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Citation: Yang, Judy, Hayoon Chung, and Heidi Nepf. "The Incipient Motion of Sediment in a Channel with Model Emergent Vegetation." River Flow 2016: Proceedings of the International Conference on Fluvial Hydraulics, 11-24 July, 2016, St. Louis, Missouri, CRC Press, 2016.

As Published: <http://dx.doi.org/10.1201/9781315644479-148>

Persistent URL: <http://hdl.handle.net/1721.1/119634>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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Incipient motion of sediment in a channel with model emergent vegetation

Judy Q. Yang, Hayoon Chung, Heidi Nepf

Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States of America

ABSTRACT: In a bare channel (without vegetation), the incipient velocity for sediment motion, U_{crit} , has historically been related to the mean bed shear stress ($\bar{\tau}$) or friction velocity ($U_* = \sqrt{\bar{\tau}/\rho}$). More recent studies, however, suggest turbulence also plays a role. This paper examines whether the onset of sediment motion in a vegetated channel is correlated with U_* , or turbulence (k_t). Images collected with a digital camera were interrogated with a particle-tracking code to measure sediment transport for different vegetation density and channel velocity. The trend in sediment transport with channel velocity was used to identify U_{crit} for each stem density. The values of k_t and U_* were estimated at U_{crit} . However, none of these parameters produced a constant threshold across all stem density and bare bed. We construct a new metric representing the peak turbulent velocities impinging on the bed that produces a constant threshold value for all cases.

1 INTRODUCTION

As reported by the Environmental Protection Agency (EPA, 2009), 15% of the rivers and streams in the U.S. contain excess levels of sediment, which can smother the habitat of aquatic organisms. The transport of contaminated sediment also poses a threat to aquatic life and humans (EPA, 2000). Vegetation, with its ability to retain more sediment than bare beds, has been widely used in river restoration (Bennett, 2008). However, the physical process controlling the retention of sediment within vegetated regions is not fully understood. The present study focuses on quantifying the incipient conditions for sediment transport in a vegetated regions.

In a bare channel without vegetation the critical velocity defining incipient sediment motion, U_{crit} , has typically been related to the time-mean bed shear stress ($\bar{\tau}$) or friction velocity ($U_* = \sqrt{\bar{\tau}/\rho}$). However, more recent studies with synchronized measurements of instantaneous velocity and sediment motion suggest that turbulence also plays a role in initiating sediment motion. For example, in the field, the acoustic signal generated by the sediment motion was found to correlate better with the instantaneous velocity (u and w), than with the instantaneous bed shear stress $\tau = -uw$ (Heathershaw et al. 1985). Further, laboratory experiments with obstacles generating additional turbulence also relate the incipient motion with the instantaneous velocity, rather than the mean velocity (Nelson et al. 1995, Diplas et al 2008). In other words, the turbulence kinetic energy k_t , which indicates the strength of the velocity fluctuation, plays a role in determining U_{crit} .

In this study, we conducted flume experiments in a channel to determine the critical velocity for incipient motion for a bare bed and within model emergent vegetation. Unlike in a bare channel, for which the turbulence is generated at the bed, in a vegetated channel the turbulence is predominantly generated by the vegetation (Tanino et. al 2008). As a result, k_t does not scale with $\bar{\tau}$. With $\bar{\tau}$ and k_t decoupled in a vegetated channel, their influence on U_{crit} can be studied separately.

2 METHODS

To create the model emergent vegetation, rigid circular cylinders with diameter $d = 6.3\text{mm}$ were fixed onto PVC boards. The frontal area per unit volume (a) of the model vegetation ranged from 1m^{-1} to 10m^{-1} , similar to conditions found in marshes. One layer of sieved brown sand with a particle size range of $d_s = 600$ to $850\mu\text{m}$ was glued to the PVC board. The boards were placed in a water-recirculating flume with a 1m wide and 10m long test section. The water depth was controlled to be 20 to 22cm. The total length of each board in the streamwise direction was 1.2m. A digital camera was placed approximately 1m from the leading edge of the board to observe the sand motion (Figure 1).

A layer of black sand with the same size distribution as the brown sand was spread on top of the brown sand. The motion of the black sand was recorded at 60 frames per second with the digital camera positioned above the channel and looking down at the sand bed (Figure 1).

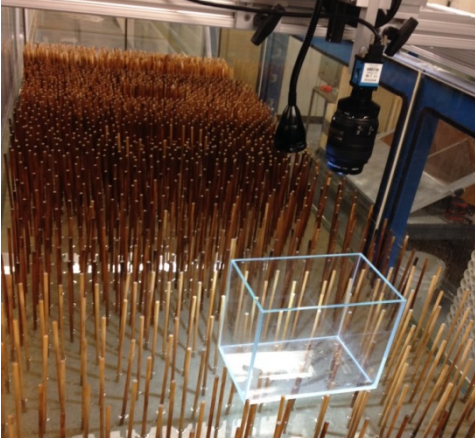


Figure 1. Experimental set up. Vertical circular cylinders represent emergent stems of vegetation. The glass tank was put on top of the wood dowels to eliminate the distortion of the image due to water surface movement. The digital camera, with polarizing lens, can be seen above the channel. One layer of brown sand was glued to the PVC board where the dowels were fixed.

The following steps were used to estimate the sand transport rate. First, the percentage of the pixels occupied by black sand grains was defined as the black sand occupancy, P_{blk} . Second, the trajectory of each black grain (Figure 2) was identified using IDL particle tracking MatLab code written by Crocker and Weeks (1996). Third, the average streamwise velocity of the black sand grains (U_p) and the volume of particles in motion per unit bed area (γ) was calculated from the trajectories. These parameters were averaged over 1800 frames, which was equivalent to 30 seconds. The black sand transport rate was then calculated as $Q_{\text{blk}} = U_p \gamma$ (Wong et al. 2007, Furbish et al. 2012). Assuming sand motion only occurs on the top layer (Houssais 2015) and all the sand motion follows the same probability distribution, the total sediment transport rate Q_s can be estimated as $Q_s = Q_{\text{blk}}/P_{\text{blk}}$.

To account for the error contributed by the impurities in the water, a reference video with no black sand was recorded for each trial. The sediment transport rate in this reference video, $Q_{s,\text{ref}}$, was used as an estimate of uncertainty in the method associated with the impurities in the water. In addition, heterogeneity in the system was evaluated by doing replicate measurements at each flow condition and stem density, with the difference in Q_s between replicate counted as the uncertainty associated with system heterogeneity. At low flow rate, $Q_{s,\text{ref}}$ was the larger uncertainty, i.e. $Q_{\text{error}} = Q_{s,\text{ref}}$. The upper limit of $Q_{s,\text{ref}}$ for all cases is $0.01 \text{ mm}^2/\text{s}$. This value was chosen as the threshold criterion for sediment motion, $Q_{s,\text{crit}} = 0.01 \text{ mm}^2/\text{s}$. At high flow rate, the variability in Q_s was the larger contribu-

tion to the error, such that Q_{error} was equal to the difference between replicates (see Figure 3).

For each stem density and over bare bed the sediment transport rate, Q_s , was measured at several channel flow rates, Q . The average channel velocity was then estimated as $U = \frac{Q}{A(1-\phi)}$ where A denotes the cross-sectional area of the flume and ϕ denotes the solid volume fraction of the vegetation.

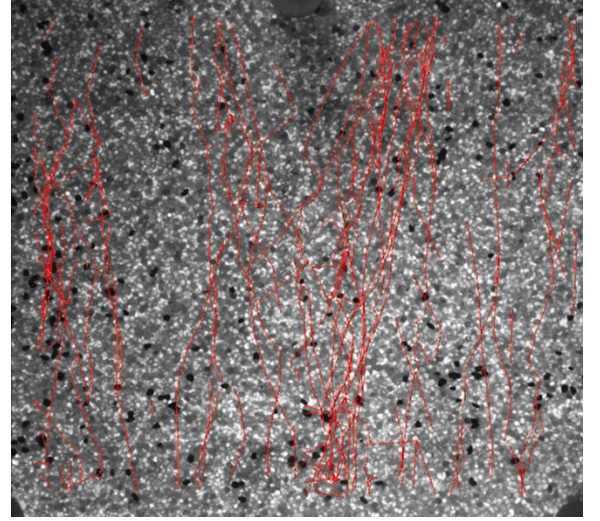


Figure 2. View of the camera. Black sand was sprinkled as tracer particles on top of the board with glued brown sand. The trajectories (red lines) of the tracer black sand were identified using IDL particle tracking method.

The bed shear velocity (U_*) and turbulent kinetic energy ($\sqrt{k_t}$) were estimated from the mean channel velocity U , using the following methods. In a bare channel with water depth (h) to sand size ratio $h/d_s \gg 1$, U_* can be found from the Darcy-Weisbach friction relation (Julien 2010):

$$\frac{U_*}{U} = \sqrt{C_f} = \frac{1}{5.75 \log \left(\frac{4h}{d_{90}} \right)} \quad (1)$$

Here C_f is the bed drag coefficient, and d_{90} is the grain diameter below which 90% of the sand grains fall. Assuming that sand is uniformly distributed over the range of $d_s = 600$ to $850 \mu\text{m}$, $d_{90} = 825 \mu\text{m}$ in our experiments.

In an emergent canopy simulated by cylinders, if vegetation density $a > 0.5 \text{ m}^{-1}$, U_* can be estimated from the following equation (Yang & Nepf, 2015):

$$U_* = \max \left(\sqrt{C_f} U, 2 \sqrt{\frac{\nu U}{d}} \right) \quad (2)$$

For an emergent canopy with cylinder diameter d much smaller than the spacing between the vegetation, the turbulence kinetic energy $k_t (= \overline{u'^2} + \overline{w'^2} + \overline{v'^2})/2$ with u' , w' , v' denoting the velocity

fluctuations) can be estimated from the energy balance (Tanino 2008):

$$\frac{\sqrt{k_t}}{U} = [C_D \frac{\phi}{(1-\phi)\pi/2}]^{1/3} \quad (3)$$

Here C_D is the vegetation drag coefficient, which can be estimated by

$$C_D = 2[(0.46 \pm 0.11) + (3.8 \pm 0.5)\phi] \quad (4)$$

For the bare bed case, k_t was measured by Acoustic Doppler Velocimetry at 1cm above the bed.

3 RESULTS

The sediment transport rate Q_s as a function of U is shown in Figure 3 for the bare bed case ($a = 0 \text{ m}^{-1}$). The critical velocity for sediment transport, U_{crit} , and its error were estimated from the two points closest to the $Q_s = Q_{s,crit}$ line (red line shown in figure 3). For the case shown in Figure 3, $U_{crit} = 0.22 \pm 0.01 \text{ m/s}$.

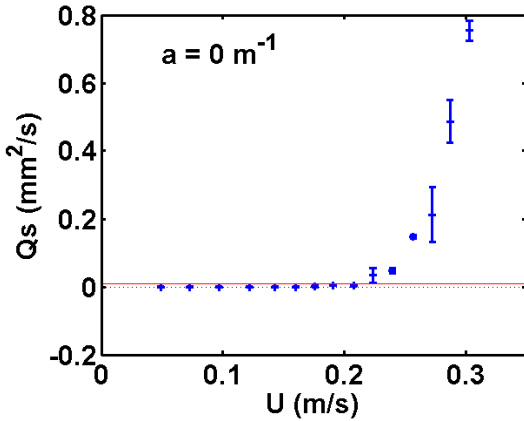


Figure 3. Sediment transport rate, Q_s , versus channel velocity, U , for the bare bed case. The red line denotes the critical sediment transport rate, $Q_{s,crit} = 0.01 \text{ mm}^2/\text{s}$, that defines the onset of sediment motion. That is, the sediment transport rate which is distinct from zero, within uncertainty.

The incipient velocity (U_{crit}) identified for five vegetation densities together with the data from a previous study using similar vegetation and grain sizes (Hongwu et al. 2013) are shown in figure 4. Although the U_{crit} values from the present study are a bit smaller than the values from Hongwu et al. (2013), they agree within uncertainty. Both studies indicate that the critical velocity declines with increasing canopy density, with the sharpest decline occurring at lowest array density, i.e. between the bare bed and the lowest array density.

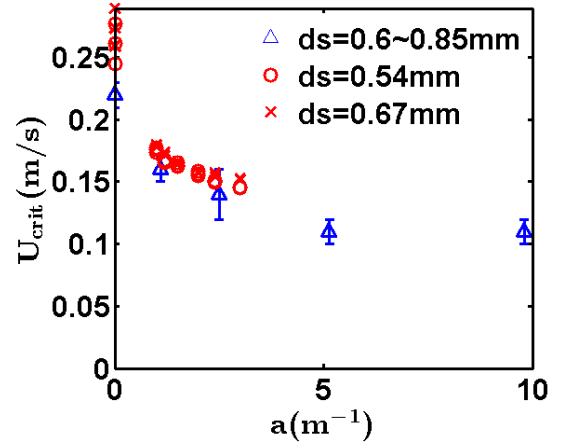


Figure 4. The critical velocity for sediment motion, U_{crit} , versus vegetation density, a . The blue triangles are from the present study. The red symbols are from Hongwu et al. 2013.

Most previous studies suggest that for the same type of sand, the initiation of sediment motion occurs when U or U_* reaches a critical and constant value, U_{crit} or U_{*c} (Yalin, 2013). Our results, however, show that neither U_{crit} nor U_{*c} is a constant (Figures 4 and 5). Instead both U_{crit} and U_{*c} decreases with vegetation density, a . Field measurements from Widdow et al. (2008) also suggest a decreasing U_{crit} and U_{*c} with increasing vegetation density.

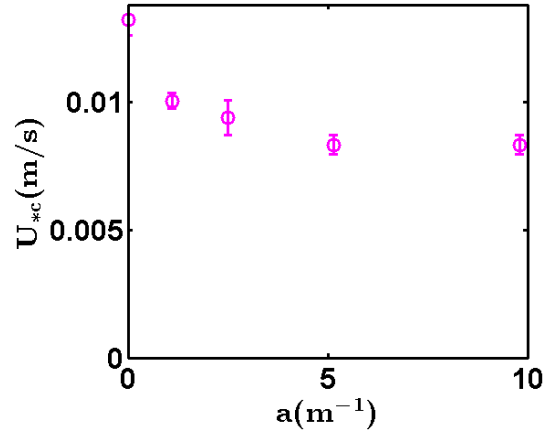


Figure 5. The mean bed friction velocity U_{*c} estimated from equation (1) and (2) at critical conditions.

We also considered whether the turbulent kinetic energy provided a clear transition threshold. However, the value of turbulent kinetic energy at the observed threshold of sediment motion increased with increasing a (Figure 6). Note that $\sqrt{k_t}_{crit}$ increased with stem density, even as U_{crit} decreased. This can be explained by the turbulence generated by the model stems. With higher stem density there are more sites (wakes) within which additional turbulence can be generated.

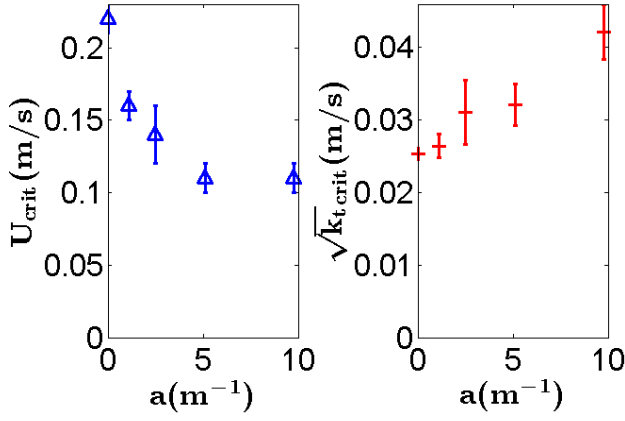


Figure 6. The critical velocity, U_{crit} , and turbulence intensity, $\sqrt{k_{t,crit}}$ for the conditions of incipient motion.

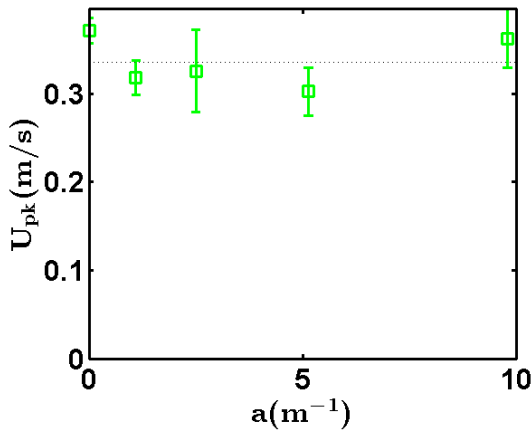


Figure 7. The new criterion $U_{pk} = U_{crit} + 6\sqrt{k_t}$ keeps relatively constant for all vegetation density at the incipient condition. The dash line denotes the average value of U_{pk} and is equal to 0.34.

The opposing trends in U_{crit} and $\sqrt{k_{t,crit}}$ with increasing stem density suggest that turbulence does play a role in initiating sediment motion. For the same channel velocity, if the turbulence intensity is higher, the peak instantaneous velocity will be higher. As a result, sediment will start to move earlier (at lower U_{crit}) for higher levels of turbulence levels. In other words, the addition of vegetation introduces larger velocity fluctuations (u', v', w'), which reduce the mean channel velocity required to initiate sediment motion, U_{crit} . We therefore propose a new metric which characterizes that the peak instantaneous velocity, U_{pk} , as the criterion to initiate sediment motion. Namely, we proposed that $U_{pk} = U_{crit} + u'_{pk}$ should be a constant for incipient motion of a particular grain size, where U_{crit} is the mean channel velocity and u'_{pk} the additional streamwise velocity fluctuation required to initiate motion. Assuming that u'_{pk} scales as $\sqrt{k_t}$, the peak velocity can be estimated from $U_{pk} = U_{crit} +$

$\alpha\sqrt{k_t}$, here α is a fitting constant coefficient. For this study, $\alpha = 6$ produced a constant value of U_{pk} for incipient motion across all cases, including the bare bed (Figure 7).

4 CONCLUSIONS

The observations reported in this paper suggest that the initiation of sediment motion depends on both the mean flow and turbulence intensity. As the vegetation density a increases, the critical velocity (U_{crit}) and critical bed friction velocity (U_{*c}) both decrease, while the critical value of turbulence intensity ($\sqrt{k_{t,crit}}$) increases. Larger $\sqrt{k_t}$ means larger velocity fluctuations, and as a result the mean velocity needed to initiate sand motion (U_{crit}) decreases. A new criterion based on peak velocity $U_{pk} = U_{crit} + 6\sqrt{k_t}$ has been proposed to define the incipient condition of sediment motion. However, more detailed observations are needed to evaluate the fitting coefficient and determine its physical connection to the turbulence structures near the bed.

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