Xu, Fang; Deng, Jin-Yun; Yue, Hong-Yan; Zhang, Xiang-Yu

Experimental Study of Impact of Dock Structures on Water Level in Mountainous Waterway

12th International Conference on Hydroscience & Engineering
Hydro-Science & Engineering for Environmental Resilience
November 6-10, 2016, Tainan, Taiwan.

Experimental Study of Impact of Dock Structures on Water Level in Mountainous Waterway

Fang Xu[1], Jin-Yun Deng[2], Hong-Yan Yue[3], Xiang-Yu Zhang[1]
1. Key Laboratory of Hydraulic and Waterway Engineering of the Ministry of Education, Chongqing Jiaotong University
Chongqing, China
2. Key Laboratory of Water Resource and Hydropower Engineering Sciences, Wuhan University
3. Yangtze River Scientific Research Institute
Wuhan, Hubei, China

ABSTRACT

The introduction of dock structures may change flow characteristics of waterways, and the magnitude of the change is very important to flood controls and project feasibility studies. This paper studies in theory the relative maximum water level rise caused by various dock structures, as well as the governing factors and estimation method for the upstream backwater extent of the dock structures. Based on hydraulic laboratory tests of 37 sets of different conditions, this paper develops an expression for the relative maximum water level rise caused by dock structures, and verifies the feasibility of some theoretical estimation method for upstream backwater extent. The results of this paper provide the theoretical foundation for the planning and design of dock structures in mountainous waterway.

KEY WORDS: mountainous waterway， dock structures， flow characteristics， backwater，hydraulic laboratory tests

INTRODUCTION

As the vigorous development of the water transport construction in the upper reaches of the Yangtze River, there will be a new round of high tide of the construction of the dock structures. The introduction of dock structures will occupy a certain discharge area and may change flow characteristics of waterways and may bring adversely affect on river navigation ,flood controls ,river stability ,dyke round safety and water transport .Different types and arrangement of dock structures may have a direct impact on flow characteristics of waterways and also is an important prerequisite of the construction of dock structures. Currently the correlation studies at home and abroad are mostly focused on numerical simulation analysis on a specific dock structure or some other similar projects just like model test for groin works, and lack of system model test of multifactor combination such as various traffic, various types of dock structures, multiple terminal length and width, different water area ratio. It is difficult to guide the mountain river pier construction of the actual needs.

This paper studies the influence of the various types of dock structures (such as solid type and high pile type) on water height near the mountain river reach (include maximum backwater height and the position, upstream backwater scope),through the combination of theoretical analysis and model test. And it also can provide a theoretical basis and reference for the engineering construction management and design of the future river pier.

DESIGN OF MODEL TESTS

Test Device

In order to reduce the influence of stream current fluctuation on the tests results, a primary and a secondary tumble bay are set at the inlet. The primary tumble bay is 2.0m×2.0m×1.5m with a stilling ridge at the bottom. The secondary tumble bay is 13.0 m×8.0 m×1.0m and an adjustable stilling grate is set at the inlet of water channel that can make the stream steady and homogenous.

Characteristic Value of Stream Current In Tests

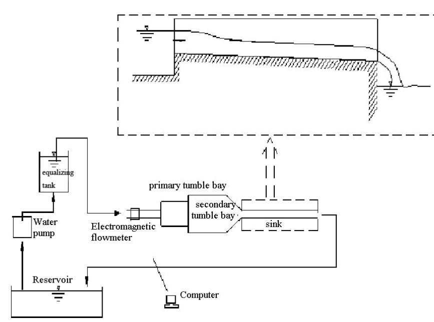

Fig. 1 Sketch of water r system

The flow and water level of mountain stream vary greatly in amplitude, and the maximum flow can be as much as hundreds of the minimum flow. The slopes of mountain stream are often about 11‰, some could even far more than 1‰. The flow pattern of mountain stream is very complex as the result of anomalous bed configuration.

In order to simulate the current of mountain stream, the experiment flume in our tests is 2.3m in width and 0.82‰ in slope. Four different flows, i.e. 60l/s, 90l/s, 120l/s and 150l/s, are applied in our tests. The current in our tests is tranquil flow since the Froude number varies in the range of 0.197～0.251.

The experiment flume in our tests meets the requirement of twodimensional flow, which is usually judged with aspect ratio (the ratio of width to depth) in open-channel flow. The aspect ratio in laboratory tests often ranges from 5 to 10, but depends more on the test objectives. The aspect ratios in our tests are 22～33, the maximum water depth is no more than o.2m. The Reynolds number varies between 30623 and 73601, which indicates that the stream current is turbulent flow since the Reynolds number is far more than 500. The water countercheck ratio in our tests is between 1.5% and 7.4%.

Design of Experiment Flume

The generalized experiment flume is rectangular in shape with the size of 18m×2.3m×0.5m and 0.82‰ in slope. The medium diameter of sand used for sand-cement grout at the bottom of experiment flume is 0.99mm based on the statistics of the sand medium diameter in the representative segments of the upstream of Changjiang River. The dock model is arranged 10-10.5m far from the inlet at the left bank. Several gauging stations are set far from 1m, 4m、6m、8m、10m、12m、14m、16m on both banks. The test segment is 8 m-12m far from the inlet. Homogeneous turbulence can form in the test segment and the tail discharge freely.

Test Scheme Design

Solid dock represented by submerge groin, non-submerge groin works and high-pile dock represented by single-row piles and group piles works are studied in our tests. Figure 2 illustrates the arrangement of experiment flume.

The piles in our tests are imitated by PVC poles 2cm in diameter and 40cm in length. The piles are uniformly arranged with the space of 8cm which is four times of its diameter.

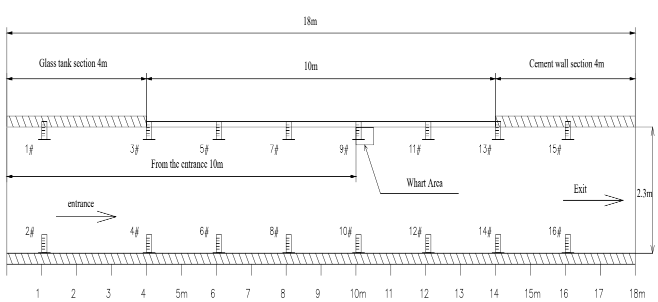

Fig. 2 Overall configuration sketch of experiment flume

ANALYSIS OF DOCK ENGINEERING RESISTANCE CHARACTERISTICS

Mechanism of Water Resistance

The building of dock in river can induces many hydrate changes in the upstream such as the current slope and velocity decrease and water level increase. At the dock section, however, the current slope and velocity increase sharply since the section narrows down. When the current passes the dock section, the current keeps narrowing and its slope and velocity increases meanwhile as the result of sluggishness. The current gradually recovers to the natural status under the action of the diffusion after the shrinkage section.

Maximum Backwater Height Theory

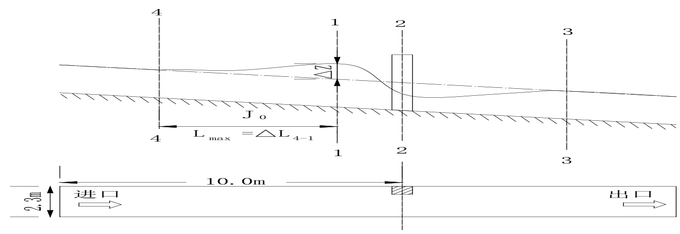

Fig. 3 Vertical section of center flow near dock engineering

Figure 3 shows the backwater level curve in dock engineering. The local head loss occurs in the segment between section 1-1(the maximum backwater level) and section 3-3(water level remains the same as that before the building of dock). The energy relationship can be expressed as follows:
Before the building of dock the equation is:

$$Z_1+\frac{\alpha_1 v_1^2}{2g}=Z_3+\frac{\alpha_3 v_3^2}{2g}+h_{f1-3} \quad (1)$$

after the building of dock the equation is:

$$Z_1'+\frac{\alpha_1' v_1'^2}{2g}=Z_3'+\frac{\alpha_3' v_3'^2}{2g}+h_f'_{1-3}+h_j \quad (2)$$

$$h_{f1-3}=\frac{Q^2}{\overline{K}_{1-3}^2}\Delta L_{1-3}=\frac{n^2\overline{v}_{1-3}^2}{\overline{H}_{1-3}^{4/3}}\Delta L_{1-3},$$

$$Z_1'+\frac{\alpha_1' v_1'^2}{2g}=Z_3'+\frac{\alpha_3' v_3'^2}{2g}+h_f'_{1-3}+h_j;$$

Where z is water level; v is the current velocity; α is the correction factor of motion energy; n is the roughness; ΔL is the length of river segment; h_f is the frictional head loss; h_j is the local head loss.

The subscript denotes the section; superscript represents the value after the building of dock, and represents the value before the building of dock.
The local head loss can be expressed as

$$h_j=\xi\frac{v_2'^2}{2g} \quad (3)$$

Where ξ is resistance coefficient; v_2' is the representative current velocity and can be replaced by the compression velocity in the central section of dock engineering,

$$v_2'=\frac{Q}{A_2-\Delta A_2}=\frac{Q}{(1-\varepsilon)A_2}=\frac{v_2}{1-\varepsilon},$$

A_2 is the total discharge area before the building of dock, ΔA_2 is the water countercheck area, ε is the water countercheck area-ratio.
Considering the water level at the section 3-3 has recovered to that before the building of dock, so we can gain:

$$\frac{\alpha_3 v_3^2}{2g} \approx \frac{\alpha_3' v_3'^2}{2g}, \quad Z_3 \approx Z_3'$$

Substitute the above equations to the equation (2)-(1), the maximum backwater height can be expressed as

$$\Delta Z = Z_1' - Z_1 = \xi \frac{v_2'^2}{2g} + \left(\frac{n^2 \overline{v'}_{1-3}^2}{\overline{H'}_{1-3}^{4/3}} - \frac{n^2 \overline{v}_{1-3}^2}{\overline{H}_{1-3}^{4/3}}\right)\Delta L_{1-3} + \left(\frac{\alpha_1 v_1^2}{2g} - \frac{\alpha_1' v_1'^2}{2g}\right) \tag{4}$$

Where

$$\overline{H'}_{1-3} = \frac{1}{2}(H_1' + H_3'), \overline{H}_{1-3} = \frac{1}{2}(H_1 + H_3)$$

$$\overline{v'}_{1-3} = \frac{1}{2}(v_1' + v_3'), \overline{v}_{1-3} = \frac{1}{2}(v_1 + v_3)$$

If ΔZ is small,

$$\left(\frac{\alpha_1 v_1^2}{2g} - \frac{\alpha_1' v_1'^2}{2g}\right) \approx 0$$

Equation (4) can be simplified as

$$\Delta Z = Z_1' - Z_1 = \xi \frac{v_2'^2}{2g} + \left(\frac{n^2 \overline{v'}_{1-3}^2}{\overline{H'}_{1-3}^{4/3}} - \frac{n^2 \overline{v}_{1-3}^2}{\overline{H}_{1-3}^{4/3}}\right)\Delta L_{1-3} \tag{5}$$

Equation 5 shows that the maximum backwater height can be divided into two parts. One is the local head loss; the other is the frictional head loss. If the frictional resistance is calculated by the hydrate factors of the central section, equation 5 and 4 can be written as

$$\Delta Z = Z_1' - Z_1 = \xi \frac{v_2'^2}{2g} + \left(\frac{n^2 v_2'^2}{H_2'^{4/3}} - \frac{n^2 v_2^2}{H_2^{4/3}}\right)\Delta L_{1-3} + \left(\frac{\alpha_1 v_1^2}{2g} - \frac{\alpha_1' v_1'^2}{2g}\right) \tag{6}$$

$$\Delta Z = Z_1' - Z_1 = \xi \frac{v_2'^2}{2g} + \left(\frac{n^2 v_2'^2}{H_2'^{4/3}} - \frac{n^2 v_2^2}{H_2^{4/3}}\right)\Delta L_{1-3} \tag{7}$$

Where

$$v_2' = \frac{Q}{A_2 - \Delta A_2} = \frac{Q}{(1-\varepsilon)A_2} = \frac{v_2}{1-\varepsilon}, v_2 = \frac{Q}{A_2},$$

H_2,H_2' is the water depth at section 2-2 before and after the building of the dock respectively,

$$H_2 = \frac{A_2}{B_2}, H_2' = \frac{A_2 - \Delta A_2}{B_2} = (1-\varepsilon) H_2$$

Equation 7 made it possible to get rid of pilot calculation. Using the Froude number before building, i.e.

$$Fr = \frac{v^2}{gH} = \frac{v_2^2}{gH_2},$$

equation 7 can be written as

$$\frac{\Delta Z}{H} = \left\{ \frac{\xi}{2(1-\varepsilon)^2} + \frac{g}{H^{4/3}} n^2 \Delta L_{1-3}\left[\frac{1}{(1-\varepsilon)^{10/3}} - 1\right] \right\} Fr \tag{8}$$

Equation 8 shows that the relative maximum backwater height is the function of water countercheck area-ratio, Froude number and local resistance factor if the variation of head loss. It is notable that ΔZ is the average maximum backwater height.

Formula for The Maximum Backwater Range

If the section 4-4 is the section where the backwater has no influence, ΔL_{4-1} is the maximum backwater range of dock engineering. The theoretic formula can be deduced as follows：
Currents at the section 4-4 and 1-1 are homogenous. The energy equation between the two sections is

$$\Delta L_{4-1} J_0 + h_{04} + \frac{\alpha_4' v_4'^2}{2g} = \Delta z + h_{01} + \frac{\alpha_1' v_1'^2}{2g} + h_{f4-1}$$

Where

$$h_{f4-1} = \overline{J_{4-1}} \Delta L_{4-1} = \frac{1}{2}(J_0 + J_1)\Delta L_{4-1}, \quad h_{01} = h_{04}$$

since the current is homogenous.
Then the maximum backwater range can be written as

$$\Delta L_{4-1} = \frac{2\left(\Delta Z + \frac{\alpha_1' v_1'^2}{2g} - \frac{\alpha_4' v_4'^2}{2g}\right)}{J_0 - J_1} \tag{9}$$

Since the slope at section 1-1 is about zero, equation 9 can be written as

$$\Delta L_{4-1} = \frac{2\left(\Delta Z + \frac{\alpha_1' v_1'^2}{2g} - \frac{\alpha_4' v_4'^2}{2g}\right)}{J_0}$$

If ΔZ is small and

$$\frac{\alpha_1' v_1'^2}{2g} \approx \frac{\alpha_4' v_4'^2}{2g},$$

it can be simplified as

$$\Delta L_{4-1} = \frac{2\Delta Z}{J_0} \tag{10}$$

Where J_0 is the slope of the water channel; ΔZ is the average maximum backwater height of the section, unlike that in the following diagram and table which represents the maximum value at the measurement station.

THE RESULT ANALYSIS OF THE SPUR DIKE BACKWATER TEST

In order to investigate the influence of solid dock on the water level, submerge groin with size 8 cm × 6 cm × 5 cm ,16 cm × 6 cm × 5 cm ,32 cm × 6 cm × 5 cm and non-submerge with size 17cm×6cm×40cm are tested when the flow is 60 l/s ,90 l/s ,120 l/s and 150 l/s respectively. The axis of groin is 10m far from the inlet.

Maximum Backwater Height of Spur Dike

According to the measurement data, in the submerge groin works, the maximum backwater level is observed at the axis of the groin when the flow is small, and near the upstream of the groin axis when the flow is large. On the other hand, the maximum backwater level is always observed near the upstream of the groin axis.

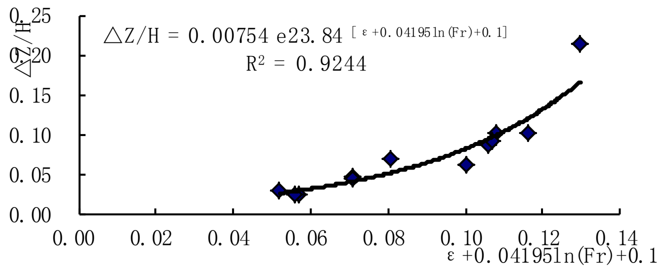

Fig. 4 Relation Curve of Spur Dike $\Delta Z/H$ and ε-Fr

Figure 4 shows the relationship of the relative maximum backwater height in the single-row pile with its water countercheck area-ratio and Froude number. The relationship can be expressed by the following statistic formula:

$$\frac{\Delta Z}{H} = 0.00754 \cdot e^{23.84(\varepsilon + 0.04195\ln(Fr) + 0.1)} \qquad (R = 0.9716) \qquad (11)$$

also written as

$$\frac{\Delta Z}{H} = 0.0818 Fr \cdot e^{23.84\varepsilon} \qquad (R = 0.9716)$$

Maximum Backwater Scope of Spur Dike

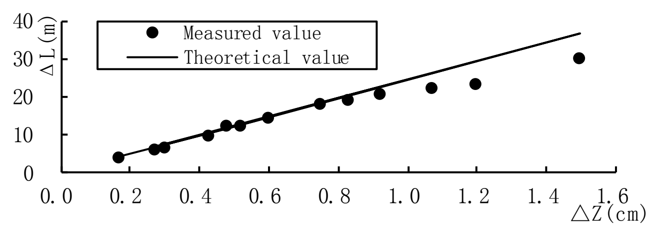

Fig. 5 Relation diagram of influence range ΔL and maximum value of back-up ΔZ at Spur dike upstream backwater

Figure 5 shows the measured and theoretical backwater range. The measured backwater range is the distance from the section with the maximum backwater height to that with no backwater. The section with the maximum backwater height is determined by linearly extending the measured backwater height. The theoretical backwater range is calculated from equation 10.

It can be seen that the theoretical value agrees well with the measured one when the maximum backwater height is less than 0.75cm. Otherwise the theoretical value is larger and the error increases with the maximum backwater height. This indicates that equation 10 is suitable to calculate the backwater range when the maximum backwater height is little.

RESULT ANALYSIS OF BACKWATER IN SINGLE-ROW PILE

In order to investigate the influences of on the water level, we carried out tests on single-row pile works at the flow is 60 l/s ,90 l/s ,120 l/s and 150 l/s respectively. In these single-row works, 2 piles, 4 piles, 6 piles and 8 piles are used respectively with the piles axis is 10m far from the inlet.

Maximum Backwater Height in Single-row Pile

According to the actual data it's apparent that for single row of piles, no matter what the water flow is, the maximum backwater height values all occur at the cross-section which is the center line of the pile on. The axis of pile aims at 10 meters away from the left of the experiment flume).

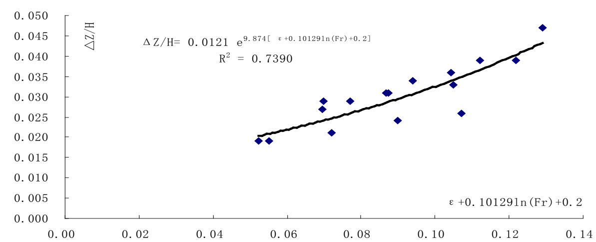

Fig. 6 Relation Curve of Single-row Pile $\Delta Z/H$ and ε, Fr

Figure 6 shows the relationship of the relative maximum backwater height in single-row pile, its resistance water area ratio and the Froude number. The relation can be expressed by the following statistic formula,

$$\frac{\Delta Z}{H} = 0.0121 \cdot e^{9.874\cdot(\varepsilon + 0.10129\ln(Fr) + 0.2)}, \quad (R=0.8597)$$

also written as

$$\frac{\Delta Z}{H} = 0.0872 \cdot Fr \cdot e^{9.874\varepsilon}, \quad (R=0.859) \qquad (12)$$

Maximum Backwater Scope of Single Row of Piles

The theoretic backwater range agrees well with the measured backwater range. The error value is less than ±20%, as in Figure 7. This indicates that equation 10 is suitable to calculate the backwater range when the maximum backwater height is less than 0.57 cm.

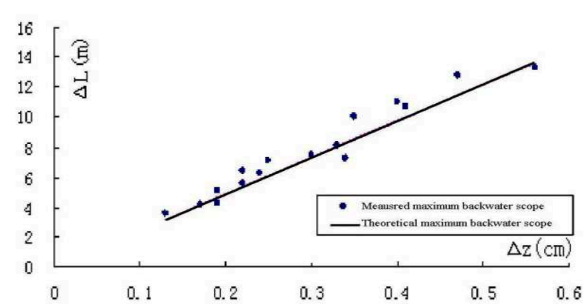

Fig. 7 Relation Diagram of r Influence range ΔL and Maximum Value of Back-up ΔZ at Single Row Pile Upstream Backwater

BACKWATER EXPERIMENT REASULT ON PILE GROUPS

In order to investigate the influence of the high-pile-pattern dock on the water level, we carried out eight tests on different rows of the piles when the flow is 120l/s. The piles are arranged in 2 and 4 rows with 2, 4, 6, 8 piles in each row respectively. The axis of the first row piles is 10 far from the inlet.

Maximum Backwater Height of Pile Groups

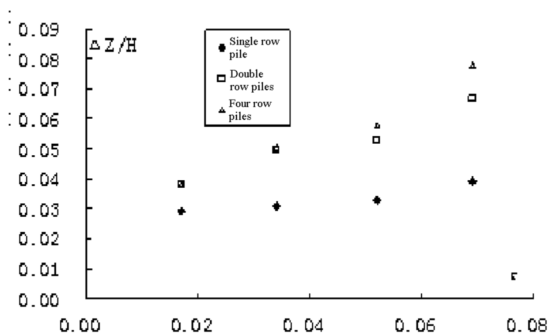

Fig. 8 Relation cure of $\Delta Z/H$ and ε at the Pile group

Figure 8 shows the relationship of the relative maximum backwater height in group piles and the resistance water area ratio. It's obvious that the relative maximum backwater height increase significantly from single-row piles works to double-row piles works. However, the relative maximum backwater height increases slightly when the piles increase from two rows to four rows. This indicates that the increase of rows has little effects on the relative maximum backwater height when it is more than two rows.

Maximum Backwater Range of Pile Groups

The theoretical backwater range agrees well with the measured backwater range within the error value $\pm 16\%$, as in Figure 9. This indicates that the equation (10) is suitable to calculate the backwater range when the maximum backwater height is less than 0.82cm.

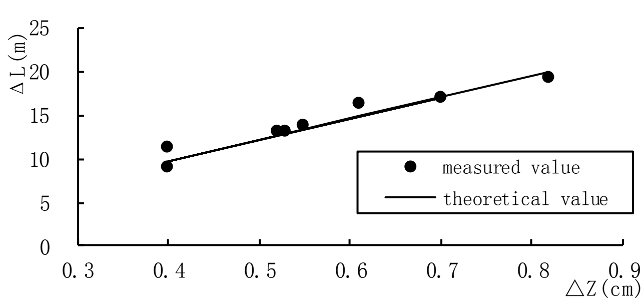

Fig. 9 Relation diagram of backwater influence range ΔL and maximum value of back-up ΔZ at the Pile group upstream

CONCLUSION

The following conclusions can be made from our experiment results:

(1) The backwater experiments on all kinds of dock engineering show that the maximum backwater levels are observed near the upstream side of the dock.

(2) The relative backwater height of groin and single-row pile cofferdam works are found closely related with water countercheck area-ratio and Froude number, which can be expressed as

$$\frac{\Delta Z}{H} = a \cdot Fr \cdot e^{b\varepsilon} \tag{13}$$

where a and b are the coefficients varying with the dock pattern.
The relative backwater height of groin works is much larger than that of single-row pile cofferdam works, while only large than that of four-rows pile works if the same ε and Fr are kept same. That means that the relative backwater height of groin works of multiple rows pile is between that of groin works and single-row pile works.

(3) Equation (10) is suitable for calculating the maximum backwater height for these dock patterns in our experiments if it is not very large.

REFERENCES

Li, Y., Deng, J., and Gan, F. (2007). Construction of channel of the Yangtze River of new opportunities and challenges and counter measures .Science & Technology Review, Vol.25, No.3:39-44.
Wu, C. (1998). Hydraulics. Beijing Higher Education Press, Beijing.
Wu, Y., Wang, D., and Wu, S. (2005). The upstream port dock structure type and its trend of development. Port Engineering Technology, Vol.12, No.4:22-24.
Xu, F. personal communication. (2008). Dock engineering on mountainous river flow influence experimental study. Chongqing Jiaotong University, a master's degree thesis project, February.
Yang, S. (2003). Water and sediment movement law and simulation technology in broad and shallow shifting river. PhD thesis, Si chuan University.