

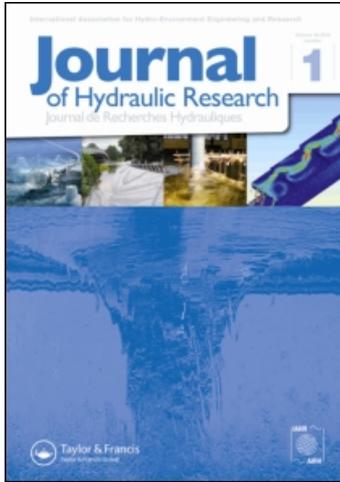
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Technical note

Predicting contraction scour with a two-dimensional depth-averaged model

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ABSTRACT

Contraction scour is often encountered in natural rivers due to natural geological controls, bridges, or river restoration structures. Such scour may be better predicted with multi-dimensional than one-dimensional models. The aim of this study is to investigate whether a two-dimensional depth-averaged model is adequate for modelling contraction scour. This study shows that improved predictions are obtained with the present model relative to previous model investigations. The study also shows that the current model is adequate for predicting contraction scour and model results are comparable with those of three-dimensional modelling except for the prediction of aggradation downstream of the contracted channel section.

Keywords: Aggradation, contraction scour, hybrid mesh, sediment transport, 2D model

1 Introduction

Scour can be broadly classified into two categories, namely general scour and local scour. According to Hoffmans and Verheij (1997), general scour consists of the long-term change in the bed level of a river, scour due to channel contraction, and scour in a bend or at a confluence. Local scour results directly from the impact of the structure on the flow. Different classifications are possible (Breusers and Raudkivi 1991, Melville and Coleman 2000). Herein, the ability of a two-dimensional (2D) model to predict contraction scour is analysed.

In recent years, mobile-bed numerical models are gaining popularity to simulate degradation and aggradation, in general, and scour location, size, and depth, in particular. One-dimensional (1D), 2D, and three-dimensional (3D) models have been developed. 1D models are most commonly used to predict reach scale river bed degradation, but contraction scour, as well as local scour in general, is better predicted with multi-dimensional models, of which most have analysed local scour near in-stream structures (Olsen and Kjellesvig 1998, Karim and Ali 2000, Roulund *et al.* 2005, Liu and Garcia 2006). There have been fewer modelling studies of contraction scour. Among these are Weise (2002) and Marek and Dittrich (2004)

using 2D models, and Bihs and Olsen (2007), and Minh Duc and Rodi (2008) using 3D models.

Weise (2002) and Marek and Dittrich (2004) reported that 2D depth-averaged models are inadequate for contraction scour prediction. The conclusion was based on a comparison between predictions from a 2D model and the scour measured in a particular laboratory channel. In both the narrowing and expanding channel sections, the predicted bed elevations did not agree with the measurement. The maximum scour location was on the opposite channel side. Also, the predicted scour ended immediately at the beginning of the channel expansion while the measured scour continued into the downstream channel. Marek and Dittrich (2004) attributed the poor prediction of the 2D model to two sources, namely its inability to account for 3D flow effects and deficiencies in the turbulence model. These findings led Bihs and Olsen (2007) and Minh Duc and Rodi (2008) to conduct 3D modelling using the Reynolds Averaged Navier–Stokes (RANS) equations. The two studies had conflicting results; however, Bihs and Olsen (2007) reported similarly poor predictions with the 3D model while Minh Duc and Rodi (2008) obtained much better results with the 3D model.

This study aims to investigate whether other factors may play an important role in 2D modelling of contraction scour.

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The specific contributions of this study are (1) expand the understanding of 2D model capabilities as related to contraction scour prediction; (2) identify factors that contribute to the poor performance of previous 2D models; and (3) demonstrate the differences and similarities between 2D and 3D RANS model capabilities. A successful computation of contraction scour with a 2D model is meaningful as an accurate 3D modelling is still beyond the computing capability for project applications.

2 Model description

2.1 Governing equations

The 2D flow solver is based on the verified model developed by Lai (2006, 2010). Sediment transport and mobile-bed dynamics are solved with the approach of Greimann *et al.* (2008). Herein, the sediment is assumed to be non-cohesive and transported as bedload, without suspended load. The sediment equation and the bed elevation equation are

$$\frac{\partial hC}{\partial t} + \frac{\partial U hC}{\partial x} + \frac{\partial V hC}{\partial y} = \frac{1}{L_b} (q_t^* - \sqrt{U^2 + V^2} hC) \quad (1)$$

$$(1 - p_b) \left(\frac{\partial z_b}{\partial t} \right) = - \frac{1}{L_b} (q_t^* - \sqrt{U^2 + V^2} hC), \quad (2)$$

where x and y are the horizontal Cartesian coordinates, t the time, h the water depth, C the depth-averaged volumetric sediment concentration, U and V the depth-averaged velocity components in the x and y directions, respectively, L_b the non-equilibrium adaptation length for bedload, q_t^* the equilibrium sediment transport capacity, z_b the bed elevation, and p_b the bed material porosity.

The non-equilibrium adaptation length characterizes the distance for the bedload transport to adjust from a non-equilibrium to equilibrium state. The average saltation length of Philips and Sutherland (1989) is used herein as

$$L_b = 4000(\theta - \theta_c)d; \quad \theta = \frac{\tau_b}{(s-1)\rho g d}, \quad (3)$$

where d is the sediment particle diameter, τ_b the bed shear stress, $s = \rho_s/\rho$, ρ the water density, ρ_s the sediment density, g the gravitational acceleration, and θ_c the critical Shields parameter.

The equilibrium sediment transport capacity may be computed from a number of equations. For gravel beds, the Meyer-Peter and Müller (1948) transport equation is most widely used. Wong and Parker (2006) modified this formula to improve the grain shear stress computation and their modified form is used as

$$\frac{q_t^*}{\sqrt{\rho g^2 d^3}} = 4.93 \left[\left(\frac{d_{50}^{1/6}}{20n} \right)^{1.5} \theta - 0.047 \right]^{1.6}, \quad (4)$$

where n is the Manning coefficient for total roughness and d_{50} the medium bed sediment diameter.

2.2 Numerical method

The solution of the 2D depth-averaged flow equations follows Lai (2010). A detailed presentation of the numerical method for the flow equations is omitted here. Basically, all governing equations are solved with the finite volume method ensuring mass conservation locally and globally. An unstructured hybrid mesh is used with an automatic wetting–drying procedure and a segregated solution procedure with the water surface elevation (WSE) as the solution variable. An implicit time marching scheme is used with the arbitrarily-shaped unstructured mesh methodology of Lai *et al.* (2003).

Equations (1) and (2) are discretized similarly to the flow equations. The sediment “depth” hC is the main dependent variable and the fractional step method is adopted as (Yanenko 1971)

$$\frac{(hC)^{\text{int}} - (hC)^k}{\Delta t} + \frac{\partial U(hC)^{\text{int}}}{\partial x} + \frac{\partial V(hC)^{\text{int}}}{\partial y} = 0 \quad (5)$$

$$\frac{(hC)^{k+1} - (hC)^{\text{int}}}{\Delta t} = \frac{1}{L_b} [q_t^* - \sqrt{U^2 + V^2} (hC)^{k+1}] \quad (6)$$

The advection Eq. (5) is solved implicitly to obtain an intermediate (superscript int) solutions $(hC)^{\text{int}}$ with known values $(hC)^k$ at time level k ; the initial value problem in Eq. (6) is solved analytically to obtain the new solution $(hC)^{k+1}$ at time level $(k+1)$.

A decoupled solution procedure between the flow and sediment modules is adopted. Within each time step, an iterative solution procedure is performed for the flow equations using known results at the old time level k . The flow variables (water elevation and flow velocities) at the new time level $(k+1)$ are thus obtained by assuming that sediment concentration and bed elevation are known. The sediment concentration and bed elevation are then solved based on the flow variables at time level $(k+1)$.

3 Contraction scour modelling

3.1 Flume case

A series of experiments were conducted to study contraction scour of a non-cohesive uniform sediment bed by Weise (2002). The rectangular flume (Fig. 1) has a 16.5 m-long test section and a width change between 1.0 m and 0.5 m for the contraction and expansion sections. The straight side wall is smooth glass while the curved side wall is rough concrete. The initial bed is flat and covered with a 20 cm layer of fine gravel of 5.5 mm mean diameter and a standard deviation in particle diameter of

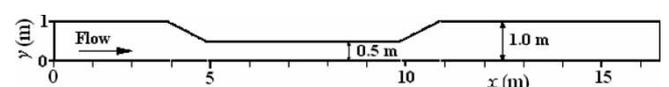


Figure 1 Plan view of test section of experimental flume and solution domain

Table 1 Parameters of flume test cases selected for simulation

Flume cases	Discharge (l/s)	Water depth at exit (m)	Test duration (min)
1	80	0.268	150
2	150	0.312	125

1.47. Two test cases are chosen for the present study with the respective parameters listed in Table 1. At the flume inlet, no sediment was supplied because no sediment was mobilized near the inlet. The same cases were simulated previously by Marek and Dittrich (2004), Bihs and Olsen (2007), and Minh Duc and Rodi (2008) with 2D or 3D models.

3.2 Numerical modelling details

A simulation domain of 15.5 m was chosen by excluding the 1.0 m entrance section (Fig. 1). A mesh of 200 × 24 cells was used. The mesh may be compared with the horizontal mesh of 123 × 23 cells of Minh *et al.* (2008) and 160 × 10 cells of Bihs and Olsen (2007). A mesh sensitivity study was carried out indicating that the 200 × 24 mesh is sufficiently fine (Figs 2–4). A fixed-bed, steady flow simulation was conducted

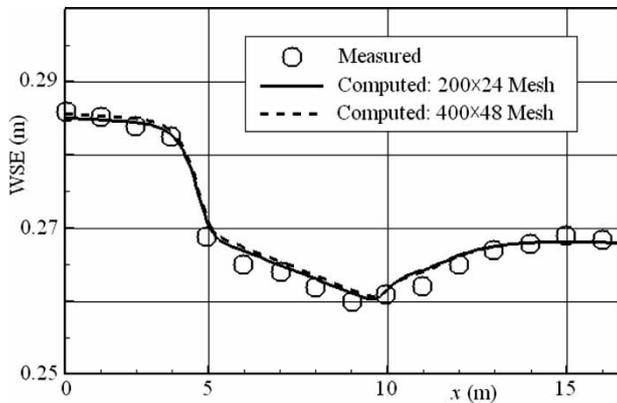


Figure 2 Comparison between predicted and measured cross-section averaged WSE for Q = 80.0 l/s

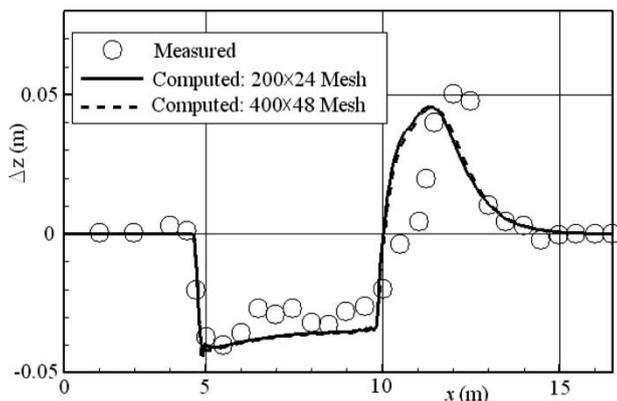


Figure 3 Comparison between predicted and measured cross-sectional averaged bed elevation changes Δz for Q = 150 l/s

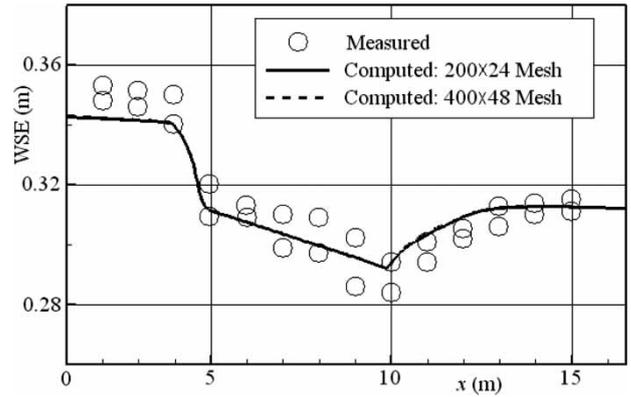


Figure 4 Comparison between predicted and measured cross-sectional averaged WSE for Q = 150 l/s

first. The flow hydraulics thus obtained is used as the initial condition for the mobile-bed simulation. A time step of 1.0 s was used for the unsteady sediment transport simulation.

The boundary conditions at the two side walls warrant some discussion. Herein, the wall function approach used in the 3D RANS model of Wu *et al.* (2000) was adopted. The first mesh cell near a vertical wall was selected. The resulting wall shear stress vector $\vec{\tau}_w$ was then calculated based on variables at the centre of the mesh cell, say point P, as

$$\vec{\tau}_w = -\frac{\rho \kappa C_\mu^{1/4} K_p^{1/2} \vec{V}_p}{\ln(E y_p^+)}; \quad y_p^+ = \frac{U_* y_p}{\nu}; \quad (7)$$

$$U_* = \sqrt{\frac{|\vec{\tau}_w|}{\rho}},$$

where \vec{V}_p is the depth-averaged velocity vector at point P, K_p the turbulent kinetic energy at point P, y_p the normal distance from point P to wall, ν the kinematic water viscosity, $\kappa = 0.41$, $C_\mu = 0.09$, and $E =$ roughness parameter (Cebeci and Bradshaw 1977).

$$E = \exp\{\kappa(5.2 - \Delta)\} \quad (8)$$

$$\Delta = \begin{cases} 0, & k_s^+ < 2.25 \\ [\ln(k_s^+)/\kappa - 3.3] \sin\{0.4258[\ln(k_s^+) - 0.811]\}, & 2.25 \leq k_s^+ < 90 \\ \ln(k_s^+)/\kappa - 3.3, & k_s^+ \geq 90 \end{cases} \quad (9)$$

where $k_s^+ = U_* k_s / \nu$ and k_s the effective roughness height. The roughness height was assumed zero for the smooth glass wall and calibrated for the vertical concrete wall.

3.3 Calibration study

The flow hydraulics needs to be computed accurately before mobile-bed modelling. The test case with a discharge of Q = 80.0 l/s was used to calibrate the roughness coefficients because no sediment transport was observed then. The

Manning roughness coefficient was calibrated to be a constant value of $0.0215 \text{ s/m}^{-1/3}$, and the roughness height of the curved wall was $k_s = 9.0 \text{ mm}$. A comparison between the simulated and measured WSEs for the calibration case is shown in Fig. 2. The agreement between the predicted and measured water elevations is adequate and similar to the 3D prediction by Minh Duc and Rodi (2008). The calibrated roughness coefficients were used for the mobile-bed modelling for $Q = 150 \text{ l/s}$.

3.4 Scour simulation

The flume experiment with $Q = 150 \text{ l/s}$ was selected for a mobile-bed model simulation. The predicted bed elevation and WSE are compared to the measured data in Figs 3 and 4; and the predicted erosion and deposition patterns are compared with the 2D results of Marek and Dittrich (2004), the 3D results of Minh Duc and Rodi (2008), and the laboratory measurements in Fig. 5. The present 2D model predicts the depth and size of the contraction scour reasonably well. The maximum scour depth is 0.0438 m while the measured maximum is 0.0400 m . The predicted maximum scour location agrees approximately with the measurement, which is an improvement over the previous 2D models. There remain two major differences between the present 2D model results and the measured data: (1) maximum scour is predicted to be along the centre of the contracted section while it was located near the wall in the measurements; and (2) location of the aggradation was predicted to be further upstream than the measured location and aggradation height is under-predicted. The first discrepancy is not unique to the 2D model and it is also present with the 3D model (Fig. 5c). It is probable that unsteady 3D flow phenomena such as flow separation or turbulence bursts are responsible which cannot be modelled by either 2D or 3D RANS models. The second discrepancy is likely due to the limitation of the 2D model in taking 3D flow effects into account.

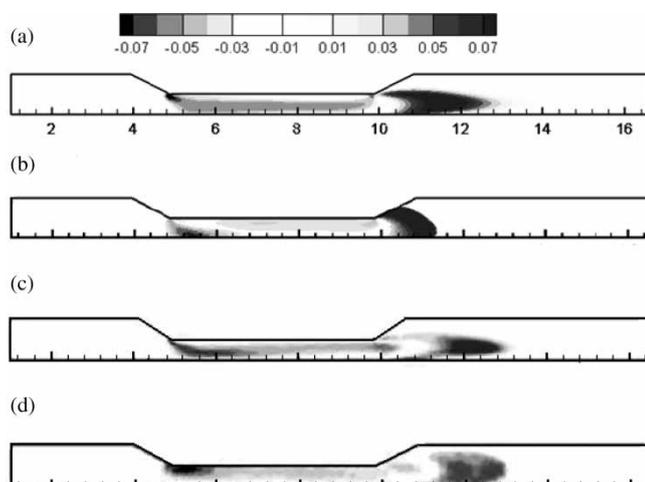


Figure 5 Comparison between predicted and measured bed elevations in (m) for $Q = 150 \text{ l/s}$ at $t = 125 \text{ min}$ for baseline case: (a) 2D model of present study, (b) 2D model of Marek and Dittrich (2004), (c) 3D model of Minh Duc and Rodi (2008), (d) measured data of Weise (2002)

A comparison between the present model results and the 2D results of Marek and Dittrich (2004) shows that improvements are achieved by the present model: maximum scour location is at the correct side and the scour depth and aggradation location are predicted better. Note, however, that the predicted WSE is less satisfactory upstream of the channel contraction (Fig. 4). There is also significant scatter in the measurement, which may have contributed to an underestimation of contraction losses at the upstream edge of the contraction.

A comparison of the present 2D results with the 3D results of Minh Duc and Rodi (2008) indicates that the scour location is similar although the magnitude of the scour depth is different. Also, the deposition in the 2D model is located upstream of that in the 3D model. This is attributed to the discrepancy in the deposition location to the inability of the 2D model to simulate 3D effects such as flow separation in the expansion section. Flow separation at the corner of the expansion is highly unsteady and turbulent in nature, and it would lead to a higher flow velocity in the channel centre downstream of the expansion.

4 Conclusions

A 2D depth-averaged mobile-bed numerical model was developed to simulate contraction scour under laboratory conditions. The main goal of this work was to investigate whether a 2D depth-averaged model is adequate for modelling contraction scour. It is found that: (1) 2D depth-averaged model, as reported herein, can simulate the measured laboratory contraction scour more accurately than reported by Marek and Dittrich (2004), (2) exact cause for the less satisfactory results of the previous 2D models remained identified, yet the use of the equilibrium sediment transport model is partly responsible; and (3) present 2D model results obtained are similar to those of the 3D modelling study by Minh Duc and Rodi (2008). However, aggradation prediction downstream of the expansion is less satisfactory with the 2D than the 3D model.

Notation

- C = depth-averaged volumetric sediment concentration
- d = sediment particle diameter
- d_{50} = medium bed sediment diameter
- g = gravitational acceleration
- h = water depth
- k_s = effective roughness height
- $k_s^+ = U_* k_s / \nu$
- K_p = turbulent kinetic energy at point P
- L_b = non-equilibrium adaptation length for bedload
- n = Manning coefficient for total roughness
- p_b = bed material porosity
- q_t^* = equilibrium sediment transport capacity
- $s = \rho_s / \rho$

- t = time
 U, V = depth-averaged velocity components in x and y directions, respectively
 U_* = frictional velocity
 \vec{V}_p = depth-averaged velocity vector at point P
 x, y = horizontal Cartesian coordinates in two directions
 y_p = normal distance from point P to wall
 z = vertical Cartesian coordinate
 z_b = bed elevation
 ρ = water density
 ρ_s = sediment density
 τ_b = bed shear stress
 ν = kinematic water viscosity
 θ, θ_c = Shields parameter and critical Shields parameter, respectively

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