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# Ski Jump Hydraulics of Leak-Floor Flip Bucket

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***Abstract:*** *Given the enormous flow velocity, large discharge rate, and narrow valley conditions, the common ski jump does not apply to flood discharge and the energy dissipation safety becomes a key issue in high dam engineering. The conventional slit-type flip bucket, using the design of side-wall contraction, results in high hydrodynamic pressure on the sidewalls, which is extremely dangerous to outlet structure. Based on research about motion characteristics of high speed flow, it is proposed that a leak-floor (dovetail shape) flip bucket is designed during the Jinping spillway construction. When water flows through the leak-floor area, the middle of the water is lifted into the atmosphere first and the natural pressure difference at lateral direction generates, making the water deflect transversely to the center-line simultaneously. This specific flipping action makes the water jet narrow-long, without high pressure on the side walls of the flip bucket. This design of leak-floor flip bucket improves structure safety and has been successfully applied to spillway outlet design with approximately 50m/s flow velocity. Based on physical model experimentation, the following items were addressed: (1) typical flow pattern of ski jump along the leak-floor flip bucket; (2) jet trajectory affected by the type parameters of flip bucket; and (3) pressure distribution on side-wall of flip bucket. Further, a comparison with previous results indicates a favourable behaviour of this flip bucket design for high-speed outlet.*

***Keywords:*** *Ski jump, dam, outlets, flip bucket, spillways.*

## 1. Introduction

Ski jumps are commonly introduced in high dam construction for energy dissipation (Glazov 1985, Xu et al. 2002, Heller et al. 2005). Flip bucket employed with appropriate geometry is pivotal for an efficient energy dissipation by discharging flow away from the dam toe into a plunge pool or a river channel (Li et al. 2012). A jet flow (with aeration and dispersion in the air and with formed submerged jets in the downstream) promotes dissipation, due to strong hydrodynamic shear and turbulence production (Steiner et al 2008, Liu and Ye 2002). Traditionally, slit-type flip bucket is implemented for streamwise diffusion by contracting the flow with symmetrically wedge-shaped deflector-sidewalls and the huge hydrodynamic pressures on its sidewalls make it difficult to construct (Wu et al., 2012). Based on the experimental observation, a leak-floor flip bucket is proposed as an attractive alternative for two reasons: (1) effective streamwise diffusion capabilities and (2) decreased level of sidewalls pressures which could benefit design and construction (Deng et al. 2016). For instance, the model test of Jinping Hydropower Station demonstrates that for a leak-floor flip bucket, the time-average pressure is three quarter smaller than that for slit-type flip bucket.

**Figure 1.** Ski-jump flow of leak-floor flip bucket in Jinping hydropower station.

Currently, the study of the leak-floor flip bucket is at its preliminary stage (Qian 2012). Initial experiments indicated that the jet flow diffused in the air after flowing from the bucket, the impact area is as long as the distance between upper and lower jet trajectory is large, and the impact energy per square is small. Thus, the bucket could contract flow slightly off the downstream channel (Deng et al. 2013). The projectile motion shows that the range of projectile is farthest when the take-off angle is equal to 45°. Considering the jump distance of upper trajectory as far as possible can benefit the streamwise diffusion, the geometry angle of upper jet trajectory is equal to approximately 45°. Thus, the streamwise extension, energy dissipation, and nearest impact point are determined by the takeoff characteristics of lower jet trajectory. The jump distance of the lower jet trajectory is determined by the lower jet takeoff angle when its takeoff velocity is fixed.

A range of proposals for ski-jump flow generation and development were stated previously. The jet generation of deflector has been discussed, showing that pre-aeration will reduce the jet length and trajectory parabola may also be applied for jet take-off angles smaller than the bucket angle (Pfister and Hager 2012, Pfister et al. 2014). Moreover, the characteristic air concentrations are described as a function of flow properties. For circular-shaped flip bucket, takeoff angle is equal to the geometry bucket angle (Wu 2007, Ting 2013), while Courant et al. (1986) considered that it is less based on the theory of high-speed jet flow. Related experiment-based research research on experiments has been conducted to confirm this phenomenon (Zhu 2004). The flattening of flow profile at the bucket and the equations were established for circular-shaped flip bucket and the bevelled flip bucket (Ning 2004). Xin (1984) demonstrated thatthe break point of flow profile occurs at the circular-shaped bucket . Based on potential flow theory, the influences of geometry were considered, as well as a correction factor of triangular wedge-shaped bucket (Pan et al. 1980). Zhang and Wu (1989) assumed that the slit-type flip bucket for ski jump is not affected by the takeoff angle of the flip bucket.

In the present study, the typical flow patterns of a ski jump along the leak-floor flip bucket are investigated using physical model experiments. The effects of shape parameters on jet trajectory and jet profile are analysed, including front takeoff angle at the inception of leak-floor area, radius of bucket and leak floor ratio. The pressure distributions on a side-wall are measured and a comparison with other flip buckets is conducted to show the application of leak-floor flip bucket.

## 2. Experimental Methods

The leak-floor flip bucket was proposed in the research on spillway energy dissipation at Jinping Hydropower Station, which is the highest arch-dam in the world, at305m high. Due to the large flow discharge (3123.5m$^3$/s) and high head (235m), the flow velocity at the end of the spillway can reach about 50m/s. Furthermore, the width of river downstream in the narrow valley is about 80m − 100m with a small intersection angle 23º at the axis of the spillway. Thus, the ski-jump energy dissipation was made difficult to achieve a good flow joint downstream and maintain flip bucket structure safety.

The 1:100 normal-scaled model based on the Froude criterion includes the whole flood discharge spillway tunnel, which is 1407m long and connected with the leak-floor flip bucket at the exit. The model is made of transparent polymethyl methacrylate. The design of leak-floor flip bucket is shown in Figure 2. The side walls keep the same wide $B$ with the spillway at plane view, and the leak-floor area is at the anti-arch ($R$) bottom floor at a certain position ($B_1$ and $\theta_1$) to the end of the flip bucket ($B_2$ and $\theta_2$). The width of the leak-floor area broadens gradually. Figure 3 shows a view of the experimental leak-floor flip bucket.

The flip bucket had a bucket radius $R$, a leak floor ratio $B_1/B_2$ and two different deflection angles, which is front takeoff $\theta_1$ and end takeoff $\theta_2$, respectively. The jet nappe included two characterized jet trajectories $L_u$ and $L_d$, with the width of jet nappe $L$. In the present study, five radii $R$ = 30m − 90m (prototype values) were considered with $B_1/B_2$ = 0.30 − 0.67. The front takeoff $\theta_1$ ranged from 0° to 25° with a constant end takeoff $\theta_2$ = 45°. Four flow discharge rate $Q$ were tested with $Q$ = 1210.6m$^3$/s, 2019.8 m$^3$/s, 2560.4 m$^3$/s, 3123.5 m$^3$/s. A series of point gauges were used to determine the typical jet flow nappe profiles, and the characterized jet trajectories $L_u$ and $L_d$. The pressure distributions on flip bucket side wall were measured using pressure manometer. Considering the 1:100 scale of physical model, the approach flow Froude number $Fr = V/(gh)^{0.5}$ is about 5.0 − 7.4 with Reynolds number $Re = Vh/v$ is about $7.1 \times 10^4 - 1.8 \times 10^5$, where $v$ is the kinematic water viscosity, $g$ is the gravitational acceleration, and $V$ and $h$ is the mean velocity and depth of approach flow, respectively. Thus, the present study will focus on the distribution of mean pressure on sidewall, typical pattern of ski-jump flow and its variation with the parameters of leak-floor flip bucket, which satisfies the Froude criterion. The scale effect on air-water properties of supercritical flow cannot be neglected regarding the surface tension and viscosity effects in high speed air-water flows (Pfister and Chanson 2014).

The RNG $k$-$\varepsilon$ turbulent model was employed in this paper, with control-volume method and SIMPLER method for numerical simulation (Launder and Spalding 1974, Deng et al. 2008). The non-slip boundary condition was used on the wall, and the near-wall condition was given by the standard wall functions with the normal velocity set as zero on the wall. The VOF method was introduced to simulate the free surface.

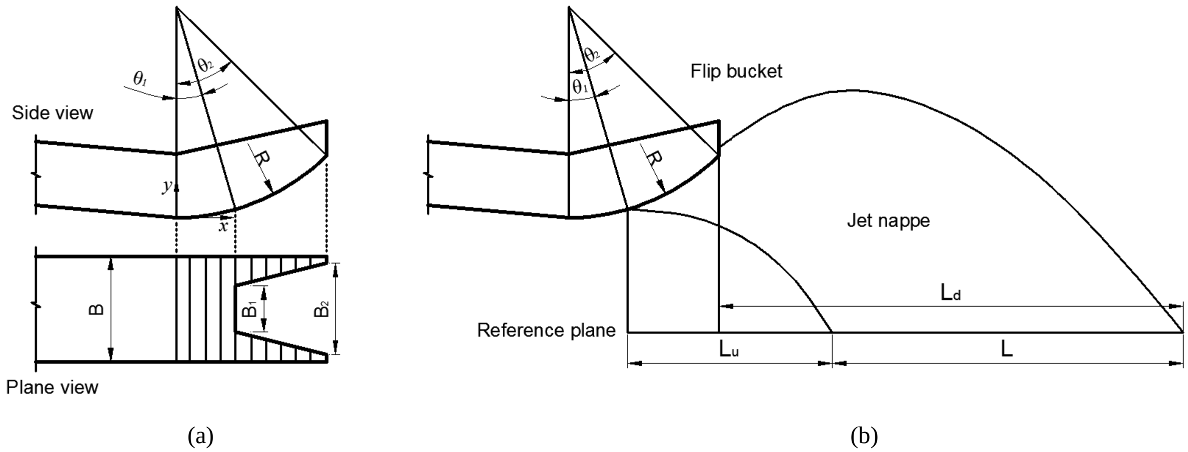



**Figure 2.** Definition sketch with investigated parameters of (a) leak-floor flip bucket and (b) jet nappe.


**Figure 3.** Model photographs of leak-floor flip bucket ($R$ = 30m, $\theta_1$ =15°, $B_1/B_2$ = 0.50) with convections for pressure manometers: (a) lateral view; (b) front view.

## 3. Results and Discussions

### 3.1. Typical Flow Pattern

Figure 4 shows the typical flow pattern of a leak-floor and a conventional flip bucket. For the leak-floor flip bucket, the water jet gets stretched longitudinally at streamwise direction and drops into the pool as long and narrow nappe shape. The distribution of water discharge falls along the whole jet trajectory, due to the coupling effect of shape parameters including front takeoff, radius of bucket, and leak floor ratio. The jet nappe from the leak-floor flip bucket is broom-shape. For conventional flip bucket, the distribution of water discharge in the air is weak stretched and falls into the downstream with a longer jet trajectory. Due to the specific design of leak-floor, it is acknowledged that more water diffuses in the low area of jet nappe with the increase of $R$ and decrease of $\theta_1$. Moreover, the uniformity of jet diffusion can be improved with the increase of $B_1/B_2$, and more water will drop into upstream area, as shown in Figure 5. Due to the different geological conditions and complex impact resistance capacity of riverbeds, these specific effects of shape parameters on the flow discharge distribution can be considered for the design of leak-floor flip bucket.

(a) (b)

**Figure 4.** Comparison of typical jet diffusion between (a) leak-floor and (b) conventional flip bucket ($R$ = 30m).

(a) (b)

**Figure 5.** Effect of $B_1/B_2$ on jet flow pattern ($R$ = 30m, $\theta_1$ = 0°): (a) $B_1/B_2$ =0.42; (b) $B_1/B_2$ =0.54.

Figure 6 shows the water depth and pressure distribution at the origin area of leak-floor flip bucket from numerical simulation. At the non-leaked floor area, the water depth and pressure profiles are smooth at the cross-section. At the initial section of the leak-floor flip bucket, although the water depth does not change, the pressure distribution changes remarkably. When the water flow moves through leak-floor area, its pressure reduces to atmospheric pressure, while the pressure in floor area near the sidewalls maintains the hydrodynamic pressure, resulting in pressure difference between bottom position and sidewalls. The water will move transversely at the cross-section because of the pressure difference. The flow on both sides moves towards the central area with the effect of pressure difference, taking off from the central leaked area and generating a long and narrow nappe shape of ski jump flow.

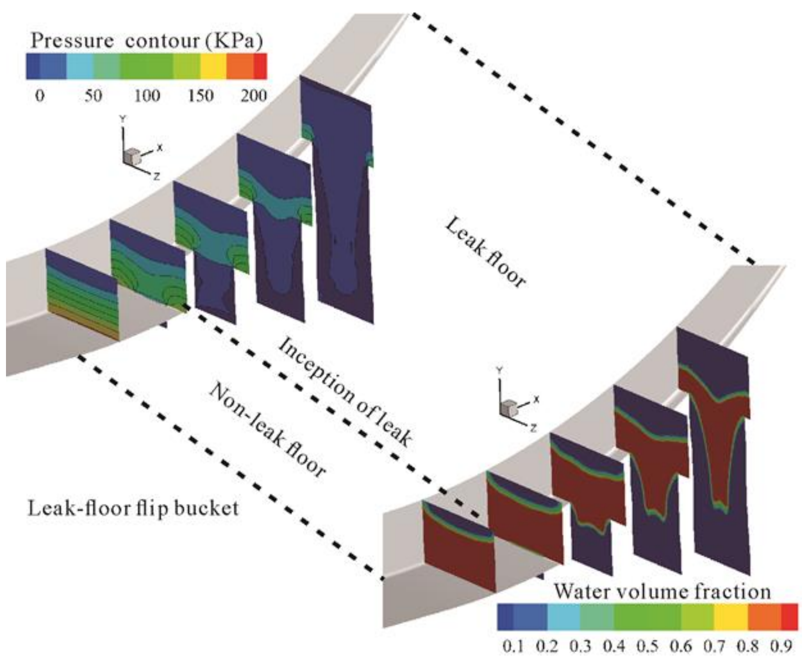



**Figure 6.** Water profile and pressure distributions through leak-floor flip bucket from numerical simulation.

Figure 7 shows the pressure distribution on the side wall of a leak-floor flip bucket ($Q$ = 3123.5 $m^3$/s). First note that as the water flows thought the bucket, the pressure on the side wall increases in the incipient part and then decreases gradually until the end of bucket (Figure 7(a)). The pressure on the side wall descends as the form of hydrostatic pressure and no obvious impact area appears, and the maximum pressure on the side wall occurs mainly at the area connected to the leaked floor. The attenuation of pressure in the leak-floor area confirms that the transverse movement of water is caused by the natural pressure difference between leaked and un-leaked area of floor. With the decrease of front takeoff $\theta_1$, the pressure on the side wall is reduced and attenuates along the bucket with an identical trend (Figure 7(b)).

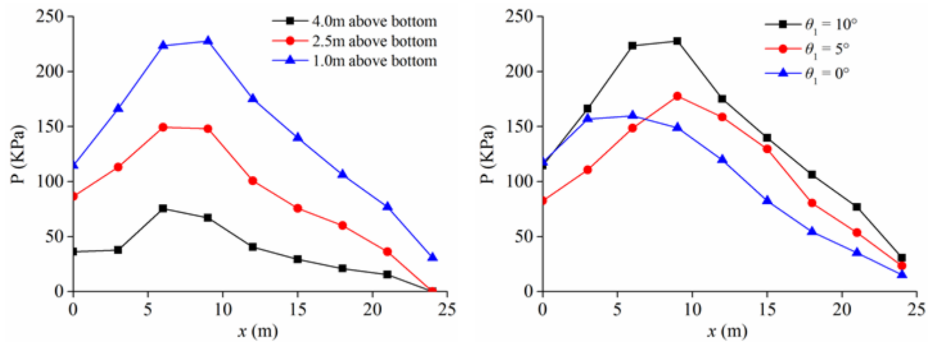



**Figure 7.** Pressure distribution on side wall ($B_1/B_2$ = 0.50): (a) $R$ = 30m and $\theta_1$ = 15°; (b) effect of $\theta_1$ ($R$ = 30m).

### 3.2. Jet Trajectory

#### 3.2.1. Effect of Flow Discharge

Figure 8 and Figure 9 show the effects of flow discharge on jet trajectory properties for leak-floor flip bucket, including an upstream jet trajectory $L_u$, a downstream jet trajectory $L_{d,}$ and a width of jet nappe $L$. First note that with flow discharge increasing from 1210.6$m^3$/s to 3123.5 $m^3$/s, the value of $L_u$ does not change obviously, while the $L_d$ gets gradually larger, which results in the increase of $L$ with flow discharge. This indicates that due to the specific leak-floor design in this flip bucket, it can adapt to a wide range of flow discharge. On the other hand, with the flow discharge getting about 3 times larger, the increases of $L_d$ is relatively smooth and the increase gradient is about 10% – 50% for all the test conditions; meanwhile, the jet nappe remains well stretched, and the width $L$ increases with $L_d$.

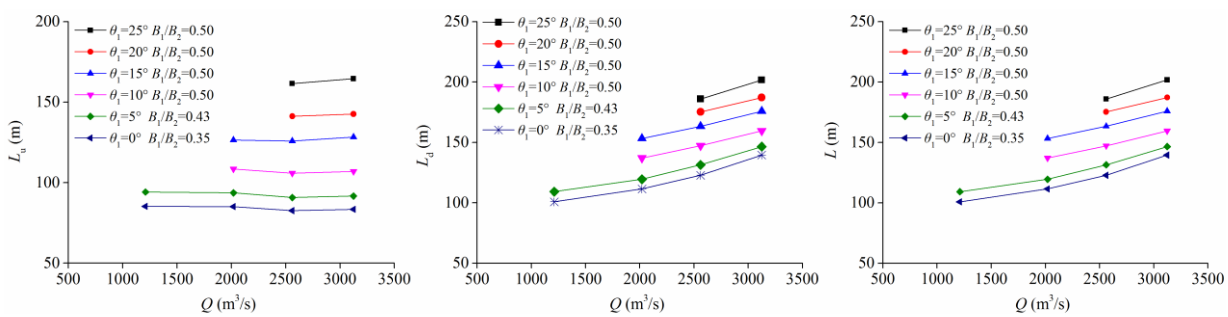
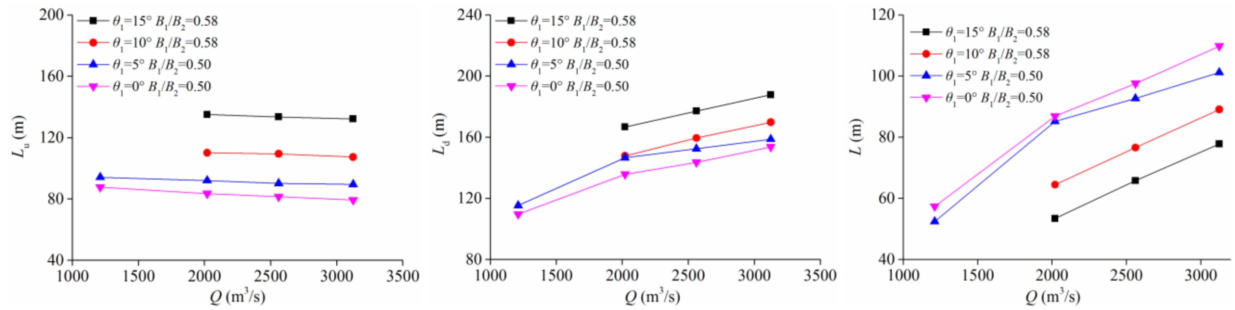



**Figure 8.** Effect of flow discharge on jet trajectory ($R$ = 90m): (a) $L_u$; (b) $L_d$; (c) $L$.



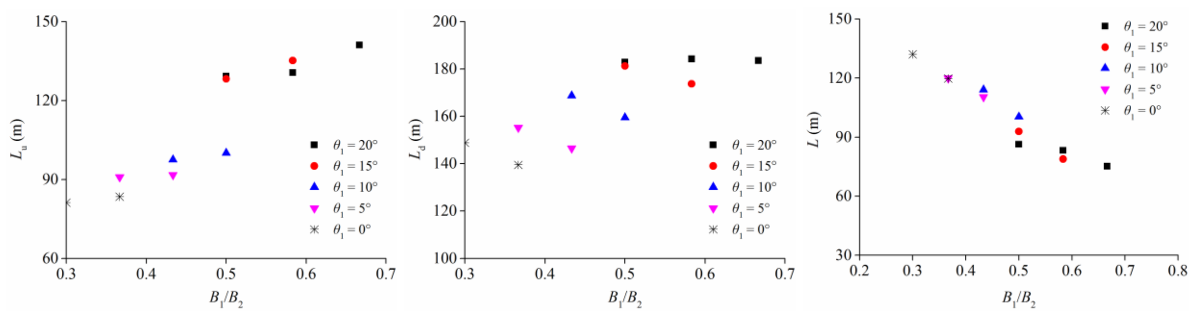

(a) (b) (c)

**Figure 9.** Effect of flow discharge on jet trajectory ($R$ = 50m): (a) $L_u$; (b) $L_d$; (c) $L$.

### 3.2.2. Effects of Shape Parameters

In a leak-floor flip bucket, the front takeoff $\theta_1$ affect both upstream and downstream jet trajectory as shown in Figure 10. The values of $L_u$ and $L_d$ get prominently greater with increase of $\theta_1$, while the width of jet nappe $L$ decreases with $\theta_1$. This indicates that for large front takeoff angles, the performance of leak-floor gets weaker, and jet flow diffuses insufficiently in the air. The water discharge gets centralized and drops far away downstream. In narrow valley, it cannot be taken full advantage of the space of flow discharge for ski-jump energy dissipation. Thus, large front takeoff angle should be limited in the design of leak-floor flip bucket.

In terms of the ratio leak-floor $B_1/B_2$, it affects both uniformity and diffusion of jet nappe. Considering that the $B_1/B_2$ determines the water discharge released from the leak-floor area, a reasonable design of $B_1/B_2$ will lead to a good distribution of flow discharge in the jet nappe area. With the increase of $B_1/B_2$, the value of $L_u$ gets slightly larger and $L_d$ gets smaller, which results in an obvious decrease of $L$. From the experimental measurement, for different front takeoff angle conditions, its influence on the gradient $L$ is almost identical. This confirms that the lateral velocity and natural pressure difference is approximately identical.



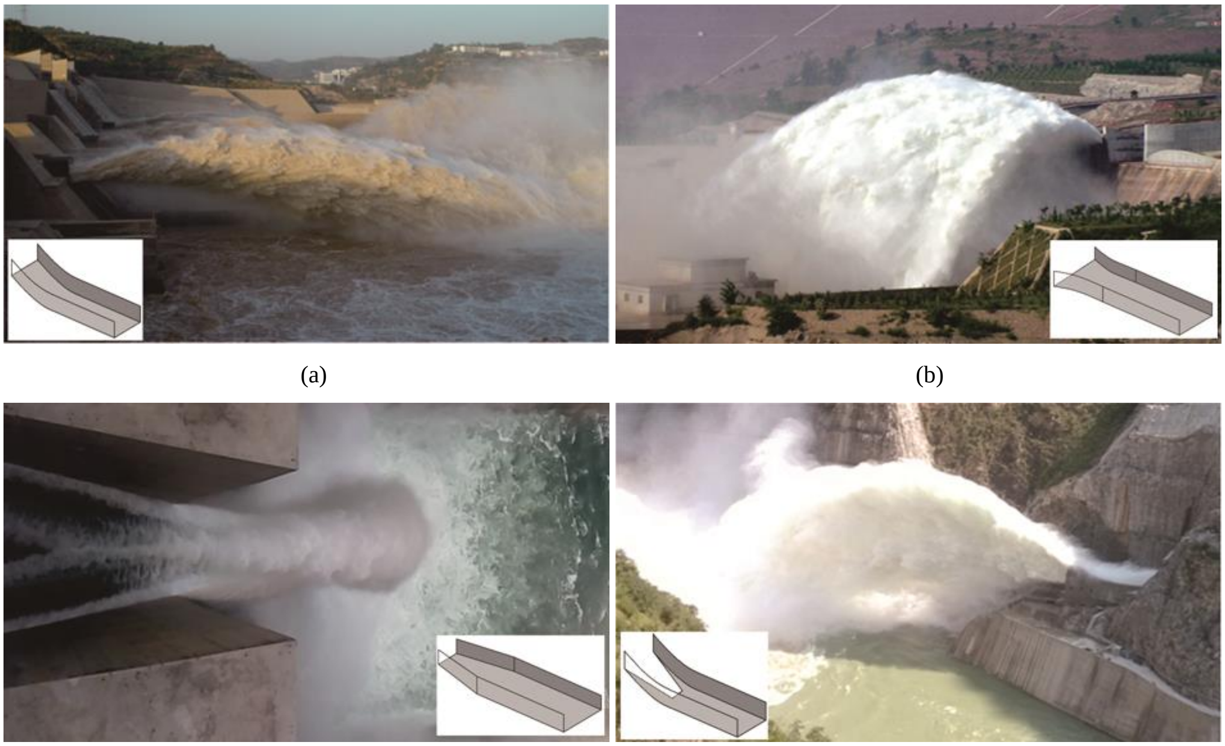

(a) (b) (c)

**Figure 10.** Effect of $\theta_1$ on jet trajectory ($R$ = 90m): (a) $L_u$; (b) $L_d$; (c) $L$.

## 4. Comparison with Other Flip Buckets

For the flip bucket application, typical indexes of ski jump energy dissipation were taken into consideration in the comparison of four flip bucket types, including conventional circular-shaped, lateral-widening, lateral-contraction and leak-floor flip buckets, as shown in Figure 11. Firstly, the flow patterns of convetional circular-shaped and lateral-widening are laterally diffused in the air, affected by the wide of flip bucket and specific parameters. The two should be applied with the wide riverbed downstream. For lateral-contraction and leak-floor flip buckets, the jet flow diffuses as "—" type along the streamwise direction. These two can be applied with the narrow riverbed condition. Based on the statement above, the leak floor ratio $B_1/B_2$ and two different deflection angles are the two specific parameters affecting jet flow pattern, beside the conventional parameters of flip bucket including approach flow condition, bucket radius, and deflection angle (Heller et al. 2005, Steiner et al. 2008, Pfister and Hager 2010).

On the other hand, the formation mechanism of jet nappe for the two flip buckets is substantially different. For lateral-contraction design, the long and narrow jet flow results by the side-wall lateral contraction. This will lead to high pressure on side wall, which is extremely dangerous to the structural safty of flip bucket, especially for cantilever design with large flow discharge and high velocity. However, The specific design of leak-floor “guides” the narrow water flow without addition force on the side wall. Previous study showed that the maximum pressure for lateral-contraction flip bucket is more than 4 times larger than that of leak-floor type (You 2009, Deng 2016), and jet trajectory characteristics for the two types are alomost identical, as shown in Table 1. This indicates that the leak-floor design is obviously better for the structural safety. This is mainly due to the formation of ski jump flow of leak-flow, driving by the natural pressure difference at transversely direction. Consequently, the leak-floor flip bucket is the final design of the outlet in Jinping spillway. In the recent operation of prototype spillway, the well ski jump performance showed that leak-floor flip bucket is an effective way to solve the energy dissipation issue in high dams.



(a) (b) (c) (d)

**Figure 11.** Typical ski-jump flows of different flip bucket in prototype: (a) conventional circular-shaped flip bucket; (b) lateral-widening flip bucket; (c) lateral-contraction flip bucket; (d) leak-floor flip bucket.

**Table 1** Comparison of hydraulic characteristics between lateral-contraction and leak-floor flip buckets

| Working conditions | $Q$ = 3123.5 m$^3$/s | $Q$ = 3123.5 m$^3$/s | | | $Q$ = 2560.4 m$^3$/s | | |
|---|---|---|---|---|---|---|---|
| Parameters | Maximum pressure on sidewall | Trajectory | | | Trajectory | | |
| | | $L_u$ | $L_d$ | $L$ | $L_u$ | $L_d$ | $L$ |
| Ratio of lateral-contraction/leak-floor | 4.65 | 1.13 | 1.09 | 1.07 | 1.13 | 1.05 | 1.01 |

## 5. Conclusions

The typical pattern of ski jump flow and jet trajectory affected by the shape parameters of a flip bucket has been investigated. The pressure distribution on a side wall confirms the formation mechanism of the narrow-long ski jump flow, which is due to the natural pressure difference caused by the central leak-floor area. This makes the leak-floor flip bucket a better choice to solve the issue of ski jump energy dissipation in the highest arch-dam Jinping hydropower station. The leak-floor design improves the flexibility of jet profile with a wide application of flow discharge. The jet trajectory is affected by the shape parameters including front takeoff angle, leak-floor ratio and radius of bucket, and the flow discharge distribution in the jet nappe is consequently different. Due to different geological conditions and impact resistance capacity of riverbeds, these specific effects of shape parameters can be considered for the design of leak-floor flip bucket.

## 6. Acknowledgements

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