Preliminary study on the erosion impact of breach floods based on numerical simulation and physical model test

Xinyuan Liu*, Dong Chen, Geng Qu, Hui Zhang
Key Laboratory of Rivers and Lakes Control and Flood Control, Ministry of Water Resources, Yangtze River Scientific Research Institute, Wuhan, Hubei Province, 430010, China
*Corresponding author’s e-mail: wishesliu@126.com

Abstract. This paper established the combination model of numerical simulation and physical model test to fully demonstrate the influence of dike-breach floods on the pipeline. Numerical models were used to analyze the effects of different flooding schemes with different breach locations and different breach widths on the engineering line. The results show that the large flow velocity is mainly distributed in the vicinity of the breach for each scheme, and the influence is most serious when the breach occurs near the pipeline. Comparing the floods of different magnitudes comprehensively, the greater is the flood magnitude, the more serious is the influence on the pipeline. As the breach width increases, most of results show some characteristics, such as the decrease of the maximum flow velocity at the breach, the increase of the maximum flow velocity in other areas of the pipeline, the increase of the maximum flow velocity contour range, and the decrease of the large flow velocity duration. The plane and range of the scouring pit were obtained by physical model test. Considering results of numerical and physical model comprehensively, the protection ranges of different grades along the project were determined according to different ranges of impact velocities and scouring pits. The research results can provide reference for the protection of the pipeline in the Jiahetao area.

1. Introduction
There are many rivers and lakes with long embankment lines in China. Most of the small and medium-sized rivers are located in underdeveloped areas, with poor quality of dikes and low design standards. Dangers of dike-break or dike-overflow appear probably when floods occur. In particular, climate change in recent years has led to frequent and intense rainstorms, and sudden flood disasters, resulting in many casualties and great economic losses. From 2008 to 2015, the Ministry of Water Resources launched the first and second phases of the national flood risk map preparation project and carried out comprehensive work in turn, which was of great significance for scientifically carrying out disaster mitigation and risk aversion. In addition, with the development of social economy and the construction of a large number of infrastructures, such as high-speed railways, electric transmission lines, water pipelines and oil pipelines, inevitably crossing many small and medium-sized rivers and floodplains with high risk of dam breach, the formation of huge scouring pits in the vicinity of the embankment collapse bring risks and hidden dangers to the safe operation of these infrastructures. The risk analysis of dike flooding has received more attention and research. Complex flow states near the breach bring great difficulty to the flow simulation [1]. There are many researches [2-9] on the analysis model and algorithm of the dike-break flood at present, however, the application research on the influencing factors, scope and extent of the dike-break flood has yet to be further studied.
The northern part of Hubei Province is a region with relatively concentrated population and arable land. It has always been a region with drought and water shortage, which seriously affects the food production and urban and rural water supply security in the region. In recent years, Hubei Province has proposed that the water resources allocation project will be beneficial to alleviate the shortage of water resources in northern Hubei. The total length of the water transmission line is 269.67 km. The water resources allocation project line in the northern part of Hubei Province passes through the Jiahetao region, which is between Tang river and Bai river, and presents a wide, narrow and narrow trumpet-like terrain from the upstream to the downstream junction, as shown in Figure 1. The water transmission line is arranged by the steel pipe bridge spanning over the Bai River and the Tang River, and the PCCP pipe being buried through the Jiahetao area in the form of inverted siphon. The total length of the inverted siphon line is 6.44 km. Affected by special topography, heavy rainstorms are prone to occur in the basin of Tangbai River, which is easy to form large floods. Due to the low standard and poor quality of dikes, catastrophic floods occurred frequently in history. The distance between Tang river and Bai river is only about 6km along the project line with the flat terrain. The dike breach of the Tang river and Bai river may cause serious erosion of the buried pipeline, and affect the stability of the project. The protection of pipelines requires a large amount of stone, which has a great impact on the surrounding environment and also increases the construction cost. It is necessary to determine the reasonable scope of protection. According to the flow characteristics of the natural river channel and the Jiahetao area, this paper established a coupled hydrodynamic dike-breach model of one-dimensional river network for the Tang river and the Bai river and two-dimensional for the Jiahetao area. This paper studied the maximum possible influence range of floods to determine the simulation scope for the physical model test. And then the scouring range along the pipelines could be carried out by movable bed model test under the most unfavorable flood condition to provide reference for the regional flood impact analysis and the determination of the pipeline protection range.

Figure 1. Project location.
2. Mathematical model and method of dike-break flood

2.1. 1-D and 2-D coupled model of dike-break flood evolution

With high speed of 1-D model calculation and high accuracy of 2-D model calculation, it is necessary to establish a coupled model of 1-D for river flood simulation and 2-D for Jiahetao region flood simulation to improve the calculation efficiency by taking the advantages of 1-D and 2-D models [8].

2.1.1. 1-D hydrodynamic model. The 1-D hydrodynamic model for river uses the Saint-Venant equations as the governing equation.

Water flow continuous equation: \[ \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \]  
Water flow equation: \[ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + gA \frac{\partial z}{\partial x} + g\frac{Q|Q|}{c^2AR} = qu \]  

Where \( x, t \) are the length and time of the river, respectively; \( A \) is the section area; \( Q \) is the section flow; \( Z \) is the section water level; \( q \) is the lateral inflow; \( u \) is the component of the inflow velocity along the inflow direction; \( n \) is the riverbed roughness; \( R \) is the hydraulic radius; \( g \) is the gravity acceleration; \( \alpha \) is the momentum correction coefficient.

2.1.2. 2-D hydrodynamic model. The regional dike-break flood evolution can be described by the two-dimensional non-constant shallow water equation for the Navier-Stokes equation along the water depth average. The equations are expressed as

\[ \frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (h\bar{u}) + \frac{\partial}{\partial y} (h\bar{v}) = hS \]  
\[ \frac{\partial h\bar{u}}{\partial t} + \frac{\partial}{\partial x} (h\bar{u}^2) + \frac{\partial}{\partial y} (h\bar{u}\bar{v}) = f\bar{v}h - gh \frac{\partial \eta}{\partial x} - \frac{h}{\rho_0} \frac{\partial p_a}{\partial x} - \frac{g\bar{u}^2}{2\rho_0} \frac{\partial}{\partial x} + \frac{\tau_{xx}-\tau_{xy}}{\rho_0} - \frac{1}{\rho_0} \left( \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) + \frac{\partial}{\partial x} \left( hT_{xx} \right) + \frac{\partial}{\partial y} \left( hT_{xy} \right) + h\nu_s \]  
\[ \frac{\partial h\bar{v}}{\partial t} + \frac{\partial}{\partial x} (h\bar{u}\bar{v}) + \frac{\partial}{\partial y} (h\bar{v}^2) = -f\bar{u}h - gh \frac{\partial \eta}{\partial y} - \frac{h}{\rho_0} \frac{\partial p_a}{\partial y} - \frac{g\bar{v}^2}{2\rho_0} \frac{\partial}{\partial y} + \frac{\tau_{yy}-\tau_{xy}}{\rho_0} - \frac{1}{\rho_0} \left( \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) + \frac{\partial}{\partial x} \left( hT_{xx} \right) + \frac{\partial}{\partial y} \left( hT_{yy} \right) + h\nu_s \]  

Where \( t \) is the time; \( h \) is the total water depth (m); \( \eta \) is the water level (m); \( \bar{u} \) and \( \bar{v} \) are the average vertical velocity components in the x and y directions of the plane coordinate, respectively; \( g \) is the acceleration of gravity; \( f \) is the coefficient of Coriolis force for the Earth’s rotation; \( S \) is the source item; \( u_s \) and \( v_s \) are the source water flow rate components, respectively; \( T \) is the horizontal viscous stress terms, including viscous forces, turbulent stresses, and horizontal convective, which are derived from eddy viscosity equations based on velocity gradients along the water depth average, \( T_{xx} = 2A \frac{\partial \bar{u}}{\partial x}, T_{yy} = 2A \frac{\partial \bar{v}}{\partial y}, T_{xy} = 2A \left( \frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) \).

2.1.3. Coupling of 1-D model and 2-D model. The 1-D model of the river network and the 2-D model of the Jiahetao region are connected by the dike breach. The connection is the inner boundary of the coupled model, and the relationship between the physical quantities at the connection point needs to be supplemented to solve the solution. The breach is assumed to be a broad crest weir, and the turbulent flow is expressed as

\[ Q = k_s c_w b_c \sqrt{g(z - z_c)(z - z_c)} \]  

Where \( z \) is the upstream water level of the weir; \( z_c \) is the crest level; \( b_c \) is the weir width; \( c_w \) is the flow coefficient, which is related to some parameters, such as the shape and size of the weir wall; \( k_s \) is the correction coefficient of submerged outflow.

2.1.4. Solution method. The MIKE series of softwares are widely-used comprehensive software developed by the Danish Institute of Hydrodynamics (DHI) for water and water environment simulation. The software provides a river 1-D hydrodynamic module MIKE11, a regional 2-D
hydrodynamic module MIKE21 and a coupling platform MIKE FLOOD. Large number of structural modules, including the dam break DAMBREAK, are also integrated into MIKE. This paper used the MIKE series softwares to solve the dike-break model. MIKE11-HD uses Abbott-Ionescu six-point finite difference format. MIKE21 uses Alternating Direction Implicit method (ADI) and the pressure correction method (SIMPLE) to solve the water level and flow velocity. Mikeflood uses a lateral connection for 1-D and 2-D coupled dike-break flood evolution by setting a lateral virtual connection channel between the 1-D river network and 2-D Jiahetao region with the dike-break model arranged on it.

2.2. Model parameters and boundary conditions

2.2.1. Simulation range and meshing. The project area is located in the Jiahetao area between the Tang River and the Bai River. The unsteady flow hydrodynamic model of 1-D river network with the length of 80km from the Guotan Station in Tang river to the interchange, the length of 35km from the Xindianpu Station in Bai river to the interchange, and the length of 7km from the interchange to the Dongpo Station in Tangbai river, was established. Section positions in the river network are determined according to the distribution of the river course and the control nodes, and the average section spacing is about 1km. Triangular meshes are used in the Jiahetao area to fit complex boundaries, and the maximum area of meshes is less than 0.05km2. For the area near the dike breach, quadrilateral meshes with local encryption are used, shown in fig. 2.

2.2.2. Roughness. Due to lack of hydrological sites in the river network, it is difficult to directly determine the roughness value. Based on existing research results [10], the roughness value is 0.0295 for the main channel and 0.05 for the side beach from Dongpo station to Guotan station; the comprehensive roughness value is 0.025 for the reach from Dongpo station to Xindianpu station. The roughness of the Jiahetao area is assigned according to the type of underlying surface. The roughness value of cultivated land is 0.05, and the value of the village is 0.08.

2.2.3. Boundary conditions. For the upper model boundary, the Guotan Station in Tang river and the Xindianpu station in Bai river adopt the 200-year design flood considering the most unfavorable situation. The Dongpo Station in the model downstream boundary adopts the water level flow relationship. The calculation of dike break flow is based on the broad crest weir flow formula. For the river channel dikes and the main traffic lines in the area, only flooding without collapse situation is considered. The model calculation assumes that dikes of 1-D model are high enough not to overflow for the 200-year design floods which is higher than the dike design standards and the river safety discharge.

2.2.4. Dike break parameters. The dike break location where the risk is the most likely to occur, and the damage to the project is most serious and the management department is most concerned about, is taken as the dike break position in model calculation, and the distribution of breaches is also considered as uniform as possible. The position of B1, B2 and B3 are proposed for Bai river, and T1, T2 and T3 are respectively proposed for Tang river. BH1, BH3, TH1 and TH3 are located in the dangerous section, and BH2 and TH2 are located in the engineering position, shown in fig. 2. The breach width is calculated according to the empirical formula [11] due to the lack of historical data. The upper and lower limits of the width of each breach are 140m and 180m, respectively. However, the breach width of 250m is also considered for comparison. It is assumed that the breach is trapezoidal, and the breach lasts for 2 hours. The initial width and depth are 1/5 of the final width and depth, respectively, and then linearly spread according to time. The bottom height of the breach is determined according to the average elevation of the ground near the river beach. The breach occurs when the water level is highest.
3. Impact analysis of dike-breach floods

3.1. Water balance analysis
For the flood risk analysis of the 1-D and 2-D coupled model, water balance analysis is required for both 1-D river model and 2-D region model. Due to large number of impact factors of water quantity error in flood analysis calculation, such as complex terrain and dry and wet boundary treatment, numerical calculation truncation and other aspects, strict water balance is difficult to achieve. Taken the 180m width breach scheme of BH2 and TH2 as an example, the percentage of the 1-D model water volume error of the river channel is 0.0000001% and 0.000008%, respectively, and the 2-D model water balance error percentage is almost close to 0. The water volume error is very small and the amount can be considered to be balanced.

3.2. Analysis of the impact range
On the condition that the flood is not overflowing with high enough dike, the greater is the flood magnitude, the higher is the river level, and the greater is the impact range of the flood. This paper only calculates 10 combination schemes of different breach locations and widths (140m, 180m and 250m), under the 0.5% design flood conditions of Tang river and Bai river. Locations with the maximum breach possibility, the most serious threat, and the most concerned attention are taken as the calculated breach position, shown in Fig. 2. The surface layer near the Bai River is dominated by medium coarse sand, and the surface layer near the Tang River is covered with a thick layer of clay. The Baihe side is easier to be scoured. The impact velocity of the Baihe and Tanghe sides is 1.3m/s and 1.5m/s, respectively.

The velocity distribution along the pipeline of different breach locations is shown in Fig. 3(a)~(b). The result shows that the impact of breach at the project location is most serious. For the different breach locations of Tang river and Bai river, the impact range of the large flow velocity is mainly limited to nearby area of the breach. For the BH2 and TH2 breach schemes at the engineering location, different breach width of 140m, 180m and 250m were selected. According to the numerical simulation results, the duration of the maximum flow velocity above 1.3m/s for the Bai river side and 1.5m/s for the Tang river side were calculated, shown in fig. 3(c)~(d) respectively. As the breach width...
increases, the maximum flow velocity at the breach decreases, the maximum flow velocity in other areas of the pipeline increases, the maximum flow velocity contour range increases, and the large flow velocity nearby the breach continues. Considering the two aspects of the maximum flow rate range and the large flow rate duration, the 180m breach scheme can be considered to be the most unfavorable.

Figure 3. Maximum flow velocity distribution and duration along each project.

Figure 4. Impact velocity range of different breach widths.

Comparing comprehensively the calculation results of different schemes, the breach scheme of Bai river and Tang river with the breach width of 180m at the project location under the 0.5% flood conditions were selected as the most unfavorable schemes, respectively. The maximum flow envelope of each calculation scheme was obtained, as shown in Fig. 4. The length along the pipeline with the
impact velocity above 1.3 m/s on the Bai river side and above 1.5 m/s on the Tang river side is 562m and 608m, respectively. The impact range on the calculation boundary conditions can provide a basis for the determination of the conditions and scope of the physical model test.

4. Impact analysis of dike-breach flood erosion

4.1. Physical model test conditions

According to the most unfavorable conditions of the mathematical model (BH2 and TH2 breach at the engineering location with 200-year design floods), the physical model simulation range was determined, and movable bed model tests and fixed bed model tests were respectively carried out for the scouring impact of the dike break flood on the Jiahetao area. The physical model adopts a normal model, and the selected model scale is shown in Table 1 according to the numerical model calculation results and comprehensive consideration of constraints such as the site and the scale of the protection project. Yellow sand and plastic synthetic sand were selected as the model sands, respectively, according to clay and sandy loam of the soil composition near the location of the Tang River and the Bai River.

Table 1. Summary table of the embankment model scale.

| Similar condition     | Scale name               | Bai river dike break Model | Tang river dike break model |
|-----------------------|--------------------------|----------------------------|-----------------------------|
| Geometric similarity  | Plane scale              | 35                         | 35                          |
|                       | Flow ratio               | 5.916                      | 5.916                       |
|                       | Roughness ratio          | 1.81                       | 1.81                        |
| Water flow similar    | Flow ratio               | 7247                       | 7247                        |
|                       | time ratio               | 5.916                      | 5.916                       |
| Sediment movement is  | Starting velocity ratio  | 5.916                      | 5.916                       |
| similar               | of sediment              | 5.916                      | 5.916                       |
| Particle size ratio   |                          | 1.25 (plastic sand simulation) | 35 (yellow sand simulation) |

The model measurement system mainly includes surface flow field system, electromagnetic flow meter, automatic water level gauge, water level stylus, automatic silt meter, etc., which are used to observe the surface flow field, flow rate change process, water level change, flow velocity distribution, and riverbed terrain and so on. Considering that the flow velocity changes rapidly during the dike break process, the mobile surface flow field system is used for measurement. The mobile surface flow field measurement range is 0.001~50 m/s, and the measurement accuracy is up to mm level. In the model test, the river water level was kept unchanged by adjusting the inlet flow rate, and three water level observation stations were arranged at the water inlet to monitor the water level. The general layout of the model is shown in Figure 5, and the photo of the model test site is shown in Figure 6. The simulation prototype range of Bai river model is about 1.2 km×1.2 km; the coverage range of Tang river model is about 1.0 km×1.4 km.

According to the Bai river BH2 breach and the Tang river TH2 breach along the project, the fixed bed and movable bed model tests were carried out under three flood conditions, including 50-year design flood, 100-year design flood and 200-year design flood. The fixed-flow model was used to verify the water flow under the same flood conditions with numerical simulation, and the movable bed model was used to carry out experimental study on scouring of breach floods. The physical model test scheme was described in the literature [10].
4.2. Result analysis of physical model test

4.2.1. Result analysis of fixed bed model test. The ranges of impact velocities of BH2 and TH2 breach schemes under the same flood conditions were compared and analyzed by fixed bed model test. The results are shown in Table 2. The impact ranges of the Tang River and the Bai River along the pipeline are 630 m and 650 m, respectively. The range and the maximum flow rate along the pipeline were also basically consistent with the results of the numerical calculation.

| Jiahe area | River water level / m | Flow rate range/ (m.s\(^{-1}\)) | influence range by fixed bed model | influence range by mathematical model |
|------------|-----------------------|-----------------------------------|-----------------------------------|--------------------------------------|
|             |                       | Range along the pipeline / m       | Maximum flow rate along the pipeline / (ms\(^{-1}\)) | Range along the pipeline / m | Maximum flow rate along the pipeline / (ms\(^{-1}\)) |
| Tang River side | 82.04 | ≥1.5 | 630 | 7.63 | 608 | 6.76 |
4.2.2. Result analysis of the movable bed model test. The movable bed model test of Tang River and Bai river dike break under various conditions was carried out. The movable bed models of the Tang river and Bai river dike-breach under the conditions of unprotected schemes, were carried out using the yellow sand and plastic synthetic sand, respectively. The calculation results of the most unfavorable conditions (200-year design flood) are shown in Table 3. The shape of the scouring pit at the breach is shown in Figure 7. In the unprotected engineering movable bed model, the range of scouring pits along the pipeline near the Tang River and Bai River is 300 m and 500 m, respectively. The range of scouring pits vertical to the pipeline near the Tang River and Bai River is 500 m and 560 m (the range of one side is 250 m, 280 m), respectively. The plane of the scouring pit is approximately elliptical, and the range is smaller than the influence range of the numerical simulation flow rate.

| Jiahetao region | River water level / m | influence range along the pipeline / m | influence range vertical to the pipeline / m |
|-----------------|----------------------|--------------------------------------|------------------------------------------|
| Tang River side | 82.04                | 301                                  | 212 (=96+116)                            |
| White river side| 78.07                | 562                                  | 288 (=143+145)                           |

Figure 7. Scour pit shape of Bai river and Tang river breaches.

4.3. Analysis of the protection scope

According to results of the mathematical model, the fixed and movable bed model, the protection range in the Jiahetao area along the pipeline was finally determined. As shown in Figure 8.
Figure 8. Impact range of different models.

In the unprotected engineering movable bed model, the range of scouring pits along the pipeline near the Tang River and Bai River is smallest among all of the model results, which is about 300m (rounded by 301m) and 500m (rounded by 497m), respectively. The range of scouring pits vertical to the pipeline near the Bai River is about 150m (rounded by 143m and 145m) upstream and downstream, and about 100m (rounded by 96m) upstream and 120m (rounded by 116m) downstream of the pipeline near the Tang River. The range may be severely damaged by the blasting flood, and need special protection along the pipeline and in the vertical direction. For the numerical model, the maximal impact range along the pipeline of BH2-180m and TH2-250m is about 650m and 710m (rounded by 709m), respectively. Although the range along the pipeline of 500–650m on the Bai River side and 300–710m on the Tang River side is less affected by flood erosion, it is within the influence range of the impact velocity. So it is also necessary to do key protection along the pipeline for security. For the rest of the pipeline in the Jiahetao area, it is not affected by scouring of floods and only simple protection is needed, such as covering soil above the pipeline. The protection range of different grades is shown in Figure 9.

Figure 9. Protection range along the pipeline.
5. Conclusions.
In this paper, the combination of numerical model and physical model is used to fully demonstrate the influence of dike-breach floods on the pipeline. The results show that the large flow velocity is mainly distributed in the vicinity of the breach for each scheme, and the influence is most serious when the breach occurs near the pipeline. Comparing the floods of different magnitudes comprehensively, the greater is the flood magnitude, the more serious is the influence on the pipeline. As the breach width increases, most of results show some characteristics, such as the decrease of the maximum flow velocity at the breach, the increase of the maximum flow velocity in other areas of the pipeline, the increase of the maximum flow velocity contour range, and the decrease of the large flow velocity duration.

Considering results of numerical and physical model comprehensively, the protection ranges of different grades along the project were determined according to different ranges of impact velocities and scouring pits. The research results can provide reference for the protection of the pipeline in the Jiahetao area.

Acknowledgments
The authors would like to express appreciation for the support of Key Research and Development Plan of the Ministry Of Science And Technology (2016YFC0402300); National Natural Science Foundation of China (51409015); Basic Scientific Research Operating Expenses Project of Central Level Public Welfare Research Institutes (CKSF2019189/HL).

References
[1] Chen, W., Zhang, X., Tan, G., et al. (2007) Numerical simulation of sediment flow considering sedimentation. Hydrodynamics Research and Progress, Series A, 22: 647-653.
[2] Hu S., Tan W. (1990) Numerical simulation of dam failure waves. Hydrodynamics Research and Progress, Series A, 5: 90-98.
[3] Wu, C., Zheng, Y., Zhao, W. (1995) A new mathematical model of hydraulic characteristics of dam breach and its general solution. Hydrodynamics Research and Progress, Series A, 10: 35-41.
[4] Wang, J., Ni, H., Jin, S. (2000) Numerical Simulation of Propagation, Reflection and Diffraction of Instantly Collapsed Dam Waves. Hydrodynamics Research and Progress, Series A, 15: 1-7.
[5] Jin, C., He, X. (2006) Unified two-dimensional mathematical model of dam break flood. Journal of Hydraulic Engineering, 37: 222-226.
[6] Liu, D. (2006) Overview of analysis and calculation methods for dike flood and scour pit. Electric Power Survey and Design, (2): 23-26.
[7] Zhang, X., Yu, M. (2001) Numerical simulation of bed deformation in dike burst. Journal of Hydrodynamics, Ser. B, 13: 60-64.
[8] Zhang, D., Li, D., et al. (2010) One-dimensional and two-dimensional coupled hydrodynamic models for dikefloods and their applications. Journal of Hydroelectric Engineering, 29: 149-154.
[9] Fread, D.L. (1984) DAMBRK: The NWS Dam-break Flood Forecasting Model. National Weather Service, Mary-land, SilverSpring.
[10] Yangtze River Planning Survey and Design Institute. (2001) The feasibility study report of the first phase of the Tangbai River mainstream flood control project.
[11] Office of the National Flood Control and Drought Relief Headquarters. (2005) Guidelines for the preparation of flood risk maps and descriptions of the provisions (for trial implementation).