Experimental study on improvement effect of guide wall to water flow in bend of spillway chute
Qinghua Zhang, Yanfang Diao, Xingtao Zhai and Shuning Li

ABSTRACT
In order to improve water flow in a bend of a spillway chute using a guide wall, modeling experiments with or without a guide wall under conditions of three different bend axial radii, three chute bottom slopes and three flow rates were carried out in this study. Two indexes were calculated, which are the improved water surface uniformity and the reduced rate of water surface difference in concave and convex banks of the cross-section. The results show that: (1) setting a guide wall in a bend can improve water flow in the bend because it increased the water surface uniformity of the cross-section and reduced the water surface difference in the concave and convex banks; (2) the smaller the bend axial radius, the better the water surface improvement effect will be using a guide wall; (3) the steeper the bottom slope, the more cross-sections with less water surface difference; and (4) flow rates have a great influence on water surface improvement in the bend, and the guide wall can improve water flow obviously when the water depth in the starting section of the bend is lower than the height of the guide wall. This study has important implications in engineering design of guide walls.

Key words | chute, guide wall, reduced rate of water surface difference, spillway, water surface uniformity

INTRODUCTION
Spillway is a major component of reservoirs, generally including intake section, control section, chute, energy dissipation section, and discharge section. The chute’s features include a large height difference of a river way in upstream and downstream, steep longitudinal gradient and rapid flow. Therefore, the engineering design requires that it should be straight and smooth with equal width as practically as possible to avoid or reduce disturbance of water flow caused by the shock wave of water. However, in a practical project, the chute is required to have a bend due to limitations of topographic and geological conditions. Affected by transverse circulation of the bend, water flow status of the bend is worsened and a transverse shock wave is produced inside the bend so that the water depth in the concave bank of the bend is great, and the opposite is true in the convex bank. It could lead to a large water surface difference in the concave and convex banks, uneven transverse current in the chute, and adverse effect on energy dissipation downstream. Therefore, if there is any bend in a spillway chute and the bend axial radius is small, some engineering measures must be adopted to improve flow character in the bend.

After Thomson (1876) found there were some transverse circulations for water flow in a bend by experiments, there have been many studies in this field. In the 1930s, Potapof (1958) investigated water flow in a bend by the Navier-Stokes equation and parabolic distribution formula of longitudinal velocity. Rosovsky (1958), a Ukraine scholar, studied water flow in a bend systematically. Ippen (1951), an American scholar, discussed shock wave of rapid flow in a bend systematically. In the 1950s, the Northwest Hydraulic Research Institute of China and some Chinese scholars such as Zhang & Lv (1993), Wang et al. (1994) and Tian (2000) proposed the computational formulas of water surface transverse gradient and mean velocity distribution in longitudinal vertical and transverse circulation vertical distribution of water flow in a bend, based on experimental researches. Han et al. (2011) researched characteristics of flow around open-channel 90° bends with vanes. Song et al. (2012) analyzed the secondary current effect in the modeling of shallow flow in open channels. Along with the development of computing technology, numerical simulation has been more and more widely used in studying water flow in...
bends. For example, Baghlan (2012) demonstrated the effectiveness of a high-resolution numerical scheme in boundary-fitted curvilinear coordinates for simulation of flow at channel bends, and Huai et al. (2012) adopted an RNG k-ε numerical model together with a laboratory measurement with a micro acoustic doppler velocimeter (ADV) to investigate the flow through a 180° curved open channel partially covered with rigid vegetation on its inner bank. All these researches provided theoretical foundation for improvement measures to water flow in bends.  

For improvement measures to water flow in bends, progress has been made in China, including canal bed super-elevation, compound bend, channel bed transverse fan-shaped elevation and inclined bottom sill. Knapp (1958), Li & Ning (1994) and Tian (2000) studied the channel bed super-elevation and compound bend, and they considered that: (1) maximum elevation for channel bed super-elevation was a fixed value so that it was applicable to the situation with one water flow and depth only; and (2) using the compound curve method could eliminate disturbing wave so that it was applicable for both a designed flow rate and other flow rates. However, the experiments showed that water surface super-elevation still appeared in the bend and was still serious, and a compound curve was not allowed in the front and rear of the bend in the channel of a completed project. The Northwest Hydraulic Research Institute of China (1961) researched the channel bed transverse fan-shaped elevation and considered that it could balance centrifugal force of bend rapid flow by channel bed fan-shaped elevation so that the water depth of water flow along the cross-section could be adjusted and flow direction could be changed to realize an even water depth and flow velocity distribution. By research of an inclined bottom sill, Knapp (1984), Bian et al. (1997) and Qiu et al. (1998) considered that an inclined bottom sill may change water flow direction in a channel bed to eliminate and reduce the water flow shock wave. Besides the above methods, the Northwest Hydraulic Research Institute of China (1958, 1959), Luo (1994) and Zhang (2006) researched the spiral line, buffer plunge pool, channel bed local elevation, wave breaking pier, curved dividing pier, artificial roughing, and compound bend. All the above methods can be used to eliminate or reduce the shock wave and improve water flow status of a bend, but some methods are limited to a certain designed flow rate, or have high construction difficulty, or are very labor-intensive.  

Using a guide wall to improve water flow in the bend of a spillway chute is an engineering technology developed in recent years. It divides the bend into two or more chutes by constructing vertical curved guide walls along or in two sides of the axial line inside the bend to reduce water surface difference in the concave and convex banks of the bend cross-section so that the water flow can be uniform. It has been applied in engineering practices, for example, spillway projects in Dongzhou Reservoir, Huangqian Reservoir and Duozhuang Reservoir of China. It has been proved by these practices that this technology could improve water flow condition in the bend of spillway wells. Most research on it resorts to modeling experiments based on specific projects; as a result, there is a lack of universality and systematism (Zhang et al. 2005; Zhou et al. 2007).  

Considering the influencing factors of bend axial radius, bottom slope and flow rate, this paper analyzes the improvement effect of a guide wall to water flow in the bend of a spillway chute based on two indexes including improved water surface uniformity and reduced rate of water surface difference in the concave and convex banks of the cross-section, by hydraulic model experiments with or without guide walls. Suggestions on engineering design of guide walls in the bend are given.

**EXPERIMENTAL METHOD**

**Experimental arrangement**

The experimental system is composed of a pump, a head water pond, water supply pipelines, a measuring weir, a flow steadying grid, channels, a model test area, a tail water pond, a backwater channel, and an underground reservoir, as shown in Figure 1. In this experimental system, the gate valve and measuring weir are used to control and measure the experimental flow rate, and the model test area is used to arrange the experimental model and measure the water depth and velocity. The design head of the head water pond is 6.0 m, the designed flow rate of the water supply pipeline is 0.6 m³/s, and the width and height of the measuring weir are 0.75 m and 0.7 m, respectively. The channel, model test area and tail water pond are in a model pond with length and width of 20 m and 6 m, respectively. The water volume of the underground reservoir is 400 m³.

**Experimental model**

The experimental model includes an intake section, a lock chamber, a straight section of chute, a bend of chute, and another straight section of chute of a spillway. The chute has a rectangular profile, whose net width is B = 0.5 m. Length of the experimental model is 2.8 m including 0.4 m...
for intake section, 0.3 m for lock chamber (three-hole gate), 0.2 m for straight section behind the chamber, 1.5 m axial line for the bend, and 0.4 m for another straight section of chute. A guide wall is located in the axial line of the bend with height of 0.07 m. Design of the experimental model is shown in Figure 2.

Some researches showed that the bend axial radius had a great influence on the water flow in a bend. Therefore, according to the Design code for spillway (Ministry of Water Resources of the People’s Republic of China, SL253-2000), the bend axial radius of a rectangular chute should be six to 10 times the width of the chute. When this condition cannot be satisfied, engineering measures must be taken to reduce the transverse water surface difference in the bend. In order to analyze the improvement effect of the guide wall to water flow under different bend axial radii, bend axial radii which are less than six to 10 times the width of the chute were selected. Therefore, the experimental model is divided into three entity models whose axial radii R are \( R = 3B \), \( R = 4B \) and \( R = 5B \), respectively. In addition, the chute bottom slope is generally a steep slope in engineering practices and it also has a great influence on the water flow in the bend. In order to analyze the improvement effect of the guide wall to water flow under different chute bottom slopes, every entity model is divided into three conditions whose bottom slopes of chute are \( i = 0.005 \), \( i = 0.01 \) and \( i = 0.02 \), respectively. By controlling flow rates, these three chute bottom slopes are steep slopes in this experiment. The experimental model is made of PVC plastic sheets with thickness of 8 mm, as shown in Figure 3.

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Experimental schemes

Eighteen experimental schemes are carried out and these schemes can be divided into three groups based on bend axial radii of chute, bottom slopes of chute, and with or without a guide wall in chute. The schemes are shown in Table 1.
Experimental measurement

The aim of this experiment is mainly the improvement of flow status after setting a guide wall. So the experimental measurement mainly focuses on the flow rate, velocity, and water depth.

(1) Flow rate measurement

This experiment adopts a rectangular weir to measure the flow rate controlled by a gate valve. There are three conditions for a guide wall in the bend of the chute: the water level is lower than, equal to, or higher than the guide wall, and flow rates under these three conditions are 19, 28, and 52 L/s by discharge test.

(2) Depth measurement device

Water depth measurement is done with a digital water level point gauge with accuracy of 0.01 mm. Compared with the traditional water level point gauge, the digital one can display the value of water level on a small screen, which can increase accuracy and be more efficient.

(3) Velocity measurement

A Vectrino+/Vectrino Plus ADV made in Norway is used for measurement of three-dimensional velocity. The maximum data acquisition frequency of the Vectrino+/Vectrino Plus ADV is 200 Hz.

(4) Measuring sections

Measuring sections are classified into two groups which are the cross-sections and profile sections. Based on experimental research demand, six cross-sections are designed for the experiment with six sounding verticals including left and right banks, left and right guide walls, and distance of 0.25B from the left and right banks for every section. The measuring sections are shown in Figure 4, in which 1, 2, 3, 4, 5 and 6 are the cross-sections and A, B, C, D, E and F are the profile sections.

RESULTS AND ANALYSIS

Analysis indexes of flow improvement effect

For water flow in a bend under the influence of transverse circulation, water depth of the cross-section changes, and water depth in the concave bank is much higher than that in the convex bank so that a transverse water surface gradient is produced and water flow is not uniform. Setting a guide wall in the axial line of the bend improves it; so analysis of water flow improvement effect in the bend can be reflected by the improved water surface uniformity of the cross-section and reduced rate of water surface difference in the concave and convex banks of the cross-section.

(1) Water surface uniformity of cross-section

Water surface uniformity of the cross-section reflects uniformity of water depths in various points of the cross-section,
and its calculation formula is as follows:

\[ C_a = \left[ 1 - \frac{\Delta h}{\bar{h}} \right] \times 100\% \]  

where \( C_a \) is the water surface uniformity of cross-section, \%; \( \Delta h \) is the average water depth difference of each measuring point of cross-section, mm; \( \bar{h} \) is the average water depth of cross-section, mm.

\( \Delta h \) and \( \bar{h} \) can be calculated by the following formulas:

\[ \Delta h = \frac{\sum_{i=1}^{n} \left| h_i - \bar{h} \right|}{n} \]  

(2)

\[ \bar{h} = \frac{\sum_{i=1}^{n} h_i}{n} \]  

(3)

where \( h_i \) is the water depth at a measuring point of cross-section, mm; \( n \) is the number of measuring points of cross-section.

Water surface uniformity of the cross-section reflects uniformity of water depths in various points of the cross-section. The larger its value, the more uniform is the water flow of the cross-section. \( C_a = 100\% \) when depths of all points are the same.

(2) Improved water surface uniformity of cross-section

Improved water surface uniformity of the cross-section is used to reflect the improvement effect of the water surface of the cross-section by setting a guide wall.

\[ C = C_{ae} - C_{an} \]  

(4)

where \( C \) is the improved water surface uniformity of cross-section, \%; \( C_{ae} \) is the water surface uniformity of a cross-section with guide wall, \%; \( C_{an} \) is the water surface uniformity of a cross-section without guide wall, \%.

(3) Reduced rate of water surface difference in concave and convex banks of cross-section

One of the purposes for setting a guide wall in a bend is to reduce water surface difference in the concave and convex banks of the cross-section; so reduced rate of water surface difference in concave and convex banks of the cross-section is used to reflect the improvement effect of water surface of the cross-section with or without guide wall.

\[ \eta = \frac{\Delta h_n - \Delta h_e}{\Delta h_n} \times 100\% \]  

(5)

where \( \eta \) is the reduced rate of water surface difference in concave and convex banks of cross-section, \%; \( \Delta h_n \) is the water surface difference in concave and convex banks without guide wall, mm, \( \Delta h_e = h_{n1} - h_{n2} \); \( \Delta h_e \) is the water surface difference in concave and convex banks with guide wall, mm, \( \Delta h_e = h_{e1} - h_{e2} \); \( h_{n1} \) is the water depth in concave bank without guide wall, mm; \( h_{e1} \) is the water depth in convex bank without guide wall, mm; \( h_{e2} \) is the water depth in concave bank with guide wall, mm; \( h_{n2} \) is the water depth in convex bank with guide wall.

Analysis of flow improvement effect

Improvement effect of water surface uniformity of cross-section

The improved water surface uniformities of cross-sections the 2, 3, 4, 5 and 6 in the bend under conditions of three bend axial radii, three bottom slopes and three flow rates are shown in Figures 5–7.

The following can be seen from Figures 5–7:

1. After setting a guide wall, water surface uniformities of 105 out of 135 cross-sections are increased as compared to condition without guide wall. The number of cross-sections with improvements in water surface uniformity accounted for 77.8% of the total number of cross-sections, and the average improvements in water surface uniformity is 4.3%, which means that setting a guide wall in the bend can increase the water surface uniformity of a cross-section.

2. Seen from the bend axial radius R, after setting a guide wall, water surface uniformities of 38 out of 45 cross-sections are higher than condition without guide wall when R = 3B, accounting for 88.4% in the number of cross-sections with improvement in water surface uniformity. It becomes 77.8% when R = 4B, and 71.1% when R = 5B, which means that the smaller the bend axial radius is, the better the improvement effect of water surface uniformity of the cross-section. However, the average improved water surface uniformity reached the maximum value of 4.6% when R = 4B, the second-highest value of 4.4% when R = 5B, and the minimum value of 3.8% when R = 3B.
3. For the flow rate, after setting a guide wall, water surface uniformities of 39 out of the 45 cross-sections are higher than condition without guide wall when the flow rate is 19 L/s, accounting for 86.7% in the number of cross-sections with improvement in water surface uniformity, and the average improved water surface uniformity is 6.1%. Number of cross-sections with improvement in water surface uniformity is 82.2% and 64.4% and average improved water surface uniformity are 5% and 1.3%, respectively, when the flow rates are 28 and 52 L/s, which means that the smaller the flow rate, the stronger the improvement effect of water surface uniformity of the cross-section.

4. For the bottom slope, after setting a guide wall, water surface uniformities of 34 out of the 45 cross-sections are higher than condition without guide wall when the bottom slope is 0.02, accounting for 75.6% in the number of cross-sections with improvement in water surface uniformity, and the average improved water surface uniformity is 4.4%. Number of cross-sections with improvement in water surface uniformity becomes 82.2% and 75.6% and average improved water surface uniformities are 5.7% and 2.4%, respectively, when \(i = 0.01\) and \(i = 0.005\). The experimental result shows that the bottom slope has no obvious influence patterns in improving water surface uniformity of the cross-section in the bend.

**Improvement effect of water surface difference in concave and convex banks of cross-section**

Reduced rate of water surface difference in concave and convex banks of cross-sections 2, 3, 4, 5 and 6 in the bend under conditions of three bend axial radii, three bottom slopes and three flow rates are shown in Figures 8–10.

The following can be seen from Figures 8–10:

1. After setting a guide wall, reduced rates of water surface differences in concave and convex banks of 119 out of 135 cross-sections are lower than condition without condition.
guide wall, accounting for 88.2% in the number of cross-sections with reduction in reduced rate of water surface difference, and the average reduced rate is 32.9%, which means that setting a guide wall in the bend can reduce water surface difference in concave and convex banks of the cross-section greatly.

2. For the bend axial radius R, after setting a guide wall, reduced rate of water surface differences in concave and convex banks of 40 out of 45 cross-sections are higher than condition without guide wall when the radius \( R = 3B \), accounting for 88.9% in the number of cross-sections with improvement in reduced rate of water surface difference. It is 88.9% when \( R = 4B \) and 86.7% when \( R = 5B \), which means that the smaller the bend axial radius, the better the reduction effect of water surface difference in concave and convex banks of the cross-section. However, for average reduced rate of water surface difference, the maximum value is 36.5% when \( R = 5B \), the second-highest value is 32% when \( R = 3B \), and the minimum value is 30.3% when \( R = 4B \).

3. Seen from the flow rate, after setting a guide wall, reduced rate of water surface differences in concave and convex banks of 44 out of 45 cross-sections are higher than condition without guide wall when the flow rate is 19 L/s, accounting for 97.8% in the number of cross-sections with improvement in reduced rate of water surface difference, and the average reduced rate is 47.6%. The cross-sections with improvement are 100% and 66.7% and average reduced rates are 42.9% and 7.3%, respectively, when flow rates are 28 and 52 L/s, which means that the smaller the flow rate, the better the reduction effect of water surface difference in concave and convex banks of the cross-section.

4. For the bottom slope, after setting a guide wall, reduced rate of water surface differences in concave and convex banks of 41 out of 45 cross-sections are higher than condition without guide wall when bottom slope \( i = 0.02 \), accounting for
91.1\% in the number of cross-sections with improvement in reduced rate of water surface difference, and the average reduced rate is 4.4\%. The number of cross-sections with improvement become 88.9\% and 84.4\% and average reduced rates are 37.4\% and 26.9\%, respectively, when $i = 0.01$ and $i = 0.005$. Therefore, seen from the proportion of cross-sections with improvement in reduced rate of water surface difference in concave and convex banks, the steeper the bottom slope is, the better the reduction effect will be, but seen from the reduced rate of water surface difference, there are no obvious patterns.

**Analysis of water surface improvement effect by chute flow**

It can be seen from the above results that water surface improvement effect of bend is the most obvious when the chute flow rate is 19 L/s and is not obvious when it is 52 L/s, which means the chute flow rate has great influence on water surface improvement effect of bend, and the reasons are as follows:

- When the chute flow rate is 19 L/s, water level in the starting section of the bend is lower than the height of the guide wall. Water flow reaching the bend is divided into two parts, the chute forms two discharge channels, and there is no mutual influence between them. Therefore, improvement effect of water surface of the cross-section is the best.

- When the chute flow rate is 52 L/s, water level in the starting section of the bend is higher than the height of the guide wall. As influenced by transverse circulation in the bend, water surface in the convex bank is higher than the height of the guide wall and water flows to the concave bank so that the separation effect by the guide wall is reduced. In addition, when water flow from the concave bank returns to the convex bank, partial flow which is lower than the guide wall cannot return to the convex bank and the water surface difference in the concave and convex banks of the cross-section is aggravated. Hence in some cases, water surface difference in the concave and convex banks with guide wall is greater than that without guide wall.

**Mechanism of improving water flow in bend of spillway chute by guide wall**

When the guide wall BB1 is set in the bend, the chute is divided into inside chute BB1C1C and outside chute AA1B1B. At the entrance of the bend, the water flow is evenly distributed to the inside and outside chutes by the guide wall, as shown in Figure 11.

In Figure 11, BB1 shows that the guide wall is along the axial line of the bend of the spillway chute, $R_1$ is the convex bank radius of the bend, $R_2$ is the concave bank radius of the bend, $R_3$ is the axial radius of the outside chute and $R_m$ is the axial radius of the bend. When the guide wall is not set up, the water surface super-elevation is as follows (Li et al. 2008):

$$\Delta Z_1 = \alpha \frac{V^2(R_2 - R_1)}{gR_m}$$

(6)

and when the guide wall is set up, the water surface super-elevation is as follows:

$$\Delta Z_2 = \alpha \frac{V^2(R_2 - R_m)}{gR_3}$$

(7)

where $\Delta Z_1$ is the water surface super-elevation without the guide wall, m; $\Delta Z_2$ is the water surface super-elevation with the guide wall, m; $\alpha$ is the coefficient of flow velocity distribution; $V$ is the average flow velocity, m/s; $g$ is the acceleration of gravity, m/s$^2$.

Because $R_3 > R_m$ and $R_m > R_1$, $\Delta Z_1 > \Delta Z_2$. In other words, the water surface super-elevation, water surface difference in concave and convex banks and water surface transverse gradient are reduced by setting a guide wall in the bend of the spillway chute. So, the water flow in the bend is improved.

**CONCLUSIONS AND SUGGESTIONS**

**Conclusions**

Conclusions can be summarized as follows. (1) Setting a guide wall in the bend of a spillway chute can improve the
water flow in the bend so that the water surface uniformity of the cross-section is increased and the water surface difference in concave and convex banks is reduced. (2) Bend axial radius has a certain influence on the water flow improvement effect, and a smaller axial radius can bring more obvious improvement in flow status by setting a guide wall when other conditions are the same. (3) The bottom slope of the chute has certain influence on the water flow improvement effect. Seen from the proportion of cross-sections with improvement in reduced rate of water surface difference in concave and convex banks, the steeper the bottom slope of the chute is, the more cross-sections with less reduced water surface difference there will be, but seen from reduced rate of water surface difference, there are no obvious rules. In addition, as seen from the water surface uniformity improvement effect of the cross-section, the influence of the bottom slope is not great. (4) Flow rate has a great influence on the water surface improvement effect. When water depth in the starting section of the bend is lower than the height of the guide wall, the guide wall has great improvement effect on water flow; otherwise, it is not obvious.

**Suggestions**

The following suggestions are given based on the above research. (1) Compared with channel bed super-elevation and channel bed fan-shaped elevation, setting a guide wall in the bend of a spillway chute to improve water flow in the bend is a simple construction with low engineering cost, and using a guide wall to improve water flow in the bend is more appropriate when the bottom slope is steep and the axial radius is small in bend. (2) Engineering design of the guide wall should strictly control its height to ensure it is higher than water depth in the starting section of the bend under designed flow rate. (3) The starting location of the guide wall should be the same as or in front of the starting location of the bend generally.

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