Bottom pressure characteristics in a stilling basin downstream of a stepped spillway for two chute slopes

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ABSTRACT

In the last decades numerous stepped spillways were built, mostly on the downstream face of roller compacted concrete (RCC) dams. Stilling basins are often used as an energy dissipater. Although the hydraulics of stepped chutes was extensively investigated in the last decades, only fragmentary information is available on the hydraulic characteristics of stilling basins preceded by stepped chutes. Therefore, an experimental campaign was performed on a large-scale physical model of a stepped chute with adjustable slope terminating in a plain stilling basin, to study the effect of stepped chute approach flows on the hydraulic features in the basin. Experiments were conducted for two chute slopes and various discharges. Results on the basin flow features as tailwater depths, dynamic bottom pressures as well as roller and jump length characteristics are presented and discussed, focusing on the effect of stepped chute slope on the basin bottom pressure characteristics. The results show that increasing the chute slope from 30° to 50° pronounces the bottom mean, fluctuating and extreme pressures up to approximately one tailwater depth downstream of the jump toe. For 50° sloping stepped chutes, the extreme pressure coefficients reached up to about 3 times the values reported in literature for smooth chutes.

Keywords: stepped spillway, hydraulic jump, stilling basin, dynamic bottom pressures.

1. INTRODUCTION

The introduction of roller compacted concrete (RCC) in the 1980s increased the number of stepped spillways worldwide. The use of such construction technique leads to a stepped downstream dam face that, if used as spillway, enhances the energy dissipation and thereby reduces the residual energy to be dissipated in the terminal energy dissipator (typically a stilling basin), as compared to conventional smooth spillways. Stepped chute hydraulics was extensively investigated in the last decades, for example by Amador et al. (2006, 2009), André (2004), Boes (2000), Boes and Hager (2003a, b), Bung (2011), Chanson (1994), Chanson and Toombes (2002), Felder and Chanson (2016), Hunt et al. (2014), Kramer and Chanson (2018), Matos (2000), Matos and Meireles (2014), Meireles and Matos (2009), Meireles et al. (2012), Pfister and Hager (2011) and Zhang and Chanson (2017). Few studies investigated the hydraulic behavior of stilling basins downstream of stepped chutes, despite its vital role for a safe flood conveyance and associated energy dissipation. Most of these studies focused on characterizing macro flow properties, such as mean bottom pressures, energy dissipation and tailwater requirements for stilling basins with or without appurtenances (e.g., Bung et al. 2012, Cardoso et al. 2007, Frizell et al. 2016, Frizell and Svoboda 2012, Meireles et al. 2005, 2010). These studies, among others, reported high mean bottom pressure heads in the vicinity of the jump toe and the independence of the step height or chute blocks on the mean bottom pressure development. The dynamic bottom pressure characteristics of a plain stilling basin was studied by Novakoski et al. (2017a, b) and Stojnic et al. (2019). They revealed that stepped chute approach flows pronounce extreme and fluctuating pressures in the vicinity of the jump toe and reported up to 75% higher extreme pressure coefficients as compared to magnitudes reported in literature for smooth chute spillways (Stojnic et al. 2019). In spite of these advances, there is limited information available on the dynamic pressures acting on the stilling basin bottom, essential for the design of slabs, joints and the evaluation of cavitation risk.
2. EXPERIMENTAL FACILITY AND INSTRUMENTATION

Experiments were conducted in a stepped spillway model at the Laboratory of Hydraulic Constructions (LCH) of the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. The spillway model comprised a (Figures 1 and 2):

- jet-box serving as a chute inlet (Schwalt and Hager 1992),
- prismatic 0.5 m wide stepped chute channel with adjustable slope, and
- horizontal and prismatic 0.5 m wide stilling basin channel.

The stepped chute channel consisted of aluminum and glass sidewalls, and folded stainless-sheet steps of height \( s = 0.06 \) m as bottom. Two chute slopes were tested, namely \( \phi = 30^\circ \) and \( 50^\circ \) with 5.9 m and 4.8 m long chutes, respectively. The stepped chute channel was followed by a 6.0 m \( (\phi = 30^\circ) \) or 6.5 m \( (\phi = 50^\circ) \) long stilling basin built with thick aluminum plates as bottom and transparent sidewalls for flow observation. A flap gate installed at the channel end allowed for tailwater depth control (Figure 2).

An electromagnetic flowmeter ABB FXE 400 (Switzerland) measured the discharge \( Q \). The flowmeter can measure up to \( Q_{\text{max}} = 0.667 \) m\(^3\)/s with an accuracy of \( \pm 0.005 Q \) for discharges above \( 0.07 Q_{\text{max}} \).

The flow conditions at the stepped chute end (i.e., the approach flow conditions of the stilling basin) were obtained from local air concentration \( C \) and velocity \( V \) measurements performed with a fiber-optical phase detection system manufactured by RBI (France). The fiber-optical probe (FOP) consisted of two in-line optical fibers with a streamwise tip distance of 1.2 mm. The air-water flow measurements were performed in the chute centerline, perpendicular to the pseudo-bottom. Three profiles at step edges close to the chute end were considered, namely at step edges 2, 3 and 4 for the \( 30^\circ \) sloping chute and at step edges 3, 4 and 5 for the \( 50^\circ \) sloping chute (Figure 2). At each profile, the local air concentration and velocity was collected in 15 to 20 points with a sampling duration of 30 s and an acquisition rate of 1 MHz.

An ultrasonic distance sensor (US) Baumer UNAM 30U9103/S14 (Switzerland) measured the flow depths along the stilling basin (Figure 2). The US sensor had a measuring range of \( 0.1 \) to 1.0 m with an accuracy better than 0.005 m. The US sensor was fixed on an automatic positioning system (APS) moving with an accuracy of \( 0.1 \) mm (Figure 2). The distance between the sensor head and the time-averaged water surface elevation ranged between 0.32 m and 0.66 m. The flow depth measurements were performed at 24 points along the basin channel centerline ranging between \( 0.2 \) m \( \leq x \leq 4.8 \) m. Each point was sampled for 328 s at a rate of 12.5 Hz.

Dynamic bottom pressures along the stilling basin were collected using sixteen Keller series 25 (Switzerland) pressure transmitters installed in the stilling basin bottom (Figure 2). The locations of the pressure transmitters are shown in Table 1. The transmitters had a measuring range of \( \pm 1.0 \) bar with an accuracy better than 0.1% FS. The measurements were performed simultaneously over 393 s at a rate of 1 kHz.
The flow depth and bottom pressure measurements along the stilling basin were performed with the hydraulic jump toe positioned at the intersection of the chute pseudo-bottom and the stilling basin invert by adjusting the tailwater level (i.e. by controlling the flap gate, Figure 2).

Table 1. Streamwise position of the pressure transmitters at the stilling basin centreline (Figure 2).

<table>
<thead>
<tr>
<th>No</th>
<th>x [m]</th>
<th>No</th>
<th>x [m]</th>
</tr>
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<tr>
<td>P1</td>
<td>0.010</td>
<td>P9</td>
<td>1.260</td>
</tr>
<tr>
<td>P2</td>
<td>0.135</td>
<td>P10</td>
<td>1.510</td>
</tr>
<tr>
<td>P3</td>
<td>0.260</td>
<td>P11</td>
<td>1.760</td>
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<tr>
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<td>P12</td>
<td>2.010</td>
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<tr>
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<td>0.510</td>
<td>P13</td>
<td>2.510</td>
</tr>
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<td>0.635</td>
<td>P14</td>
<td>2.760</td>
</tr>
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<td>0.760</td>
<td>P15</td>
<td>2.010</td>
</tr>
<tr>
<td>P8</td>
<td>1.010</td>
<td>P16</td>
<td>4.010</td>
</tr>
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</table>

3. TEST PROGRAM AND INFLOW CONDITIONS

The experimental campaign included the six tests listed in Table 2. The unit discharge \( q \) was varied between \( 0.204 \text{ m}^2/\text{s} \leq q \leq 0.364 \text{ m}^2/\text{s} \), corresponding to a range of relative critical flow depths between \( 2.70 \leq h_c/s \leq 3.97 \) with \( h_c = (q^2/g)^{1/3} \) as the critical flow depth and \( g \) as the acceleration due to gravity. For such a range of unit discharges, the stepped chute operated in the skimming flow regime. The most downstream measured section at the stepped chute end (i.e. step edge 2 or 3 for 30° or 50° sloping chute, respectively) was defined as inflow section for the stilling basin analysis (section 1-1, Figure 2). The depth averaged air concentration at the inflow section was (Wood 1983):

\[
C_i = \frac{1}{y_{90}} \int_{0}^{y_{90}} Cdy
\]

with \( y_{90} \) as characteristic flow depth defined at \( y(C = 0.90) \).
The equivalent clear water parameters derived from the air concentration measurements at the inflow section were computed and used for the stilling basin analysis. They include: (1) the inflow equivalent clear water depth $h_1 = (1-C_1) y_{90}$, (2) the inflow mean velocity $V_1 = q / h_1$, (3) the inflow Froude number $F_1 = V_1 / (h_1 g)^{0.5}$, (4) the inflow Reynolds number $R_1 = (V_1 h_1) / \nu$ and (5) the inflow Weber number $W_1 = (\rho V_1^2 h_1) / \sigma$, where $\rho$ is the water density, $\nu$ is the kinematic viscosity of water and $\sigma$ is the water surface tension.

The measured air concentration profiles at the step edges close to the chute end are plotted against the dimensionless vertical coordinate $y / y_{90}$ in Figure 3a and b for 30° and 50° sloping chutes, respectively. The air concentration profiles for 30° sloping stepped chutes were practically invariant with distance, indicating quasi-uniform flow conditions at the stepped chute end (Figure 3a). The measured values of the depth-averaged air concentration at the inflow section of $0.41 \leq C_1 \leq 0.42$ were in close agreement with the quasi-uniform values of $0.42 \leq C_u \leq 0.44$ reported by Takahashi and Ohtsu (2012) for the same stepped chute slope and relative critical flow depth range (Table 2).

Table 2. Test program.

<table>
<thead>
<tr>
<th>Run</th>
<th>$\phi$ [°]</th>
<th>$q$ [m²/s]</th>
<th>$h_i/s$</th>
<th>$C_1$</th>
<th>$h_1$ [m]</th>
<th>$V_1$ [m/s]</th>
<th>$\alpha$</th>
<th>$F_1$</th>
<th>$R_1 \times 10^4$</th>
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<td>1</td>
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<td>0.204</td>
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<td>0.42</td>
<td>0.048</td>
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<td>6.2</td>
<td>2.04</td>
<td>109</td>
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<tr>
<td>2</td>
<td>30</td>
<td>0.284</td>
<td>3.36</td>
<td>0.42</td>
<td>0.058</td>
<td>4.91</td>
<td>1.18</td>
<td>6.5</td>
<td>2.84</td>
<td>138</td>
</tr>
<tr>
<td>3</td>
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<td>0.362</td>
<td>3.95</td>
<td>0.41</td>
<td>0.066</td>
<td>5.35</td>
<td>1.18</td>
<td>6.6</td>
<td>3.62</td>
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</tr>
<tr>
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<td>50</td>
<td>0.205</td>
<td>2.71</td>
<td>0.55</td>
<td>0.041</td>
<td>4.95</td>
<td>1.18</td>
<td>7.8</td>
<td>2.05</td>
<td>118</td>
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<tr>
<td>5</td>
<td>50</td>
<td>0.284</td>
<td>3.36</td>
<td>0.53</td>
<td>0.051</td>
<td>5.52</td>
<td>1.19</td>
<td>7.8</td>
<td>2.84</td>
<td>147</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>0.364</td>
<td>3.97</td>
<td>0.50</td>
<td>0.061</td>
<td>5.96</td>
<td>1.19</td>
<td>7.8</td>
<td>3.64</td>
<td>173</td>
</tr>
</tbody>
</table>

Although the air concentration profiles of the 50° stepped chute end were quasi-similar (Figure 3b), the shape of the profiles suggested that quasi-uniform flow conditions were not precisely attained for all test runs (Table 2). Note that the quasi-uniform depth-averaged air concentration for the same chute slope and relative critical depth range is about $C_u \approx 0.57$ according to Takahashi and Ohtsu (2012).

In Figure 3, the air concentration profiles are compared to the advection diffusion model proposed by Chanson and Toombes (2002), showing a good agreement with an underestimation in the lower half and a slight overestimation in the mid of the profile. The dimensionless velocity $V / V_{90}$ profiles at the 30° and 50° sloping chute end are shown in Figure 4a and b, respectively. They tended to follow a power law equation:

$$\frac{V}{V_{90}} = \left(\frac{y}{y_{90}}\right)^N$$

for $y / y_{90} \leq 1$

with $N = 5.5$ ($R^2 = 0.87$, Figure 4a) and $N = 4.9$ ($R^2 = 0.91$, Figure 4b) for 30° and 50° sloping chutes, respectively.

Figure 3. Air concentration profiles at the stepped chute end for (a) 30° chute slopes and comparison with the advective diffusion model of Chanson and Toombes (2002) with $C_1 = 0.41$ (b) 50° chute slopes and comparison with the advective diffusion model of Chanson and Toombes (2002) with $C_1 = 0.50$ and $C_1 = 0.55$. 
For the tested range of $R_i$ and $W_i$ (Table 2), scale effects in terms of air concentration and velocity for stepped chute flow are expected to be small, as stated by Boes and Hager (2003b) and Pfister and Chanson (2014). Moreover, scale effects for the stilling basin flow are expected to be negligible, given that the tests were conducted for $R_i \geq 2.04 \times 10^5$ (Chanson and Chachereau 2013; Chanson and Gualtieri 2008; Murzy and Chanson 2008).

4. TAILWATER DEPTH AND ROLLER LENGTH

Figure 5 shows the streamwise development of time-averaged flow depths $\eta$ along the stilling basin from the ultrasonic distance sensor. The flow depths rapidly increased in the streamwise direction, reaching a maximum in the bulking zone of the flow, herein defined as a roller length $L_R$ (e.g., at $x = 2.0$ m for Run 1, Figure 5). Further downstream, the mean flow depths decreased due to the intense flow de-aeration, attaining quasi-constant tailwater magnitudes $h_2$. As expected, the higher approach flow Froude number $F_1$ at the 50° stepped chute end, as compared to 30° stepped chute, led to higher flow depths along the stilling basin for a similar unit discharge $q$.

The measured flow depth ratios $h_2/h_1$ are plotted against the approach flow Froude number $F_1$ in Figure 6 (full symbols) and compared with the solution of the momentum equation for hydraulic jumps:

$$\frac{h_2}{h_1} = 0.5 \left( \sqrt{1 + 8F_1^2} - 1 \right)$$  \hspace{1cm} (3)

showing a good agreement for all tests.
Accordingly, for identical approach Froude number, the sequent depth ratio is practically independent of the approach flow conditions. These results strengthen the conclusions outlined in Stojnic et al. (2019), that the use of equivalent clear-water parameters at the stepped chute end results in a good prediction of the sequent depth ratio using the momentum principle.

The measured dimensionless roller lengths $L_R/h_2$ are also shown in Figure 6 (open symbols). They were independent of the approach flow conditions or chute slope i.e. inflow Froude number $F_1$ with a typical value of $L_R \approx 5.0h_2$.

![Figure 6](image)

**5. BOTTOM PRESSURE CHARACTERISTICS**

Dynamic pressures are random in nature. They are usually described with the following statistical parameters (Abdul Khader and Elago 1974; Fiorotto and Rinaldo 1992; Lopardo et al. 1982; Lopardo and Romagnoli 2009; Pinheiro 1995; Toso and Bowers 1988): (1) mean (time-averaged) pressure $p_m$, (2) fluctuating pressure characterized by its standard deviation $p'$, (3) extreme maximum pressure $p_{max}$, (4) extreme minimum pressure $p_{min}$, (5) skewness defined as $S = \sum (p_i - p_m)^3/(n(p')^3)$ where $p_i$ is the pressure at a given instance and $n$ is number of samples, and (6) excess kurtosis defined as $K = \sum (p_i - p_m)^4/(n(p')^4) - 3$. Herein, the dynamic pressures were analyzed on the basis of the following dimensionless pressure coefficients: (1) mean coefficient $P_m = (p_m - h_1)/(h_2 - h_1)$, (2) fluctuation coefficient $C_{p'} = p'/(aV_1^2/(2g))$ where $a$ is the kinetic energy correction coefficient (Table 2), (3) extreme maximum coefficient $C_{p_{max}} = (p_{max} - p_m)/(aV_1^2/(2g))$ and (4) extreme minimum coefficient $C_{p_{min}} = (p_m - p_{min})/(aV_1^2/(2g))$. The streamwise pressure coefficients, skewness and kurtosis are plotted in Figure 7 against the normalized streamwise coordinate $x/h_2$ for all tests.

The streamwise development of the mean pressure coefficient $P_m$ downstream of the 50° stepped chutes (black symbols, Figure 7a) and of the 30° stepped chutes (open symbols, Figure 7a), indicate three flow zones (Stojnic et al. 2019):

1. **impact zone** along $0 < x/h_2 < 1.3$, characterized by pronounced mean bottom pressure coefficients due to the impact and curvature of the flow
2. **transition zone** along $1.3 < x/h_2 < 7$, where mean bottom pressure coefficients qualitatively follow the dimensionless mean flow depths $Z = (\eta - h_1)/(h_2 - h_1)$, and
3. **tailwater zone** along $x/h_2 > 7$, where mean bottom pressures are practically hydrostatic.
Figure 7. Streamwise development of (a) dimensionless mean pressure coefficient $P_m$ compared to dimensionless flow depth $Z$, (b) pressure fluctuation coefficient $C_P'$, (c) extreme maximum pressure coefficient $C_P^{\text{max}}$, (d) extreme minimum pressure coefficient $C_P^{\text{min}}$, (e) skewness $S$, and (f) excess kurtosis $K$.

From Figure 7a, an effect of the chute slope on the mean pressure coefficient is noticeable within the impact zone, i.e. $0 < x/h_2 < 1.3$. The streamwise position of maximum mean pressure coefficients after $50^\circ$ stepped
chutes occurred further downstream, i.e., at $x/h_2 \approx 0.2$, as compared to that after 30° stepped chutes, i.e., at $x/h_2 = 0$. The relative downstream shift of the maximum mean pressure position after 50° sloping stepped chutes can be explained by the smaller impact area of the internal jet, typical of stepped chute flows, close to the jump toe. As observed by Takahashi and Ohtsu (2012), the impact region of the internal jet decreases with increasing chute slope. Therefore, in case of the 30° sloping chutes, a major portion of the approaching flow is “deflected” towards the inner part of the most downstream step cavity (i.e. upstream of the first pressure transmitter P1, see Figure 2) resulting in a concentrated impact at the jump toe, i.e. at $x/h_2 = 0$. On the other hand, for the 50° chutes, only a small portion of the flow impacts near the jump toe (i.e. fictitious step edge) resulting in a flow curvature. The mean pressures coefficients reached a local minimum at $x/h_2 \approx 0.2$ for 30° and 50° sloping chutes, respectively, up to 55% higher $P_m$ values were observed after 50° chutes due to the higher angle of the impact. Further downstream, the mean pressure coefficients after 50° chutes reduced in a similar manner as after 30° chutes, however with higher magnitudes caused by the stronger flow curvature. The mean pressures coefficients reached a local minimum at $x/h_2 \approx 1.3$, where the flow curvature diminished, beyond which they coincided with the 30° chute approach flow magnitudes along the remaining stilling basin reach, i.e., in the transition and tailwater zones. The influence reach of the flow curvature was thus somewhat longer after 50° chutes, i.e. $x/h_2 \approx 1.3$, as compared to that after 30° chutes, i.e. $x/h_2 \approx 1.0$ (Figure 7a).

If comparing the streamwise fluctuating and extreme pressure coefficient development (Figure 7b to d), then a major effect of chute slope is noticeable at the flow impact zone. The extreme and fluctuating pressure coefficients after 50° stepped chutes increased downstream of the jump toe and reached maximum values at the flow impact point, i.e. $x/h_2 \approx 0.2$. At this point, up to two times higher fluctuating and extreme pressure coefficients were observed, as compared to 30° chutes at the jump toe, with values reaching up to $CP' \approx 0.15$, $CP_{\max} \approx 1.2$ and $CP_{\min} \approx 0.6$. The latter extreme pressure magnitudes are up to approximately 2 and 3 times higher than the highest $CP_{\min}$ and $CP_{\max}$ magnitudes reported by Tosso and Bowers (1988) for smooth chute approach flows, respectively. Apart of the flow impact point, the 50° chutes tended to pronounce the $CP'$ and $CP_{\max}$ magnitudes at the jump toe with up to 30% and 60% higher magnitudes, respectively, as compared to 30° chutes (Figure 7b and c). The $CP_{\min}$ magnitudes at the jump toe were mostly independent of the chute slope (Figure 7d). Downstream of the flow impact point, i.e. within $0.2 \leq x/h_2 \leq 1.0$, the extreme and fluctuating pressure coefficients for 50° sloping chutes decreased and reached the 30° sloping chute magnitudes at $x/h_2 \approx 1.0$ (Figure 7b to d). Further downstream, i.e. $x/h_2 \geq 1.0$, the extreme and fluctuating pressure coefficients were mostly independent of the chute slope and monotonically decreased reaching quasi-constant tailwater magnitudes at $x/h_2 \approx 7.0$ for $CP'$ and $CP_{\max}$ (Figure 7b and d), and $x/h_2 = 6.0$ for $CP_{\min}$ (Figure 7c).

Within the flow impact zone, i.e. $0 < x/h_2 < 1.3$, higher skewness and excess kurtosis values were observed after 50° sloping chutes, as compared to those after 30° sloping chutes, due to the stronger flow curvature (Figure 7e and f). Further downstream, i.e. $x/h_2 > 1.3$, these values were mostly independent of the chute slope. At $x/h_2 = 3.5$, the skewness coefficients attained negative values indicating the detachment of the bottom jet flow (Lopardo et al. 1982; Lopardo and Henning 1985). Further downstream, the skewness coefficients further decreased and reached minimal values at $x/h_2 = 5.0$, irrespective of the chute slope, in line with the roller length measurements (Figure 6). The skewness and excess kurtosis coefficients attained zero values in the tailwater zone, i.e., at $x/h_2 > 7.0$.

Based upon the present data, it can be concluded that the influence reach of the hydraulic jump on the bottom pressure characteristics is within $x/h_2 \leq 7.0$, irrespective of the chute slope $\varphi$ (Figure 7). Accordingly, the hydraulic jump length and thus the required bottom protection length (i.e. the stilling basin length) is independent of the chute slope with a value of about $L_J = 7h_2$. These results further support the observations made in Stojnic et al. (2019) that hydraulic jumps initiated with stepped chute approach flows are approximately 17% longer as compared to those initiated downstream of conventional smooth chute spillways, i.e. $L_J \approx 6h_2$ as recommended by Peterka (1958).

6. CONCLUSIONS

The present study investigated the effect of the bottom slope of stepped chutes on the hydraulic characteristics of a plain stilling basin. Physical modelling was conducted using a relatively large-scale facility of a plain stilling basin preceded by a 30° or 50° sloping stepped chute. The experimental campaign included six test runs with stepped chute operating in the skimming flow regime. Tailwater depth, bottom pressure and length characteristics were investigated. The special emphasis was put on the effect of the stepped chute slope on the bottom pressure characteristics.
The following conclusions can be drawn:

- The use of equivalent clear-water parameters at the stepped chute end leads to a good prediction of the conjugate depth ratio using the classical momentum principle, irrespective of the chute slope.
- The roller length is mostly independent of the approach flow conditions or the stepped chute slope with a typical value of \( L_R = 5h_2 \).
- Increasing the stepped chute slope from 30° to 50° pronounces mean bottom pressures within a length approximately equal to one tailwater depth downstream of the jump toe, due to the stronger flow curvature.
- Increasing the stepped chute slope from 30° to 50° magnifies the extreme and fluctuating pressure coefficients within a length approximately equal to one tailwater depth downstream of the jump toe. For 50° sloping stepped chutes, the extreme pressure coefficients can reach up to approximately 3 times higher magnitudes compared to reported literature values for smooth chute spillways of a similar chute slope.

The present observations strictly apply to skimming flow conditions for moderate to steep stepped chutes (i.e. 30° ≤ \( \varphi \) ≤ 50°) for relative critical depths ranging between \( 2.70 \leq h_c/s \leq 3.97 \).

7. ACKNOWLEDGMENTS

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8. REFERENCES


