Particle dynamics class, SMS 618, Emmanuel Boss (last edited on 11/18/2003)
Resuspension and bedload transport

Initiation of motion of a particle from the bed (resuspension):

Gravity, buoyancy and inter-particle van der Waals forces act on a particle on a bed when no motion is present. When there is flow, however, the interaction between the flow and the particle result in hydrodynamic forces (drag and lift) which have uneven distribution of shear stress and pressure along the particle's body. A net force and net torque (moment) result. If this force and moment exceeds the forces present when there is no flow, the particle will start moving.
The balance of forces is presented in Fig. 1 and the balance of moments in Fig. 2.

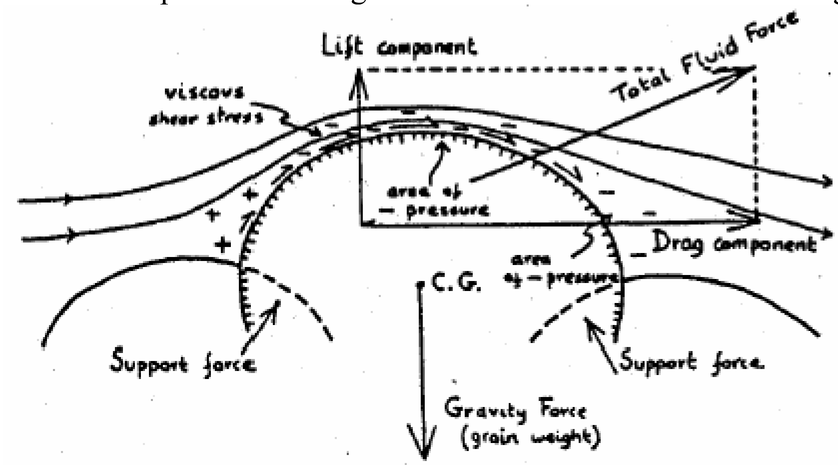

Figure 1. Distribution of forces, pressure and shear along a particle. Pressure force is maximal and of opposite sign at the front and back of the particle due to acceleration and deceleration of flow there. The pressure is minimal at the top of the particle, where velocity is maximal (Bernoulli), resulting in a net lift force. From: [*http://courses.washington.edu/hydclass/Cive474/Motion.pdf*](http://courses.washington.edu/hydclass/Cive474/Motion.pdf)

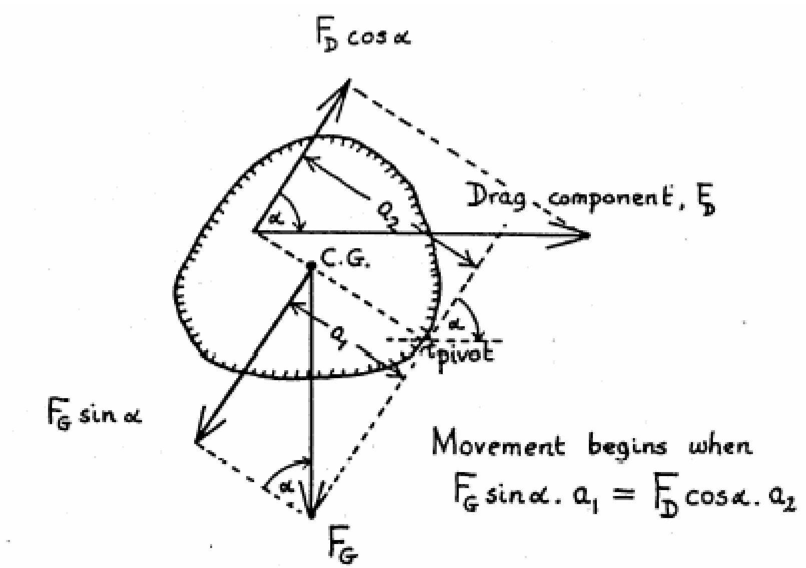

Figure 2. Torques (moments) acting on a particle in bed (lift is neglected). From: http://courses.washington.edu/hydclass/Cive474/Motion.pdf

A common way to represent the minimum shear needed to move particles is to plot laboratory data of the nondimensionalized bottom shear stress ($\tau_0/gD(\rho_p-\rho_f)$) as function bottom Reynold's number ($Re_*=u_*D/\nu= (\tau_0/\rho)^{1/2}D/\nu$), Fig. 3 and 4.
This representation assumes the presence of a viscous layer. Note that both axis are not independent (though it is not a big deal, since if we have an equation for the relation, we can find τ_0 explicitly as function of D, ($\rho_p-\rho_f$), ρ, and ν.

A fit to the laboratory data is (Guo, 2002) give a relation between the critical stress and the characteristics of the particles (see Fig 3 and 4):

$$\frac{\tau_c}{gD(\rho_p-\rho_f)}=\frac{0.1}{\mathrm{Re}_*^{2/3}}+0.054\left[1-\exp\left(-\frac{\mathrm{Re}_*^{0.52}}{10}\right)\right]$$

and

$$\frac{\tau_c}{gD(\rho_p-\rho_f)}=\frac{0.1}{D_*}+0.054\left[1-\exp\left(-\frac{D_*^{0.85}}{23}\right)\right], D_*\equiv D\left(\frac{gD(\rho_p-\rho_f)}{\nu^2}\right)^{2/3}.$$

Note the increase in shear needed to suspend small particles and clays. This is due to the presence of inter-particle cohesion forces in the bed.
A problem with the Shields approach is that it is typically based on laboratory experiments with a single grain present. Mixed grains beds *armor* themselves, such that the flow will move sediment according to the shear stress of the larges material within the flow.

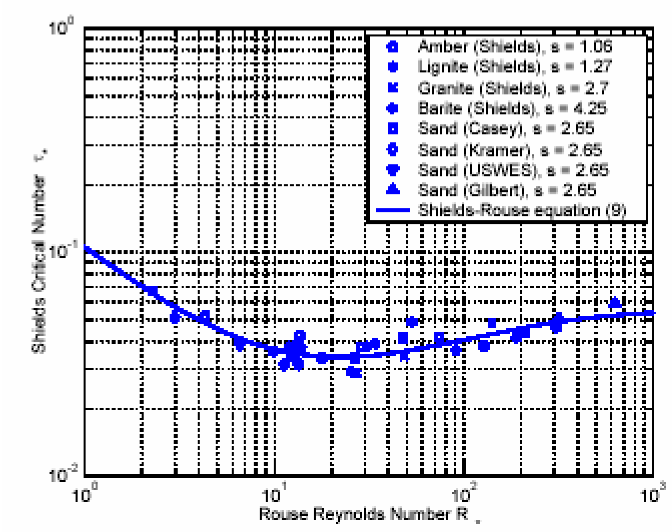

Figure 3. A Shields diagram, representing the nondimensional shear needed to suspend particles as function of the bottom Reynolds number. From: Guo (2002) see: http://courses.nus.edu.sg/course/cveguoj/ce5309/papers/Junke%20Guo-Rouse.pdf

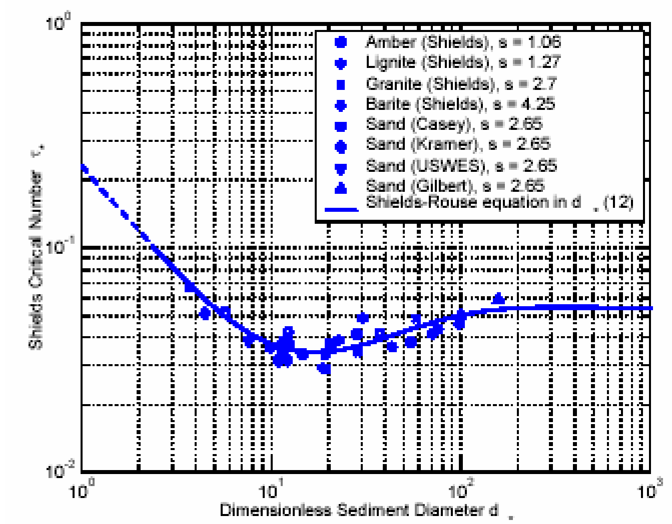

Figure 4. A Shields diagram, representing the nondimensional shear needed to suspend particles as function of the dimensionless sediment diameter. From: Guo (2002) see: http://courses.nus.edu.sg/course/cveguoj/ce5309/papers/Junke%20Guo-Rouse.pdf

For small particles such as clay, sediment concentration (porosity), degree of flocculation and degree of consolidation are all crucial to determine the critical shear stress.

From the above it is obvious that it is not straightforward to know, a-priori, *how many* particles will get entrained given a specific flow. In the field, measurements close to the bed are used to model the entrainment of particles into the water column.

Bedload transport:

For particles for which $R=w_s/ku_*>1$ but $\tau_0> \tau_{critical}$ the dominant mode of transport is roling saltation (Fig. 5). Suspension requires $R=w_s/ku_*<1$, as discussed in the previous lecture.

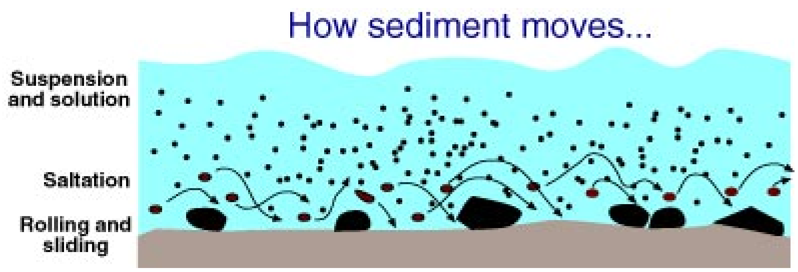

Figure 5. Modes of motion of single particles. Figure from: http://www.usask.ca/geology/classes/geol243/243notes/243week3b.html

There are many formulations for bedload transport (Q). One of the most common: $Q\propto(\tau_0-\tau_c)^b$ for $\tau_0-\tau_c>0$. The proportionality constant and b are determined empirically.

Two hypothesis have been put forward explaining the relationship of bed sediment and moving sediment:

Selective transport hypothesis (Komar): this hypothesis states that finer sediment is winnowed away from the bed due to increased mobility (though some hiding occurs). A pavement of large particles exists on the bedin high flows due to resuspension of finer material.

The equal mobility hypothesis (Parker and co.): this hypothesis states that the bed adjust under shear until there is enough coarse material at the surface to ensure that it is as mobile as the finer particles. This occurs through the 'paving' by the coarser sediment burying the finer sediments below as it roles along the bed. Bedload transport under this hypothesis is easy to model since size details are not necessary.

The two hypotheses are not mutually exclusive; selective transport is likely to occur in transient condition eventually leading to equal mobility if conditions stay put for a long time.

Gravity-driven sediment transport:
When sediment is entrained into water, horizontal pressure gradient (due to lateral weight differences) can cause the heavy fluid to flow. Combined with a bottom slope, a gravity current can form (often referred to as turbidity currents). Since it involves only the lower portion of the water column, such flows have seldom been observed in the field, though evidence for their existence abound, and they have been generated in the lab. Such gravity currents have large impact both in terms of sediment transport as well as the implication on the boundary condition for sediment and flow above the bed.

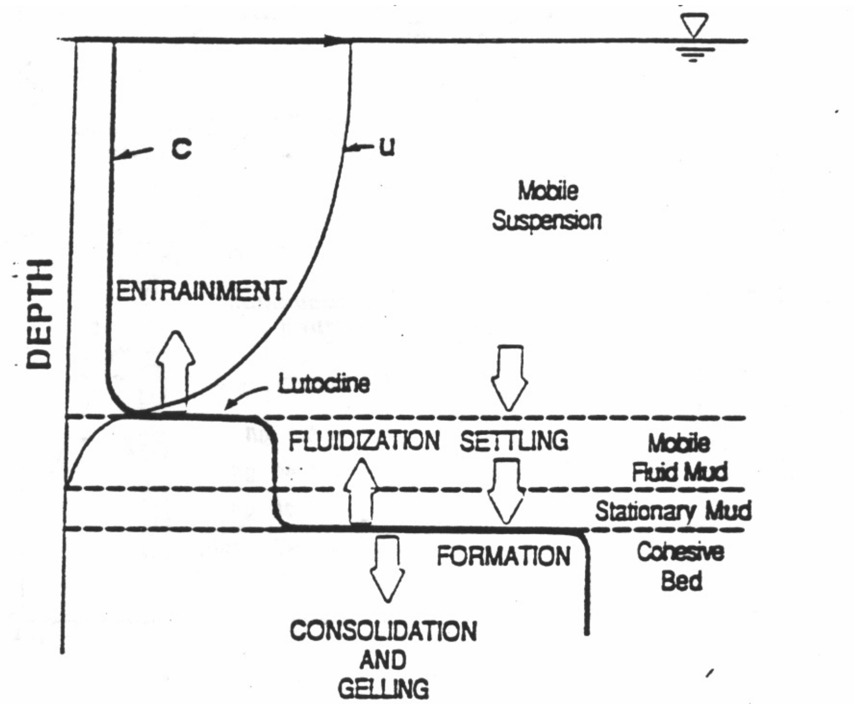

Figure 5. Schematic of particle and velocity distribution above a bed with a suspension of fluidized mud. From: http://www.ocean.washington.edu/people/faculty/parsons/OCEAN542/entrain-lect.htm

L. D. Wright and C. T. Friedrichs (VIMS) have recently provided a theory that not only explains how riverine deposits can be transported down the shelf slope but also link that process to the overall shape of the continental slope as result from wave mediated sediment suspension. The summary of their theory is as follows:

Assume a heavy sediment laden layer of height h, on a bed of slope θ experiences a gravitational force per unit area (or pressure) at its base:

$$P=g(1-\rho_w/\rho_s)C\ h\ \sin\theta,$$

where C is the averaged sediment concentration in the heavy layer, ρ_s the sediment density, and ρ_w the fluids' density.
Assuming this layer to flow down hill at a constant speed, it will be balanced by a frictional stress:

$$\tau=\rho C_D|u|u_g$$

where C_D is the bottom drag coefficient (~0.0025-0.005). |u| is the rms of all velocities present (wave, gravity current and water), while u_g is the gravity current's speed.
Equating the last two equation (e.g. when the gravity current propagate at a constant speed) we can solve for |u|.
The Richardson number for the wave boundary layer is (see appendix):

$$Ri= (g(1-\rho_w/\rho_s)Ch)/\rho|u|^2.$$

When Ri<Ric=0.25, turbulence suspends additional sediment increasing C and Ri. When Ri>0.25, decrease in shear instability cause sediment to settle, increasing stratification and thus decreasing Ri. Thus as long as there is a constant supply of easily suspended

material we could expect $Ri \sim Ric=0.25$. Given this constrain both u_g and C can be predicted and the bed transport (u_g*C).
Another consequence is that gravity flows depends on wave support for existence only when $\sin\theta<C_D/Ric$ ($C_D/Ric \sim 0.01$-0.02, the conditions on most shelves). When $\sin\theta>C_D/Ric$ the bed is sufficiently steep for critically stratified gravity flows to auto-suspend as they accelerate down slope.
Assuming an equilibrium between sediment flux from rivers and bedload they derive an equilibrium shelf profile for the transfer of sediment by wave forced bedload transport and find it to correlate well with observed morphologies near many river mouths (see: Friedrichs and Wright, 2003, Gravity driven sediment transport on the contitntal shelf: implication for equilibrium profiles near rive mouths, accepted to Coastal Engineering).

Appendix I: Richardson number
The presence of stratification tends to stabilize a fluid, damping turbulence. Shear, on the other hand, tends to provide energy to mix the fluid (thus raising its center of gravity). The relative magnitude of the two competing forces is measured by the Richardson number:

$$R_f=\{g<w'\rho'>/<\rho>\}/\{<u'w'>d<u>/dz\}$$

R_f is hard to measure and is often estimated using a *gradient* Richardson number is substituted (this is done by equating the Reynolds' fluxes with the eddy diffusion times the mean gradient and assuming the same eddy coefficient for both momentum and density):

$$Ri=\{gd<\rho>/dz/<\rho>\}/\{d<u>/dz\}^2.$$

When $Ri>0$ stratificcation is stable. When Ri is large, turbulence is damped and the flow is laminar. The transition to turbulence (and thus mixing across isopycnal) occurs near $Ri=0.25$.

Appendix II: Order of movies to accompany the class.
From: CD-R of INTRODUCTION TO SEDIMENT PROCESS VIDEOS (v.1.0, March 2001) by Paul L. Heller, Yvette Widman, Andrew M. Bryson, Department of Geology & Geophysics, University of Wyoming (NSF supported project).

Bedloads: Bedload transport: bdld. Roling and saltation of sand and gravel.

Sand Sheet: Sand sheet: sheet. Coherent motion of sand.

Rivers Colorado river bars: colors. Migration of underwater dunes.

Turb: Low density Turb: Fill and Spill Turbs: turbrwg: Fluidized fine material in motion. Notice how the stratified fluid does not mix with the overlying waters.

Turb: Subaq DF confined:pdfst6: extreme behavior of visco elastic turbidity flow.