Flood threshold value for bridge scour prediction and warning

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ABSTRACT: In Taiwan, owing to deep slope, frequency of extreme rail fall, typhoon attacking and earthquake impacts, huge amount of sediment would generate from mountain area and flow with flood toward downstream river. Then, the bridge safety issue is serious discussed during flood event. Therefore, bridge-scour problems have attracted considerable attention in Taiwan, spatially in Zhuo-shui River. In this study, the effects of bend and contraction scours could be neglected because of the river reach near the bridge is roughly straight and the channel width are substantially larger than the pier diameters, respectively. In addition, according to the river bathymetry survey, the bed elevation is generally steady around the bridge area. Therefore, the total scour depth of monitoring bridge is dominated by the local scour. It indicates that a two-dimensional numerical model is adopted to simulate flow field and water depth without sediment transport calculation for collected local scour depth formulas. An appropriate turbulence model, K-epsilon (k-ε) turbulence model, is the most common model used in Computational Fluid Dynamics (CFD) to simulate mean flow characteristics for turbulent flow conditions, spatially near bridge piers. Herein, the adapted empirical equations have been validated experimentally; using return-period hydrograph events, and they can give satisfactory simulation results. Then, flood threshold value for bridge scour prediction and warning can be established in the future. In the present study, based on the experimental results, those empirical equations will be suggested to compute the local scour depth evolution under unsteady flow caused by rapid changes of flow depth and velocity in field.

Keywords: bridge scour, local scour, numerical model, physical model

1 INTRODUCTION

The hydraulic impact is one of the major causes of bridge scour and bridge failure [Gee, 2003; Melville et al., 2006]. Bridge scour is a complex hydraulic process that comprises the development of down flows, vortices, and separation bubbles [Hong et al., 2014]. Flooding has been a common hazard and has major causes of bridge failure [Gee, 2003; Melville et al., 2006] such as collapse of piers and inundation in Taiwan metropolitan areas [Lin et al., 2010]. For example, six bridges collapsed in Taiwan were caused by pier scouring in Typhoon Sinlaku. In 2008, at 6:50 pm on September 14 six lives in three vehicles were lost because of the sudden collapse of the Ho-Fong Bridge which crosses the Dajia River in the central Taiwan collapsed [Lin et al., 2010]. Therefore, a real time flood forecasting model with the capability of predicting scour depth is established in Dajia River. There are different types of flood forecasting techniques have been developed by many researchers [Norbiato et al., 2008; Bartholmes et al., 2009; Thielen et al., 2009; Versini et al., 2010]. In addition, three main approaches for establishing a flood forecasting system: (1) deterministic models, (2) stochastic and statistical models, and (3) artificial neural network and fuzzy logic techniques [Guo et al., 2013]. Most of works focused on dynamic flood routing and did not consider pier scour due to floods. Hence, this paper presents the development of the scour depth predicting system and suggests to implement at Zhong-sha Bridge in Zhuo-shui River to prevent bridge failure as same as happened at Ho-Fong Bridge.

The depth of scour around bridge piers is an important parameter for evaluating bridge safety. The method to predict the scour depth can be generally divided into two categories: empirical formula and numerical model. Many researchers investigated the complex process of pier scour based on the laboratory models and proposed the empirical formula to estimate the equilibrium scour depth at bridge piers [Heza et al., 2007]. However, it is difficult to develop the so-called generic formula, which can be applied to all pier cases. According to the comparison of several empirical formulas of local scour depth, the predicted values of specific formula are proposed in this study for predicting the scour depth at Zhongsha Bridge. The adopted scour-estimating formula is suggested to combine the flood forecasting system, which is based on the integration of the Flood Early Warning. System (FEWS) and the flood routing models, for real time scour depth predicting. The scour depth prediction system is applied to Zhuoshui River for forecasting the flood stage as well as the scour depth at Zhong-sha Bridge, National Freeway No. 1. The photo of Zhong-sha Bridge is shown in Fig. 1. In the present study, based on the experimental results, those empirical equations will be suggested to compute the local scour depth evolution under unsteady flow caused by rapid changes of flow depth and velocity in field.

Figure 1. Photo of Zhong-sha Bridge

2 NUMERICAL MODEL

2.1 *Hydraulic model and simulation*

Most open-channel flows considering hydraulic scour depths are assumed shallow and the effect of vertical flow motions are not calculated if the down flow along the bridge pier is implicated in hydraulic scour equations. As a result, the 3D Navier-Stokes equations may be vertically averaged to obtain a set of depth-averaged 2D equations to calculate water depth and flow velocity [Lai, 2009, Lai, 2010, Lai, 2012]. The NTU-SFM2D model is one of a depth-averaged 2D model developed for studying open-channel flows. The model is used for solving the 2D shallow-water flow equations by using the finite-volume numerical method on unstructured hybrid mesh system [Lai, 2010]. The model can simulate the sub/supercritical flow and steady/unsteady flows in rivers that are generated by hydraulic structures such as bridge piers [Hong, et al., 2014]. Moreover, the model has been tested in several experimental or field cases in shallow-water flows [Lai, 2009, Lai, 2010, Lai, 2012], which has demonstrated that the model is suitable for practical applications in hydraulic engineering. However, NTU-SFM2D model cannot be used to compute the local scour evolution directly [Lai, 2012, Guo, et al., 2014]. Therefore, we adopt four different empirical equations to predict the local scour depth based on the simulated hydraulic patterns from the NTU-SFM2D model. Therefore, the NTU-SFM2D model is used in this study to simulate the temporal variation of general scour depth coupling with local scour depth.

Most open channel flows are relatively shallow and the effect of vertical motions is negligible. As a result, the three-dimensional Navier-Stokes equations may be vertically averaged to obtain a set of depth-averaged 2D equations, leading to the following standard de Saint-Venant equations:

The conservation system of governing equations are:

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{F}_{\text{conv}}}{\partial x}+\frac{\partial \mathbf{G}_{\text{conv}}}{\partial y}=\frac{\partial \mathbf{F}_{\text{diff}}}{\partial x}+\frac{\partial \mathbf{G}_{\text{diff}}}{\partial y}+\mathbf{S}, \tag{1}$$

$$Q=\begin{bmatrix} h \\ hu \\ hv \end{bmatrix},\quad \mathrm{F}_{\text{conv}}=\begin{bmatrix} hu \\ u^2+gh^2/2 \\ huv \end{bmatrix},\quad \mathrm{G}_{\text{conv}}=\begin{bmatrix} hv \\ huv \\ hv^2+gh^2/2 \end{bmatrix},$$

$$\mathrm{F}_{\text{diff}}=\begin{bmatrix} 0 \\ \frac{hT_{xx}}{\rho} \\ \frac{hT_{xy}}{\rho} \end{bmatrix},\quad \mathrm{G}_{\text{diff}}=\begin{bmatrix} 0 \\ \frac{hT_{xy}}{\rho} \\ \frac{hT_{yy}}{\rho} \end{bmatrix},\quad \mathrm{S}=\begin{bmatrix} 0 \\ gh(s_{0x}-s_{\mathrm{f}x}) \\ gh(s_{0y}-s_{\mathrm{f}y}) \end{bmatrix} \tag{2}$$

where Q is the conserved physical vector; F_{conv} and G_{conv} are the convection flux vectors in the x- and y-directions, respectively; F_{diff} and G_{diff} are the diffusion flux vectors in the x- and y-directions, respectively; S is the source term; h is the water depth; u and v are the depth-averaged velocity components in the x- and y-directions, respectively; g is the gravitational acceleration; $s_{0x}=-\partial z_b/\partial x$ and $s_{0y}=-\partial z_b/\partial y$ are the bed slopes in the x- and y-directions, respectively; z_b is the bed elevation; $s_{\mathrm{f}x}$ and $s_{\mathrm{f}y}$ are the friction slopes in the x- and y-directions, respectively; and T_{xx}, T_{xy} and T_{yy} are the depth-averaged turbulent stresses. The friction slopes are estimated according to the following Manning formula

$$s_{\mathrm{f}x}=\frac{u n_{\text{Mann}}^2\sqrt{u^2+v^2}}{h^{4/3}},\quad s_{\mathrm{f}y}=\frac{v n_{\text{Mann}}^2\sqrt{u^2+v^2}}{h^{4/3}} \tag{3}$$

where n_{Mann} is the Manning roughness coefficient. The turbulent shear stresses are determined by the Boussinesq's assumption

$$T_{xx}=\frac{2\rho\mu_t}{h}\frac{\partial(hu)}{\partial x},\quad T_{xy}=\frac{\rho\mu_t}{h}\left[\frac{\partial(hu)}{\partial y}+\frac{\partial(hv)}{\partial x}\right],\quad T_{yy}=\frac{2\rho\mu_t}{h}\frac{\partial(hv)}{\partial y} \tag{4}$$

where μ_t is the eddy viscosity due to turbulence, calculated by $\mu_t = 1/6\kappa u_* h$; κ is the von Karman coefficient of 0.4; $u_* = (\sqrt{(\tau_{bx}^2+\tau_{by}^2)}/\rho)^{1/2}$ is the bed shear velocity; and $\tau_{bx}=\rho g h s_{fx}$ and $\tau_{by}=\rho g h s_{fy}$ are the bed shear stresses in the x- and y-directions, respectively.

2.2 *Hydraulic scour estimation*

The hydraulic scour depth in front of a pier is affected by general scour, local scour, contraction scour, and bend scour [Deng and Cai, 2010, Hong et al., 2014]. In this study, the effects of bend scours could be neglected because of the river reach near the Zhong-sha Bridge is roughly straight. In addition, contraction scour is a function of the channel width upstream relative to the channel width through the bridge reach. Owing to the spans of the bridge piers are substantially larger than the pier diameters, the channel width does not change significantly. Therefore, contraction scours could be ignored.

The local scour depth evolution at the pier nose is computed by a specific position proposed by Shen et al. (1969), Laursen (1962), Inglis (1949), and Froehlich (1991) in this study. The selected four different empirical equations are described as following:

$$S_l/Y_1 = 2.5F_r^{0.40}(D/Y_1)^{0.60} \tag{5}$$

$$S_l/Y_1 = 1.5D^{0.7}/Y_1^{0.7} \tag{6}$$

$$S_l/Y_1 = 4.2DF_r^{0.52}b^{0.73}/Y_1^{0.27} \tag{7}$$

$$S_l/Y_1 = 0.32\phi b^{0.62}F_r^{0.22}/D_{50}^{0.09}/Y_1^{0.53} \tag{8}$$

In which, $S_l=$local scour depth；$Y_1=$Water depth of bridge upstream reach； $F_r=$Froude number of bridge upstream reach；$\Phi=$Correction coefficient of bridge noise shape；$\Phi=1.3$ for rectangular bridge noise；$\Phi=1.0$ for rounded bridge noise ；$\Phi=0.7$ for triangle bridge noise； $b=$ Pier width of transverse to the flow direction；$D_{50}=$ Mean diameter of sediment size and $D=$ Pier diameter.

3 PHYSICAL MODEL

Zhong-sha Bridge locates at 3km upstream of Zhuo-shui River mouth and spans a total length of 2,345 meters. It is an important traffic connection between Changhua County and Yunlin County. It was the longest bridge when it completed. This study includes physical model test and numerical model simulation. The experimental area includes 300m upstream and downstream river reach of Zhong-sha Bridge. Bridge floor, bridge pier and bridge foundation are set up in physical model. Experimental cases includes 100-year, 50-year and 25-year return period scenarios. The d_{50} grain size is about 0.5mm in the field and 0.014mm in the physical model. It means the physical scale is 1/36 of field. The incoming flow velocity, water depth and scour depth at the front of bridge pier are measured within physical test. The water-level needle gage is adapted for water depth and scour depth measurement and the accuracy is about ±0.1mm. The flow meter, ACM-200P, is selected for flow velocity measurement and the accuracy is about ±0.02m/s. In this study, the Froude similarity was adopted to scale the dimensions of flow patterns due to the free surface condition. According to the specific ratio (X-Y-Z scale = λ =36) of physical model, the theoretical scale of flow patterns were derived from similarity process and the results are listed in Table 1.

Table 1. Theoretical scale of flow patterns

Items	Flow patterns				
	X ,Y, Z scale [m]	Water level [m]	Velocity [m/s]	Discharge [m^3/s]	Roughness
Ratio	λ_X	λ_Z	$\lambda_X^{1/2}$	$\lambda_X^{5/2}$	$\lambda_X^{1/6}$
Scale	36	36	$36^{1/2}$	$36^{5/2}$	$36^{1/6}$

4 RESULTS AND DISCUSSION

This research interests on geometry setup and flow direction for bridge scour estimation. Mobile bed condition and bridge pier geometry are both considered around bridge scour impact location. Based on design discharge of return period in Zhuo-shui River, the 100-year, 50-year and 25-year are adapted for physical model test. The average flow velocity and water depth are measured on bridge pier which locates at main channel.

In this study described in numerical model, the NTU-SFM2D model was adapted to simulate the hydraulic patterns at different flow conditions including water levels, water depths and velocities, and general scour depths. Based on simulated results using the NTU-SFM2D model, the maximum value and temporal variation of total scour depths are calculated coupling with local scour equations. To estimate the general scour depth during the scouring process, the general scour is estimated by NTU-SFM2D using sediment transport equations. Owing to the limited hydraulic power within event period, general scour depths result from sediment transport simulation within flood-duration are not significant. This indicates that the local scour depth dominates the total scour depth in this event. The time-dependent local scour depth calculation using Eq. (5), Eq. (6), Eq. (7) and Eq. (8) are related to water depth of bridge upstream reach, Froude number of bridge upstream reach, correction coefficient of bridge noise shape, pier width of transverse to the flow direction, mean diameter of sediment size and pier diameter.

Given the hydraulic information from NTU-SFM2D model at peak discharge, Eq. (5), Eq. (6), Eq. (7) and Eq. (8) are employed to simulate local scour depth. Table 2 lists the results of the local scour depth calculated for the flood induced by three return period discharge. Comparison with experimental results in Table 2, the estimated local scour depth show that Shen et al. (1969), Laursen (1962) and Inglis (1949) are higher than Froehlich (1991). By contrast, incorporating with the NTU-SFM2D model and the algorithm of Froehlich (1991) was appropriately estimation of local scour depth. The Froehlich (1991) equation developed on larger data bases and this lead to the calculated local scour depth is further agreed with measured data. By real-time Freeway Bridge scour early warning system in the field, the investigated results indicate that the real-time warning system has the potential for further applications coupling with hydraulic simulation and feasibility scour depth equation. In addition, the suggested bridge scour warning system is not only useful for monitoring the water depth, scour depth and deposition height at piers, but it also could promote the accelerometers onto a single sensor board to diagnose the structural health of a bridge during footing failure. The accelerometers signal could show that the river bottom is scouring and could be closed to traffic prior to losing its structural integrity.

Table 2. Estimated scour depth of empirical equations (units：m)

Return period (year)	Shen et al., 1966	Laursen, 1962	Inglis, 1949	Froehlich, 1991
100	0.21	0.20	0.31	0.05
50	0.23	0.20	0.32	0.05
25	0.22	0.19	0.29	0.05

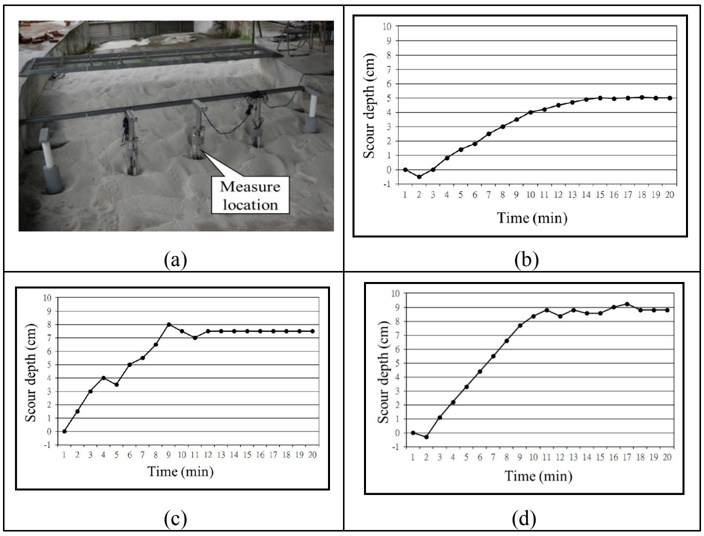

Figure 2. Scour depth evolution (a) measure location of scour depth (b) 25-year return period test (c) 50-year return period test (d) 100-year return period test

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