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Experimental study on water-wing characteristics induced by piers in flood drainage culverts

Ch. Sheng*, **Zh. Jian, H. Ming and A. Hazrati**

College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, P.R. China.

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Abstract. Setting piers is an effective way to overcome the limits of manufacture and operation of the gates for large span culverts or tunnels. However, the piers, if designed improperly, will bring about water-wing to strike the top and the side walls, and hence affect the operation of hydraulic structures. This present study deals with the water-wing caused by the obstruction of the pier placed in front of a flood drainage culvert. Based on the dimension analysis, the influencing factors of water-wing were analyzed, the hydraulic characteristics were experimentally investigated, and finally a kind of new piers was proposed. The results showed that it is the initial height of piers that is the key factor, as well as the radius and inclination angle of piers, approached flow velocity and depth.

1. Introduction

Water-wing, a kind of flow, separating from the main flow and then falling down to normal water surface, is a natural phenomenon caused by the obstruction of the hydraulic structures such as piers in some tunnels or culverts. In the construction of South-to-North Water Diversion Project, flood drainage culvert is an indispensable part to ensure the safety of the main channel. Usually, the size of the culvert is very large, and setting piers in the entrance region can divide the culvert into more than two parts, which has been proved to be an effective way to reduce the size and overcome the limits of manufacture and operation of the gates. Moreover, placing piers in the inlet of the culverts also has good effect on optimization of flow pattern and uniform distribution of discharge. But it will bring about the water-wing to strike the top and side walls, which may lead to a reduced support, damaged geological environment and atomization, and hence constitutes a potential catastrophic hazard. Therefore, in order to guarantee the safety operations of the hydraulic structures, we should pay more attention to the design of piers, so that water-wing can be reduced to minimum.

According to the generation mechanisms, water-wing can be broadly lumped into three categories. The first one is induced because of the lateral enlargement at the position of a gate for an aerator as prevention from cavitations. The second one is produced due to the steep bottom slope of stepped spillways. And the last one is brought about by the pier just as the previous description.

Since the threats of the water-wing were discovered, the hydraulic characteristics of water-wing have been extensively studied experimentally, which cover all three types. Regarding the first type of water-wing, Quintela. AC [1] mentioned that the flow jetted from flip bucket could form water-wing, in his research, on flow aeration. Pan et al. [2] pointed out that abrupt enlargement for aeration, to prevent cavitation erosion behind the working gate, could result in water-wing as well. And he also put forward the empirical equations for calculating the length and height of water-wing. Hu [3] worked on the hydraulic model tests of the left

*. *Corresponding author. Tel: +86 13914482300*
E-mail address: chensheng@hhu.edu.cn (Ch. Sheng)

bank discharge tunnel of Lubuge hydropower station, and Chen et al. [4] conducted experiment on a gate with flexible water seal in Ertan project. Both, their studies also confirmed the previous results. From the study of Wang [5] and Nie et al. [6] it was concluded that the length and height of water-wing obviously increased with the rise of the reservoir level, and the higher water-wing would strike the support of a gate, resulting in unsafe operation of the gate.

Most researchers referred to the second-type water-wing as nappe flow, which was found for low discharges and large steps of the stepped spillways. In their pioneering and relevant report, Essery and Horner [7] have categorized the various types of flow that occur down the stepped spillways. According to their report, visual comparison indicated that two types of flow existed:

1. Nappe flow (or jet flow) which is distinguished by the formation of a nappe in each drop;
2. Skimming flow which is typified by both the complete submergence of the steps (no nappes being formed as such) and the high air content in the flow.

Identical types of flow were also reported by Peyras et al. [8]. Matos [9] proposed that nappe flow could be also subdivided into isolated nappe flow when all the efflux from a step struck the tread portion of the step below, and nappe interference flow (or partial nappe flow) in which only a part of efflux overshot the step below. The lower limit of the step height for the formation of the nappe flow is expressed [10] as $(h/y_c) = 0.57(\tan\theta)^3 + 1.3$, where h is the step height; y_c is the critical flow depth and θ is the angle of inclination of steps. Based on the dimension analysis, Feng et al. [11] discussed the influence of Froude number, Reynolds number, Weber number, step height and chute angle to water-wing. As observed visually by Feng et al., in their experimental studies of models, later, the water-wing nearly existed in the whole nappe flow when the chute angle was in the range of 40° to 60°, and water-wing increased with increasing the bottom slope of the stepped spillway, while water-wing decreased as the step size deduced.

As for the third type, it can be also subdivided into two categories one of which is induced at the end of the pier placed in the inlet of a discharge tunnel and the other caused in front of the pier set in the drainage culvert. Wu et al. [12-14] did a lot of efforts on the first category. Based on the dimensional analysis and physical model tests, Wu et al. [13] investigated the hydraulic characteristics and the causes of water-wing. Their results show that the height and length of the water-wing increased with increasing Froude number of the outlet of the pressure section, the depth of the water surface concave at the end of the pier and the impact length of the two flows separated by the pier. Followed by a series of experiments of the six comparing plans, a kind of new bodily form of pier so-called bottom, underlay type pier, was developed by Wu et al. [12,14] in water-wing control. However, for the second category, less effort so far has been devoted to the behavior and control of water-wing generated in front of piers in a drainage culvert. Similarly, Zhou and Liu [15] conducted an experiment on this kind of water-wing induced by separating baffles on the steep channels, and drew the conclusion that the main influential factors of the height of water-wing was the angle between the surface facing water and the bottom plate of the steep channel; the relative water depth, Froude number of section in front of the battles and the distance between the two baffles. But the functions of the separating baffle and the piers are completely different. Only Hu et al. [16] presented the frontal water-wing phenomenon when they conducted the hydraulic model test of a flood drainage culvert, which was a branch from the middle route of South-to-North Water Diversion Project in China. Therefore, there is no doubt that a study of hydraulic behavior of frontal water-wing is needed to propose the schemes to reduce the frontal water-wing for the safety operation of the South-to-North Water Diversion Project, due to its important status in China.

Consequently, the present study is concerned with the extensive theoretical, experimental study on the problem of water-wing, due to the obstruction of pier in a flood drainage culvert. The dimensional analysis is employed to study the influencing factors of water-wing. Then a series of comparing experiments are also conducted in the flume to find how these factors influence the characteristics of water-wing, and which factors are the critical ones. Furthermore, according to the influencing factors, a newly designed pier is proposed to be applied in the practical flood drainage culvert for water-wing control.

2. Dimensional analysis

The hydraulic parameters are defined as shown in Figure 1.

When the dimension of a flood drainage culvert is given, frontal water-wing depends on pier geometry (pier width, initial pier height, pier radius, initial pier inclination angle), water-wing characteristics (water-wing width, water-wing height), flow conditions (approached depth and discharge or velocity) and fluid parameters (density and viscosity). Therefore, for height and width of water-wing H and W, one can write:

$$H, W = f\left(B, H_h, R, \theta, h, v, \rho, \mu, g\right), \qquad (1)$$

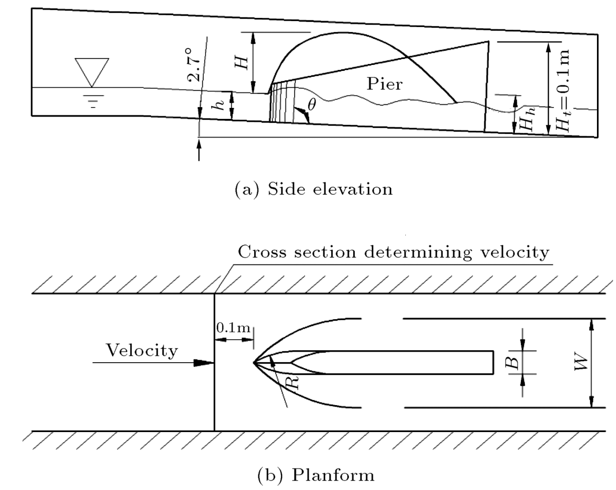


Figure 1. Illustrations of water-wing and pier hydraulic parameters.

in which B is the width of pier, H_h is the initial height of pier, R is the radius of pier, θ is the initial inclination angle of pier, h is the approached flow depth, v is the approached flow velocity, ρ is the density of water, μ is the viscosity of water, and g is the gravitational acceleration. Using dimensional analysis, Eq. (1) can be described as:

$$\frac{H}{B},\frac{W}{B}=f\left(\frac{R}{B},\mathrm{Re},\frac{H_h}{B},\frac{h}{B},\mathrm{Fr},\theta\right), \quad (2)$$

where $\mathrm{Fr}=\frac{v}{\sqrt{gB}}$ is Froude number and Re is Reynolds number.

Kobus [17] presented that the effect of viscous force was the secondary factor when Reynolds number is greater than 10^5, thus the effect of Reynolds number can be eliminated, which yields:

$$\frac{H}{B},\frac{W}{B}=f\left(\frac{R}{B},\frac{H_h}{B},\frac{h}{B},\mathrm{Fr},\theta\right). \quad (3)$$

The results of dimensional analysis show that the dimensionless quantities of water-wing characteristics are functions of $\frac{R}{B}$, $\frac{H_h}{B}$, $\frac{h}{B}$, Fr and θ. It should be noted that B is a constant in this research, so Fr is proportional to v. In addition, the factor $\frac{h}{B}$ is closely related to $\frac{H_h}{B}$, hence $\frac{h}{H_h}$ is introduced to take these two factors into consideration, comprehensively.

3. Experimental study

3.1. Experimental set-up

The circulating water flow system used in this study consists of a water tank, a pump and a flume. All experiments were conducted in a prismatic rectangular flume of width b = 0.5 m and length l = 5.2 m with bottom angle Φ = 2.7°. At the end of this flume, a controlling gate was designed to adjust the water surface height at the desired levels. A two-tip fiber-optical probe was used to measure the flow velocities in the selected cross section, as shown in Figure 1(b).

The dimensions of piers in this study were defined to meet the criteria, which have been defined by other investigators. Chiew and Melville [18] defined that pier width should not be more than 10% of flume width to avoid wall effect. The pier models were made of wood. Melville and Sutherland [19] defined that B/L (L=length of pier) should not be more than 1/3. Thus, all model piers of width 0.05 m and length 0.45 m were used for the study (Table 1).

3.2. Results and discussion

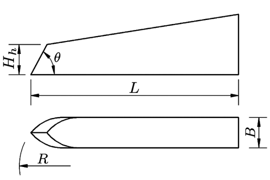
3.2.1. Influence of different Froude numbers on water-wing

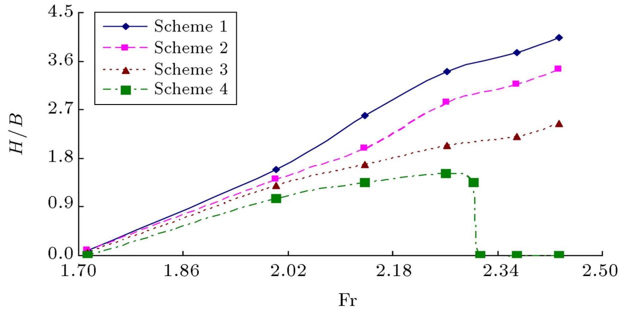
Due to the width of piers, B is a constant in this research, the relationship between water-wing and Fr actually is equivalent to the one between water-wing and v. Figure 2 gives dimensionless height H/B and dimensionless wide W/B of water-wing for various Froude numbers Fr. For the previous three schemes, as the results show, Froude number increases the intensity of the water-wing including H/B, and W/B also increases.

For the fourth scheme, when Froude number reaches 2.31 (corresponding velocity is 1.62 m^3/s), the height H and the width W of the water-wing drop abruptly to zero, the tendency of which is distinctly different from those of the other three ones. Form the data collected in the experiment process, we can see that the approached flow depth h is 27.5 mm at this time, while the initial height of the fourth pier is 30.0 mm. Thus, the main reason of such finding is that the pier head is almost fully immerged into water, which just likes the flow around the cylinder, and the

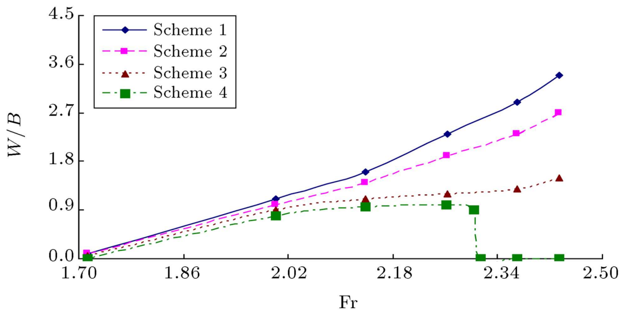
Table 1. Parameters of piers tested.

Scheme	B (m)	L (m)	R (m)	H_h (m)	θ
No. 1	0.05	0.45	0.025	0.1	90°
No. 2	0.05	0.45	0.080	0.1	90°
No. 3	0.05	0.45	0.080	0.1	60°
No. 4	0.05	0.45	0.080	0.03	90°





(a) Variation of H/B with Fr



(b) Variation of W/B with Fr

Figure 2. Variation of water-wing with Froude numbers Fr for different piers.

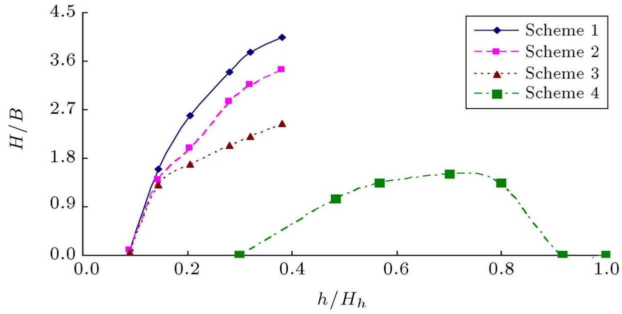
obstructed area is relatively smaller, so that there is no water-wing happening.

However, the four schemes have the same tendency that the water-wing parameters approached zero when Fr(v) is decreasing. This result is due to the low flow rate and the approached water depth, so that it does not have enough energy to produce water-wing. Consequently, we can believe that water-wing will definitely happen when Fr(v) reaches a critical value, as long as the head of pier is not fully submerged into water.

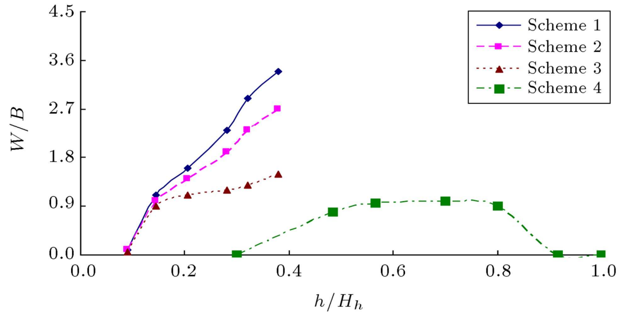
3.2.2. Influence of different approached flow depths and initial heights of piers on water-wing

As mentioned previously, if the approached water depth h is greater than the initial height of pier H_h, there will be no water-wing observeable. Hence, the intensity of water-wing not only depends on the approached flow velocity, but also is closely related to the ratio of the approached flow depth and the initial height of pier h/H_h. Figure 3 presents the relationship between the variations of the water-wing parameters, either H/B or W/B and h/H_h whose trend is similar to that of Figure 3. Still, for the previous three cases whose initial heights are all the same (100 mm), H/B and W/B decrease as h/H_h decreases and approaches zero at $h/H_h = 0.09$. That is to say when the approached flow depth is less than $0.09 \times 100 = 9$ mm, there will be no water-wing capable of generating.

The variations of H/B and W/B with h/H_h of the



(a) Variation of H/B with h/H_h



(b) Variation of W/B with h/H_h

Figure 3. Variation of water-wing with the ratio of approached flow depths and initial height of pier h/H_h for different piers.

forth scheme is represented by a dot and chain line in Figure 3. Because of the difference in initial height, water-wing will not occur before the value of h/H_h reaches 0.3, due to the small approached flow depth. Then the height and width of the water-wing increase with increasing h/H_h, and attain a maximum value at $h/H_h = 0.7$ for the tests. Further increase of h/H_h results in a reduction of H/B and W/B. Finally, both parameters of the water-wing approached zero when $h/H_h > 0.92$, from which one can easily draw the same conclusion, as previously shown, that if the head of pier is fully submerged into water, there will be no water-wing any more.

3.2.3. Influence of different radius of piers on the water-wing

The radius of Schemes No. 1 and No. 2 are 25 mm and 80 mm, respectively. Comparing the water-wing induced by Schemes No. 1 and No. 2, which can be seen in Figure 3, the radius of piers have great influence on the characteristics of the water-wing, and the H/B and the W/B which occur at $R = 25$ mm are, respectively, higher and wider than those at $R = 80$ mm, under the same approached flow velocity.

These results can explain that as the radius of pier increases, the cross sectional area along the length, obstructing the flow, increases slowly in the direction of the flow. And to weaken the water-wing through increasing the radius of piers is commonly used in engineering practice.

3.2.4. Influence of different initial inclination angle on water-wing

Thpagebreak[3] initial inclination angle of Schemes No. 2 and No. 3 are 90° and 60°, respectively. The effect of the increment of inclination is clearly visible in both Figures 2 and 3, as the magnitude of H/B or W/B is the smallest at all values of h/H_h, for the third scheme. This result indicates that the inclination angle of pier head is also an effective method to control water-wing. And the larger the flow rate, the more significant the effect of reducing the water-wing through increasing the radius and inclination angle of pier head.

From Figures 2 and 3 and the above analysis, it is known that the increment of radius and inclination angle can reduce the intensity of the water-wing to some extent. However, these two methods can not eliminate the generation of water-wing, radically. Fortunately, from the different trends and results between the first three schemes and the fourth one, it is found that approached flow velocity V, approached flow depth h and initial height of pier H_h are the critical factors for water-wing generation, especially the initial height of pier head. And if the approached flow rate is slow enough or the pier head is fully submerged into water, there will be no water-wing induced. Considering that in engineering practice, such as the flood drainage culvert, the discharge and velocity are large, it is not realistic to eliminate the water-wing by controlling the approached flow velocity and flow depth. Based on the cause analysis of water-wing, the only way to eliminate water-wing radically is to decrease the initial height of pier head. Therefore, a new pier is designed with a triangle profile whose initial height is zero (Figure 4). And a further series of experiments were conducted in the flume to observe whether this kind of pier can play an important role in eliminating water-wing.

As the initial height of Scheme No. 5, $H_h = 0$, Head of the pier can be submerged into water at any approached flow depth, and in the whole experimental process, there was no water-wing induced, even if Froude number reached the maximum 2.43 (corresponding velocity is 1.70 m^3/s). Figure 5 presents the phenomenon of water-wing caused by traditional and the newly designed piers at the maximum Froude number, respectively. Obviously, the newly-designed pier has a good effect on water-wing elimination, as well as on the flow pattern improvement. And it validates experimentally that the initial height of pier is just the critical factor of water-wing generation as well.

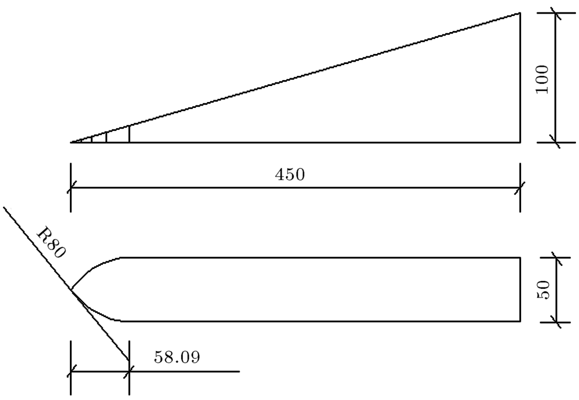
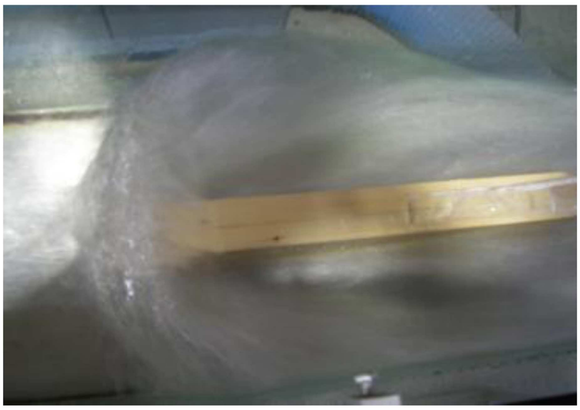
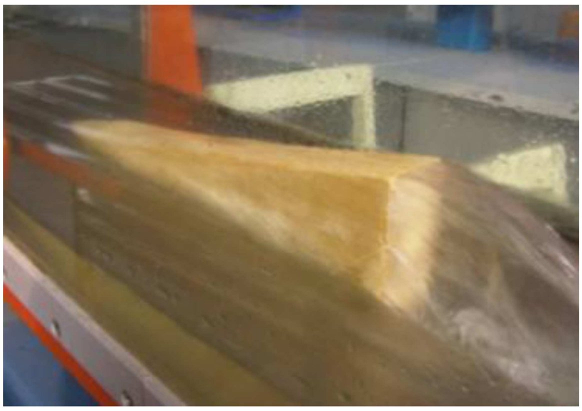


Figure 4. Scheme of the newly designed pier (No.5)



(a) Traditional pier



(b) Newly designed pier

Figure 5. Phenomenon of water-wing induced by pier.

4. Conclusions

In this article, we presented the results of a series of comparing water-wing laboratory experiments induced by the obstruction of pier. The experimental study focuses on the generation mechanism and the influencing factors of water-wing. The results show that both the radius and inclination angle are not the main influencing factors, although their increment can reduce the intensity of water-wing to some extent. Further study indicates that the Froude number (flow velocity), flow depth and initial height of the pier are the critical factors for water-wing generation, among which the initial height of pier head is the most important influencing factor. When the initial height of pier equals zero, it can adapt to various approached flow depths, and effectively eliminate water-wing. A newly pier has been designed for engineering purpose according to the influencing factors. The model experiment result of this newly designed pier receives very good effect on water-wing reduction, and also validates the above conclusions about the influencing factors in another aspect.

Although, how the discussed factors influencing the characteristics of water-wing have been obtained in the present experimental investigation and analysis, the results also indicate that more efforts need to be put on this area if the newly designed pier is extended to the practical flood drainage culvert. More parameters such as the length and width of the pier, energy dissipation, cavitation feature, and further improvement of the pier somatotype will be investigated in the future.

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Biographies

Chen Sheng is a PhD degree candidate in the College of Water Conservancy and Hydropower Engineering at Hohai University, China, from where he received his BS and MS degrees. His research interests include Computational Fluid Dynamics (CFD) and physical modeling of hydraulic structures, as well as hydraulic transient simulation.

Zhang Jian is a professor in the College of Water

Conservancy and Hydropower Engineering at Hohai University, Nanjing, China. He received his BS and MS degrees from Zhengzhou University, and his PhD degree from Hohai University. His research interests include hydraulic transients (free surface, pressurized and mixed flows), Computational Fluid Dynamics (CFD) and physical modeling of hydraulic structures. He has published more than 40 technical papers and is the author of two textbooks about hydraulic transients.

Hu Ming is a professor in the College of Water Conservancy and Hydropower Engineering at Hohai University, Nanjing, China. He received his BS degree from Zhejiang University, and his MS degree from Hohai University. His research interests include hydraulic transients simulation and modeling experiment.

Arash Hazrati is a PhD degree candidate at the College of Water Conservancy and Hydropower Engineering at Hohai University, China. His research interests include: turbulent and transient flow in hydraulics and hydropower systems, employing Computational Fluid Dynamics (CFD) and physical modeling of hydraulic structures simultaneously. He received his BS degree in Civil Engineering from the Islamic Azad University of Iran, and also an MS degree in Hydropower Engineering from University of Engineering and Technology (Center of Excellence in Water Resource Engineering, CEWRE) UET, Lahore.