Analysis of local hydrodynamic characteristics of wading buildings under tidal action

Tingting Xiao 1,2*, Yutong Chen 1,2, Ya Zhang 1,2, Zhiyong Zhang 3, Qin Zhang 1,2,4, Li Ma 1,2, Nan Li 4, Xiao ZONG 1,2,4, Jinyu Yang 4, Chan YU 1,2

1Powerchina Guiyang Engineering Corporation Limited, Guiyang 550081, China
2Guizhou BIM Engineering and Technology Research Center, Guiyang, 550081, China
3Key Lab. of Estuary and Coast of Zhejiang Province, Zhejiang Inst. of Hydraulics and Estuary, Hangzhou 310020, China
4Power China Ecological Environment Design Research Corporation Limited, Suzhou, 215131, China
*gzxiaott@163.com

Abstract—The tidal bore is a kind of nonlinear strong discontinuous flow that has a great impact on the wading buildings. During the tidal wave propagation, the local water flow structure of the wading buildings changes significantly. In order to analyze the evolution characteristics of local hydrodynamics of wading buildings under tidal action, a small-scale mathematical model of tidal current is established, and the local hydrodynamic changes of different forms of spur dikes and piers are studied. The results show that the flow velocity fluctuations in front of the non-submerged shoal dam and the dam head are more fluctuating than the submerged spur dikes, and the influence of the tidal dam on the submerged shoal dam area is more severe; the square piers under the tidal wave The turbulent energy and backwater recirculation zones are larger than circular and streamlined piers.

1. Introduction
Tidal bore, also called bore, often occurs along a coast where there is a large tidal range or where a river empties into an ocean or sea. It is the front of flood tide as the water level and flow velocity vary suddenly [1]. Many scholars have studied and made numerous achievements on bore propagation velocity [2], water flow structural characteristics [3-5], and morphological characteristics of the tide rip [6]. However, the water resistance by buildings within the tide-prone reaches changes the hydrodynamic factors during the bore propagation. The impact upon the tidal level and current at the estuaries further exacerbates the sediment transportation, pollutant dispersion, and other problems. The strong impact of the tidal bore is also closely related to the standards for construction of spur dikes, sluices, and other water conservancy facilities within the estuaries. Therefore, it is essential to explore and study local hydrodynamic characteristics of wading buildings under tidal action. Li, et al. [7] stimulated the water flow turbulent characteristics of the tidal bore flowing through piers with the SPH method. Rong Guiwen, et al. [8] and Chen Haijun, et al. [9] studied the pressure changes on surfaces of spur dikes and piers under the tidal current action. There are limited system researches on change characteristics of local hydrodynamic factors of wading buildings during the bore propagation. To this end, this paper selected common spur
dikes and piers in estuaries as the research objects, to explore the evolution of local hydrodynamic factors of buildings in the tidal bore process, providing a reference for similar and associated researches.

2. Mathematical Model

2.1 Governing Equation

The basic governing equations are continuity equation and momentum equation [10]:

\[
\begin{align*}
\frac{\partial (u_i A_i)}{\partial x_j} + \frac{\partial (v_i A_i)}{\partial y_j} + \frac{\partial (w_i A_i)}{\partial z_j} &= 0 \\
\frac{\partial u}{\partial t} + \frac{1}{V_f} \left( u A_i \frac{\partial u}{\partial x_j} + v A_i \frac{\partial v}{\partial y_j} + w A_i \frac{\partial w}{\partial z_j} \right) &= - \frac{1}{\rho} \frac{\partial p}{\partial x} + G_x + f_x \\
\frac{\partial v}{\partial t} + \frac{1}{V_f} \left( u A_i \frac{\partial v}{\partial x_j} + v A_i \frac{\partial v}{\partial y_j} + w A_i \frac{\partial w}{\partial z_j} \right) &= - \frac{1}{\rho} \frac{\partial p}{\partial y} + G_y + f_y \\
\frac{\partial w}{\partial t} + \frac{1}{V_f} \left( u A_i \frac{\partial w}{\partial x_j} + v A_i \frac{\partial w}{\partial y_j} + w A_i \frac{\partial w}{\partial z_j} \right) &= - \frac{1}{\rho} \frac{\partial p}{\partial z} + G_z + f_z
\end{align*}
\]

(1)

Where, \( u \), \( v \), and \( w \) are velocity components of \( x \), \( y \), and \( z \) respectively; \( A_x, A_y, \) and \( A_z \) are flow area percentages in \( x \), \( y \), and \( z \) directions respectively; \( V_f \) is the flow area volume percentage; \( G_x, G_y, \) and \( G_z \) are accelerations of gravity of the object in \( x \), \( y \), and \( z \) directions respectively; \( \rho \) is the fluid density; \( p \) is the pressure; \( f_x, f_y, \) and \( f_z \) are viscous forces in \( x \), \( y \), and \( z \) directions respectively.

2.2 Turbulence Model and Introduction to VOF

Aiming to repeat the change characteristics of free water surface waves and flow field structures, the simulation has the major difficulty in accurately reproducing the turbulence caused by the transient free surface evolution and non-steady flows in the tidal bore process. Therefore, this paper selected the large eddy simulation (LES) technology which is widely applied to simulation of fluid flow details. The main principle of the LES technology is to waive the numerical simulation of the turbulence with a completely accurate governing equation, but to divide the eddy structure into large-scale eddies and small-small eddies and screen out the small-scale eddy structure through water filtering. The large-scale eddy structure is numerically simulated with the N-S equation. The impact of the small-scale eddy structure relative to the large-scale one in the motion equation acts as an additional item like the Reynolds stress, named as sub-grid stress, calculated according to the Reynolds averaged equation. The VOF method is to simulate the flow of two or more non-mixed fluids based on a combination of momentum equation and continuity equation by tracking the free liquid face, suitable for researches of stratified flow or topics associated with free surface flow.

2.3 Calculation Zone and Boundary Conditions

Figure 1. Schematic diagram of initial conditions for tidal generation

Figure 1 shows the generation process of a tidal bore, where, \( V_0 \) indicates the ebb strength; \( h_0 \) indicates the water depth before tide; \( c \) indicates the propagation velocity of the tidal bore; \( H \) indicates the height of the tidal bore; \( h_1 \) and \( V_1 \) indicate the water level and flow velocity when the tidal bore...
occurs. Before the tidal bore occurs, the body of water flows downstream, and both the upstream and downstream water levels and flow velocities are $h_0$ and $V_0$. When the tidal bore occurs, the upstream boundary conditions remain unchanged, but at the downstream boundary, the water level rises suddenly, the flow changes its direction, the flow velocity augments, and subsequently the body of water propagates upstream. In the numerical simulations of small-scale eddies both at home and abroad, different generation modes of tidal bores are selected. For example, the tidal bore generated by dam failure yields nearly zero transverse velocity ($V_1$) of the body of water when the separator is pulled out, which is impracticable. The tidal bore generated by piston wave-making has the upstream and downstream velocities ($V_0$ and $V_1$) changing in the same direction, which is also impracticable. For the tidal bore generated by water lashing the upright wall, the initial water level and flow velocity ($h_1$ and $V_1$) cannot be effectively controlled, and the resulting tidal bore process is obviously random. Clearly, to achieve the mall-scale mathematical model of the tidal bore, it is critical to set appropriate $h_1$ and $V_1$, however, it is quite difficult to measures the flood strength when the tidal bore is coming. Ni Xingye, et al. [11] split the boundary flow into water level and flow velocity for separate control based on the SPH technology, to achieve the numerical simulation of the surge and the use of the 2010 Yanguan reaches of the field measurement data, verifying the effectiveness of this boundary setting method. This is also to keep the propagation velocity in line with the actual one by constantly adjusting the flood strength. Based on the one-dimensional continuity equation and momentum equation, Pan Cunhong, et al. [12] deduced the equation for propagation velocity of tidal bore:

$$ c = V_0 + \frac{gh_0(h_1 + h_0)}{2h_0} \tag{3} $$

$$ c = V_1 + \frac{gh_0(h_1 + h_0)}{2h_1} \tag{4} $$

From the above equations, under ideal fluid conditions, when $V_0$, $H$, and $h_0$ are given among the boundary conditions, it is possible to obtain $h_1$ and $V_1$ when the tidal bore occurs by combining Equation (3) with Equation (4), to control the boundary conditions for repeating the generation process of the tidal bore.

This paper established a numerical model based on the above boundary conditions setting method, applied the generalized minimal residual method (GMRES) to separately obtain the pressure and velocity, and based on the finite difference discrete control equation, studied the evolution law of local flow state of wading buildings during the tidal bore propagation.

3. Analysis of Local Flow State of Spur Dike Under Tidal Action

A spur dike is a common building for river channel training, especially in Qiantang River area in Zhejiang. Taking a vertical spur dike that is 0.4 m long, 0.15 m wide and 0.4 m high as the research object, this section studied the local flow state of the water flow near non-submerged and submerged spur dikes separately by changing the water flow conditions of the tidal bore. In order to reflect the impact of the tidal bore on local flow state near the spur dike, five observation points were set out each in the damming area, in front of the dike head, and at the pre-tide water depth in the recirculation zone, as shown in Figure 2, where the number indicates the distance, in m. To study the local flow state of the non-submerged spur dike, assume the pre-tide water depth $h = 0.1$ m and the tidal bore height $H = 0.025$ m; while for the submerged spur dike, assume the pre-tide water depth $h_0 = 0.5$ m and the tidal bore height $H = 0.025$ m.
Figure 3(1) shows the local vector on the X-Y plane at Z = 0.1 m when and at a moment after the tide rip just lashes the non-submerged spur dike during the tidal bore propagation. From this figure, due to the narrowing action of the spur dike, the water flow increases largely when the tidal bore propagates to the dike head. Then under the water jet action of the spur dike, the water flow deflects and forms small eddies near the dike head. After detouring around the spur dike, the water flow forms a local recirculation zone. Figure 3(2) shows the local flow field vector on the X-Z plane at Y = 0.2 m when and at a moment after the tide rip goes over the spur dike during the tidal bore propagation. For the submerged spur dike, under the jacking action of the spur dike, the body of water moves vertically at an obvious and large acceleration when the tidal bore flows over the spur dike. After the tide rip goes over the spur dike, a significant recirculating eddy area is formed at the area behind the dike, and the velocity is smaller at this area. There were local smally eddy areas at the bottom near the eddy area due to the impact of water flow separation.
In order to compare the velocity fluctuation process at each area during the tidal bore, the velocity fluctuations in three directions in the tidal bore process at each observation point were plotted, as shown in Figures 4–6, where $u$, $v$, and $w$ indicate longitudinal, transverse, and vertical velocities respectively.

Overall, when the tidal bore propagates near the non-submerged spur dike, the body of water in the damming area gradually turns into the flood tide. At this moment, the transverse and vertical velocities increase quickly. When the tidal bore propagates forward to lash the spur dike, due to that the water flow is too low to cross over the spur dike, a “recirculating tide” occurs on the side near the dike under the water resistance by the spur dike. That is, a new tidal bore vortex forms in this area and runs forward in a reverse direction. Therefore, at the observation points (A1 and A2) near the bank of the spur dike, the transverse velocities have two phases with obvious negative values. Coerced by the tidal bore in forward direction, the reverse vortex diminishes gradually, and the longitudinal velocities at A1 and A2 finally return to positive. At the observation points far away from the spur dike, there is no “recirculating tide”, so the longitudinal velocities are always positive. Because A1 is shielded by the dike and A5 is far away from the dike and subject to smaller water jet of the spur dike, the transverse velocities at these two points are less fluctuated. Under the impact of the tidal bore detouring around the dike head after the water resistance by the dike at A2 and A3, the transverse velocities are larger. For vertical velocities, their change laws are substantially same at all observation points, showing a distinct cyclical ebb and flow change. The vertical velocity fluctuations become more and more gentle from A1 to A5, that is, it is easier for the vertical velocities to return to a stable state. When the tidal bore propagates to the completely submerged spur dike, so there is no “recirculating tide”. Longitudinal velocities at all observation points as shown in the figure are positive. With the water resistance by the spur dike, the longitudinal velocities at the points near the spur dike are obviously smaller. Due to the large water jet
of the spur dike, the tidal bore deflects toward the bank far away from the spur dike. From the figures, the transverse velocities at A2 and A3 near the spur dike are larger, and that at A1 near the dike root is smaller due to the shielding action. As the spur dike is submerged into water, the tidal flow rolls over dramatically; therefore, its vertical velocity increases largely when the tide rip is crossing over the dike. Besides, it is observed that, from A1 to A5, as the relative distance from the observation points to the spur dike root increases, the jacking action of the spur dike decreases, and the vertical velocity peaks decline successively. Both longitudinal and vertical velocity changes at each point feature obvious ebb and flow cycle.

During its propagation, the tidal bore dashes against the back of the non-submerged spur dike. The water flow far away from the spur dike continues to flow forward, and the other near the spur dike detours around the dike toward the dike head. For the figures, longitudinal velocities at all observation points increase to their peaks in the flood state and then attenuate in the ebb state, except for that at B1 closer to the dike head experiencing a shorter period of attenuation and gradually increasing under the help of the detoured body of water. The longitudinal velocity changes at other points are substantially same as those at relative observations points in Zone A. The transverse velocity at B1 changes faster, and after the water flow detours around the dike head, some flow continues deflecting toward the recirculation zone behind the dike; therefore, from the figure, longitudinal velocities at B1 have obvious negative values. For vertical velocities, as there are local eddies near the dike head during the detouring, the velocity attenuations at B1 are tailed by a short period of continuous attenuation. Then continuously replenished by subsequent water flows, the eddies disappear gradually, and the velocities start a cyclical fluctuation. The change law of longitudinal and transverse velocities at each observation point in Zone A of the submerged spur dike is similar with that at observation points in Zone A, but under the narrowing action on the river channel due to the existence of the spur dike, the longitudinal velocities at observation points in Zone B are slightly larger than those at observation points in Zone A, and the closer the observation point is located to the dike head, the larger its longitudinal velocities are. Due to the absence of jacking action by the spur dike, the vertical velocities at observation points in Zone B are slightly smaller than those in Zone A, and there is a little difference between these velocities at different points. For transverse velocities, under the water jet action of the spur dike, the observation points closer to the dike head have larger transverse velocities, and all larger than those at observation points in Zone A.
After the tidal bore water detours around the non-submerged spur dike, some flows continue to propagate forward, and the others deflect at the dike head and form a recirculation zone behind the dike. From the figures, the change laws of velocities to different directions at different observation points remain substantially the same. The closer the observation point is located to the spur dike, the larger the backflow impact it will be subject to. After the tidal bore detours around the spur dike, some flows continue to deflect toward the dike and form a recirculation zone, and the others converge with the forward flows. For longitudinal velocities, the figures show that the velocities increase to the peak, then attenuate, and later rise again. At C1 and C2, due to the larger recirculating impact, the velocities decline gradually from the peak to zero and then rise again. For other observation points that are subject to more obvious impact by the forward tidal bore, the longitudinal velocities are substantially positive. For transverse velocities from C1 to C5, their peaks decrease gradually. For vertical velocities, their change laws at different points are substantially same as those of the subsequent tidal flows, and the velocity peak at C1 is much less than those at other points. Under the cascade action of the spur dike, a certain accelerative flow occurs after the tidal bore crosses over the submerged spur dike. The longitudinal velocity peaks decline gradually from C1 to C5 in Zone C. Carried by the tidal flow, the water flows resulting from the water jet of the spur dike deflect to one bank of the spur dike. Transverse velocities at points keep negative for a certain period. As C1 is close to the spur dike, the vertical velocity is positive at the very beginning when the water flows run in the recirculating vortex area behind the dike. As the tide rip propagates forward, the turbulence characteristics of the subsequent tidal flow attenuate gradually. The vortex area behind the spur dike moves downward constantly, so the transverse velocities at different points attenuate in succession from negative to positive. The closer observation points are located to the spur dike, the larger the down-cutting motion caused by the water jump action, the less the minimum vertical velocity, and all are less than those at Zones A and B. The decrease in difference between water levels in front of and behind the spur dike after the tide rip propagates leads to obvious water jump resulting from the subsequent tidal flow, therefore, the vertical velocities at different points feature cyclical changes along with the ebb and flow.

4. Analysis of Local Flow State Under Tidal Action
Circular, square, and streamlined piers were studied. Pier centers were at X = 5 m. These piers had the same sectional width. Given that h = 0.1 m and H = 0.025 m, the sections at d = 0.096 m were sampled for hydraulic analysis. Figure 7 shows the flow field when the tide rip arrives at the piers (t = 4.35 s). Figure 8 shows the flow field when the tidal bore propagates forward (t = 7.00 s).
From Figures 7~8, when the tide rip arrives near the pier, due to the water resistance by the piers, the tidal flow lashes the piers and rises along the upstream faces of the piers to form local damming areas in front of the piers, therefore, small local areas with increased pressures occur in front of the piers as shown in the figures. The square pier has a larger affected area and a higher-pressure extremum. Three piers have substantially identical gradient distribution of pressure. After detouring around the piers, the tide rip continues propagating. The damming velocities on both sides of the piers increase locally, and obvious flow separation and eddy recirculation zone occur behind the piers. The recirculation zones are ranked as square pier > circular pier > streamlined pier according to their sizes, which may be because the detouring separation point of the square pier is farther than those of other two piers. The recirculation zone behind the pier is larger. From the velocity distribution of the three piers, the velocity on the upstream face is small, that on the detouring face is the largest and the velocity gradient distribution is denser near the piers, the velocity for detouring around the streamlined pier is larger than those for other two piers, and velocities of the circular and square piers have similar contour of distribution.

When the tidal bore arrives at the piers ($t = 4.35$ s) and the tide rip detours around the piers ($t = 7.00$ s), the local turbulence energy distributions are plotted as shown in Figures 9. From these figures, the local turbulence energy changes of three piers appear as obvious gradients. When the tidal bore arrives at the both sides of the piers, the turbulence energy is the largest. At the points far away from these three piers, the turbulence energy distributions are almost the same. The flow state near the piers is relatively turbulent. The cylindric pier has the largest turbulence energy extremum. After the tidal bore propagates for a period, the areas with the largest turbulent energy moves from both sides of the piers to the back of the piers. The figures show that the turbulence energy of the square pier is obviously larger those of the other two pier types. This indicates that the eddy behind the square pier is more intense.
5. Conclusion

In this paper, a small-scale mathematical model for local flow structure characteristics of wading buildings under tidal action is established, and the local hydrodynamic changes of non-submerged and submerged spur dikes and piers with three different sectional forms are studied. The conclusions are as follows:

(1) The tidal dams on two spur dikes under the tidal action show obvious eddy structures. The local hydrodynamic characteristics differ largely between the non-submerged and submerged spur dikes. The flow velocity fluctuations in front of the submerged spur dike and the dike head are less obvious than those at the submerged spur dike, and the influence of the tidal dam is more severe under the impact of the tidal current which flows over the dike.

(2) Under the tidal action, the pressure extremum on the upstream face of the square pier is larger than those of circular and streamlined piers, and the backwater recirculation zone is also larger.

(3) The turbulence energy is larger on both sides of the piers when the tidal bore just arrives. As the tide rip propagates, the areas with the largest turbulence energy shift gradually to both backwater sides of the pier. The local turbulence energy of the square pier is larger than those of the other pier types.

References

[1] LIU Wenhu, ZHU Xiaohua, ZHANG Zhongzhe, et al. Observation and dynamic characteristics of tidal bore in Qiantang River, China[J]. Journal of Dalian Ocean University, 2015, 30(5):567-572. (in Chinese)

[2] XIE Dongfeng, PAN Cunhong, LU Bo, et al. A study on the hydrodynamic characteristics of the Qiantang tidal bore based on field data[J]. Chinese Journal of Hydrodynamics, 2012, 27(5):501-508. (in Chinese)

[3] Leng X, Chanson H. Breaking bore: Physical observations of roller characteristics[J]. Mechanics Research Communications, 2015,65:24-29.

[4] Koch C, Chanson H. Turbulence measurements in positive surges and bores[J]. Journal of
Hydraulic Research, 2010,47(1):29-40.

[5] Khezri N, Chanson H. Undular and breaking bores on fixed and movable gravel beds[J]. Journal of Hydraulic Research, 2012,50(4):353-363.

[6] Lubin P, Chanson H, Glockner S. Large Eddy Simulation of turbulence generated by a weak breaking tidal bore[J]. Environmental Fluid Mechanics, 2010,10(5):587-602.

[7] Li J, Liu H, Tan S K. Lagrangian modeling of tidal bores passing through bridge piers[J]. Journal of Hydrodynamics, 2010,22(S1):496-502

[8] Rong G W, Wei W L, Liu Y L, et al. Study on flow characteristics near spur dikes under tidal bore[J]. Journal of Hydraulic Engineering, 2012, 43(3):296-301. (in Chinese)

[9] Jun C H, Sheng Y, Jie X C, et al. Dynamic measurement and study of the bore pressure on a vertical square cylinder in Qian-tang River[J]. Journal of Hydrodynamics, 2006, 21(3):411-417. (in Chinese)

[10] Qi Lan, Xiao Tingting, Zhang Zhiyong, et al. Numerical simulation of tidal bore based on CFD method[J]. Hydro-Science and Engineering,2019(3):32-40. (in Chinese)

[11] Ni X, Huang S, Feng W, et al. Numerical Simulation of Tidal Bores using SPH Method[J]. Journal of Coastal Research, 2018,85(85):951-955.

[12] PAN Cunhong, LU Haiyan, ZENG Jian. Characteristic and numerical simulation of tidal bore in Qiantang River[J]. Hydro-Science and Engineering, 2008, 2008(2):1-9. (in Chinese)