Numerical and experimental study of trajectory for free falling jets

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ABSTRACT

The water flow over the dam spillways has a lot of energy and if this energy is not dissipated, the flowing water can cause irreparable damage to the dam and downstream structures. One way to dissipate this extra energy is to get water out of the jets into the plunging pool. Water free jets often cause erosion and scouring downstream of the structure, affecting the abutments and the downstream channel. In the present study, the trajectory of free falling jets is investigated numerically and experimentally. Ansys-Fluent software is used for numerical simulation and laboratory work is carried out in the hydraulic laboratory. The results showed that the domain of free falling jet in laboratory work is less than its calculated value using the projectile equations and the sample simulated using Ansys-Fluent software is due to air resistance. The equations of the projectile prediction and the simulated path in Ansys-Fluent have an error of 20.6% and 25.5%, respectively, compared to the laboratory data. Since none of the previously presented equations for calculating the path of falling jets were obtained using laboratory results and did not consider air resistance, therefore, they have errors in calculating the path of falling jets. In the present study, two equations have been presented to calculate the path of the free falling jet, which have a relative error of 3.02% and 9.14%, respectively. These relationships significantly reduce the error of calculating the path of the free-falling jet. By reducing the outlet cross section of the free falling jet and increasing the head passing through the dam spillway, the free falling jet reaches the ground at a greater distance from the dam body. Since none of the equations presented for calculating the trajectory of jets have been obtained using laboratory results and have not considered air resistance, so they have an average error of 21% in estimation of trajectory jet. In the present study, in addition to providing equations to calculate the trajectory of a free-falling jet, the air resistance also entered the main equation of the projectile by fitting an equation (using laboratory data). The simulation results also showed that the water flow velocity with a 247% increase compared to the velocity at the end of the dam overflow, hits the ground, which requires more attention in the design of stilling basin at the end of the dams.

KEYWORDS

Free jet, plunging pool, trajectory, projectile equation, air resistance.

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Introduction

Falling jets are one of the most important issues in hydraulic structures. Often these jets enter the plunge pool and lose their energy. The main mechanism of energy dissipation is the scattering of the jet into the air, followed by the entry of air into the jet, and finally the scattering and turbulence of the jet at the plunge pool. Falling water jets have a core that projects some distance and causes pressure increases on the bed and the wall of the pool. Along its trajectory, the jet core gradually shrinks because of the infiltration of air and from turbulence and eventually breaks apart [1].

Rouse [2] referred to the Froude number in an upstream section and showed that the thickness of the vertical jet is almost constant. Wall et al. [3] examined and compared the trajectory of the free and pressurized falling jets. The results showed that when calculating the trajectory of a free jet, the initial velocity of the jet (V_0) or the initial velocity head (h_0) should always be used.

In the present study, the characteristics of free-falling jets are investigated using physical models and CFD. The effect of the width of the outlet cross section of the free jet and the head passing through the dam to the jet is examined. A comparison is made between the equations presented by prior researchers and the results of the laboratory and numerical studies of the present work will be used to calculate the trajectory of a free jet.

Methodology

2.1 Equations governing projectile trajectory

A falling jet with a velocity of v_0 is launched from the dam crest. Considering the dam crest as the origin of the coordinates, the vertical position equation is taken from [4]:

$$y = x\tan\theta_0 - \frac{gx^2}{2v_0^2\cos^2\theta_0} \qquad (1)$$

In Eq. 1, x and y are the coordinates of the lower edge of the jet, v0 is the initial velocity of the jet, θ_0 is the initial angle of the jet from the horizon (zero if the jet is horizontal, positive if the jet issues upward, and negative if the jet is initially inclined downward), and g is the gravitational acceleration. When the jet begins horizontally (the initial angle of the jet from the horizon is zero), the equation is simplified as follows [4]:

$$y = -\frac{gx^2}{2v_0^2} \qquad (2)$$

These equations describe the motion of a projectile that is not affected by air resistance.

2.2 Geometric specifications of the physical model

In the present study, experiments were performed in the hydraulic laboratory of the Faculty of Agriculture, Department of Water Engineering, University of Tabriz, Iran. A cubic tank with a length of 2 m, a width of 1.5 m, and a height of 1.2 m was used as a reservoir. A rectangular broad-crested weir was installed on this tank. At the downstream section, a flume was installed to transfer water to the main underground reservoir. In upstream section, a vertical cylindrical water tower was provided to supply the water needed to simulate the downstream free-falling jet. To provide the height required for the fall of the jet, the water tank was elevated 2 m. Parameters that affect the launch jet trajectory are listed in Table 1. Figure 1 shows a schematic diagram of the laboratory arrangement for measuring the trajectory of the jet.

Table 1 Range of parameters used in study

Parameter	V_0 (m/s)	$H_{overtop}$ (m)	D (m)
max	1.55	0.22	0.12
min	0.3	0.011	0.01

In the above table, Hovertop is the water head over the spillway (overtopping head), V0 is the initial velocity of the jet, Xmax is the maximum range of the free-fall jets and D is the width of the outlet of the free jet.

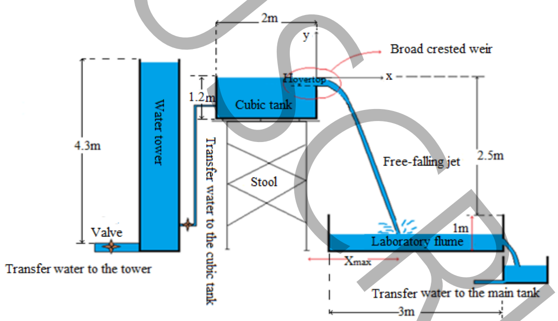

Fig. 1 Schematic of the free-falling jet laboratory facility

2.3 Numerical simulation with Fluent software

To incorporate turbulence, the k - ε (RNG) turbulence model was used. For solving free surface flow equation, the void of fluid (VOF) method was used [5]. To discretize the pressure expression, the Pressure-Implicit with Splitting of Operator (PISO) method and a Second Order Upward (SOU) method was used to discretize the momentum expression. Numerical simulation of a flow passing over a broad-crested weir in an open channel is a two-phase and turbulent flow.

Results and Discussion

3.1 Proposed equation for trajectory of free falling jet

One hundred experiments were performed with different discharges and widths of different sections. In total, 1600 data points (x and y locations) were extracted from the trajectory of the jet. Figure 2 shows an example of the trajectory of free-falling jet [6, 7].

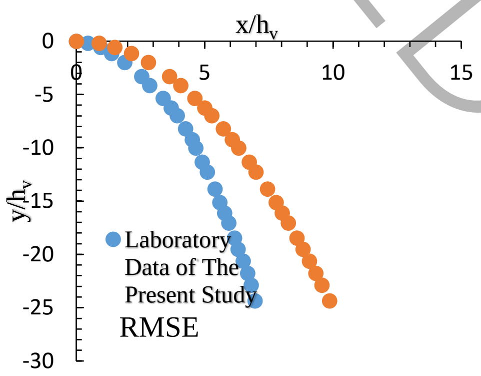

Fig. 2 Trajectory of a free-falling jet (laboratory measurements and projectile equation)

It can be seen that the trajectory length calculated using Eq. 2 is greater than its actual value because air resistance is ignored. In other words, the actual value of the projectile range is shorter than the value obtained from Eq. 2 due to air resistance. By analyzing the laboratory results and comparing it with the results of the projectile equation, it was found that the trajectory of the falling jet extracted from the equations, compared to its true value (laboratory data), has an average error of about 21%.

3.2 Effect of head and cross section width on falling jet

By increasing the cross-sectional width of the rectangular broad crest weir, the lesser the range of jet. With increasing discharge through the spillway, the range of the jet increases. In other words, for a constant discharge, with increasing width, the place where the jet falls to the ground surface is closer to the toe of the dam and for a constant width, with increasing discharge, the place where the jet falls to the ground surface is farther from the toe of the dam.

Conclusions

Few studies have been done on the trajectory of falling jets over storage dams. In the present study, the trajectory of falling jets was investigated experimentally and numerically. The height of the falling jet over the dam spillway in the laboratory model was 2.5 m. The results show that the trajectory of falling jets is affected by air resistance and the range of falling jets in laboratory work is less than the values calculated by various equations that omit air resistance.

Also, the effect of the passing head on the dam and the width of the flow passage section on the range of the free-falling jet was investigated and the results showed that decreasing the width at constant discharge and increasing the passing head over the dam at constant width be increased the falling jet range. The simulation results also showed that the velocity and pressure of the flow at the point of impact of the jet to the toe of the dam has its maximum value that should be considered in design.

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