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Research paper

A physical, movable-bed model for non-uniform sediment transport, fluvial erosion and bank failure in rivers

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Abstract

Sediment transport processes in rivers continue to pose a challenge when designing movable-bed physical models, particularly for reproducing the grain sorting and bank erosion (fluvial erosion and mass failure). This paper presents and discusses scale effects of a specific scaling approach for multi-grain size mixtures that preserves similarity of initial motion for each grain size class and of the bank stability coefficient between the model and the prototype, but relaxes strict similarity of the Shields and particle Reynolds numbers. This approach is appropriate when bed load transport near incipient motion conditions is being studied, and allows for larger grain size scales than when full Shields parameter similarity is enforced. As part of an environmental project to rehabilitate sediment transport through bank erosion, this method has been applied to scale a Froude number criterion physical model of a reach of the Old Rhine (France). This has resulted in an undistorted scale of 40, and the use of sand as the model bank material. Each grain size has a different geometrical scale. The time scale for sediment motion is grain size and flow discharge dependent. An average time scale of 6 has therefore been used (four model hours = one prototype day). A strategy devised for the field case consists of two higher, larger island groynes that replace the three existing groynes, producing bank erosion for flow rates below the mean annual flow rate. Extrapolation of model behaviour to the prototype is not a major problem, but the volume of eroded bank material may be underestimated, mainly because of the relaxation of the Shields number similarity and the apparent cohesive properties of the model bank material.

Keywords: Bank failure; Old Rhine; Physical model; Sediment transport; Scale effects; Similarity

1. Introduction

Several approaches can be used for studying fluvial morphology, including fieldwork; theoretical, conceptual and numerical modelling; or experimental and physical models, and each approach has its own advantages and limitations. Physical and numerical models are often combined to provide solutions to practical problems. Numerical models are widely used in engineering applications, especially for large-scale

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problems where scale effects in physical models may become significant. However, they currently still include empirical formulations for flow (e.g. turbulence closure equations) and sediment transport (e.g. sediment sorting, flow—sediment—structure interaction) that cannot represent the details of these processes. For instance, multi-layered bank failure, bed forms and transport of widely graded sediments over partially armoured layers are still complex for accurate description in existing numerical models. The reliability of the numerical results may therefore be questioned.

Physical modelling can be used as an alternative visual display tool for investigating complex systems. Form—process—response interactions can be replicated intrinsically, without simplifying the assumptions that have to be made for numerical models. This is especially true when studying flow and sediment transport with local three-dimensional (3-D) features in complex geometries near structures (e.g. dams, weirs, groynes). The basic aim is to ensure that the relative magnitudes of all dominant processes and their associated sediment response are the same in the model and prototype (Gill and Pugh, 2009). The fluvial processes can then be observed in a reduced time-frame, within a controlled and manageable laboratory environment, while gathering a comprehensive set of quantitative data that can be used to calibrate numerical models, thus allowing further, long-term simulations to be carried out numerically (Peakall et al., 1996).

1.1. Dimensionless parameters

Similarity relationships for scaling hydraulic phenomena are well established and thoroughly tested against prototype-scale data (Heller, 2011). Similarity laws for sediment movement are far from unanimous. Various approaches based on the governing equations of flow and sediment dynamics, dimensionless analysis and semi-empirical concepts have been published on the topic (e.g. Yalin, 1971; Franco, 1978; Shen, 1991; ASCE, 2000; Ettema et al., 2000; Jain, 2001; Julien, 2002; Gill and Pugh, 2009). A basic dimensional analysis yields seven independent dimensionless parameters or groupings for the flow and sediment transport in the following form Π_A (Yalin, 1971; Julien, 2002):

$$\Pi_A = f_A\left(\underbrace{\frac{V}{\sqrt{gh}}}_{F}, \underbrace{\frac{u_* h}{\upsilon}}_{\mathrm{Re}}, \underbrace{\frac{\rho u_*^2}{g(\rho_s-\rho)d}}_{\theta}, \underbrace{\frac{u_* d}{\upsilon}}_{\mathrm{Re}_*}, \frac{u_*}{w_s}, \frac{h}{d}, \frac{\rho_s-\rho}{\rho}\right) \tag{1}$$

where the dependent variable A in Π_A might be energy gradient (i.e. flow resistance), sediment transport, or some other variable in the channel. Variables and dimensionless parameters in Eq. (1) are defined in Table 1. In theory all dimensionless parameters should be matched between the prototype and model for exact quantitative similarity. However, this is difficult to obtain without distorting the model and changing the sediment density ρ_s (ASCE, 2000), so similarity of some parameters must be relaxed.

Table 1
Model bank material scaling according to the geometric length scale Z_r, with $\theta_r = 1$.

Variables/Parameters	Definition
V, h	Velocity and flow depth, respectively
g	Gravitational acceleration
ν	Kinematic viscosity of water
ρ, ρ_s	Water and sediment density, respectively
d	Sediment diameter
w_s	Settling velocity
$u_* = (\tau/\rho)^{1/2}$	Bed shear velocity with τ as the bed shear stress
$F = V/(gh)^{0.5}$	Froude number
$\mathrm{Re} = u_* h/\nu$	Flow Reynolds number
$\theta = \rho u_*^2/[g(\rho_s - \rho)d]$	Shields number
$\mathrm{Re}_* = u_* d/\nu$	Particle Reynolds number
u_*/w_s	Relative particle fall velocity
h/d	Relative roughness in the absence of bed forms
$(\rho_s - \rho)/\rho$	Submerged specific gravity

1.2. Similarity laws for water flow

Most physical models of rivers are designed to ensure Froude number F similarity between prototype (subscript p) and model (subscript m), so that their ratio (subscript r) is equal to unity, i.e. $F_r = F_p/F_m = 1$. The flow Reynolds number Re is relaxed, assuming fully turbulent conditions in both prototype and model. The similarity of flow resistance is ensured by matching the relative bed roughness d/h between the prototype and model.

The Froude number similarity is necessary for local-scale models for which the velocity field should be replicated accurately in the model, but can be relaxed for large-scale cases with small to moderate Froude number ($F < 0.8$ in both prototype and model) in order to replicate sediment transport dynamics accurately (Song and Yang, 1979; De Vries, 1993; Maynord, 2006; Ho et al., 2010). Similarity of the relative bed roughness ratio d/h is rarely achieved for sand-bed rivers, because they are usually associated with low d/h values (ASCE, 2000; Maynord, 2006). However, Ettema et al. (2000) have shown a significant scale effect of d/h on bridge pier scour. Similarity of d/h becomes important in gravel-bed rivers without bed forms (Young and Warburton, 1996). This criterion is generally satisfied in undistorted models by scaling the prototype sediment diameter according to the vertical geometrical scale of the model ($d_r = h_r$), along with using non-cohesive sand in the model.

1.3. Similarity laws for bed load transport

Scaling sediment transport is based on ensuring similarity between prototype and model for several key parameters, such as Shields number θ, particle Reynolds number Re_* and relative particle fall velocity w_s/u_*. Simultaneous similarity may not be possible for all sediment transport parameters, and therefore care must be taken to determine when deviating from