SCOUR AND DYNAMIC PRESSURE OF IMPINGING JETS WITH AND WITHOUT AERATION: AN ANNOTATED REVIEW

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This paper deals with scour and dynamic pressure of impinging jets with and without aeration in the plunge pool. At present, though we have over 30 empirical formulas of scour depth, there are considerable differences between calculated results from these formulas and measured data. It is easily found that the maximum error is up to 400% and the minimum error is at least 30%. So it is imperative to further develop more reasonable formula of scour depth due to impinging jets. Many researchers have conducted experimental and theoretical studies on it. Some researchers think impinging jets with air entrainment would weaken scour capacity of the jet; however, the other researchers suggest impinging jet with air entrainment would deepen the scour. In addition, this paper deals with impinging dynamic pressure on the plunge pool bottom, including time-averaged and fluctuation distribution of pressure, correlation and frequency-spectrum properties of pressure fluctuation, effects of air entrainment on time-averaged pressure and pressure fluctuation etc.

1 Introduction

Flip bucket and free overfall jets are of the advantages of lower cost, simple structures and short construction period as well as stronger adaptability to tail water level, which are most used in hydraulic engineering and have become effective ways of energy dissipation for flood release structures with high-head and large discharge per unit width. A huge energy carried by the jets primarily dissipates in the process of turbulent diffusion in the plunge pool. So a great deal of attention to whether or not the impinging jets may result in severe erosion of river bed, instability and destruction of apron, and vibration of structures etc have been being paid. According to the investigated data, if we would compare the over 30 calculation formulas available in the world for the scour depth with the model and prototype data, we can find the maximum error is up high to 400%, and the minimum is even to 30%. The questions as mentioned above give us food and thought: whether we have been poorly considering the other factors that stand for important hydraulic characteristics of prototype except for the discrepancy in geological conditions. In fact, the high velocity jets issued from flip buckets have entrained a large amount of air in the process of diffusion, and form high concentration air-water two-phase flows. In addition, the impinging jets also entrain air at the point of entry(Dong 1997).

Scour of impinging jet on rock base is related to scour capacity of jet and scour resistance of rock base, which is complicated. There are different points of view on scour mechanism of rock base. Most of researchers would think scour of impinging jet on rock base is originated from pressure fluctuation within joints and cracks on rock base(Hartung 和 Hausler 1973, Chen 1980).

2 Dynamic Pressure of Impinging Jet with and without Aeration

2.1. Time-averaged Pressure

Dimensionless time-averaged pressure profile of two-dimensional jet on the plunge pool bottom indicates that either vertical jet or oblique jet, either jet with aeration or jet without aeration, the experimental data points gather together, which exhibits a good similarity and can be expressed as Gaussian distribution(Dong, Yang and Wu 1994):

$$\overline{p}/\overline{p}_m = \exp\left(-0.5\eta^2\right) \tag{1}$$

where $\overline{p}$ and $\overline{p}_m$ denote time-averaged pressure and maximum time-averaged pressure, respectively； $\eta = y/b_{1/2}$ ， in which y is distance from maximum time-averaged pressure point, $b_{1/2}$ is half-value width，i.e., value of y at $\overline{p} = 0.5\overline{p}_m$.

The first author of this paper found on the basis of experimental results of impinging jet with and without aeration that impinging jet with aeration makes time-averaged pressure within the impingement region on the plunge pool bottom decrease as shown in Fig.1, which results from density decrease of aerated flow in the pool after impinging jet entrained air. The symbol C in the Figure denotes air concentration.

Xu and Yu（1983）investigated impingement dynamic pressure of plane water jet on the pool bottom under an oblique jet, and compared it with plane gaseous impinging jet(Beltaos 1976). They obtained that time-averaged pressure distributions between water jet and gaseous jet are basically agreeable.

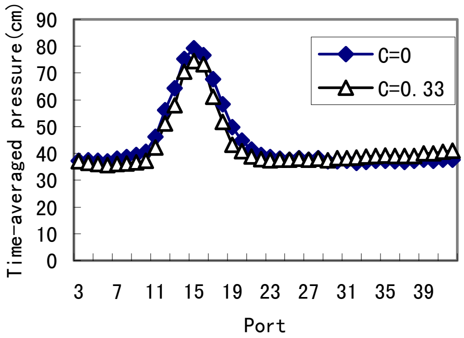

Figure 1. Effect of impinging jet with aeration on time-averaged pressure in the plunge pool

1.2. Intensity of Pressure Fluctuation

Dimensionless, the root-mean-square values of pressure fluctuation showed experimental points with and without aeration gathered under various impinging angles(Dong, Yang and Wu 1994). Certain similarity also exists within impingement region. However, the data points located below the rollers are scattered. Especially with impinging angle decrease, the points within the lower roller scattered more. Within impinging region, intensity of pressure fluctuation can be written as

$$\sqrt{\overline{p'^2}} \Big/ \sqrt{\overline{p_m'^2}} = \exp\left(-0.824\eta^{0.5}\right) \qquad (2)$$

in which p' denotes pressure fluctuation, and p'_m maximum pressure fluctuation.

Relation between maximum fluctuation intensity of pressure and pool depth is shown in Fig.2(Dong 1993). It follows from the Figure that maximum fluctuation intensity of pressure increases with pool depth because potential core converges and turbulent boundary layer spreads in the zone of flow establishment. Conversely, in the zone of established flow that is fully developed turbulent boundary layer, fluctuation intensity gradually decays with pool depth.

Pressure fluctuation on the bottom of plunge pool results from lower frequency large-scale vortices, and fluctuation energy was under lower frequency domain(10Hz). There was no dominant frequency in the fluctuation energy, which approached a white-noise spectrum(Dong, Wu and Yang 1994). In addition, variation in maximum dynamic pressure, frequency-spectrum correlation and transversion between point and area of pressure fluctuation were in detail discussed (Dong 1997).

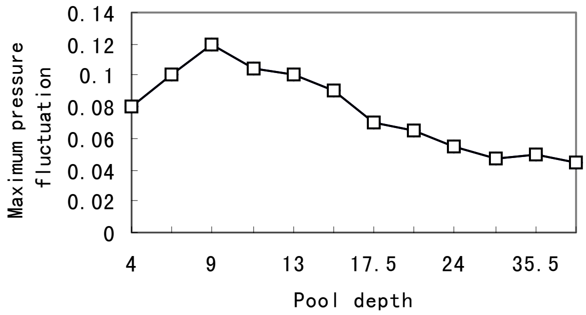

Figure 2. Relation between maximum fluctuation intensity of pressure and pool depth

Some researchers investigated effects of air entrainment on dynamic pressure on the pool bottom impinged by jets. Luo and Guo(1992), Dong, Yang and Wu(1994) obtained that jet with air entrainment would make time-averaged pressure decrease and pressure fluctuation intensity increase.

1.3. Theoretical Analysis of Effects of Air Entrainment on Dynamic Pressure

Dynamic pressure can be expressed as

$$p = \rho V^2 / 2 \tag{3}$$

If we express instantaneous value as a sum of time-averaged and fluctuation values, we have

$$p_w = \overline{p}_w + p'_w, p_m = \overline{p}_m + p'_m, \rho_w = \overline{\rho}_w + \rho'$$

$$\rho_m = \overline{\rho}_m + \rho'_m, \overline{\rho}_m \approx (1 - \overline{C})\overline{\rho}_w, V = \overline{V} + V'$$

in which the subscripts w and m denote water and air-water mixture, respectively.

For clear water, dynamic pressure can be written as

$$p_w = \frac{1}{2}\rho_w V^2 = \frac{1}{2}\overline{\rho}_w \left(\overline{V} + V'\right)^2 \tag{4}$$

After averaging Eq.(4), we have

$$p_w = \frac{1}{2}\overline{\rho}_w \left(\overline{V}^2 + \overline{V'^2}\right) \tag{5}$$

Dynamic pressure of air-water mixture can be written as

$$p_m = \frac{1}{2}\rho_m V^2 = \frac{1}{2}\left(\overline{\rho}_m + \rho'_m\right)\left(\overline{V} + V'\right)^2 \tag{6}$$

After averaging Eq.(6), we obtain

$$\overline{p}_m = \frac{1}{2}\left(1-\overline{C}\right)\overline{\rho}_w\left(\overline{V}^2 + \overline{V'^2}\right) \tag{7}$$

Subtracting Eq(5) from Eq.(7), we have

$$\overline{p}_m - \overline{p}_w = -\frac{1}{2}\overline{C}\overline{\rho}_w\left(\overline{V}^2 + \overline{V'^2}\right) \tag{8}$$

Obviously, $\overline{p}_m < \overline{p}_w$ (9)

It follows from Eq.(9) that jet with air entrainment would make time-averaged pressure decrease.

Mechanism of pressure fluctuation has not completely understood well yet. Two hypotheses are suggested, that is, velocity field effects and vortex transfer. The former, based on the basic equation of pressure fluctuation(Chou 1945), suggested pressure fluctuation at certain location in turbulent flow arose from velocity fluctuation at the location, which divided into two types of fluctuating sources of interaction between turbulence-shear and turbulence-turbulence. The latter suggested pressure fluctuation arose from stochastic motion of vortex in turbulent flow. Also, with the development of coherent structures hypothesis, it is considered that vortex in shear layer of jet is characterized by topology. It is the results of vortex pairing that the jet entrains surrounding fluid and its cross-section spreads. Wall pressure fluctuation is mainly caused by low frequency large-scale coherent structures.

3 Effects of Jet with Air Entrainment on Plunge Pool Scour

Since the earlier research of Schoklitch on jet scour, many formulas of scour depth have been developed so far. Zhu and Cai(1963), Mason and his co-authors(1985, 1989) once made an assess about the formulas of scour depth in the world and suggested these formulas awaited on further study. Regarding effects of air entrainment on jet scour, an identical conclusion has not been reached yet. The earlier researcher of effect of air entrainment on impinging jet scour is Vizko (1947). Thereafter, Nanjing Hydraulic Research Institute of China (1959), Yu (1962) et al also conducted this experimental investigation. Vizko suggested the empirical formula of scour depth t as follows

$$t = AK_1\sqrt{q\sqrt{P_0}} \tag{10}$$

where A denotes a coefficient of air entrainment, the value is 0.4~0.9; K_1 a coefficient of scour，q discharge per unit width and P_0 action head. It follows from Eq.(10) that air entrainment would mitigate scour. Sokolov (1958) suggested that air entrainment would mitigate the jet scour because of interaction between air and water that increased energy dissipation.

Yu(1962) experimentally investigated effect of oblique jet with splitting air entrainment on scour. He suggested that effect of splitting air entrainment on scour was not only related to splitting range, but also internal structures of splitting aerated flow. Uniform mixing air-water jet flow was superior to splitting thin jet flow from the view of energy dissipation, so it should try to force jet to uniformly entrain air as much as possible in the engineering design. Mitigation of jet with splitting air entrainment to scour would increase with plunge pool depth. Under a semi-round nozzle and air concentration of 50%, Johnson (1967) investigated effect of jet with air entrainment on scour. After compared 4 types of jets, i.e. solid water jet with moving tail water, splitting water jet, air-water mixture jet and solid water jet with static tail water, he obtained that air-water mixture jet diffused rapidly, and the corresponding tail water that needed to stop scouring was equivalent to half of tail water that solid water jet stopped scouring. At the same water level, air entrainment made scour depth decrease.

Mason's (1989) experiments showed that scour hole profile for the jet with air entrainment was flattener than that for the jet without air entrainment, and removed with air entrainment more bed materials than that without air entrainment. Based on model tests and prototype observations, Mason and Arumugam(1985) checked over 30 empirical formulas of scour hole, and suggested the reasonable expression should be written as

$$t = K_2 q^x H^y / d^z \qquad (11)$$

where D, q, H and d denote scour depth, unit discharge, action head and grain size, respectively; the values of x, y and z are 0.5~0.6, 0.1~0.5, 0.5, respectively. After the contrastive experiments with and without air entrainment, Mason（1989）obtained that the values of x and y without air entrainment were 1 and 0, respectively; Whereas, x and y with air entrainment were 0.59~0.71 and 0.08~0.20, respectively. These values approached the ones as above-mentioned. Therefore he concluded that the values of x and y would be related to air entrainment. Further experimental study showed that H in the Eq.(11) can be more reasonably expressed by air-water ratio β because air entrainment was not only function of H, but also jet thickness, turbulence and impinging angle. On the basis of 47 runs data of model experiment, Mason suggested calculation formula of three-dimensional jet scour as follows

$$t = \frac{3.39 q^{0.60} (H\beta)^{0.30} h^{0.16}}{g^{0.30} d^{0.06}} \qquad (12)$$

where h denotes tail water depth, β denotes ratio of air volume to water volume, and the other symbols are the same as the above-mentioned. It follows from Eq.(12) that jet with air entrainment would make scour hole increase under the same conditions.

4 Concluding Remarks

With the development of hydropower and progress in dam technology, more and more high dams will be constructed in China. Flows released from discharge works would entrain a large amount of air. So it is very significant to correctly estimate or predict lower scour depth. Naturally, air entrainment by impinging jet is an important fact that can not be ignored in the riverbed scour because flip bucket jet of prototype is high aerated flow.

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