Experimental Mechanics of Sand Stratification

PIERRE Y. JULIEN, YONGQIANG LAN AND Y. RASLAN

ABSTRACT

The specific objectives of this study of heterogeneous sand mixtures are to:

(1) define particle segregation mechanics in terms of the mechanical interaction between moving particles in the bed layer at the interface with the stationary particles on the bed;

(2) report on several laboratory experiments where lamination and stratification of sand deposits were obtained in a large laboratory flume under steady flow and a continuous sediment supply.

The interaction of moving sand particles at the interface with stationary bed material is paramount to the understanding of sand stratification. The shearing motion of a mixture of coarse and fines, and particles of identical mass density, is considered. The percentage of grain kinetic energy lost is large when small rolling particles impact larger stationary particles. Conversely, the kinetic energy of large rolling particles is almost unchanged after impacting small stationary particles. Consequently, the grain kinetic energy of the fine fractions of a mixture is rapidly depleted and the fine particles first cover the bed surface to form thin elongated fine-grained lenses. Coarse sand particles maintain their ability to roll on top of the fine-grained bed surface. As the kinetic energy of coarser particles is gradually depleted, they deposit on top of the fine-grained lenses, thus resulting in particle segregation.

Under continuous settling, the fine-grained lenses find themselves buried under coarser particles and repetitive segregation produces the distinct features of laminated deposits. Large scale stratification experiments demonstrate that thick stratified deposits can be obtained under steady flow and a continuous supply of heterogeneous sand particles. Plane-bed deltas are characterised by a fine-grained laminated topset and a coarse-grained foreset. Fine-grained lenses indicate particle segregation at the interface between the stationary surface and the moving bed layer.

PARTICLE SEGREGATION MECHANICS

The interaction between particles moving in the bed layer at the interface with the stationary bed material is examined to define the ability of a particle rolling within the bed layer to overcome surface roughness elements. Consider a particle of mass m, diameter d_t and specific weight γ_s submerged in a fluid of specific weight γ_m and mass density ρ_m. Fluid flow at a velocity u relative to the moving submerged particle exerts hydrodynamic forces to generate motion.[1] The fluid forces include the buoyancy force $F_B \sim \gamma_m d_t^3$, the lift force $F_L = C_L \rho_m u^2 d_t^2$ given the life coefficient C_L, the drag force $F_D = C_D \rho_m u^2 d_t^2$ given the drag coefficient C_D. The forces abating the motion include the particle weight $F_W \sim \gamma_s d_t^3$ and the resisting force F_R is applied through the point of contact between the rolling particle and the stationary bed particle. For particles rolling in continuous contact with the stationary particle, the resultant force $\vec{F} = \sum_i \vec{F}$ is applied in the direction tangential to the point of contact.

A particle rolls in continuous contact with the boundary at a constant angular velocity ω_0 and translation velocity

$v_0 = \omega_0 r_t$. The moment of inertia of the particle about its centroid is $\bar{I} = mk^2$, where k is the radius of gyration ($k^2 = 0.4r_t^2$ for a sphere; $k^2 = 0.5r_t^2$ for a cylinder) and the kinetic energy E_0 of the rolling particle is

$$E_0 = \frac{1}{2}mv_0^2 + \frac{1}{2}\bar{I}\omega_0^2 = 0.5\left(1+\frac{k^2}{r_t^2}\right)mv_0^2 = \frac{2}{3}\left(1+\frac{k^2}{r_t^2}\right)\pi\rho_s r_t^3 v_0^2 \quad (1)$$

For instance, the kinetic energy of a sphere rolling on a plane surface is $E_0 = 0.7mv_0^2$

The energy lost through impact is determined from the conservation of angular momentum about the point of impact. The angular momentum of the rolling particle before impact, $H_1 = \bar{I}\omega + mv_1(r_t - \Delta h)$ equals the angular momentum after impact, $H_2 = \bar{I}\omega_2 + mv_2 r_1$. The velocity after impact v_2 relates to the initial velocity v_1 in the following manner:

$$\frac{v_2}{v_1} = \frac{r_t^2 + k^2 - r_t\Delta h}{r_t^2 + k^2} \quad \textbf{(2)}$$

The position of the point of impact defines the distance Δh which describes the height a rolling particle has to overcome. In the case of circular cylinders, $k^2 = 0.5r^2$ and

$$\Delta h = \frac{2r_t}{(1+r_*)^2}$$

where $r_* = r_t/r_b$. The square-based pyramidal arrangement of spheres gives $k^2 = 0.4r_t^2$ and

$$\Delta h = \frac{2r_t}{(1+r_*)^2}\sqrt{\frac{(1+r_*)^2-1}{1+r_*}}$$

where

$$r_* > 0.414$$

The ratio of the grain kinetic energy after impact E_2 to the initial kinetic energy E_1 for cylinders and spheres becomes explicit function of $r_* = r_t/r_b$:

$$\frac{E_2}{E_1} = \left[1 - \frac{4}{3(1+r_*)^2}\right]^2 \quad \text{for cylinders} \quad \textbf{(3)}$$

$$\frac{E_2}{E_1} = \left[1 - \sqrt{\frac{(1+r_*)^2-1}{0.7(1+r_*)^3}}\right]^2 \quad \textbf{(4)}$$

for spheres when $r_* > 0.414$

These relationships plotted in Figure 1 show quite similar results for different types of particles and geometrical configurations. At a given bed particle size r_b, the fraction of grain kinetic energy lost through impact is considerably larger for particles finer than r_b ($r_t < r_b$) than for coarse particles ($r_t > r_b$). In a sediment mixture, the smaller particles lose a significant proportion of their kinetic energy through impact with stationary bed material while larger particles maintain a high level of grain kinetic energy. This corroborates the experiments of Steidtmann.[2] The kinetic energy of smaller particles is rapidly depleted through repeated impact with stationary bed particles, thus fine particles first deposit on the bed-surface and form a film of fine particles. Comparatively, coarse particles maintain an higher kinetic energy level and roll on top of the film of fines. Coarse particles eventually deposit on the film of fine particles. This is referred to as the particle segregation mechanism. The forthcoming analysis intends to demonstrate that the particle segregation mechanism finds important applications in the analysis of bedload motion of heterogeneous particles.

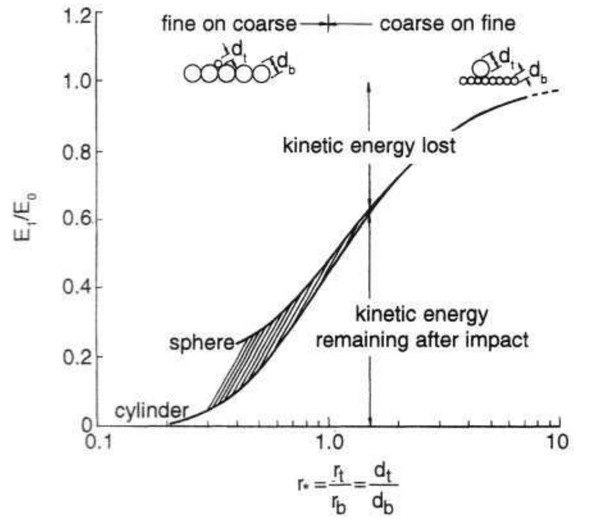

Figure 1. Kinetic energy of top particle d_t before, E_1 and after, E_2, impact with a bed particle d_b.

PARTICLE SEGREGATION EXPERIMENTS

For the experiments, an equal volume mixture of two sands is used: a white fine sand with median diameter d_{50} = 0.2 mm, a black coarse sand with median grain diameter d_{50} = 0.6 mm. The visual recognition of the stratification patterns during the experiments was greatly enhanced by the black/white contrast between coarse and fine sand particles.

Julien *et al.*,[3] observed that larger particles roll on top of smaller particles when a dry mixture is brought into lateral motion on a horizontal surface. Recent experiments indicate that particle segregation is also possible at very low rates of deformation near the angle of repose of the dry granular material. This is illustrated from the creeping motion of particles within an initially uniform mixture of coarse and fine sands in the upper part of a settling tube. As soon as the particles enter motion near the angle of repose particle segregation occurs with coarse sand particles

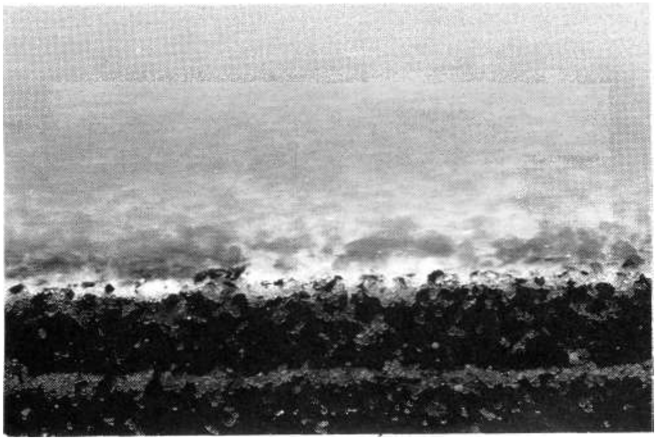

Figure 2. *Film of fine sands covering the bed surface.*

in black rolling on top of fine sand particles in white. It is important to consider that the forces applied on single particles are simply reduced to the constant gravitational force and the grain resistance leading energy losses through inter-particles impact.

In a subaqueous environment, the additional buoyancy, lift and drag forces contribute to particle motion. The results of particle segregation are well illustrated in Figure 2 through an enlarged view of sediment transport in the bed layer. Notice the film of fine sand particles in white that covers the bed and generates a smooth surface which enhances the transport of coarse sand particles in black.

LAMINATION EXPERIMENTS

A fundamental question about lamination can be stated as follows: can nature produce repetitive segregation under a continuous supply of sediment? Several settling tube experiments in air produced lamination.[4,5] During settling experiments in air, particles were supplied at a constant rate and avalanching was continuous.

Clear lamination (about 6-8 mm thick) was obtained in the laboratory. During the course of this experiment, the lenses of fine sands in white were observed[6] to get thicker as the mixture avalanched down the side slope at the angle of repose of the material, as expected from the particle segregation mechanism.

The laboratory flume experiment in Figure 2 shows aggradation in the upper-regime plane bed at a high rate of sediment transport. Under a continuous supply of coarse and fine sands in equal proportion, the submerged lamination experiments in a wide flume were filmed,[6,7] and sequences show the formation of a laminated deposit under plane bed conditions without any bedform. The sheet of moving particles in the bed layer is subjected to particle segregation where fine particles deplete their kinetic energy faster than coarse particles and deposit first, followed by coarse particles. The preferential alignment of fines formed lenses or laminae as the bed aggraded. It is inferred that the particle segregation mechanism is conducive to lamination under a continuous supply of sediment.

LARGE SCALE EXPERIMENTS

The final component of this investigation focuses on the role played by the particle segregation mechanism in forming fine lenses in stratified beds at thicknesses exceeding 1 cm, given a continuous supply of coarse and fine sand mixture under steady discharge conditions.

Large scale experiments detailed in Julien and Raslan[8] were carried out at the Hydraulics Laboratory of the Colorado State University Engineering Research Center. The laboratory flume measured 18 m long, 1.2 m wide and 0.6 m deep, and recirculated both water and sediment. Prior to all experiments, equal volumes of the coarse black (d_{50} = 0.6 mm) and fine white (d_{50} = 0.2 mm) sands totalling 2.7 m^3 were supplied to the mixing chamber filled with clean water. The flume bed slope was set prior to each experiment and held fixed.

Hydraulic conditions were initially set for upper-regime plane bed with sediment transport. From these steady-uniform flow conditions, backwater is induced by raising the tailwater elevation at the downstream end of the flume. The resulting steady non-uniform flow is identified as a M-l backwater curve typical of sedimentation areas behind reservoirs and estuaries. The reduced sediment transport capacity causes a deltaic accumulation of sediment propagating in the downstream direction. A stratified deposit clearly forms in which both the bottomset and the topset slopes are primarily composed of fine sands, while the foreset slope of the delta contains mostly coarse sands.

The aforementioned particle segregation mechanism is at the origin of the stratification structure in which a cross-laminated deposit of mostly coarse particles lies between two near-parallelled laminated deposits. Indeed, both the plane-bed topset and the bottom-set are characterised by laminated deposits of mostly fine sands at surface angles with the horizontal ranging from 0.625 per cent to 1.25 per cent. Coarse particles are observed to roll on a film of fine particles, as previously shown in Figure 2. The topset is slowly aggrading with preferential accumulation of fine particles on the plane-bed topset surface, to form fine lenses with reduced accumulation of coarse sands. Coarse sands avalanche down the foreset slope.

After draining the deposit over several days, a cross-section can be cut through the delta to examine the primary features of deposits of sand mixtures under steady flow and a continuous supply of a mixture of coarse and fine sands. The near-foreset cross-section shown on Figure 3 displays a clear superposition of strata of fine sands in white and coarse sands in black. The experimental fact, that clear stratification is possible under a continuous supply of a sediment mixture, can be explained by the particle segregation mechanism. Accordingly, several strata of

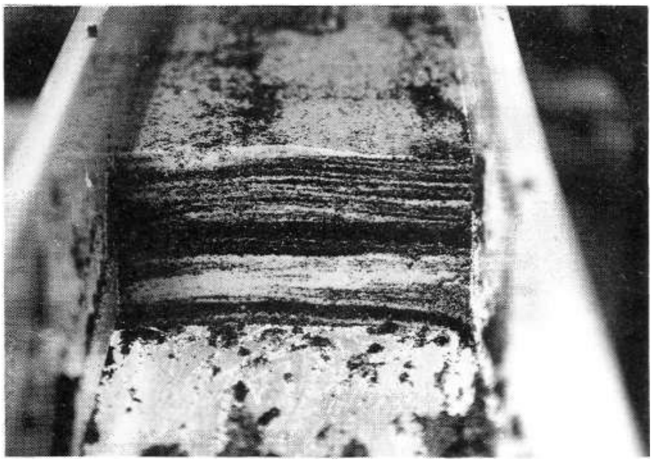

Figure 3. *Stratification from continuously mixed supply of coarse and fine sands.*

coarse and fine particles can form simultaneously at different locations.

SUMMARY AND CONCLUSIONS

This investigation proposes that bedload grain sorting depends on the particle segregation mechanism related to the kinetic energy of rolling bedload particles. The mechanics of particle segregation leading to Equations 3 and 4 demonstrates that smaller particles rolling on a bed of larger particles lose kinetic energy through impact and cover the surface. Conversely, larger particles maintain a high kinetic energy level when rolling on a surface of smaller particles. Smaller particles deposit in lenses prior to the coarser fractions of the mixture.

Large scale laboratory experiments demonstrate that large scale sediment stratification, at a scale exceeding 1 cm in thickness, is possible under steady flow discharge and a continuous supply of coarse and fine sands. Fine-grained lenses are systematically observed at the surface of stratified sediment deposits, precisely at the interface with the moving bed layer. The particle segregation mechanism is thus found to play a paramount role in the formation of thick stratified sediment deposits.

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Pierre Julien is an Associate Professor in the Department of Civil Engineering, and like **Yongqiang Lan** and **Y. Raslan** is on the staff of the Engineering Research Center, Colorado State University, Fort Collins, Colorado (USA).

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