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# Head Loss Estimation of Water Jets from Flip Bucket of Cakmak-1 Diversion Weir and HEPP

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**Abstract:** A jet issued from flip bucket of spillway of a dam interacts with the surrounding air and develops into an aerated turbulent jet. Depending on the relative jet thickness, the fall height and the level of turbulence, the jet may be dispersed in air forming an aerated water body which will eventually plunge into the river surface at sufficiently far downstream of the flip bucket. If not aerated, the jet may have a larger impact on the river bed causing excessive scouring of the river bed. Dispersion of jet by aeration is the practical tool to reduce the jet impact. The spillway of Cakmak I Diversion Weir and HEPP project located in Kahramanmaras province of Turkey is used as a case study to estimate trajectory lengths with air entrainment. Depending on projectile motion theory, head losses due to the air entrainment can be determined between the difference of the trajectory lengths with and without air resistance. Empirical equations were used to calculate the jet trajectory length with and without air entrainment. For the same conditions, the flow is modelled with commercially available computer software that uses volume of fluid (VOF) technique. Results from empirical equations and from numerical simulations are compared and differences between the results are discussed.

**Key words:** Water Jet, Flip Bucket, Trajectory Length, Head Loss, Jet Dispersion, Air Entrainment, Scour, Flow-3D

**Nomenclature:**

| | |
|---|---|
| $g$ | Gravitational acceleration (m2/s) |
| $y_0$ | Water depth on the bucket lip(m) |
| $h_L$ | Head loss due to the air entrainment (m) |
| $H_0$ | Water level above the sharp crested weir(m) |
| $H_t$ | Total head at the bucket lip(m) |
| $H_{j1}$ | Jet head without considering air entrainment (m) |
| $H_{j2}$ | Jet head with considering air entrainment(m) |
| $L_t$ | Throw distance calculated using Projectile motion formula(m) |
| $L_1$ | Throw distance considering air resistance calculated Kawakami's formula(m) |
| $L_{ts}$ | Throw distance obtained from numerical solution (m) |
| $L_{1s}$ | Throw distance considering air resistance obtained from numerical solution (m) |
| $k$ | Constant related to air resistance |
| $Q$ | Water discharge (m3/s) |
| $V_j$ | Velocity at the bucket lip (m/s) |
| $V_t$ | Velocity at impingement point(m/s) |
| $z_i$ | Vertical drop from lip to tail water level (m) |
| $\alpha$ | Trajectory length constant from Equation 6 |
| $\alpha_j$ | Flip bucket lip angle (degree) |
| $\alpha_t$ | Trajectory angle(degree) |

## 1. Introduction

Flip buckets are used to dissipate energy of the water coming from the spillway especially for large flow velocities. Flip buckets can be designed in various shapes and scales according to geological and economic circumstances involving relative curvature, deflection angles, take-off angles and special components are in operation. Mason (1993) collected the studies on ski jump and recommended some points of design as follows;

a) Minimum bucket radius should be designed three out of five times the approach flow of the bucket.

b) Take off angle of the flip bucket between 200 and 350.

c) Water jet should be spread in air with the angle of 50.

d) Lip of the bucket ought to be flat due to the cavitation risk.

When these considerations were made, the scour was not taken into account [1]. Khatsuria (2005) decided to investigate the general form of the ski jump to identify the whole purpose of it [2]. Ervine and Falvey (1987) and Ervine et al. (1997) showed that the presence of air bubbles inside the shear layer which limits the jet diffusion zone reduces the mean dynamic pressures on the plunge pool floor. They also considered, as a simplification that the flow velocity reduction in aerated conditions is negligible [3]. Steiner R., Heller V., Hager W.H., and Minor H.E. (2008) decided to investigate the effects of the triangular-shaped flip bucket placed at the take-off of ski jump rather than the general form of the circular-shaped bucket. They obtained the following results which can be significant for the design of the flip bucket. Pressure on the flip bucket depends on the approach flow Froude number and the deflector angle of the bucket. They found the limits of the Froude number according to their model to prevent choking of the spillway bucket. They analyzed the shock wave heights which depend on Froude number and the oscillation zone below the trajectory jet in prismatic channel. Energy dissipation of the water jet depends on the deflector angle of the flip bucket and the drop height of the bucket take-off to the channel [4]. Johnson (1967) conducted some experiments with a compact water jet, an air-water jet and a dispersed jet to study scour. Experimental set-up was consisting of a tank with a vertical jet nozzle and a gravel bed. He performed the tests and found that aeration of water jet reduces scouring the river bed nearly half of the tail-water depth required for no scour with the water jet [5]. Lukas Schmocker et al. (2008) focused on the analysis of the jet air entrainment characteristics of a plane jet downstream of a ski jump with and without aerated approach flow conditions. They changed the discharge which resulting the change of the flow depth on the spillway and variation of the Froude number. Via this experimental study they analyzed that the air concentration of the jet and its distribution, determination of the region of the minimum air concentration along the jet flow and evaluation of the air entrainment characteristics of water jet on which the circular-shaped bucket placed at the take-off of ski jump. They used the hydraulic model of Heller et al (2006) [6]. Kawakami (1973) investigated some prototypes as field research on trajectories with air entrainment and defined an aeration coefficient, k, to determine the trajectory length with air resistance [7]. An experimental study was conducted to analyze the trajectory lengths with and without air entrainment in order to estimate the head loss due to air resistance in Hydromechanics

Laboratory at Middle East Technical University in Turkey [8].

In this study, hydraulic data of Cakmak I Dam and HEPP is used to express the calculations. Reservoir is connected to an ogee-crested spillway with a chute angle of $\alpha s=550$. At the end of the chute, circular-shape flip bucket geometry is used into create a water jet. The width of the spillway channel is 14 m. Vertical drop from lip to riverbed, zi is 3.1 m and the take-off angle is $\alpha j=350$. The dimensions of the spillway and the flip bucket are shown in Fig. 1. Note that all dimensions are given in centimeters. In the figure, the elevations of normal water level (N.W.L.) and maximum water level (MAX.W.L.) are shown as 1572.50 m and 1575 m, respectively [9].

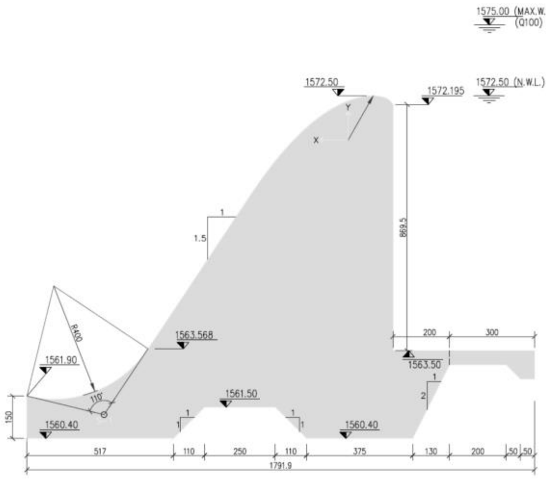

**Fig. 1 Sketch of the prototype [9]**

## 2. Materials and Methods

### 2.1 Provided Data

Following data given in Table 1 is provided from the project and trajectory lengths are calculated according to these data. $H_0$ is the water depth on ogee crested weir. Q is the water discharge according to the water depth on ogee crested weir. $y_0$ is the water depth at flip bucket lip and $V_j$ is the water jet velocity at flip bucket lip which can be calculated from continuity equation.

**Table 1 Provided data from the project.**

| $H_0$ (m) | Q ($m^3/s$) | $y_0$ (m) | $V_j$ (m/s) |
|---|---|---|---|
| 1.0 | 27.35 | 0.12 | 16.44 |
| 1.5 | 52.50 | 0.18 | 21.34 |
| 2.0 | 83.60 | 0.23 | 25.71 |
| 2.5 | 116.10 | 0.28 | 29.31 |

### 2.2 Jet Trajectories

Based on the main characteristics of the project, trajectory lengths are calculated according to projectile motion theory. In this theory, an object is thrown into the air near the earth and moves along a projectile path under the action of gravity force. This motion occurs under the frictionless domain. Equation of the projectile motion theory can be expressed [2] as

$$\frac{L_t}{H_j} = \sin\alpha_j + 2\cos\alpha_j\left(\sin^2\alpha_j + \frac{z_i}{H_j}\right)^{0.5} \qquad (1)$$

Where

$L_t$ = Throw distance at the point the jet strikes the tail-water,

$z_i$= Vertical drop from lip to tail-water level,

$H_j$= Velocity head of the jet at bucket lip ($V_j^2/2g$),

$\alpha_j$= Flip bucket lip angle, (degrees)

Eq. (1) can be rearranged and written as follows;

$$L_t = \frac{V_j\cos\alpha_j}{g}\left(V_j\sin\alpha_j + \sqrt{\left(V_j\sin\alpha_j\right)^2 + 2gz_i}\right)^{0.5} \qquad (2)$$

However, actual trajectory lengths are affected by air entrainment due to high flow velocities. Trajectory lengths considering air entrainment are calculated based on field research on trajectories [7]. Kawakami presented results of some field research on trajectories affected by air resistance and defined a coefficient, k for the following equations

$$L_1 = \left(\frac{1}{gk^2}\right)\ln\left(1 + 2k\alpha V_j \cos\alpha_j\right) \qquad (3)$$

where

$$\alpha = \tan^{-1}\left(kV_j \sin\alpha_j\right) \qquad (4)$$

and

$L_1$=Throw distance considering air resistance,

k = Constant related to air resistance,

$V_j$= Velocity at the bucket lip.

Various parameters related to projectile motion of the jet are defined in Fig. 2.

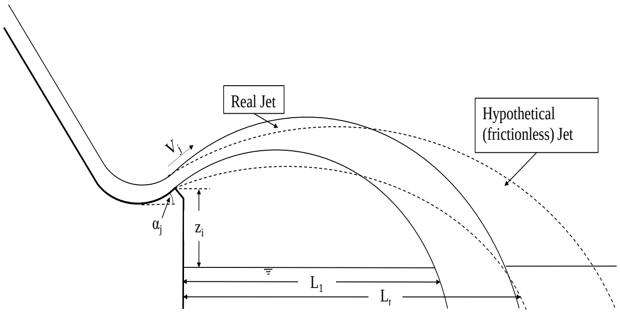

Fig. 2 Throw distance of jet[8]

Fig. 3 shows experimental relationship between $V_j$ and k and also $L_1/L_t$ values for different values of $V_j$, according to (Kawakami, 1973), where $L_t$ is the throw distance without considering the air resistance. $\alpha_t$ represents the trajectory angle at the impingement point.

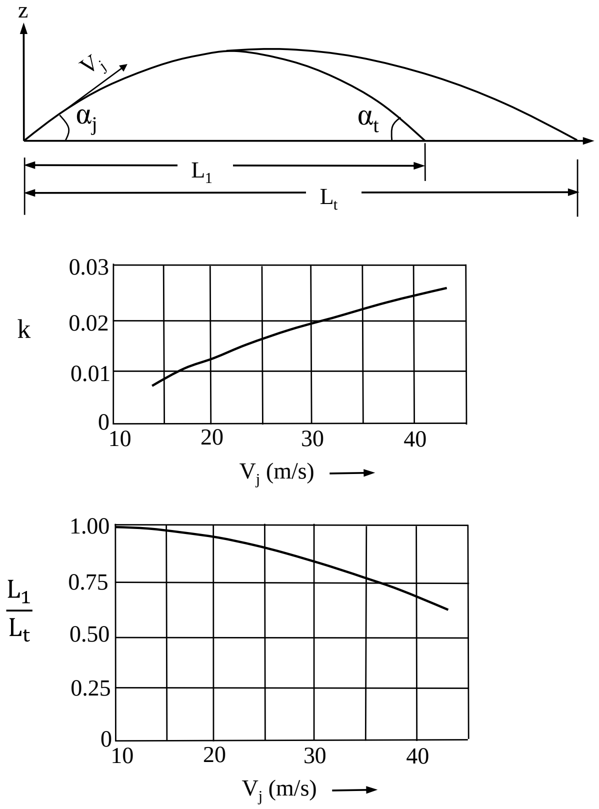

**Fig. 3 Effect of air resistance on jet trajectory. [7]**

It is observed that the effect of air resistance is small whenever $V_j$ is less than about 20 m/s, but the throw distance is reduced by about 30% when the velocity is close to 40 m/s.

### 2.3 Head Loss

The main purpose of the ski jump is moving the jet impact region away from the structure and creating jet dispersion. The jet dispersion can be largely increased by introducing splitters at the bucket lip. If water jet disperses in the air, a large amount of air is entrained into the water jet. This amount of air entrainment reduces the jet velocity and creates significant head losses. Head loss due to the air entrainment can then be calculated by comparing the measured and calculated trajectory lengths. The measured length is affected by the head losses due to air entrainment whereas the calculated length is obtained from the projectile theory without air entrainment therefore no head losses. The difference of the two heads will then be equal to the head loss of the projectile motion of the water jet [8].

$$H_{j1} = H_{j2} + h_L \qquad (5)$$

where

$H_{j1} = \frac{V_j^2}{2g}$ = Jet head without considering air entrainment

$H_{j2} = \frac{V_{j2}^2}{2g}$ = Hypothetical Jet head. ($V_{j2}$ is obtained by using the measured trajectory length $L_1$ in Eq. (2))

$h_L$= Head loss due to air entrainment

## 3. Analysis of Interrelationship between Jet Parameters

### 3.1 Comparison of the Calculated Trajectory Lengths with and without Air Entrainment

The profile of the trajectory leaving a bucket depends on the velocity at the bucket lip and the lip angle. The jet trajectory can be calculated on the basis of projectile theory from Eq. (2). Trajectory length considering air entrainment is also calculated from Eq. (3). Results of the calculated trajectory lengths with and without air entrainment are given in Table 2.

**Table 2 Trajectory lengths with and without air entrainment.**

| $L_t$ (m) | $V_j$(m/s) | k from Fig. 3 | α from Eq. (3) | $L_1$ (m) |
|---|---|---|---|---|
| 28.37 | 16.44 | 0.009 | 0.07 | 23.63 |
| 45.00 | 21.34 | 0.012 | 0.13 | 38.91 |
| 63.30 | 25.71 | 0.016 | 0.20 | 53.75 |
| 80.87 | 29.31 | 0.020 | 0.29 | 64.78 |

On the average, a 16.3% difference is observed between the trajectory lengths. Trajectory length, $L_t$, found by using projectile motion formula contains no air entrainment or air resistance. But, trajectory length, $L_1$ is reduced by significant amount of air absorbed which turned the water jet into air-water mixture. Hence, its velocity has reduced significantly. Consequently, there is a big difference between the aerated and non-aerated lengths. This retardation due to air mixing creates a head loss from the jet energy available at the lip of the flip bucket.

### 3.2 Calculation of Head Loss Due to Air Entrainment

Calculation of head loss due to air entrainment can be reasonable via calculating the velocity difference considering the trajectory lengths by neglecting the air entrainment from Eq. (2). Initially given jet velocities are used and required trajectory lengths without air entrainment are calculated. Same calculations are made on the lengths by including the air entrainment. Head loss value is calculated using the velocity head difference between calculations from Eq. (5). Head loss calculations are given in Table 3 for given discharges.

**Table 3 Head loss due to air entrainment**

| $L_t$ (m) | $V_j$ (m/s) | $H_t$ (m) | $L_1$ (m) | $V_1$ (m/s) | $H_1$ (m) | $h_L$ (m) |
|---|---|---|---|---|---|---|
| 28.37 | 16.44 | 13.78 | 23.63 | 14.77 | 11.12 | 2.66 |
| 45.00 | 21.34 | 23.22 | 38.91 | 19.68 | 19.74 | 3.48 |
| 63.30 | 25.71 | 33.69 | 53.75 | 23.53 | 28.22 | 5.47 |
| 80.87 | 29.31 | 43.78 | 64.78 | 26.04 | 34.56 | 9.22 |

## 4. Simulations of Trajectory Lengths by Using Flow-3D

### 4.1 Brief Information about Flow-3D

With developing technology and computer science, engineering problems can be modelled by using software or computer codes. In this manner, simulations are run after defining flow domain with appropriate grid system and boundary conditions which depend on situations. Flow-3D is an appropriate CFD tool to model free surface flows in fluid mechanics problems. It uses fractional area volume obstacle representation (FAVOR), improved volume of fluid technique (VOF) and multi block meshing to increase its capabilities. For more information, the manuals provided by Flow-3D community can be investigated. (www.flow3d.com) [10]. CFD software solves the domain which is divided into smaller regions called meshes/grids. Constructing unstructured grid is time consuming and difficult compared to structured grid generation. Flow 3D generate structured grids by free gridding method so that time required for grid generation and computation decreased. Mesh generation without considering the domain geometry can reduce the accuracy of the solution but this can be overcome by using FAVOR which allow user to divide parts with solid and fluid regions. In order to model a spillway in Flow 3D, a 3D model of the spillway was constructed in AutoCAD and inserted to Flow 3D as stl file. After obtaining geometry in Flow 3D, fluid type, physical conditions (such as gravity, air entrainment etc.) as well as turbulence model and corresponding solving methods were determined and explained in the next section. Then meshes were constructed along the flow domain with proper boundary conditions. Boundary conditions were determined as specified pressure in flow inlet, symmetry in side walls and top of the spillway and outflow at the downstream of the spillway. Also time interval is chosen depending on Courant–Friedrichs–Lewy (CFL) condition [11].

### 4.2 Application of Flow-3D for Cakmak-1 Dam

In order to model a spillway in Flow-3D, a 3D model of the spillway is constructed in AutoCAD and inserted as stl file. In Fig. 4, the 3D model of the spillway of Cakmak-1 Dam can be seen. After obtaining the geometry in Flow-3D, fluid type, physical conditions (such as gravity, air entrainment etc.) as well as turbulence model and corresponding solving methods are determined according to data given for 1.0 m water height on ogee crested-weir. Then meshes are constructed along the flow domain with proper boundary conditions. Boundary conditions are determined as specified pressure in flow inlet, symmetry in side walls and top of the spillway and outflow at the downstream of the spillway. Also time interval, simulation type and output data can be selected according to the given data. In the model, k-Ɛ turbulence model is used. For the turbulence model, turbulent mixing length is dynamically computed. In addition, 1st order momentum advection is chosen. The mesh sizes all over the system are taken constant and equal to 0.05m. This is a very small value, but it is necessary in order to model the wall shear stresses and slip effects between the boundary and the water correctly. Due to the small mesh sizes, the system is solved in two dimensions. In fact, a three dimensional model has also been solved. The results are very close between the solutions of 2D and 3D. In order to lower the computational time, all the calculations in the model are in 2D.

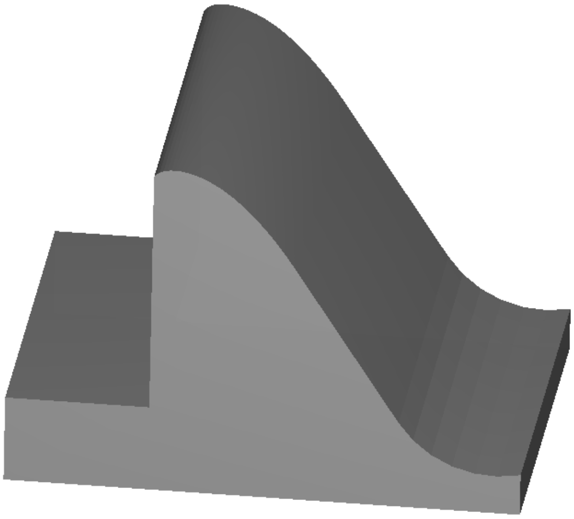

Fig. 4 3D model of the spillway of Cakmak-1 Dam

### 4.3 Jet trajectories with and without Air Entrainment

After simulation is completed, required data as well as 3D simulation of the flow can be obtained by analyzes section of the Flow-3D. The simulations are done for all water depth on ogee crested weir ($H_0$). And the related discharges. Flow-3D is used to compare the correctness of the numerical results. In Fig. 5, trajectory length without air entrainment for $H_0$= 1.0 m and for the discharge Q=27.35 $m^3/s$ are shown respectively. As can be seen, the trajectory length of the jet is about 29 m. Trajectory length with air entrainment is also given in Fig. 6. Trajectory length of the water for this case is about 24 m. According to this study, the minimum water head on ogee crested weir and the corresponding discharge is the most critical case for the aeration amount of the jet, these figures are selected to demonstrate the aerated and non-aerated trajectory lengths determined from the numerical solution.

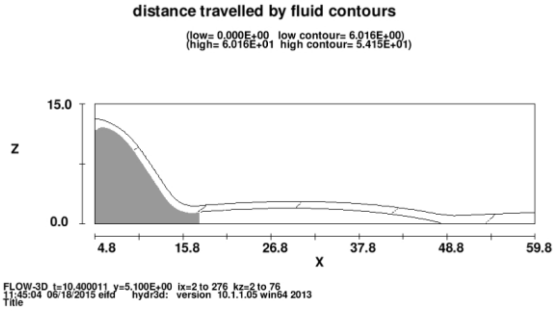

Fig. 5 Trajectory length without air entrainment for $H_0$= 1.0 m

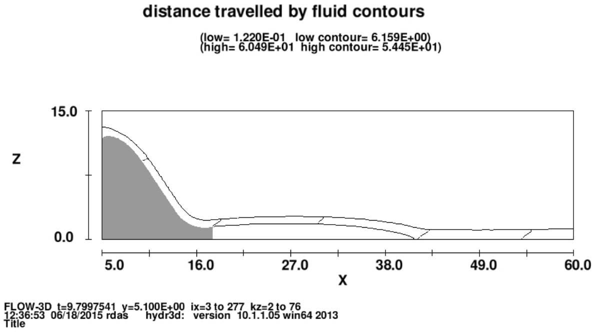

Fig. 6 Trajectory length with air entrainment for $H_0$= 1.0 m

### 5. Results and Discussion

In the present study, influence of air entrainment in a water jet issued from a flip bucket has been studied in two ways. First, empirical equations were used to calculate the jet trajectory length with and without air entrainment for 4 different discharges. The other way to determine the jet trajectories is simulation by using Flow-3D for the same conditions. The computed and simulated trajectory lengths are compared to determine the consistency of the calculations. Differences between the calculated and simulated jet trajectories for all $H_0$ and Q values are given in Table 4. $L_{ts}$ represents the simulated trajectory length without air entrainment and $L_{1s}$ represents the simulated trajectory length with air entrainment respectively.

**Table 4 Comparisons of the calculated and simulated trajectory lengths**

| $H_0$ (m) | Q ($m^3/s$) | $L_t$ (m) | $L_{ts}$ (m) | $L_1$ (m) | $L_{1s}$ (m) |
|---|---|---|---|---|---|
| 1.0 | 27.35 | 28.37 | 29.00 | 23.63 | 24.00 |
| 1.5 | 52.50 | 45.00 | 45.50 | 38.91 | 39.50 |
| 2.0 | 83.60 | 63.30 | 63.00 | 53.75 | 55.00 |
| 2.5 | 116.1 | 80.87 | 80.00 | 64.78 | 66.00 |

Measured trajectory lengths coincide with the calculated trajectory lengths with air entrainment using Kawakami’s formula. Obtained results from the experimental study can be a proof of the correctness of the empirical methods using in this study[8]. As a result both empirical equations and numerical solutions are applicable to determine the head loss due to air entrainment for water jets from flip buckets. Since the aeration of the jet coming from the flip buckets depends on the discharge as the only changing condition for these cases, trajectory lengths determined by the empirical equations and the numerical solutions are almost coincide each other. The percentage of the difference between the trajectory lengths is 3% on the average.

## 6. Conclusion

Empirical equations for with and without air entraining jet trajectory and trajectory angle were derived from data as a function of air entrainment, bucket angle and the jet head. Results were validated by comparing with other data in the literature. Considering the projectile motion of the jet without air entrainment, trajectory lengths for four different discharges were computed and compared with the numerical results. Air entrainment is significantly effective in energy dissipation.

In order to define the head loss due to air entrainment difference between the trajectory lengths considering air entrainment and without air entrainment both empirical equations and Flow-3D simulation can be used. By determining the difference between the trajectory lengths, head loss due to air entrainment can be easily obtained from energy equation. Both empirical equations and numerical solutions applied on this case study give good results.

This study is beneficial for the comparison of the computed trajectory length with and without air entrainment and calculation of the head loss due to air entrainment using both numerical and empirical methods. Further studies should be conducted for different bucket angles and dimensionless parameters should be extended to determine the trajectory length considering the air entrainment and dynamic pressure levels with respect to different water discharges. Head loss owing to the air entrainment in uncontrolled section should be investigated by using different methods in order to obtain the precise data for determining the impingement point of the water jet at the downstream of the spillway and flip bucket.

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