SEDIMENT TRANSPORT CAPACITY OF SHALLOW FLOWS IN UPLAND AREAS

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Abstract

In this paper, the sediment transport in flow on steep, shallow channels is discussed. The fundamental mode of flow organization of a solid-fluid mixture is described both qualitatively and quantitatively and their interactive organizational relevance in overland transport processes is discussed. Laboratory channel flow experiments were conducted on a variable slope flume with vibratory hopper arrangements to feed dry sediments under controlled conditions. Traditional hydraulic and sediment measurements were made to determine the basic parameters but new photonic measurements are introduced to reveal information of the sediment dynamics. Specifically, particle velocity and solid fraction measurements were made under various flow conditions. Measurements of the sediment transport rates indicate that the highest values were obtained at the limit of the sediment saltation mode. There exist critical values of the solid fraction when patterns begin to form on the bed at which point dramatic decrease in the sediment transport rates were noted. This paper summarizes results of these findings.

Additional Keywords: granular, morphology, concentration, saltation, stripes, meanders

Introduction

The shallow grain flow in an inclined channel (Prasad *et al.,* 2000) demonstrated that the moving particles redistribute themselves in the direction of the mean flow; as a result longitudinal waves evolve on the surface of the chute. Shallow flows of upland processes are believed to be modifications of dry granular processes with the additional controlling parameters being fluid phase turbulence, fluid kinetic energy and the fluid transmitted stress. In the sediment transport processes the solid-fluid interaction is quite complex, the exchange of momentum keeps the solid granules in motion under the influence of fluid turbulence, bed and wall friction, inter-particle collisions, particle-wall collisions apart from the inertial and gravitational forces. In this work we describe an experiment in which the sand transport in a laboratory channel depicts several morphological features under supercritical flows with Froude (Fr) numbers in the range 1-2. The transport rates associated with various bed forms in quasi-equilibrium are presented for sand with d_s = (600-850 µm) (referred as 'medium sand'). The information on grain velocity estimated by the cross-correlation of the twin optical ('Fotonic') probes are also presented. The pre-calibrated single probe measurements of Fotonic unit are used to evaluate the temporal evaluation of solids concentration.

Experimental

The test section consists of a 700 cm x 10.7 cm x 4.4 cm deep rectangular open aluminum channel with an inclination <1. Water enters the upstream end from city mains through a surge tank, regulating valve and an intermediate tank. The desired water flow rate can be attained by means of the regulating valve and experiments are performed by keeping the valve opening constant and by varying the solids feed rate into the water stream. Poly-dispersed sand, of size 600-850 µm ('medium sand') is used as sediments under various hydraulic conditions with the Froude number being 1-2. The desired solids feed rate can be obtained by adjusting the clearance between the hopper with the feeder, frequency and amplitude of vibrations and the feeder inclination. A set of twin Fotonic probes located at about 4.3 m from the upstream end is mounted on a solid block and a micrometer allows predetermined gaps. The probes (model 2125H, MTI Instruments Inc., NY) with sensing diameters 2.5 mm are connected to a dynamic signal analyzer (HP35665A) are used for the online recording of data of particle concentration and particle velocity. The sensor probe consists of emitting source and receiving optics mounted into a steel sheath which is connected to the signal analyzer by means of fiber optics. When the emitted light from the source optics is obstructed by a reflective surface, a portion of the reflective light is detected by the receiving optics. The signal response of detecting optics depends on the magnitude and nature of obstruction and obviously on the distance between the probe surface and the reflective property. The probes are calibrated for the solids concentration measurements in a water column with known amount of solid grains. When the probes are completely covered by the solid grains the concentration upper bound is referred to a value 1, conversely when there are no solid grains under the probe light exposure area the lower bound solids concentration value is 0. The real time recordings for solids concentration is corrected for the packing factor (ratio between bulk and true density values).

Results and Discussion

The transport rates corresponding to different feed rates for medium sand are shown in Figure 1. The water flow rate (q_l) has been kept constant at 15.7 l min^{-1} (Fr_l = 1.45). Observations with feeding below 28.6 g min^{-1} revealed that the mode of transport of solid grains is by saltation. Steady state conditions were established quickly and showed that the transport rates are equal to feed rates within the measurement uncertainty. When solid feed rates exceed 37.4 g min^{-1}, saltation is minimized and the transport quickly transforms into organized structures such as stripes. There exist one or more nucleation sites along the channel, where the stripes are located at first and the strip mode seems to evolve all along the channel over the time. While the transport is being evolved into stripe mode the measured transport rates under steady operating conditions are reduced by 23.3% to 72.5% of the feed rates, the maximum reduction being at the largest feed rate of 118.5 g min^{-1}. This process might take anywhere between, an hour to several hours depending on the solid feed rates. At higher feed rates solid grains form into large scale structures known as meanders through the stripe phase. The meander data in the fork shape corresponds to two values of feed rates, 150.7 and 168.9 g min^{-1} giving rise to transport rates in the range 85.6% - 97.4% smaller. The transport rates seem to reflect the equilibrium conditions prevailing in the dynamically changing channel morphology. The feed rates even smaller than 150.7 g min^{-1} might favour meander formation exploring the possibility of several branches leaning from the stripe mode of transport. The current experiment is limited to the meandering features and the quantitative study beyond meandering is not in the scope of the current work. The incipience, development and maturity of meanders are discussed in detail in one of the following sections. Similar flow patterns are also observed with the coarse sand (d_s = 1000-1400 µm). Such a fluctuating nature of transport rates were also observed by Kuhnle and Southard (1988), however with a comparatively large size gravel-sand mixture of about 3mm size, maximum value associated with a dune like bed form. The time scales in their experiments were large compared to the present study.
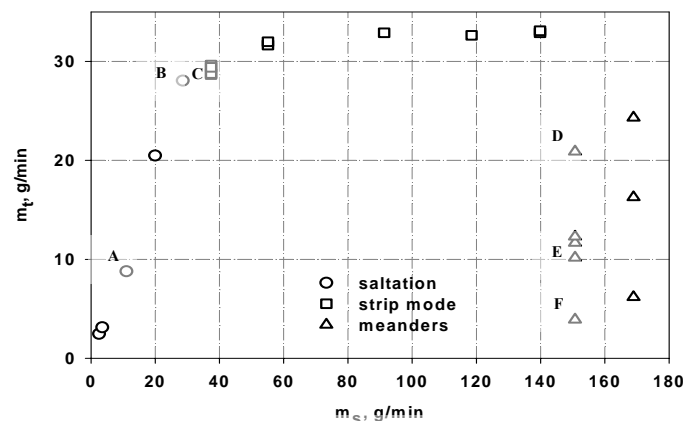

Figure 1. Measured transport rates of sand granules at different feed rates (d_s = 600-850 µm), water flow rate q_l=15.7 l min^{-1} (Fr_l = 1.45). The channel is inclined at ~ 1° with the reference plane.

Saltating flow

Saltation is characterized by individual ejection of particles from the surface in distinctive trajectories under the influence of water resistance and gravity (Owen, 1964). The momentum exchange between the interstitial fluid and the grains keep the saltating conditions prevalent. In this mode, the hypothesis proposed (Owen, 1964) is relevant that the broad scale turbulence created by the saltating particles is in the order of magnitude to the depth of the saltating layer. In the saltating layer the downward moving particles have more time to acquire greater horizontal momentum from the fluid than the upward moving particles in the trajectories. Since the total rate of momentum is constant in the saltation layer, near the surface the shear stress borne by the fluid falls to a minimum value just enough to keep the grains in mobile state. Higher amount of solid in the liquid phase leads to intense grain collisions. At the upper threshold (referred as bed capacity) these frequently colliding grains start agglomerating into several clouds. The time evolution of the solids concentration (α_s) data for a dispersed condition under small feed rates and a collision intense situation with high feed rates are presented in Figures 2(a), (b) respectively. Figure 2 (c) shows the time averaged solids concentration (α) measurements from the single probe measurements plotted against the grain velocity measurements obtained by the cross-correlation of twin probe data. The data suggests an initial increase followed by decrease in the grain velocity with increasing solids concentration. The modulation of turbulence by the presence of solid grains results into reduction of the drag coefficient and thus responsible for grain velocities observed in Figure 2(c). From the epoxy-coated hot-film sensor measurements on the suspensions of clay, Li and Gust (2000) also observed particle drag reduction with relatively large solids

concentrations. In our experiments, this phenomenon is consistently observed for the all three kinds of particles considered (due to space constraint only limited data is presented).
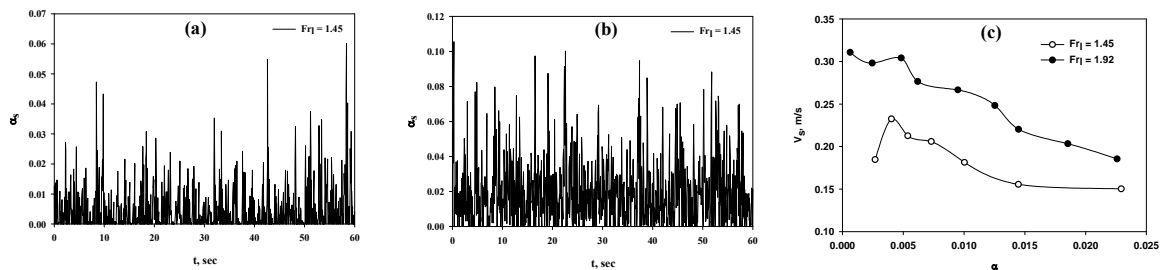
Figure 2: Saltating flow regime; medium sand (d_s = 600-850 µm); Channel inclined at ~ 1° with the reference plane. (a) Time evolution of solids concentration in the plane perpendicular to the flow direction, m_t = 8.8 g/min (data Label A in fig. 1) (b) Time evolution of solids concentration in the plane perpendicular to the flow direction, m_t = 28.2 g/min (data Label B in fig. 1) (c) Variation of the grain velocity with the solids concentration for two hydraulic conditions; Particle velocities are obtained from the cross-correlation of twin Fotonic probes and the solids concentration from the pre-calibrated individual Fotonic probes.

Stripe mode

Certain upper threshold of saltation mode with intense particle collisions is the incipient condition for stripe formation. These structures extend towards the upstream end slowly, might take several hours depending on the feed rates. The direction of propagation of these structures seems to be unchanged even after establishing the equilibrium conditions. Here two transport mechanisms seem to be apparent. Firstly, individual grains in the upstream stripes travel through the rarefied regions of stripe mode by saltation via grain detachment at the downstream front or across the stripe, joining the upstream front of the downstream stripe. Secondly, a contemporary mechanism is identified by which stripes propagate towards the upstream direction. As a consequence of these two transport mechanisms, the flow field seems to be modified. The features of the stripe mode seem to be similar to the longitudinal waves found from the gravity driven granular flow of glass beads under dry operating conditions (Figure 3a) by Prasad *et al.* (2004). The typical photograph of stripe mode for medium sand is shown in Figure 3b (corresponds to label C in Figure 1). Figure 3(c) shows the time evolution of solids concentration, α_s (fraction of the area covered by solids under the Fotonic probe). The wavelength of these stripes for a given material seems to be constant for a fixed hydraulic condition and the higher feed rates results in increased propagation of stripes hence resulting in slightly higher transport rates. The formation of sand ripples under oscillating behavior of a shallow column of water was reported by Bagnold (1946). In the upland erosion and the other sediment transport processes the solid-fluid interaction is quite complex due to the continuous exchange of momentum between the liquid and the solid phases as a result, the organization of the sand structure seems to undergo a non-linear evolution process.
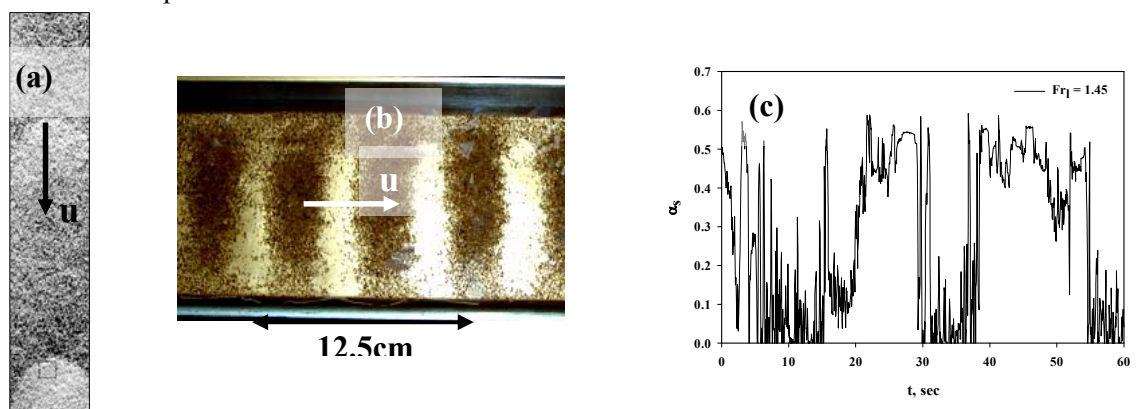
Figure 3. (a) Photograph of periodic density fronts (wavelength, λ_s ~ 12.5 cm) in the gravity driven granular flow of glass beads, d_s = 200-250 µm; m_t = 90 g/min; channel inclination, θ = 26° (b) Typical photograph of a stripe mode of transport with medium sand, d_s = 600-850 µm (corresponds to data label C in fig. 1), m_t = 48 g/min, Fr_l = 1.45; wavelength of stripes, λ_s ~ 5.1cm (c) time evolution of the solids concentration, α_s in the stripe mode corresponds to (b).

Meandering of grains

The necessary but not sufficient condition for the formation of large scale structures is the stripe mode of transport. The hydraulic characteristics, sediment concentration level in the channel, particle shape and size are some of the controlling parameters for the large scale structures. Under favorable conditions the stripes erode half way and coalesce into a wave shape. The individual particles are being transported by saltation thus establishing at least three transport mechanisms i.e, saltation, propagation of stripes and the migration of large scale patterns. Figure 4 (data labels E in Figure 1 respectively) show the meandering of medium sand. The wavelengths of these meanders vary along the channel with larger values at both ends and relatively smaller values in the channel halfway. Also the initial shape of large scale structures show a relatively thin grain wave at the drain end compared to the upstream end. The typical scale of these large structures are about 43-63 cm for medium sand where as they are in the range of 36-84 cm for the coarse sand. The availability of excess amount of solids in the channel aids maturing the meanders into braided (bar) structures. Recently, Smith (1998) simulated many characteristics of large meandering streams in a small flume of dimensions 3 m long and 1.2 m wide by running water ($Fr_l < 1$) on a pre-moistened smooth clay bed. The use of powder like particles of size < 45 µm only allowed him to understand that the bank cohesion was responsible for the sinuous shape and size of the migration channels. The meandering patterns were observed after a few hours of sediment process. However, in the present investigation the sand granules are barely cohesive and the time scale of mender formation is only several minutes, meanders are fully developed in about 12min, suggesting that the bank cohesion solely is not responsible for the sinuous shape. There seems to be great degree of freedom including the transient manipulation of hydraulics, grain collisions and the energy exchange mechanism between the two phases.

63.5cm

**Figure 4. Medium sand (ds = 600-850 µm); Fully developed meander structure,
$m_t = 10.2$ g min⁻¹, $Fr_l = 1.45$ (data label E in Figure 1)**

Conclusions
The transport rates in the shallow sediment transport processes seem to be sensitive to the morphological condition of the upstream bank processes. Grain transport by saltation is the most common mode of transport and the solids concentration in the channel controls the fate of channel morphology. Inter-particle and particle-wall collisions at the upper threshold of pure saltation regime transform the sediment transport from hydraulic intensive to grain intensive process. The presence of solids beyond the bed capacity is characterized by the existence of several nucleation sites with clusters of grains. Higher solids concentration beyond a limit triggers the natural selection process of grains at nucleation sites and organizes them into small scale structures such as stripes. These organized structures evolve into large scale meanders under the continual modulation of hydraulics together with grains. The measured transport rates are small while the grains are organized into structures. The smallest transport rates are measured with the large scale structures.

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