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Experimental study on effects of geometric distortion upon suspended sediments in bending channels

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ABSTRACT

Different geometries of bending channels are set up without distortion and with distortion ratios of 2, 4, 6, 8 and 10 in order to study its influence on bed deformation induced by suspended sediment transport in these channels. Experiment results show that the kinematics of suspended sediment is inversely proportional to the distortion ratio of the physical model, but proportional to the width–depth ratio and curvature ratio. The similar bed deformation to that of the non-distorted model is only observed in the distorted models with distortion ratios of not more than 4 and width–depth ratios of not less than 6.3. It is recommended that the geometric distortion ratio be less than 4 in order to meet the similarity requirements of river bed deformation in bending channels. With the same distortion ratio, deviation of bed deformation was observed more in the bending reaches than in the straight ones and more with a fixed convex bank than with a mobile convex bank. The geometric distortion affects the river bed deformation in the model, i.e., the amount of deposition and erosion and the profiles of river bed deformation in longitude and transverse directions.

1. Introduction

The river physical model is a very useful tool to study river mechanics (Ettema, 2000). The river model is designed as normal or undistorted model where the horizontal and the vertical scales are set as the same value. Generally, the upper limits for the geometric scales of a physical model are limited by the physical properties of water as the model fluid; in particular, viscosity and surface tension. The modeled scale is usually limited by the flume area and water discharge capacity. In order to satisfy constraints on both the upper and lower limits of model size, it should be necessary to design a model with two geometric scales, generally using a larger scale for horizontal lengths than for vertical lengths (Ettema, 2000). As a result, there is a geometric distortion between the physical model and the prototype simulated by the physical model. Although the distorted physical model satisfies the experimental conditions, it does not necessarily obey the Froude Similarity Principle thoroughly.

In the distorted physical model, there are deviations not only in geometric similarity but also in kinematic and dynamic similarity (Yalin, 1971). The physical models of rivers are usually set up based on the Froude similitude law. According to the similarity principle, the hydraulic similarity in the vertical direction is affected by the scale distortion in the distorted model (Ettema, 2000; Zhao and Visser, 2010; Zhao et al., 2013). The variations in flow influence sediment transport and these variations increase due to mutual effects between the flow and sediment transport. Therefore there are some deviations not only in the velocity distribution but also the sediment transport between the model experiment results and field measurements.

The influence of geometric distortion on bed load is mainly reflected in sediment movement and transport rates. The vertical and horizontal slopes of the riverbed increase by some multiples of the distortion ratio. Sediment discharge is large in the positive slope and small in the adverse slope. The deviation is also larger when the distortion ratio is greater and the underwater angle of repose of model sand is not larger than that of prototype sand in the field. The model sand is unable to stay on the bed surface when the river bed gradient is larger than the underwater angle of repose. So, the deposition rate rises, changing the side slope angles in the channel, and the distribution of erosion and deposition is not similar to the prototype in the plan.

Although a large number of studies have addressed the problem of geometric distortion on physical river models, most are limited in assessing the impact of flow movement caused by geometric distortion (Maynord, 2006; Zhao and Visser, 2010; Zhao et al., 2013), and few have addressed the geometric distortion's effect on the riverbed deformation (Yen and Lee, 1995; Wei et al., 2001; Waldron, 2008). Many experiments and conceptual models (Lu and Peng, 1994; Sellin et al., 2001; Wallerstein et al., 2001; Duan, 2004; Fang et al., 2008) have been conducted to study the riverbed deformation caused by suspended sediment movement from the perspective of geometric distortion. However, it has not been proposed how the distortion ratio gives the effects on riverbed deformation and morphodynamic

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processes within bending channels. The geometric distortion affects the river bed deformation in the model, mainly by changing the amount of deposition and erosion, and the profiles of river bed deformation in longitudinal and transversal directions.

This paper proposes a series of generalized model tests to study the effects on riverbed deformation caused by suspended sediment movement from the perspective of geometric distortion. Experiments have been done in the bending channels of five types of physical models with different distortion ratios. The riverbed deformation induced by the suspended sediment is analyzed in the different models and the deviations between the normal model and distorted model experiment results are simultaneously taken into account. It is important to improve the accuracy of results and the simulation techniques of distorted physical river models.

This study is concerned with the geometric distortion's effect on river bed deformation induced by the suspended load. Sedimentation equilibrium can be indicated using the rate of deposition and erosion, including the total amount of deposition and erosion, deposition and erosion in cross-section, and the variation of cross-sectional morphology over the time. The deposition and erosion of the river bed reaches equilibrium when the rate of deposition and erosion is mainly stable. According to the experimental results of bending channels with fixed and movable convex banks, the study proposes the analysis of the plan variation of the riverbed, including the geometric change, the thalweg variation and the cross-sectional variation, due to sediment deposition and erosion in the river bed.

2. Dynamic similarity of physical model

Generally, similarity to the prototype is one of the most important factors in the physical model test. The similarity of flow is fundamental to the physical model test and it affects the similarity of sediment transport which reflects the characteristics of the sediment model or movable bed model. The degree of similarity influences the accuracy of model experiment results directly and is much more important in the distorted physical model than that in the normal model (undistorted model) (Zhao and Visser, 2010; Zhao et al., 2013).

2.1. Similarity of flow

The similarity of flow must be firstly satisfied in the movable bed model. According to the similarity theory principle, the similarity of flow can be derived from the continuity equation and Saint-Venant Flow equation (Sturm, 2010). The relationships of similarity can be written as:

$$\text{Continuity similarity}: \quad \alpha_Q = \alpha_l \alpha_h \alpha_v \tag{1}$$

$$\text{Gravity similarity}: \quad \alpha_v = \alpha_h^{\frac{1}{2}} \tag{2}$$

$$\text{Resistance similarity}: \quad \alpha_n = \alpha_h^{\frac{2}{3}} / \alpha_l^{\frac{1}{2}} \tag{3}$$

where α_Q, α_v, α_l, α_h and α_n are the discharge scale, velocity scale, horizontal scale and vertical scale, and roughness scale, respectively; h and l are vertical and horizontal dimensions respectively.

2.2. Similarity of sediment transport

Sediment moves in the channel mainly by suspended load and bed load. The sediment transport similarity refers to suspension similarity and incipient similarity, including the transport capacity similarity and riverbed deformation similarity.

2.2.1. Similarity of suspended load

The similarity condition of suspended load movement can be obtained according to the fundamental equations of sediment-laden flow derived from turbulent diffusion theory (Julien, 2002). According to similarity theory, the deposition similarity and suspension similarity can be written as

$$\text{Deposition similarity} \quad \alpha_\omega = \alpha_v \left(\frac{\alpha_h}{\alpha_l} \right) \tag{4}$$

$$\text{Suspended similarity} \quad \alpha_{v_*} = \alpha_v \left(\frac{\alpha_h}{\alpha_l} \right)^{0.5} \tag{5}$$

where α_ω is the deposition scale; α_h is the vertical scale; α_l is the horizontal scale; α_v is the velocity scale; and α_{v^*} is the suspension scale.

Eqs. (4) and (5) can be written in general as

$$\alpha_\omega = \alpha_u \left(\frac{\alpha_h}{\alpha_l} \right)^m \tag{6}$$

where $m = 1$ in Eq. (4) and $m = 0.5$ in Eq. (5).

Eq. (6) can be satisfied in the normal model ($\alpha_h = \alpha_l$), however, it does not work in the distorted model since the deposition similarity cannot reach the change of the bending channel in prototype, i.e., the deposition scales are different in horizontal direction and vertical direction. This disagreement brings difficulties in the model sand design. To approximately meet the two opposite similarity conditions, Eq. (6) can simultaneously be used to take into account the similarity of time-averaged velocity and turbulent diffusion on the impacts of suspended sediment movement. According to Eq. (6), the measurement accuracy is higher with $m = 1.0$ than with $m = 0.5$ in the analysis of similarity of suspended sediment movement. But the deposition deviation is larger with $m = 1.0$ than with $m = 0.50$. Considering sediment movement as well as deposition and erosion, a reasonable value of m is $0.5 < m < 1.0$. In practice, $m = 0.75$ is usually proposed.

Generally the suspended load is very fine grained, for example, the median size is approximately 0.03 mm in the middle Yangtze River (Wang et al., 2005; Li et al., 2010). Therefore the prototype sand can be considered as moving by suspension in the stagnant flow region. The settling velocity of model sand is typically smaller than that of prototype sand, and it also moves in the stagnant flow region. Therefore the formula of settling velocity in the stagnant flow region (Stokes equation) can be used to express settling velocity (Lamb, 1994)

$$\omega = \frac{1}{k} \frac{\gamma_s - \gamma}{\gamma} g \frac{d^2}{\nu'} \tag{7}$$

where ω is the settling velocity; k is the Stokes friction coefficient; γ_s and γ are the bulk density of suspended sediment and water, respectively; g is the gravitational acceleration; d is the sand diameter; v' is the velocity in stagnant flow region.

The diameter scale of suspended load can be written as

$$\alpha_d = \left(\frac{\alpha_\omega}{\alpha_{\frac{\gamma_s - \gamma}{\gamma}}} \right)^{1/2} \tag{8}$$

where α_d is the suspended load diameter scale; α_ω is the settling velocity scale; $\alpha_{\frac{\gamma_s - \gamma}{\gamma}}$ is the bulk specific gravity; α_k is the Stokes coefficient scale, and α_v is the velocity scale in stagnant flow region, with value of $\alpha_k = 1$, $\alpha_{v'} = 1$.

2.2.2. Similarity of incipient velocity

The scale of incipient velocity is equal to the velocity scale according to the condition of incipient similarity and can be written as

$$\alpha_{v_0} = \alpha_v \tag{9}$$

where α_{v_0} is the incipient velocity scale, and α_v is the velocity scale.