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A Physical Model Study of Scouring Effects on Upstream/Downstream of the Bridge

A PHYSICAL MODEL STUDY OF SCOURING EFFECTS ON UPSTREAM/DOWNSTREAM OF THE BRIDGE

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Dredging in an alluvial channel to increase the cross-section area of the channel can reduce the flooding risk. However, it may also create the potential of the scouring problem, especially around hydraulic structures such as bridge piers. This study focuses on the river reach at Yueh-mei-tan Bridge over the Pu-zi River in southern Taiwan. A physical model was constructed to investigate the scouring effects around bridge due to the excavation of the sediment deposits upstream and downstream of the bridge. The geometric scale ratios of prototype to physical model were determined to be 40 in vertical direction and 100 in horizontal direction.

1 Introduction

In Taiwan, the geologic formations are relatively young and unstable. Frequent earthquake and typhoon events cause drastic variations in river flow as well as sediment yield brought from watersheds. As a result, deposition and scour in river channels occur quite frequently and significantly to affect the channel stabilization, especially with the existing of hydraulic structures such as bridge pier, abutment, groyne, etc. In the deposition reaches, sediment deposition may reduce the channel cross-sectional area and decrease flow capacity, and hamper flood protection function to endanger traffic safety on the bridge. To understand the scouring effects on upstream/downstream of the bridge in the present study, a physical model is constructed to investigate the scouring effects around bridge piers due to the excavation of the sediment deposits upstream and downstream of the bridge.

The study reach in the Pu-zi River is located upstream and downstream of the Yueh-mei-tan Bridge. The Pu-zi River has a natural drainage area of 427 km^2 with average slope of 1/53. It flows from the mountain area to the alluvial plain and runs through the Jianan Plain in which is famous for its agriculture products. Cities are developed along the Pu-zi River with Dense population. There are 26 bridges crossing the river. The mean annual rainfall is 1,400 mm. However, the average slope of the study reach is 1/2,400, which represents the mild slope on the Jianan Plain.

2 Model Scaling

The geometric scale ratios of prototype to model were determined to be 40 in vertical direction and 100 in horizontal direction due to the limitation of the construction space. In other words, the physical model as a distorted model has the geometry scales of $\lambda_L = 100$ and $\lambda_h = 40$ in vertical and horizontal directions. λ is denoted as the ratio of prototype to model. The subscripts L and h denote horizontal length dimension and vertical length dimension, respectively. The physical model must satisfy the similarity of geometric, kinematic and dynamic conditions, and it should enable to simulate closely the phenomena which take place in the prototype. In the open channel flow, most of the cases satisfying the dynamic condition by Froude number similarity are sufficient. According to the geometric scale constraints; therefore, the flow velocity scale is $\lambda_u = \lambda_h^{1/2} = 6.32$, the flow discharge scale is $\lambda_Q = \lambda_u \lambda_A = 25{,}298$, and the time scale is $\lambda_t = \lambda_h^{1/2} / \lambda_L = 15.82$, The subscripts *u*, *Q*, *A* and *t* denote velocity dimension, discharge dimension, cross-sectional area dimension and time dimension, respectively.

For model scaling in the movable bed physical model, parameters describing the sediment transport behaviors are usually adopted to achieve dynamic similarity in an alluvial system with the Froude number similarity. According the study reported by the Water Resources Agency, it was found that with the Yang's sediment transport formula the numerical model could simulate the longitudinal bed variations through the period from 1975 to 1996 quite well. In the Yang's sediment transport formula, the unit stream power (*VS*/*w*) is the key parameter, in which *V* is the average velocity of the cross section, *S* is energy slope, and *w* is fall velocity of the sediment particle. According to the grain size data of bed materials in the study reach of the Pu-zi River, the sediment grain size is fair uniform and the d_{50} in the samples is about 0.3 mm. The fall velocity can be related to $f(d_{50})$. To satisfy the sediment transport dynamic condition by similarity, we can obtain the following relationship in Equation (1) based on the parameter: unit stream power.

$$\lambda_{D_s} = \lambda_V \lambda_S = \lambda_h^{3/2} \lambda_L^{-1} \tag{1}$$

For sediment concentration *C* in the water column, it is assumed that the *C* in the model is the same as that in the prototype. Thus, the ratio of sediment transport rate q_s per unit channel width is obtained as:

$$\lambda_{Q_s} = \lambda_Q \lambda_C = \lambda_Q = \lambda_h^{3/2} \lambda_L \tag{2}$$

According to Equation (1), the ratio of model to prototype for sediment size can be derived to be $\lambda_{D_s} = \lambda_h^{3/2} \lambda_L^{-1} = (40)^{3/2}(100)^{-1} = 2.53$, and the ratio of sediment transport rate is $\lambda_{Q_s} = \lambda_h^{3/2} \lambda_L = (40)^{3/2}(100) = 25{,}298$. Based on the ratio of the grain size, relatively uniform sand with d_{50} = 0.12 mm should be used in the model.

3 Experimental Setup and Results

Based on the constraints in the geometric scale ratios of prototype to model, the model construction is set to be 40 in vertical direction and 100 in horizontal direction. The cross section selected at the upstream end as the inflow boundary should be relatively straight and uniform for water and sediment supply control purposes. The river reach near Section 55 located before the river bend is relatively straight, and the patterns of deposition and erosion at Section 55 had been quite stable from 1996 to 2002. The downstream boundary is set at Section 48 at which locates before another river bend emerges. The layout of the physical model is sketched in Figure 1.

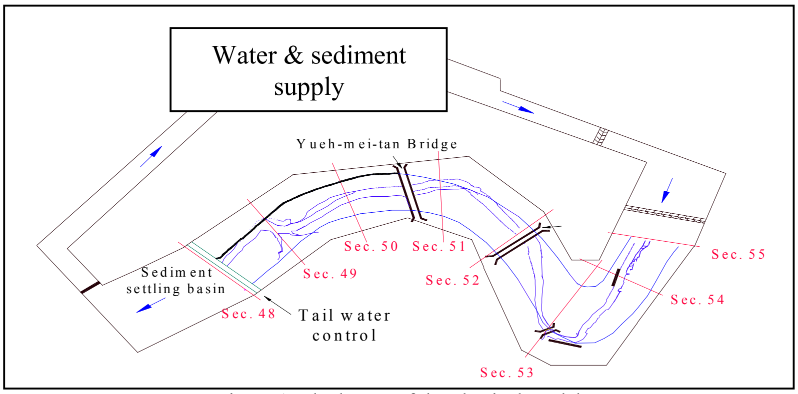

Figure 1. The layout of the physical model

The movable bed physical model is constructed to study the scouring on upstream and downstream of the Yueh-mei-tan Bridge at the Nanshijiao Hydraulic Field Station of Water Resource Agency, Taipei. The main testing cases herein are modeling the effects on the excavation of sediment deposits under the design flood event for the 100-yr return period flood. Before each experiment, the sand with d_{50} = 0.12 mm is carefully paved along the study reach by matching the topographical data from field survey obtained in 2002. The sediment supply released at the upstream boundary (Section 55) is obtained based on the sediment transport rate calculated by the NSTARTS model. The relationship between the sediment transport rate and discharge is plotted in Figure 2. The discharge hydrograph for the design 100-yr return period flood is cited from the report by the Water Resources Planning Institute (2002) and shown in Figure 3(a). Using Equation (2) and Figure 3(a), the sediment transport rate in the physical model can be calculated as shown in Figure 3(b). The hydrographs of unsteady flow presented in Figure 3(a) are given stepwise at the headwater tank and controlled by a sluice gate, which needs to be calibrated accurately.

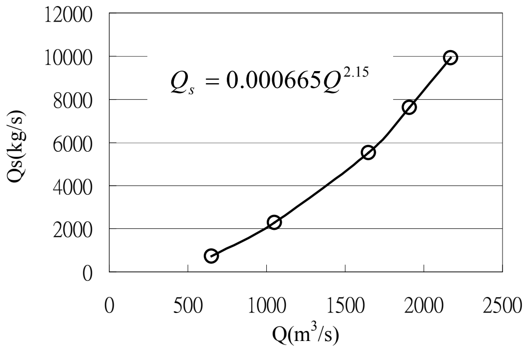

Figure 2. The regressed relation between Q and Q_s

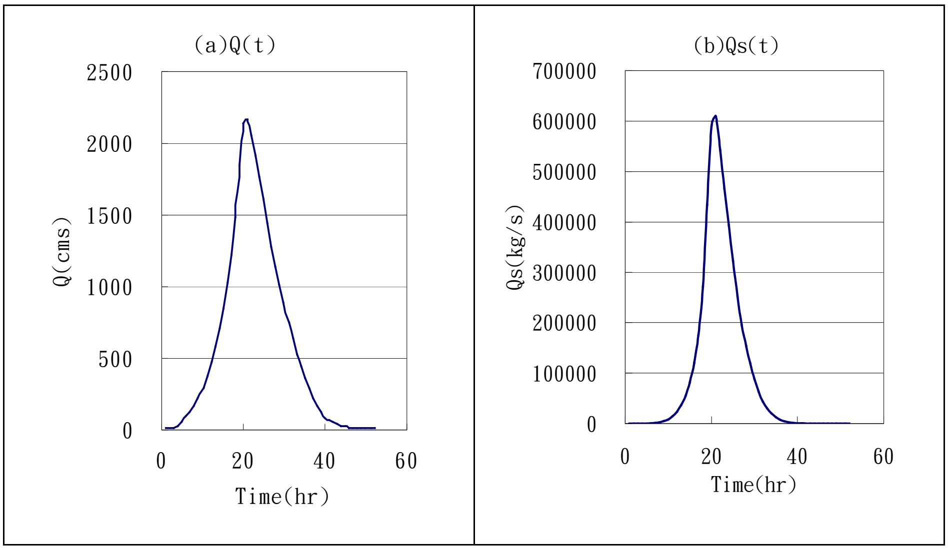

Figure 3. Hydrographs of (a) prototype discharge (b) sediment transport rate

The survey of bed elevation contour lines between Section 51 and Section 49 is plotted using fine solid lines in Figure 4. Various proportions for the reduction of the cross sectional area are investigated and modeled by the NSTARTS model. It is found that removing about 20% of sediment deposits along the left bank between Section 51 and Section 49 is beneficial for reducing the scour depth downstream and the flood stage upstream from the bridge. However, the NSTARTS model may simulate the quasi-two-dimensional (quasi-2D) behaviors of scouring as well as deposition in lateral direction, but it still is a one-dimensional (1D) model. In order to obtain the 3D flow and sediment movement near the piers locally, the experimental results from the physical model are essentially important.

To increase the cross-sectional area of the Yueh-mei-tan Bridge, excavation of sediment deposits between Section 51 and Section 49 is designed as plotted using thick solid lines in Figure 4. Under the 100-yr return period design flood with excavated cross section shown in Figure 5, the hydrographs of discharge and sediment supply are imposed at the upstream of the physical model. There are two testing cases including excavation with/without gabions using rock-and-wire baskets along the cross section to protect the piers. In the case without gabion protection around the piers, the measured bed elevation contour presenting degradation in the river reach between Section 51 and Section 49 is plotted in Figure 6. The result shows that scouring is severe around the first four piers. It may comprise the general scour as well as contraction scour. Due to the bend effect of the river reach between Section 51 and 52, the scour depths adjacent to the bridge piers between Pier 2 and Pier 4 are relatively deeper. However, the scour depth downstream of the bridge is not larger than that before excavation. The deeper scour hole may occur because water drop through the lower part of the gabions during the low flow. Similarly, the case with gabion protection results in a scour hole downstream of the bridge which is smaller than that before excavation, because it only goes through one flood event.

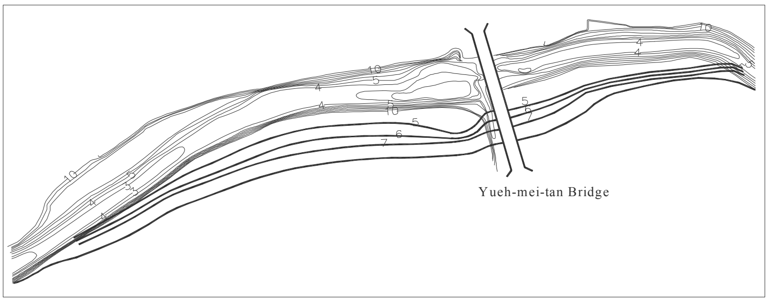

Figure 4. Bed elevation contour lines before (fine solid lines) and after (think solid lines) excavation

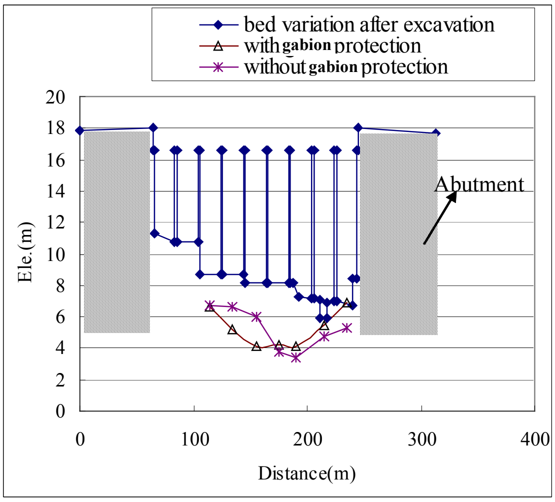

Figure 5. The bed variations at the cross section downstream side of the bridge

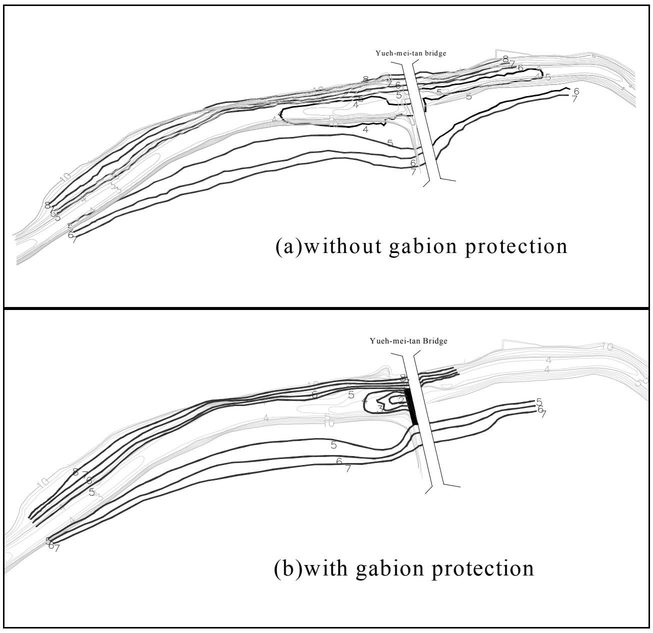

Figure 6. The effects of scouring (a) without (b) with gabion protection

4 Concluding Remarks

The present study focuses on the scouring problem in the river reach near the Yueh-mei-tan Bridge over the Pu-zi River in southern Taiwan. The geometric scale ratios of prototype to physical model are set to be 40 in vertical direction and 100 in horizontal direction. The physical model is constructed to investigate the scouring effects around bridge due to the excavation of the sediment deposits upstream and downstream of the bridge. The result shows that scouring is significant around the first four piers. It may comprise the general scour as well as contraction scour. It shows that using rock-and-wire basket gabions along the cross section to protect the piers is necessary in this case.

Acknowledgments

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