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Study of Sediment Transport in Shallow Channel Flows

*D. Pal, S.N. Prasad and M.J.M. Römkens**

ABSTRACT

Soil erosion on upland areas is a multifaceted phenomenon involving processes of soil detachment, transport and infiltration. Sediment transport in itself is a highly complex process involving factors of flow depth, flow velocity, velocity profiles, particle sizes, particle density and distributions, as well as surface matrix conditions and surface topologic irregularities. Many transport equations describing sediment movement in two-phase flows have been developed. However, they are mostly applicable to flow in channel systems with Froude number smaller than one. On upland areas, the surface flow regime and associated sediment transport is less defined and understood and varies from thin film flows to concentrated flows with Froude number greater than one. In this article, selected aspects of our current research in sediment transport are presented. This fundamental research examines the different modes, mechanisms and conditions of sediment movement in fluid-grain mixtures by wave-power action. The study is designed to obtain a better understanding of the physical processes and their roles in controlling the modes and magnitudes of sediment in upland areas of concentrated flows. In our experimental observations, it is found that wave power induced transport of sediment is controlled by the momentum redistribution processes in the sediment phase. The modes are highly dependent upon the inertial and other dynamical parameters of the grains. This is in contrast to the conventional approach where hydraulic shear stress is used as a criterion and a measure of transportability. This information would help in improving prediction models and for devising more effective erosion control strategies.

INTRODUCTION

Current sediment transport relationships in soil erosion processes are based on shear or streampower concepts. These concepts are fluid based and have as a premise that: (1) a minimum shear stress (critical shear; Foster and Meyer, 1975) or streampower (critical streampower; Rose et al., 1983) is needed for incipient motion to occur, and (2) the rate of sediment transport is related to the excess shear stress or streampower relative to their critical values. While some aspects of sediment transport in channels or streams may be described by these relationships, they do not reflect the momentum redistributions involved in the continuum of the sediment phase. The exclusion of the dynamic balance of forces in the sediment phase in these relationships is an oversimplification of shallow flows. Thus, it appears that there is a need for a systematic study of momentum transport of granular material, which will identify the effect of grain size, slope, and the flow rate. When the depth of moving grains is small (less than 100d), as the case on upland areas, cyclic flow of energy is likely to take place in which the free surface effects become significant leading to their steepening and breaking. The entire sequence is in essence controlled by certain energy optimality condition providing an opportunity for the grains to develop self-organization in the form of traveling waves. The criticality of this self-organization appears to be quite robust and various aspects of these waves are presented in this study in the form of experimental evidence.

As the sediment is carried by the fluid phase (i.e., water), the particle undergoes a systematic acceleration and deceleration process whose cumulative effect is similar to the previously discussed case resulting into an organization in the form of progressive sediment waveforms. Though the energy of transport is provided by the fluid, its redistribution in the solid phase and the resulting sediment movement is controlled by the dynamics of this organization process. Our experimental investigations on sediment transport in shallow flows suggest that for certain flow and sediment transport regimes, inter-particle collisions and the resulting kinetic energy dissipation control the sediment movement in a major way. In fact, this argument is even better demonstrated in the absence of water such as in granular transport, which has its own characteristic length scales in the form of turbulent eddies. There appears to be a strong commonality between the overall energy transfer mechanism in sediment-laden shallow channel flows and that in a gravitational flow of dry grains down an inclined plane. Therefore, experimental transport studies, which involved both dry granular flows and sediment-laden shallow overland flows, were conducted to better understand and to explain the interaction between the dynamics of each phase.

The present study is directed towards a better understanding of the transportability of sediment as a continuum in which the laws of physics apply. In particular we are seeking to determine the roles played by the mechanical and geometric parameters of sediment in the transport modes. Thus, the emphasis at this stage is on identifying the intrinsic features which will not be destroyed completely either when the mechanical properties (i.e.., density, cohesion etc.) or deriving mechanisms are altered.

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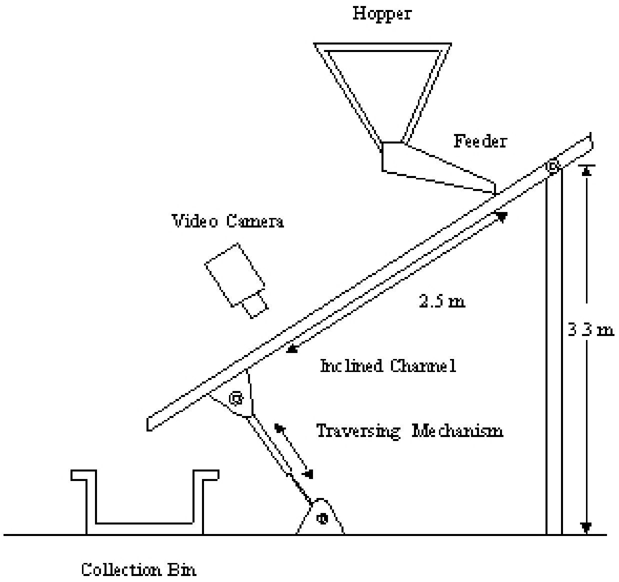
*D. Pal and S. N. Prasad, Department of Civil Engineering, 203 Carrier Hall, University of Mississippi, P. O. Box 6388, University, MS 38677, USA; M. J. M. Römkens, USDA ARS National Sedimentation Laboratory, 598 McElroy Drive, P. O. Box - 1157, Oxford, MS 38655, USA. *Corresponding author: romkens@sedlab.olemiss.edu

It is expected that numerical values will be dependent on these parameters including the bed roughness and the raindrop impact effect. These issues will be more completely addressed in continuing studies.

Sediment–laden shallow channel flows

Laboratory channel flow experiments were conducted on a variable slope flume (Fig. 1). The channel was 57 mm wide, 3.6 m long and its slope was varied in the range of 5% $< S <$ 17%. Water was supplied from a constant-head tank at the upstream end of the channel at relatively small water-flow rates ($V <$ 5 liters min^{-1}). The average flow depth on the channel was less than one centimeter. Sand was added from a hopper-feeder arrangement at an upstream location on the channel and its subsequent passage was photographed at a predetermined location on the downstream side. The observations shown in a series of frames in Fig. 1, indicate a gradual increase in the sediment concentration for a given flow regime thereby reflecting a consistent tendency for the sediment phase to become self-organized. Sediment movement, which at low concentrations is dispersed and locally homogeneous, becomes periodically concentrated at higher densities and moves in waves as shown in Fig. 1. The shape, size and wavelength (typically of the order of a few centimeters) of the periodic structures could be manipulated by varying the channel slope, water-flow rate, average grain diameter and sediment addition rate. For all experimental conditions, the velocity of the sediment waves was much smaller than the average flow velocity (e.g., $c < 0.01u_{av}$). In shallow channel flows on steep inclines, the flowfield is generally unsteady and the transport is dominated by roll-waves. Fig. 2 shows the observed relationships of net sediment transport as a function of sediment feed rate for two channel slopes and two flow rates. It shows that the sediment transport capacity of such channels depends heavily on the available wave energy that is dissipated in the process of carrying the bed load and the suspended sediment. As the sediment addition rate increases, the flow cannot fully carry the entire amount and, therefore, storage of sediment starts on the channel bottom. The water waves are actively modulated to a point of maximum capacity of sediment transport rate beyond which the dynamics of permanent bed formation controls the sediment transport rate.



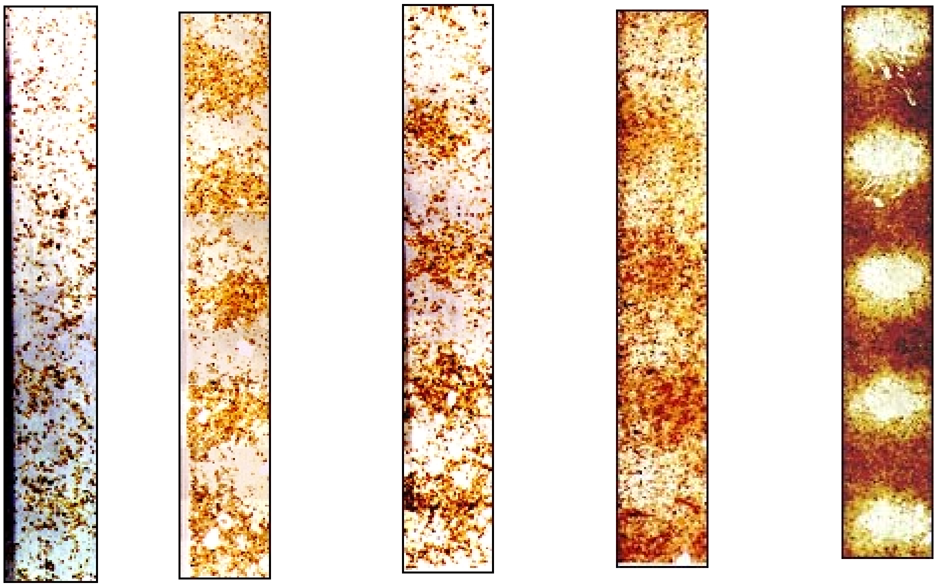


Figure 1. Experimental setup (top) for studying granular transport in shallow flows under the action of gravity. The hopper and feeder arrangement was used to introduce the grains (sand in channel flow experiment and glass-beads in dry chute experiment) on the inclined surface and the collection bin recorded the material flow rate. The series of frames (bottom) shows sequences of granular organization in a sediment-laden shallow channel flow. Coarse sand (d_{av} = 1.5 mm) was used in water as the granular medium. Water flow is from the top to the bottom of each frame. Sediment density increases from left to right of the series of frames.

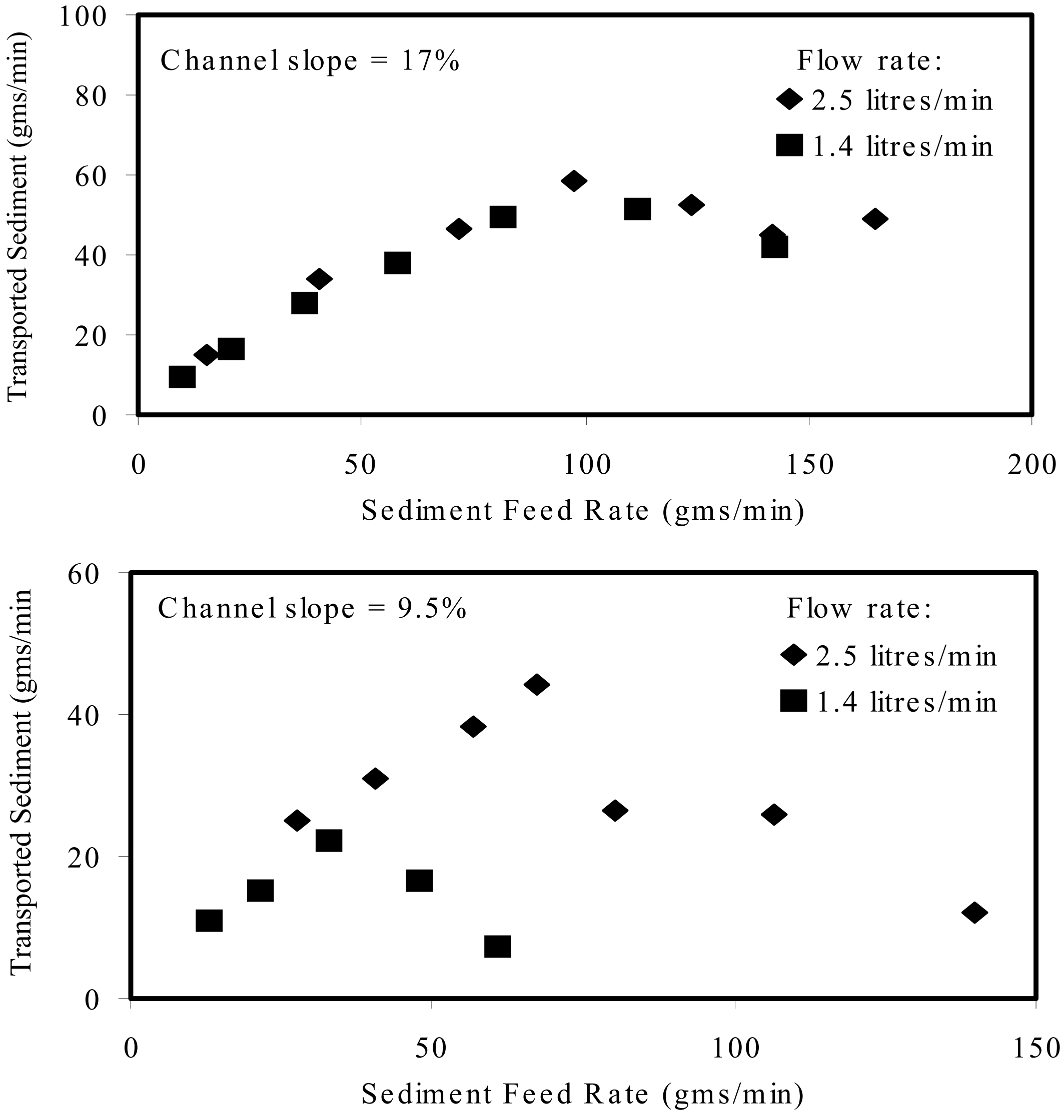


Figure 2. Typical variations in sediment transport rate with sediment addition rate in a laboratory channel flow experiment. The sediment is carried in an unsteady manner by the waves as it also tends to modulate the water waves. The dissipation of excess energy at the wave fronts is effectively utilized in transporting the sediment. Consequently, the sediment transport rate maximizes to a point beyond which a permanent sand-bed evolves on the channel bottom.

The observed response of dynamic wave formation in the sediment phase depends on the relative magnitude of energy contained in the fluid and that dissipated in the solid phase. The strong interaction between the fluid waves phase and solid phase is through an energy-sharing mechanism, which may result in sharp discontinuities in both phases. Certain explanations of such mechanisms have been provided in a recent article by the authors (Prasad et al., 2000). The appearance of spatial structures similar to ripples and dunes can be viewed as a manifestation of variations in the total flow energy in fluid and sediment instead of the more conventional technique of treating the bottom sediment as only a boundary of deformable shape which responds to local shear created by the inviscid freestream and the viscous boundary layer (Kennedy, 1963; Reynolds, 1965). The wave-like bedforms, whether forward-moving, backward-moving or stationary, are caused by the interaction of cyclic processes of generation, convection and dissipation of fluctuating kinetic energy existing in both the fluid and solid phases. The individual energy-cycles of the two phases can possess distinctive length and time scales, which under favorable flow conditions, can interact constructively to exhibit steady organization. This treatment of unsteady transport behavior is expected to provide an insight into the instantaneous rates of local erosion and sediment transport without depending solely on the critical shear concept.

Longitudinal Organization in Dry Granular Transport on Steep Inclines

As described above, the dynamic interactions between the fluid and solid phases in our shallow channel flow experiment appears to be quite intriguing, but can be difficult to comprehend in these macro-scale experiments due to the presence of fluid turbulence effects. Since the solid phase shows organization within itself, it appeared that laboratory experiments involving the flow of dry granular material might facilitate the understanding of the transport mode in a thin sheet of particle flow. Therefore, in another series of tests with the same experimental setup, the rapid flow of dry and dispersed granular solids under gravity was investigated to study the intrinsic periodicity in its transport mode. Spherical glass-beads of varied mean diameters were used as the granular medium in this set of experiments. The glass beads had specified size ranges and the particles were 85% spherical in shape.

It was observed that when a shallow layer of grains moves downslope, it is dominated by the passage of progressive longitudinal waves. Demonstrations of such dynamic waves are shown in the photographs of Fig. 3 for different channel slopes (θ), mean particle sizes (d_{av}) and grain flow rates (Q). The shear at the side-walls of the channel increased with the wave velocities and with increasing channel slope. In this fully inertial regime of dispersed grain flows, each solid particle moves separately from its immediate neighbors and not as a part of a contiguous solid mass. The typical range of volumetric solid fraction (ν) of the solid-gas mixture was in the range of 0.01-0.1 depending upon the measurement location in one wavelength. The natural tendency of a free particle, which tries to maintain contact with the bed due to its self-weight, is to expend the minimum amount of energy to reach a state of lower potential.

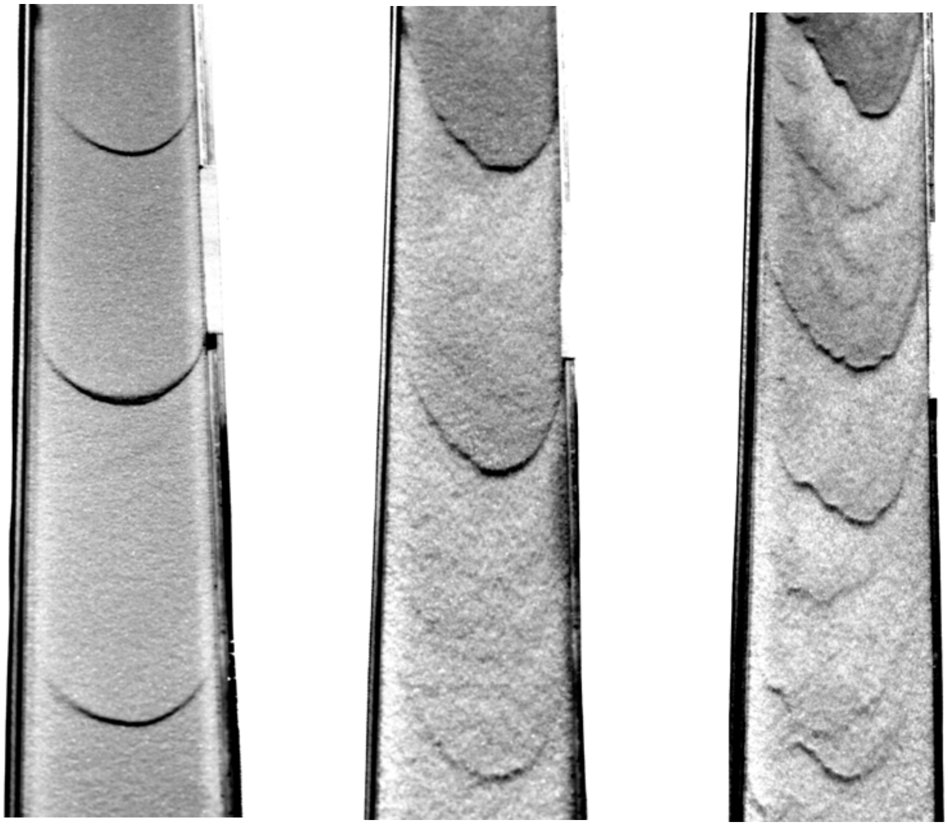


Figure 3. Representative flow visualization photographs of shallow granular flows at different flow conditions. The flow direction is from top to bottom of each frame. (a) $\theta = 30°$, $d_{av} = 106.5\ \mu$m, $Q = 1500$ gms min^{-1}, **(b) $\theta = 35°$, $d_{av} = 213.5\ \mu$m, $Q = 2200$ gms min^{-1}, and (c) $\theta = 38°$, $d_{av} = 151\ \mu$m, $Q = 1200$ gms min^{-1}.**

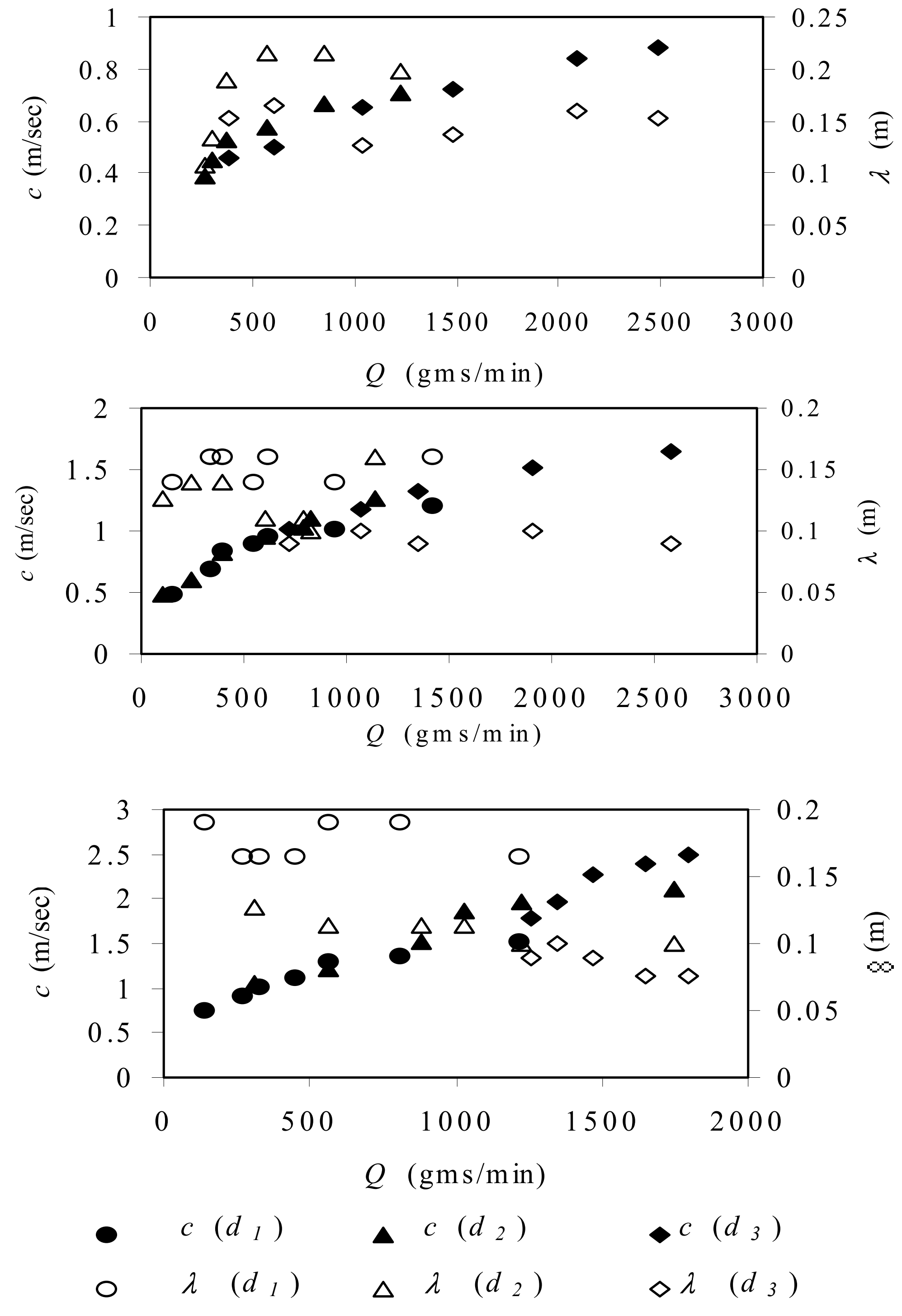


Figure 4. **Wave velocity and wavelength variations with material flow rate in granular chute flow experiments. Here, d_1 = 106.5 μm, d_2 = 151 μm and d_3 = 213.5 μm. (a) θ = 30°, (b) θ = 35° and (c) θ = 38°.**

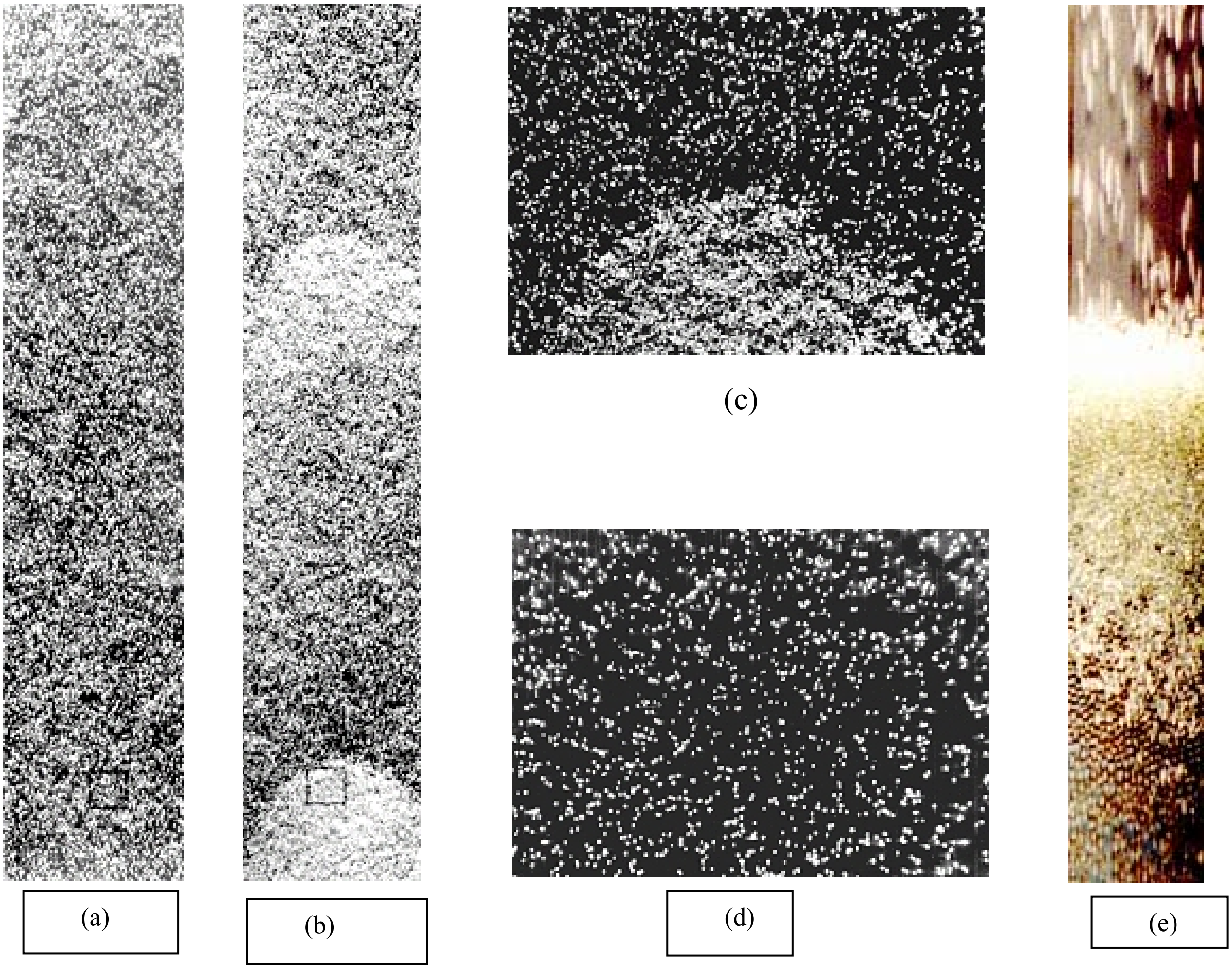


Figure 5. Granular organization through longitudinal density variations. Flow is from the top to the bottom of each photograph. *2* = 26E , d_{av} = 225 μm. (a) Fully fluidized state of dispersed granular flow, Q = 40 g min^{-1}, (b) appearance of shockfronts due to density variations, Q = 90 gms min^{-1}, (c) magnified photo of fluidized state showing inter-particle distances, (d) magnified photo of a single shockfront showing particle density and distribution, and (e) particle streak lengths showing differences in particle velocities within one wavelength at *2* = 7.5E and d_{av} = 800 μm.

Therefore, it is expected that the particle would exhibit a rolling rather than a sliding motion on the inclined surface except when it becomes air-borne due to saltation. Saltations occur when a particle leaves the bed due to non-uniformity of either its own geometry or that of the bed, and due to collisions with other particles moving at different velocities and/or in different directions. The situation of freely moving particles is prevalent in the acceleration domain of the evolving longitudinal flow structures (or wavelength). At the wavefronts, the mean particle velocity changes from its supercritical state to a subcritical state. When this sudden deceleration in the motion becomes significant, shockfronts appear that may become well-defined. The flowfield usually shows a series of low particle-density regions separated by shock waves which exhibit high particle-densities. The particle velocity in the low-density regions is larger than that in the high-density regions. The variation in the free surface profile due to wave formation is not as strong as in shallow water flows, though the mechanism of nonlinear steepening near the shockfronts helps increasing the frequency of particle collisions that consume the additional fluctuation energy of the particles. In the fully inertial regime of grain flow at shallow depth, the wave velocities are always larger than the average particle velocities in the rarefied flow regions.

As the mass flow rate of grains (Q) is increased, the wave velocity (c) is enhanced, though the wavelengths (λ) show very little variations (as shown in Fig. 4). For the purpose of accurate measurements of wavelengths and wave velocities, larger particles had to be tested at higher flow rates than those for the smaller particles. The selection of the range of flow rates for different particle sizes insured that the wave features were pronounced for all the flow conditions. This intrinsic dynamic mode of transport in shallow granular flows shows the importance of energy cyclic processes in determining the steady transport rates of grains. In our experiments, no apparent longitudinal organization was visible for flow rates less than 100 gms min^{-1}. The particles had very large saltating motions when the volumetric solid fractions were very low corresponding to small flow rates. For flow rates larger than 2800 gms min^{-1}, the shock fronts became diffused and their motion could not be tracked with sufficient accuracy with the present video-taping technique.

Intrinsic Fluidization and Density Fronts in Dry and Dispersed Grain Flows

In comparison to the dynamic wave formation in the fully inertial regime of dispersed grain flows, a different granular organization can be observed at much lower values of the average volumetric solid fraction (ν). If the flow rate of granular solids on an inclined plane is decreased to attain very low particle densities, there exists a state of natural fluidization when no apparent organization is observed. In such a state of dispersed grain flow, the inter-particle distances (or linear solid fraction) remain locally homogeneous. In a real granular flow at low densities (e.g., $\nu \sim 0.001$), the particles cannot maintain contact with the bed at all time due to geometric non-uniformities (roughness elements) and, therefore, do not continuously slide or roll on the inclined surface. They intermittently bounce off the surface and get air-borne when they continue their spinning motion approximately about a spanwise axis passing through their centers of mass. The spinning motion of particles in air continues until they encounter collision with other moving particles. Apart from the instances of collision with other particles and the inclined bed, the particles, in a fully submerged state in air, can be assumed to possess two components of linear velocity and one component of angular velocity. The dissipation of kinetic energy of individual particles in this state is caused by the hydrodynamic drag force exerted by the surrounding air. As the grain flow rate increases causing a subsequent decrease in the inter-particle distances, the frequency of inter-particle collisions also increases. This results in a possibility of enhanced energy dissipation through inelastic collisions.

Increasing the mean particle-density of the fluidized state of grain flow ultimately destroys the steady-state behavior of granular transport. Beyond the limit of intrinsic fluidization, the flowing grains start exhibiting density fronts (Fig. 5)

These density fronts do not exhibit any substantial variation in the free surface profile. The volumetric solid fraction of the mixture changes by at least an order of magnitude across the shock front. Since the shock fronts in this semi-inertial regime of grain flow move slower than the dispersed particles, the particle velocities also reduce dramatically as it approaches the front. This organization through particle-density variations is primarily periodic, though higher order nonlinear or dispersive effects tend to exhibit wave-coalescing in an intermittent manner. The appearance of periodic high-density fronts can be attributed to a rapid dissipation of the fluctuating kinetic energy of the grains caused by the enhanced inter-particle collisions in these fronts. As the fluidized state approaches the limit of thermo-mechanical equilibrium of an aggregate of particles,

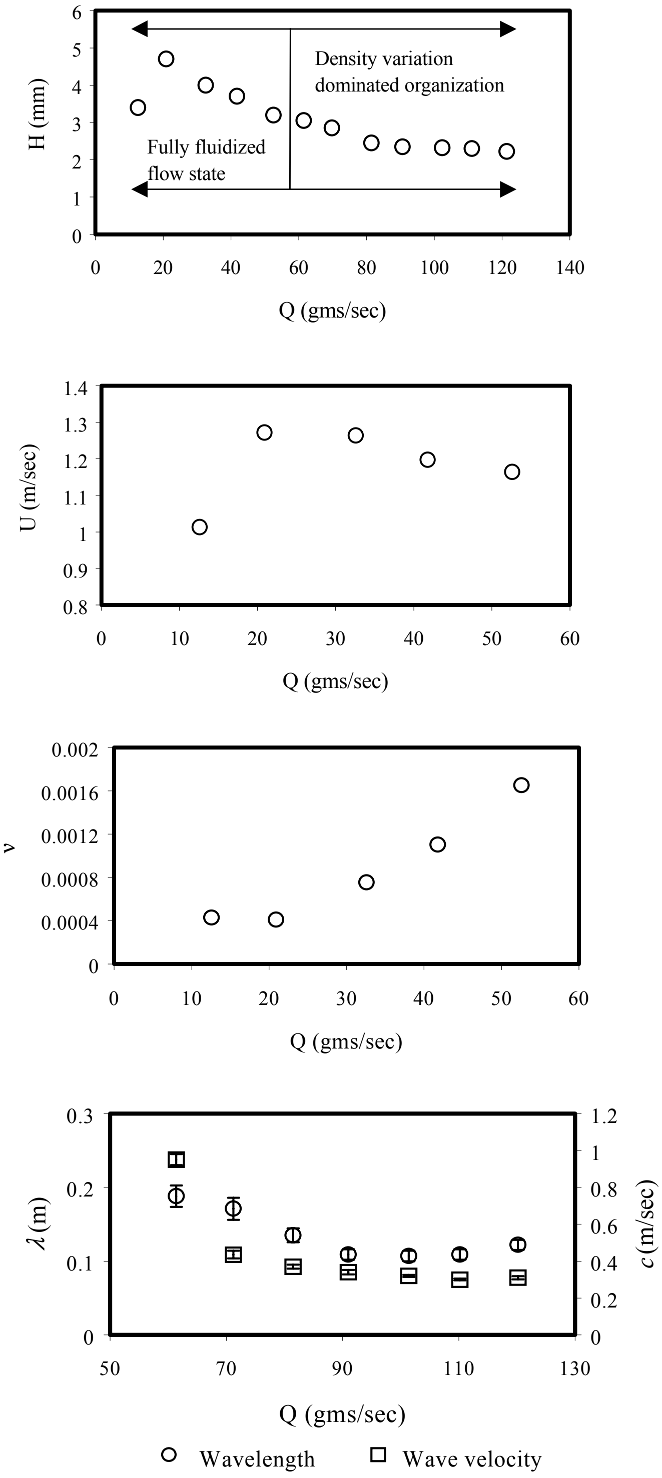


Figure 6. Measurements and estimates of various flow parameters (2= 26° , d_{av} = 225 μm) as a function of the grain flow rate in a fully fluidized state [(a), (b), (c)] of granular flow and subsequent organized state (d) dominated by density variations. (a) Mean flow depth, (b) depth-averaged mean flow velocity, (c) depth-averaged volumetric solid fraction, and (d) wave-velocity and wavelength variations (vertical bars represent experimental uncertainty).

such an enhancement in the energy-dissipation rate is required to maintain a state of flow. In this experiment, additional measurements of mean flow depth and particle velocity profiles were obtained using a depth gage and a pair of photonic sensors, respectively. The volumetric solid fraction of the solid-gas mixture could be indirectly estimated from these measurements. Fig. 6 shows that the increased collisions at higher particle densities causes an overall decrease in the average flow depth (*H*) and the depth-averaged mean velocity (*U*) of particles. The volumetric solid fraction increases rapidly as the threshold of organization is approached. Also, the wavelength and wave velocity of the density fronts reduce with increasing degree of organization through density variations. This particular feature of the semi-inertial regime of organization is in contrast to the behavior in a fully inertial regime where increasing flow rate results in enhanced wave velocities. Further increase in the material flow rate tends to transform the flow to the fully inertial regime of granular organization.

CONCLUDING REMARKS

Our laboratory experiments on wet and dry grain flows demonstrate the significance of a new approach of explaining unsteady transport rates in shallow granular flows. The self-organization behavior in a thin sheet of particle flow lies in the fact that an assemblage of loosely packed grains establishes an intrinsic energy cycle within its own phase. In the absence of substantial shear, the entire mass of particles tends to maximize its transport rate by developing and maintaining this energy-cycle. In comparison to the dry granular flows, where the flow energy is obtained from gravity only, the sediment-phase in channel flows derives its energy from an unsteady flow that tends to minimize its transport rate. The modulations in the water waves in shallow flows are an outcome of this energy sharing mechanism. The authors are currently developing mathematical models of dispersed grain flows to validate their experimental data on granular organization.

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