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Experiments on the short-term development of sine-generated meandering rivers

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Abstract

This paper presents recent works on the simulation of short-term development of sine-generated meandering river in laboratory conditions. The influences of initial system parameters on the evolution process of rivers are investigated, including control over channel sinuousness, channel width and dominant discharge, eventually leading to different results of planforms. Measurements on the bank-line, flow field, bed topography and sediment transport rate were carried out. Braided rivers are easy to produce using non-cohesive sediments in floodplains, whereas environmental temperatures and humidities could influence the fluvial process by their effects on material cohesion. Channelized rivers were obtained in the “High Flow” conditions and the river corridor width was proven to be mainly connected with initial channel sinuousness and water discharge. Sickle-shaped and bamboo leaves-shaped sandbars were formed in the channels during the transformation process of meandering to braiding, the stability degree of sandbars reflects the adaption of channel morphology to hydrodynamic condition. Quantitative analysis confirms the formation of free steady bars, which manifests the free response as a downstream oscillation of the perturbation. Damping length is mainly affected by dominant discharge, channel width is the secondary factor, and channel sinuousness is the weakest factor. The wavelength of steady bars approximately equals to half of the initial streamwise wavelength. Sediment transport rate tends to increase with the increasing of channel sinuousness but stops growing due to the excessive increase of flow route and flow friction. The experiment results could be useful for verifying river pattern discriminant functions and offer a basis for further study on the morphological evolution of large-scale natural rivers, such as Yangtze River.

Keywords: Laboratory condition; Sine-generated; River pattern; Channelization; Cohesion

1. Introduction

In recent years, the transformation of river pattern has been given considerable attention; particularly, it is of great significance in promoting understanding of the dynamic behavioral process of river system (Nanson and Knighton, 1996). The patterns have been greatly expanded to mainly include straight, meandering, braiding and anabranching (Burge, 2006; Eaton et al., 2010; Song and Bai, 2015), of which meandering is the most common and fundamental phenomenon. Many researchers have devoted their efforts into modeling meandering in laboratory conditions, while proved to be technically challenging. The use of cohesive sediments or vegetation adds strength to river banks and is found to be a necessary condition for maintaining meandering (Ferguson, 1987; Smith, 1998). Whereas, rivers with non-cohesive floodplains would evolved from the stage of uniform bends into a braided state eventually (Murray and Paola, 1994; Schumm et al., 1987; Zimpfer, 1975). Considering the significant importance of cohesion on the river planforms, thus we can control the experimental river to develop toward the expected direction, and try to deeper understand the nonlinear changing characteristics of channel morphology (Pittaluga and Seminara, 2011).

Many studies focused attention on bank strength to create meandering river (Peakall et al., 2007; Smith, 1998). Bank strength has profound effects on width–depth ratios. If both bank and bed are composed of the same non-cohesive sediment, even without sharp bends (Hooke, 2003), the bends will migrate enormously through bank erosion and become wider and shallower (Crosato and Mosselman, 2009). Then braiding is initiated by chute cutoff (Friedkin, 1945). Dijk et al. (2012) summarized that a sustained dynamic upstream perturbation and floodplain formation are the sufficient conditions for the

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reformation of meandering after chute cutoff. Dulal and Shimizu (2010) concluded that the meandering should be regarded as the transition stage toward straight channel by cutoff or toward braiding by distributing flow over whole width. While, the development of river channels is actually controlled by complex nonlinear morphodynamic causes (Seminara, 1998). Perucca et al. (2005) applied some robust nonlinearity tests to the spatial series of local channel curvatures on the issue. Lee and Julien (2006) performed a nonlinear regression analysis on a large data set on downstream hydraulic geometry of alluvial rivers. Hooke (2007) suggested that significant autogenic element occurs in the dynamics of the most active meanders and this should not be underestimated in explanation of changes in morphology over time. He found evidence of some non-linearity and positive feedbacks in meander evolution, but at lower levels of activity, much of the behavior is simpler and linear. Lately, Gutierrez and Abad (2014) used a methodology that combines the capabilities of the principal component analysis and the discrete wavelet transforms to study meandering river, and found that compound bends, multiple loops and cutoff events are all associated with peaks in their proposed MC local curvature.

Due to lack of deep understanding of the flow–bed interaction mechanisms, there are still many issues to be addressed concerning bed morphology in alluvial rivers, whereas it is very difficult to model theoretically or numerically considering the variety and complexity (Xu and Bai, 2013), despite the existence of some encouraging achievements (Blanckaert and De Vriend, 2010; Camporeale et al., 2007; Posner and Duan, 2012; Xu et al., 2011a). Some experiments have been performed to reproduce and visualize sediment–flow interactions and bed morphology (Lajeunesse et al., 2010) after overcoming the defects of independent measurement (Limare et al., 2011). Huang et al. (2010) arranged a laser stripe across the experimental surface and mixed fluorescent dye into the flowing water, allowing simultaneous mapping of both bed topography and water depth at millimetric resolution. Limare et al. (2011) used an optical method known as moiré (Lancien et al., 2005; Tal et al., 2009) for analyzing the relevant processes and timescales that drive braided river evolution. Many researchers (Dijk et al., 2012, 2013; Lageweg et al., 2013) showed that typical point-bar ridge-and-swale topography developed under constant discharge in meandering river. van de Lageweg et al. (2014) hold that channel width variation along meander bends cause outer-bank erosion and scroll-bar formation. Various morphologic features including pools, point bars, and riffles are all genetically linked to the planform geometry via curvature effects on turbulent flow structure (Engel and Rhoads, 2012). While, bed morphology is the consequence of sediment transport and sedimentation. Alluvial channel bed alters its topography in response to changes in flow rates and sediment supply through measureable changes in sediment transport rates and channel bed slope (Curran et al., 2015). Church (2006) gave attention to qualitative relation between them and established a basis to gain new insights into the origins of alluvial channel morphology. Constantine et al. (2014) suggested that imposed sediment loads mainly influence planform changes in lowland rivers. Sergeant (2012) confirmed that a more recently modified stream would carry less sediment than a natural or unmodified stream. In addition, considering overbank sedimentation rates on floodplains provide a key indicator of the intensity of sediment and sediment-associated pollutant redistribution in river basins and the efficiency of sediment delivery (Golosov and Walling, 2014), there are still plenty of techniques on determining the sedimentation rates (Golosov et al., 2013; Macklin et al., 2006; Ritchie et al., 2004; Terry et al., 2002; Walling and He, 1998).

This paper reports on a series of physical model experiment conducted, allowing for the development of different planforms that started from meandering. The objective is to understand the influence of initial river system parameters on the changing process of planforms using simple cohesionless material in the floodplain. Environmental temperature and humidity are monitored for the first time in the laboratory planform evolution experiments.

2. Experiments

2.1. Experiment facilities

The experimental setup was designed as simple as possible. The experiments were conducted in a flume 12 m long and 3 m wide, made of concrete with sides that were 50 cm in height. In order to represent a meandering gravel bed river, the flood-plain was prepared with non-uniform riversand ($D_{50} = 0.58$ mm, $\sigma = (d_{84}/d_{16})^{0.5} = 1.77$) up to total thickness of 16 cm. The discharge flowing in the flume was regulated by the use of a control valve in the inlet pipe. Water circulated through the pipe with centrifugal pumps (discharge range up to 2700 cm^3/s), and together with sediment, were collected in the water bank and deposit bank respectively. A removable measuring bridge was mounted on both sides of the flume for collecting river regime and topographic data. In addition, 4 CCD cameras were fixed above water surface for measuring the surface flow field and recording channel morphology. Considering that these low-end cameras couldn't shoot widely, they were located just 2 m from the flume. Fig. 1 shows the schematic diagram of the experimental facility.

2.2. Experiment methods

The aim of the research is to study the effects of initial channel sinuousness, width and water discharge on the short-term fluvial processes. The main experiment procedures are: (1) in order to reduce the permeation loss, prior to the experiment, water is added to the flume until the pore water reaches saturation; (2) rough leveling the channel bed, setting channel ground control points based on pre-computing, and using digital level to ensure uniform bed slope, then excavating the sine-generated initial channel; (3) starting water pumps and delivering water to the channel gradually up to the designed discharge; (4) keeping the discharge constant, running the experiment for 5 h; recording the river bank location at an interval of 2~10 min, measuring the bed topography and surface flow velocity every 1 h; meanwhile continuously observing the development of river regime; (5) in order to prevent consecutive river-bed deepening and maintain the overall balance of sediment, the collected sand from the deposit tank is added to the channel inlet, reentering