

Experiment Study on Water Diversion and Sediment Control of North Canal Expansion Project

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Abstract. This paper mainly analyses the evolution trend of river bed before and after the construction of water intake project, and optimizes the layout of water intake project and sluice by comparing the difference through physical model experiment study. Meanwhile, it examines the limit scour ability and protective measures for energy dissipation of sluice by using theoretical analysis and experimental research and verifies the diversion capacity of the channel after the construction of water intake project and put forward the corresponding sediment control measures. The experiment results show that the layout of water intake project and sluice is reasonable, and it is less affected the flow characteristics of the river channel and changes in scouring and silting of the bed surface; it is met the requirements of the design that the amount of water for design sluice can reach $149\text{m}^3/\text{s}$; it is recommended to appropriately increase the design size of stiller and apron for the actual needs; the measure of sediment control is proposed that scouring sediment by using sluice can reduce the bed surface elevation near Fish Mouth in order to reduce the coarse sediment into the diversion channel. This research provides the scientific basis and technical support for the optimization design of North Canal expansion project.

1. Introduction

1.1. Project overview

The headwork of Northern Nen River Diversion Project is located in the mainstream of Nen River about 6 km away from the northwest of Laha Town, Nehe County, of which the control basin area is $96,211\text{ km}^2$. The control area of Nierji Reservoir in the mainstream of Nen River is $66,382\text{ km}^2$, accounting for 69% of total headwork. Since the headwork of Northern Nen River Diversion Project was completed in 1976, great economic and social benefits have been brought to the downstream industrial and agricultural development. In recent years, with the development of downstream industrial and agricultural production and the increase of urban residential living water, the diversion scale of original headwork (no-dam diversion) has become increasingly inadequate and needs to be expanded. On the other hand, the upstream Nierji Reservoir has been completed to be put into use, which will guarantee to provide favorable conditions for the safety and diversion expansion of the headwork of Northern Nen River Diversion Project. However, due to the headwork of Northern Nen River Diversion Project located in the midstream of Nen River, this segment of river channel is flat and braided with slow drop gradient and small swale difference. Although renovation has been

carried out for many years, the current big regime has been under control, but local erosion and deposition has still occurred. In particular, after the use of Nierji Reservoir and the barrage construction of headwork with backwater, the conditions of inflow water and sediment as well as water flow before the gate have changed greatly.

1.2. Basic characteristics of water and sediment in Nen River

Nen River originates from the south slope of Yilehuli Mountain in the Greater Khingan Mountains with a total channel length of 1,370 km and a basin area of $29.70 \times 10^4 \text{ km}^2$. This basin belongs to the mid-temperate continental monsoon climate zone, and the average precipitation in the middle and lower reaches is 400~460 mm. The inter-annual precipitation is relatively large, and the intra-annual precipitation is unevenly distributed. Precipitation is mainly concentrated in July - September, accounting for about 70% of annual total. Heavy rains mainly occur in July and August, accounting for 83.7% of annual total, of which July presents the most rainstorms, accounting for 60%. Torrential rain is the main factor for the formation of flood in Nen River Basin, and the flood in Nen River Basin is consistent with the characteristics of rainstorm, i.e., the floods of Nen River Basin are mainly induced by several rainstorms [1].

Nen River has less sediment with a small number of sediment observation data. According to statistics, the multi-year average suspended sediment discharge rate of Ayanqian Station is 13.54 kg/s, multi-year average suspended sediment discharge is $42.7 \times 10^4 \text{ t}$, multi-year average suspended sediment content is 0.041 kg/m^3 , and the measured maximum suspended sediment content is 0.323 kg/m^3 . There are no observation data of bed load in Nen River Basin, and the bed-load sediment discharge is calculated as $4.27 \times 10^4 \text{ t}$ according to the suspended load ratio of 10%, the multi-year average total sediment discharge of Ayanqian Station is $47 \times 10^4 \text{ t}$, and that at the headword of Northern Nen River Diversion Project is calculated as $69 \times 10^4 \text{ t}$ according to the area [2].

2. Model design and validation

2.1. Model design

This model test is mainly to study the erosion and deposition evolution of the channel in the mainstream of Nen River after building the sluice gate as well as the water intake and sediment control situations of diversion channel. Due to Nen River with large water flow and small sediment content, the channel evolution is mainly dominated by bed load. Therefore, during model designing, in addition to consider the similar motion of water flow, it is mainly required to guarantee similar motion of bed load with the consideration of similar motion of suspended sediment. Based on the comprehensive consideration of model test requirements, test technical conditions, sediment grain size, test simulation range and other factors, normal model is used in this local model test. According to the gravity similarity criterion for design, model geometry scale is set as 80, and natural sediment is used for model sediment. Due to no measured bed load data of this channel, the empirical formulas such as the Sharmov Formula are adopted to estimate the bed-load sediment discharge rate and the bed-load gradation under different flow levels. The results are shown in Figure 1.

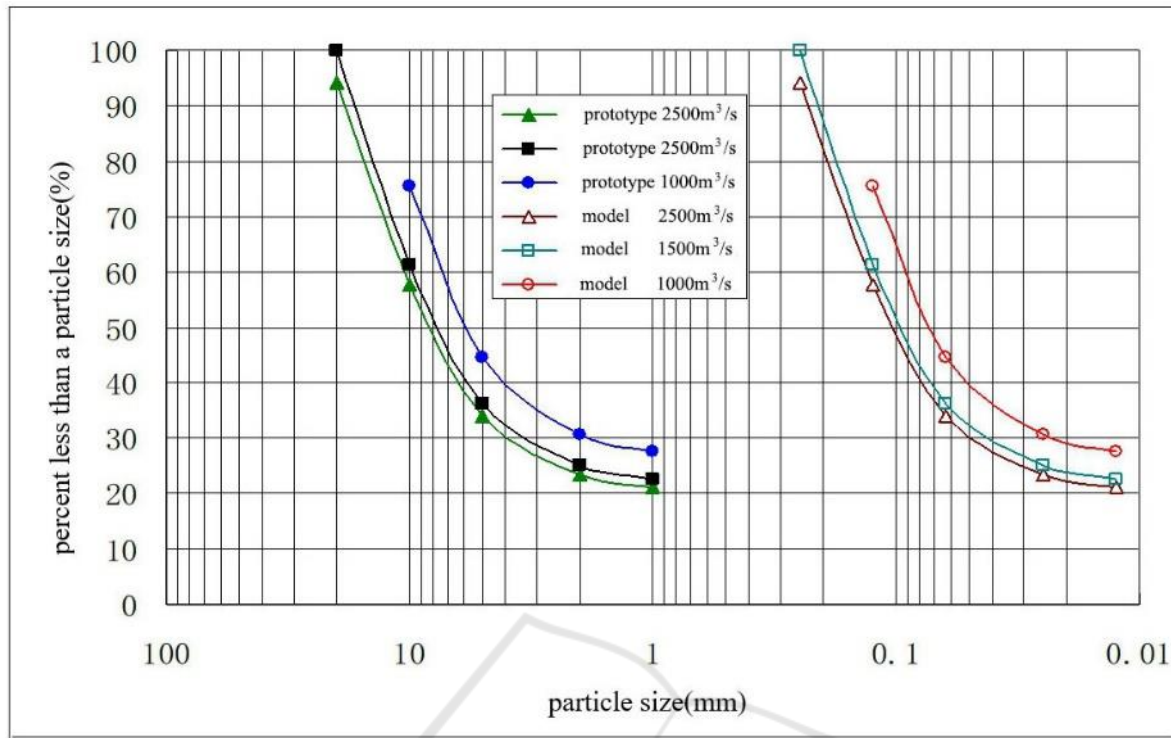


Figure 1. Bed-load gradation under different flow levels.

2.2. Model validation

The channel segment simulated by this model test is short in lack of validation data, but in order to ensure the reliability and accuracy of test results, based on the collected measured data and theoretical analysis, this model test is mainly to validate several aspects such as water level, channel erosion and deposition as well as the current diversion quantity of diversion channel.

For water level validation, except the local point with small water flow, the prototype under other conditions accords well with model level, showing that model roughness and resistance are similar, thus satisfying the precision requirement of model test. With the increase of river flow, the water level error between the prototype and model is gradually decreasing, which is mainly due to the large influence of channel morphology resistance in the case of small flow. For the validation of channel erosion and deposition, the prototype and the model are consistent in the on-way erosion and deposition trend, and the erosion and deposition places basically coincide. Moreover, the lateral distribution of bed surface erosion and deposition has the basically consistent trend, showing that the model is basically similar in the location and amplitude of erosion and deposition. For the calibration of channel diversion quantity, when the great river flow is 126.00 ~ 445.00 m³/s, actual natural diversion quantity is basically 8.02 ~ 40.00 m³/s, and the measured diversion quantity of the model is basically 8.70 ~ 40.53 m³/s. The absolute error of the two values is nearly less than 0.70 m³/s. Except for the minimum level with larger relative error, other flow levels have the relative error below 3%. Therefore, model measurement value is basically close to natural measurement value, indicating that the accuracy of model production can meet the test requirements.

3. Analysis on river channel evolution before and after the construction of diversion junction

3.1. Water level changes of river channel before and after the construction of diversion junction

Test observation is carried out on the changes of channel water level at different flow levels of 500, 1500 and 2500 m³/s under four conditions, i.e., before the gate construction of diversion junction and the constructions of 8-hole, 11-hole and 12-hole sluice gates. The results show that in the case of small flow level, the backwater of small flow level has a large amplitude, which is about 100 cm. But in the case of large inflow, the channel water level of normal inflow has exceeded control-application water level, so the discharge gate is open to use, when the backwater at corresponding flow level has a smaller amplitude, basic under 20 cm. In addition, under three arrangement schemes of 8-hole, 11-hole and 12-hole sluice gates, the backwater amplitudes are basically approaching, and those of 11-hole and 12-hole sluice gates are slightly smaller than 8-hole sluice gate.

3.2. River regime changes of river channel before and after the construction of diversion junction

In this test, the changes of river regime under the three flow levels of 500, 1500 and 2500 m³/s are observed. When the flow is 500 m³/s, the mainstream bending is obvious. However, the mainstream bending degrees at the two flow levels of 1500 and 2500 m³/s are reduced to a certain extent, but artificial groin has more significant control on the mainstream than the natural change of river channel. Through comparing the running trajectory of mainstream line before and after the gate construction at three flow levels, it can be seen that there are no obvious changes in river regime before and after the gate construction at the flow levels of 500, 1500 and 2500 m³/s. Therefore, after the construction of diversion junction, whether the combination of 8-hole or 11-hole gates is used or the scheme of total 12-hole gate is applied, the three arrangement schemes have basically not changed the current running trend of original channel.

3.3. Flow velocity changes before and after the construction of diversion junction

As viewed from the test results of mean vertical velocity at three flow levels of 500, 1500 and 2500 m³/s before and after the construction of diversion junction, the location of maximum vertical velocity at different flow levels on different cross sections basically corresponds to the lowest point of river section, and the basic rule of velocity distribution is almost consistent with water depth changes. The greater the water depth is, the larger the mean vertical velocity will be. Therefore, before and after the construction of diversion junction, when the big river inflow is small, the control of sluice gate is applied, resulting in sharp decrease of flow velocity in backwater segment. For the flow of 500 m³ / s, flow velocity decreases by about 50%. When the big river inflow is large, the floodgate is open to use, when the water intake junction has less effect on river velocity, and the change rule of flow velocity and water level change correspond to each other.

3.4. Changes in riverbed erosion and deposition of river channel before and after the construction of diversion junction

In order to increase comparability, the inlet water and sediment, outlet water level, initial topography and other conditions of this erosion and deposition test scheme are identical. The on-way changes in channel erosion and deposition before and after the construction of diversion junction are shown in Figure 2. As viewed from the overall change trend, the on-way riverbed erosion quantity from test inlet to fish-mouth river segment shows a gradual increase trend, while that from fish-mouth segment to outlet segment presents a gradual decrease trend, and the on-way erosion and deposition changes of the entire test river segment is basically “V-shaped”. The construction of water intake junction has not changed the overall trend of the changes in river channel erosion and deposition, but it still has some impacts on the changes in river channel erosion and deposition. Thus, it can be seen that after the construction of water intake junction, the riverbed surface erosion ability of test river segment has

a tendency to decrease, i.e., the riverbed surface deposition in the deposition segment before construction will increase to a certain extent, and the riverbed surface erosion degree in the erosion segment before construction will be reduced, but the reduced amplitude is relatively small. Therefore, it can be considered the construction of water intake junction has little impacts on the erosion and deposition changes on the test river segment.

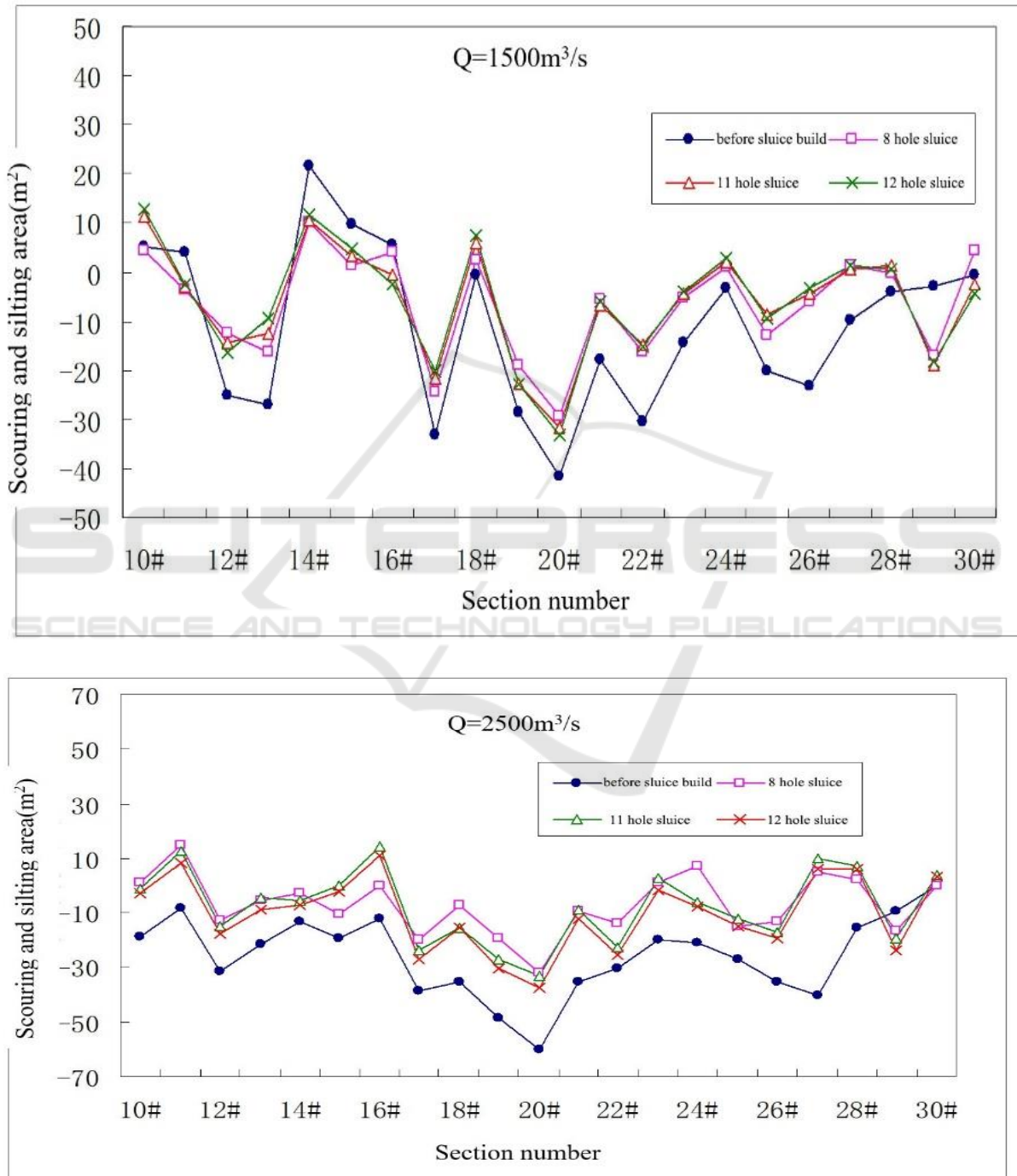


Figure 2. On-way changes of river channel erosion and deposition before and after the construction of diversion junction.

4. Comparison in the layout of diversion junction and different arrangement patterns of sluice gate

According to the preliminary design scheme requirements of this diversion junction project, the water intake junction of this test will be arranged in two layout patterns, i.e., the dam-gate combination and the total gate. In the test combination scheme, three layout patterns are included, i.e., 8-hole sluice gate + overflow weir (hereinafter referred to as 8-hole + weir), 11-hole sluice gate + overflow dam (hereinafter referred to as 11-hole dam gate) and 12-hole sluice gate (hereinafter referred to 12-hole total gate). The three design schemes have basically the same layout positions, and the gate hole size of sluice gate and bottom elevation are all the same.

4.1. Comparison in the flow characteristics of three layout patterns

In terms of the water level changes in three different layout schemes, the backwater amplitudes of the three schemes are basically the same, and those of 11-hole dam gate and 12-hole total gate are slightly less than the combination scheme of 8-hole dam gate. For regime changes under different layout schemes, three kinds of layout schemes have basically the same mainstream lines. Only in the river segment near water intake junction, the mainstream lines of 11-hole dam gate or 12-hole total gate are slightly towards the right bank over 8-hole + weir, but the deviation is small, which can be negligible relative to the whole test river segment. For velocity variation under different layout schemes, the influences of three layout schemes on flow velocity are mainly concentrated near the sluice gate, where the two schemes of 11-hole dam gate and 12-hole total gate have almost the same maximum velocity, but the positions of maximum velocity of the two schemes are slightly towards right bank, while the three kinds of layout schemes have basically approaching maximum velocity value. Therefore, it can be considered that the three layout mechanisms have a certain effect on velocity distribution, but have little impact on flow velocity.

4.2. The effect of three layout patterns on the change of river channel erosion and deposition

As known from the foregoing analysis, after the construction of water intake junction, the erosion and deposition evolutionary trend of the test river segment has not changed, but the change amplitude is reduced to a certain extent, and the influence degrees of three layout patterns are different. Test results show that the erosion and deposition change amplitudes of 11-hole dam gate and 12-hole total gate are slightly bigger than that of 8-hole + weir, and such change characteristics are more obvious in the case of larger flow. However, the erosion and deposition change amplitudes of 11-hole dam gate and 12-hole total gate are basically approaching with no obvious difference.

4.3. Comparison in different layout patterns of sluice gate

By comparing the changes in mainstream regime, flow velocity, main-channel erosion and deposition as well as other indexes of river channel before the construction of sluice gate, it can be seen that the influences of total gate scheme or gate dam scheme on current river channel are slightly less than that of 8-hole + weir. As viewed from flood and sediment discharge, the total gate scheme or the gate dam scheme is superior to the 8-hole + weir scheme. Therefore, it is recommended to use the total gate scheme or the gate dam scheme. For eventual adoption of 11-hole dam gate scheme or 12-hole total gate scheme, due to a small difference of the two schemes, as viewed from model test results, two kinds of schemes can be used either. But in the comprehensive considerations of various factors such as hydraulic design technique and economic benefit, this design is suggested to use 11-hole dam gate scheme.

5. Ultimate scour ability under sluice gate and its energy dissipation protection measures

5.1. Ultimate scour ability under sluice gate

Table 1. Ultimate scour depth table under sluice gate in different working conditions.

working condition	1	2	3	4
Water Level before sluice /m	174.50	176.50	174.50	176.50
Elevation below sluice /m	169.00	169.00	169.00	169.00
Water level after sluice	Free flow	Free low	Free flow	Free flow
Number of sluice holes	1	1	4	4
Length of scour pit (measured) /m	82.00	129.00	73.00	120.00
Maximum scour depth (measured) /m	3.71	14.25	3.42	12.77
Minimum starting velocity (calculated) /($m s^{-1}$)	1.32	1.43	1.32	1.43
Minimum coarsening particle size(calculated) /(mm)	20.00	21.00	20.00	21.00
Maximum scour depth(calculated)/m	3.96	14.80	3.70	13.87

After the construction of river sluice in natural channel, due to the change of flow boundary condition, riverbed scouring will occur to the channel in the lower reaches of sluice, so that riverbed sediment compositions become coarse. For the riverbed with pebble and sediment, the fine particles of riverbed will be rushed away by flow, or migrated towards downstream in the form of sediment waves. Coarser particles are gradually gathered to eventually form an anti-rushing coarsening layer. In order to ensure the safety operation of diversion junction, this study is based on the ultimate scour experiment under the most unfavorable working conditions, using the riverbed surface coarsening theory proposed by the Academician Han of the China Institute of Water Resources and Hydropower Research[3] to calculate the ultimate scour depth of riverbed in the lower reaches of sluice in diversion junction under the corresponding working conditions. Meanwhile, the calculated results are compared with experimental results for analysis (see Table 1). It can be seen from Table 1 that the calculation results are slightly larger than the experimental results, but both are basically close to each other. In addition, it can be seen from the test results that the maximum impact distance of ultimate scour pit can reach about 120 m in the downstream of sluice gate.

5.2. Energy dissipation protection measures under sluice gate

As viewed from the model test and theoretical analysis results of ultimate scour depth, the ultimate scour depth of sluice gate can be up to about 15 m, and the influence scope of scour pit is up to 120 m. Therefore, hydraulic energy dissipation facilities must be built in the downstream of sluice gate. In the feasibility study report of water intake junction, the stilling basin is used for energy dissipation after sluice gate. The stilling basin is designed with a length of 20 m and a depth of 2 m, and the apron is designed with a length of 40 m. In order to test the energy dissipation effect of designed stilling basin, through analyzing all operation conditions of sluice gate, it is believed in this experiment that when the water level in front of sluice gate is 176.2 m and the downstream discharge is ecological water demand, the operation condition of sluice gate suddenly open for flood discharge is the most unfavorable. The experimental results show that in the above-mentioned most unfavorable conditions, the design dimension of sluice-gate stilling basin is slightly small, and the current design dimension of stilling basin can meet the requirement of energy dissipation for the single-hole discharge of about $35 m^3/s$. Therefore, it is suggested to increase the design dimensions of sluice-gate stilling basin and apron. If the dimension of existing stilling basin is kept unchanged, it is suggested to operate in the dry season of sluice gate. If the discharge amount is larger, it should be

to adopt the pattern of multi-hole operation. The single-hole discharge at the early stage of opening is advised to be no more than $35 \text{ m}^3/\text{s}$. With the increase of water level in the downstream of sluice gate, single-hole discharge can be increased gradually.

6. Analysis on diversion capacity and sediment control measures of water diversion channel after the construction of water intake junction

6.1. Diversion capacity analysis of water diversion channel

After the expansion of diversion sluice, whether the diversion capacity can meet the design requirement is a key point of this study. According to the design requirements, when the water levels above and under diversion sluice are 176.2 m and 176.0 m after the expansion respectively, the diversion capacity of diversion sluice should reach the requirement of $145 \text{ m}^3/\text{s}$. Test results about the flow coefficients of diversion sluice design scheme are shown in Table 2. It can be seen from Table 2 that under the combination of such working conditions, the diversion flow of model test is about $149 \text{ m}^3/\text{s}$. Therefore, the expanded diversion sluice can basically meet the design requirements. However, regarding the outflow of this sluice gate with high submergence degree, the accuracy of test results is reduced to a certain extent, so it is suggested to be considered in the design.

Table 2. Flow coefficient table of diversion sluice design scheme.

Group	Water Level before sluice /m	Water level after sluice/m	Water level difference /m	Weir measurement flow/($\text{m}^3 \text{ s}^{-1}$)	Discharge coefficient/ m_c
1	176.51	176.30	0.21	156	0.328
2	176.51	176.01	0.50	224	0.332
3	176.52	175.00	1.52	246	0.334
4	176.23	176.01	0.22	147	0.333
5	176.22	175.82	0.40	194	0.341
6	176.22	174.87	1.35	221	0.336

6.2. Sediment control measures of diversion channel and their effect analysis

As viewed from the existing layout of water intake junction, the main factors influencing the sediment into diversion channel are the elevation difference between diversion channel bottom and riverbed surface and the diversion quantity. After determining the diversion quantity and the elevation of diversion channel bottom, the riverbed surface elevation near fish-mouth plays a decisive role in the coarse sediment quantity into the diversion channel[4-6]. As viewed from previous analysis and the results of this test, after the construction of diversion junction, cumulative deposition is not generally produced in the river segment near fish-mouth, so that it is beneficial to reduce the coarse sediment into diversion channel. But in order to study the sediment situation into diversion channel under the most adverse circumstances, this experimental study is assumed under the riverbed surface elevation of 172 m near fish-mouth for the sediment flushing of sluice gate and sediment intake test of diversion channel in two working conditions with inlet flow of $500 \text{ m}^3/\text{s}$ and $2500 \text{ m}^3/\text{s}$. During the experiment, two cases of existing fixed bed and no fixed bed are considered. Under different working conditions, the on-way distribution of maximum scour depth of river channel is shown in Figure 3. When the riverbed surface elevation is 172 m, the sediment flushing effect of sluice gate is more obvious. For the two cases of existing fixed bed and no fixed bed, the maximum scour depth of typical section in the case of no fixed bed is generally larger than that of existing fixed bed. It can be seen that the existing fixed bed has a certain influence on the sediment block effect of sluice gate. In addition, as viewed from the experimental results of different working conditions, the sediment intake of diversion channel accounts for about 1%-3% of river sediment intake.

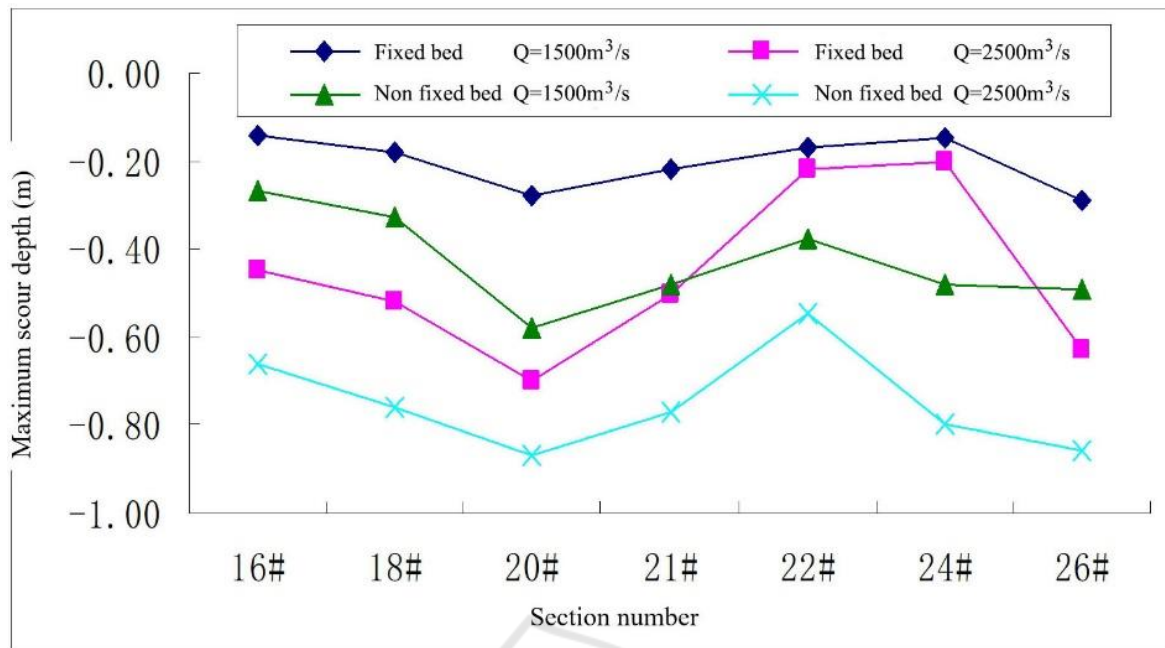


Figure 3. On-way distribution map of maximum scour depth of river channel under different working conditions.

7. Conclusions

- 1) The construction of water intake junction will not have a great impact on current water sediment characteristics and riverbed evolution of Nen River. The layout of sluice gate in water intake junction is basically reasonable, which has less influence on the river flow characteristics and the change of riverbed surface erosion and deposition. For three kinds of layout schemes, the influences of 11-hole dam gate and 12-hole total gate schemes are slightly less than that of 8-hole + weir design scheme. In comprehensive consideration of economy and design technology, this design is recommended to adopt the layout scheme of 11-hole dam gate.
- 2) When the water level in front of sluice gate is 176.2 m and the downstream discharge is ecological water demand, the stilling-basin design dimension of sluice gate is slightly small, and the existing design dimension can only meet the energy dissipation requirement for single-hole discharge of about 35 m³/s. Therefore, it is suggested to appropriately increase the design dimensions of stilling basin and apron in sluice gate. If the current dimension of stilling basin is maintained, it is recommended to use the pattern of multi-hole operation, and the initial single-hole discharge should be appropriate without exceeding 35 m³/s.
- 3) Under the water and sediment conditions of model test, the riverbed surface in the river segment near the fish-mouth of water intake junction is dominated by scour with no cumulative sediment deposition. However, sediment deposition will occur in the diversion channel, and the channel sediment intake is about 1% ~ 3% of big river sediment intake. In terms of sediment control measures, the changes in the open position of sluice gate have little influence on the reduction of sediment intake in diversion channel. However, in the case of cumulative deposition on channel riverbed surface, the sediment flushing of sluice gate can reduce the riverbed surface elevation near the fish-mouth, thus beneficial to reduce coarse sediment into the diversion channel.
- 4) In the case of sluice gate expanded to 3 holes with each hole width of 7 m for the working conditions of water level above and under gate as 176.2 m and 176.0 m respectively, the water diversion of sluice gate can reach 149 m³/s, basically meeting the design requirement for water diversion of 145 m³/s.

Acknowledgement

This research was supported by “13th Five-Year Plan” to Support National key R & D project (Grant No.2017YFC0405201) and IWHR Special Project (Grant NO. SC0145B172017) respectively.

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