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Characteristics of intermittent turbulent structures for river bank undercut depth increment

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ABSTRACT

The complex interplay between the resistive forces of the bank material and Reynolds shear stress of the turbulent flow field control the fluvial bank erosion. In-depth knowledge on the interactions of the flow-form at the river bank is a prerequisite to understand erosion mechanism and quantification of the erosion rate. Measurement at 1.5 m from the bank face as reported in the literature revealed that turbulent lateral flux of stream-wise momentum propagated towards the bank face that was held responsible for the removal of material from the bank face. Further experimental results from the literature depict that the stream-wise and lateral fluctuating velocity components deploy a random forcing effect on the river bank face which may be one of the primary agents for sediment particle entrainment from the bank face. It is gestated from these previous studies that the momentum flux and turbulent structures of the flow field has a great impact on the river bank erosion. Nevertheless, the previous field and experimental studies do not focus on the flow turbulence and sediment interaction that extracts information on the detailed temporal features of sediment entrainment process. Thus, the present study was carried out to understand the coupled dynamics of the effect of intermittent flow structures on the intermittent removal of river bank materials, and for advancing the knowledge on river bank erosion process. The present experimental study focuses on the evaluation of the turbulent flow characteristics when the undercut mechanism initiates in a cohesive river bank. Based on the results it is evident that moderate scale intermittent stream-wise flow structures probably imposes a periodic loading on the cohesive aggregates of the bank face. This accelerates the entrainment of aggregates from the bank face. The study also reveals that the undercut increment is a small scale intermittent process. Findings of the present study may be helpful for the improved design of bank protection measures.

1. Introduction

Land cover changes due to the removal of bank material of rivers are considered to be of great socio-economic importance (Nadal-Romero et al., 2013). Thus the mechanism of undercut development in a river bank needs detailed exploration to clarify fundamental issues governing bank erosion. The geomorphological and ecological diversity of river stream bank adds to the complexity of the problem (Florsheim et al., 2008; Camporeale et al., 2013). Investigations on floodplain erosion by the processes of sediment dislodgement, mass failure, and transportation have far reaching consequences in the ecology, geomorphology, contaminant and nutrient conveyance capacity of the river system (e.g. Marron, 1992; Reneau et al., 2004; Zinger et al., 2011). To understand the erosion mechanism and to quantify the erosion rate, knowledge of the flow form interaction with river bank sediments is a prerequisite.

Numerous scientific investigations have been the focus on the fluvial dynamics of cohesive river banks, including processes related to outer bank erosion. These studies include: experiments on river bank erosion at laboratory scale (Nagata et al., 2000), in situ field investigations (Thorne and Tovey, 1981; Debnath et al., 2007b; Zaimes and Schultz, 2015) as well as numerical studies (Darby and Thorne, 1996; Chen and Duan, 2006). These studies primarily focussed on bank-line shifting over large timescale and reported that this shift of bank-line was proportional to the excess near-bank flow shear stress over the critical threshold shear stress of the bank material. Kean and Smith (2006a, 2006b) observed that the bank-line topography modulation leads to the augmentation of the bank hydraulic roughness. Further recent studies (Dulal et al., 2010; Parker et al., 2011; Asahi et al., 2013; Eke et al., 2014) have endorsed that cohesive slump blocks that arise out of mass failure camouflage the bank face and results in the

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retardation of the erosion rate. However, bank erosion rate may also be enhanced due to the cohesive slump blocks by deflecting flow upward, and onto the bank, thereby increasing the shear stress as the geometric properties of the slump block change (Hackney et al., 2015). The determination of the characteristics of 3-D turbulent flow field that interacts with the random complex roughness geometry of the temporally evolving bank face is challenging. Recent progress in profiling using acoustic Doppler method (Szupiany et al., 2009; Vermeulen et al., 2014) and data collection by high-resolution topographic methods (Aalho et al., 2009; Nittrouer et al., 2011; Lotsari et al., 2014; Leyland et al., 2015) facilitate the data collection on instantaneous flow field and morphological evolution of the near-bank region. Literature suggests that the turbulent bursting events [ejection, sweep, outward and inward interactions (Nakagawa and Nezu, 1977)] of the flow have a significant influence on the sediment removal and transportation process from the river bed (Nakagawa and Nezu, 1977). At the near bank region, the contribution of these events to the total shear stress still remains unclear. To investigate the turbulent stress, Engel and Rhoads (2017) studied the flow structures using ADCP under field conditions. Their findings highlighted a net turbulent lateral flux of streamwise momentum towards the surface of the bank material at the measurement location (1.5 m from the bank face). However, the study did not report shear stress of the turbulent fluctuations within the bank undercut. Moreover, Yu et al. (2015) reported the bank failure mechanisms for both non-cohesive and cohesive bank based on laboratory studies. They collected instantaneous velocity data using ADV and reported that the streamwise and lateral fluctuating velocity components deploy random force on the river bank face. It was argued that these fluctuating forces are the primary agents for sediment particle entrainment from the bank face. This study, however, did not focus on the intermittent flow structures and its effect on the intermittent undercut depth increments.

The role of intermittent flow turbulence and turbulent bursting events (Lohse and Grossmann, 1993) remains elusive for the understanding of the hydraulic processes of outer bank erosion. Since natural river flows are fully turbulent, the erosive stresses acting on the banks of rivers should be related to the intermittent behaviour of turbulent structures. Recent models of outer bank erosion by Darby and Thorne (1996), Simon et al. (2000), Langendoen and Simon (2008), Blanckaert et al. (2012), Motta et al. (2012, 2014) rely on plain parameterization of the flow through excess shear stress, velocity and flow depth at the bank toe region. These basic models faintly describe the direct effects of turbulence structures and its intermittent characters, which impact bank erosion through bed-material transport at the toe of the bank.

An improved understanding of turbulence structures near bank face will help to refine representation of intermittent flow structures and mechanisms of bank erosion in morphodynamic models of cohesive river banks. Field based studies do not provide controlled conditions to extract specific information on changes in the turbulent intermittent bursting structures with evolving morphology of evolving bank. Thus laboratory studies are essential to meet this end. The present study in particular attempts to understand in particular:

- the component of Reynolds shear stress primarily responsible for the removal of sediment from the bank face;
- the major contributors of the turbulent bursting structures to total shear stress responsible for the removal of sediment from the bank face;
- the dominant turbulent length and time scale and their role in sediment removal from the bank face.

To test the hypothesis made herein, the local intermittency measure of random fluctuations is quantified. Furthermore, the third and the fourth order moments of undercut depth increments and instantaneous Reynolds stress of the corresponding velocity fluctuations were evaluated. In addition, the joint probability density function and power spectral density of both random turbulent fluctuations, as well as undercut depth increment, was evaluated to quantify the energy contain frequency range as well as the dominating frequency of undercut depth increments and their interconnection. It is expected that the results from this analysis will add some useful information towards the improved understanding of the initiation of the cohesive bank undercut processes. Furthermore, a model for the prediction of temporal variation of undercut depths as a function of sediment and flow properties is presented which may be of use to the river restoration planners. The study may be also of importance for calibration of the numerical simulation of the bank erosion processes.

2. Method

2.1. Test channel and set-up

The experiments were carried out in a tilting flume (kept at constant slope = 0.001) of dimension 18.3 m long, 0.9 m wide and 0.9 m deep. Main channel breadth of the flume was reduced to 0.6 m except for the sediment trap region. The sediment recess was 3 m long, 0.85 m and 0.25 m deep and located 10 m downstream from the flume entrance. The new left side wall (NLSW) and the new right side wall (NRSW) were fabricated 0.25 m and 0.05 m inward from the original main flume wall, respectively. This provided room for accommodation of the sediment

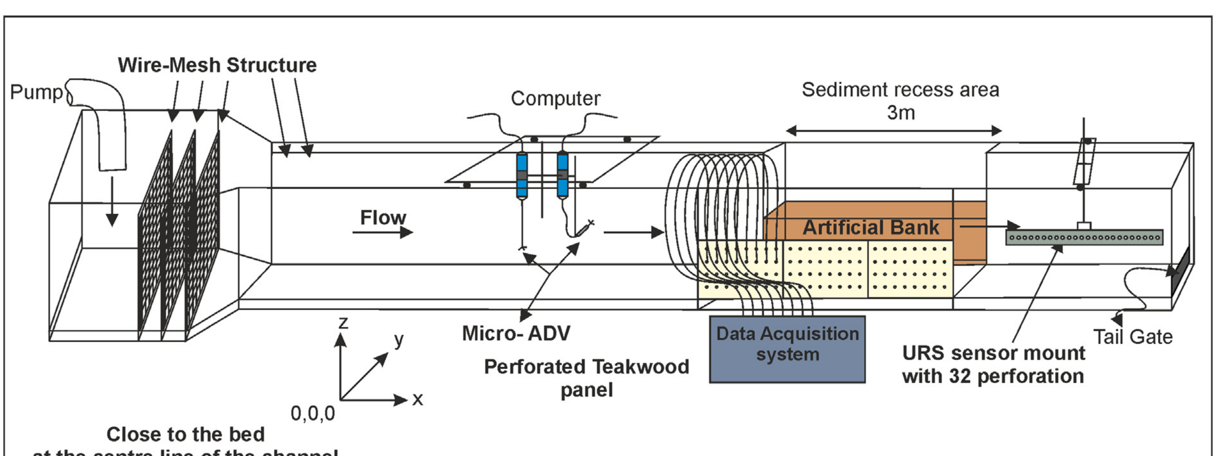

Fig. 1. Schematic diagram of the experimental flume with sediment recess for accommodating artificial bank, side-looking and down-looking micro ADV, URS sensor (Seatek).