MEASURING BEDLOAD FRACTION WITH THE ASSET FLUME

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ABSTRACT

Soil and sediments play an important role in water management and water quality. Issues such as water turbidity, associated contaminants, reservoir sedimentation, undesirable erosion and scour, and aquatic habitat are all linked to sediment properties and behaviors. In situ analysis is necessary to develop an understanding of the erosion and transport of sediments. Sandia National Laboratories has recently patented the ASSET Flume that quantifies in situ erosion of a sediment core with depth while affording simultaneous examination of transport modes (bedload vs. suspended load) of the eroded material. Core erosion rates and ratios of bedload to suspended load transport of quartz sediments were studied with the ASSET Flume. The erosion and transport of a fine-grained natural cohesive sediment were also observed. Experiments using quartz sands revealed that the ratio of suspended load to bedload sediment transport is a function of grain diameter and shear stress at the sediment surface. Data collected from the ASSET Flume were used to formulate a novel empirical relation for predicting the ratio of bedload to suspended load as a function of shear stress and grain diameter for non-cohesive sediments.

INTRODUCTION

There are many studies of the erosional properties of non-cohesive, relatively coarse, and narrowly graded sediments. However, few published studies discuss the subsequent transport modes of these sediments. The erosion and transport properties of sediments are highly dependent upon material characteristics and it is not well understood how the geotechnical (bulk) parameters govern or control these properties. Because the goal of many investigators and regulators is to extrapolate field data to estimate future behaviors of a system, it is important to correlate sediment properties with transport characteristics. Ultimately, predictive capabilities are limited without a clearer understanding of how bulk sediment properties impact erosion rates, scour rates, and modes of transport.

Sandia National Laboratories has designed, constructed, tested, and patented a high-shear flume that directly measures both erosion rate and sediment transport modes as a function of bed shear stress and depth in the sediment core. The apparatus is named the Adjustable Shear Stress Erosion and Transport (ASSET) Flume and it is a ‘next generation’ SEDflume (McNeil and others, 1996) in that it maintains all capabilities of its predecessor while also quantifying the transport modes of the sediments after erosion.

There are three major modes of sediment transport in aquatic systems: suspension, saltation, and rolling/sliding of sediments. Suspension of a sediment grain (or aggregate) occurs when the magnitude of the vertical component of the turbulent velocity is greater than the settling speed of the grain. A saltating grain may only momentarily leave the bed and rise no higher than a few (<4) grain diameters. Rolling and sliding particles move along the bed surface under the force of the overlying flow of water. It is often unimportant to distinguish saltation from rolling or sliding because saltation is restricted to only a few grain diameters in height (Dyer, 1986). Bagnold (1973) argued that the major distinction in sediment transport modes is between suspended and unsuspended (bedload) transport. Bedload sediment grains and aggregates transport under the combined processes of saltation, rolling, and sliding, and receive insufficient hydrodynamic impulses to overcome gravitational settling. Their only significant upward impulse is derived from successive contacts with the bed (Dyer, 1986).

Van Rijn (1984a, 1984b, 1984c) conducted detailed analyses of sediment transport, and in a series of articles he discusses at length the mechanisms of bedload, suspended load, and effects of bed form. These manuscripts contain some of the best information available for modeling sediment transport. His study of bedload considered the transport of large-grained non-cohesive sediments of uniform shape, size, and density that ranged from 200 to 2,000 μm in diameter and that erode particle-by-particle. While van Rijn does quantify the parameters describing the onset of bedload transport, he makes no attempt to define the ratio of bedload to suspended load transport as a function of these parameters.

This work describes the development of the ASSET Flume and summarizes one of its applications. The transport modes of several quartz sediment cores are quantified and compared to published results. An empirical expression relating the bedload fraction to particle size and erosion shear stress is also developed. Finally, erosion and transport tests are performed on natural, cohesive sediment from the Mid Channel of the Boston Harbor to demonstrate the effective application of the ASSET Flume on a field sample.

DESCRIPTION OF THE ASSET FLUME

As stated above, the erosion test section of the ASSET Flume is identical (except for a taller channel) in design and operation to the SEDflume. The peer-reviewed literature relating to the design and operation of the SEDflume is extensive (e.g., Jepsen and others, 1997; Roberts and others, 1998; Jepsen and others, 1999; Roberts and Jepsen, 2001). In particular, the interested reader should review the work of McNeil and others (1996) who introduced the SEDflume and discussed at great length its design, operation, and ability to measure sediment erosion rates with depth.

The ASSET Flume consists of eight primary components. There is a 120 gallon reservoir, a 150 gpm centrifugal pump, a motor controlled screw jack, an erosion channel including erosion test section, a transport channel including bedload traps, a three way valve, a paddlewheel flow meter, and connective plumbing. Water is pumped from the reservoir through the three-way valve, which either sends water directly back to the reservoir or through the flow meter to the erosion and transport channels (and then back to the reservoir). A manually controlled screw jack is used to push the sediments through the core tube to keep the sediment surface flush with the channel floor such that, as closely as possible, the sediments are exposed only to an applied shear stress and no normal stresses (this procedure will be discussed in detail later).

The ASSET Flume's enclosed (internal flow) erosion and transport channels are 5 cm tall, 10.5 cm wide (Figure 1). Several meters of inlet pipe are connected to the erosion channel with 20 cm circular to rectangular flow converter. The erosion test section is preceded by 180 cm of enclosed rectangular channel to ensure fully developed turbulent flow over the sediment core. Note that the rectangular sediment core tube is 15 cm long, but only 10 cm wide. This helps to reduce wall effects because the channel is 10.5 cm wide. The transport channel includes three sediment traps downstream from the sediment core. The first trap is located 1 m from the center of the erosion test section, and the center of each successive trap (not shown in **Figure 1**) is 1 m from the center of the preceding one. Based on the theoretical definition of bedload in combination with fluid velocities and particle/aggregate settling speeds, a bedload particle/aggregate should contact the flume floor at least once every 15 cm of downstream travel (Dyer, 1986). Consequently, the traps are 15 cm long and span the width of the channel (10.5 cm). Capture basins that are 10 cm deep and have a 2 L volume are located below the traps, each with a baffle system that reduces recirculation and minimizes the resuspension of trapped sediments. As the sediment core is eroded upstream, some of the material is suspended and some is transported as bedload. All sediment that falls into the traps is considered bedload.

Ahead of the erosion test section is a 180 cm of flow channel preceded by several meters of piping and a circular to rectangular flow converter.

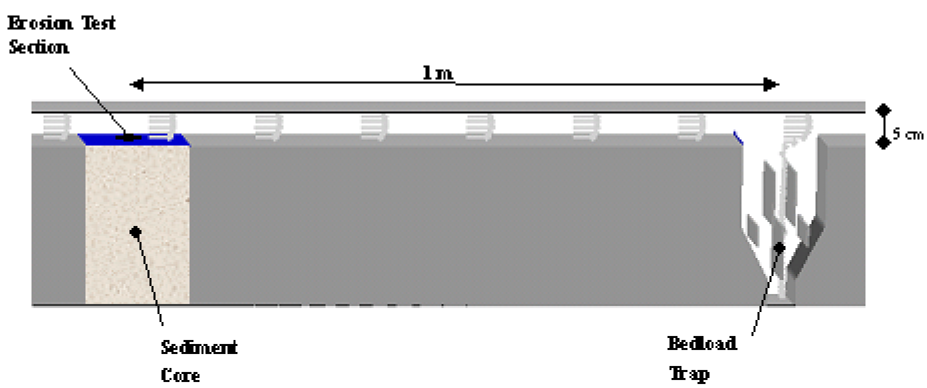

Figure 1: Schematic of ASSET Flume Showing the Flow Direction, Flume Channel Duct, Sediment Core, Erosion Test Section, and First Bedload Trap.

EXPERIMENTAL PROCEDURES

Sediment cores consisting of 99.5% pure quartz particles with mean diameters, d = 19, 98, 170, 304, 411, and 1,250 μm, were used to preliminarily test the ASSET Flume. They were poured to a depth of 30 cm and consolidated for two days in a 10×15 cm^2 rectangular, acrylic core tube for erosion analysis. As sediment erodes from the core and travels downstream, the material that is transported as bedload falls into the bedload traps while the suspended sediments pass over the traps and into the reservoir tank (which re-circulates back through the system as suspended load). To validate the transport channel's ability to capture bedload, the quartz sediments were tested at at progressively higher shear stresses (flow rates) yielding boundary stresses of 0.5, 1.0, and 2.0 Pa with all three bedload traps open for collection. Each sample was run in triplicate to ensure repeatability and shear stress was applied to the surface of a core until at least 1 cm of the sample eroded. At the end of the erosion test for each shear stress, the valves under each bedload traps were opened to collect the captured sediment. These samples were dried in an oven at approximately 75°C. The bedload fraction was calculated as

$$B = \frac{m_b}{M_T}, \tag{1}$$

where m_b is the dried mass of sediment captured in the bedload trap. Bedload sediment was subsequently sized with the Malvern Mastersizer S or sieved if enough material was present to allow the analysis. The reservoir tank was emptied and filled with clear water between runs.

A very small amount of suspended load, on the order of grams, might be collected along with the 2 L of water gathered with the bedload sample. Because the net effect is very small for sediments that travel predominantly as bedload, this extra mass is ignored. It should be noted, however, that for sediments that travel largely as suspended load (i.e., 19 μm quartz), the suspended sediment captured in the 2 L of water sampled from the bedload trap may artificially inflate the bedload fraction. To correct for this, if the mass captured in the bedload trap is less than 2 g, then the mass of suspended sediments (the calculation of which is described below) contained in the 2 L sample is subtracted from the bedload mass. Although corroborating measurements were taken, because of the ability to measure m_b and M_T more accurately than suspended sediment mass, m_s, suspended load fraction is calculated as one minus the bedload fraction.

RESULTS

The 19 μm quartz was visually observed to erode as both aggregates and individual particles (although it may be impossible to see the smallest particles), however, aggregates quickly disintegrated and were not visible beyond a few centimeters downstream from the erosion test section. This is consistent with the observations of Roberts and others (1998) and is indicative of sediment with weak cohesive properties. For the fine-grained quartz (19 μm), there was some material measured in each bedload trap at each shear stress. Unfortunately, the trapped grains amounted to less than one gram and lack of material prevented the sample from being sized. We suspect, however, that the grains were suspended in the 2 L of water collected with each trap sample. This notion is further supported by the suspended load measurements because the amount trapped was very close to the total amount suspended in the 2 L of water collected with the bedload sample. Moreover, all of the traps caught nearly the same amount of material suggesting that the upstream traps were not separating larger grains. Next, experiments were performed with quartz sediment cores with mean diameters of 98, 170, 304, and 411 μm. All of these sediments were observed to erode non-cohesively and particle size analysis showed that the sediment captured as bedload was comparable in size distribution to the original sediment core. The coarse-grained quartz (1,250 μm) show that all of the material was transported as bedload and nearly all the material was captured in the first trap. Only for the 2.0 Pa (high velocity) test was material captured in traps 2 and 3. In the 2.0 Pa run, trap 2 captured only 1% of the total eroded material, and particle size analysis demonstrated that it was composed of the fine fraction of the coarse-grained quartz. About 5% of the size distribution for the coarse-grained quartz is smaller than 850 μm, and of all material captured in trap 2 during the 2.0 Pa test, 34% was smaller than 850 μm. Trap 3 did not contain enough sediment for particle size analysis. This indicates that bedload trap 1 captures virtually all of the bedload. Bedload fractions for all quartz sediments at each shear stress are shown in Table 1.

Table 1: Bedload Fractions for Quartz Sediments.

d (μm)	τ (Pa)	B (–)
19	0.5	0.0
	1.0	0.0
	2.0	0.0
98	0.5	0.07
	1.0	0.02
	2.0	0.0
170	0.5	0.52
	1.0	0.18
	2.0	0.09
304	0.5	0.94
	1.0	0.75
	2.0	0.49
411	0.5	0.98
	1.0	0.89
	2.0	0.61
1,250	0.5	N/A
	1.0	0.97
	2.0	1.03

N/A – below critical shear stress.

ANALYSIS

The percentage of eroded material transported as bedload for each quartz size class at each shear stress is shown in Figure 2. The data are plotted as a function of the Shields parameter because the initiation of erosion and bedload transport is often described as a function of this parameter. The Shields parameter is

$$\theta_s = \frac{\tau}{(\rho_s - \rho_w) g d}, \tag{2}$$

where g is the acceleration due to gravity. Figure 2 shows the Shields curve that defines the initiation of erosion at critical shear stress, as well as the theoretical curve representing the initiation of suspension developed by McCave (1971). McCave asserts that particles begin to travel as suspended load when $\theta_s > 0.19 u_s^2 / gd$, where u_s is the particle settling speed. The shape of the McCave curve is due to particle settling speeds increasing nonlinearly with increases in particle diameter. Essentially, for particle diameters less than 200 μm, $u_s \propto d^2$ (viscous Stokes regime) and therefore, $\theta_s \propto d^3$. For particles larger than 2,000 μm, $u_s \propto d^{1/2}$ (Impact Law), and θ_s is independent of d. Of course, between these two particle sizes there is a smooth transition.

Data collected from the ASSET Flume define a transition region from bedload to suspended load. Using the bedload fraction data collected with the ASSET Flume, a least squares fit was used to recalibrate the coefficient, C, from the McCave equation to estimate 5%, 50%, and 95% bedload fractions. Essentially, the McCave equation with C defined as a function of bedload fraction generates a set of parallel curves that are translated with changes in the bedload fraction. Results are presented in Table 2. It should be noted that data points for bedload fractions less that 5% or greater than 95% were excluded from the least squares calculations because it was felt that they were not within the error tolerances for the ASSET Flume. For example, consider the 411 μm quartz eroded at 0.5 Pa. Because the measured bedload fraction is within the 5% error estimate of the ASSET Flume (and could actually be 100%), there is no way of knowing if it was this particular particle size (and not 380 μm, for example) that yielded 100% bedload fraction. Therefore, bedload fractions at either extreme are excluded from the calculations. More experiments performed with quartz particles near this size would help to refine the results.

The transition zone from complete bedload to fully suspended load is quite broad and it is important to analyze this regime because it includes particle sizes and shear stress conditions common to rivers, lakes, and coastal regions. Such a large transition zone begs the question: What 'mechanism' explains why a certain fraction of sediment suspends while the remainder travels as bedload? In response, Figure 2 data define shear stress contours that demonstrate that as boundary shear stress is increased for a given grain size, more sediment goes into suspension, decreasing the percentage of particles traveling as bedload. Consequently, the percentage of bedload for a given sediment mixture depends on the magnitude of the applied shear stress. For poorly sorted mixtures, the resultant bedload contours will likely depend upon the size distribution of the bed material and the abundance of fine sediment available for suspension. However, mixture gradation does not appear to be a factor in our study because we observe comparable size distributions between the original core and trapped bedload sediments. Thus we conclude that the observed bedload contours do not result from size-selective suspension of the finer sediments within each well-sorted mixture. Rather, we hypothesize that the turbulent eddies, which grow with increasing velocity and shear stress, lift an increasing portion of the bedload into suspension, illustrating the importance of non-steady conditions and turbulence.

Note that in Figure 2 the data collected at a given shear stress form lines of constant shear with bedload fractions that increase as a function of particle diameter. It therefore seems reasonable to chart constant shear curves on a bedload versus particle diameter plot. Furthermore, previously collected data examining erosion rates as functions of bulk density have been empirically fit to an exponential equation (Roberts and others, 1998, eq. 8). Based on this notion, the data from Figure 2 are re-plotted in Figure 3 as bedload fraction versus particle diameter and the transition from bedload to suspended load is fit to a logarithmic, constitutive relation

$$B = \alpha \ln\left(\frac{d}{\tau^{\beta}}\right) - \gamma, \qquad (3)$$

where α, β, and γ are empirical constants valid for quartz particles. In this relation, d has units of microns and τ has units of Pascals. This equation is only valid within the range of data collected from the ASSET Flume (see Figure 2), but this includes a wide range of shear stresses and particle diameters. A least squares fit of all bedload fraction data between 5% and 95% yields values of α=0.732, β=0.457, and γ=6.613.

Table 2: Equation Coefficients for the Threshold Curves of Figure 2– $\theta = Cv^2/gd$

Threshold curve	C
Initiation of suspended load (McCave)	0.19
95% bedload	0.16
50% bedload	1.02
5% bedload	5.11

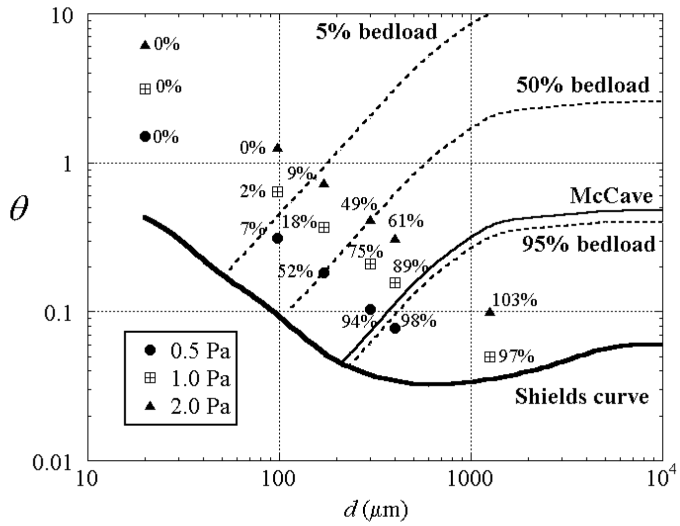

Figure 2: Dimensionless Shear Stress, θ_s, Versus Particle Diameter, d. Shields Curve Defines the Initiation of Grain Motion and the McCave Curve Estimates the Initiation of Suspension. Based on Data Collected from the ASSET Flume, the 95% Bedload Threshold Curve, the 50% Bedload Threshold Curve, and the 5% Bedload Threshold Curve are Drawn. Also Shown are the Measured Values of Bedload Fraction (in Percent) Measured at Shear Stresses of 0.5, 1.0, and 2.0 Pa as a Function of Quartz Particle Diameter.

SUMMARY AND CONCLUSIONS

Bulk erosion rate measurements from the SEDflume for both the quartz and natural sediments yield little if any information about the subsequent transport of the eroded material. Although the SEDflume has proven an important advance in measuring erosion properties of sediments, its use should be limited to cases when erosion potential of a particular sediment is the sole concern. If the scour, exposure, and subsequent fate of underlying sediments are of concern (such as when contaminated sediments are overlain by clean sediments), the transport modes of the eroded sediments must be understood.

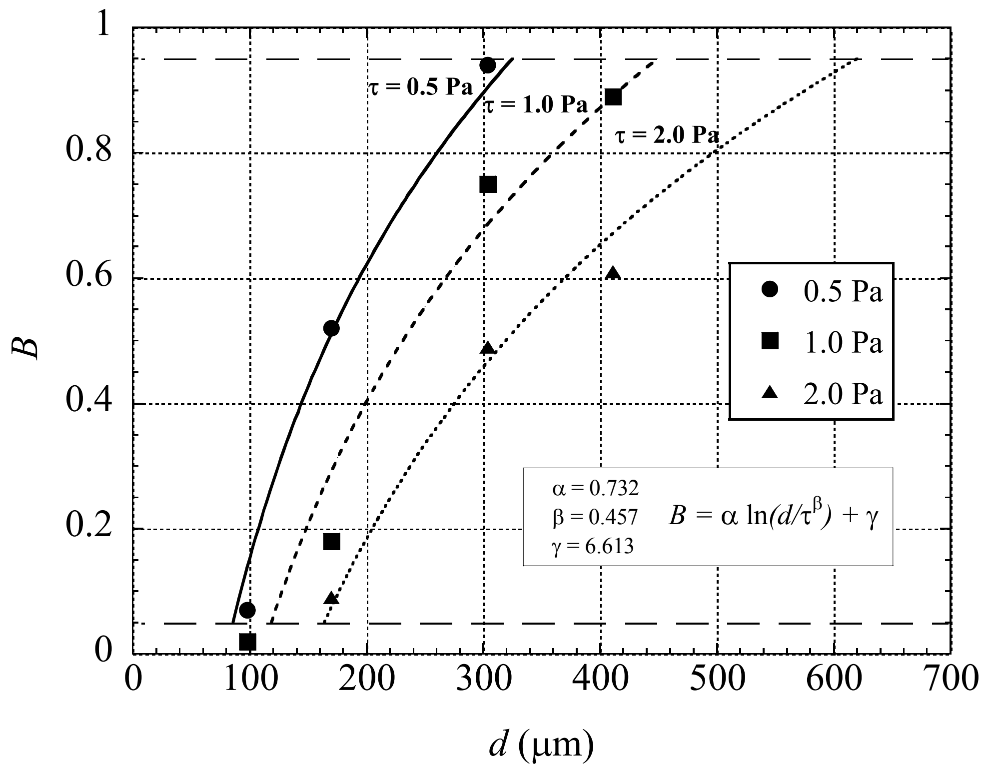

Figure 3: Bedload Fractions as a Function of Particle Diameter for Quartz Sediments at Shear Stresses of 0.5, 1.0, and 2.0 Pa. The Curves Represent the Bedload Fraction Calculated from (3).

The ASSET Flume was developed, tested, patented, and shown to accurately measure sediment erosion and transport with depth at high shear stresses. In this work, the flume was used to measure the bedload fraction for quartz particles from 19 to 1,250 μm. Additionally, a functional relation was developed to specify the bedload fraction as a function of particle size and shear stress for narrowly graded quartz sediments. The 95% bedload fraction matches well with McCave's equation defining the onset of suspended load transport.

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