CHAPTER EIGHTY NINE

FLOW RESISTANCE DUE TO INTENSE BEDLOAD TRANSPORT

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Introduction

When water flows over a stationary bed the fluid motion is retarded by both skin the friction and local pressure gradient forces related to the roughness of the bed. If the bed itself is composed of discreet movable grains, the boundary is less clearly defined and the dynamics poorly understood (see Gust and Southard, 1983). Owen (1964) proposed that saltating grains (grains which lift off the bed, move through the fluid, and fall back to the bed without colliding with other grains) have the effect of increasing the frictional resistance of the bottom.

At higher flow stages, Hanes and Bowen (1984) have suggested a model for bedload transport which is based upon the dynamics of collisional grain flows following Bagnold (1954, 1956). In such a collision dominated flow, it appears that the resistance of the bed to the overlying flow can be less than the resistance of a fixed bed to the same overlying flow. This result is consistent with the dynamics of rapid granular-fluid flows, as will be discussed below.

Drag relation for rapid granular-fluid flows

In a collision dominated granular-fluid flow the relation between the shear stress and the flow parameters for rectilinear shear flow is given by Bagnold (1954) as:

$$U_*^2 = C \frac{\rho_s}{\rho} (\lambda D)^2 (dU/dz)^2 \tag{1}$$

where $U_* = (\tau/\rho)^{1/2}$, D is the grain diameter, ρ is the fluid density, ρ_s is the grain density, and λ is the linear concentration. λ is related to the volume concentration N by:

$$\lambda = [(N_*/N)^{1/3} - 1]^{-1}, \tag{2}$$

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where N_* is the maximum possible concentration of the granular material. The relation (1) has been experimentally verified with differing materials and apparatus by Bagnold (1954), Savage and Sayed (1984), and Hanes and Inman (1984a).

Equation (1) appears similar in form to the analagous relation for a wall bounded turbulent shear flow as given by:

$$u_*^2 = (\kappa z)^2 (du/dz)^2 \tag{3}$$

where κ is von Kármáns coefficient and is approximately 0.4. We can define "resistance coefficients" for equations 1 and 3 as:

$$\varepsilon_g = C \frac{\rho_1}{\rho} D^2 \lambda^2 \tag{4a}$$

$$\varepsilon_t = \kappa^2 z^2 \tag{4b}$$

where the subscript g refers to granular-fluid and the subscript t refers to turbulent clear fluid. The ratio of these two terms is given by:

$$\varepsilon_g / \varepsilon_t = \frac{C \ \rho_s \ D^2 \ \lambda^2}{\rho \ \kappa^2 \ z^2} \tag{5}$$

Equation 5 represents the ratio of the stress in a granular-fluid layer of thickness z to the stress in a wall bounded turbulent shear flow at a distance z away from the wall, where both flows have the same shear rate at z. Using values of $C = 0.013$ (Bagnold, 1954), $\rho_s = 2.65\rho$, and $\kappa = 0.4$, equation 5 is shown in Figure 1 for differing values of λ. The natural limits on λ are 1 and 20. For $\lambda < 1$ the concentration is too low to apply a collisional model, and for $\lambda > 20$ the grains are so tightly packed the granular assembly takes on solid behavior. A typical value for λ is 5, corresponding to a volume concentration N of approximately 0.38. Clearly if z is greater than only a few grains diameters, the stress for the granular-fluid <u>less</u> than the stress for the turbulent fluid.

Observational evidence

There have been very few observations of flow resistance under conditions of intense bedload transport. The most comprehensive data set is Williams (1970). Williams varied the flume width and discharge independently. He was therefore able to evaluate and correct for side wall friction in estimating the bottom stress.

Williams data for flat bed conditions are shown in Figure 2, where $(u_*/\overline{u})^2$, representing a quadratic drag coefficient, has been plotted

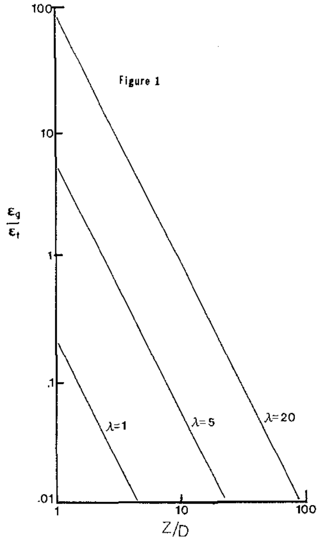

Figure 1: The ratio of granular-fluid flow resistance to clear turbulent fluid flow resistance indicates the granular-fluid has lower resistance for flows thicker than a few grain diameters over the range of possible concentrations.

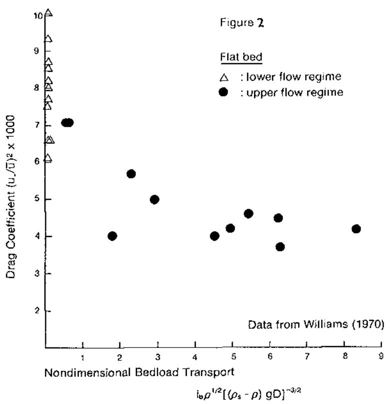

Figure 2: Drag coefficients from Williams (1970) data indicates lower flow resistance under high transport conditions. All data displayed are from flat bed experiments.

against nondimensional bedload transport. The lower flow regime occurs near the threshold for sediment motion, while the upper flow regime occurs at high flow stage after ripples disappear. The drag coefficients for the lower flow regime are clearly higher than those for the intense bedload upper flow regime. There appears to be a trend toward decreased resistance with increasing bedload transport.

Discussion

The largest uncertainty in this presentation is proof of the existance of the granular-fluid layer during intense bedload transport. If such a layer exists, it is not difficult to conceptualize the system as two fluiid layers, where the lower (granular-fluid) layer is less viscous than the upper (turbulent fluid) layer.

Observations of intense bedload are inherently difficult to make. Horikawa et. al.(1982) used photographic and electro-resistance wires to measure sediment concentration near the bed under large oscillatory flows. They found a thin layer (10 to 20 grain diameters thick) of highly concentrated grains undergoing rapid shear. These observations are strongly supportive of a thin granular-fluid layer.

Other evidence comes from the laboratory shear cell experiments of Hanes and Inman (1984b), who suggest a dynamic Coulomb yield criterion applies at the boundary between the stationary bed and the moving grains. Unless there is a downward normal stress to counteract the shear stress, stationary grains will be mobilized into the flow. As argued by Bagnold (1956), the normal stress must arise from the immersed weight of the grains in the granular-fluid layer.

The applicability of these concepts to situations involving waves is unclear. During the peak phase of velocity the stress may be high enough to cause a granular-fluid layer. Because the motion is oscillatory, though, the system must pass through a stage of zero shear stress at which time there would not be a granular-fluid layer. The flow resistance and energy dissipation related to the mobilization and formation of the granular-fluid layer are unknown. It is therefore uncertain whether the net energy dissipation under large waves on a movable bed will be greater or less than the energy dissipation resulting from the interaction of same waves with a fixed bed.

Conclusions

The effects of intense bedload transport are shown to decrease the resistance of the bed to the overlying fluid. This is because the grain-to-grain collisions dominate the dynamics in the granular-fluid layer, which acts somewhat like a boundary layer of less viscous fluid. The adaptation and extrapolation of Owens (1964) saltation model to intense bedload transport conditions will result in an overestimation of the drag coefficient.

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