

Numerical study on local loss at right angle diversion under the different cross section shapes

Jian Zou^{1, a}, Tao Li^{2, b}, Shaojun Qu^{2, c} and Ping Gao^{3, d}

¹ Institute of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou, 450045, China

² Yellow River Institute of Hydraulic Research, Zhengzhou, 450003, China

³ College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing, 210098, China

^a847813641@qq.com, ^blitao@hky.yrcc.gov.cn, ^cqushaojun@hky.yrcc.gov.cn, ^d1260700565@qq.com

Keywords: different shapes of cross sections, 90° lateral diversion, local head loss, numerical simulation

Abstract: Lateral diversion from an open channel is a common flow regime and easily produces swirl which causes large head loss. The previous research mainly focused on the split flow about the fixed shapes of channel and small slopes. The paper investigated the local head loss at the diversion gate under three different cross sections (rectangle, trapezoid, and triangle) with Mike21 mathematical simulation method, and proposed the relationship between Froude number and local head loss coefficient under the different cross-sectional shape. The results show that the local head loss gradual increases at the diversion entrance, with the increase of the inlet discharge, under the same cross-section shape. At the same discharge, the local head loss of the triangular section is the largest, followed by the trapezoid, and the rectangle is the smallest. In the subcritical flow of open channel, the local head loss coefficient decreases with the increase of Froude number. The research results not only enrich the hydraulic discipline, but also provide technical support for similar projects.

Introduction

Lateral flow diversion from an open channel is a common water phenomena. For the study of flow regime at the split gate between main stream and tributary, Luo Fuan^[1], Wang Xingkui^[2] and Cao Jiwen^[3] had studied the hydraulic characteristics of lateral water intake in the experimental flume. Chang Hongxing et al.^[4], A.S. Ramamurthy^[5] and Huang Jianchun^[6] used numerical simulation to study the flow field structure of the distributary zone, of which the angle between the main stream and tributary is 90°. Yang Fan^[7] conducted a quantitative study on the "water withdrawal effect" of lateral water withdrawal at the open channel bank. However, their research on lateral diversion focused on the flow regime in front of the diversion gate and the water diversion width, and few studies on the local water head loss at the water diversion gate.

For the study on local head loss, Mao Zeyu et al.^[8] proposed general expression of the local energy loss coefficient suitable for the analysis and calculation of arbitrary angle confluence flow through the experimental study and the hydrodynamic principle, based on the analysis of hydraulic characteristics and energy loss mechanism at the junction. Chen Chao^[9] used three-dimensional turbulence model to simulate 11 kinds of common pipelines, analyzed the influence of pipe geometry on water flow regime and local head loss, and obtained the relationship between local head loss coefficient and Reynolds number of various types of pipelines. Li Donghao et al.^[10] conducted the local head loss experiment of plastic pipe with different sudden shrinkage ratio, measured the discharge, water temperature, piezometric head, and analyzed the relationship of local friction factors and velocity, pipe diameter and temperature. Yan Xufeng et al.^[11] used acoustic Doppler flow meter to measure the flow structure of the gradually changed river model, conducted the two-dimensional numerical simulation of flow characteristics of this river model, and analyzed the variation law of local friction factors along the course, of which the results agree well with the measured values. Zhang Zhichang et al.^[12] studied the line head loss and local head loss in the Hydraulic Jump Region of the open channel,

and analyzed the ratio of the total head to the head, the relative head loss, the local drag coefficient Relationship with Froude. Previous studies on the law of local resistance coefficient mostly focus on the local head loss in different forms of pipeline flow, while most of the research objects on the local loss of open channel flow are mostly single channel or two channel confluence, especially right-angle diversion less. Due to the different shapes of the boundary which affect the loss of local head and respective characteristics of formation and separation of local whirlpool, except for some simple conditions, local head loss can be calculated by its empirical formula, such as the sudden expansion or shrink of the flow section. In other cases, it is difficult to analyze the local head loss in theory, only can the local head loss be studied by experiment or mathematical model.

The paper established a two-dimensional mathematical model of the flume with Mike21, simulated the flow motion under the three different cross sections, investigated the local head loss at the water diversion gate, built the relationship diagram between local head loss coefficient ξ and Froude number, and proposed the relational expression about local head loss coefficient and Fr.

Establishment of mathematical model

The paper used Mike21 to build a two-dimensional hydrodynamic model of flume, of which the sections of main channel are rectangular, trapezoidal and triangular, as shown in Figure 1. In the model, the length of the main channel is 30 m and the slope is 1%; the branch channels are all rectangular sections with the length of 7.2 m and width of 0.3 m, zero slope before 2.4 m along the branch, then 1% slope, connected with the flat base after the main channel hollowed out.

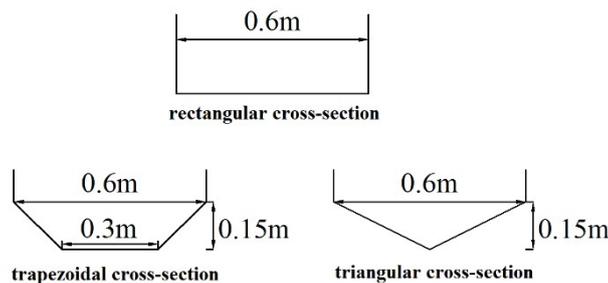


Fig.°1 Three channel cross-sections of different shapes

Model mesh generation and section selection. The size of the main groove of the model is 30m × 0.6m. The branch groove is located on the left bank with a distance of 9.6m from the entrance and its size is 7.2m × 0.3m. Quadrilateral grid with a size of 0.1m × 0.05m for main groove and properly encrypted to 0.05m × 0.05m in the range of 9m ~ 10.2m at the diversion outlet. Triangular grids for tributary. Model mesh shown in Figure 2. The number of grids is 7257 and the number of nodes is 6071.

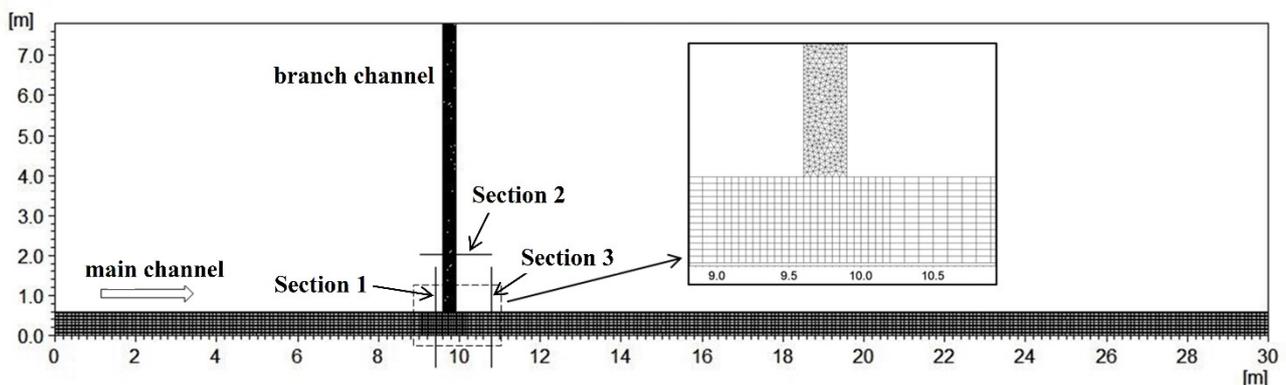


Fig.°2 Computational mesh and three control cross-sections

According to the flow disturbance range caused by transverse diversion at right angle, the cross section 1 is taken from 9.4 m at the inlet and the cross section 3 taken from 10.8 m at the inlet. For the tributary, the return flow area enlarged due to the increase of the inlet discharge, thus the cross section

2 varied with the change of inlet discharge and should be taken at the edge of the affected area of the recirculation zone, where the cross-sectional velocity is well-distributed.

Model verification. According to the flume experiment results, verification should be conducted with the conditions that the section of main channel is trapezoidal and the discharge is 5L/s and 10L/s respectively. Choose the section 1 and section 2 as main channel section. When the discharge is 5L/s, the cross-section of the branch is located at 2.5m of the ordinate axis of Fig. 2; when the discharge is 10L/s, the cross-sectional position is at 2.9m. Read the water depth h at the center of the four sections. The calculated results of the model are compared with the experimental results as shown in Table 1.

Table 1 The error analysis of water depth (unit: cm)

	Section 1			Section 3			Section 2		
	Calculate value	Experiment value	Relative error	Calculate value	Experiment value	Relative error	Calculate value	Experiment value	Relative error
5 L/s	3.20	3.1	3.2%	3.02	3.0	0.7%	1.67	1.7	1.8%
10 L/s	4.58	4.7	2.6%	4.32	4.2	2.9%	1.96	2.0	2.0%

Note: Relative error= $|\text{Calculate value}-\text{Experiment value}|/\text{Experiment value}\times 100\%$

From Table 1, we can see that the maximum relative error is 3.2% through the comparison of water depth between the mathematical model and physical model and is within accepted error [13], which tests and verifies the reliability of the mathematical model, and strengthens the credibility of the calculation results.

Local head loss coefficient

Hydraulic radius. Hydraulic radius is a comprehensive index that reflects the geometric characteristics of flow cross section and flow resistance.

$$R = \frac{A}{\chi} \quad (4)$$

Where: R is the hydraulic radius, A is the wetted area calculated according to the simulation of the cross-section of the water depth and shape shown in Figure 1, χ is wetted perimeter. Calculation results are shown in Table 2. As can be seen from Table 2, the calculated value of hydraulic radius for each section is different due to the different wetted perimeter of the section. Under the same discharge of 5L/s, the minimum of the rectangular section is 1.99cm, the maximum of the triangular section is 2.86cm and the trapezoidal section is 2.38cm.

Table 2 Hydraulic radius of section 1 with different cross-section shapes

	rectangular cross section	trapezoidal cross section	triangular cross section (cm)
	(cm)	(cm)	
5L/s	1.99	2.38	2.86
10 L/s	2.92	3.34	3.95

Changes of water level and average velocity at cross sections. For the rectangular flume, the water level and flow velocity of the numerical results can be directly used. For the trapezoidal and triangular flume, mean velocity in section should be solved as following formula since flow velocity distribution is not uniform.

$$\bar{V} = \frac{Q}{A} \quad (5)$$

Where: \bar{V} is the mean flow velocity of cross section; Q is the discharge; A is the discharge area.

Figure 3 shows the variation relation of mean flow velocity following inlet discharge at the position of section 1 and 2. As can be seen from Figure 3, with the increase of discharge, the average flow velocity at section 1 and section 2 is also gradually increased. Under the same inlet discharge, the triangular cross section and the trapezoidal cross section play the role of narrowing flow, so the velocity is the largest at the triangular section 1 and the minimum flow velocity at the rectangular section 1.

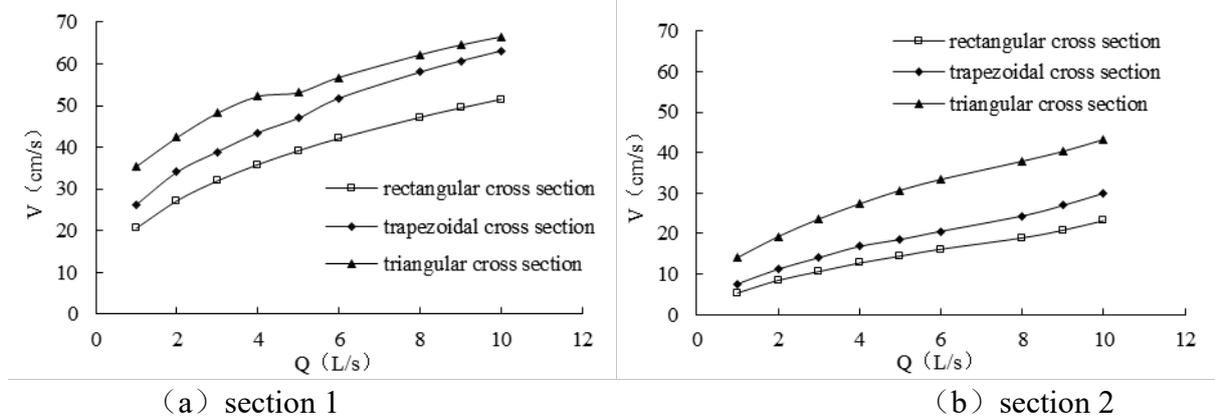


Fig. 3 Variations in velocity with flow rate at sections 1 and 2 with three different cross-section shapes

Local head loss varies with inlet flow. The model shows the open water flow, and the total flow energy equation of the section 1 and the section 2 taken is as follows:

$$Z_1 + \frac{\alpha_1 \bar{V}_1^2}{2g} = Z_2 + \frac{\alpha_2 \bar{V}_2^2}{2g} + h_w \quad (6)$$

Where: Z_1 and Z_2 are the water level of sections 1 and 2, \bar{V}_1 and \bar{V}_2 are the mean flow velocity of sections 1 and 2, α_1 and α_2 is the correction coefficient of kinetic energy taken as 1, and h_w is the total head loss.

$$h_w = h_f + h_j \quad (7)$$

Where: h_f is the frictional head loss, and h_j is the local head loss.

$$h_f = \frac{n^2 \bar{V}^2}{R^{4/3}} l \quad (8)$$

Where: n is roughness coefficient, \bar{V} is section average velocity, R is hydraulic radius, and l is the length.

The frictional head losses are divided into two parts: the head loss along the main stream and the head loss along the tributary, and the head loss along the two paths can be calculated respectively by the formula (8).

The local head loss change relationship can be obtained as shown in Fig. 4. As can be seen from Figure 4, with the inlet discharge increasing, the local head loss is also gradually increasing at the diversion. At the same discharge, local head loss of triangular section at the flow dividing gate > local head loss of trapezoidal section at the flow dividing gate > local head loss of rectangular section at the flow dividing gate, which indicates that the flow turbulence is the most drastic at the triangular section, second at the trapezoidal section, the smallest at rectangular section.

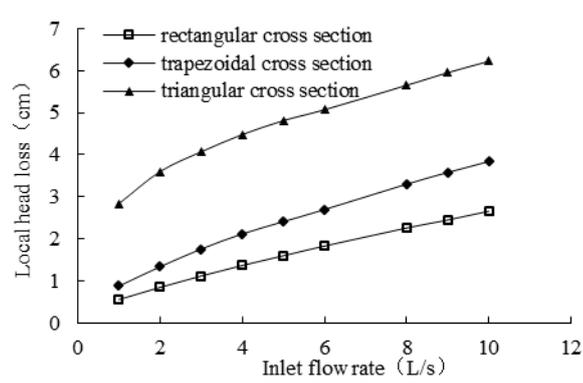


Fig.°4 Variations in local head loss with inlet flow rate

The local head loss coefficient varies with Fr. Froude number and the local head loss coefficient are derived with the average velocity and average depth of section 2.

$$Fr = \frac{\overline{V_2}}{\sqrt{gh_2}} \tag{9}$$

$$\xi = h_j / \frac{\overline{V_2}^2}{2g} \tag{10}$$

From Figure 5, with the increase of inlet discharge, the Froude number in tributaries increases, and the local head coefficient decreases gradually at the diversion gate compared with the velocity head of tributary section 2. The tributary section 2 has a relatively small velocity, and the local head loss coefficient is larger correspondingly.

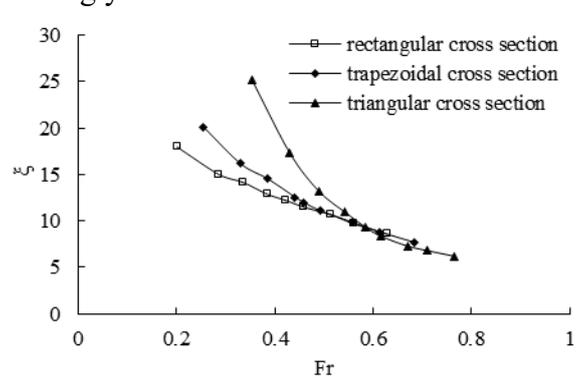


Fig.°5 Variations in minor loss coefficient vs. Froude number

The fitted relational expression about ξ and Fr is got by the numerical results. According to the variation characteristics of the data, the analysis for ξ shows a trend of decay with the change of Fr. Therefore, the variation function is fitted by the power function. The fitting formula is as follows.

$$\xi = a_1 Fr^{a_2} \tag{11}$$

Where: a_1 and a_2 are two pending coefficients.

Local head loss factor and Froude number are all dimensionless numbers, so the formula of three kinds of section shapes can be directly deduced by the least square method, as shown in the following:

Rectangular cross section:

$$\xi = 6.8779 Fr^{-0.629} \quad (R^2=0.9721) \tag{12}$$

Trapezoidal cross section:

$$\xi = 5.5579 Fr^{-0.97} \quad (R^2=0.9923) \tag{13}$$

Triangular cross section:

$$\xi = 3.5471Fr^{-1.861} \quad (R^2=0.9949) \quad (14)$$

It can be seen that ξ and Fr are negatively correlated, indicating that the local head loss coefficient decreases gradually with the increase of Froude number in the case of subcritical flow of open channel.

Discussion

This paper uses Mike21 model to calculate the local head loss, analyzes the effects of local head loss under different discharge and different cross at the diversion gate, and establish the variation relationship between the local head loss at the water diversion gate under different cross-sectional forms and the upstream discharge. As the flow rate increases, the local head loss increases. Establish the relationship of local head loss coefficient with the Froude number: As the Froude number increases, the local head loss coefficient decreases. Tian Shouxia^[14] only studied the shape of the rectangular section and did not consider the variation of the local head loss under various section, and it is considered that the local head loss increases with the increase of Froude number, which can be drawn as well from Figure 4 and Figure 5. This indirectly verify the reliability of the conclusion of the paper. The conclusion of the research on local head loss in this paper is only limited to the subcritical flow with the Froude number less than 1, and it is only a theoretical study, yet there is not a lot of actual observation data support.

There are many mountain canyon sections of the heavily silt-carrying river in our country. When building a similar transverse right-angle diversion project, the handling of the sediment problem may be the key to the project's success or failure. In this paper, Mike21 is used to study the characteristics of diversion in the clear water, and no sediment problem is involved. Whether Mike21 can be used to study the problem of sediment at the entrance is worthy of further exploration, such as the relationship between water diversion ratio and sand sediment diversion ratio, the function of local sand control facilities.

Conclusions

In this paper, two-dimensional hydrodynamic mathematical model is used to simulate the diversion of main channel under three different cross-sections concerning different upstream flow conditions. The result shows that local head loss increases with the increase of discharge.

The relationship curve between local head loss coefficient and Froude number is established under three different cross sections, and the relational expression about ξ and Fr is proposed. For the subcritical flow of open channel, the local head loss coefficient decreases gradually as the Froude number increases.

It is suggested that further research should be carried out, enhance the collection of observation datum and consider the impact of sediment on the results in order to meet the needs of solving problems in the engineering operation of river courses and reservoirs in the sediment-laden river.

Acknowledgements

This paper is supported by national nature science foundation of China (51679103, 51309110, 51509100, 51509103), Non-profit Industry Financial Program of MWR of China (No.201401023) and Yellow River Institute of Hydraulic Research Central level, scientific research institutes for basic R & D operating expenses of special funds of China (compact number: HKY-JBYW-2018-02).

References

- [1] Luo Fuan, Liang Zhiyong, Zhang Deru. Experimental Studies on Division of Flow. *Advances in Water Science*, 6(1):71-75. (1995)

- [2] Wang Xingkui, Zhang Ren, Chen Zhicong. Test Study on Transverse Diversion from Wide-shallow Open Channel. *Journal of Hydrodynamics*, 10(4):361-370. (1995)
- [3] Cao Jiwen, Chen Huiquan, He Yiyi. Experimental Study on Hydraulic Characteristics of Lateral Intake in Open Channel. *Journal of Hydraulic Engineering*, 34(10):32-37. (2003)
- [4] Chang Hongxing, Lu Song, Wu Yahui, et al. Effect Analysis of Split Ratio on the Channel Flow Pattern in the Braided River. *Water Sciences and Engineering Technology*, (6):43-45. (2013)
- [5] A. S. Ramamurthy, J. Qu, et al. 3-D Simulation of Dividing Flows in 90° Rectangular Closed Conduits. *Journal of Fluids Engineering*, 128(5):1126-1129. (2006)
- [6] Huang J, Weber L J, Lai Y G. Three-Dimensional Numerical Study of Flows in Open-Channel Junctions. *Journal of Hydraulic Engineering*, 128(3):268-280. (2002)
- [7] Yang Fan. Study on “Diversion Angle Effect” of Lateral Intake Flow. *China Institute of Water Resources and Hydropower Research*, 2007.
- [8] Mao Zeyu, Zhao Kai, Zhao Xuan, et al. Experimental study on local flow resistance at junctions of circular pipes. *Journal of Hydraulic Engineering*, 38(7):812-818. (2007)
- [9] Chen Chao. *The Numerical Simulation of Local Head Losses in Common Pipes*. Tianjin University, 2008.
- [10] Li Donghao, Wang Wene, Ge Maosheng, et al. Study on Local Drag Parameter of Subcontract Tube. *Journal of Water Resources and Architectural Engineering*, 09(4):22-24. (2011)
- [11] Yan Xufeng, Yi Zijiang, Liu Tonghuan, et al. Flow Structure and Characteristics of Local Head Loss in Transition Channel. *Journal of Yangtze River Scientific Research Institute*, 28(9):1-5. (2011)
- [12] Zhang Zhichang, Zhao Ying. Calculation of frictional and minor head losses for hydraulic jump section in rectangular open channels. *Journal of Hydroelectric Engineering*, 34(11):88-94. (2015)
- [13] Wang Yingying, Wang Wene, Hu Xiaotao, et al. Experimental and numerical studies on hydraulic characteristics of sharp-crested side weirs in rectangular channels. *Journal of Hydroelectric Engineering*, 34(11):88-94. (2015)
- [14] Tian Shouxia. *Study on 3D Hydraulic Behavior of Lateral Dam less Canal Head Work*. Tianjin University, 2010.