SEDIMENT TRANSPORT MECHANICS IN SHALLOW FLOW DURING THE SALTATION PHASE

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Abstract For several years, the National Sedimentation Laboratory has been engaged in predicting sediment transport in shallow overland flow from grain transport mechanics. This paper summarizes the findings of this research. Experimental research complemented with theoretical analysis focused on laboratory studies in a small flume with a constant, supercritical flow regime into which coarse (1000-1400 µm) and medium (600-850 µm) size grains and glass beads (600-1000 µm) were added at a controlled rate. Changes in the grain transport mode were determined with increasing grain additions to the flow by using a vibrating hopper and particle feeder arrangement. The frequency and amplitude of the vibrations controlled the feeding rate. Depending on the grain feeding rate, movement of the material was observed to be either by saltation, strip development, or meanders. The velocity of the individual grains was determined by a pair of photonic sensors. The analysis are based on the formulation of a two layered model, the bottom part being a sediment containing layer overlain by a layer of clear water. For each layer the continuity equation and the momentum equations described the flow regime. In the sediment laden layer, the momentum equation included components for particle pressure, gravitational force, and the effective dispersion due to the solid phase-water interaction. The hydrodynamic influence of the water layer on the sediment layer is given by the St. Venant equations for shallow flow. It was observed that for increasing grain concentrations the particle velocity increased, which anomalous result was attributed to the break-up of water structure, but that with a further increase in the particle concentration the particle velocity rapidly decreased due to the loss of kinetic energy as result of inter-particle collisions and interactions with the boundary. For very low solid concentrations good agreement was obtained between the observed particle velocity and the calculated values. However, at higher solid concentration an allowance had to be made for the effect of particles impacting the solid surface. The introduction of a relationship between the saltation height and the approach velocity of the particle a coefficient of restitution could be obtained which in turn showed that the particle velocity decreased with solid concentration. The velocity decrease was consistent with the experimental observations. Also, a relationship was derived that allowed to predict the transition from saltation to a strip mode of grain movement.

INTRODUCTION

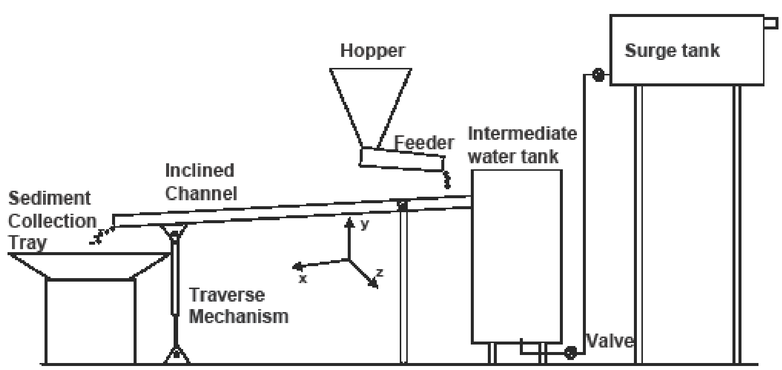
For several years the National Sedimentation Laboratory has conducted sediment transport studies in shallow overland flow. At the Seventh Federal Interagency Conference results were reported that concerned the development of organizational structures in granular gravity flow, when sand grains and glass beads were dropped at a constant rate onto an inclined plane of 30 to 38 degree (Pal et al., 2001). The article focused on possible similarities and dissimilarities between the origins of structured flow of granular material in a gravity flow field in water or air.

The study was motivated by the observation that grains, dropped into a constant flow regime, changed their mode of transport when the concentration increased and exceeded the transport capacity. The results of this preliminary experiment led to far more detailed and systematic studies in which sediment movement in shallow flow under highly controlled sediment addition rates and flow regimes were examined. Since the primary objective was to obtain a better insight and understanding of factors and mechanisms that determine sediment transport capacity in shallow overland flow, our studies focused on the early, low sediment concentration regimes in which sediment is usually in a saltation mode. In this regime, micro-mechanical interactions between flow and sediment particles, between particles and boundary, and between particle with their surrounding water hull become of increasing importance as the sediment concentration is increased. This report represents a summary of the current state of knowledge derived from these sediment transport studies.

EXPERIMENTS

The experiments were performed in a 700 cm x 10.7 cm x 4.4 cm rectangular open aluminum channel with an inclined slope of < 1 degree having a constant flow rate into which grains of different size materials (coarse sand (1000-1400 µm), medium size sand (600-850 µm), and spherical glass beads (600-1000 µm)) were seeded at a controlled rate. A schematic diagram of the experimental set-up is shown in Fig. 1. Details of this set-up are given in Prasad et al. (2009) and Suryadevara et al. (2004). Briefly, water enters at the upstream end through a surge tank and the flow is regulated with a control valve and an intermediate tank. Experiments were performed by keeping the valve opening constant while varying the granular feed rate. Two hydraulic conditions were used with Froude numbers ($Fr=U/\sqrt{gH}$) 1.45 and 1.92 that corresponded to 15.7 and 21.6 l/min^{-1}, respectively. The grains were added to the water stream 50 cm from the upstream end of the channel using a vibrating hopper and feeder arrangement.

Figure 1 Schematic diagram of the experimental set-up.



The desired feed rate was obtained by adjusting the clearance between the hopper with the feeder, the frequency and amplitude of vibrations, and the inclination of the feed tray. The feeding hopper was isolated from the flume. Two optical probes with an 8-mm sensor diameter (MTI Instruments Inc., NY, model 2125H) and a dynamic signal analyzer (HP35665A) were used for making the critical recordings of particle velocity and concentration data. The probes were located at about 4.3 m from the upstream end of the channel. A micrometer allowed clearance adjustment between the sensing surface of the probes and the channel bottom where a very thin (~0.064 mm) reflective tape was affixed to facilitate signal detection. The probes were calibrated for the solid or particle concentration by using a still water column with a known amount of solid grains. The complete coverage of the illuminated area by the solid grains, the concentration upper bound, was assigned the value 1. Conversely, when no grains were in the field of vision of the probe, the lower bound, the concentration was assigned the value 0. Also, signal response from the probes captured the solid cluster propagation through the field of vision. Particle velocity was estimated by cross correlating the signal data of the two probe recordings of saltating grains over a 60 sec period. The time averaged particle concentration is found by averaging the concentration $\alpha(x,t)$ over a time period t , usually 500 ms. The measured linear concentration range a ($\alpha = \frac{d_s}{s}\alpha \approx \sqrt{\frac{\alpha}{s}}$) varies between 2.2 and 19.4 %. Photographic recordings of saltating grains were captured with a Sony digital camera, Model DSC-F707, from which several parameters were determined such as the total number of grains per unit area, number of clusters per unit area, average free path of clusters, and average number of grains in the clusters. The sizes of the captured images were 2560x1920 mega pixels and two 49 cm^2 areas were marked to extract this information. In a manual mode, the camera could operate at a frame rate of 30-1000 per second. Average values of these parameters were calculated for 4 or 5 photographs for a given grain addition rate. From these data, additional information of a micro-mechanical nature during the saltation phase can be deduced.

OBSERVATIONS

At the Eighth Federal Interagency Conference we presented the results of additional studies that specifically focused on quantitative aspects of sediment transport in shallow flow (Römkens et al., 2006). Several modes of transport were recognized as the grain addition rate to a constant shallow flow regime was gradually increased. These modes consisted of : 1. A saltation mode in which individual particles move downslope in the flow without apparent or limited interference from neighboring particles. 2. Sediment moves in a wave-like structure once the sediment concentration has reached a critical value. At that point the sediment particles have lost kinetic energy due to collisions with neighboring particles. The sediment concentrates in packets or waves spaced at regular intervals. 3. Meanders that gradually develop from the wave structure. While the individual sediment particles move downslope, the waves move up-slope and grow in numbers starting from the bottom of the experimental channel. Also, at very low sediment concentrations, the measured particle velocities initially increased, reaching a maximum value, after which a decrease was noted. Then, at some concentration level, particles agglomerated by collisions or for reasons of minimum transport energy requirements leading to the transport mode by waves. The similarity of sediment movement in water flow with modes of granular gravity flow of saltation and semi-inertial gravity flow as reported by Pal et al. (2001)

is striking. Fig. 2 shows the sediment transport rate in relation to sediment addition rate for coarse sand at a flow rate with Froude number 1.45. Visual observation also indicated that the experiments could be described by a two-layer flow system in which the sediment particles are mainly concentrated in a shallow layer near the channel bottom of which the thickness appears to be decreasing with
increasing concentrations. The top layer was, at least for this system, clear water.

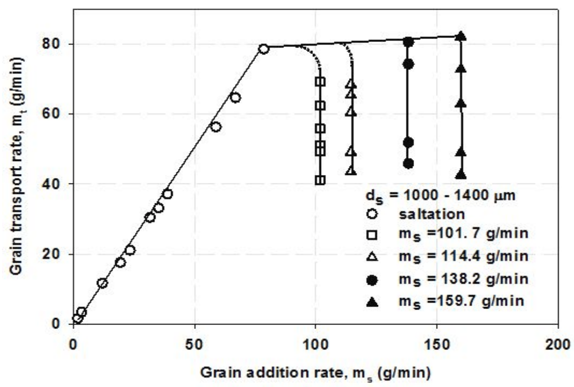


Figure 2 Sediment transport rates in relation to sediment addition rates for coarse sand (d_s=1000-1400 µm) and water flow rate of 15.7 liters/min. (Fr= 1.45).

In the Prasad et al.(2009) article a detailed analysis is made of total sediment movement using a two phase model. For each layer the continuity equation and the momentum equations described the flow regime. In the sediment laden layer, the momentum equation included components for particle pressure, gravitational force, and the effective dispersion due to the solid phase-water interaction. The hydrodynamic influence of the water layer on the sediment layer is given by the St. Venant equations for shallow flow. A schematic representation of this model is shown in Fig. 3. In the analysis emphasis is placed on the transition of the saltation mode to transport of sediment by waves. The transport mode change is of fundamental interest in sediment transport mechanics since at this point the maximum transport capacity is reached for the flow regime and the material under consideration.

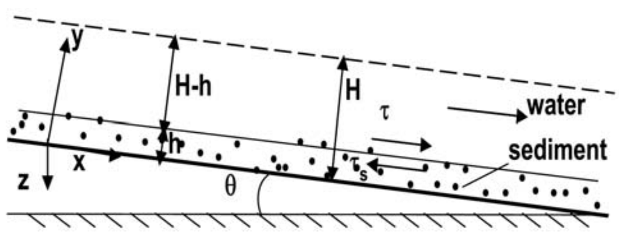


Figure 3 Schematic representation of the sediment transport in water over an inclined channel.

ANALYSIS

The analysis consisted of solving the continuity and momentum equations for the coupled two-layer flow regime (Römkens et al., 2006; Prasad et al., 2009). A number of concepts and relationships as they apply to this flow regime are needed to solve this system of equations. Those include the shear and normal dispersive pressure relationships of Bagnold (1954), the density number relationship as a function of the linear solid concentration, and the modified density number. The dispersive pressure relationship accounts for the dilation effects of the water flow regime on the sediment particles. Substitution of these relationships into the solution of the continuity and momentum equations yield (Prasad et al. 2009):

$$3\rho_0 \frac{(u-c)^2}{\alpha^2}\left(1+\frac{1}{\alpha}\right)^{-4}\frac{d\alpha}{dX} - \frac{5h}{\rho_s d_s}\mu\gamma\alpha^{\frac{1}{2}}\frac{d\alpha}{dX} = \frac{\rho_w hg}{\rho_s d_s}\frac{d\eta}{dX} - \rho_0 g\left(1+\frac{1}{\alpha}\right)^{-3}\sin\theta + \frac{h}{\rho_s d_s}\left(2.25\mu\gamma\alpha^{\frac{3}{2}} - \tau\right) \quad (1)$$

where X =x-ct is the moving coordinate, c is the velocity of the sediment wave, u is the particle velocity, h is the saltation height, d_s is the particle diameter, ρ_s is the solid density, ρ_0 is a modified density number that equals C_0h/d_s, where C_0 is the maximum possible volumetric concentration which is ~0.78 for spherical particles, g is the constant of acceleration, μ is the liquid dynamic viscosity, τ is the shear stress, α is the linear solid concentration, and γ is the shear rate of solid grains u/h. Eq.1 basically expresses the relationship between the particle velocity and the solid concentration. The point of interest is the solid concentration where the saltation mode transitions into the wave packet mode of transport. At that point dα/dX equals zero. Then Eq.1 will yield the following identity (Prasad et al. 2009):

$$\frac{24\,\rho_w\,\nu\,C_m C_o U\,\alpha^3}{bd_s} = \frac{9\,\mu\,\gamma\,\alpha^{\frac{3}{2}}}{4b} \quad (2)$$

where C_m is the additive mass coefficient for the particle matrix (Eames et al., 2004), b is the channel width, and U is the mean free stream velocity. This expression can be further simplified to read (Prasad et al. 2009):

$$u = 10.7 C_m C_0 U \alpha^{\frac{3}{2}}\left(\frac{h}{d_s}\right) \quad (3)$$

This solution expresses the particle velocity u in terms of the linear solid concentration α(X). It shows that with increasing linear solid concentration the velocity of the particle increases. This finding is consistent with the experimental observations at low solid concentrations. However, the monotonic increase in the particle velocity with increasing solid concentration is at variance with the data at higher concentrations that show a decrease in the particle velocity. Fig. 4 shows the experimental results of the sediment particle velocity versus solid concentration relationship for glass beads and coarse sand in a flow regime with Froude number 1.92. The anomaly with the experimental results is attributed to the fact that the flow equations were derived for a situation that did not include the boundary effect of the flow. Significant energy dissipation takes place, among others, in the collisions of sediment particles with the channel wall. If one assumes a dynamic steady state flow regime then, in the ideal case, the saltation height remains on the average constant as the flow imparts the necessary momentum on the particles. A schematic of the saltating particle trajectory is shown in Fig.5 and of the component velocity profiles of a particle before and after impact is shown in Fig.6. The suffixes 1 and 2 refer to the incoming and rebounding particle situations and velocity components. The normal velocity components are given by v (v1 and v2) and the tangential velocity components are indicated by u (u1 and u2), respectively. The pulse impact relationship can now be used to derive an expression

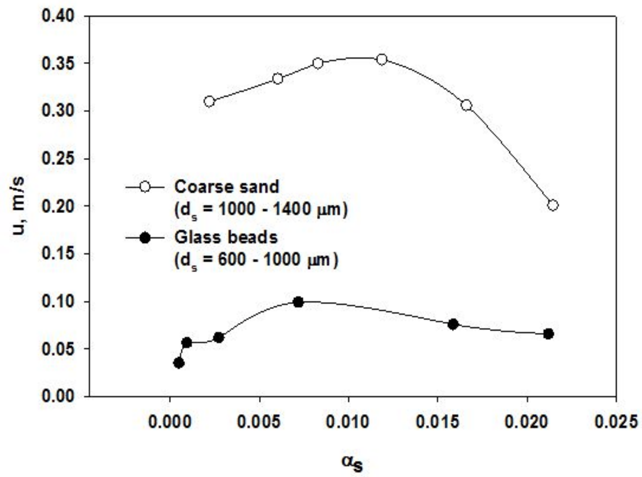


Figure 4 Observed relationship between sediment particle velocity and solid concentration for glass beads and coarse sand at a flow rate of Froude number 1.92. Because of the absence of direct saltation height measurement, the calculated particle velocity measurements were obtained from the Stokes number relationship of e_t.

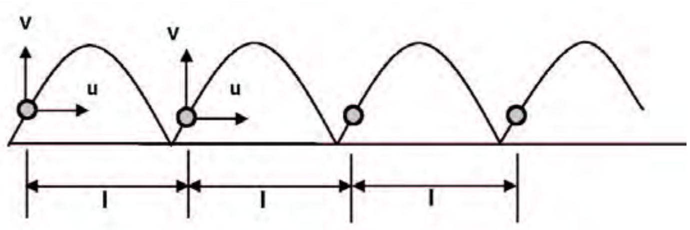


Figure 5 Saltating particles with uniform trajectories and constant height.

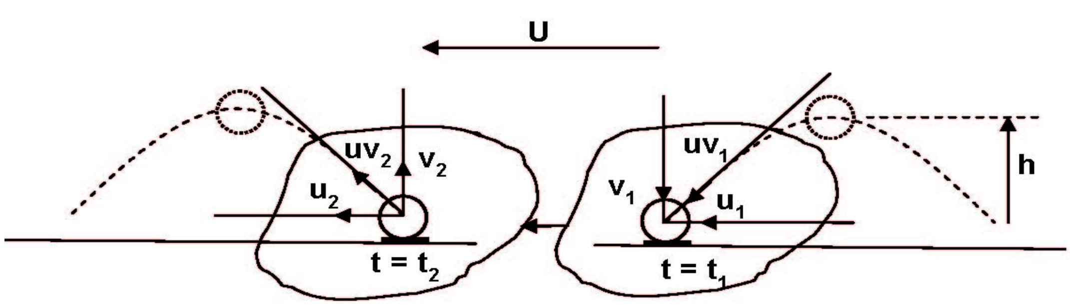


Figure 6 A schematic representation of particle impact (before and after) with the surface.

(SI units) for the saltation height as a function of the tangential incoming flow velocity (see Prasad et al. 2009):

$$\boldsymbol{h} = 206.61(1-\boldsymbol{e}_t)^2 \boldsymbol{u}_0^{\,2} \tag{4}$$

where e_t is the coefficient of restitution in a tangential impact. Additional simplifications can be made in which the tangential particle velocity $u_t = u_2 = e_0 u_0$ during the impact is approximated as the averaged value of the incoming and outgoing tangential velocity $u = (u_0 + u_t)/2$ components yielding the relationship:

$$\boldsymbol{h} = 8.26\boldsymbol{x}10^2 \left(\frac{1-\boldsymbol{e}_t}{1+\boldsymbol{e}_t}\right)^2 \boldsymbol{u}^2 \tag{5}$$

Substitution of this relationship in Eq. (3) yields an explicit expression of the saltation height as a function of the solid concentration:

$$\boldsymbol{u} = \frac{1.13\boldsymbol{x}10^{-4}\boldsymbol{d}_s}{\boldsymbol{C}_m \boldsymbol{C}_0 \boldsymbol{U} \boldsymbol{\alpha}^{1.5}} \left(\frac{1+\boldsymbol{e}_t}{1-\boldsymbol{e}_t}\right)^2 \tag{6}$$

The right hand term of Eq. (6) represents a rather complex dependency of the particle velocity on the solid concentration since the coefficient of restitution is also a function of the solid concentration. The e_t values can be estimated from the Stokes relationship:

$$(1-e_t) = 0.0172 + \frac{0.5952}{St} \tag{7}$$

DISCUSSION

The results of Fig. 2 indicate the rather complex nature of sediment transport. Even for a simple steady state flow regime of controlled flow rates and grain additions, sediment transport is all but constant. Over a period of 20 min. one could observe a continuous change in the transport regime as indicated by the bed form development. The changes were attributed to the micro-mechanical interactions between particles. At very low solid concentrations when interactions between grains were limited or absent, the sediment particles moved by saltation. In that regime the grains that enters the flow moved in full through the channel and the transport capacity increased as long as interactions did not lead to depositions. Fig. 2 also shows the significant changes up to 40% of the transport capacity of the flow regimes for the sand sizes tested. These results bring into question the validity of many transport capacity values that are used in erosion and sedimentation models.

A second major finding is of this work is the changing nature of the particle velocity relationship at low solid concentrations. This finding indicates the impact of micro-mechanical properties and processes on particle/sediment movement in overland flow. Their influences became more apparent, as this study shows, as the solid concentration increases. It is expected that the transport capacity is further impacted as particle sizes in relation to the thickness of the boundary layer, or when the electro-chemical properties of particles (clay) affect the fluidity (viscosity) of the flow medium. The model proposed in this work suggests a varying tangential rectitution coefficient e_t. This by itself could explain the observed valocity-solid concentrations relationship Fig. 7 shows the predicted values for coarse sand and glass beads. Varying e_t values for dry impacts of spherical particles with planar surfaces have been observed by Sondergaard et al. (1990). However, e_t measurements of impacting particles on solid surfaces with shallow streams are few, if any, in the literature. Our work suggests the need for these measurements in order to establish a generalized expression to estimate e_t values in terms of surface properties of the channel bed, particle properties, flow variables, and the obliqueness of the saltation impact.

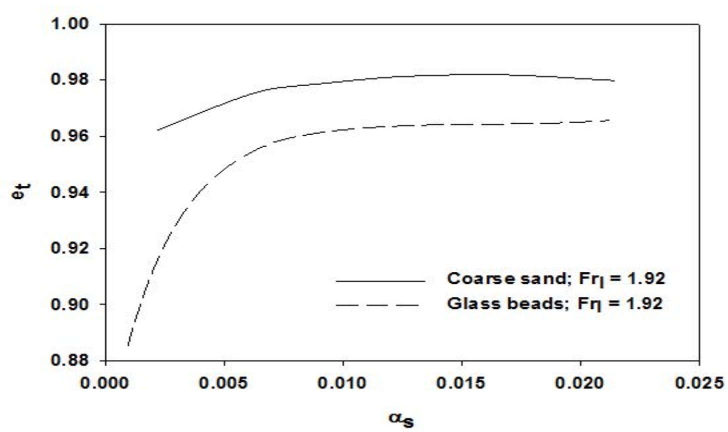


Figure 7 Model predicted e_t values for coarse sand and glass beads in a flow regime with Fr=1.92.

SUMMARY

In this paper, on-going research of sediment movement in shallow overland flow at the USDA-ARS National Sedimentation Laboratory has been summarized. Studies involved the controlled addition of grains of three different particle sizes, two sand sizes and one of glass beads, to a constant flow rate. Two flow rates were used with Froude numbers of 1.45 and 1.92, respectively. Different modes of transport were observed as the grain addition rate was increased: saltation, wave-like transport mode, and a meander bed, Measurements consisted of determinations of the grain velocity and the linear solid concentration. Specific attention was given to sediment movement in the saltation mode in order to determine the maximum transport capacity which condition was obtained at the moment when saltation transits into transport by wave motion or formation. Sediment movement was analyzed by solving the system of continuity and momentum equations of couple flow layers: a sediment laden layer and the sediment free water layer. The solution yielded an ordinary differential equation from which the maximum transportation capacity could be determined. The experimental results also showed changes in the particle velocity with increasing sediment concentration during the saltation mode.

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