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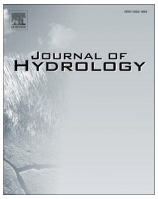

Research papers

The effect of floodplain grass on the flow characteristics of meandering compound channels

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ABSTRACT

Laboratory experiments were conducted in a large-scale meandering compound channel to investigate the effect of floodplain grass on the main flow field in the channel. Three-dimensional velocity fields, turbulences, and Reynolds shear stresses were measured along half a meander. The experiments revealed that flexible artificial grass planted on a floodplain can significantly reduce the conveyance capability of the entire channel. Two parallel stage-discharge curves increased with increasing flow depth. The additional resistance of the floodplain grass increased the streamwise velocity and conveyance in the main channel along a meander. An analysis of the generation mechanism of secondary flows in the main channel indicated that the secondary current consisted of an enhanced original secondary cell that was strengthened by the centrifugal force and a component of the upstream floodplain flow. The relative dominance of these two components in the secondary flows was primarily determined by the angle between the floodplain flow and the main channel ridge, and also the floodplain roughness. At the same flow depth, the secondary flow in cases with grass on the floodplain was generally stronger than that in the case of a smooth meander bend, although it was weaker near the middle cross-over section. Floodplain grass enhanced the intensity of the lateral turbulence above the bankfull level and significantly modified the turbulence structure, although it had a negligible effect on the vertical turbulence except at the bend entrance. Floodplain grass also affected the Reynolds shear stresses in the main channel, generating stronger lateral shear stresses at a low flow depth. In contrast, at a high flow depth, the distribution of the interface shear stresses changed entirely while its magnitude remained the same. When the floodplains were grassed, the vertical shear stress that was induced by secondary flows was greater at the apexes but reduced at the cross-over sections. These observations highlight the important effects of floodplain grass on the main channel flow.

1. Introduction

Vegetation is often present in natural rivers and significantly affects river systems. Many laboratory experiments have investigated the role of emergent vegetation in open channel flows, including those by Nepf (1999), López and García (2001), Bennett et al. (2002), James and Makoa (2006) and Zong and Nepf (2011). These studies revealed the basic physical characteristics of rigid emergent vegetation such as variations in drag, alterations in streamwise velocity, turbulence structures, the occurrence of periodic vortices, deposition distributions, additional flow resistance and decreased conveyance capabilities.

In natural rivers, vegetation is often found in patches with finite lengths and widths rather than in continuous segments. The interaction of sediment deposition with a single finite patch of vegetation was recently investigated; in particular, both erosion and deposition was observed within a model vegetation patch (Follett and Nepf, 2012; Kim et al., 2015; Bouma et al., 2007). The deposition pattern (enhanced or diminished) within an emergent patch is related to stem scale turbulence, which is triggered when the stem Reynolds number, Re_d (=ud/ν), is above a threshold value for vortex shedding in the stem wake. In this case, u is the velocity within the vegetation, d is the stem diameter, and ν (=0.01 cm^2/s) is the kinematic viscosity. The threshold Re_d is approximately 120 but may vary somewhat with stem density. The increased or decreased net deposition compared to the control (or upstream reference)

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is associated with Re_d values less than or greater than 120, respectively (Liu and Nepf, 2016).

In aquatic habitats, vegetation can be fully submerged and have different effects on the flow structure than emergent vegetation. The influence of submerged vegetation is primarily related to its submergence depth and stem type (rigid or flexible). Submerged vegetation living on the river bed slows the flow velocity behind it and enhances sediment deposition. Wu et al. (1999), Nepf et al. (2007), Nezu and Sanjou (2008) and Stoesser et al. (2010) experimentally investigated the flow patterns in open channels with submerged vegetation. Huthoff et al. (2007), Nikora et al. (2007a,b), Huai et al. (2009), and Poggi et al. (2009) proposed theoretical and numerical methods of predicting the vertical velocity distribution. In these studies, most of the investigated vegetation was rigidly stemmed, unlike a typical situation in which the vegetation on a channel bed is flexible. As for flexible vegetation, Stephan and Gutknecht (2002), Järvelä (2005), Wilson (2007), Zhang and Nepf (2009), Rominger et al. (2010), and Ortiz et al. (2013) experimentally investigated complex flow structures, particularly the flow behaviors around the canopies of deflected flexible plants.

The cross section of a natural river can often be modeled as a regular geometry in a compound channel. Flow patterns in straight compound channels with smooth floodplains have been experimentally investigated by Knight and Demetriou (1983), Shiono and Knight (1991), Tominaga and Nezu (1991) and Hu et al. (2010). In fact, the floodplains of natural rivers are ideal homes for vegetation. As such, river flows in compound channels often inundate floodplains and submerge floodplain vegetation at high flow depths. Because of the additional drag force of vegetation on the floodplain, the significant difference in velocity between the main channel flow and the floodplain flow in a vegetated straight compound channel causes a momentum transfer, generating longitudinal and vertical vortices and a lateral shear layer. These flow phenomena have been extensively studied by Pasche and Rouvé (1985), Rameshwaran and Shiono (2007), Yang et al. (2007), Sun and Shiono (2009), and Liu et al. (2013). Their studies systematically revealed the differences in flow features between vegetated and non-vegetated regions.

The flow in a meandering channel differs considerably from that in a straight compound channel. Based on experimental data from the U.S. Army and the UK Flood Channel Facility (FCF), Ervine et al. (1993) discussed the determining factors for conveyance ability in curved compound channels. Shiono et al. (1999), Khatua et al. (2011) Shan et al. (2015) and Liu et al. (2014, 2016) proposed methods for estimating discharge and lateral velocity distributions, including the flow interaction between the main channel and the floodplain in a meandering compound channel. Shiono and Muto (1998) observed that in a non-vegetated curved compound channel, the water within the smooth main channel below the bankfull level tends to flow in the meandering main channel, whereas the water above the bankfull level follows the valley direction. The rotational direction of the dominant secondary current at the apex of the in-bank case was opposite that of the overbank case. More complicated flow structures in curved compound channels with erodible beds have been experimentally investigated by Lyness et al. (2001), Spooner (2001), and Wormleaton et al. (2004). As expected in the erodible case, the bed morphology in a meandering main channel is associated with flow structures and variations with flow depth when overbank flows occur. In a meander bend, centrifugal force is the dominant factor in the formation of bedforms and secondary currents. Shiono et al. (2009) conducted experiments to explore the effect of floodplain roughness on flow structures and bedforms. Their experimental results indicated that under different floodplain roughness conditions, multiple secondary flow cells generated a series of wavy bedforms along the meandering main channel. Although the flow patterns in both smooth meandering compound channels and vegetated meandering compound channels with mobile beds have been extensively investigated, there is a lack of research regarding the flow structure in a vegetated meandering main channel with a non-mobile bed. Furthermore, the generation mechanism of secondary flows within a meandering main channel is still unclear. These two points serve as the motivation for this study. This paper investigates the direct effect of submerged floodplain grass on flow structures and explores the underlying mechanism of secondary flows in a meandering main channel. To this end, a series of experiments were performed in a vegetated meandering channel with a non-mobile bed.

2. Experimental methods

The experiments were conducted in a 35 m long, 4 m wide and 1 m high flume at the State Key Laboratory of Hydraulics and Mountain River Engineering (SKLH), Sichuan University, China (Fig. 1). Three runs (MN1–MN3) were performed in the smooth meandering channel (Liu et al., 2014; Shan et al., 2015). To explore the effect of floodplain grass on the main channel flow, three further runs (MV1–MV3) were performed in the same meandering channel with flood plain grass. A triangular weir was installed in front of the flume to measure the flow discharge. The

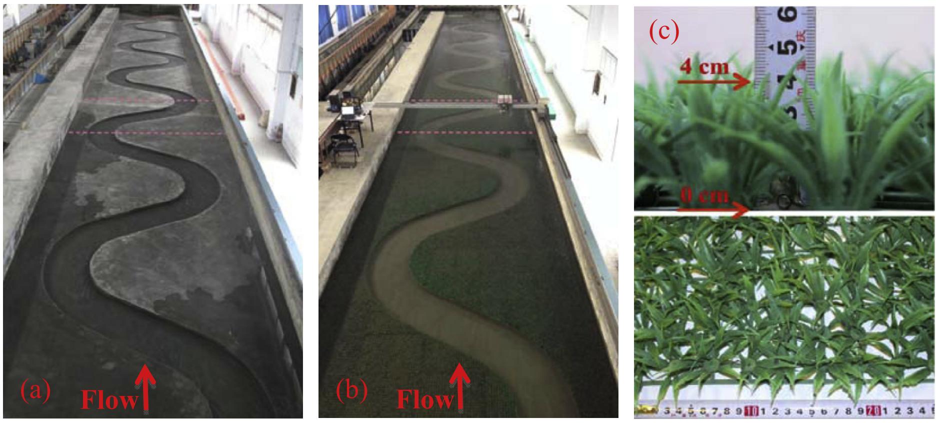

Fig. 1. Photographs of the meandering compound channel at SKLH (looking downstream), (a) smooth case; (b) grassed case; and (c) model grass. For the two investigated cases, the test meander was situated between the two pink dashed lines. The flow direction was from the downside to the upside, as indicated by the red arrow. This experimental channel was 35 m long, 4 m wide and 1 m high. The grass height was h_v = 4.0–4.5 cm and the density was N = 0.89 stems/cm^2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)