traps. This was consistent for all traps and shear stresses.

By mass, over 99% of the measured material (bedload and suspended load combined) was in suspension. The total mass balance between that eroded and that captured as bedload and suspended load was between 83% and 114% and was determined almost entirely by the suspended load measurements.

#### **4.2.2 Coarse Grained Quartz**

The data for the coarse grained quartz shows that all of the material transported as bedload and virtually all the material was captured in the first trap. The exception is for the 2.0 Pa test in which some of the material was captured in traps 2 and 3. Trap 2 captured only 1% of the total eroded material, and particle size analysis determined that it was made up of the finer fraction associated with the coarse grained quartz (1250  $\mu\text{m}$  mean size). The size distribution for the coarse grained quartz shows that only 5% is less than 850  $\mu\text{m}$ . The material captured in trap 2 during the 2.0 Pa test had 34% less than 850  $\mu\text{m}$ . Trap 3 did not contain enough sample for particle size analysis.

By mass, 100% of the measured material (bedload and suspended load combined) was transported as bedload. The total mass balance between that eroded and that captured as bedload and suspended load was between 88% and 108% and was determined entirely by the bedload measurements.

### **4.2.3 Fine-Coarse Mixture**

The data for the mixed sample shows that bedload and suspended load were separated by the particle size of the material eroded. None of the coarse grained material was transported in suspension and the amount of coarse material measured in the traps was essentially equal to the amount of coarse material (37% of total) eroded for each test. Likewise, the amount of material measured in suspension was within 80% of the fine grain fraction (63% of total) eroded.

The 1.0 Pa test was done without refilling the tank with clean water upon completion of the 0.5 Pa test. In addition, the re-used water was also allowed to set without flow for over 15 minutes. Much of the material from the 0.5 Pa test may have settled and was not accounted for in the measurement. Therefore, the data for the 1.0 Pa test is suspect.

## 5. Summary and Concluding Remarks

By means of the experiments described here, bedload and suspended load were measured as a function of shear stress for three quartz sediments. From these experiments, the following was determined for all shear stresses tested. (1) For the fine grained quartz, virtually all of the material was in suspension and measured as such. (2) For the coarse grained quartz, essentially all of the material was observed and measured as bedload. (3) For the mixed quartz test, bedload and suspended load transport were separated by the size of the particles eroded.

The experiments demonstrate that the Trap Channel is effective in capturing bedload accurately and can be combined with suspended load measurements to determine total transport. Mass balance shows experimental error of +/- 17% for the suspended load measurements, +/- 13% for the bedload measurement, and +/- 15% when there is significant combined bedload and suspended load transport. Therefore, by means of combining the High Shear Stress Sediment Erosion Flume with the downstream Trap Channel, sediment transport characteristics can be quantitatively determined in conjunction with erosion characteristics. This unique device will provide essential information with regard to transport of natural sediments.

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**Table 1**

**Fine Grained Quartz**  
 Mean Particle Size of 19.0  $\mu\text{m}$   
 Erosion Surface Area of 153.52  $\text{cm}^2$

Shear Stress (Pa)	Bulk Density ( $\text{g}/\text{cm}^3$ )	Trap #	Depth Eroded (cm)	Sediment Mass (dry) Caught in Trap (g)	Sediment Mass (dry) in Suspension (g)	Total Mass Eroded (dry) (g)	$\frac{\text{MassCaptured}}{\text{MassEroded}}$ (%)	$\frac{\text{MassSuspended}}{\text{MassEroded}}$ (%)	Trap Efficiency (%)	Mass Balance (%)	Erosion Rate (cm/s)
0.5	1.72	1	1.0	0.9	163.2	179.6	0.5	90.9	36.0	92.2	0.0007
		2		0.8			0.4		32.0		
		3		0.8			0.4		32.0		
1.0	1.80	1	2.35	1.5	464.6	468.8	0.3	99.1	34.1	100.0	0.0026
		2		1.4			0.3		31.8		
		3		1.5			0.3		34.1		
2.0	1.89	1	1.8	1.3	406.9	399.7	0.4	101.8	37.1	102.9	0.0075
		2		1.3			0.4		37.1		
		3		0.9			0.3		25.8		

**Table 2**

**Coarse Grained Quartz**  
 Mean Particle Size of 1250  $\mu\text{m}$   
 Erosion Surface Area of 153.52  $\text{cm}^2$

Shear Stress (Pa)	Bulk Density ( $\text{g/cm}^3$ )	Trap #	Depth Eroded (cm)	Sediment Mass (dry) Caught in Trap (g)	Sediment Mass (dry) in Suspension (g)	Total Mass Eroded (dry) (g)	$\frac{\text{Mass Captured}}{\text{Mass Eroded}}$ (%)	$\frac{\text{Mass Suspended}}{\text{Mass Eroded}}$ (%)	Trap Efficiency (%)	Mass Balance (%)	Erosion Rate (cm/s)
0.5	1.925	1	1.2	253.8	0.0	276.6	92	0.0	100	91.8	0.002
		2		0.0			0.0		-		
		3		0.0			0.0		-		
1.0	1.925	1	3.7	828.6	0.0	852.9	97	0.0	100	97.2	0.031
		2		0.0			0.0		-		
		3		0.0			0.0		-		
2.0	1.925	1	5.9	1401.7	0.0	1360.0	103	0.0	98.5	104.5	0.098
		2		16.6			1.2		1.2		
		3		3.6			0.3		0.3		
0.5	1.925	1	1.8	364.4	0.0	414.9	88	0.0	100	87.8	0.0038
		2		0.0			0.0		-		
		3		0.0			0.0		-		
1.0	1.925	1	2.6	647.2	0.0	599.3	108	0.0	100	108.0	0.022
		2		0.0			0.0		-		
		3		0.0			0.0		-		

**Table 3**

**Fine-Coarse Quartz Mixture**

37% 1250  $\mu\text{m}$  Quartz / 63% 19.0  $\mu\text{m}$  Quartz

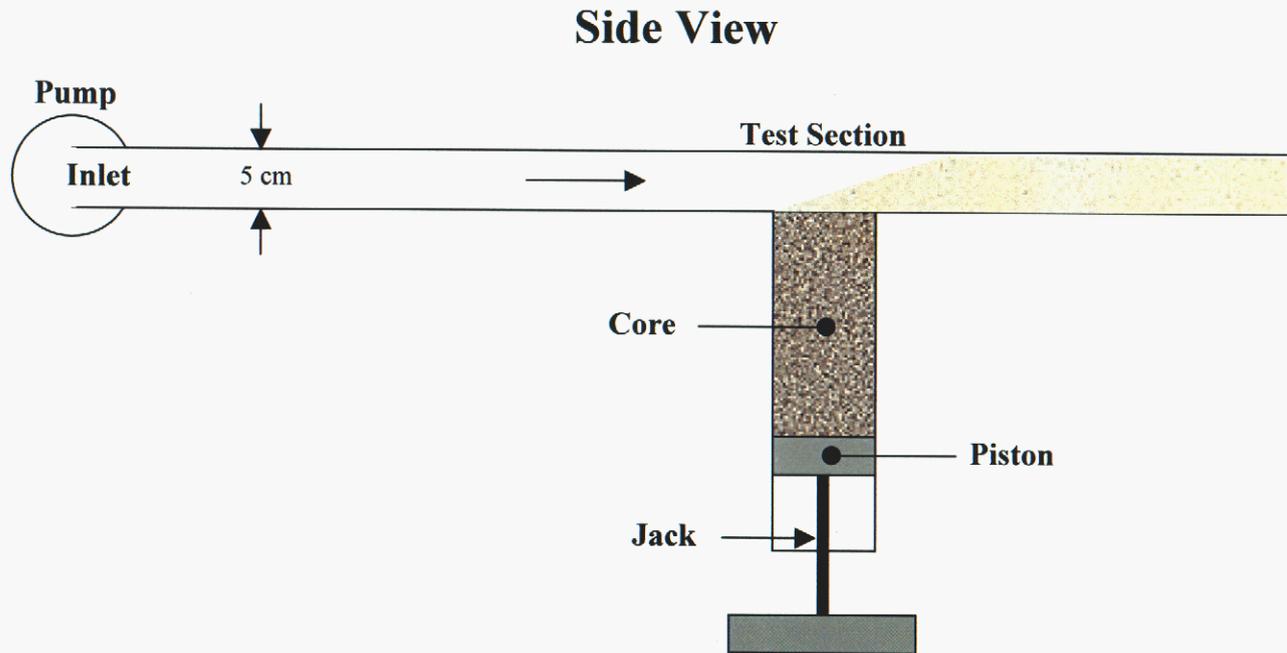
Mean Particle Size of 474.5  $\mu\text{m}$

Average Bulk Density of 2.07  $\text{g}/\text{cm}^3$

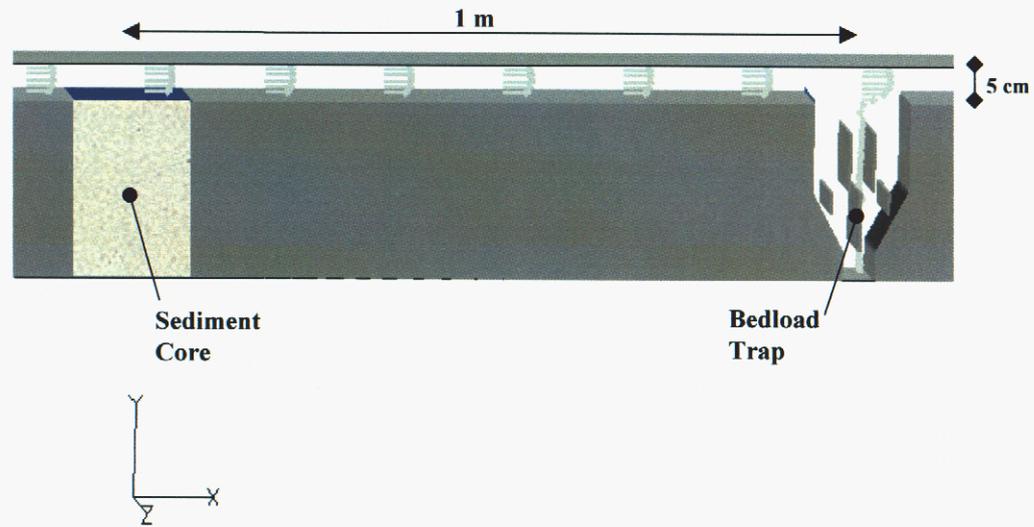
Erosion Surface Area of 153.52  $\text{cm}^2$

Shear Stress (Pa)	Bulk Density ( $\text{g}/\text{cm}^3$ )	Trap #	Depth Eroded (cm)	Sediment Mass (dry) Caught in Trap (g)	Sediment Mass (dry) in Suspension (g)	Total Mass Eroded (dry) (g)	$\frac{\text{MassCaptured}}{\text{MassEroded}}$ (%)	$\frac{\text{MassSuspended}}{\text{MassEroded}}$ (%)	Trap Efficiency (%)	Mass Balance (%)	Erosion Rate (cm/s)
0.5	2.03	1	1.0	89.8	132.0	257.0	34.9	51.4	95.0	88.2	0.0007
		2		2.8			1.1		3.0		
		3		2.0			0.8		2.0		
1.0	2.05	1	1.75	152.0	148.2*	458.4	33.2	32.3*	99.5	65.8*	0.0029
		2		0.8			0.2		0.5		
		3		0.0			0.0		0.0		
2.0	2.09	1	2.25	214.56	307.7	593.8	36.1	51.8	97.6	88.8	0.0075
		2		4.41			0.8		2.0		
		3		0.84			0.1		0.4		

\* Tank water was not emptied and refilled with clean water from the 0.5 Pa test to the 1.0 Pa test

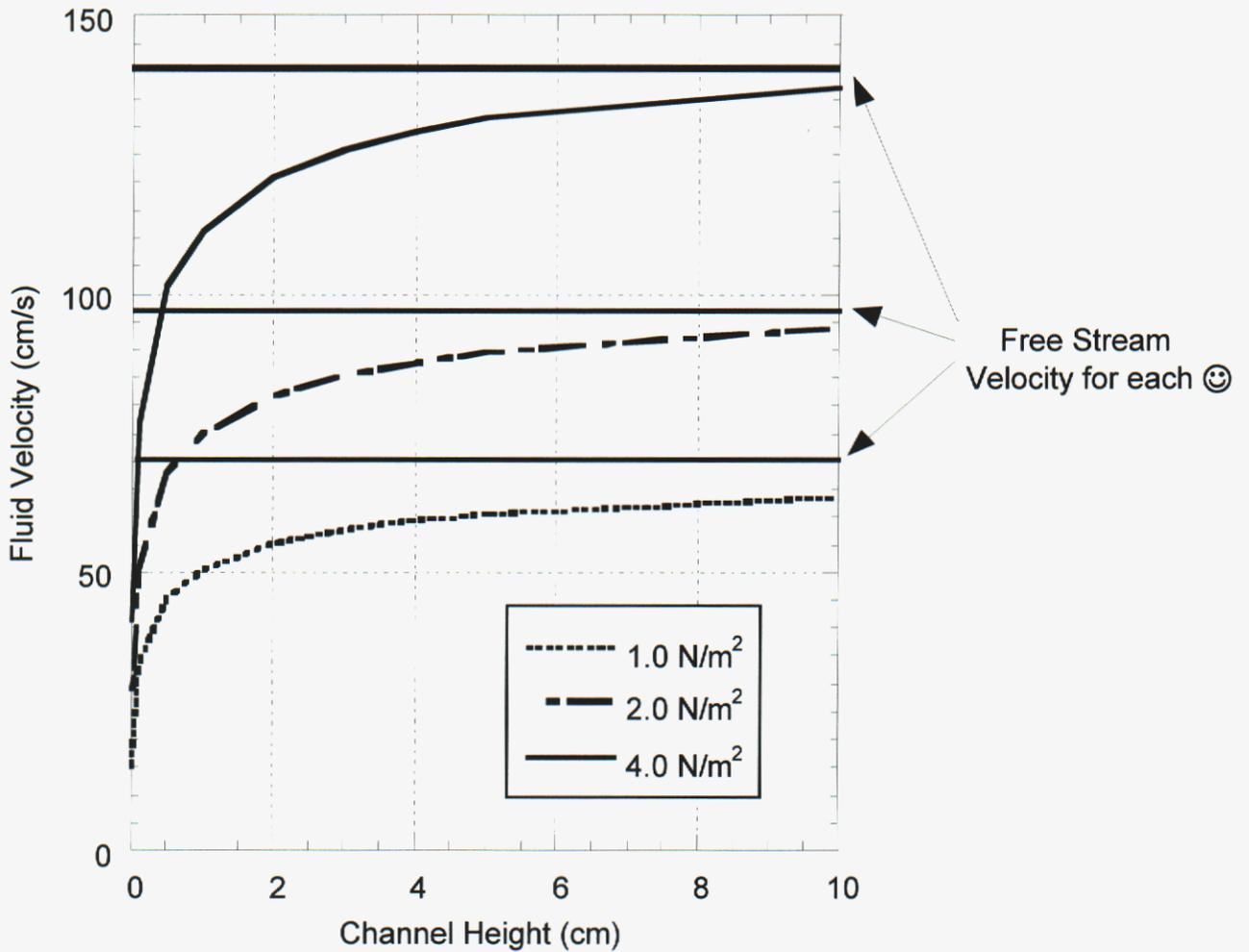


**Figure 1.** Schematic of High Shear Stress Sediment Erosion Flume



**Figure 2.** Schematic of High Shear Stress Sediment Erosion Flume with Trap Channel. Only the first trap is shown.

### Fluid Velocity as a Function of Shear Stress and Channel Height.



**Figure 3.** Mean fluid velocity as a function of channel height and shear stress. Compared are the mean fluid velocity for internal flow and free surface flow.

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Richard Langford  
Department of Geological Sciences  
University of Texas at El Paso  
El Paso, TX 79968-0555

US Army Corps of Engineers  
Coastal and Hydraulics Laboratory  
CEWES-CC-C  
Vicksburg, MS 39180  
Attn: Joseph Gailani

Rong Kuo  
International Boundary and Water Commission  
4171 N. Mesa C-310  
El Paso, TX 79902

Manuel Rubio, Jr.  
International Boundary and Water Commission  
4171 N. Mesa C-310  
El Paso, TX 79902-1441

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U.S. Army Corps of Engineers  
Coastal and Hydraulics Laboratory  
3909 Halls Ferry Rd  
Vicksburg, MS 39180  
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John R. Gray  
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Atlanta, GA 30303

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Montvale, NJ 07645

Joseph V. DePinto  
Senior Scientist  
Limno-Tech, Inc.  
501 Avis Drive  
Ann Arbor, MI 48108

Wilbert J. Lick  
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