MATEC Web of Conferences 77, 06001 (2016) DOI: 10.1051/matecconf/20167706001
ICMMR 2016

Study on Hydraulic Characteristic of Submerged Jet with Depression Angle Dived into Plunge Pool from the Underwater Surface

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Abstract. Experiment research on submerged jet with depression angle dived into plunge pool from near-surface was carried out. The results showed that this type of energy dissipation type has good effect in improving the energy dissipation rate, reducing the surface fluctuation and reducing near-bed velocity and so on. Calculation formulas of conjugate depth and energy dissipation were obtained through theory analysis of submerged hydraulic jump in water cushion. Formula analysis showed that for high Froude number flow at a certain downstream depth, to obtain stable submerge hydraulic jump through adjusting size of jet exit, by decreasing its width is better way than by increasing height. When flow Froude number is larger sudden expansion ratio is more sensitive to energy dissipation, therefor to improving effect of energy dissipation by decreasing jet exit's width or increasing plunge pool's width can be used.

1 Introduction

In the last thirty years of reform and opening up, the country's hydropower has made great achievements attracting worldwide attention. Especially since the implementation of the western development strategy, hydropower projects of southwest reign have started construction, dam construction in these areas mostly on mountain rivers, with head high, large flow, narrow valleys and other features. Traditional underflow energy dissipation cannot meet requirements of spillway with large unit power, near-bed flow velocity is high and bottom stability is poor in plunge pool [1, 2]; ski-jump energy dissipation of flood discharge has good effect, but atomization is difficult to avoid the impact on the environment [3-6]. For this reason, Sichuan University and Mid-South Design and Research Institute proposed horizontal submerged jets energy dissipation in setting the vertical drop and sudden enlargement of stilling pool and applied in Xiangjiaba hydropower project, and good results were achieved [7-12]. In addition, Mid-South Design and Research Institute in conjunction Tuoba dam energy dissipation proposed submerged jet with depression angle dived into plunge pool from the underwater surface and conduct experimental studies [13], but this is a new type of energy dissipation type, water structure is complex and engineering practical experience is lack, so it is necessary to carry out in-depth research. In this paper, experiment was conducted to observation flow field and flow pattern of submerged jet with depression angle, hydraulics basic theories were used to establish submerged jet calculation formulas of conjugate water depth and energy dissipation, and transformation laws of plunge pool water depth and energy dissipation rate variation of Froude number were analysed in different condition of depression angle, water cushion expansion ratio and vertical drop. Findings enriched the study results of high-dam spillway energy dissipation and provided theoretical supports for engineering applications.

2 Flow pattern of submerged jet with depression angle

As shown in Fig. 1, physical model in the laboratory was established to format submerged jet with depression angle dived into plunge pool from the underwater surface, model including steel tanks, test section (jet segment and plunge pool), backwater reach and underground storage reservoir is self-circulation system. Pressure jet from jet segment inject into water cushion from the underwater surface with depression angle, and plunge pool dissipate its energy by the surrounded violent eddies. So two flow regimes of submerge jet and ternary water jump were observed through experimental in water plunge pool. As shown in Fig. 2, water cushion can be divided into several regions including submerged jet zone, impact jet zone, upstream and downstream wall attached jet zones, upstream and downstream eddy zones, left and right side eddy zones. Upstream and downstream eddies are the horizontal axis vortexes at the top and bottom edges of jet, and left and right eddies are the vertical shaft vortexes on both sides of the sudden enlargement plunge pool. Shear layer formed by vortexes can significantly increase the rate of energy dissipation units of water. After the end of the mainstream area submerged submarine jets in water cushion pool bottom, the range of water surface fluctuation is little. Energy dissipation effect of shear between submerged jet and eddies is significant, as shown in Table 1, the maximum near-bed velocity in wall attached jet zone downstream is about half of the jet exit velocity.

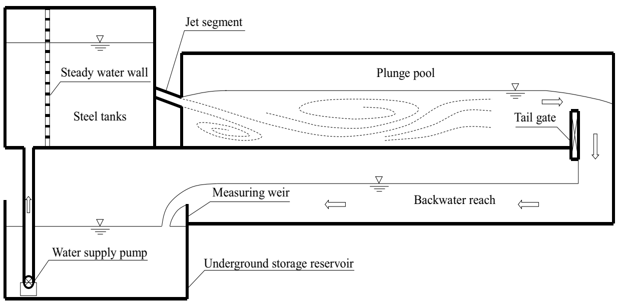

Figure 1. Model layout sketch of submerged jet with depression angle dived into plunge pool from the underwater surface.

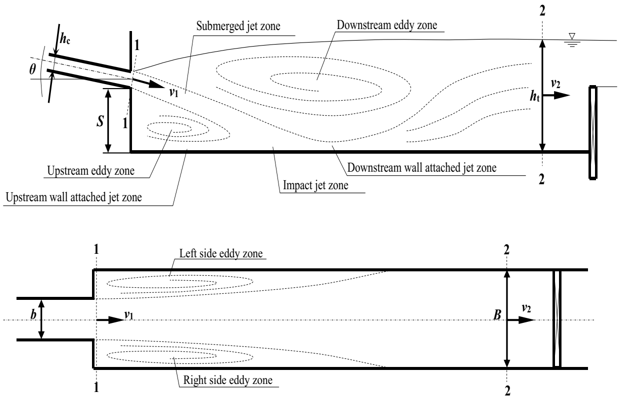

Figure 2. Flow state sketch of submerged jet.

Table 1. Average Flow Velocity of Jet Exit and Maximum Near-bed Velocity of Wall Attached Jet Zone.

Flux Q / $m^3 \cdot s^{-1}$	Average flow velocity of jet exit v_1 / $m \cdot s^{-1}$	Maximum near-bed velocity of wall attached jet zone v_{0m} / $m \cdot s^{-1}$	Relative value $v_{0m} \cdot v_1^{-1}$ / %
4.33×10^{-2}	3.8510	1.5909	41.31
4.54×10^{-2}	4.0382	1.6673	41.29
4.75×10^{-2}	4.2218	1.7421	41.27
4.96×10^{-2}	4.4054	2.0593	46.75
5.15×10^{-2}	4.5757	2.1383	46.73
5.34×10^{-2}	4.7468	2.2168	46.70

Note: Depression angle of model is 10°, the jet exit width × height is 0.150m × 0.075m, plunge pool width is 0.30m, vertical drop height is 0.40m.

3 Theoretical formula of submerged jet

3.1 Conjugate water depth

As shown in Fig. 2, the jet exit width is b and height is h_c, depression angle is θ, vertical drop height s, plunge pool width is B, water cushion depth of submerged jet in plunge pool is h_t. Section 1-1 of the jet outlet and section 2-2 of downstream depth of submerged hydraulic jump were selected to apply momentum equation:

$$\frac{1}{2}\gamma h_c^2 b\cos\theta + \gamma BS\left(h_c\cos\theta + \frac{S}{2}\right) - \frac{1}{2}\gamma h_t^2 B = \rho\left(\frac{Q^2}{h_t B} - \frac{Q^2\cos\theta}{h_c b}\right) \tag{1}$$

where γ and ρ are the water density and density, Q is discharge flow. The formula rearranging above is:

$$\overline{H} = \frac{2Fr_1^2\left(\overline{H}\cdot\cos\theta - \frac{1}{\overline{B}}\right)}{\overline{B}\left[\overline{H}^2 - \left(\overline{S}+\cos\theta\right)^2 + \frac{\cos\theta}{\overline{B}}\left(\overline{B}\cdot\cos\theta - 1\right)\right]} \tag{2}$$

where Fr_1 is the jet outlet Froude number; $\overline{H}$ is sequent depth radio, $\overline{H} = h_t/h_c$; $\overline{B}$ is sudden expansion ratio of water cushion, $\overline{B} = B/b$; $\overline{S}$ is the radio between the vertical drop height and the jet outlet, $\overline{S} = s/h_c$.

3.2 Energy dissipation ratio

In Fig. 2, section 1-1 and section 2-2 were selected to apply energy equation:

$$E_1 = H_1 + s = h_c\cos\theta + \frac{v_1^2}{2g} + s \tag{3}$$

$$E_2 = H_2 = h_t + \frac{v_2^2}{2g} \tag{4}$$

$$\Delta E = H_1 + s - H_2 \tag{5}$$

where v_1 is the section 1-1 average velocity of jet outlet; v_2 is the section 2-2 average velocity of the submerged jet downstream; ΔE is the energy loss of submerged jet. Then energy dissipation rate of submerged jet is η:

$$\eta = \frac{\Delta E}{E_1} = \frac{H_1 + S - H_2}{H_1 + S} = 1 - \frac{\overline{H} + \frac{Fr_1^2}{2\overline{B}^2\,\overline{H}^2}}{\cos\theta + \overline{S} + \frac{Fr_1^2}{2}} \tag{6}$$

4 Formulas analysis

Fig. 3 shows the curves of water cushion depth dimensionless number $\overline{H}$ and the jet exit Froude number Fr_1 at different depression angle θ. From this, the same as the width of water cushion, vertical drop height, width and the height of jet exit, with increasing Froude number, water depth required to form stability submerged jump increases significantly. Fig. 4 shows the curves of energy dissipation rate η and jet exit Froude number Fr_1 at different jet depression θ. From this, under certain export jet outlet and water cushion size, energy dissipation with increasing Froude number increases, and the changes of depression angle little effect on the rate of energy dissipation; less Froude number impact energy dissipation rate significantly greater than the larger Froude number. When the Froude number is equal to 6, submerged jet energy dissipation rate is 70%; when the Froude number is equal to 10, the energy dissipation rate is over 80%. Integrated Fig. 3 and Fig. 4 shows, when other conditions are the same and the change of the depression angle less than 15°, the change of the depression angle has little effect on the water cushion depth and energy dissipation rate.

angle, the width of water cushion and jet exit, the greater height of vertical drop or the smaller height of jet exit, downstream water depth required to formed stability submerged jump increases. Comprehensive seen in Fig. 5 and Fig. 6, when the Froude number is less than 6, jet exit width is more sensitive than vertical drop height impacted on downstream water depth. Therefore, under certain water depth conditions, if the formation of a stable submerged jump through adjusting the size of the jet exit, it is effective by increasing the height of jet exit when the Froude number is smaller and reducing the width of jet exit when the Froude number is larger.

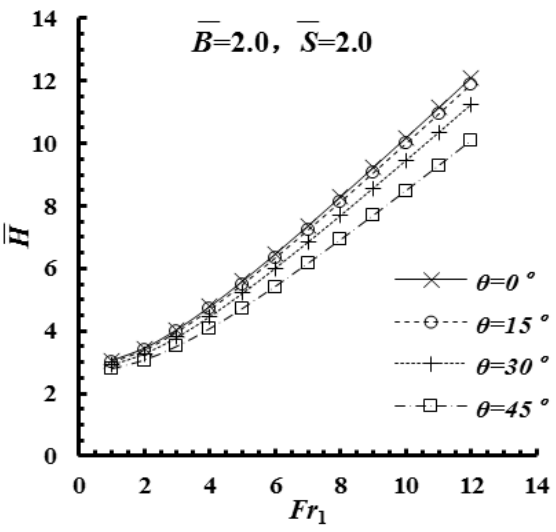

Figure 3. Relationship between Fr_1 and $\overline{H}$ in different θ.

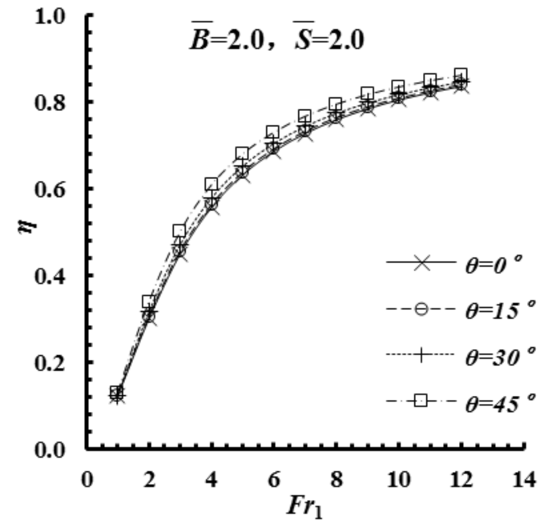

Figure 4. Relationship between Fr_1 and η in different θ.

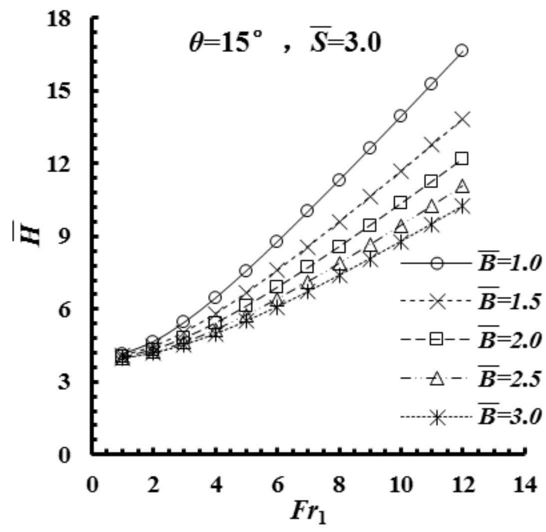

Figure 5. Relationship between Fr_1 and $\overline{H}$ in different $\overline{B}$.

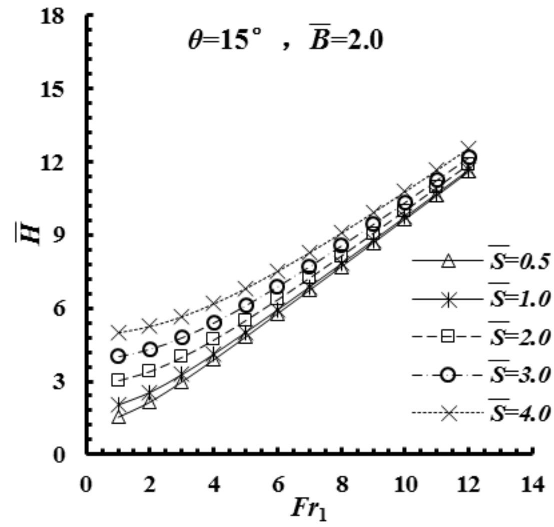

Figure 6. Relationship between Fr_1 and $\overline{H}$ in different $\overline{S}$.

Fig. 5 and Fig. 6 show the curves of water cushion depth dimensionless number $\overline{H}$ and the jet exit Froude number Fr_1. Seen from Figure 5, the same as the Froude number, depression angle, the height of vertical drop and the jet exit, the water cushion width is smaller or the jet exit width is larger, downstream water depth required to formed stability submerged jump increases. It is seen from Fig. 6, the same as the Froude number, depression

Fig. 7 and Fig. 8 show the curves of energy dissipation rate η and jet exit Froude number Fr_1. Seen from Fig. 7, the same as the Froude number, depression angle, the height of vertical drop and the jet exit, the water cushion width is larger or the jet exit width is smaller, energy dissipation rate is improved; the bigger ratio of water cushion sudden expansion, the smaller impact of increasing energy dissipation rate. It is seen from Fig. 8, the same as the Froude number, depression angle, the width of water cushion and jet exit, the greater height of vertical drop or the smaller height of jet exit, energy dissipation rate is improved. Integrated Fig. 7 and Fig. 8 show that the sudden expansion ratio is more sensitive than the radio between the height of vertical drop and the jet outlet impacted on energy dissipation especially when the Froude number of jet outlet is larger. Therefore, if the jet by adjusting the size of the outlet to obtain a higher rate of energy dissipation, it is effective by reducing the width of the jet outlet when Froude number is larger.

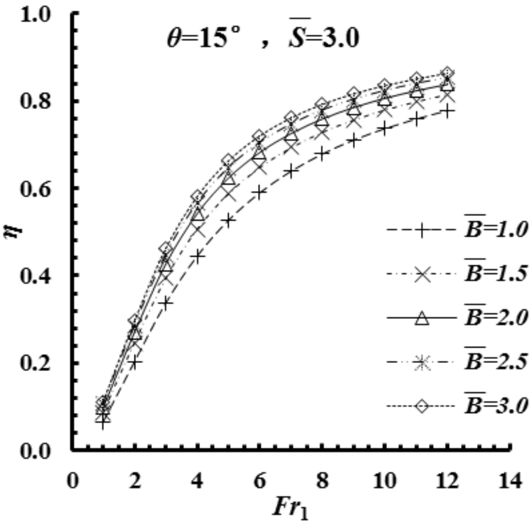

Figure 7. Relationship between Fr_1 and η in different $\overline{B}$.

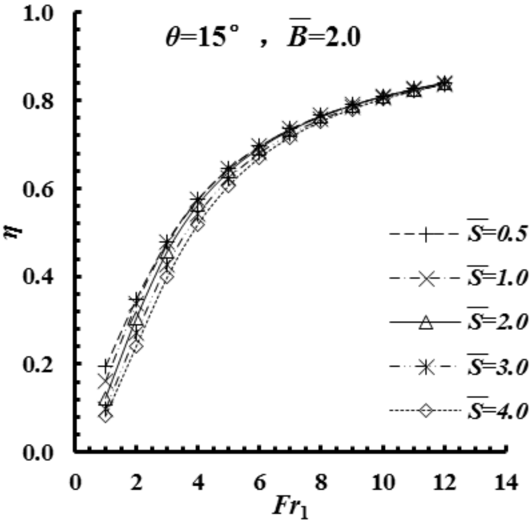

Figure 8. Relationship between Fr_1 and η in different $\overline{S}$.

5 Conclusions

Submerged jet with depression angle dived into plunge pool from the underwater surface is a new energy dissipation type, and has a complex flow structure. Hydraulic characteristics of one jet flow field were carried out in the paper.

(1) Experimental study on flow field of plunge pool results indicate that, the existing more eddies can improve the unit water energy dissipation rate, the mainstream of the dive reduces water fluctuations, and significantly reduces the near-bed velocity of plunge pool.

(2) Through theoretical analysis, calculation formulas of conjugate water depth and energy dissipation, relationships between the conjugate water depths, energy dissipation and the jet exit Froude number. Analysis showed that other things being equal to form stability submerged jump downstream water depth increases significantly with increasing Froude number, and when the depression angle less than 15° it changes little effect on downstream water depth. Under certain water depth conditions, if the formation of a stable submerged jump by adjusting the size of the jet exit, it is effective by increasing the height of jet exit when the Froude number is smaller and reducing the width of jet exit when the Froude number is larger. The sudden expansion ratio is more sensitive impacted on energy dissipation when the Froude number is larger, and therefore, it is effective by reducing the width of the jet outlet or increasing the width of water cushion to obtain a higher rate of energy dissipation.

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