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A simple method for estimating bed shear stress in smooth and vegetated compound channels*

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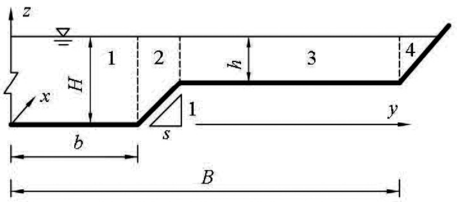
Abstract: Instead of a large number of measurements of the streamwise velocity, a simple method is proposed to estimate the bed shear stress in smooth and vegetated compound channels, based on the Darcy-Weisbach equation. This method contains a dimensionless parameter A_i, to represent the relationship between the bed shear stress and the velocity close to the channel bed (U_b), which is determined in each divided domain. This method is verified in two smooth compound channels with different geometries, and in one compound channel with emergent floodplain vegetation. The comparison of predicted and measured bed shear stresses indicates the good predictive capability of this method, particularly in the mixing region. This method is further discussed for a channel with submerged vegetation. Once the values of A_i in the main channel and the floodplain are determined, this method is a practical tool for estimating the bed shear stress based on a small number of measurements of U_b in compound channels.

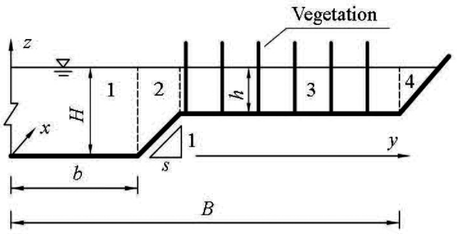
Key words: predictive method, bed shear stress, compound channel, vegetation

Introduction

In natural rivers, the bed shear stress is important in determining the local bed erosion, the sediment bedload and the particle resuspension. The sediment deposition enhances the potential of the macrophyte expansion, to reinforce the development of river banks, vegetated islands and floodplains. This is an efficient way to stabilize the channel bed and protect the river bank. The flow often inundates floodplains during the flood period, and thus a compound channel emerges, whose flow characteristics (e.g. the vertical profile of velocity, and the secondary flow) were extensively investigated[1,2]. The geometry of the compound channel can be discretized into several linear elements and the most common type is the trapezoidal compound channel (see Fig.1(a)). Compared to the main



(a) Smooth floodplains



(b) Emergent vegetation on floodplains

Fig.1 Cross-sections of compound channels. Regions 1, 2, 3 and 4 represent the main channel, the main channel side slope region, the floodplain, and the floodplain side slope region, respectively

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Table 1 Experimental parameters in compound channels

Series No.	H / m	Dr	B / m	B/b	s	Main channel shape	Floodplain condition
FCF 01	0.165-0.250	0.092-0.400	5.00	6.67	1	Trapezoidal	Smooth
FCF 02	0.170-0.249	0.117-0.396	3.15	4.20	1	Trapezoidal	Smooth
FCF 03	0.166-0.248	0.098-0.395	1.65	2.20	1	Trapezoidal	Smooth
FCF 07	0.166-0.250	0.094-0.400	3.15	4.20	1	Trapezoidal	Emergent vegetation
FCF 08	0.167-0.250	0.102-0.400	3.00	4.00	0	Rectangular	Smooth
FCF 10	0.167-0.249	0.100-0.398	3.30	4.40	2	Trapezoidal	Smooth

channel, the floodplains with low velocities provide a more suitable environment for the sediment deposition and the growth of macrophyte. Thus a compound channel with vegetation floodplains is formed, as shown in Fig.1(b). Particularly, the significant enhancement of the shear stress can be observed in the mixing region (wider than Region 2 in Fig.1) due to the velocity difference between the main channel and floodplain flows[3]. Moreover, a complicated lateral distribution of the bed shear stress can be observed in that region, which is difficult to be accurately predicted.

Three-dimensional velocities measured by the acoustic Doppler velocimeter (ADV) were related to the bed shear stress[4]. To determine the bed shear stress, a relation between the turbulent kinetic energy (TKE) and the Reynolds shear stress (τ_{yx}) was proposed with a dimensionless parameter to be separately calibrated in laboratory experiments[5] and natural rivers[6]. However, those methods can only provide accurate predictions of the bed shear stress in single channels. In compound channels, some analytical and numerical methods might be used in predicting the lateral distribution of the bed shear stress[3,7-12], but the common disadvantage of these models is the fact that one has to determine the effect of secondary flows (specifically, the secondary flow parameter in these models). To calibrate the secondary flow parameter, detailed measurements of three-dimensional velocities at a transection of a compound channel are needed[8,9].

The Darcy-Weisbach equation may be used to predict the bed shear stress (τ_b) as

$$\tau_b = \rho \frac{f}{8} U_d^{\ 2} \tag{1}$$

where ρ is the flow density, f is the friction factor, U_d is the depth-averaged velocity.

To obtain the accurate lateral distribution of U_d, a large number of measurements for U have to be made, where U is the time-average velocity. The inaccurate measurement for U_d may directly result in a poor prediction of τ_b due to the relation $\tau_b \sim U_d^{\ 2}$. Until now laboratory experiments are the most efficient approach to obtain sufficient data at large temporal and spatial scales under a specific flow condition, but it is difficult to make a large number of measurements due to limited resources. In field measurements (particularly in rapidly flowing large rivers), it is most difficult to ensure the accuracy with a reasonable expense. Therefore, in the current research we propose a simple method to estimate the bed shear stress with a small number of measurements of velocity.

1. Data from published literature

All experimental data in this paper are obtained from the flood channel facility (FCF) in the UK. Different channel geometries and floodplain conditions are considered (see Table 1). The details of the data acquisition system were described in Knight and Sellin[13], Knight and Shiono[14] and Rameshwaran and Shiono[3], and a brief description is as follows.

The UK-FCF consisted of a 56 m long and 10 m wide experimental flume with a maximal discharge capacity of 1.1 m^3/s. Six groups of experiments were conducted in a straight compound channel with smooth floodplains (FCF 01, 02, 03, 08 and 10) and vegetated floodplains (FCF 07). In all cases, the width of the main channel $(b = 0.75\ \text{m})$ was the same, but the floodplain condition and the main channel side slope (s) were different (see details in Table 1). The measurement section was at a position 36 m downstream from the inlet of the flume. Velocity was measured by a two-dimensional LDA system, and the bed shear stress was measured by the Preston tube. The bed slope (S_0) was 0.001027, and the bank height $(H-h)$ was 0.15 m. The surface of those compound channels was smooth, and the Manning coefficient was 0.0099 in smooth channels. The floodplain vegetation was modeled by rigid wooden rods, which were placed vertically on smooth floodplains. The vegetation diameter was 0.025 m and the vegetation density was 12 rods/m^2. Cross-sections of both smooth and vegetated compound channels are shown in Fig.1. Regions 1, 2, 3 and 4