Vermont Stream Geomorphic Assessment

Appendix O

Particle Entrainment and Transport

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Particle Entrainment and Transport

Introduction

What follows is an introduction to basic concepts associated with measurement and prediction of entrainment and transport of bed material in natural rivers. The purpose of this discussion is to familiarize the reader with methods for predicting particle entrainment and their limitations. This discussion does not represent the full breadth of study and research on this subject matter. Rather it introduces core principles and gives background on methods of entrainment prediction most commonly used by river management practitioners.

The Importance of Bedload Transport: Understanding characteristics of sediment transport benefits many applications including prediction of the effects of land use or flow regime change and channel restoration efforts (Wilcock, 2001). The relationship between discharge and bedload transport rate through a reach and the ability of the existing channel to transport the bedload (sediment transport capacity) is critical to the establishment of river equilibrium in river corridor protection and restoration efforts. Measuring the size and quantity of bedload particles moving through a reach at different discharges and developing a sediment rating curve is the ideal predictive tool for project design. Once the conditions required for bedload transport are known they can be translated into an understanding of the channel dimension, pattern, and profile that will result in sufficient transport of the expected sediment supply.

Measuring Bedload Transport: Unfortunately, bedload transport is not simple to measure or predict. It is a sporadic process that occurs through a variety of mechanisms. Its variability both spatially and temporally add to the difficulty. Bedload measurement is particularly challenging for river managers to conduct due to its high cost and the length of time over which it takes to accurately complete. Additionally, sampling devices placed in the flow may perturb local hydraulics sufficiently to create anomalously high or low transport conditions (Wohl, 2000). Despite these difficulties, efforts to understand bed-load transport and its relation to flow discharge are worthwhile and can lead to better assessment and project design.

Sediment Entrainment Calculation

In lieu of creating sediment rating curves on a project by project basis, practitioners have had fairly good results using empirically derived equations for the prediction of the conditions necessary to entrain bed particles and designing channels to produce those conditions. While the first efforts in this area resulted in equations that were accurate only when applied to channels with homogeneous bed sediments, more recent efforts have resulted in equations that are applicable to natural rivers.

The parameter often used as a measure of the stream's ability to entrain bed material is the shear stress created by the flow acting on the bed material. Shear stress acts in the direction of the flow as it slides along the channel bed and banks. Critical shear stress is the shear stress required to mobilize sediments delivered to the channel. When the shear stress equals the critical shear stress, the channel will likely be in equilibrium. Where shear stress is excessively greater than critical shear stress, channel degradation will likely result. Where the shear stress is less than critical shear stress, channel aggradation will likely result. Thus the ability to calculate or measure both shear and critical shear stress is crucial in understanding channel adjustments.

Calculating Shear Stress: Unfortunately, attempts to calculate or measure shear stress values in mountain rivers are complicated by the channel bed roughness and the associated turbulence and velocity fluctuations (Wohl, 2000). Turbulence can lead to substantial variability in velocity and shear stress at a point during constant discharge. Heterogeneities caused by grains and bedforms may create substantial velocity and shear stress variations across the channel or downstream during a constant discharge. Despite these issues measurement of the general shear stress in a reach is feasible and useful.

Based upon the physical properties involved, the following theoretical equation for general shear stress has been developed.

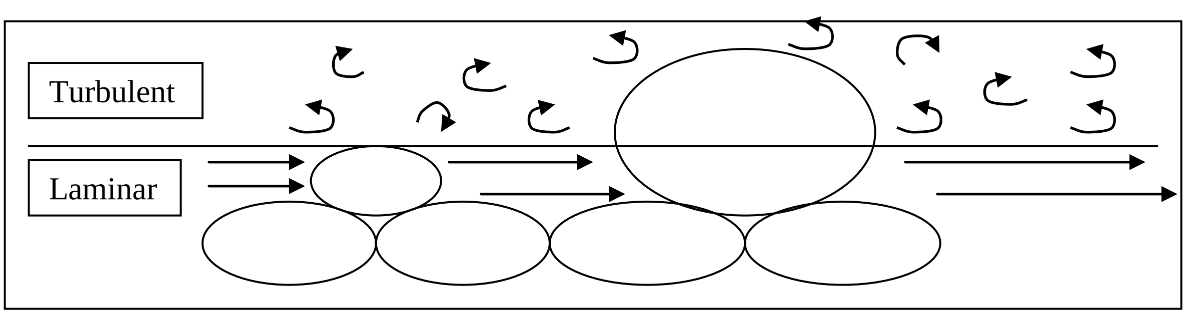
$$\tau = \gamma R s \text{ (lbs./sq.ft.)},$$

where τ is the fluid shear stress
γ is the specific gravity of water
(density x gravitational acceleration)
(1.94 slugs x 32.2 ft/sq.sec) = 62.4 lbs./sq.ft.
R is the hydraulic radius (approximately mean depth)
s is the slope of the channel

The Physical Properties Involved
Initiation of motion involves mass, force, friction and stress. Gravity and friction are the two primary forces in play as water flows through a channel. Gravity acts upon water to move it down slope. Friction exerted on the water by the bed and banks of the channel works to slow the movement of the water. When the force of gravity is equal and opposite to the force of friction the water flows through the channel at a constant velocity. When the force of gravity is greater than the force of friction the water accelerates (Leopold et.al., 1964).

Shear Stress vs. a Particle Resistance to Movement: A given particle will move only when the shear stress acting on it is greater than the resistance of the particle to movement. The magnitude of shear stress required to move a given particle is known as the critical shear stress (τ_{cr}). The resistance of the particles to movement and thus its entrainment will vary depending on its size, its size relative to surrounding particles, how it is oriented and the degree to which it is embedded. The size of the particle will influence the weight of the particle. The size of the particles relative to surrounding particles will affect the amount of shear stress the particle is exposed to via the "hiding" factor. Orientation of the particle will affect the force required to roll the particle along the bed. Packing or embeddedness will affect the amount of shear stress that the particle is exposed to.

Because of turbulence the hiding affect may be the primary factor in determining critical shear stress. Turbulence can result in shear stress spikes that are four times greater than the average shear stress. Thus a particle exposed to turbulence will experience greater fluid force than a particle not exposed to the turbulence. There is a layer of water just above the stream bed that is not turbulent. The thickness of this layer is sufficient to cover the average particle size of the bed. A larger particle however, will extend above this zone of non-turbulent flow and be exposed to turbulent flow. Thus, a particle surrounded by smaller particles will experience turbulence while a particle that is the same size as the average bed size will experience only non-turbulent flow and thus be exposed to less fluid shear stress. Accurate estimations of critical shear stress requires accurate characterization of these parameters (Wohl, 2000).



Calculating Critical Shear Stress: With the above principles in mind, Shields in 1936 conducted flume experiments to develop an expression for the critical shear stress to move a particle of a given size (Knighton, 1998). His work resulted in the following equation:

$$\tau_{cr} = \tau_{ci} \times g(\rho_s - \rho_w)d$$

where;

τ_{cr} is critical shear stress,

τ_{ci} is dimensionless critical shear stress,

g is acceleration due to gravity,

ρ_s is the density of sediment,

ρ_{ws} is the density of water; and

d is the size of the particle of interest.

Shields' studies showed that in gravel bed channels of homogeneous sediment sizes and turbulent flow the value of dimensionless critical shear stress is 0.06. Shields' still serves as a basis for defining critical shear stress (Fischenich, 2001). However, since Sheilds' work other researchers have developed derivations of Shields' equation in an effort to improve the prediction of critical shear in natural channels with heterogeneous substrate sizes.

Fischenich, (2001) lists the following equations presented by Julien to approximate the critical shear stress for particles of various sizes.

$$\tau_{cr} = 0.5 \times g(\rho_s - \rho_w)d \times Tan\phi \qquad \text{:For clays}$$
$$\tau_{cr} = 0.25 d_*^{-0.6} \times g(\rho_s - \rho_w)d \times Tan\phi \qquad \text{:For silts and sands}$$
$$\tau_{cr} = 0.06 \times g(\rho_s - \rho_w)d \times Tan\phi \qquad \text{:For gravels and cobbles}$$

Where;

$$d_* = d\left[\frac{(G-1)g}{v^2}\right]^{1/3}$$

ϕ is the angle of repose of the particle

G is the specific gravity of sediment

g is acceleration due to gravity,

ρ_s is the density of sediment,

ρ_{ws} is the density of water

v is the kinematic velocity; and

d is the size of the particle of interest.

Angles of repose are given in Table 1 (Julien, 1995). Critical shear stresses are also provided in Table 1. It is important to realize that mixtures of sediments behave differently than uniform sediments. Particles larger than the median will be entrained at shear stresses lower than those given in Table 1 and, conversely, larger shear stresses than those listed in the table are required to entrain particles smaller than the median size (Fischenich, 2001).

Table 1 Limiting Shear Stress and Velocity For Uniform Noncohesive Sediments

Class name	d_s (in)	ϕ (deg)	τ_c	τ_{cr} (lb/sf)	V_{*c} (ft/s)
Boulder					
Very large	>80	42	0.054	37.4	4.36
Large	>40	42	0.054	18.7	3.08
Medium	>20	42	0.054	9.3	2.20
Small	>10	42	0.054	4.7	1.54
Cobble					
Large	>5	42	0.054	2.3	1.08
Small	>2.5	41	0.052	1.1	0.75
Gravel					
Very coarse	>1.3	40	0.050	0.54	0.52
Coarse	>0.6	38	0.047	0.25	0.36
Medium	>0.3	36	0.044	0.12	0.24
Fine	>0.16	35	0.042	0.06	0.17
Very fine	>0.08	33	0.039	0.03	0.12
Sands					
Very coarse	>0.04	32	0.029	0.01	0.070
Coarse	>0.02	31	0.033	0.006	0.055
Medium	>0.01	30	0.048	0.004	0.045
Fine	>0.005	30	0.072	0.003	0.040
Very fine	>0.003	30	0.109	0.002	0.035
Silts					
Coarse	>0.002	30	0.165	0.001	0.030
Medium	>0.001	30	0.25	0.001	0.025

Since Shields conducted his work further research has shown that τ_{ci} can range from 0.25-0.02 depending upon the size distribution of the bed particles. Andrews (1984) showed that τ_{ci} can be calculated using the following equation:

$$\tau*_{ci} = 0.0834\left(\frac{d_i}{d_{s_{50}}}\right)^{-0.872}$$

where;

d_i is the particle size of interest

$d_{S_{50}}$ is the median particle size of the sub-surface

Andrews equation can be used to calculate $\tau*_{ci}$ which can then be used in the Shields equation to determine the critical shear stress required to move a particle of a given size in gravel-cobble bed streams. As discussed in Step 2.7 of the Phase 3 handbook, d_i and $d_{S_{50}}$ can be determined through field sampling.

Cautions and the use of Multiple Methodologies

It is important to remember that the equations presented above, while used widely, are not used exclusively. The predictive tools presented here are understood to be general in nature and may not be appropriate for all situations. As stated above there are many variables associated with measurement or calculation of shear stress, critical shear stress and bed-load transport. Despite the uncertainties, the weighing of river management alternatives will benefit from attempts to develop as accurate an understanding as possible. Otherwise, assessment, river corridor protection, and restoration efforts are less likely to meet established goals. Careful use of prediction and application methods and an understanding of the limitations of those methods, will greatly improve project outcomes and helps explain the variables and uncertainties that are inherent in river assessment and management work. Following these guidelines will increase the likelihood of success.

- **Increase your own expertise by reviewing the literature**. Below is a list references that pertain to the subject of sediment transport processes. A review of this literature will greatly increase your understanding of the methods for analyzing sediment transport processes and associated limitations.
- **Employ multiple methodologies and seek convergence.** Methods for calculation and measurement of shear stress and critical shear stress are described above. This is by no means a complete list: nor are the individual methods in the list preferred by the River management Program. Use as many various analyses as possible given particular circumstances and evaluate the results on how well they agree with other data pertaining to the project or assessment.

References

1. Andrews, E.D., Entrainment of Gravel From Naturally Sorted Riverbed Material. Geological Society of America Bulletin, v.94, p. 1225-1231, October 1983.

2. Knighton, D., Fluvial Forms and Processes A New Perspective. 1998. Oxford University Press Inc. New York.

3. Fischenich. 2001. Stability Thresholds for Stream Restoration Materials. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-29), U.S. Army Engineer Research and Development Center, Vicksburg, M.S. www.wes.army.mil/e/emrrp

4. Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial Processes in Geomorphology. W.H. Freeman and Co. San Fransisco.

5. Wohl, E. 2000. Mountain Rivers. American Geophysical Union. Washington, D.C.

6. Wilcock, P.R. Toward a Practical Method For Estimating Sediment Transport Rates in Gravel Bed Rivers. Earth Surface Processes and Landforms, v.26, p. 1395-1408, September 2001.