Measurements and analysis of sediment transport capacity in shallow overland flow

Prasad, S.N.[1] – Suryadevara, M.R. – Römkens, M.J.M.

[1]Department of Civil Engineering, University of Mississippi, University, MS 38677, USA. Tel.: +1-662-915-5367; Fax: +1-662-915-5523; E-mail: cvprasad@olemiss.edu

1. Abstract

Investigations on sediment transport in laboratory flume reveal a significant decrease in transport capacity when bed conditions change from saltation mode to structured modes such as stripes and meanders. This decrease is 20% for stripe mode and up to 94% in large-scale modes such as meanders. Optical probe measurements of solid concentrations reveal the characteristics of transport modes such as saltation, stripes, and meanders. Sediment transport rates evaluated from these measurements are in confirmation with the transport rates measured by grab samples obtained at the downstream end using a rotating sampler. The power spectra of solid concentration fluctuations are in reasonable agreement with the transport rate measurements. Moreover, these spectra of solid concentrations fingerprint the intrinsic nature of bed patterns, which are not easily identifiable by transport rate measurements. A simple analysis on the trajectory motion of grains in flight revealed a condition for the onset of grain clustering as a function of saltation mean free path, which is a key parameter for the study of sediment transport in general.

2. Introduction

Sediment transport in shallow overland flows have been studied at the ARS/USDA National Sedimentation Laboratory for several years. Primarily sediment transport takes place by solitary grain motion i.e., saltating flow, and therefore solid concentration and solid velocity measurements in saltating modes were emphasized in Prasad *et al.* (2004). It was also observed that when the volumetric solid concentration increases beyond a critical limit, solid density nucleation and growth takes place as a result of inter-granular collisions. These nucleation sites organize into density patterns such as stripes and meanders and begin to move in waveforms. The initiation, development and the fate of these waves are controlled by several factors such as the amount of solids in water, particle shape and size, and the hydraulic Froude number. The transport rates associated with the stripe and meander modes measured using a rotating sampler are described in Rao *et al*. (2007). However, an attempt to characterize the density patterns migration was limited by the sampling time of the sediment (5, 20 sec) collector as compared to time scales of meanders (10-100 min), stripes (less than a minute), and the smallest being saltation with a few seconds. In this work the trajectory motion of a series of equidistat grains is analyzed to derive a condition for the critical solids concentration at which grains starts to coalesce. New photonic probe measurements on solids concentration from meanders and stripe patterns are summarized for different hydraulic conditions and solid addition rates. The temporal variations together with their spectra are compared with the transport rate measurements estimated from the same batch of experiments.

3. Experimental details

The experimental set-up is the same as Prasad et al. (2004). The test section consisted of a 700 cm x 10.7cm x 4.4 cm rectangular open aluminum channel with an inclination of 0.6☐. Experiments were performed by keeping the valve opening constant while varying the solid feed rate into the water stream. Coarse sand granules of size (1000-1400 μm) were used for three hydraulic conditions with volumetric flow rates 10 l/min, 15.7 and 21.6 l/min respectively. These granules were entrained into the water stream 50 cm from the upstream end by using a vibrating hopper and feeder arrangement. The desired solid feed rate can be obtained by adjusting the frequency and amplitude of vibrations. Two optical probes (MTI Instruments Inc., NY, model 2125H) with a sensor diameter 8 mm (illumination diameter is much larger) together with Labview, DAQmx were used for the online recording of data for particle concentration. The sampling frequency of solid concentration was 20 hz. The sampling times for meander, stripe and saltation modes were 40 min, 5 min, and 1 min respectively. These probes were located at about 4.3 m from the upstream end, mounted on a bracket and a micrometer allowed clearance adjustment between the sensing surface of probes with the channel bottom surface where a very thin (~0.0025 inches) reflective tape was affixed. The probes were calibrated for the solid concentration measurements in a still water column with a known amount of solid grains. When the illuminated portion under the probes was completely covered by the solid grains the concentration upper bound was defined by a value 1. Conversely, when there were no solid grains in the light exposure area of the probes, the lower bound solids concentration value was defined as 0. The concentration value was corrected for the packing factor which was defined as the ratio between the true and the bulk densities of solids. The experimental details were given in Suryadevara *et al.* (2004). A computer controlled rotary sediment sampler with 20 sieves [Rao *et al*., 2007] uniformly arranged around the circumference was used to measure sediment transport rates with prescribed sampling intervals. The sampling times were 5 sec and 20 sec for stripe and meander modes respectively.

4. Analysis of the data

When small amounts of sediment is present in the stream the sole mode of transport is by saltation [Owen, 1964]. The mean free path of solids l is several particle diameters. We assume that the homogenous, steady saltation will end with the condition when particles next to each other collide. Let l be the projected linear distance on a horizontal plane between two closest particles of diameter d_s as shown in figure 1. Thus, the linear concentration α is given by

$$\alpha = \frac{d_s}{l} \qquad (1)$$

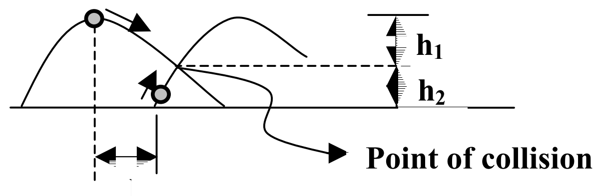

Figure 1 Asymmetric geometry of parabolic profiles of two trajectories in which two grains colliding

It is obvious that each of these particles lie on a point in a trajectory traversed by the particle. If we assume the horizontal velocity of the particle, remains constant throughout, the trajectory will be a parabola. Obviously $l = \Delta s$, or when $l < \Delta s$ the partciles collide (where Δs is the base lenghth of the trajectory). Furthermore, if the horizontal component of the particle velocity remains constant u_0, the particle will not collide with each other and saltation will remain homogeneous and steady. Thus an upperbound of steady saltation may be obtained by

$$\alpha^* = \frac{d_s}{\Delta s} = \frac{d_s}{2u_0\sqrt{\frac{2h}{g}}} < \alpha_c \qquad (2)$$

where α_c is the limit of saltation coincident with simultaneous collisions of particles with their neighbors. Our analysis of particle collision with the bed predicts emergent horizontal velocity u_0^* smaller than the incident value u_0, i.e.

$$u_0^* = e_t u_0 \text{ , } e_t < 1 \qquad (3)$$

Where $\mathbf{e_t}$ be the coefficient of restitution in tangential impact (Sondergaard *et al.,*1990). Note that the decrease in the horizontal velocity is recovered during upward flight due to increased hydrodynamic force of the flow away from the bed. Thus, the particle recovers to the value of horizontal velocity which equals u_0 when the height h is reached. This energy loss mechanism introduces a lag between the particle moving upwards with the one moving downwards. This lag is in essense responsible for particle collisions. Based on this lag mechanism we can determine the critical concentration responsible for loss of free saltation leading to bed structures. By considering the assymetry of particle trajectories the critical concentration estimated to be:

$$\alpha_c = \frac{d_s}{l} = \frac{d_s\sqrt{\frac{2g}{h}}}{(1 - e_t)u_0} \qquad (4)$$

Where $h = (h_1+h_2)$ is the saltation height and g, the gravitational constant.

The amount of sediment above α_c value lead to nucleation and natural organization into stripe mode. When large amounts of sediments are added into the stream, the flow quickly transits from saltation to stripes and then into meander pattern. A sediment addition rate of 90.9 g/min is selected to moniter such flow pattern changes into meanders with three hydraulic conditions of 10 l/min, 15.7 l/min, and 21.6 l/min. The temporal changes in the measured transport rates are presented in figure 2. The measured ransport rates are averaged values over a sampling period of 2 mins. It may be observed that the mean values of transport rates in these three hydraulics i.e q_l = 10, 15.7, & 21.6 l/min are 5.42, 35.2, & 60.8 g/min respectively. The lowest value is 94 % smaller where as the largest value is 34 % smaller than the solids addition rate. The temporal values of transport rates fluctuate upto 200,50, & 20% with 10,15.7, & 21.6 l/min respectively.

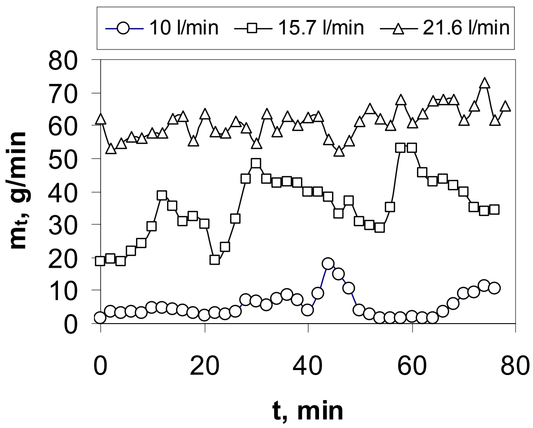

Figure 2 Temporal evolution of transport rates in meander mode : Coarse Sand, Solids addition rate m_s = 90.9 g/min [(O)+1.25 g/min, (Δ)-0.5 g/min]

Visual observations suggest that during the propagation of meanders, which slowly takes place several events co-exist in the sediment bed at any time. Grains detach from the meander waves, saltate along the stream, organize into stripes and reorganize in to meander segments with a phase shift of 180°. This process results in larger fluctuations of transport rates. The sampling time 2 min may be large to capture all the intrinsic details of the transport process. Hence solid concentration fluctuations are recorded at a location on the meandering bed. Figure 3 (a) presents the fluctuations of solid concentration measurements (α_s) from a representative area over a period of 40 mins. The sampling frequency is 20 hz.. The power spectra of these fluctuations indicate a dominant peak at a frequency of 0.00167 hz. This suggests that meanders pass over the measured location for every 10 mins. On the other hand a dominant peak frequency of 0.00083 hz (20 min) is found for 10 l/min (data not shown). The dominant peak with 15.7 l/min is not much different from 10 l/min (about 19.9 min). The faster propagation of meanders with 21.7 l/min is due to the coexistence of stripes (figure 4) in the meander structures. The smaller peaks in the power spectra correspond to the stripe mode.

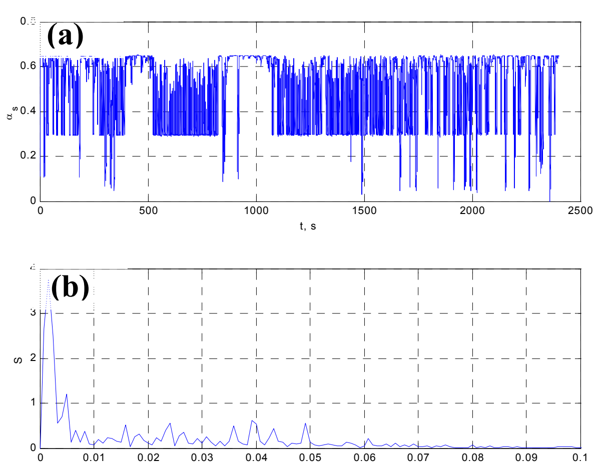

Figure 3 Solid concentration measurements, Coarse Sand, Meander mode, Solids addition rate m_s = 90.4 g/min, q_l = 21.6 l/min. (a)Temporal evolution (b) Power spectra of fluctuations

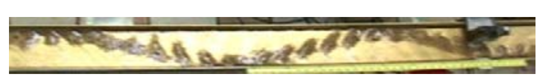

Figure 4 Photograph of a meander mode of transport with coarse sand, d_s = 1000-1400 µm , m_s = 90.4 g/min, q_l = 21.6 l/min

More stable stripe modes are observed at solid addition rates much smaller than those for the meander mode. For comparison purpose, in the initial phase we quickly capture the stripe propagation data at m_s values 95.9 g/min before the flow transits into meanders. The sampling frequency of solid concentration data is 20 hz and the sampling rate for transport rates is 5 sec. It may be observed from figures 5(c) and (d) that the transport rate measurements fail to capture all the details of temporal variations. The high sampling frequency of the solids concentration data includes all the features of the stripe mode f transport. The power spectra of concentration fluctuations (figure 5 b) show dominant peak at 0.074 hz correspond to 13.5 sec, whereas the dominant peak with transport rates show at 0.032 hz (31.3 sec) which may not accurately characterize the stripe mode. The secondary peaks noticed with solid concentration spectra suggest that there are stripes with varying geometry which may occur less frequently.

5. Conclusions

Sediment transport rates in shallow flows are largely affected by the mode of transport. Saltation is the most common mode of transport however grain collisions arising from the smaller mean free paths initiates deposition of solids. Sediment presence in the stream larger than a critical value results in natural organization into density waves such as stripes and meanders. Solid concentration data from optical probe measurements indicate that hydraulic changes modify density wave patterns with stripes and meanders existing together thus allowing faster transport of sediment. The power spectra of solid concentration fluctuations characterize the sediment transport modes which may be used for fingerprinting of the sedimentation process.

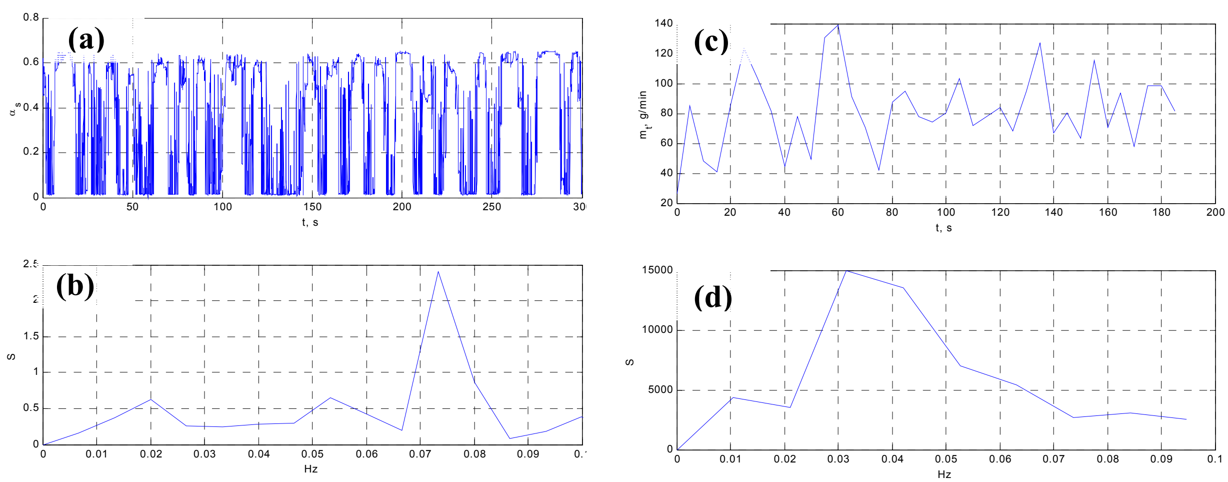

Figure 5 Solid concentration data compared to transport rate measurements for stripe mode, coarse sand, solids addition rate m_s = 95.9 g/min, q_l = 21.6 l/min. (a) Temporal evolution of solid concentration (b) Power spectra of concentration fluctuations (c) Temporal evolution of transport rates (d) Power spectra of transport rate

6. References

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