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Incipient motion of sediment in presence of submerged flexible vegetation

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Abstract

The presence of submerged vegetation on river beds can change the water flow structure and alter the state of sediment motion. In this study, the incipient motion of sediment in the presence of submerged flexible vegetation in open channels was investigated in a laboratory experiment. The vegetation was simulated with flexible rubber cylinders arranged in parallel arrays. The effect of the vegetation density, water depth, and sediment grain size on the incipient motion was investigated. The experimental results indicate that the incipient motion velocity of sediment increases as the vegetation density decreases and the water depth and sediment grain size increase. With flexible plants, the incipient motion velocity of sediment is lower than it is without vegetation, and is larger than it is with rigid vegetation. A general incipient motion velocity equation was derived, which can be applied to both flexible and rigid vegetation conditions.

Keywords: Sediment incipient motion; Submerged flexible vegetation; Open channel; Experimentation; Sediment grain size; Water depth

1. Introduction

As economic development continues to cause deterioration in the state of our environment, there is increasing interest in ecological management. One of the ecological issues associated with river mechanics is the water flow and sediment behavior in the presence of vegetation. The mechanics involving vegetation and sediment is complicated (Stephan and Gutknecht, 2002; Kouwen et al., 1981; Tang et al., 2007). The existence of vegetation increases the flow resistance, raises the water depth, and promotes the deposition of sediment, and the vegetation may sway with the flow pressure, promoting the stirring motion of the flow body, and washing away the sediment around the plant. Vegetation on river beds absorbs pollutants in the channels and provides habitat for aquatic animals. Although river vegetation plays an important role in the river ecosystem, research on aquatic vegetation within the framework of river mechanics has been limited. It is therefore useful to conduct further research that will broaden our understanding of the effect of aquatic vegetation on river flow patterns and sediment behavior.

Unlike flow characteristics in open channels without vegetation, the flow velocity distribution with vegetation is not subject to the exponential rule, and anisotropy is significant (Wu, 2007). Experiments by Lü (2008) showed that the flow velocity distribution is uniform along the water depth direction in open channels with emergent rigid vegetation. Li and Shen (1973) suggested that the vegetation arrangement on the river bed affects the sediment transport rate. Less sediment is transported when plants are arranged in a staggered pattern, as compared with the traditional parallel pattern. Wang and Wang (2010) found that vegetation increases the deposition of suspended sediment in water.

Generally, studies on the incipient motion of sediment without vegetation from the point of view of the traditional river mechanics examine three aspects: the probability of sediment incipient motion, flow shear stress, and the sediment

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transport rate (Zhang, 1998). Only a few studies have focused on the incipient motion of sediment with vegetation. Jordanova and James (2003) and Kothyari et al. (2009) compared bed load transport rates in flows with and without vegetation. They found that the incipient motion of sediment on a vegetation bed and a flat bed (without vegetation) were similar. Tang et al. (2013) studied the incipient motion of sediment in the presence of emergent rigid vegetation, classified the sediment movement process before the sediment reached the incipient motion state into three stages, and defined the third stage as the incipient motion state. They concluded that sediment moved more easily in flows with vegetation, and the bed surface was deformed before the sediment reached the stage of incipient motion. Wang et al. (2014) showed that when the sediment was in the stage of incipient motion, the bed shear stress could be divided into two parts: the grain shear stress and the shear stress caused by sand dunes, which are the bed form after it has been deformed by the sediment incipient motion. The criterion for the sediment incipient motion adopted in Tang et al. (2013) and Wang et al. (2014) is similar to that without vegetation proposed by Kramer (Zhang, 1998), i.e., the moment when there are few countable sediment particles on the bed beginning to move. Both of them are qualitative but can express the stage of the incipient motion of sediment very well. This study is based on the criterion described above.

Even though most vegetation found on river beds is flexible, studies on the effects of flexible plants on the flow and sediment behavior, such as the incipient motion of sediment in the water channel, are rare. In this study we investigated the incipient motion of sediment in an open channel that contain submerged flexible vegetation, which were represented by arrays of thin rubber cylinders arranged in a regular pattern. We examined the factors influencing the incipient motion via changes in vegetation density, water depth, and sediment grain size. Based on comparison of the results for rigid and flexible vegetation, we derive a general equation for the incipient motion velocity of sediment that can be applied to both rigid and flexible vegetation.

2. Materials and methods

The experiment was carried out in a tilting rectangular flume, 12 m long, 0.42 m wide, and 0.7 m deep (Tang et al., 2013), with a marble bottom and glass side walls for observing the state of the sediment. The flume was connected to a tank through a pump, which controlled the water discharge to the flume. A sluice at the end of the flume controlled the discharge out of the flume. Different uniform flows were achieved by adjusting the water pump, sluice, and flume slope. The quartz sand used in the experiment was collected from the Nanjing reach of the Yangtze River. The sand was graded according to its particle diameter d; two diameters were selected for the experiment: $d = 0.58$ mm and $d = 0.67$ mm, and the relative density was $(\rho_s - \rho)/\rho = 1.65$, where ρ_s is the density of sediment, and ρ is the density of water. The sediment used herein was the same as that in Tang et al. (2013). The incipient motion velocity without vegetation was calculated with the equation of Г.И.ЩаМов (in Russian) (Zhang, 1998).

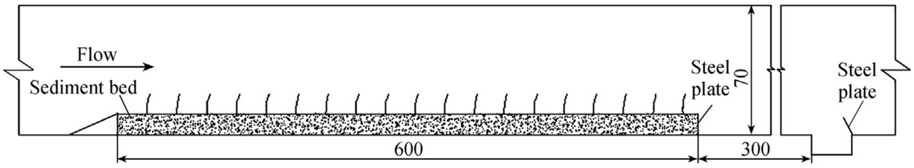
A 6 m-long section in the middle of the flume was selected as the experiment zone (Fig. 1). To simulate vegetation accurately in a geometric configuration, thin rubber cylinders with a height of 12 cm, a diameter of 0.6 cm, and stiffness similar to that of natural plants, were used to imitate the vegetation on the river bed. A horizontal plastic board with holes of 1 cm apart served as a base for fixing the artificial plants. Once the simulated plants were set in the board, a 5 cm-thick layer of sand was spread over the board. The actual length of the vegetation in water was $H = 6$ cm. As the number of holes in the board was larger than the number of plants, the density and pattern of the vegetation could be changed by altering the number of holes between the adjacent plants. The plants were arranged in the holes according to the given vegetation density λ (Table 1), defined as (Tang et al., 2013):

$$\lambda = \frac{\pi D^2}{4XY} \tag{1}$$

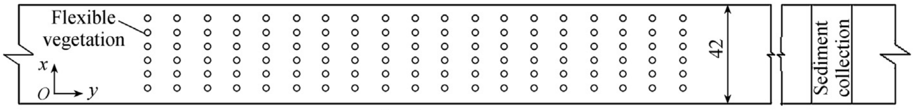
where D is the diameter of the vegetation, and X and Y are the distance between the centers of adjacent plants in the x and y directions, respectively.

Combining the vegetation density λ with the discharge Q obtained from the pump monitor, the average flow velocity u in the vegetation zone can be derived from the following equation (Yan, 2008; Stone and Shen, 2002):

$$u = \frac{Q}{Bh(1 - \lambda h_v/h)} \tag{2}$$



(a) Front graph



(b) Plane graph

Fig. 1. Experimental flume and vegetation arrangement (units: cm).

Table 1
Summary of experimental conditions.

d (mm)	Vegetation arrangement $X \times Y$ (cm × cm)	λ	Water depth h (cm)
0.58	3 × 5	0.018 9	12
			15
			18
	4 × 5	0.014 1	12
			15
			18
	5 × 5	0.011 3	12
			15
			18
	3 × 10	0.009 4	12
			15
			18
	4 × 10	0.007 1	12
			15
			18
	5 × 10	0.005 7	12
			15
			18
0.67	3 × 5	0.018 9	12
			15
			18
	4 × 5	0.014 1	12
			15
			18
	5 × 5	0.011 3	12
			15
			18
	3 × 10	0.009 4	12
			15
			18
	4 × 10	0.007 1	12
			15
			18
	5 × 10	0.005 7	12
			15
			18

where B is the flume width, and h_v is the height of the flexible vegetation under the flow force. Eq. (2) was adopted to calculate the incipient motion velocity when sediments were in a stage of incipient motion. We conducted a series of experiments where the vegetation corresponding to the sediment incipient motion was in a state of swaying motion. We assumed that the height of the vegetation in the water and the vegetation density did not change with the flow conditions (Kuowen and Unny, 1973). Here, $h_v = 5.7$ cm.

Initially, the water was pumped into the flume slowly while the sluice gate was closed, so that the water could infiltrate the sand without disturbing it. The discharge could be raised gradually, and the flume slope and the opening of the sluice gate was adjusted rapidly to keep the flow uniform and stable while ensuring a fixed water depth. This step was repeated until incipient motion of sediment occurred, and at this time, the discharge Q was recorded. Incipient motion is defined, according to Tang et al. (2013), as noticeable sediment transport out of the scour holes and outside the vegetation zone. Sediment movement begins at this stage described above, but it is very minimal.

3. Results and discussion

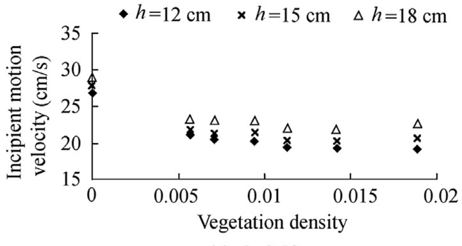
3.1. Influence of vegetation density and water depth on incipient motion of sediment

Fig. 2 shows the experimental results of the incipient motion velocity of sediment from 36 cases with submerged flexible vegetation and results calculated with the equation of Г.И.ЩаМов (in Russian) (Zhang, 1998) in flow without vegetation.

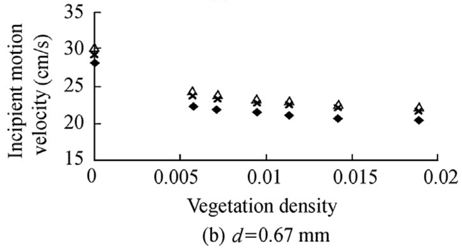
Fig. 2 indicates that the sediment incipient motion velocity U_{pc} is related to the vegetation density λ, and shows a decreasing trend with increasing λ, in contrast to the positive correlation between U_{pc} and the water depth and sediment grain size. The motion of the vegetation in response to the flow force (Kuowen and Unny, 1973) disturbs the water body and causes the sand to move. Additionally, the downward flow along the plant's upstream face scours the root of the plant and shifts the sediment there. This action becomes more significant as λ increases. For deep flow depths, the relative height of the vegetation is low, the plant effects may not be as significant as in shallow water, and U_{pc} will increase. Larger-size sand grains are harder to move in flow with or without vegetation. The observed value of U_{pc} is at least 20% lower in flow through submerged flexible vegetation than that in flow without vegetation calculated using the equation of Г.И.ЩаМов (in Russian) (Zhang, 1998), as shown in Fig. 2. This indicates that the existence of submerged flexible vegetation can promote sediment transport to some extent.

3.2. Incipient motion velocity of sediment in flows with rigid and flexible vegetation

We compared some of our experimental data of the incipient sediment motion velocity in flow with flexible vegetation with those with rigid vegetation (Tang et al., 2013), assuming that the other experimental conditions were similar. The



(a) d=0.58 mm



(b) d=0.67 mm

Fig. 2. Incipient motion velocity of sediment in different conditions.

results show that U_{pc} in flow with flexible vegetation is generally higher than U_{pc} with rigid vegetation (Fig. 3). Hence, the equation that applies to flow with rigid vegetation cannot be applied to flow with flexible vegetation.

We can analyze this phenomenon based on the rule of conservation of energy. In flow with rigid vegetation, the upstream kinetic energy is used to maintain the motion of the downstream flow, sediment transport, and to some extent the dissipation of the stirring motion. In flow with flexible vegetation, in addition to the above functions, some of the energy is dissipated by the plant's swaying motion. To maintain the same state of motion, much more energy is required in flow with flexible vegetation than with rigid vegetation. Moreover, with rigid vegetation, the downward flow at the plant's upstream face is vertical to the bed. Flexible vegetation tends to bend with the flow force. Thus, the downward flow suffers the resistance force from the swaying of flexible vegetation. This force restrains sediment motion. Hence, compared with rigid vegetation, flexible vegetation has a positive effect on control of flow scouring by absorbing more energy with its motion.

3.3. Equation of incipient motion velocity of sediment in presence of vegetation

Tang et al. (2013) defined the incipient motion velocity of sediment in the presence of emergent rigid vegetation as

$$U_{pc}=f\left(\frac{h}{D},\frac{d}{D},\lambda\right)\left(\frac{2ka_3}{ka_1C_L+a_2C_d}\right)^{\frac{1}{2}}\left(\frac{\rho_s-\rho}{\rho}gd\right)^{\frac{1}{2}} \tag{3}$$

where k, a_1, a_2, and a_3 are constants, and C_L and C_d are coefficients for the lift force and drag force, respectively, when the bed load interacts with current moving. Their result was based on research on rigid vegetation. In flow with submerged flexible vegetation, U_{pc} is also related to h/h_v and H/h_v, and can be expressed as

$$U_{pc}=f\left(\frac{h}{D},\frac{d}{D},\lambda,\frac{h}{h_v},\frac{H}{h_v}\right)\left(\frac{2ka_3}{ka_1C_L+a_2C_d}\right)^{\frac{1}{2}}\left(\frac{\rho_s-\rho}{\rho}gd\right)^{\frac{1}{2}} \tag{4}$$

where h/h_v indicates the relative degree of submergence, and H/h_v indicates the winding level.

Substituting the experimental data into Eq. (4), the incipient motion velocity of sediment in the presence of submerged flexible vegetation can be derived:

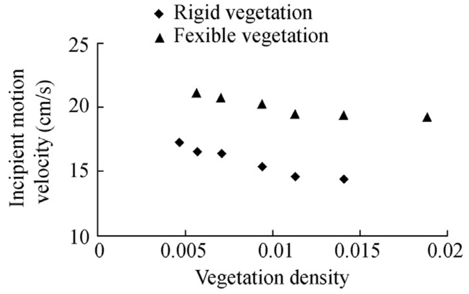
$$U_{pc}=\left[0.36\sqrt{\frac{\rho_s-\rho}{\rho}gd}\left(\frac{h}{d}\right)^{\frac{1}{6}}\left(\frac{D\sqrt{(\pi/4-\lambda)/\lambda}}{\sqrt{hd}}\right)^{0.319}\right]\times\left[\left(\frac{H}{h_v}\right)^{3.5}\left(\frac{h}{h_v}\right)^{0.18}\right] \tag{5}$$

The first part on the right side of Eq. (5) represents the incipient motion velocity of sediment in emergent rigid vegetation conditions; the second part reflects the factors that depend on the characteristics of the flexible vegetation. For the emergent rigid plant, the second expression is constant and is equal to 1. Fig. 4 presents a comparison between the observed values of U_{pc} and those calculated with Eq. (5). The velocity U_{pc} depends on the relative degree of submergence while the plant sways in the water. According to Kuowen and Unny (1973), the vegetation changes from swaying motion to a constant oblique condition when the flow velocity increases. Therefore, while in this study we focused on swaying vegetation, further study on U_{pc} around vegetation in an oblique condition should be carried out.

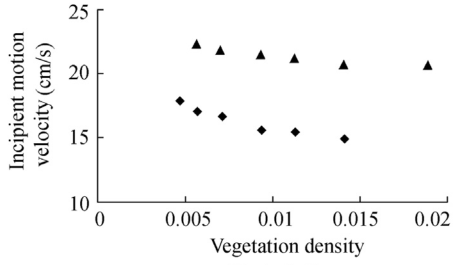
Eq. (5) can be rewritten as

$$U_{pc}=\left[1.14\sqrt{\frac{\rho_s-\rho}{\rho}gd}\left(\frac{h}{d}\right)^{\frac{1}{6}}\right]\times\left[0.316\left(\frac{D\sqrt{(\pi/4-\lambda)/\lambda}}{\sqrt{hd}}\right)^{0.319}\left(\frac{H}{h_v}\right)^{3.5}\left(\frac{h}{h_v}\right)^{0.18}\right] \tag{6}$$

based on the equation of Г.И.ЩаМов (in Russian), which is fitted for the incipient motion velocity of sediment without



(a) d=0.58 mm



(b) d=0.67 mm

Fig. 3. Incipient motion velocity of sediment in flows with rigid and flexible vegetation.

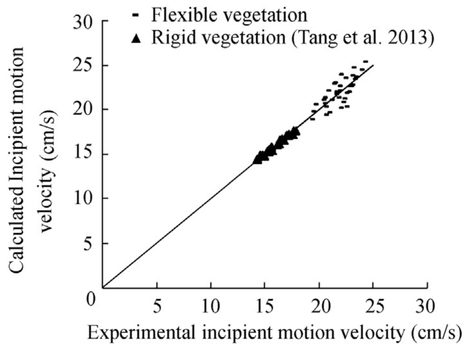


Fig. 4. Comparison of experimental and calculated incipient motion velocities of sediment.

vegetation. The equation of Г.И.ЩаМов (in Russian) only includes the first part on the right side of Eq. (6). The second part is the vegetation factor. Setting the value of the vegetation factor to 1 yields the following equation:

$$0.316\left(\frac{D\sqrt{(\pi/4-\lambda)/\lambda}}{\sqrt{hd}}\right)^{0.319}\left(\frac{H}{h_{\mathrm{v}}}\right)^{3.5}\left(\frac{h}{h_{\mathrm{v}}}\right)^{0.18}=1 \tag{7}$$

In contrast to that of emerged rigid vegetation (Tang et al., 2013), the vegetation factor of submerged flexible vegetation consists of the winding level and the relative degree of submergence in different flow conditions. Eq. (7) appears to be a critical equation. If the value of the vegetation factor is less than 1, the effect of vegetation is not negligible. Therefore, the vegetation factor is a key factor that determines whether the vegetation has influence on the incipient motion velocity of sediment. In fact, the value of the vegetation factor could be greater than 1. For a significant water depth, when the height of vegetation is less than a threshold value, the vegetation factor is greater than 1. In this case, the vegetation can be regarded as roughness elements, the influence of the vegetation on sediment transport can be ignored, and the vegetation factor can be considered 1. In fact, the vegetation factor is the parameter that describes the relationships between plants, the water depth, the density of vegetation, and the sediment in the influenced zone.

4. Conclusions

We conducted laboratory experiments to investigate the factors that affect the incipient motion of sediment on river beds. Our main conclusions are as follows:

(1) The plant density and the relative degree of submergence influence the incipient motion velocity of sediment in the presence of submerged flexible vegetation. The incipient motion velocity of sediment increases as the plant density decreases and the water depth and sediment grain size increase.

(2) With flexible plants, the value of incipient motion velocity of sediment is lower than that in the case without vegetation, but is larger than it is with rigid vegetation.

(3) A general incipient motion velocity equation (Eq. (6)) was derived, which can be applied to both rigid and flexible vegetation.

(4) Factors such as the pattern of vegetation growth on the bottom, the plant dimensions, and the vegetation state were not investigated in this study. Further study on incipient motion of sediment in the presence of vegetation should focus on these aspects.

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