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Numerical Simulation on the Influence of Bridge Construction on River Flood Control in a Bottleneck Reach

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Abstract. Bottleneck reach regions with narrow and deep cross sections prevent sediment transport and weaken flood control capacity. In addition, bridge constructions can exacerbate the risk of flooding in these areas. In this study, the Longhai Railway Extension Project at the Xianyang reach of the Weihe River in China was selected as a typical object. A horizontal 2-D numerical model was used to assess the effects of three engineering plans on flood discharge capacity under three flood frequencies. Plan 1 was designed to include building a new bridge, demolishing the three original bridges and dredging a single section of the channel. Plan 2 was the same as Plan 1, except for the compound sections. Plan 3 was designed with the four bridges coexisting and no dredging projects carried out. The results indicated that Plan 3 will increase the water level by 0.2-0.3 m in the upstream reach. The cross-sectional area was approximately 370 m^2 larger under Plan 1 than under Plan 2. Water levels of 300-, 100-, and 5-year flooding around the bridge were reduced by 0.9, 0.9, and 0.6 m, respectively. To improve flood control capacity, an effective dredging project must be executed to widen the river and reduce the water stage in the bottleneck reach where the bridge is constructed.

Keywords: *bottle-neck reach; bridge construction; flood control; numerical simulation; Wei River.*

1 Introduction

An alternate distribution of wide and narrow reaches is the main feature of alluvial rivers [1,2]. The river's width is markedly decreased in a local area, called a bottleneck reach, because of geological conditions or human activities, thereby hindering flow transport and raising the water level upstream [3-5]. For example, the Tianjiazhen reach in the Yangtze River, which is a channel boundary that protrudes from the hills, is a typical bottleneck reach. Floods greater than 50,000 m^3/s can be virtually entrapped upstream for 2-3 days

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because the Yangtze River water covers above narrow rock-controlled points. High water periods of 3-5 days frequently occur in the reach and upstream toward Wuhan [6].

A bottleneck reach is an appropriate location for the construction of a bridge. However, bridge construction leads to a reduction of the discharge area, which threatens river flood safety [7-10]. Thus, considerable attention should be given to the influence of bridge construction on flood control in bottleneck reaches. Mathematical and physical models are two key methods that can be used to assess the effects of wading engineering on river flood control. Mathematical models are extensively used because of their convenience and low cost owing to the development of numerical simulation technology [11-14]. Because of the specific situation that the river width is small and the section is narrow and deep in a bottleneck reach, a horizontal 2-D numerical model is a suitable method that can accurately describe the plane shape and cross section of the river to simulate the influence of bridge construction on river flood control [15].

The Xianyang reach of the Weihe River, China is a typical bottleneck reach, in which bridges with spans of up to 100 m are located. The Longhai Railway Extension Project (LREP) of the Weihe River includes building a new bridge in the Xianyang reach and simultaneously dismantling three old bridges. The bridge has a length of 611.80 m and has 11 spans across the river. LREP is a typical project and was therefore selected as the study object in this research. The effects of different engineering plans under three flood frequencies on river flood control were evaluated through a horizontal 2-D numerical model. The results can provide technical support for bridge construction in bottleneck reaches.

2 Study Area

The Weihe River is the largest tributary of the Yellow River. The length and basin area of the Weihe River are 818 km and 134,766 km^2, respectively. The river flows through Baoji, Xianyang, Xian, and Weinan in Shaanxi Province. River flood control is important in the Xianyang reach of the Weihe River [16]. The widths in the upstream and downstream reaches of the LREP channel range from 500 to 700 m and expand to more than 1000 m by 338 m. LREP is located in a bottleneck reach. Currently, three bridges with spans of 100 m are located in the reach and their existence increases the backwater effect and reduces flood transport capacity (Figure 1).

Reinforcement and overhaul projects have been conducted several times on the existing Longhai railway bridges in the Weihe River. The bridges are 338.9 m long, the bridge span arrangement measures 12 × 27.1 m and the diameters of the piers are 2.4, 2.5, and 2.0-2.6 m. The bridges require reconstruction due to river flood control pressure and engineering safety.

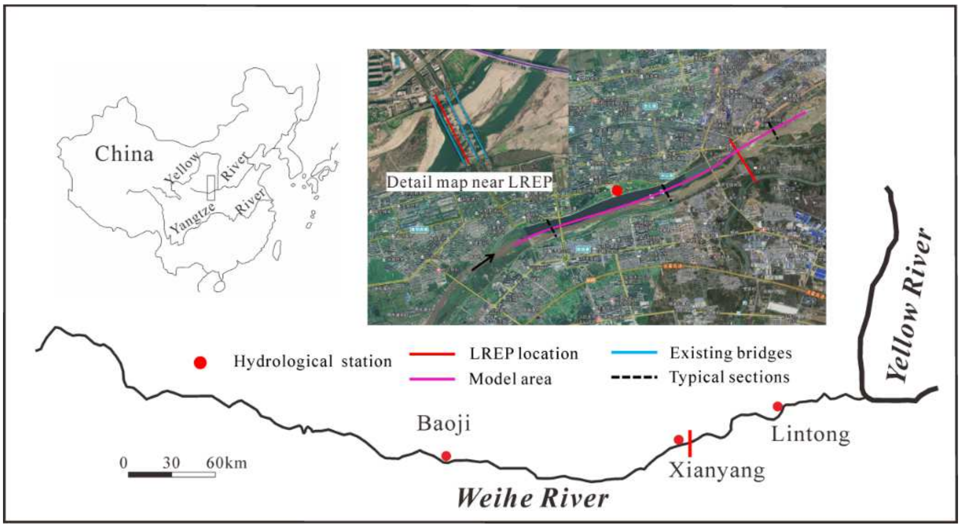


Figure 1 Sketch map of the Xianyang reach in the Weihe River.

3 Methods

3.1 Establishment of a 2-D Numerical Model

In this study, a 2-D flow mathematical model was used to investigate the effects of bridge construction on flood transport [17,18]. The control equations of the model are expressed as follows:

1. Flow continuity equation

$$\frac{\partial H}{\partial t} + \frac{1}{C_\xi C_\eta}\frac{\partial}{\partial \xi}\left(huC_\eta\right) + \frac{1}{C_\xi C_\eta}\frac{\partial}{\partial \eta}\left(hvC_\xi\right) = 0 \quad (1)$$

where H is the water stage, h is the water depth, t is the time, ζ represents the first coordinate in the orthogonal curvilinear coordinate system, and η represents the second coordinate in the coordinate orthogonal curvilinear coordinate system. C_ζ and C_η are the Lame moduli, and u and v are the velocities in the ζ and η directions, respectively.

2. Flow momentum equation

ξ direction:

$$\frac{\partial u}{\partial t}+\frac{1}{C_\xi C_\eta}\left[\frac{\partial}{\partial \xi}\left(C_\eta u^2\right)+\frac{\partial}{\partial \eta}\left(C_\xi vu\right)+vu\frac{\partial C_\eta}{\partial \eta}-v^2\frac{\partial C_\eta}{\partial \xi}\right]=-g\frac{1}{C_\xi}\frac{\partial H}{\partial \xi}$$

$$-\frac{u\sqrt{u^2+v^2}n^2 g}{h^{4/3}}+\frac{1}{C_\xi C_\eta}\left[\frac{\partial}{\partial \xi}\left(C_\eta \sigma_{\xi\xi}\right)+\frac{\partial}{\partial \eta}\left(C_\xi \sigma_{\eta\xi}\right)+\sigma_{\xi\eta}\frac{\partial C_\xi}{\partial \eta}-\sigma_{\eta\eta}\frac{\partial C_\eta}{\partial \xi}\right] \quad (2)$$

η direction:

$$\frac{\partial v}{\partial t}+\frac{1}{C_\xi C_\eta}\left[\frac{\partial}{\partial \xi}\left(C_\eta vu\right)+\frac{\partial}{\partial \eta}\left(C_\xi v^2\right)+uv\frac{\partial C_\eta}{\partial \xi}-u^2\frac{\partial C_\xi}{\partial \eta}\right]=-g\frac{1}{C_\eta}\frac{\partial H}{\partial \eta}$$

$$-\frac{v\sqrt{u^2+v^2}n^2 g}{h^{4/3}}+\frac{1}{C_\xi C_\eta}\left[\frac{\partial}{\partial \xi}\left(C_\eta \sigma_{\xi\eta}\right)+\frac{\partial}{\partial \eta}\left(C_\xi \sigma_{\eta\eta}\right)+\sigma_{\eta\xi}\frac{\partial C_\eta}{\partial \xi}-\sigma_{\xi\xi}\frac{\partial C_\xi}{\partial \eta}\right] \quad (3)$$

where n is the roughness coefficient, g is the acceleration due to gravity, and $\sigma_{\zeta\zeta}$, $\sigma_{\zeta\eta}$ and $\sigma_{\eta\zeta}$ are the turbulent shear stresses.

The differential equations presented above are discretely expressed through a finite-volume method to adapt to the complex river boundary. A staggered grid is applied to prevent the occurrence of jagged flow and pressure fields. The result of the discrete equations is solved by using a SIMPLEC algorithm, which can be found in Ref. [19].

3.2 Model Calibration and Validation

The model uses 200 × 100 grid points and its roughness n was determined by data measured in 2011 (Figure 2). The n in the beach and channel ranged from 0.035 to 0.041 and from approximately 0.016 to 0.027, respectively. The water stage verification at a 100-year flood is displayed in Table 1.

The errors of the calculated and measured values were less than 0.1 m in LREP. However, the value calculated at the Xianyang hydrological station was lower than the measured 0.74 m because the cross section in the water tank side has been broadened by approximately 100 m after the construction of Xianyang Lake and the water stage in Xianyang station decreased by 0.64 m under the same discharge.

The above comparison between the calculated and measured values indicates that the model can accurately simulate the characteristics of water transport and can be used to conduct the assessment.

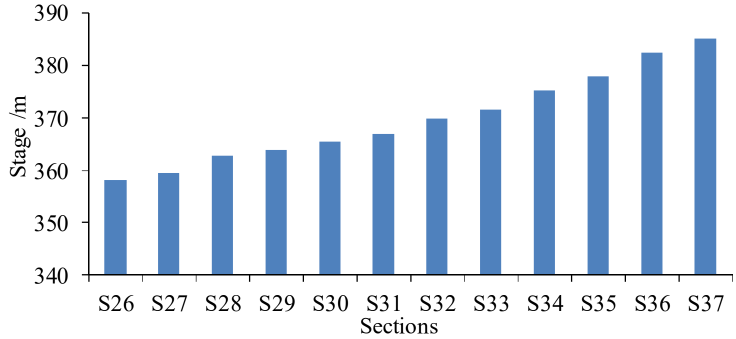


Figure 2 Flood mark stage of each section of the Xianyang reach in 2011.

Table 1 Comparison between calculated and measured values of water stage in a 100-year flood.

Section	Location	Measured water stage	Calculated water stage	Error
1	Xianyang station	388.74 m	388.00 m	−0.74 m
2	-	386.67 m	386.36 m	−0.31 m
3	LREP	385.58 m	385.49 m	−0.09 m

3.3 Simulation Conditions

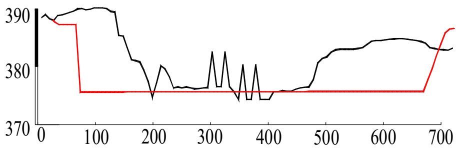
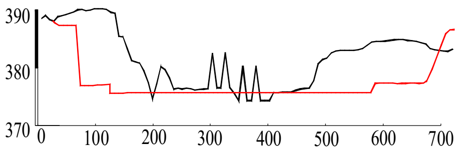
The designed floods for the bridge were determined on the basis of the flood water line frequency at Lintong and Xianyang stations. The hydrological calculation results are summarized in Table 2. This study used 0.33% (300-year flood, LREP flood design), 1% (100-year flood, levee flood design), and 20% (5-year flood, navigation flood design) frequencies of a typical flood, which reflect the critical hydrological conditions in the study area.

Table 2 Flood designs in LREP.

Hydrological station	Catchment area (km^2)	Designed flood (m^3/s)		
		300-year flood	100-year flood	5-year flood
Xianyang	46,827	10,810	9,170	3,890
Lintong	97,299	17,000	14,200	6,600
		LREP design flood	Levee design flood	Navigation design flood

Three plans were developed in this study. Plans 1 and 2 were designed with various dredging sections. The section shapes of Plans 1 and 2 are single and compound, respectively, and Plan 1 has a slightly smaller dredging amount. Plan 3 represents unfavorable conditions in construction, in which four bridges coexist and dredging projects are unfinished. The engineering of the three plans is shown in Table 3.

Table 3 Experimental scenarios design.

Plans	Dredging section profile	Short description
Plan 1		Building a new bridge and demolition of the original three bridges. Dredging a single section of the channel. Dredging parameters: riverbed elevation is 375.6m, river bank slope is 1:3.
Plan 2		Difference with Plan 1: the dredging section is designated as the beach trough and the beach body's height is 377.6m.
Plan 3	No dredging	Most dangerous condition in the process of construction, four bridges coexist and dredging projects are unfinished.

4 Results and Discussions

4.1 Changes in Hydraulic Factors at Bridge Site

The wetted area, width and velocity of the cross section near the bridge for the three different plans are illustrated in Figure 3. Under unfavorable conditions (Plan 3), the newly built bridge blocks water flow, there is a decrease of wetted area and width, and an increase of the section's average flow velocity. A large flow discharge indicates a significant engineering effect. The percentage of an appropriate water area near the new bridge is 11.62% under all flood conditions. For Plan 1, the wetted area and flow width increase and the section's average flow velocity significantly decreases; moreover, the water area near the bridge increases by 69.58%, and the river width increases by 143 m for a 100-year flood. For Plan 2, the amplitude and width of the cross-section area increase, while the reduction of velocity is relatively small because the amount of dredging is smaller than in Plan 1. For the change in hydraulic factors of the bridge, the new bridge in the bottleneck reach threatens river flood safety and the hydraulic factors are beneficial to reducing the pressure of flood control with dredging engineering.

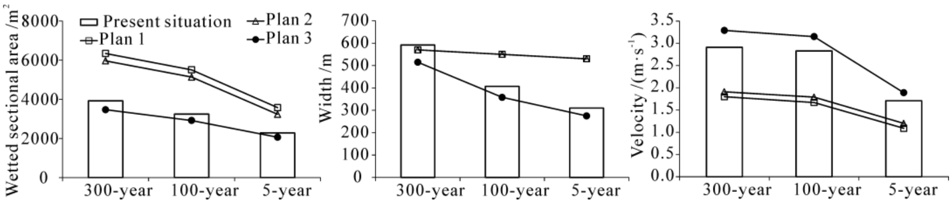


Figure 3 Hydraulic factor changes in LREP under different plans.

4.2 Changes in Flood Stage

The changes in flood stage near the bridge are depicted in Figure 4 and the water stage variations in the upstream reach are displayed in Figure 5. For dangerous conditions (Plan 3), the values of the water stage for 300-, 100-, and 5-year floods increase by 0.3, 0.25, and 0.2 m, respectively. The water stage zone greater than 0.1 m in the upstream of the bridge increases by 540, 450, and 35 m at the three floods, respectively. For Plan 1, the values of the water stage for 300, 100, and 5-year floods increase by 1.25, 1.25, and 1.10 m, respectively. The water stage zone greater than 1 m in the upstream reach of the bridge ranged from 200 m to 2200 m. The changing trend in the water stage for Plan 2 is almost the same as for Plan 1, but the amplitude is small.

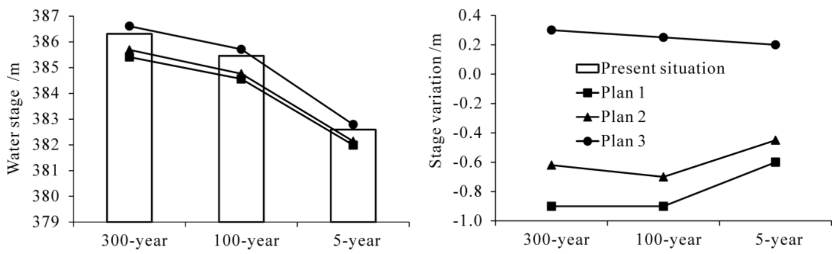


Figure 4 Flood stage changes in LREP under different plans.

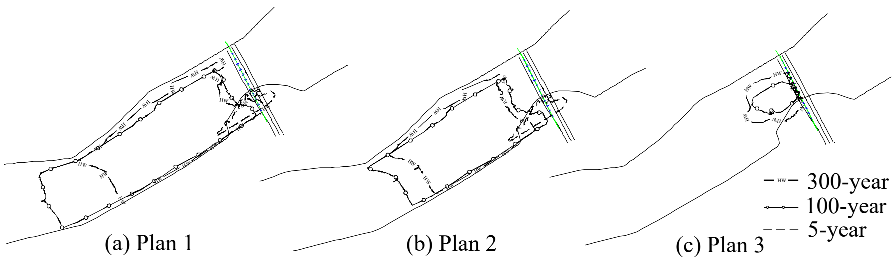


Figure 5 Ranges of water stage variation under three flood designs: (a) ranges of stage reduction greater than 1.0 m; (b) ranges of stage reduction greater than 1.0 m; (c) ranges of stage increment greater than 0.1 m.

In summary, the new bridge in the bottleneck reach increases the area of the backwater effect and the backwater scope may exceed 500 m on the basis of the changes in the flood stage for different plans. Dredging engineering reduces the flood stage; a high intensity of dredging has a favorable effect on flood control through a decline in the water level.

4.3 Influence of Bridge Constructions on River Flood Control in Bottleneck Reach

The new bridge encroaches the wetted area and increases the flood stage. Considerable studies have suggested that increased stage induced by bridge construction is approximately 0.1 m, which is less than our results (0.2-0.3 m) because the wetted area in the bottleneck reach occupied additional areas [8,15]. For example, the percentage of an appropriate water area in LREP is 11.62%, which is greater than the 7.66% induced by the Fenghuang Bridge in the Xibei River. Hence, the flood risk is high when bridges are built in the bottleneck reach.

The results of this study indicate that the flood stage will decrease when dredging activities are conducted along with bridge construction. River dredging will lower the flood stage considering the increase in wetted area [20]. Thus, an appropriate dredging project must be combined with bridge construction in bottleneck reaches, which will increase the flood river width, smoothen the flow, and improve flood control capacity.

5 Conclusions

To explore the effects on flood control of bridge construction in a bottle-neck reach, a horizontal 2-D numerical model was employed to simulate the changes in flood hydraulic factors and the stage after construction under different flood conditions. The conclusions can be summarized as follows:

1. The construction of a new bridge as part of the Longhai Railway Extension Project at the Xianyang bottleneck reach of the Weihe River in China threatens river flood safety. The flood stage increases by 0.2-0.3 m under dangerous conditions (Plan 3, four bridges coexisting).
2. The cross-section area is larger in Plan 1 than in Plan 2. Reduced amplitude of the water stage for the 300, 100, and 5-year flood in Plan 1, i.e. 0.9, 0.9, and 0.6 m, respectively. The effects are larger in Plan 1 than in Plan 2 because the dredging amount is greater in Plan 1 than in Plan 2.
3. An appropriate dredging project must be combined with bridge construction in the bottleneck reach, thereby increasing the flood river width, smoothing the flow, and improving the flood control capacity.

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