Comparative study of the scaling of sediment transport in a bifurcated channel with reference to the river Kangasabati

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1.ABSTRACT

An experimental study on a scaled physical model of the bifurcation in river Kangsabati was conducted with the main objective to produce model-prototype similitude for the aspect of sediment transport and the approximate transport capacity. The approach that has been employed for physical model studies is based on a relationship between the dimensionless bed shear (shield parameter) and grain Reynold number. The model was tested with different sediment sizes of varying densities with a set of predetermined discharges. In order to compare the applicability of the model to physical ones in river engineering applications, a thorough analysis and discussion of the results are presented in this article.

Keywords: Similitude, Shield Parameter, Grain Reynold Number

2.INTRODUCTION

If the criteria for hydraulic similitude are satisfied, scale model studies of hydraulic systems have shown to be a practical way to assess the performance of a proposed construction or of suggested system improvements. The ratio of the relevant pairs of forces that are important to the physical processes under study in both the prototype and the scaled model must be matched. The ratio of inertial forces to viscous forces, also known as the Reynolds Number, and the ratio of inertial forces to gravity, also known as the Froude Number, are frequently of importance in both models and prototypes. For wide, shallow channels, the product of the fluid's velocity (V) and flow depth (y) is divided by the fluid's kinematic viscosity (ν) , giving the stream Reynolds Number (Re) (v). The fluid velocity (V) divided by the square root of the product of the gravitational constant (g) and the flow depth (y) yields the Froude Number (Fr).

$$Re=\frac{Vy}{\nu} \qquad\qquad Fr=\frac{V}{\sqrt{gy}}$$

Meeting both conditions in real-world applications would necessitate scaling of not just physical dimensions but also fluid parameters (such as viscosity and fluid density), which is nearly never possible because fluids with appropriately scaled properties are so rare. For economic considerations, water is both the model and prototype fluid in the majority of physical model studies of water conveyance and control systems. Viscous force effects are greatly reduced and observations from model performance will relate to prototype performance to a reasonable degree of precision if turbulent flow conditions are present for the aspect(s) of a system being studied in both model and prototype. Therefore, in order to prevent viscous effects (commonly referred to as "Reynolds effects") from impairing model performance, physical open channel flow hydraulic models are typically designed to adhere to Froude number scaling and to maintain turbulent flow conditions for the modelled aspects of interest. A stream Reynolds number of 2000 represents the lowest range for turbulent flow conditions.

A scaled physical model of horizontal and vertical scale ratio of 1: 350 and 1:70 respectively was conducted at Haringhata Central Laboratory (HCl), River Research Institute (RRI). The methods utilised to choose the right parameters for model design are presented in this work. Models involving of non-cohesive bed material must simulate bed shear stress because the bed shear stress causes the drag force required to overcome the submerged weight of a particle holding in place. The amount of drag force generated is a function of the Reynolds Number and is dependent on the degree of turbulence. The "Grain" Reynolds Number, abbreviated Re*, is the form of the Reynolds Number taken into account at the bed particle scale. For sediment movement, the hydraulic scale of interest is at the bed sediment particle diameter. Particle movement is a function of shear force – or the drag force – exerted by fluid moving past bed particles that exceeds forces holding the particles in place. Dimensionless bed shear known as Shields' Parameter is defined as the bed shear (τ_0) divided by the product of buoyant specific weight (γ_s-γ) and particle size (d_s). Dimensionless shear values representing the incipient motion state are plotted against grain Reynolds number to produce a curve for the condition of incipient motion. Dimensionless shear values that lie on this curve are known as "critical" Shields parameter values (Vanoni 1975). Pugh and Dodge (1991) proposed that the parallel relationship Taylor had shown between Shields' parameter values associated with constant Taylor's function values for small rates of sediment discharge and the critical Shields' values might hold for higher sediment discharge rates. Thomas W. Gill and Clifford A. Pugh (2009) Used a method that includes selection of model particle size and density based on terminal velocity (fall velocity) for particles in both scale model and prototype to produce sediment transport mechanism with useful degree of similarity.

3.MATERIALS AND METHODS

At the Haringhata Central Laboratory (HCL), River Research Institute (RRI), West Bengal, India, a rigid bed channels with fixed bank were used for the model experiments simulating the bifurcation at Kapastikri in the river Kangsabati. The River Kangsabati originates in Chotonagpur plateau of the Purulia district, runs through Bankura, Paschim Medinipur, and Purba Medinipur, and then merges with river Hooghly. The river progressively descends from old alluvium to deltaic soil until splitting into two branches near Kapastikri, known as the Old Kasai (or Cossye) and New Kasai.. The width of the Kasai river bed is 545m, just downstream of Mohanpur anicut, which gets reduced to only 91m in Kapastikri (45km D/S of the anicut). The studied region of this article is the bifurcation zone of river Kangsabati near Kapastikri.

The model has been laid down considering horizontal and vertical scale ratios 1:350 and 1:70, respectively (fig.-3). Here the distortion factor is 5. The discharge ratio of prototype and model is 1: 0.000005. The layout of the model is comprised of three branches: a main branch which bifurcates into two branches: New kasai (right branch) and Old kasai (left branch). The diversion angle of New kasai (right branch) is 14º and Old kasai (left branch) is 23º from the line of symmetry. The radius of curvature for New kasai (r_2) is 0.777 m and Old kasai (r_1) is 0.56 m respectively. Figure 1 depicts the main arrangement of the physical model. First, turbulence was eliminated from the water drawn from a well by passing it through a stilling chamber before it entered the experimental channel. An indigenously developed sand feeder used to the supply of sediments at the main branch such a distance that allows the sediments to be evenly dispersed before they reach the bifurcation point.

Fig-1: Physical Model set-up

4.EXPERIMENTAL PROCEDURE

The physical model has been done with primary goal to determine how sediments were distributed at a channel bifurcation. Prior to the main object, the present study demonstrates the procedure of scaling of sediment transport to be done in a physical model. The test rig consisted of a straight main channel, which bifurcated into two branch channels of different widths. Three different sizes of sediment of different densities were used to study the phenomenon. For each sediment size, five upstream discharges of 0.002, 0.004, 0.006, 0.008 and 0.010 m^3/sec have been used. The v-notch arrangement as shown in figure 2 used to measure the flow rate. The first step is to prepare the model bed with selected sediment and then run the model with selected discharges. The upstream sediment load supplied during an experiment for a particular discharge has been determined from Engelund–Hansen sediment transport formula. For the upstream discharges of 0.002, 0.004, 0.006, 0.008 and 0.010 m^3/sec, the average sediment loads were 3, 5, 8, 11.5 and 15 kg/hr respectively. The amounts of sediments estimated by using the Engelund–Hansen sediment transport formula corresponded very closely to the above sediment loads, i.e., the sediment transport in the main channel followed the Engelund–Hansen sediment transport formula (S.O. Sulaiman et.al., 2021).

Sediment transport capacity is calculated as follows:

$$q_t = 0.05\gamma_s V^2 \left[\frac{d_{50}}{\left(\frac{\gamma_s}{\gamma}-1\right)}\right]^{\frac{1}{2}} \left[\frac{\tau}{\left(\frac{\gamma_s}{\gamma}-1\right)d_{50}}\right]^{\frac{3}{2}} \quad \text{Eq-(1)}$$

Where,

q_t = Sediment load discharge in kg/hr;

γ_s= Unit weight of sediment in kN/m^3;

V= Mean velocity of the channel in m/sec;

g= Gravitational acceleration in m/sec^2;

ρ= Density of the water in kg/m^3;

τ = Bed shear stress in N/m^2;

d_{50}= Diameter of sediment particle in m;

The sediment transport consists of bed load only. The mean diameters (d_{50}) of the sediments used in the experiments were 0.190, 0.260 and 0.275 mm. A sand feeder is placed at the beginning of main branch provides the supply of the sediments. The sediment was supplied in such a distance so that the sediment uniformly distributed before reaching the bifurcation point. The sediment has been supplied uniformly across the width of main channel using a manually adjustable perforated device. The pores of the perforated device are being adjusted in such a way that it can supply the sediment uniformly across the width at a rate of 3, 5, 8, 11.5 and 15 kg/hr, respectively for the

Fig-2: V-notch arrangement to supply discharge on main channel

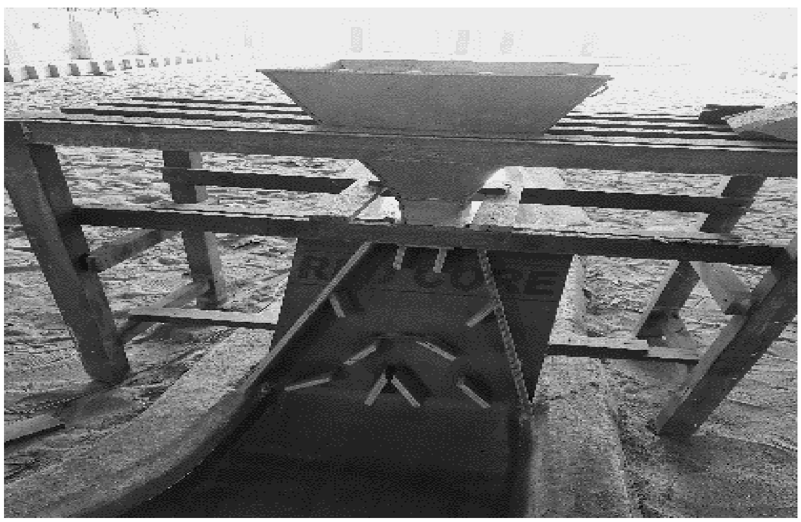

Fig-3: Arrangement of sediment supply

upstream discharges of 0.002, 0.004, 0.006, 0.008 and 0.010 m^3/sec. The sediment falls from the hopper into the wooden structure (Figure 3), which distribute the sediment evenly over the channel width. The model has been run for several hours with continuous supply of sediment at estimated rate. Each experimental run was continued till confirm the equilibrium condition was achieved i.e., when the discharges become constant in the downstream branches. After completing a set of experiment, the bed slope of model changes and continued with same procedure. The distributed discharges in the bifurcated branches (New kasai and Old kasai) were measured using calibrating stage-discharge chart for model. Ripples were found to formed in the channel bed at the end of the experiment. The transported sediments pass through the bifurcated branches captured in the sand traps, located in the downstream potion of each branch. The deposited sediment in the sand trap was collected, oven dried for 24 hours and weighted We utilized this method to calculate the rate of sediment movement in the downstream bifurcation branches.

3.RESULTS & HIGHLIGHTS OF IMPOINTANT POINTS

For this study model adjustments were identified following an iterative sediment transport model scaling methodology described by Pugh (Pugh 2008). The initial step was to look at Shields' values for particle of prototype density and of geometrically scaled size with equivalent channel slope in both model and prototype. Analysis of filed samples of prototype sediments indicated a prototype grain size of 0.415 mm. For scaled models, choosing the sediment size is getting more challenging, we can't simply reduce particle size in accordance with model scale as particle size become very small that may cause major changes in cohesiveness qualities, entirely changing the sediment transport mechanics between the model and prototype. To achieve transport mechanics that are usefully comparable between model and prototype, choosing a model particle size that is larger than the scaled value, utilizing a lower density bed material in the model, distorting bed slope, or a combination of both density and slope changes. Three different grain sizes of 0.190 mm, 0.260 mm, and 0.275 mm of different densities have been utilized in the model study. Corresponding Shields values calculated for model and prototype grain sizes were determined for the flow of 0.002, 0.004, 0.006, 0.008, and 0.010 cumec. Formulas were entered into spreadsheet cells to calculate dimensionless shear and grain Reynolds number for model and prototype at each of the selected flows and are shown in Table 1. Figure 4 clearly shows that dimensionless shear values for increasing grain sizes are far from lying on curves that are parallel to prototype values. For the next adjustment, reduced grain size of lesser density used for model study. Shield parameter for finer particle size of lesser density, d=0.190 mm, is shifted closer and roughly parallel to the prototype value out of three selected sediments used for the experiment, but it doesn't bring these values close enough to lying on parallel curves with corresponding prototype dimensionless shear values. Exaggerating the model bed slope would be another parameter that may be changed for the iterative design technique. Up to the link displayed in figure 6 was discovered, different slope distortions were investigated. From figure 6, a model slope of 1:250 appears to have curve exactly parallel to the prototype values but still away from corresponding prototype values. Further the unit sediment transport ratio for model compared with the prototype data for the corresponding discharges for model and prototype and compare the result as shown in Figure 2. Figure 7 compares the dimensionless shear values for the relevant discharges to the prototype values using crushed coal with a grain size of 0.80 mm and a specific gravity of 1.05 as the model sediment. Figure 6 appears to show that the 1:250 slope exaggeration and usage of lighter-weight sediment (crushed coal) as model sediment are suitable alterations that will allow the model and prototype

Table-1: Experimental data of dimensionless shear stress and grain Reynold number

Discharge in Cumec	Grain size d_{50}=0.190mm		Grain size d_{50}=0.250mm		Grain size d_{50}=0.285mm	
	Dimensionless shear stress (τ*)	Grain Reynold Number Re*	Dimensionless shear stress (τ*)	Grain Reynold Number Re*	Dimensionless shear stress (τ*)	Grain Reynold Number Re*
0.002	1.20783	5.631539	0.619068	7.40992	0.39783	8.4473
0.004	1.73810	6.755565	0.891631	8.88890	0.57249	10.1333
0.006	2.26635	7.714145	1.162619	10.1501	0.74649	11.5712
0.008	2.60174	8.265251	1.334670	10.8753	0.85696	12.3978
0.010	2.88907	8.709695	1.482067	11.4601	0.95160	13.0646

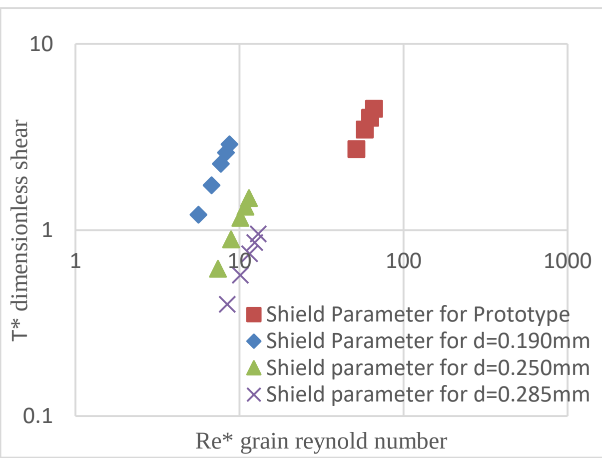

Figure 4: Dimensionless shear stress vs grain Reynold number for model & prototype

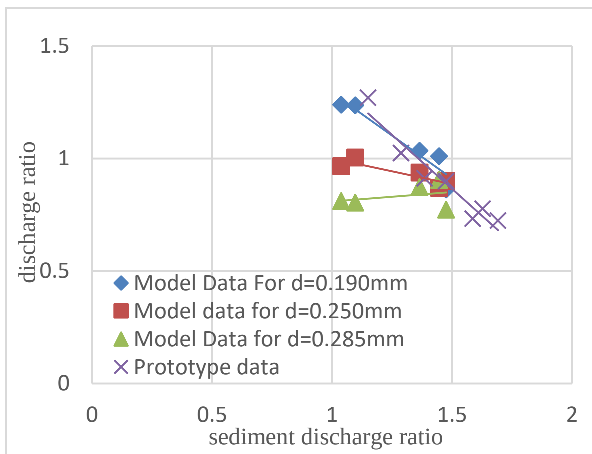

Figure 5: Discharge Ratio vs Sediment discharge ratio graph for model and prototype with slope distortion

to have sediment transport similitude. The transported sediment measured in model plotted with respect to discharge ratio shown in figure 5 compared with the prototype data. It's showing the grain size of 0.190 mm with slope distortion of 1:250 the discharge ratio and sediment transport ratio for model nearly match with the prototype values. Figure 7 presented here is not tested in the model study. The graph showing in figure 7 plotted based on the assumption that crushed coal of lower density and larger in size if used as a model sediment for the flow condition of 0.002, 0.004, 0.006, 0.008, and 0.010 cumec, dimensionless shear values match appropriately with the prototype values. The model will be examined further, taking into account assumed crushed coal with known particle sizes and specific gravities, to similitude sediment transport mechanism corresponds to the prototype.

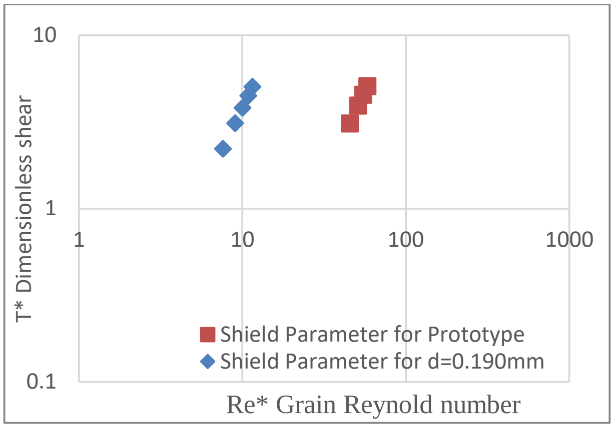

Figure 6: Dimensionless shear values for d=0.190 mm with slope exaggeration

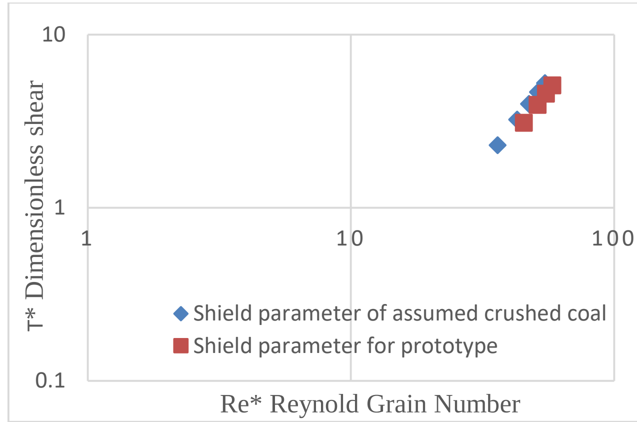

Figure 7: Dimensionless shear values assuming crush coal as model sediment with slope exaggeration

4. CONCLUTION

Dimensionless shear stress is an important parameter should have the same values in the model and the prototype to properly simulate sediment transport. It is readily apparent from figure 4 that dimensionless shear values for three different grain size come nowhere near lying on curves parallel to prototype values but got an idea that as the sediment size reduced the dimensionless shear value gradually shifted parallelly towards prototype values. For model adjustment slope distortion were examined until the relationship plotted in figure 6 was identified. From figure 6, it's identified a model slope of 1:250 appears to have curve exactly parallel to the prototype values but still away from corresponding prototype values. An assumption has been made if crushed coal is used as a model sediment, grain size of 0.80 mm and specific gravity 1.05, the dimensionless shear stress appropriately match with the prototype values as shown in figure 7. We may infer from the present study that utilizing a lower density bed material in the model, distorting bed slope, or a combination of both density and slope changes, the sediment transport similitude for scaled models and prototypes can be achieved.

5.ACKNOWLEDGEMANTS

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