PREDICTING THE FLOW VELOCITY AT THE TOE OF A LABYRINTH STEPPED SPILLWAY

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ABSTRACT: The velocity at the toe of a spillway is a major variable when designing a stilling basin. Reducing this velocity leads to reduce the size of the basin as well as the required appurtenances needed for dissipating the surplus kinetic energy of the flow. If the spillway chute is able to dissipate more kinetic energy, then the resulting flow velocity at the toe of the spillway will be reduced. Typically, a stepped spillway is able to dissipate more kinetic energy than that of a smooth surface. In the present study, the typical uniform shape of the steps has been modified to a labyrinth shape. It is logical to expect that the labyrinth shape will lead to dissipate more kinetic energy. This impression comes through creating more regions of circulation and turbulence along the lateral sides of each step in addition to those that occur towards the streamwise. This action can also reduce the jet velocities near the surfaces, thus minimizing cavitation. At the same time, the increase in circulation regions will maximize the opportunity for air entrainment, which also helps to dissipate more kinetic energy. The undertaken physical models consisted of three labyrinths of stepped spillways with magnification ratios (width of the labyrinth to width of conventional step) \(W_L/W\) are 1.1, 1.2, and 1.3 as well as testing a conventional stepped spillway \((W_L/W=1)\). Two empirical forms of the coefficient are proposed, one for labyrinth shape stepped spillway denoted \(K_L\) and another for conventional stepped spillway denoted \(K_S\). Once the value of the coefficient is known, the actual flow velocity at the toe of a stepped spillway can easily be computed without having to resort to measurements on-site. It is concluded that the spillway chute coefficient is directly proportional to the labyrinth ratio and its value decreases as this ratio increases.

Keywords: Stepped spillway; Labyrinth spillway; Energy dissipation; Labyrinth shape; Magnification ratio; Chute coefficient.

حساب سرعة الجريان عند قمة المطفح المدرج على شكل متناة

الملخص: تعتبر السرعة عند قمة المطفح من المتغيرات الرئيسية عند تصميم أحواض التسكيك. وبالتالي التقليل من تلك السرعة يعني التقليل من الحجم المطلوب لحوض التسكيك وكذلك من الملمحات الخاصة بتدد طاقة الجريان الحركية.

فهناك سبب يكمن في سطح المطفح قادر على تتبديد مقدار أكبر من طاقة الجريان الحركية، حيث ستكون سرعة الجريان الناصية عن القدمة واعدة. عموما، المطافح المدرجة لها القدرة على تتبديد طاقة الجريان الحركية أكثر من تلك ذات الأسطح المتساوية. في هذه الدراسة تم تطوير السطح المطفح المدرج بشكل مختلفة من القطاع التوقع أن يكون لكل المظهة له الفائدة على تتبديد المزيد من طاقة الجريان الحركية من خلال زيادة تداخل بين تدفق علات الجريان التي سوف تؤدي إلى المزيد من الدوامات. هذا التأثير سوف يقلل من انبعاث الجريان بالقرب من السطح وبالتالي التقليل من التيار. في هذا الوقت

زيادة مناطق الدوامات سوف تزيد من فرصة تداخل الهواء مع الجريان الذي يدوره يساعد على تتبديد المزيد من الطاقة الحركية. النموذج الفيزيائي المقترح في هذه الدراسة قد يتضمن ثلاثة نماذج لمطالعة شكل المظاهرة مع نسبة أكبر لعرض المطفح \((W_L/W)\) 1.1 و 1.2 و 1.3 بالإضافة إلى نموذج المطفح المدرج التقليدي ذو النسبة، تم اقتراح معدلين \((W_L/W)\) 1.1 و 1.2 و 1.3 بالإضافة إلى نموذج المطفح المدرج التقليدي ذو النسبة، تم اقتراح معدلين.

تتيح هذه النماذج التدفق المتغير في نموذج انماط التداخل والأخير في النموذج التقليدي. في حال معرفة قيمة المعدل

التجريبي يمكن عندنا حساب سرعة الجريان عند قمة المطفح بسهولة دون الحاجة لإجراء قياسات موقعة من خلال

النتائج يمكن القول بأن معدل المطفح قد تأتي بشكل مباشر مع نسبة الزيادة وبالتالي قيمته تقل مع زيادة في تلك النسبة.

الكلمات المفتاحية: المطفح المدرج؛ تقدير الطاقة؛ شكل المظاهرة؛ معدل المنزلق؛ نسبة التكبير.

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1. INTRODUCTION

The behaviour of flow down conventional uniform stepped spillways has been investigated both experimentally and numerically by numerous researchers. Some studies have been conducted into modifications of the conventional configuration of a stepped spillway to improve its hydraulic performance by increasing the kinetic energy dissipation and/or enhancing the resistance to cavitation. Such modifications included; inclined upward steps, installing end sills, adding baffle blocks at the downstream end of each step, turbulence manipulators and macro-roughness systems consisting of concrete blocks (Manso and Schleiss, 2002; Chanson and Gonzalez, 2004; EL-Jumaily and Al-Lami, 2009). With respect to the values of the flow velocity at the toe of the spillway, Bradley, and Paterka (1957) and more recently Zahra et al. (2015) have applied a correction coefficient, Cf to the theoretical velocity to give the actual velocity. In these studies, the hydraulic effects and the roughness along the chute of the spillway are implicitly reflected in this coefficient. Abdul-Mehdi et al. (2016) from the laboratory study which has been conducted on steps roughed by three different sizes of gravel. The authors concluded that the energy dissipation increases with the increasing the size of the gravel and the maximum percent of different sizes of gravel. The authors concluded that the energy dissipation increases with the increasing the size of the gravel and the maximum percent of different sizes of gravel. The authors concluded that the energy dissipation increases with the increasing the size of the gravel and the maximum percent of different sizes of gravel. The authors concluded that the energy dissipation increases with the increasing the size of the gravel and the maximum percent of different sizes of gravel. The authors concluded that the energy dissipation increases with the increasing the size of the gravel and the maximum percent of different sizes of gravel. The authors concluded that the energy dissipation increases with the increasing the size of the gravel and the maximum percent of different sizes of gravel.

Physical model testing was undertaken of three labyrinths stepped spillways with the labyrinth magnification ratios of $W_L/W = 1.1, 1.2, and 1.3$ as well as testing the conventional stepped spillway ($W_L/W = 1$). This study has focused on investigating the impact of the $W_L/W$ ratio on the actual flow velocity at the toe of the spillway.

2. MODELS AND PROCEDURE

Physical modelling was undertaken in a flume located at the hydraulic laboratory of the University of Technology-Baghdad. This flume has a working section 0.3m wide, 0.45m in depth and its length is 12.5m. Three physical models of the stepped spillway at chute angles, $\theta=35^o, 45^o$, and $55^o$ were adopted with a crest fixed at height 0.32m (i.e., the height of dam), these inclination angles gave ratios of step height (h) to step tread length (s), $h/s = 0.7, 1, \text{ and } 1.428$, respectively. Each inclination, four-step configurations were tested. The first was a traditional stepped spillway configuration. The other three models were labyrinth step shapes at $n=\text{ three cycles each of width equal, } \omega \text{ to give } W_L/W = 1.1, 1.2, \text{ and } 1.3$, where the lateral length of labyrinth step $W_L = n(4a+2lc)$, and $W$ is representing a lateral length of traditional step, see Fig. 1. The twelve models were divided into three groups based on the spillway angle. In all models the step rise, $h$ was kept at 0.04m, while the tread lengths were, $s = 0.057m, 0.04m, \text{ and } 0.028m$. The dimensions as illustrated in Fig.1 were selected according to the available hydraulic conditions and flume dimensions.

The flow rate was measured using an electromagnetic flowmeter, which can record flows between 0 to 30 l/s for accuracy within $\pm0.01$ l/s. Based on the limitation ten different discharges ranged between 2 l/s and 16 l/s were selected to achieve flow conditions between nappe and skimming flow regimes. For each run after the stabilizing of the flow, the depths of flow over the crest and at the toe of the spillway were recorded using a digital point gauge with accuracy $\pm0.1$mm. The Pitot tube mounted with a water manometer installed on the centre line of the flume was used to measure the velocity at the toe of the spillway for each
run. This reading is the actual velocity denoted as \( V_a \). After calibrating the Pitot tube and applying the calibration coefficient, velocity was calculated by:

\[
V_a = C\sqrt{2g\Delta h}
\]  

(1)

where \( \Delta h \) is the water level difference of the manometer and \( C=0.9 \) in this study as determined from calibration.

This actual velocity is compared with the theoretical velocity which calculated from the relationship has been published by Bradley and Paterka (1957), in the form of a chart, its ordinate based on the fall from the reservoir level to the stilling basin floor and its abscissa is the ratio of the actual velocity to the theoretical velocity at the entrance of the stilling basin (toe of spillway). Accordingly, Bradley and Paterka (1957) proposed the following formula for calculating the theoretical velocity:

\[
V_t = \sqrt{2g\left(Z - \frac{H}{2}\right)}
\]

(2)

where, \( Z \) is the vertical distance between the elevation of the head, \( H \), over the crest of the spillway and the floor level at the toe of the spillway (see Fig. 2).

The aim of the present study is to assess the functional relationship for the labyrinth coefficient \( (K_L) \) which represents the ratio of the actual velocity, \( V_a \) to the theoretical velocity, \( V_t \):

\[
K_L = \frac{V_a}{V_t}
\]

(3)

This coefficient depends on the geometrical properties of the spillway surface and the working head over the crest. The lower the value of this coefficient the greater the dissipation of kinetic energy along the surface of the spillway.

3. RESULTS AND DISCUSSION

Under conditions of skimming flows down a stepped spillway the flow rotation in the triangular area at a front of the step and on the back of the tread can have a significant impact on energy dissipation. In a conventional stepped spillway, this zone of flow rotation has the same influencing action transversely (i.e., across the width of the spillway). A labyrinth step configuration disrupts this transverse uniformity of flow. The labyrinth step shape can increase the interlocking between a streamwise recirculation as well as a secondary circulation created locally in the labyrinth cycle which definitely increases the ability to dissipate more kinetic energy.

The flow conditions and the hydraulic performance of a stepped spillway are governed by the step height, step length, and discharge (Chanson, 2002; Bose and Hager, 2003; Ohtsu et al., 2004; Khatsuria, 2005). The new concept introduced here is the labyrinth ratio, \( W_L/W \). In Fig. 3 the variation of \( K_L \) as the dependent variable under the influence of, \( H/L \) is illustrated, where \( L \) is the length of the chute (measured along the chute surface) as illustrated in Fig. 1(b). As expected \( K_L \) increases i.e., the velocity at the toe of the spillway becomes closer to the theoretical velocity, as the \( H/L \) ratio increases, wherewith increasing the head \( (H) \) over the crest at the same length of the chute \( L \) the actual velocity \( (V_a) \) at the toe definitely increased.

Figure 1. Physical model of labyrinth stepped spillway; (a) Plane view and (b) 3-D view (Maatooq and Ojaimi 2014).

Figure 2. Parameters provided for Eqn. (1) (Bradley and Paterka, 1957).
This physical point is hydraulically known for such structure through increasing the value of incoming Froude number for the hydraulic jump when it occurs just at the toe of a spillway as evident through a sketch in Fig. 1. Figure 3 illustrates the hydraulic impact of the labyrinth steps where the value of $K_L$ decreased with increasing the labyrinth ratio $W_L/W$ for any given $H/L$. This effect seems greater at higher $H/L$. This finding is also demonstrated in Fig. 4, where the labyrinth coefficient dramatically decreases as the labyrinth ratio increase for all spillway slope angles. In terms of the effect of inclination or slope angle of the spillway on the labyrinth factor, the $h/s=1.428$ ($\theta=55^\circ$) has a greater influence. The values of $K_L$ however, nearly coincide for labyrinth ratio $W_L/W=1.3$ when the spillway inclination is between $\theta=35^\circ$ and $45^\circ$ as shown in Fig. 5. In general, Fig. 5 indicates that for any given value of the labyrinth ratio, $W_L/W$ the $h/s$ does not have an effective influence on the $K_L$, but at the same time the noticeable influence was inversely proportional instead of the case with the traditional steps.

The statistical software (STATISTICA-10) was used to derive the following functional relationship based on experimental data by multiple nonlinear regression analysis with $R^2=0.921$.

$$K_L = 1.143 \left(\frac{H}{L}\right)^{0.329} \left(\frac{W_L}{W}\right)^{-0.075} \left(\frac{h}{s}\right)^{-0.228} \quad (4)$$

Equation 4 can be applied with high reliability when the rise of step to the tread ($h/s$) is ranged between 0.7 and 1.4, the labyrinth does not exceed 3-cycle, the labyrinth magnification ratio ($W_L/W$) up to 1.3, and the lower head over the crest ($H$) and its maximum value are 5% to 25% of the chute length ($L$) respectively.

Figure (6) demonstrates the relationship between the predicted values of the labyrinth coefficient based on Eqn. (4) and the observed values of this coefficient that resulted through the application of the experimental data at Eqns.1 and 2. It should note here that Eqn. (4) is solely applicable for the labyrinth shape (i.e., $W_L/W>1$).

For conventional stepped spillway, $W_L$ is equal to $W$. Thus the ratio $W_L/W$ does not have an effect on $K_L$. Since the spillway chute here is consisting of traditional steps, the coefficient should take another characterization and denote as $K_s$. In this situation the effect of two parameters $H/L$ and $h/s$ has been used in regression analysis to get the following relationship with $R^2=0.938$;

$$K_s = 1.491 \left(\frac{H}{L}\right)^{0.449} \left(\frac{h}{s}\right)^{-0.174} \quad (5)$$
4. CONCLUSION

The velocity at the toe of a spillway is a major variable when designing a stilling basin. Reducing this velocity reduces the required size of a stilling basin with dissipator appurtenances which usually need to dissipate the surplus energy of the flow. If the spillway chute is able to dissipate more kinetic energy then the resulting flow velocity at the toe of the spillway will be reduced. Typically stepped spillway is able to dissipate more kinetic energy than a smooth chute. In the present study, the uniform shape of the steps in a spillway has been modified and a labyrinth shape has been adopted. Physical models of three labyrinth stepped spillways with magnification ratios of $W_{L}/W > 1$, where $W_{L}$ and $W$ are the widths of the labyrinth step and the spillway, respectively, have been used for experimental work as well as a conventional stepped spillway at which $W_{L}/W = 1$.

The experimental results show the significant and direct effect of the labyrinth configuration on decreasing the values of flow velocity at the toe of the spillway. The aim of the experimental work is to establish a simple empirical formula to facilitate the calculation of the flow velocity at the toe of the spillway. Consequently, two empirical forms of the coefficient are proposed, one for labyrinth shape stepped spillway denoted $K_{L}$ and another for conventional stepped spillway denoted $K_{S}$. Once the value of the coefficient is known the actual flow velocity at the toe of a stepped spillway can easily computing by using Eqn. (2). It should be noted that the labyrinth coefficient calculated by Eqn. (4) has practical limitations such as the labyrinth cycle and the magnification ratio do not exceed 3 and 1.3 respectively along the head over the crest do not exceed the 0.25L. These boundary conditions are established to further researches to expand the scope of applicability.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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