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Shock waves and water wing in slit-type energy dissipaters*

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Abstract: The slit-type energy dissipater (STED) is widely used in hydraulic projects of high water head, large discharge, and narrow river valley, thanks to its simple structure and high efficiency. However, the water wing caused by the shock waves in the contraction section of the STED may bring about harmful effects. A coefficient is introduced for the application of Ippen's theory in the STED. The expression of the coefficient is experimentally obtained. Simplified formulas to calculate the shock wave angle and the water wing scope are theoretically derived, with relative errors within 5%.

Key words: Slit-type energy dissipater (STED), shock wave, water wing, hydraulic modelling

Introduction

The slit-type energy dissipater (STED) changes the trajectories of a nappe by using a contraction flip bucket[1,2]. The flow energy is greatly dissipated in this process and then the erosion of the downstream channel can be relieved[3,4]. Because of its simple structure and high efficiency, the STEDs were widely used in hydropower projects with high water head, large discharge, and narrow river valley. The energy dissipations in many large scale hydraulic projects in China, such as the Longyangxia dam[5], the Ertan dam[6], the Shuibuya dam[7], and the Geheyan dam[8] were greatly relieved by the application of the STEDs.

The STEDs were studied theoretically and experimentally from the aspects of the energy dissipation[9], the structure safety[10], the flow surface in the channel[11], the characteristics of pressure and cavitation[12], the shape of the nappe[13], and the scouring effect of the downstream riverbed[14]. Zhang and Wu (1989), Dai and Yu (1992) experimentally observed the movement and extension features of the nappe, and proposed estimated formulas for the flow profile in the contraction section. Wu et al.[15] suggested empirically the conversion conditions of the nappe forms, and experimentally investigated the behaviour of the flow choking[16]. The estimated formulas for the nappe maximum width and the locations of slit-type flip buckets were presented by Liu et al.[17]. Huang et al.[18] developed a method to calculate the dynamic water pressure in the contraction section of the STED.

As a special hydraulic phenomenon, the water wing of the STED may harm the stability of the bank and the safety of downstream buildings[19]. In the hydraulics prototype observation of the Geheyan project, it was found that, the water wing diffused transversely, and scoured the side bank slope. And the operation of the flood-releasing surface outlets on both sides was then limited. The results of the model test of the Shiubuya project indicate that, the collision of the shock waves in the contraction section causes part of the water detached from the main flow and scours the river bank. However, previous studies paid little attention to the harmful effects caused by the water wings. Hence, it is necessary to study the formation mechanism and the movement features of the shock waves and the water wings.

In the present study, physical model experiments and theoretical analyses are conducted to reveal the internal relationship between the shock wave and the movement characteristics of the water wing.

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1. Experimental set-up and methodology

The experimental set-up consists of a high pressure water tank, a sloping flume, a STED structure, and a downstream pool. The high pressure water tank is 10.0 m high to provide an adequate flow of suitable water head. Through a Plexiglas-made sloping flume the flow goes into the STED structure. The sloping flume is 3.2 m long, 0.2 m wide and 2.0 m high.

Figure 1 is the definition sketch of the flow through a STED, in which α is the bucket angles of the STED, L is the length of the contraction section, and B and b are the widths before and after the contraction section, respectively, resulting in a contraction ratio of b/B.

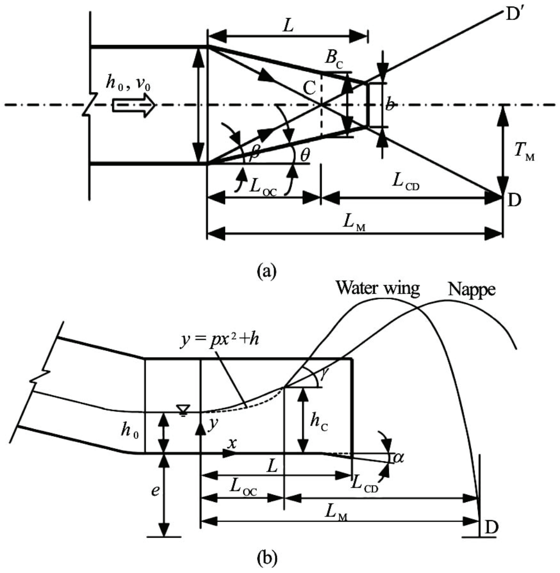

Fig.1 Definition sketch for flow through a STED

The origin of the coordinate system (x, y) is at the beginning of the STED bottom. e is the height from some base level to the bottom, C is the colliding point of the shock waves produced by the contraction sidewalls, γ is the maximum angle of the water wing to the horizontal level at the Point C, D is the position of the water wing at the base level, T_M is the distance from the Point D to the coordinate axis x, L_{OC} is the distance from the origin of the coordinate system to the Point C, and L_{CD} is the distance between C and D in the direction of the coordinate axis x, with $L_M = L_{OC} + L_{CD}$. Therefore, the scope of the water wing in the directions of the coordinate axes x and y could be expressed as L_M and T_M. h_0 and v_0 are the depth and the average velocity of the approach flow, respectively, and then we have the Froude number of the flow.

Table 1 lists the cases and geometric parameters of the STED models with various bucket angles and contraction ratios. Fr_0 varies from 4.10 to 5.90 in the present work.

Table 1 Geometric parameters of STED models

Cases	$\alpha/^\circ$	b/B	$\theta/$rad
M1	0	0.20	0.186
M2	0	0.25	0.175
M3	0	0.30	0.163
M4	5	0.20	0.186
M5	5	0.25	0.175
M6	5	0.30	0.163
M7	10	0.20	0.186
M8	10	0.25	0.175
M9	10	0.30	0.163

2. Flow observation

Figure 2 and Fig.3 show the flows in the top and side views. It could be clearly noticed that the flow is contracted transversely and extended longitudinally while passing through the STED. Especially, the shock waves occur from the beginning of the STED due to the contraction effects of the side walls. There are strong water wings over the top and the two sides of the main nappe due to the collision of the shock wave effects. Those water wings may impact the banks and then bring about harmful effects. So, it is necessary to estimate the scope of the water wings.

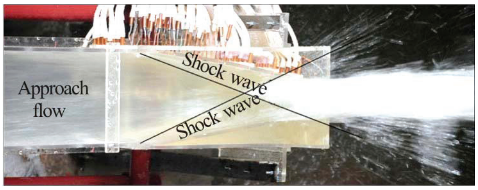

Fig.2 (Color online) Top view of flow through a STED

Fig.3 (Color online) Side view of flow through a STED

3. Shock waves

Ippen put forward an ideal shock wave theory based on the assumption of the hydrostatic pressure distribution over the depth, with the basic equations for the shock wave[20]. Figure 4 shows the plane view