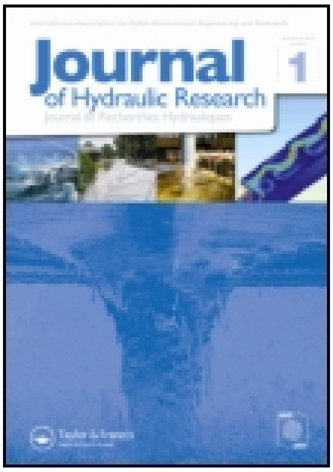

Journal of Hydraulic Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tjhr20

Experimental study on time-averaged pressures in stepped spillway

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Published online: 03 Apr 2012.

Journal of Hydraulic Research Vol. 50, No. 2 (2012), pp. 236–240
http://dx.doi.org/10.1080/00221686.2012.666879

Technical note

Experimental study on time-averaged pressures in stepped spillway

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ABSTRACT
Steps located in the non-aerated flow region of a chute are prone to cavitation damage. Two models operated with various Froude numbers and bottom slopes were employed to measure the pressure on the steps. The minimum and maximum pressures on the horizontal step surfaces occurred at the chute beginning and at the chute end, respectively. These characteristics were also found in the fully-developed flow region. The time-averaged pressure on the horizontal step surfaces is negative at the chute start, and then becomes positive along the flow direction in the non-uniform flow region. On the vertical step surfaces, the pressure is always negative at the top and remains negative along the entire vertical surface if the unit discharges are high enough in the non-uniform flow region. These results differ from the pressure characteristics in the uniform aerated flow region.

Keywords: Experimentation; flow pattern; non-aerated flow; pressure characteristic; stepped spillway

1 Introduction

Stepped spillways are used as energy dissipaters (Wu *et al*. 2008, Chen *et al*. 2010). High steps are prone to cavitation damage under a large unit discharge, a high water head, and a high flow velocity. The first steps located in the non-aerated flow region are particularly prone to damage (Lin and Han 2001, Pfister *et al*. 2006a, Pfister *et al*. 2006b, Zhang *et al*. 2011). Ohtsu and Yasuda (1997), Sánchez-Juny (2000), Matos and Quintela (2000), Tian *et al*. (2005), Li (2005), and Zhang *et al*. (2003) performed experimental investigations on the time-averaged pressure characteristics in the fully-developed flow region, referred to as the uniform aerated flow region herein. It was found that the time-averaged negative pressures appeared at the top of vertical surfaces and that a positive pressure appeared on the horizontal step surfaces. Chen *et al*. (2002) simulated the flow on the chute surfaces with the volume of fluid (VOF) method. The results indicate that negative pressures frequently appear at the upper part of vertical surfaces, that the pressure is positive and the maximum time-averaged pressure is located at the flow impact region on the horizontal step surfaces in the fully-developed flow region. Cheng *et al*. (2006) studied the air entrainment of stepped spillway flow, using the VOF and the mixture models combined with the renormalization group κ–ε turbulence model. The pressure distribution was similar to that proposed by Chen *et al*. (2002). Sánchez-Juny and Dolz (2005, 2008) and Sánchez-Juny *et al.* (2007) found that the extreme pressures are located upstream of the inception point of the boundary layer, where the pressure varies more than in the downstream region of the fully-developed flow. A minimum air concentration of ∼approximately 5–8% is considered sufficient to avoid cavitation damage. Knowing the location of the inception point is, therefore, important to determine the non-aerated chute zone potentially prone to cavitation damage.

The characteristics of the pressure distribution have not been entirely studied in the non-aerated and non-uniform aerated flow regions of stepped chutes. Herein, an experimental study is presented to examine the pressure distribution on these regions.

Revision received 13 February 2012/Open for discussion until 31 October 2012.

ISSN 0022-1686 print/ISSN 1814-2079 online
http://www.tandfonline.com

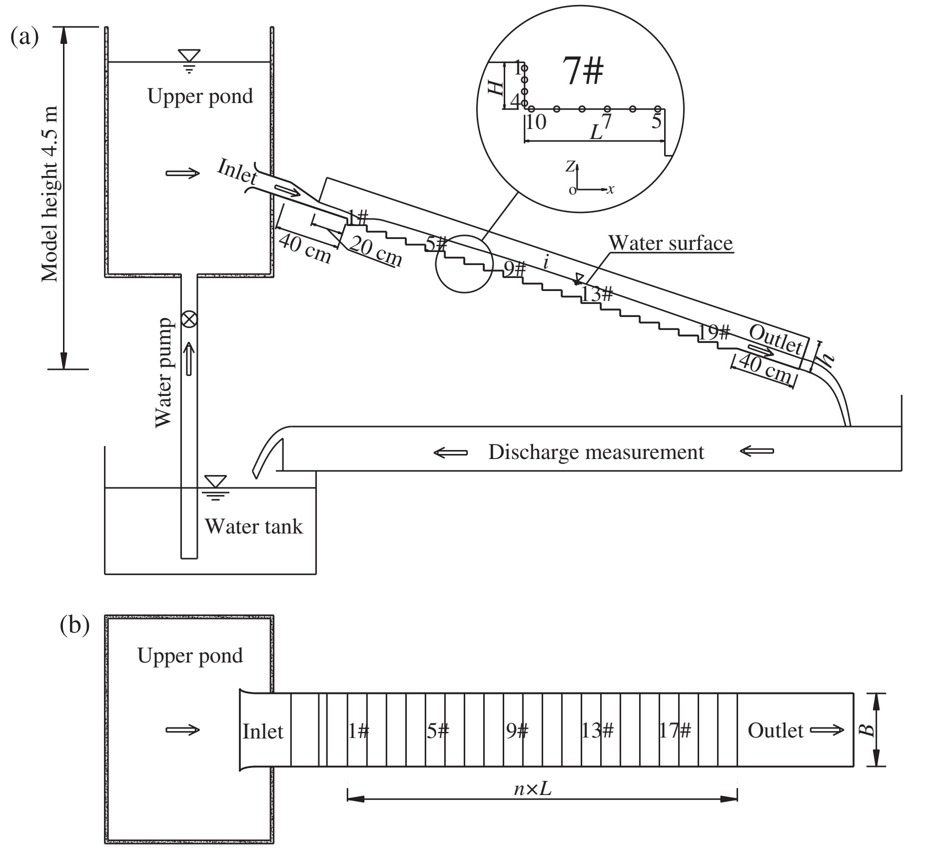

Figure 1 Experimental set-up

2 Experimental set-up

The experiments were conducted in the State Key Laboratory of Hydraulic and Mountain River Engineering, Sichuan University, Chengdu. The model consisted of an upper water tank, an inlet, a stepped chute, an outlet, and a downstream water tank. To observe the flow pattern on the steps, the model was made of Plexiglass whose roughness height was $\cong 10^{-6}$ m. The total model height was 4.5 m, and the chute width was $B = 0.15$ m. The approach flow velocity varied from 2.2 to 5.9 m/s, so that the Froude number $\mathsf{F} = V/(gh)^{1/2}$ varied from 3.5 to 9.4, and the Reynolds number $\mathsf{R} = VD_H/\nu$ varied from 57,420 to 151,200, which was large enough to suppress the wall effects. Here, V is the approach flow velocity, g the acceleration of gravity, h the approach flow depth, D_H the approach flow hydraulic diameter, and ν the kinematic water viscosity. According to the wall similarity hypothesis of Townsend (1976), the turbulence outside of the roughness sub-layer, a layer extending five roughness heights from the wall, is independent of the surface condition at sufficiently high Reynolds numbers, with 5×10^{-6} m as thickness. At high R, the viscous stresses are negligible compared with the Reynolds stresses. Near the wall, the velocity profile depends mainly upon R because of viscosity (Pope 2010). If the flow follows the quadratic resistance law, i.e. if R is large enough, viscous forces can be ignored. The pressure data were taken at the centre of the step surfaces, so that the wall effect can be considered negligible. The discharge measured by a rectangular weir varied from 88 to 234 l/s. Four or five piezometers were fixed on each vertical and horizontal step surfaces to measure mean pressures. These data were not only measured in the fully-aerated region but also in the non-fully aerated region. The model scheme is shown in Fig. 1, and the geometric and hydraulic parameters are listed in Table 1.

Table 1 Experimental details

	Geometric parameters			
Case	i	H (cm)	L (cm)	n
1	1:2	6	12	20
2	1:3	4	12	20

3 Results and analysis

3.1 *Flow pattern*

For a given stepped chute, the flow patterns for increasing discharge include nappe flow, transition flow, and skimming flow regions (Boes and Hager 2003, Chanson and Toombes 2004). In the skimming flow region, the flow behaves as a coherent stream skimming over the steps. Three different zones exist: (1) non-aerated flow region, (2) non-uniform aerated flow region, and

Table 2 Lengths (m) of non-aerated and non-uniform aerated flow regions

		Case 1		Case 2	
Q(l/s)	F	Zone I	Zone II	Zone I	Zone II
$Q_1 = 13.2$	3.51	0.35	1.08	0.41	1.12
$Q_2 = 18.0$	4.79	–	–	0.43	1.14
$Q_3 = 22.5$	5.99	0.39	1.10	0.44	1.14
$Q_4 = 24.8$	6.59	–	–	0.45	1.15
$Q_5 = 27.6$	7.34	0.43	1.13	0.46	1.17
$Q_6 = 30.6$	8.14	0.46	1.16	0.49	1.21
$Q_7 = 35.1$	9.34	0.49	1.28	0.53	1.33

(3) fully-developed flow region. The lengths of regions 1 and 2 are stated in Table 2, from where the inception point and the uniform aeration point move downstream with increasing discharge for otherwise identical geometry. Note that the first eight steps are not in the uniform-aerated flow region.

3.2 *Pressure on the horizontal step surfaces*

The time-averaged pressure distribution on the horizontal step surfaces in the non-aerated and non-uniform aerated flow regions is shown in Fig. 2, where x is the distance from the measuring points to the inner edges of the surfaces ($x/L = 0$), L the length of the horizontal step surfaces, P the time-averaged pressure, and $P_{H,\max}$ the maximum time-averaged pressure on the horizontal step surfaces. Note from Fig. 2 that the pressures show a S-shaped variation; its trend is similar to that of Sánchez-Juny *et al.* (2007). The lines give the data at step 20, whereas the other symbols give the data at steps 2–7. The latter are all located in the non-uniform flow region. The pressure distribution on the second step, which is located in the non-aerated flow region, is different from that in the uniform aerated flow region. The absolute values of the time-averaged pressures on the horizontal step surfaces increase with F. The extreme pressures on the horizontal step surfaces for Cases 1 and 2 are shown in Fig. 3. The maximum pressure occurred between $x/L = 0.75$ and $x/L = 0.80$, whereas the location of the minimum pressure on the horizontal surfaces occurred between $x/L = 0.2$ and $x/L = 0.3$, respectively. It was found that the horizontal step surfaces in the non-aerated and non-uniform aerated flow regions were subjected by negative pressure, while the mean pressure on the horizontal step surfaces was normally positive in the fully-developed flow region. Note from Fig. 3 that the maximum negative pressure increases with the discharge. There is a

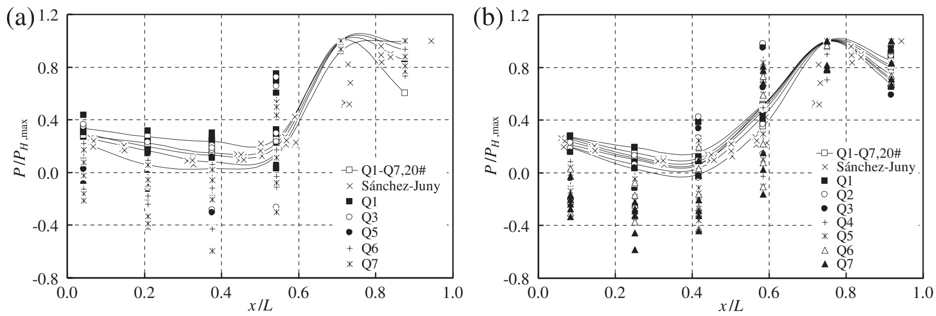

Figure 2 Pressure distribution on the horizontal step surfaces for various unit discharges: (a) Case 1 and (b) Case 2

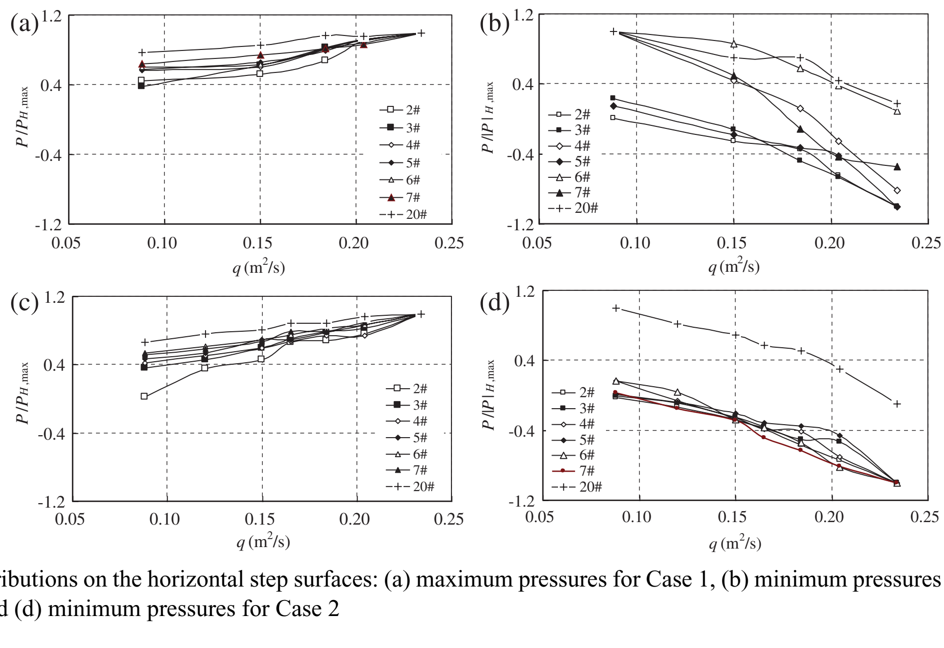

Figure 3 Pressure distributions on the horizontal step surfaces: (a) maximum pressures for Case 1, (b) minimum pressures for Case 1, (c) maximum pressures for Case 2, and (d) minimum pressures for Case 2

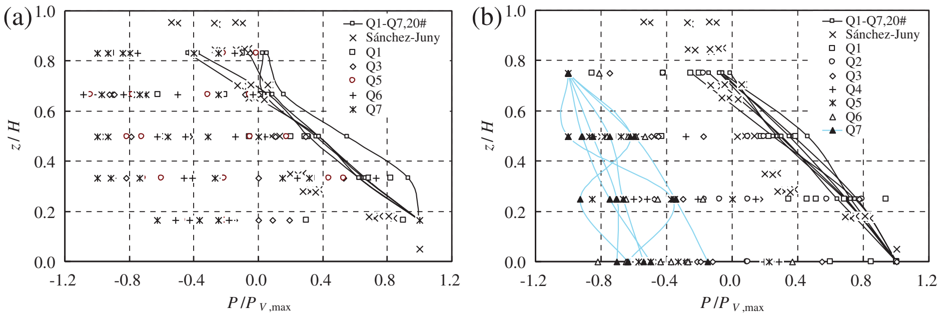

Figure 4 Pressure distribution on the vertical step surfaces for various unit discharges: (a) Case 1 and (b) Case 2

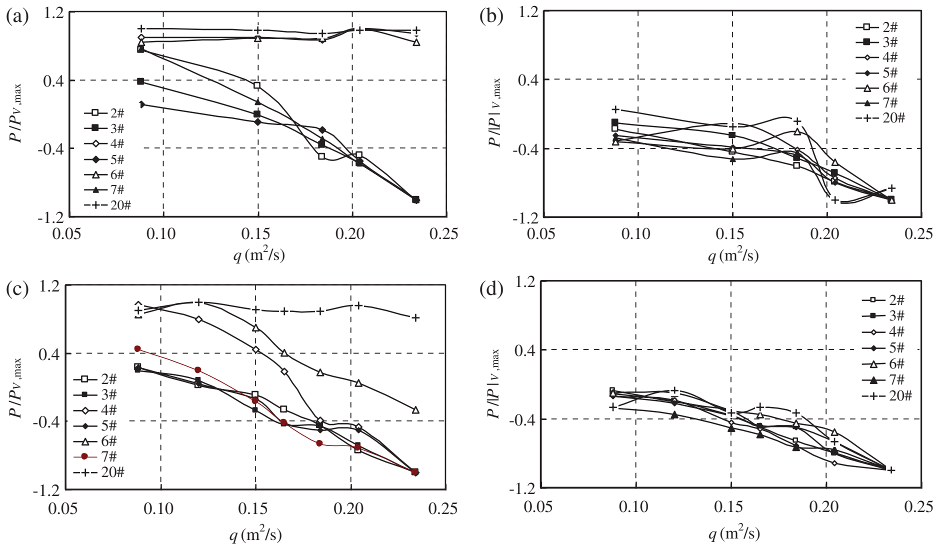

Figure 5 Pressure distributions on the vertical step surfaces: (a) maximum pressures for Case 1, (b) minimum pressures for Case 1, (c) maximum pressures for Case 2, and (d) minimum pressures for Case 2

slight change in the location of the maximum pressure on the horizontal surfaces with discharge.

3.3 *Pressure on the vertical step surfaces*

The pressure distribution on the vertical surfaces in the non-aerated and non-uniform aerated flow regions is shown in Fig. 4 for Cases 1 and 2, respectively. Here, z is the distance from the measuring points to the horizontal step surfaces, H the step height, and $P_{V,\max}$ the maximum time-averaged pressure on the vertical step surfaces. Note that the pressure on these gradually increases from top to bottom, with each step in the non-fully aerated flow region having a negative top pressure. The time-averaged pressure on these surfaces in the non-fully aerated flow region is negative as F increases, whereas the time-averaged pressure is negative and decreases as H/L increases, explaining why cavitation damage typically occurs along the first step.

The extreme pressures on the vertical step surfaces are shown in Fig. 5. Because the flow affects the bottom of the vertical step surfaces, the pressure is higher than at the top. The pressure behaviour is characterized by a boundary separation of the eddy at the top of the vertical surfaces so that negative pressures occur.

4 Conclusions

The characteristics of time-averaged pressure distributions on the step surface in the non-aerated and non-uniform aerated flow regions were studied for two bottom slopes of the stepped chutes. The following conclusions are drawn:

(1) The mean pressure on the horizontal step surfaces is positive in the uniform-aerated flow region. The minimum pressure is negative on the horizontal step surfaces in the non-uniform aerated flow region reaching from the first to the seventh step; moreover, the pressure in the non-aerated flow region is smaller than that in the developing flow region.
(2) The pressure distribution on the horizontal step surfaces shows an S-shaped variation, and the location of the maximum pressure on the horizontal step surfaces occurs towards the chute end, while the location of the minimum pressure on the horizontal surface extends over the chute start.
(3) The negative pressure increases with the unit discharge, but there was only a slight change of the maximum pressure location on the horizontal surfaces.
(4) Negative pressures occur at the top of the vertical step surfaces, increasing gradually from the top to the bottom

along the vertical surface. The time-averaged pressure in the non-uniform aerated flow region was negative over the entire vertical surface for large unit discharges.

Acknowledgements

This project was supported by the National Key Basic Research Program of China (973 Program, grant no: 2007CB714105), the Key Projects in the National Science and Technology Pillar Program (no: 2008BAB29B04), and the Program for New Century Excellent Talents in the University (grant no: NCET-08-0378) and the Science foundation of Ministry of Education of China (no: 2008108111).

Notation

B = width of chute (m)
D_H = approach flow hydraulic diameter (m)
F = approach flow Froude number (–)
g = acceleration of gravity (m/s^2)
h = approach flow depth (m)
H = step height (cm)
i = chute slope (–)
L = step length (cm)
n = total step number (–)
P = pressure on the step (Pa)
$P_{H,\max}$ = maximum time-averaged pressure on the horizontal step surfaces (Pa)
$P_{V,\max}$ = maximum time-averaged pressure on the vertical step surfaces (Pa)
q = unit discharge (m^2/s)
Q = discharge (l/s)
R = hydraulic radius (m)
R = Reynolds number (–)
V = approach flow velocity (m/s)
x = distance from measuring points to inner surface edge (m)
z = distance from measuring points to the horizontal step surfaces (m)
ν = kinematic water viscosity (m^2/s)

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