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ENERGY DISSIPATION AND ATOMIZATION OF FLOOD DISCHARGE OF HYDROPOWER STATIONS ON CANYON RIVERS

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ABSTRACT

A hydropower station on a canyon river typically features with high water head and large unit discharge. This type of hydropower station is also surrounded by thick burden of riverbed and complex geological and topographical conditions. Energy dissipation and atomization of flood discharge are quite important to the design and construction of these hydropower stations. Energy dissipation of flood discharge of two hydropower stations (hydropower station A and Shuibuya hydropower station) are studied on in the present paper. Both prototype observations and physical model tests have been carried out to study the characteristics of downstream riverbed erosion, distribution and development of flood discharge atomization near the damsite. The principle and methodology of layout a hydropower station on a canyon river are discussed. The results could be useful for the design and operation of similar hydropower stations.

Keywords: canyon river; side spillway; energy dissipation and erosion control; atomization

1 INTRODUCTION

In the mountainous area of the Southwest China, many hydropower stations with high dams are built on canyon rivers benefiting from the abundant hydroenergy and large slope of riverbed. These stations are typically with high water head and large unit discharge, and they are surrounded by thick burden of riverbed. Due to the size of the river cross-section and the geological condition of the riverbed and bank slope near the damsite, it is difficult to select the appropriate dam type and arrange the layouts of hydraulic structures.

By far, as statistical data shows, there are 191 reservoirs with dams over 100 metres that are completed or under construction in China. According to the construction materials of dam, there are 99 concrete dams (including gravity dams and gravity arch dams) and 90 rockfill dams (including 68 concrete face rockfill dams and 22 core rockfill dams). The concrete face rockfill dam became popular in the 1990s, and it has been the mainstream dam type due to easy access to local materials, short construction period, and strong impermeability. The concrete face rockfill dams are widely used in the canyon areas.

There are two kind of layouts for flood discharge structures on canyon rivers. One is that the flood is discharged through the sluices on the dam body. The structures are built with flaring gate piers and slit-type form for energy dissipation. The other is using stilling basins in the downstream of the dams in combination with outflow impact in air from sluices of different heights to dissipate the energy of flood discharge.

The flood situations and geological conditions vary in different areas, therefore the layout of energy dissipators for flood discharge has to be designed according to the local conditions. Under the condition of high water head and large unit discharge on narrow canyon rivers, the energy dissipators are mainly deployed for preventing atomization and reducing erosion in the slope and the downstream riverbed . It is essential for flood discharge structures to deal with the tradeoff between the atomization in air and the river erosion in the downstream.

The present study focuses on the side spillway of concrete face rockfill dams of two typical hydropower stations, i.e.,hydropower station A and Shuibuya hydropower station, in the same area. Hydropower station A deploys the tunnel spillway with skew bucket lip for energy dissipation. The atomization and river erosion in the downstream of these hydropower stations are analysed and compared. The principle and layout plan of flood discharge energy dissipators of hydropower stations on canyon rivers are discussed. The results could be useful for the design and operation of similar hydraulic projects.

2 RIVER REOSION IN THE DOWNSTREAM

Hydropower station A is a large hydraulic project of type (1) in Tier I. The height of the dam is 219.00 metres, and the unit discharge of spillway is 268.64 m3/s/m. This hydraulic project consists of a concrete face rockfill dam, spillways, spillway tunnels, diversion structures, a ground powerhouse on bank, etc.

The river section in the upstream of the dam is 113 kilometres long, and the average gradient of the river is 11.8‰. The elevation of the bedrock of riverbed is 258.00～270.00 metres. The dam is built at a V-shaped valley. The thickness of the riverbed burden is 19～32 metres. The gullies on both banks are locally covered with thick burden, including 2～5 metres of gravel layer on the top and 15～25 metres of fine sand layer (including clay power) at the bottom. In the downstream river, the threshold erosion flow velocity is very low and the geological condition is complex, and thus it is tough for energy dissipation and erosion control in the downstream.

2.1. Layout plan of energy dissipation of flood discharge

The two tunnel spillways are parallel to each other, and both are built on the right bank. The open-style WES weir is with a net width of 14.00 metres for a single orifice, and the outlet is connected with a flip bucket. The distance between the centrelines of the two spillways is 35 metres. Spillway ① deploys a special-shaped skew bucket lip at the outlet, with a diffusion radius of 45 metres for the left guide wall and a diffusion angle of 18°. The radius of the flip bucket is 80 metres and the bucket angle is 7°52′～31°30′. Spillway ② deploys an oblique bucket at the outlet, with a diffusion radius of 59.431 metres for the left guide wall and a diffusion angle of 17°8′, and a diffusion radius of 689.965 metres for the right guide wall and a diffusion angle of 4°53′. The radius of the flip bucket is 90 metres and the bucket angle is 5°～33°. The details of the spillways are shown in attached figure 1-2.

The spillway tunnel is located on the right hand side of entrance channel in the upstream. The inlet bottom elevation is 370.00 metres. A skew flip bucket is applied for energy dissipation. The diffusion radius of left guide wall is 44.87 meteres and the diffusion angle is 18°25′. The radius of the flip bucket is 80 metres and the bucket angle is 12°23′～23°47′. The bucket lip elevation is 331.588～335.567 metres. The layout plan of flood discharge energy dissipation is shown in figure 2.1. and figure 2.2

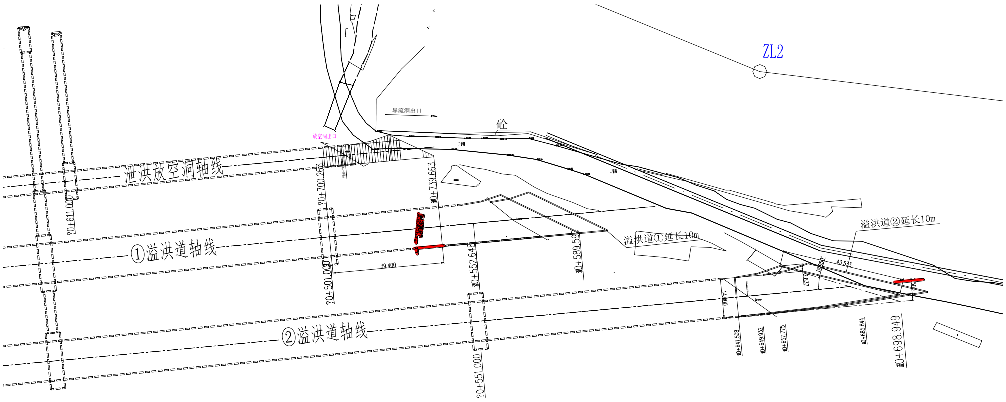


Figure 2.1 Layout plan of optimised spillways.

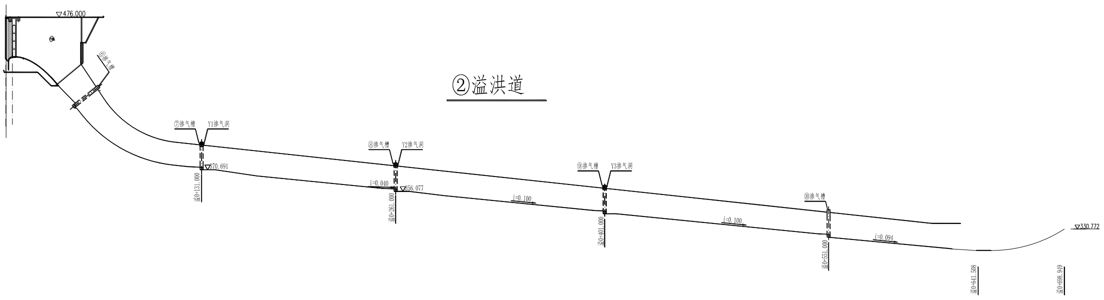


Figure 2.2 Profile of discharge chute of spillways.

2.2. Methodology and facility of experiments

It is critical to ensure the safety of the project and bank slope in the downstream of the hydropower station. Hydraulic model tests are often used to reduce the workload of protection and cost of experiments. In the present study, in order to optimize the energy dissipation plan for flood discharge, hydraulic model tests have been carried out in accordance with the latest geological condition of downstream river sections, burden of riverbed, threshold erosion flow velocity of bedrock and protection boundary on the bank.

Hydraulic model tests of hydropower station are designed based on gravity similarity theory. A $\lambda L=1/100$ hydraulic model is used for both fixed bed and movable bed model tests.

For the movable bed model test, it is not easy to determine the maximum allowable flow velocity when riverbed erosion does not happen, and it is also difficult to simulate the sand scale of the movable bed. Due to the thick burden of riverbed at the present damsite, two rounds of adjustment tests were performed to determine the maximum allowable flow velocity according to different layers of riverbed burden. For the first round of tests, considering the erosion-resistant ability at different elevations of the riverbed burden and river depth hd in the downstream, 3.0 m/s～4.5m/s was chosen as the threshold erosion flow velocity for bedrock in the downstream river sections. It should be noted that the velocity here is much lower than tests in literature. To validate river erosion in the downstream sections, energy dissipation and erosion area is simulated as movable bed, and this can be used to assess the suitability of the present flip bucket design. Alum stones with an average diameter of D50=5～8 mm are used as the material for the movable bed model tests. The sand elevation of the movable river bed is 290.00 metres.

For the second round of tests, 6 m/s was chosen as the threshold erosion flow velocity in the optimised test plan, considering only the weakly-weathered bedrock. The median diameter of model sand is calculated by (2-1), and the value is D50=7.7mm.

$$v = k\sqrt{\frac{\gamma - \gamma_w}{\gamma_w} 2gD_{50}}$$

（2-1）

where, the sand unit weight is γ = 26.1kN/m3, the water unit weight is γw = 9.81kN/m3, the erosion-resistant flow velocity is v, the acceleration of gravity is g = 9.81m/s2, and the erosion-resistant stability coefficient is k = 1.2.

2.3. Test results

To investigate the energy dissipation and erosion control in the downstream of hydropower station A, outflow patterns of flood discharge structure, river patterns, water surface profile, flow velocity and erosion patterns have been observed in the downstream river sections. The main results are as follows.

① When flood is discharged, flows from the spillways and the tunnels are separated, and nappes develop properly. The nappes land longitudinally in the middle of the riverbed along the river. Although the discharged flow did not impact on the banks directly, diffused flow and tumbling flow caused by the nappes have a great impact on the two banks due to the narrow width of downstream valley. Large surface waves are observed at the landing area of nappes, and flow patterns near the left bank are more chaotic. The flow patterns are shown in figure 2.2(a).

② The measured flow velocity is higher in the middle and left side of the cross-sections in the downstream, and it is lower close to the right bank. The maximum flow velocity in the optimisation scheme is 6.36 m/s and 3.73 m/s on the left bank and right bank, respectively. The maximum velocity is located at 0+1000 m and 0+1200 m respectively. The water surface profile of the left bank is higher than that of the right bank at each measuring cross-sections. The elevation of highest water surface profile is lower when discharge of flood is smaller.

③ The deepest point of riverbed erosion is located in the middle area of the river under each working condition. The elevation of the lowest point of scour pool is 270.0 m under PMF (Probably Maximum Frequency) condition. The range of erosion is between measuring stake number 0+600 m and 0+900 m. Riverbed erosion is observed at toe of slope of both left and right banks, and erosion on the left bank is severer than that on the right bank. It is found that additional protection is needed for slope of the left bank. The topography of river erosion is shown in 2.2(b).

④ The river is narrow in the downstream and the slope of bank is steep. Landslide occurred in the history in the downstream area of the flood discharge structures. Atomization caused by flood discharge may have an impact on the stability of slope in the downstream, thus appropriate protection scheme is needed.

⑤ When small flood is discharged, nappes from both spillways ① and ② impact on slope protection measures in the downstream. To tackle with this issue, the tail part of the spillways has been optimised according to the downstream river patterns when small flood is discharged.

(a) (b)

Figure 2.2 (a) Flow patterns and (b) landscape of erosion when flood is discharged as designed. Under PMF condition, Q is 8850m3/s，Hu is 475.14 m，Hd is 309.04 m.

Based on flow patterns in the downstream river when the small flood is released, the tail part of the spillways has been optimised to deal with the issue that nappes impact on Road No. 310 and slope protection. On one hand, the shape of the tail part of spillways is modified to change the transverse and longitudinal angel of nappes. On the other hand, the outlet of spillways is extended appropriately to prevent the nappes from impacting on the banks. The optimisation scheme is as follows based on calculations and observations.

i The flip buckets of both spillways are extended for 10 metres along their axial lines towards the downstream direction.

ii The arch radius is changed from 80 metres to 50 metres in the transition section of spillway ①. The arch radius of flip bucket is not changed. The elevations of left and right outlets of the bucket are 337.759m (337.811m in the original design) and 344.656m (344.708m in the original design), respectively. The outlets are located at stake number 0+573.195m (0+563.195m in the original design) and 0+599.590m (0+589.605m in the original design), respectively.

iii For spillway ②, the elevations of left and right outlets of the bucket are 316.595m (316.466m in the original design) and 330.772m (330.644m in the original design), respectively. The outlets are located at stake number 0+667.775m and 0+708.949m, respectively.

In the optimised scheme for modelling the movable bed, two tests have been performed and the results are compared. For the first test, the elevation in the middle of riverbed is 275m. For the second test, each river cross-section is designed according to the lower limit of strongly-weathered layer. Two working conditions were selected, namely PMF and P=1%. The largest possible erosion range and depth are investigated.

The results show that, for the first test, the deepest point of erosion is located in the middle of the riverbed. The elevation of the point is between 267.9m ~ 270.1m, and the erosion depth is about 5m ~ 7m. For the second test, the elevation of deepest erosion point at each typical cross-section is about 265m under PMF and P=1% conditions. The middle area of riverbed is not eroded. The results of erosion for the optimised scheme is similar to that of the design scheme.

3 ATOMIZATION TEST AND PROTOTYPE OBSERVATION

Shuibuya hydropower station has been operated since 2007. The main structures of this project consist of a concrete face rockfill dam, spillway on the left bank, underground powerhouse and tunnels on the right bank, etc. There are three main characteristics of the flood discharge energy dissipation for this project. First, the largest spillway discharge of flood is 18320m3/s. The head drop of flood discharge is 171m. The largest flood power is 31000MW. Second, bedrock in the energy dissipation area is shale of Xiejing Temple. The shale is fragile and weak to resist erosion. There are large rock slides (5800000m3) on the left bank of energy dissipation area, and Maya high slope (350m in height) and Mayanwan slide (1800000m3) on the right bank. Third, the exit of tail-race tunnel is located at the convex bank of bend reach due to geological reasons, and it is close to the energy dissipation area near the toe of slope. When flood is discharged, large tailwater fluctuation and sedimentation issue can affect the safety of the hydropower station.

3.1. Layout of energy dissipation of flood discharge

According to the optimisation tests of hydraulic model, a layout scheme (shown in figures 3.1 and 3.2) with stepped slit-type flip bucket of zoned chute is proposed. There are a few novel points about this sheme.

First, hole 5 on the right bank deploys asymmetric and oblique cut slip-type bucket (2m skewed to the right). The trajectory of nappe is perpendicular to the steep slope on the right bank. The water levelrise near the slope effectively reduces erosion of the slope and strength of circulating flow at toe of slope in the downstream. Meanwhile meantime, sedimentation caused by impact of nappes is avoided at the exit of tail-race tunnel. This ensures that no sedimentation occurs at the exit of tail water under different working conditions, and that almost no sedimentation is observed for the riverbed on the right bank.

Second, hole 1 on the left bank deploys slit-type bucket of curved surface. When this type of bucket is used, the water-wing at the tip of nappes would not emerge with small and middle openings of the sluice gate, thus no impact on the bank slope. This also ensures the typical shape of slit-type nappe under different discharge conditions.

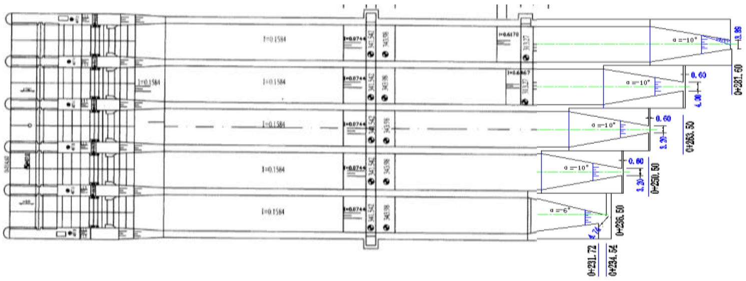


Figure 3.1 Layout of stepped flip bucket of spillways.

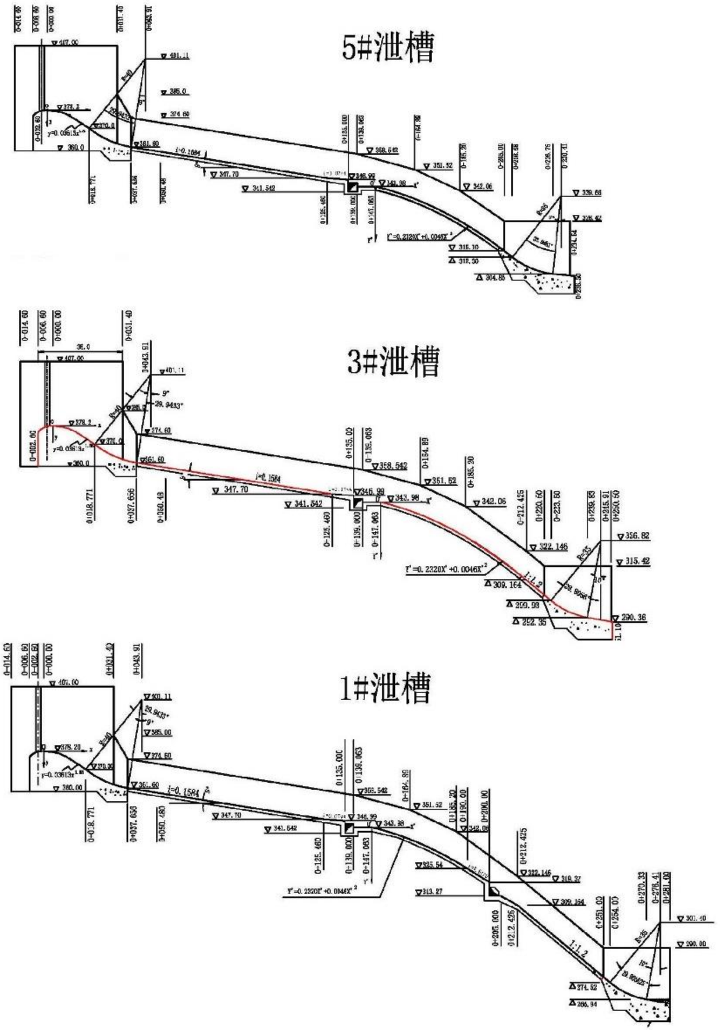


Figure 3.2 Profile of discharge chute of spillways.

3.2. Model test of atomization

Model test of flood discharge atomization has been carried out based on the flood discharge condition and layout of energy dissipator of Shuibuya hydraulic project. A 1/50 normal integral model is used. Flow patterns in model test is shown in figure 3.3.

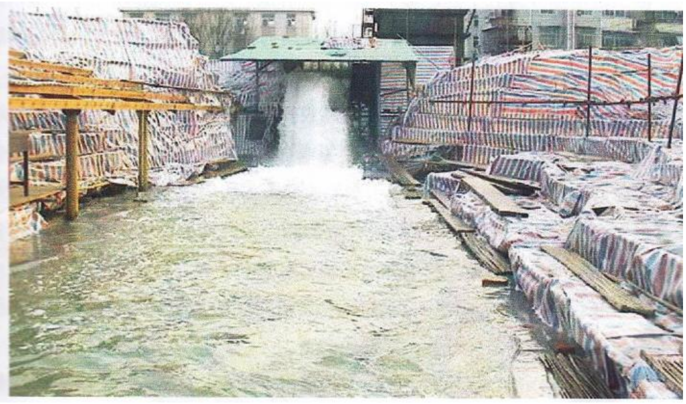


Figure 3.3 Model test of flood discharge atomization of Shuibuya hydraulic project.

The results of model test show that, atomization rainfall of flood discharge at Shuibuya hydropower station has strong intensity and large scope, and atomization distribution is asymmetric at the left and right banks. When flood is discharged, rainfall intensity is observed to be very high (1000 ~ 4000mm/h) in the splash region of nappes. The splash region is close to the landing point of nappes and the low elevation region. The regions of splash and dispersion induced by nappes are different at the two banks. The maximum rainfall intensity observed at the left bank is 5624mm/h, whereas it is 6170mm/h at the right bank.

Referring to prototype observed data in literature of similar projects and calculation of empirical formula, the atomization rainfall scope of Shuibuya project is as follows. The longitudinal length and horizontal width of rainfall are 950m and 600m, respectively. The longitudinal length and horizontal width of area affected by rainfall are 1050m and 850m, respectively. Rainfall intensity distribution under each typical flood discharge condition is also investigated. The influence of flood discharge atomization on the hydraulic project is analysed, including the influence on downstream bank slides, outlets of the power station, traffic hole of powerhouse, and tailwater platform. Protection scheme for atomized rainfall is proposed.

The design sector has adopted the results of model tests, and making the P = 1% flood discharge condition as the design condition of atomization protection for Shuibuya hydropower station. Different protective measures are applied in different regions according to the intensity (from Tier I to Tier III) of atomized rainfall.

3.3. Prototype observation of atomization

Prototype observation is carried out every year ever since the operation of Shuibuya hydropower station. Safety and reliability of flood discharge is assessed by analysing the hydraulic characteristics of spillways, flow aeration, energy dissipation and erosion control, and the intensity and scope of atomization rainfall. In order to monitor the scope and intensity of atomization rainfall at Shuibuya, 30 measuring points are distributed in the downstream of the damsite. The present study compares the observed data of July 24, 2008 and the duration from July 19, 2016 to July 23, 2016.

3.3.1. Initial impoundment period

Flood discharge regulation condition: Spillways $1^{\#}$, $2^{\#}$ and $3^{\#}$ operates at the same time with sluice opening at opening rate e = 7.0m, and sluice gate 3# is fully opened. During the observation period, the reservoir level was about 393.0m, and the maximum discharge of flood was 3300m^3/s.

⑴ Scope of atomization

In general, intense atomization is distributed at the two bank slopes of splash region and in the air of downstream riverbed. Part of the atomization extended over the dam crest towards the updtream reservoir. The intensity of atomization decreased along the vertical direction from the ground to air, and decreased along the radial direction from the splash region to bank roads.

When three sluice gates opened evenly, intense atomization diffused to both sides from the splash region, and it elevated along the mountain body. The highest point (about 520m) was at the top of Maya high slope. The maximum diffusion width was 500m. The atomization reached as far as 1100m from the dam axis. These observed data are very close to that of the model tests.

⑵ Intensity of rainfall

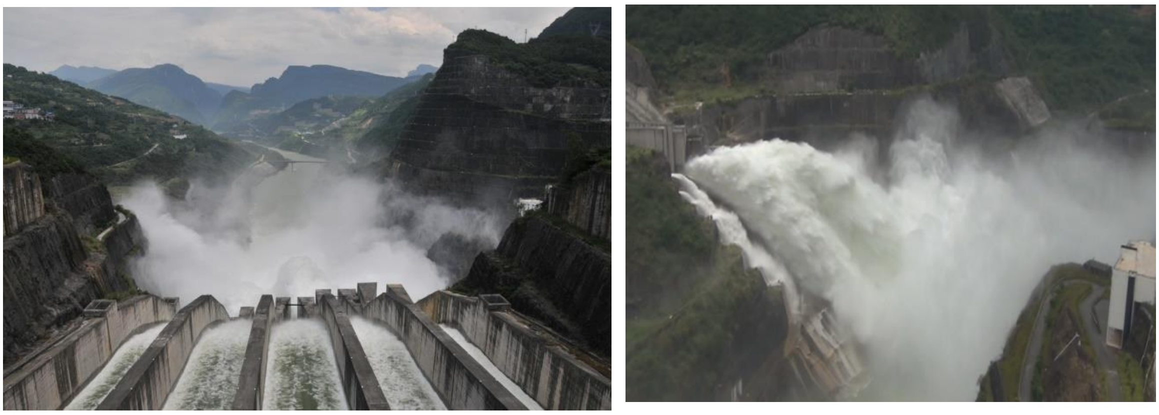
During the prototype observation, 15 measuring points were operational before the flood was discharged. In the intense rainfall area, downpours of rain, storm, blowing sand and thick fog are observed. A few temporary houses on the large rock slide of the left bank were seriously damaged. Many trees were left with only the branches, and some even removed from the ground. The $22^{\#}$ measuring point at stake number 0+550m on the left bank road (elevation of 230m) were taken away by the storm. Hyetometers made of steel at measuring point 10# and $11^{\#}$ (fixed by anchor bolt in the upstream of tailwater platform) were also removed from the ground and damaged completely. The rainfall intensity at $5^{\#}$ and $9^{\#}$ measuring points were over 1000mm/h. The traffic bridge in the downstream is located in the lightly atomized region (Grade V), where rainfall is weak and visibility is good. Traffic on the bridge is not affected by the atomization.

3.3.2. Operational period

Flood discharge regulation condition: Flood was discharged continuously at Shuibuya from July 19, 2016 to July 21, 2016. During the observation period, the reservoir level was about 397.17m, and the maximum discharge of flood was 4500m^3/s. Sluice gates $1^{\#}$, $2^{\#}$, $3^{\#}$ and $4^{\#}$ were opened with a maximum opening of 8m.

On July 23, the reservoir level was at 393.7m ~ 394.3m, and the maximum discharge of flood was 3848m3/s. Sluice gate 3# was opened for 1m, 2m, 4m, 6m, 8m and fully opened. The duration of discharge for the four sluice gates were around 0.5h. Sluice 5# was abnormal when the gate opened, therefore the gate was only opened at 0.52m.

The main observation is as follows.



(a) Scope of atomization (b) Slit-type nappes

Figure 3.4 Distribution of flood discharge atomization. Gate opening of $5^{\#}$ sluice was e_1 = 3m, e_2 = 3m, e_3 = 4m, e_4 = 2m, e_5 = 0.52m.

⑴ Scope of atomization

Atomized flow induced by atomization is affected by the flood discharge and weather. On July 23, it was cloudy, the temperature was 25 ~ 35℃, and no sustainable wind (weaker than level 3) was observed. The wind speed at the sightseeing platform at Road No. 1 on the left bank was 1.0 ~ 1.5m/s.

Atomization was most intense at the landing region of nappes and within 200m of the downstream river section. On the left bank, atomization mainly occurred at the landing region of nappe from 1# sluice and in the downstream. Atomization rainfall diffused along the large rock slide towards broad field. On the right bank, rainfall concentrated at the tailwater platform and Maya high slope. Strong nappe wind was observed along with the atomization. Trees and bushes on the slopes were damaged by the wind and rain, and this continued until stake number 1+100m. On the right bank, the guardrails made of stainless steel in the upstream of tailwater platform were completely destructed. The scope of atomization is shown in figure 3.4.

⑵ Trajectory of atomized flow

Under the weather condition of the day, atomization in the downstream of the dam was not very intense, and it did not extend over the dam crest towards the reservoir. On the Maya slope of right bank, atomized flow recirculated towards downstream of the dam, it then moved from the right bank to the left bank, and eventually moved towards the exit of spillway, creating a clockwise circulating flow. Intense atomization above the river raised up to elevation of 360m ～390m. Overall, atomization at Maya slope on the right bank raised higher than that on the left bank. Waterfalls of different intensity were observed on each berm of Maya slope. The light atomization above the river raised to elevation of 420m.

⑶ Intensity of rainfall

i According to the distribution of rainfall at Shuibuya hydropower station, strong rainfall occurs in local regions, and the intensity of rainfall changes rapidly.

ii Strong rainfall locates at the landing region of nappes from 1# discharge chute, the downstream slope region (0+400~0+730m) under ▽270m on the left bank, and the region between toe of dam (0+450m) and exit of tunnel (0+800m) under ▽330m on Maya high slope on the right bank. The measured maximum rainfall intensity was 2760mm/h at the tailwater platform (▽230m) of 2# unit (0+650m) on the right bank, 2400mm/h at 1# unit (0+700m), 380mm/h at the exit of tunnel (0+785m), and 134mm/h at the exit of 1# traffic hole. The measured maximum rainfall intensity was over 10000mm/h at the platform (▽230m) on the left bank (0+630m). The intensity decreases rapidly to only 64mm/h at 0+800m, and to less than 10mm/h at 0+950m.

iii The measured maximum rainfall intensity at the toe of rockfill dam (▽230m) was 405mm/h, and 29mm/h at ▽240m. The effect of atomization is negligible at ▽270m, with only little rainfall at the left dam abutment. The rainfall intensity was only 0.2mm/h at 3# measuring point in the middle of berm at ▽270m. Atomization flow occasionally raises from the left dam abutment to the dam crest.

iv The measured maximum rainfall intensity at the substation office building and the switch station were 156mm/h and 52mm/h, respectively. When discharge of flood is below 2000m3/s, the rainfall intensity at these locations decreases below the level of natural torrential rain (11.7mm/h).

v The traffic bridge in the downstream is located in the lightly atomized region (Grade V), where rainfall is weak and visibility is good. Traffic on the bridge is not affected by the atomization.

Atomization patterns of flood discharge and rainfall intensity are investigated through two rounds of prototype observation. Strong atomization induced by flood discharge of spillway is observed at Shuibuya hydropower station. During the discharge of flood, high-speed flow compresses the air nearby to form the nappe. The nappe moves fast with air entrainment, diffusing the atomized rainfall. The other reason being for the atomization is splash and dispersion of nappes. In this case, local intense rainfall is observed, and the distribution of rainfall changes rapidly. Intense atomization rainfall is often observed in the downstream of spillway outlet between 0+300m ~ 0+800m in the valley and on the banks. The large rock slide on the left bank and Maya high slope on the right bank are in the areas of intense rainfall. Heavy rain and nappe wind could damage the protective slope, measuring facilities and structures on the tailwater platform within these areas. The observed data show that the present design of atomization protection is suitable considering the distribution of rainfall. The results are useful for safety assessment of flood discharge regulation at Shuibuya hydropower station.

4 CONCLUSIONS

i A hydropower station on a canyon river is typically built with high water head and large unit discharge. This type of hydropower station is surrounded by thick burden of riverbed and complex geological and topographical conditions. The tradeoff between energy dissipation and atomization of flood discharge in the downstream is critical to the design and construction of these hydropower stations.

ii The angle between overflow centreline and downstream river is troublesome when river bank spillway and spillway tunnel are deployed. Ideally, the landing points of nappes should be separated (when multiple spillways are used) and be in the middle of the river. The fluctuation of water level, especially at the tailwater region, should be avoided. Therefore, the energy dissipator should be designed based on the local flow regimes and geological conditions.

iii The movable model test results show that, for thick riverbed burden, it is significant to apply protective measures to bank slopes within certain range of downstream river section. The key is to determine the appropriate maximum allowable flow velocity for bedrock erosion, , and this is closely related to the thickness of riverbed burden and grain composition.

iv The scope and intensity of atomization rainfall of flood discharge through spillways are linked with the discharge of flood, river pattern in the downstream and landscape of bank slope. During the discharge of flood, high-speed flow compresses the air nearby to form the nappe. The nappe moves fast with air entrainment, diffusing the atomized rainfall. The other reason to the atomization is splash and dispersion of nappes. In this case, local intense rainfall is observed, and the distribution of rainfall changes rapidly. Intense atomization rainfall concentrates in certain downstream regions of river and bank slopes. The elevation of atomization is below the dam crest in most cases. The impact of flood discharge atomization on the hydraulic project is analysed in combination with the layout of hydraulic structures. The present study could be useful for the design of hydraulic project and protection of bank slopes.

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