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Research paper

Cavitation characteristics of offset-into-flow and effect of aeration

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ABSTRACT
An experimental investigation of the cavitation characteristics of high-velocity flow over an offset-into-flow with various heights and chamfers b the presence and absence of aeration was conducted in a cavitation tunnel of the Hydraulics Laboratory, Zhejiang University of Technology in (The 2- and 5-mm abrupt and sloping offsets into flows were employed to be models of surface irregularities. Cavitation phenomena of high-ve flow over the various offsets were carefully observed. A range of air concentrations was considered. Variations of wall pressures downstrea upstream of the offset were measured in terms of the air concentration. The effects of air concentration and chamfer on the cavitation characte of the offsets were analysed. In addition, the cavitation cloud over the offset-into-flow and the turbulent boundary layer over a flat plate are com

Keywords: Air concentration, cavitation cloud, cavitation number, offset, wall pressure

1 Introduction

Chute or tunnel spillways for high dams involve high-velocity flow, so cavitation damage may occur if projections or depressions such as cylindrical and triangular protrusions, offsets into and away from the flow, and other irregularities during construction of flood release structures exist on the chute surface. A serious problem is cavitation damage. Hydraulic practice demonstrated that severe cavitation damage occurred even for irregularities of a few millimetres. An early case of cavitation damage was reported for Hoover Dam (Warnock 1947) within and just below its 50° vertical bend upon its initial and only operation in 1941. The velocity was as high as 45 m/s. The cavitation damage consisted of erosion of the concrete tunnel lining and underlying rock to a depth of 13.7 m and a length of 35 m, which was triggered by a bulge in the invert concrete. Another severe cavitation damage occurred in a right tunnel spillway of the Liujiaxia Hydropower Station in China (Liu 1983), arising from three 8 mm steel bars protruding on the concrete surface near the end of vertical bend of the tunnel spillway in 1972. The cavitation hole was 100 m long and 4.8 m deep.

Falvey's (1990) measurements indicate that velociti 12–20 m/s may cause cavitation damage at local irregula along spillway or chute surfaces. Shalnev (1951) investi issues of cavitation damage due to surface irregularitie blades of hydraulic turbine. His experimental data indi that cavitation was related to the relative height of an irregul to the velocity distribution within the boundary layer and thickness. Ball (1959, 1963 and 1976) experimentally in gated the hydraulic consequences of surface irregularities developed a relationship among the critical pressure, the cr velocity and its effect on cavitation inception for several ty irregularities. He suggested that a cavitation damage d irregularities may be prevented, if the cavitation number c overflow was higher than the incipient cavitation numb the irregularity. Holl (1960) made experiments on cavit inception of arc and triangular irregularities, to analyse boundary layer effect on cavitation inception. Chen (1 suggested a numerical approach to control spillway su irregularities based on his experimental data. Benson (1 investigated cavitation inception of a three-dimensional

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lated irregularity. Arndt and Ippen (1968) explored the ıracteristics of cavitation inception of an isolated irregularity both smooth and rough surfaces. Wang and Zhou (1979) ggested a numerical method to control overflow surface gularities based on the cavitation intensity using prototype ervations and model test data. Xu and Zhou (1982) analysed pressure distribution and the incipient cavitation number of and semi-arc irregularities in open-channel and pipe flows ed on the theory of complex function. Liu (1983) systemati-ly investigated the incipient cavitation number of several es of irregularities for open-channel and pipe flows, and ntified the Reynolds number and the velocity profile within boundary layer as the main effects on incipient cavitation nber. He proposed that the larger the aspect ratio of gularity was, the lower is the incipient cavitation number.

As the cavitation phenomenon is inevitable, an economic and ective measure is the aerator to force aeration within the ler-pressure cavitation zone or other locations liable to cavita-ı damage to prevent damage. Peterka (1953) investigated the chanism of cavitation control by aeration. The ratios of air to ter discharges in his tests ranged from 0.4% to 7.4%. He erved bursting and hammer-beating sounds due to cavitation, ich reduced with increasing air discharge; the cavitation noise ished completely as 7% air was supplied. Rasmussen's 56) experimental tests indicated that an air–water ratio of was sufficient to control cavitation for aluminum-alloy cimens. Colgate (1959) determined a correlation between itation inception of multiple irregularities and wall turbu-ce. Colgate and Legas (1972) applied aerators to control cavi-on for rehabilitating cavitation damage due to irregularities in ınnel spillway at the Yellowtail dam in the USA, resulting in cavitation damage after remediation by epoxy sand grout. d observations to control cavitation damage of a triangular gularity by air supply to the left and right tunnel spillways the left ski-jump spillway of flood release structures with erent overflow type, head and air concentration were conducted Deng and Ha (1988) at Wujiangdu Hydropower Station, na. The cavitation damage of a 20 mm triangular irregularity removed as the air concentration reached 1.1% and 50 mm 4.1%. Similar studies were carried out by Johnson (1963), (1983), Chai and Wu (1995), Wilhelms and Gulliver (2005), ıs *et al.* (2007), Hocevar *et al.* (2007) or Dong *et al.* (2008a, 8b). Regarding the cavitation characteristics of the offset--flow, Cai (1985) and Yuan and Zheng (1990) investigated effect of pressure fluctuation on cavitation inception. This arch aims at experimentally testing the cavitation character-s of the offset-into-flow in presence and absence of aeration.

Experimental facility and methodology

test work was carried out at the Hydraulic Research Institute, jiang University of Technology, China. The working sections ıe tunnel system consisted mainly of a rectangular contraction, and expansion sections made of stainless steel plates and processed by computer-controlled machine (Fig. 1). The dimension of working sections involved a cross-sectional area of 2×3.5 cm 50 cm long test section, the 20 cm long inflow and outflow cross-sec-tions of the contraction section of 15×15 cm^2 and 3.5×4 cm^2 and the 40 cm long inflow and outflow of the expansion sectior of 3.5×4 cm^2 and 15×15 cm^2, and observation windows Also, there was a transition between the contraction (expansion and the test sections. The surface irregularity was abrupt involvin sloping offsets-into-flow made of stainless steel processed by com-puter-controlled machinery. The offset-into-flow may be dividec into four types: 2 mm abrupt, 2 mm sloping, 5 mm abrupt anc 5 mm sloping. Locations of pressure transducers in the test sectior were −15, 15, 45, 75 and 105 mm from the leading offset edge (Fig. 2). The slope of the sloping offsets-into-flow was $\tan\theta = 1/2$.

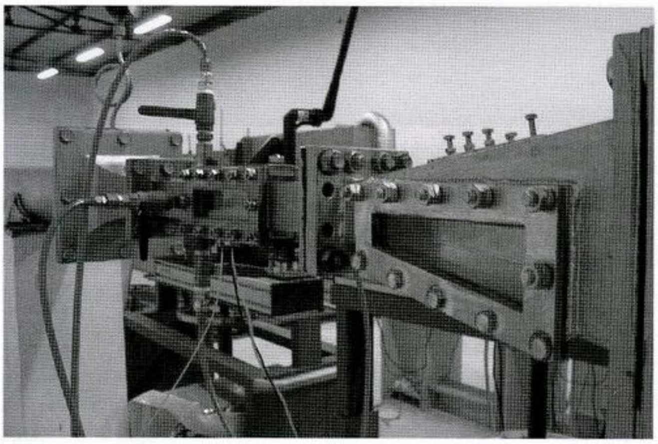


Figure 1 Experimental set-up

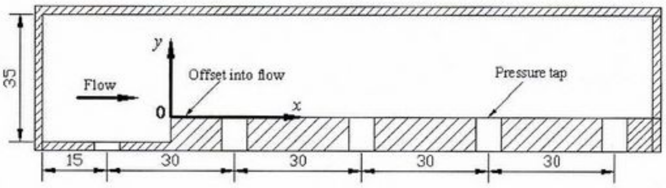
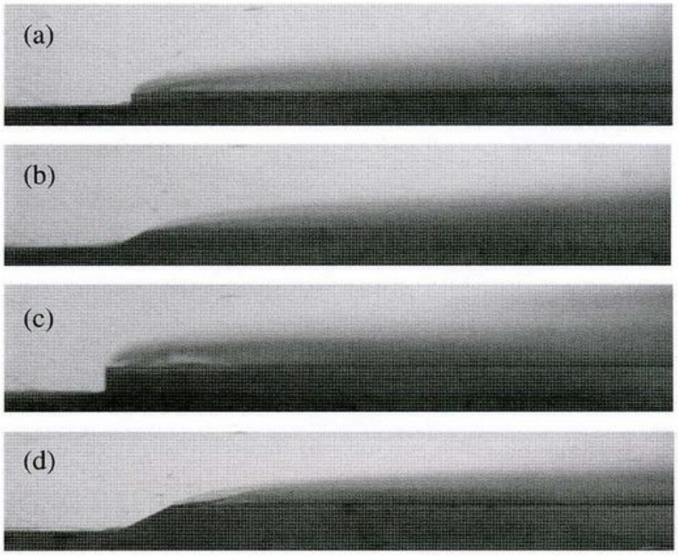


Figure 2 Locations of pressure transducers in test section of cavitatior tunnel (unit: mm)

The water discharge was measured with an UFLO2000F Ultrasonic Doppler flow meter, and the air discharge with LZB-15 and LZB-40 rotator flowmeters. MPX400D pressure transducers and the real-time data acquisition system SINO-CERA-YE6263 were used to record wall pressures. The flow velocity ranged from 36.9 to 40.3 m/s.

3 Cavitation phenomena of offset-into-flow

Cavitation phenomena of abrupt and sloping offsets-into-flow are shown in Fig. 3. Figure 3(a) and (b) shows cavitatior clouds due to the 2 mm abrupt and sloping offsets, and Fig. 3 (c) and (d) due to the 5 mm abrupt and sloping elements. Accordingly, considerable cavitation phenomena of high-velocity flow over offset-into-flow are seen to occur no matter whether the offsets are abrupt or sloping. The thickness of the



igure 3 Cavitation clouds over offsets-into-flow (a) 2 mm abrupt,) 2 mm sloping, (c) 5 mm abrupt and (d) 5 mm sloping

avitation cloud over the sloping offset was thinner than that of e abrupt of same height, especially close to the leading offset dge. As the height of the offset increases, the thickness of avitation cloud thickened (Fig. 3c and d).

Considering a cavitation cloud over an offset-into-flow as a rbulent boundary layer growth over a flat plate, the boundary yer momentum deficit thickness δ_2 can be expressed as

$$\delta_2 = \int_0^{\delta} \frac{u}{U_0}\left(1 - \frac{u}{U_0}\right)\mathrm{d}y \tag{1}$$

here u is the velocity within boundary layer, U_0 the approach ow velocity, y the vertical coordinate and δ the boundary yer thickness. Eq. (1) can also be written as

$$\frac{\delta_2}{\delta} = \int_0^{1} \frac{u}{U_0}\left(1 - \frac{u}{U_0}\right)\mathrm{d}\left(\frac{y}{\delta}\right) \tag{2}$$

The velocity distribution within a turbulent boundary layer sing the $1/7$ power law is

$$\frac{u}{U_0} = \left(\frac{y}{\delta}\right)^{1/7} \tag{3}$$

Substituting Eq. (3) into Eq. (2) gives

$$\frac{\delta_2}{\delta} = \int_0^{1}\left(\frac{y}{\delta}\right)^{1/7}\left[1 - \left(\frac{y}{\delta}\right)^{1/7}\right]\mathrm{d}\left(\frac{y}{\delta}\right) = \frac{7}{72} \tag{4}$$

Based on Blasius's (1913) formula, the wall shear stress is xpressed as

$$\tau_0 = 0.0225\rho U_0^2\left(\frac{\nu}{U_0\delta}\right)^{1/4} \tag{5}$$

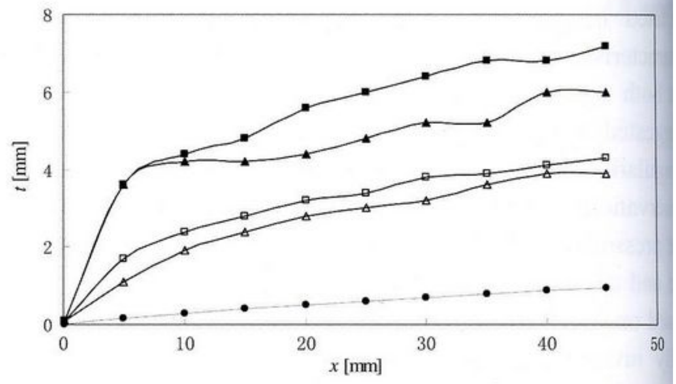


Figure 4 Comparison between cavitation cloud $t(x)$ and bound layer thicknesses for (▲) 2 (mm) abrupt, (△) 2 (mm) sloping, (■ (mm) abrupt, (□)5 (mm) sloping, (•) boundary layer thickness

where τ_0 = wall shear stress. The momentum integral equati of the flat plate boundary layer under zero pressure gradient

$$\frac{\tau_0}{\rho U_0^2} = \frac{\mathrm{d}\delta_2}{\mathrm{d}x}$$

Substituting Eqs (4) and (5) into Eq. (6) gives after integrat

$$\frac{\delta}{x} = \frac{0.37}{\mathsf{R}_x^{1/5}} \cong 9.5 \times 10^{-9}\left(\frac{1}{x}\right)$$

where $\mathsf{R}_x = U_0 x/\nu$ = Reynolds number of boundary layer. streamwise variation of the turbulent boundary layer thickr $\delta(x)$ on the smooth flat plate is obtained from Eq. (7). A comp son between the calculated boundary layer and the measured c tation cloud thickness $t(x)$ is shown in Fig. 4. It follows that thickness of the cavitation cloud is considerably larger than of the boundary layer, namely 6 to 22 and 4 to 10, respectiv times thicker than the boundary layer.

4 Measured pressure with and without aeration

The air concentration C is defined as

$$C = Q_a/(Q_a + Q_w)$$

where Q_a = air discharge (0.6 to 2.8 L/s) and Q_w = w discharge (22.8 to 28.3 L/s), respectively. The measured dat wall pressure in high-velocity flow over both the 2 mm ab and sloping offsets and the 5 mm abrupt and sloping of for C = 0.0, 2.3, 4.0, 6.0, 8.0 and 10.0% are listed in Tab Taking the 2 mm abrupt offset-into-flow for example follows that the wall pressure without aeration is positiv $x = -15$ mm, i.e. upstream from the offset. However, the pres downstream of the offset becomes negative, i.e. $p = -9$ -95.3, -92.1 kPa at x = 15, 45 and 105 mm. The maxir wall pressure drop is located close to the leading offset e The wall pressure gradually decreased with x. Further, the

Table 1 Measured pressures with and without aeration

	Wall pressure p (kPa)				
	2 mm high		5 mm high		
x (mm)	Abrupt offset	Sloping offset	Abrupt offset	Sloping offset	Air concentration C (%)
-15	250.2	248.2	255.4	260.2	
15	−97.5	−98.5	−97.5	−97.1	
45	−95.3	−96.5	−97.5	−95.4	0.0
75	−92.1	−94.0	48.1	−80.5	
105	−78.8	−90.3	50.4	−71.2	
-15	279.8	300.5	282.1	285.1	
15	−80.5	−70.6	−80.6	−70.4	
45	−73.4	−65.3	−75.3	−65.2	2.3
75	18.7	28.5	−40.4	30.6	
105	23.4	−18.1	−55.2	−22.3	
-15	319.5	315.4	324.0	316.8	
15	−60.7	−50.6	−93.5	−45.2	
45	−45.5	−45.5	−65.3	−40.5	4.0
75	40.6	50.8	30.4	60.7	
105	28.5	8.4	−65.1	10.4	
-15	351.4	330.7	356.9	361.5	
15	−40.2	−30.3	−50.2	−25.2	
45	−20.5	−15.4	−37.7	−10.4	6.0
75	60.4	85.2	10.3	95.2	
105	50.1	35.6	−37.4	32.5	
-15	370.1	374.8	373.4	380.4	
15	−20.2	−5.4	−31.5	0.0	
45	20.7	30.6	−17.2	30.5	8.0
75	100.1	110.3	40.5	102.2	
05	78.7	50.8	−28.4	48.6	
15	389.7	380.1	394.2	391.3	
15	10.3	20.5	−22.4	17.5	
45	70.2	75.4	5.3	70.2	10.0
75	150.6	115.3	65.4	120.5	
05	90.8	63.3	−17.6	58.4	

ssures downstream of the offset at x =15, 45 and 105 mm rease with air concentration.

Cavitation number of offset-into-flow

Cavitation number without aeration

: cavitation number is essentially a pressure coefficient, reflect- the effect of pressure change on the fluid property, expressed as

$$\sigma = \frac{h - h_v}{U_0^2/2g} \tag{9}$$

ere σ is the cavitation number, h the absolute pressure head, h_v saturated vapour pressure head related to the water temperature, h_v = 0.198 m water column for 17°C used in the tests.

Table 2 Cavitation numbers without aeration

	Cavitation number σ			
	2 mm high		5 mm high	
x (mm)	Abrupt offset	Sloping offset	Abrupt offset	Sloping offset
−15	0.4296	0.4168	0.5547	0.4968
15	0.0007	0.0001	0.0009	0.0015
45	0.0038	0.0019	0.0049	0.0043
75	0.0075	0.0049	0.0206	0.0251
105	0.0248	0.0097	0.0378	0.0376

The cavitation numbers downstream and upstream of t offset without aeration are shown in Table 2. It follows tl σ downstream of offset-into-flow is low almost approachi $\sigma = 0$, whereas $\sigma \cong 0.4$ upstream of the offset.

5.2 *Cavitation number of 2 mm abrupt offset-into-flow with aeration*

The cavitation number of the 2 mm abrupt offset is shown Fig. 5. It follows that σ downstream of the offset without aerati nearly tends to zero. However, the cavitation number downstrea of the offset with aeration gradually increases with the air conce tration C = 2.3, 4.0, 6.0, 8.0 and 10.0%. Note that the cavitati number downstream of the test section decreases, because tl measuring point was influenced by the expansion section. presence of aeration, the cavitation number is therefore seen first abruptly decrease and then gradually increase.

5.3 *Comparison of cavitation numbers between 2 mm slopi and abrupt offsets*

A comparison of the cavitation numbers between sloping a abrupt offsets 2 mm high is shown in Fig. 6. The differer of cavitation numbers between the 2 mm sloping and abru

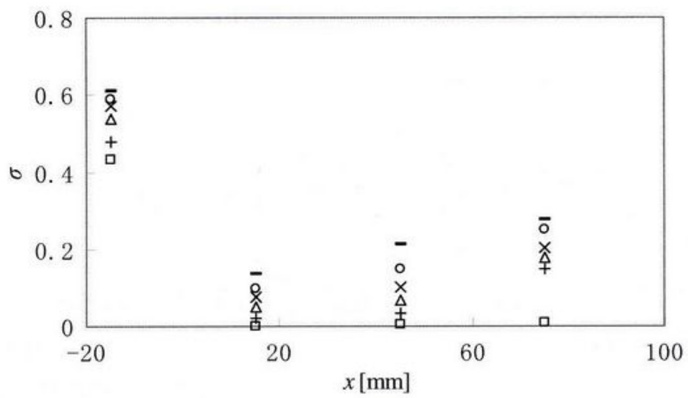


Figure 5 Cavitation number of 2 mm abrupt offset for C (%) = (□ (+) 2.3, (△) 4.0, (×) 6.0, (○) 8.0, (−) 10.0

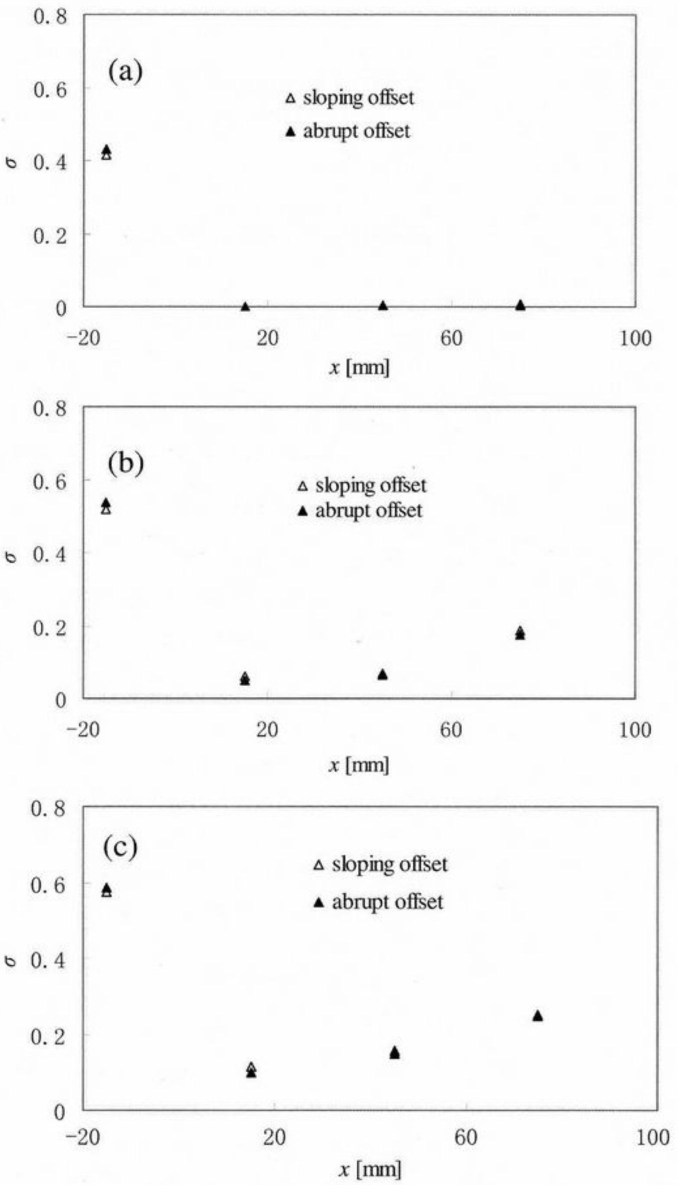


Figure 6 Comparison of cavitation number between sloping and abrupt 2 mm offsets for C (%) = (a) 0, (b) 4.0 and (c) 8.0

offsets is seen to be negligible for $C = 2.3, 4.0, 6.0, 8.0, 10.0\%$ and for $C = 0.0\%$, due to the lower offset height.

5.4 *Cavitation number of 5 mm abrupt offset with aeration*

The variation of the cavitation number for the 5 mm abrupt offset is shown in Fig. 7, which is seen to be similar to that of the 2 mm abrupt offset (Fig. 5). Accordingly, the effect of offset height on σ is small.

5.5 *Comparison of cavitation numbers between 5 mm sloping and abrupt offsets*

For 5 mm abrupt offsets, the variation in the cavitation number between the sloping and the abrupt as shown in Fig. 8 differs from the 2 mm offset. The cavitation number of sloping offsets is obviously larger than that of abrupt offsets for $C > 0$.

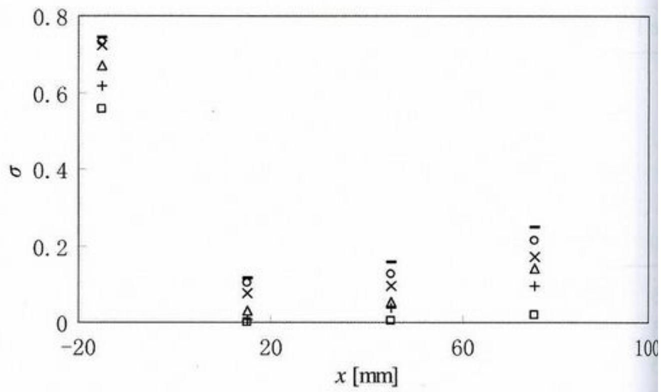


Figure 7 Cavitation number of 5 mm abrupt offset for C (%) = (□ (+) 2.3, (△) 4.0, (×) 6.0, (○) 8.0, (–) 10.0

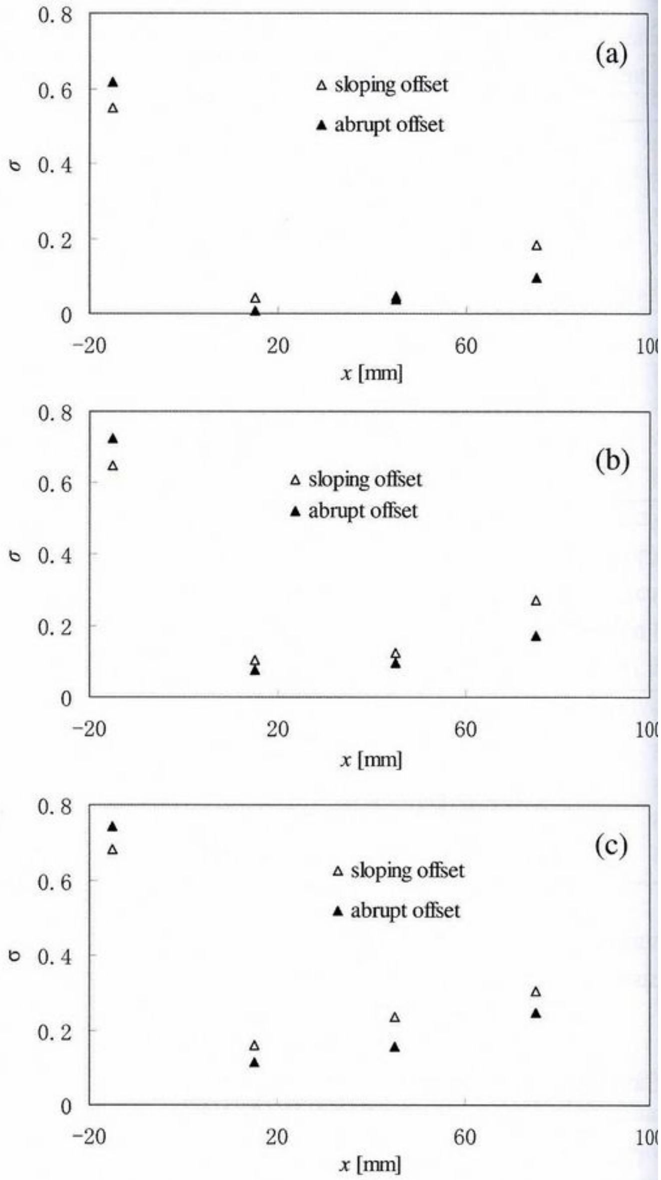


Figure 8 Comparison of cavitation number between 5 mm slo and abrupt offsets for C [%] = (a) 2.3, (b) 6.0 and (c) 10.0

6 Conclusions

Based on an experimental study of the cavitation characteri of the abrupt and sloping offsets-into-flow of various heights following conclusions are made:

- A thick cavitation cloud over the offset was generated even for an offset height of only 2 mm provided high-velocity flow in the order of 40 m/s is considered.
- Using a sloping instead of an abrupt offset did not improve the cavitation number.
- Negative pressures downstream of abrupt and sloping offsets approached − 1.0 atmospheric pressure in the absence of aeration.
- Aeration increases the pressure downstream of the offset considerably.
- The cavitation numbers downstream of both the abrupt and sloping offsets nearly tend to zero in the absence of aeration. However, the cavitation number downstream of the offset gradually increases with the presence of aeration.
- For 5 mm offsets, the cavitation number of the sloping offset was apparently larger than that of the abrupt in presence of aeration. In addition, the thickness of cavitation cloud over the offset is considerably larger than that of the corresponding boundary layer over a flat plate.

These test results are important relative to surface irregularity control during construction of high-head flood release structures.

Acknowledgements

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Notation

C air concentration
h, h_v absolute and saturated vapour pressure head
p wall pressure
Q_a, Q_w air and water discharge
R_x Reynolds number of boundary layer
u velocity within boundary layer
V_0 approach flow velocity
x streamwise coordinate
δ thickness of boundary layer
θ momentum deficit thickness of boundary layer
σ cavitation number
τ wall shear stress

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