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Formation and mechanics of granular waves in gravity and shallow overland flow

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Sediment transport in overland flow is a highly complex process involving many properties relative to the flow regime characteristics, soil surface conditions, and type of sediment. From a practical standpoint, most sediment transport studies are concerned with developing relationships of rates of sediment movement under different hydraulic regimes in channel flow for use in soil erosion and sediment transport prediction models. Relatively few studies have focused on the more basic aspects of sediment movement in which particle-to-particle, particle-to-boundary, and particle-to-fluid interactions determine in an important way the nature of the movement. Our experimental work under highly controlled experimental conditions with both gravity flow of granular material (glass beads) in air and sediment transport (sand particles and glass beads) in shallow overland flow have shown that sediment movement is not a simple phenomenon solely determined by flow rates on a proportional basis, but that it is represented by a highly structured and organized regime determined by sedimentary fluid mechanical principles which yield very characteristic waves during transport.

In the gravity flow case involving granular chute flow, two-dimensional grain waves developed into the rolling and saltating moving grain mass at certain grain concentrations. This phenomenon appeared to be related to an energy exchange process as a result of collisions between moving grain particles that led to reduced kinetic velocities. As a result, particle concentration differences in the direction of flow developed that were noted as denser zones. In these zones, particles dropped out at the upstream part of these denser zones to resume their accelerating motion once they reached the downstream part of the zone until, during the next collision event, the process is repeated. Thus a periodic granular wave structure evolved. Depending on the addition rate, the granular flow regime may be a fluidized (homogeneous concentration), mid-inertial (regularly spaced waves with denser particle concentration moving up-slope), or fully inertial (dense waves with higher flight depth moving down-slope) gravity flow regime. In this model, the drag effect of the solid boundary and higher order particle interaction are neglected. (Prasad et al., J. Fluid Mech. 413: 89-110, 2000)

In the shallow flow case and following an initial saltation regime at very low concentrations, a highly organized and structured flow regime developed consisting of sediment waves which move upstream while individual particles move downstream in the flow. Eventually, the waves form a meander with distinct large scale waves with "snake-like" motion that, for the coarse sand (1000-1400 μm), the medium size sand (600-850 μm), and glass beads (600-1000 μm) material used, reached wavelength of about 1 m at super-critical flow rates with Froude numbers of 1.45 and 1.92. In this model all three interactions of particle-to-particle, particle-to-fluid, and particle-to-boundary are considered. (Prasad et al., Ecohydrology 2: 248-256, 2009)

In both cases, the analysis involves solutions of the continuity and momentum equations together with the relevant relationships for shear stress and Bagnold dispersive pressure and shear rates. For the shallow flow regime, a model was developed that simulated the particle velocity-solid concentration relationship. The analysis yielded a relationship at which sediment saltation transits into sediment waves with short wave lengths. The findings of this study also demonstrated the importance of sedimentary fluid mechanics in sediment transport beyond the usual hydro-mechanical considerations and the potential limitations and short-comings of traditional transport capacity relationships used in most erosion and transport models.

Key words: gravity flow, shallow flow.