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Experimental investigation of scour at a channel junctions of different diversion angles and bed width ratios

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ABSTRACT

Diversion flows from rivers or main channels affect bed morphology and cause erosion and sedimentation at the diversion channel junction. In a diversion channel flow system, the scour depth and scour length are considered important parameters and should be taken into account during the project construction stage because it affect the stability of main channel banks and crossing structures. In this study, the scour depth produced by diversion flow in a main channel was investigated using a physical sand bed model. The investigations considered five diversion angles (30°, 45°, 60°, 75°, and 90°), three bed width ratios (29%, 38%, and 48%), and five total discharges (7.25, 8.5, 9.75, 11, and 12.25 L/s). Results indicated that the scour depth in the main channel reduced as the diversion angle reduced. Empirical relationship to demonstrate relative scour depth (K_{ds}) for different diversion angles and bed width ratios was proposed. Relative scour depth can be defined as a relative scour depth in case of a diversion angle of θ° to that with 90° for the same flow condition and bed width ratio. Empirical relationships to estimate the scour depth and scour length with the governing hydraulic parameters were also established with a good accuracy. Testing the proposed relationships gave reasonable mean errors of 3.46% and 10.3% in predicting scour depth and scour length, respectively.

1. Introduction

The occurrence of scouring on the beds of rivers or unlined open channels is considered as the main factor causing the failure of hydraulic structures because it reduces the foundation cover of the structures and thereby threatens their stability. Diversion channels are widely used in irrigation networks, domestic use and hydropower projects (Meselhe et al., 2016). Moreover, diversion channel or river bifurcations are commonly found in natural rivers as a result of the rivers' dynamics processes (Kleinhans et al., 2013; Redolfi et al., 2016). Studying the flow behaviour in the diversion channel and flow diversion location is important for water management (Yousefi et al., 2011) and for sedimentation management downstream of the diversion (Baker et al., 2011).

Flow in diversion channels with rigid boundaries has been investigated extensively for a long time (Grace and Priest, 1958; Taylor, 1944) and still receives attention (Mignot et al., 2014; Mignot et al., 2013; Seyedian et al., 2014). Hsu et al. (2002), Ramamurthy and Satish (1988), and Ramamurthy et al. (1990) studied the hydraulics of right-angle diversion channels and found diversion channel-to-main channel discharge ratio is a function of the Froude number upstream or downstream of the main channel and the water depths. This flow phenomenon is governed by many variables such as hydraulic, diversion geometry, and boundary material parameters.

Although bed morphology is considered as an essential element of the design of a diversion channel (Xu et al., 2016), most of the studies related to diversion channel flow have been carried out with the rigid boundary condition (Mignot et al., 2014; Mignot et al., 2013; Momplot et al., 2017). Regarding sand bed condition, most of the diversion channel flow studies with a movable bed condition focused only on diversion channel flow with a diversion angle of 90° (Barkdoll et al., 1999; Herrero et al., 2015). While a few investigations have shown that the flow behaviour changes significantly at some diversion angles < 90°. For example, with fixing the diversion channel entrance width, the discharge in a diversion channel is maximum at an angle of 60° (Alomari et al., 2016). Keshavarzi and Habibi (2005) found from a laboratory study and by comparing separation zone sizes in different diversion angles (45°, 56°, 67°, 79° and 90°) that the optimum diversion angle is 55° according to separation zone size in the intake channel. Dehghani et al. (2009) recommended using an 115° rather than 150° diversion angle of the diversion channel from the bend flow because its recorded shorter length of the scour. Moghadam and Keshavarzi (2010)

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reported that the secondary currents consider as an important factor affect the erosion and sedimentation at the entrance of the diversion channel. These secondary currents depend upon many factors, such as the diversion angle and bed width ratio.

Many investigators to determine the safe foundation depth for the structures have studied the scour depth in the beds of rivers and movable bed channels around hydraulic structures. These studies have investigated different types of hydraulic structures such as pile group (Amini et al., 2012), complex bridge piers (Amini and Mohammad, 2017) and complex pier component (Amini et al., 2011), rock structures (Khosronejad et al., 2013; Pagliara et al., 2016), groynes (Dehghani et al., 2013), submerged obstacles (Euler and Herget, 2012), spur dykes (Duan et al., 2009), cross-vane structures (Pagliara and Kurdistani, 2013) and downstream hydraulic structures (Termini, 2011). At the open channel junctions in right-angle diversion channels, Barkdoll et al. (1999) and Herrero et al. (2015) observed a scour hole in the main channel bed at the downstream diversion channel conjunction edge. This scour hole is caused by secondary vortexes generated in the junction region. These vortexes play a major role in changing the bed morphology in the main channel downstream of the diversion channel.

The main objective of the current study, which is drawn from the above literature review, is to investigate the effect of the diversion channel flow with different diversion angles and bed widths on both the scour depth and scour length and to describe the flow field at diversion. Other objectives of the study are to study the influence of a range of water discharge, water depth and velocity in the main channel at upstream of the diversion section on the scour hole, and find empirical relationships to determine the scour depth and scour length under laboratory-controlled conditions.

2. Methodology

2.1. Dimensional analysis

Many parameters affect the scour hole size. In case of the local scour due to bridge piers, (Melville and Chiew, 1999) classified these parameters as follows:

1. Geometrical parameters
2. Flow property parameters
3. Fluid property parameters
4. Bed material parameters
5. Experiments running duration (t)

In diversion channel flow, the geometric parameters represented by the bed widths of the main and diversion channels B_m and B_b, respectively; and the diversion angle θ. Flow property parameters represented by the water discharge in the main channel at the upstream Q_u (Note that Q_u reflects the total discharge); the water discharge in the diversion channel Q_b; the main channel velocity and water depth at the upstream V_u and y_u, respectively; and the acceleration due to gravity g. Fluid property parameters represented by the water density and viscosity ρ and υ, respectively. Bed material parameters represented by the medium particles diameter d_{50}; the standard deviation for the bed material σ_g; the density of the bed material ρ_s; and the critical shear velocity and critical velocity of the particles inception motion U_c^* and V_c, respectively. Because only one type of bed material was used and the temperature of the water was kept constant during the experiments, the fluid property parameters for the bed material are not included in the analyses. With respect to experiments running duration, Aǵaçcioǵlu and Önen (2005) and Yanmaz and Altinbilek (1991) reported that the 6 h can be considered as a sufficient experiment running duration of scour modelling because the prototype duration corresponding to the modelling duration is quite long. The experimental work for Yanmaz and Altinbilek (1991) was included investigation of scour depth around the piers. While, Aǵaçcioǵlu and Önen (2005) investigated the scour depth in the main flow due to diverting some of the flow over side weir. In addition, Melville and Chiew (1999) reported that development of the scour depth reaches to 80% of the equilibrium scour depth during a time of 5% to almost 40% of the equilibrium time. Therefore, 12 h running duration was chosen for the experiments of this study.

The scour depth and scour length can be characterised as follows:

$$d_s \text{ or } L_s = f\,(B_m, B_b, \theta, V_u, Q_u, Q_b, y_u, g, V_c) \tag{1}$$

Carrying out dimensional analysis (Pi theory) yields these dimensionless parameters:

$$\pi_1 = \frac{d_s}{B_b} \text{ or } \frac{L_s}{B_b}$$
$$\pi_2 = \frac{V_u}{V_c}$$
$$\pi_3 = \frac{y_u}{B_b}$$
$$\pi_4 = B_r$$
$$\pi_5 = \theta$$
$$\pi_6 = Q_r$$
$$\pi_7 = F_u$$

The scour depth and scour length can be described as shown in Eqs. (2) and (3):

$$\frac{d_s}{B_b} = f\left[\frac{V_u}{V_c}, \frac{y_u}{B_b}, B_r, \theta, Q_r, F_u\right] \tag{2}$$

$$\frac{L_s}{B_b} = f\left[\frac{V_u}{V_c}, \frac{y_u}{B_b}, B_r, \theta, Q_r, F_u\right] \tag{3}$$

where L_s is the scour length, F_u is the Froude number for the main channel at the upstream, V_u/V_c is the flow intensity, B_r is the bed width ratio, and Q_r is the discharge ratio. The bed width ratio and discharge ratio can be expressed as follows:

$$B_r = \frac{B_b}{B_m} \tag{4}$$

$$Q_r = \frac{Q_b}{Q_u} \tag{5}$$

2.2. Experimental work

In this study, experiments were performed at the hydraulic laboratory of the Department of Civil Engineering, Universiti Putra Malaysia. For the experiments, a rectangular diversion channel system was used, which consisted of a main channel (12.5-m long, 0.6-m deep, and 0.313-m wide) and a diversion channel (2.75-m long and 0.6-m deep). The diversion channel was connected firmly to the left side wall of the main channel, and its bed width could be adjusted to 0.15, 0.12, and 0.09 m. Both the main and diversion channels had glass side walls. The diversion channel was designed to be flexible so that its connection angle with the main channel could be adjusted to obtain the required diversion angle. A sufficient amount of bed material was prepared by sieving sandy soil and re-distributing it again to obtain sand particles with medium diameter of 0.4 mm (standard deviation of 1.46) and specific gravity of 2.53. Part of the prepared sand was used to fill the flume bed with a 0.18-m-thick sand layer and addition amount was stored in a storage tank. Before starting each experiment, sand bed was flattened and if there any deficiency in the bed material, the sand in the storage tank can be used. Chiew (1984) considered a bed material with $\sigma_g < 1.5$ as being uniform. The diversion channel is fitted at the middle of the working section. Water and sediment are re-circulated through the diversion channel system by collecting them at the ends of the system and pumping them into the system again. A control valve and flow meter were installed at the pump outlet to control and measure the total discharge in the main channel, respectively. A volumetric method was used to measure the discharge in the diversion channel. A