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ScienceDirect

Water Science and Engineering 2015, 8(1): 63–67

http://www.waterjournal.cn

Incipient motion of sediment in presence of submerged flexible vegetation

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Received 23 December 2013; accepted 28 May 2014
Available online 17 January 2015

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

This work was supported by the China National Funds for Distinguished Young Scientists (Grant No. 51125034), the State Key Program of the National Natural Science Foundation of China (Grant No. 51239003), and the National Natural Science Foundation of China (Grants No. 51109066 and 51109065).
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Peer review under responsibility of Hohai University.

http://dx.doi.org/10.1016/j.wse.2015.01.002
1674-2370/

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 Γ.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):

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

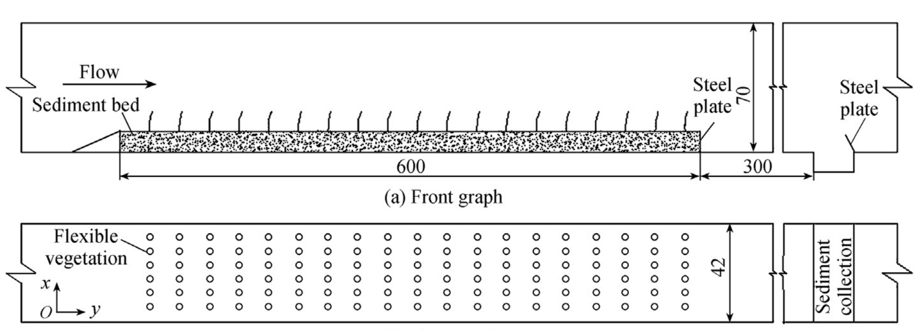

Fig. 1. Experimental flume and vegetation arrangement (units: cm).