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ENERGY DISSIPATION SCALE FOR DAM PROTOTYPES

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ABSTRACT

This study offers a novel empirical equation for those involved in ski-jump type energy dissipator, stilling basin, and plunge pool designs to determine the energy dissipation level due to air resistance. The equation verified by conducting experimental, empirical, and numerical regression analyses at the prototype scale. Energy dissipation due to air resistance can then be easily calculated for the discharges reaching up to 10000 m^3/s by using the equation.

Keywords: *Air resistance, Energy dissipation, Flip bucket, Ski-jump jet*

BARAJ PROTOTİPLERİNDE DOLUSAVAK SU JETİ ENERJİ SÖNÜMLEME YÖNTEMİ

ÖZET

Bu çalısma sıçratma eşiği, çökeltim havuzu ve düşü havuzu gibi önemli baraj bileşenleri alanında araştırmalar yapan bilim insanları ve tasarım çalışmaları yürüten mühendisler için dolusavaktan çıkan su jetindeki hava direnci yoluyla oluşan enerji sönümlemesi miktarının kolaylıkla hesaplanmasını sağlayacak özgün bir ampirik denklem sunulmaktadır. Bu denklem, gerçek boyutlarda baraj prototipi üzerinde uygulanan deneysel, ampirik ve nümerik hesaplamaların dikkate alınarak karşılaştırılması ile elde edilmistir. Çalışmada verilen bu denklem ile, su jeti üzerinde hava direncinden kaynaklanan enerji sönümlemesini 10000 m^3/s deşarj değerine kadar hesaplamak mümkündür.

Anahtar Kelimeler: *Enerji sonümlenmesi, Hava direnci, Sıçratma eşiği, Su jeti*

1. Introduction

Energy dissipation of the excess water coming from a dam reservoir through the spillway is vital for the prevention of the scouring phenomenon downstream of the dam body [1]. Experimental, empirical, and numerical scour estimation methods have been comprehensively investigating by the scientists and engineers for a century [2-8]. Although spillways can easily discharge the excess water coming from the reservoir, it is not commonly an adequate solution to dissipate the energy of the water discharged. Because this amount of water could have an enormous energy and this energy can be a reason for scour problems at the downstream of the spillway of a dam, there needs to be provisions for energy dissipation structures or mechanisms which will reduce the water jet impact [9-11]. Therefore, suitable energy dissipating system has to be designed and installed on the downstream sections of the

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spillway [12,13]. These systems may consist of several applications. Although a variety of designs are used for energy dissipation at the base of spillways, the dissipation of energy is mainly through internal friction, turbulence, impact and diffusion of the high velocity flow in a pool of water. Khatsuria [14] stated that ski-jump, plunge pool, baffle blocks, hydraulic jump etc. may help the process of energy dissipation and may also create some problems like scour, cavitation at the plunge pool floor, bank erosion need to be identified and solved. Fraser [15] conducted an Ms thesis focused on the passage of extensive rainfalls from the reservoir by means of the proper spillway and outlet structures such as ski-jump buckets and plunge pools. Fraser [15] performed several hydraulic tests to maximize energy dissipation and air resistance on a physical hydraulic model. Various types of flip buckets were tested to disperse the water jet coming from the spillway. The results obtained from the study demonstrate that the Froude number, bucket angle, and shape of the bucket significantly affect the energy dissipation rate of the jet. He proposed a flip bucket design different from 400 circular-shaped buckets and managed to increase the air resistance up to 20%. Qian et al., [16] worked on a recently used ski-jump-step energy dissipator to increase water discharge through the spillway. Experimental studies were conducted on a hydraulic model. They mentioned that the ski-jump-step energy dissipator provides highly aerated flow which helps to prevent cavitation problems on the spillway itself and energy dissipation at the impingement area. The results showed that significant energy dissipation (up to 75%) and air concentration (up to 3.6%) were provided even for high discharge values. Moghadam et al., [17] performed a hydraulic model study inspecting the dynamic pressure variations at the impingement area by changing the plunge pool angle, level of water cushion, and discharge. They mentioned that increasing the plunge pool angle for high drop lengths of the jet can cause a decrease on dynamic pressure levels. It was also stated that, increasing the water level at the plunge pool helps the reduction of the dynamic pressure values at the downstream of the spillway. The rate of change of the dynamic pressure levels were obtained between 34% and 95% for different design conditions. Lauria and Alfonsi [18] inspected the ski-jump jets numerically and stated that the results help to characterize the problem for these types of dam structures. They provided some suggestions for the designers for constructing the ski-jump type energy dissipators. Yavuz [19] conducted a Ms thesis to examine the impact of the water jet released from the bucket lip on the river bed. Dynamic pressure values were recorded using pressure transmitters. Trajectory lengths are also measured for all test cases. The results revealed that air resistance significantly disperses the energy of the jet until a certain discharge value. Then, air suction dramatically reduced due to the low bucket lip velocity.

This study provides a novel estimation method for the energy dissipation amount of ski-jump jets by revealing experimental, empirical, and numerical solutions. Trajectory length with air resistance were measured (L_m), calculated (L_c) , and simulated (L_s) to compare with the non-aerated trajectory length (L_t) to determine the energy dissipation amount due to air resistance for prototype scale. Even under large discharge level conditions reaching up to 10000 m^3/s, the amount of energy dissipation can be estimated by using newly provided head loss (h_l) - discharge (Q) equation depending on experimental, empirical, and numerical regression analyses. Thereafter, both the amount of energy dissipation of ski-jump jet and jet trajectories can easily be calculated by means of the equation provided in this study. Experimental study was conducted on $1/25$ scaled Laleli Dam and Hydroelectric Power Plant (HEPP) model (see Figure 1) in the Hydromechanics Laboratory of Civil Engineering Department, METU [19].

Laleli Dam and HEPP located on Coruh River, Turkey currently operational and producing 244.55 GWh electricity annually. Its height is 127.5 m, spillway width is 38 m, flip bucket angle is 55^0, and height of the bucket lip from stilling basin is 30 m [20].

Figure 1. Hydraulic Model of Laleli Dam and HEPP [20]

2. Materials and Methodology

The flowchart of the methodology is shown in Figure 2. The experiments are conducted for 6 different discharges (i.e. Q (m^3/s) = 0.07, 0.10, 0.13, 0.16, 0.19, 0.22). Since the aeration on the spillway is negligibly small compared with the aeration amount after the bucket lip, non-aerated flow is assumed at the bucket lip. Jet head at the bucket lip (h), jet velocity at the bucket lip (V_j), and L_m are measured for each test case. h and V_j are used to calculate L_c. Experiments were performed for 6 different discharges and measured data can be seen in Table 1.

Table 1. Measured data from the experiments [19]

Q_m (m^3/s)	h_m (m)	V_{jm} (m/s)	L_m (m)
0.22	0.035	7.86	5.49
0.19	0.031	7.66	5.10
0.16	0.027	7.41	5.04
0.13	0.023	7.07	4.67
0.10	0.019	6.58	4.07
0.07	0.015	5.83	3.55

The experimental data are converted to prototype values using Froude similarity law to compare with the prototype simulation results [21]. Empirical and numerical solutions are conducted using related equations and Flow 3Dv11.2 [22], respectively. Then, trajectory lengths are compared to determine the coincidence between L_m, L_c, and L_s outputs. Energy dissipation due to air resistance is calculated by subtracting the total head considering air resistance (H_{j2}) from the hypothetical total head (H_{j1}) at the bucket lip (see Figure 3).

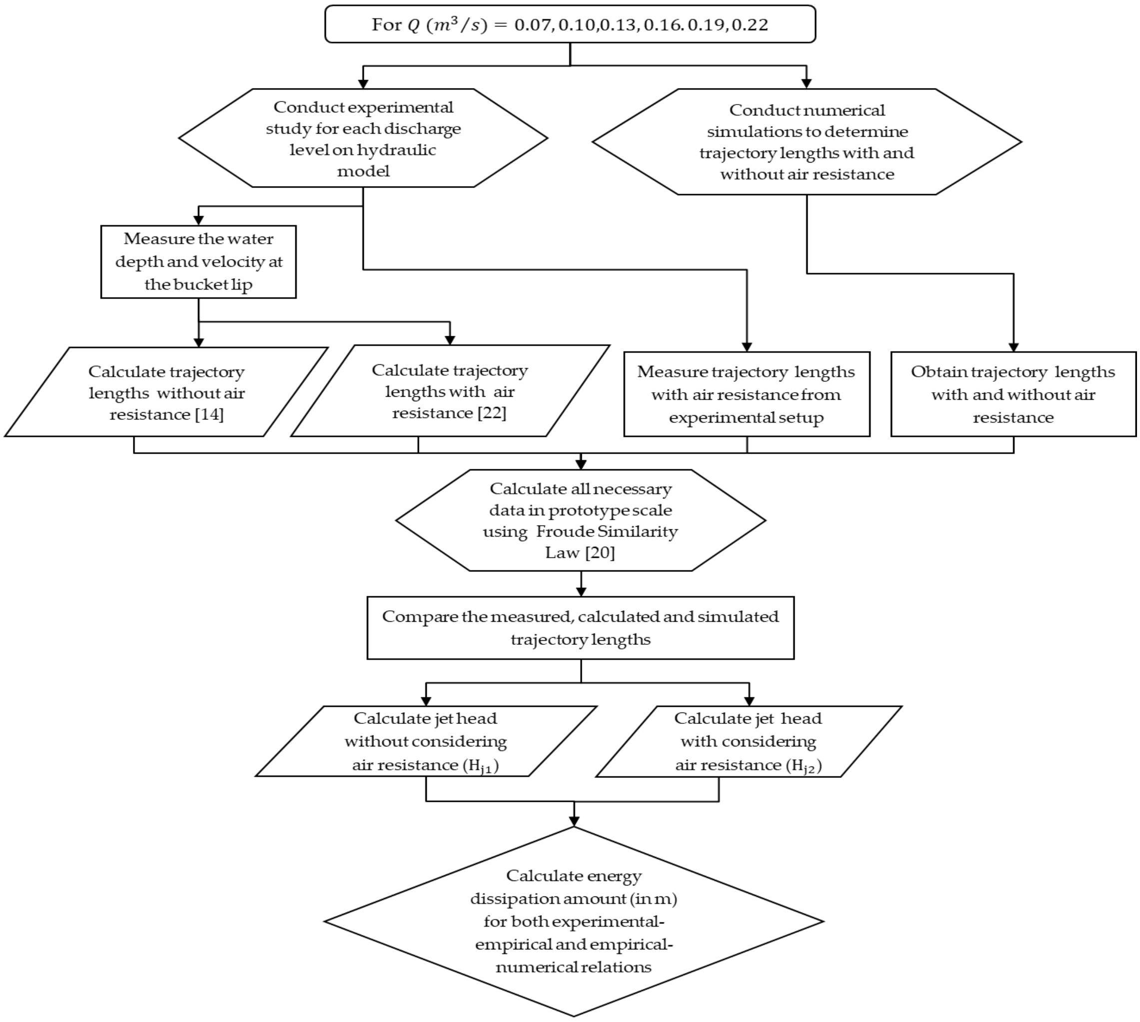

Figure 2. Flowchart of the methodology

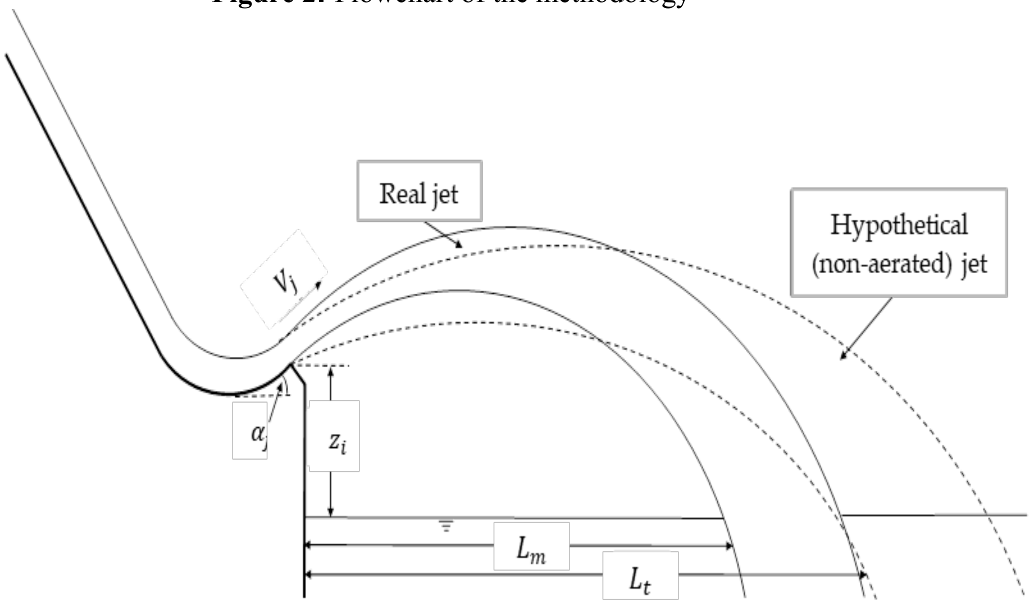

Figure 3. Sketch of L_m and L_t after the flip bucket of a spillway [20]

2.1. Calculation of Discharge Characteristics

Sharp-crested weir is a basic and suitable device for discharge measurements especially in rectangular open channel. The experimental setup includes a sharp-crested weir installed at the model exit. Measuring the head of overtopping water on the weir is used to calculate the discharge (Q_m) coming from the reservoir. A head-discharge relationship is generally governed to calculate discharge of flow over a sharp-crested weir and is shown in Equation 1;

$$Q = \left(\frac{2}{3}\right) C_d w \sqrt{2gH^3}, \tag{1}$$

where C_d is the discharge coefficient, H is the water level above the weir crest, and w is the channel width. Several studies had stated the discharge coefficient is a function of flow conditions and weir geometry. Rehbock's [23] experimental results on discharge coefficient are presented in Equation 2;

$$C_d = 0.611 + 0.08\left(\frac{H}{P}\right), \qquad \text{for } \frac{H}{P} \leq 5 \tag{2}$$

where P is the height of the sharp crested weir.

2.2. Calculation of Jet Characteristics

L_t of ski-jump jet can be calculated using projectile motion theory. The theory describes as a form of motion of a particle in a frictionless domain. Projectile motion equation can be stated as [14];

$$L_t = \frac{V_j \cos\alpha_j}{g}\left(V_j \sin\alpha_j + \sqrt{\left(V_j \sin\alpha_j\right)^2 + 2gz_i}\right), \tag{3}$$

where L_t is the trajectory length in a frictionless domain, z_i is the vertical drop from flip bucket lip to datum, V_j is the velocity of the jet at bucket lip, α_j is the bucket lip angle, (in degrees), g is the gravitational acceleration.

Kawakami [24] conducted some experiments on spillway prototypes and end up with an equation to describe air resistance effect on ski-jump jets. The equation generated by Kawakami [24] can be expressed as

$$L_c = \left(\frac{1}{gk^2}\right) \ln\left(1 + 2k\alpha V_j \cos\alpha_j\right), \tag{4}$$

where

$$\alpha = \tan^{-1}\left(kV_j \sin\alpha_j\right), \tag{5}$$

and L_c is the calculated trajectory length considering air resistance, k is the coefficient related to air resistance, and V_j is the velocity of the jet at bucket lip. Figure 4 constituted by Kawakami [24] shows the relationship between k, and V_j in prototype scale.

Reasonable coincidence is seen between the comparisons of L_m and L_c obtained from the performed experiments and calculations, respectively (see Figure 5). This matches revealed good fitness between the experimental and empirical applications.

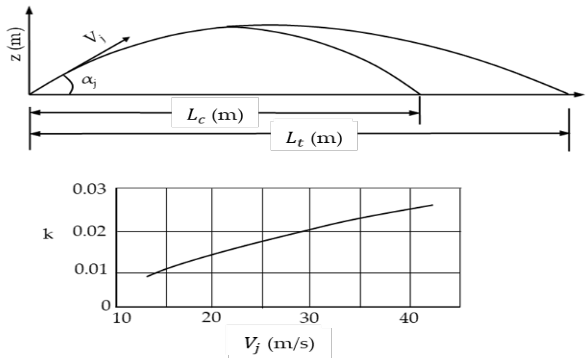

Figure 4. Relationship between k, and V_j in prototype scale, [24]

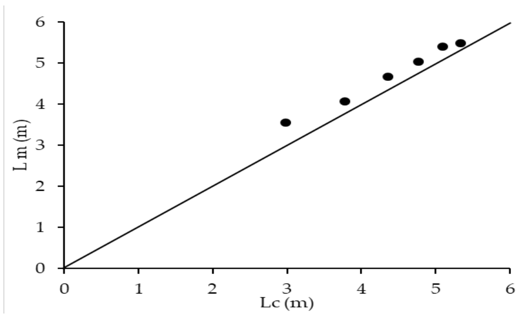

Figure 5. Comparison of L_m and L_c

To calculate energy dissipation for prototype scale, the projections of h, k and V_j are computed depending on h_m, Kawakami's [24] air resistance coefficient and V_{jm}, respectively. (Figure 6(a) and (b)). Once the required data is projected as shown in Figure 6, the prototype scale of L_t and L_c can be calculated for any discharge value using Equations 3 and 4, respectively.

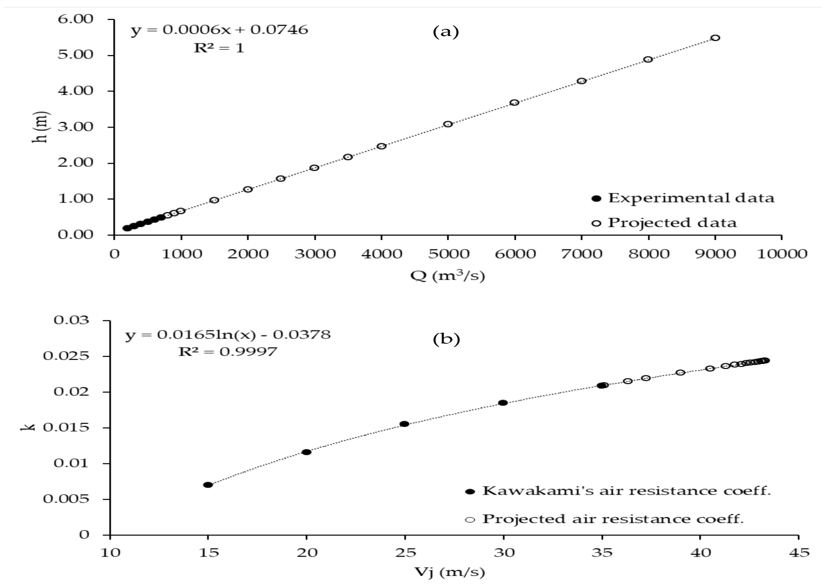

Figure 6. Projected (a) h versus Q, and (b) k versus V_j values in prototype scale

2.3. Calculation of Energy Dissipation (Head Loss)

Main purpose behind the ski-jump jets is to create energy dissipation by air resistance. Head loss due to air resistance can be estimated by comparing the throw distances calculated by Equation 3 and Equation 4. Since, L_a is shorter than L_t head loss due to air resistance can be calculated by using the following equation.

$$\mathrm{h_L} = \mathrm{H_{j1}} - \mathrm{H_{j2}}, \quad (6)$$

where h_L is the head loss due to air resistance, $\mathrm{H_{j1}}$ is the total jet head without considering air resistance obtained by manipulating Equation 3, and $\mathrm{H_{j2}}$ is the total jet head with considering air resistance. Calculated ($\mathrm{h_{Lc}}$) and simulated ($\mathrm{h_{Ls}}$) head losses will be shown in Section 3.

2.4. Numerical Simulation Method

Flow characteristics of the experimental study are re-evaluated by numerical modeling defined as Computational Fluid Dynamics (CFD) in the literature. 3D numerical model is prepared by commercially available AutoCAD software (see Figure 7).

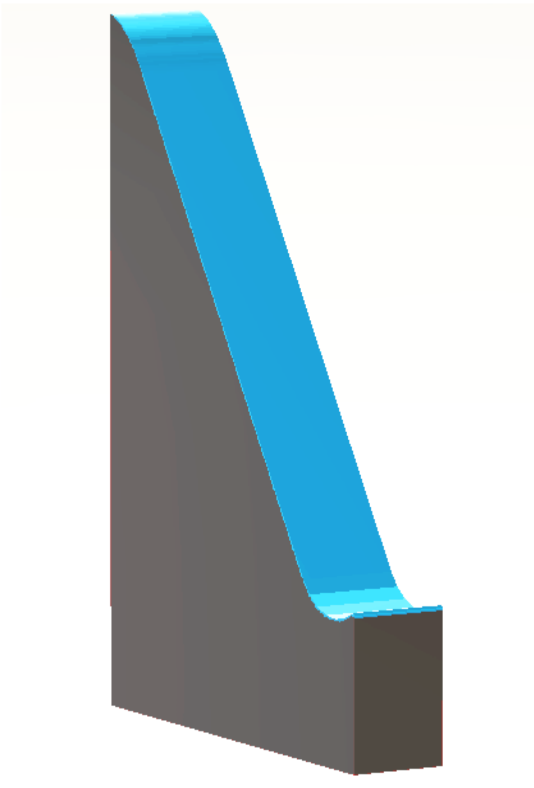

Figure 7. 3D numerical model of the spillway and flip bucket in prototype scale

Mesh format is generated to conduct simulations on the model. Mesh sizes are defined to create proper slip and wall shear stress conditions between the water and boundary of the numerical model. The numerical model is implanted in the simulation with its actual size. The mesh sizes of the water body are determined as 100 mm, 20 mm, and 50 mm in x, y, and z directions, respectively. Constant water depth and specified pressure on the spillway crest are determined for each released discharge level from the reservoir. Boundary conditions of the numerical model are identified as symmetrical for sidewalls, downstream, and at the top of the spillway. Time intervals are described according to Courant-Friedrichs-Lewy (CFL) condition.

Numerical solution for each discharge level is conducted using Flow 3D v11.2 software [22]. Flow 3D is widely used numerical simulation program which includes Volume of Fluid (VOF) and multi-block meshing techniques. Additionally, the software uses Fractional Area Volume Obstacle Representation (FAVOR) method [22]. Free gridding method is used to discretize the flow domain. In this way, the required time for the grid generation and computation significantly decreases. Fluid properties are defined as incompressible and Newtonian. The software used Reynolds-Averaged Navier-Stokes (RANS) equations to perform numerical solutions. The $k-\varepsilon$ turbulence model is used to compute turbulent viscosity and Reynolds stresses [25]. The $k-\varepsilon$ model is assumed to have some advantages especially for open channel flows having high Reynolds numbers [26,27].

Continuity and Reynolds-Averaged Navier-Stokes (RANS) equations are given in Equation (7) and Equation (8), respectively.

$$\mathrm{u_j}\frac{\partial \mathrm{u_i}}{\partial \mathrm{x_i}} = -\frac{1}{\rho}\frac{\partial \mathrm{P}}{\partial \mathrm{x_i}} + \vartheta\frac{\partial^2 \mathrm{u_i}}{\partial \mathrm{x_j}\,\partial \mathrm{x_j}} + \frac{1}{\rho}\frac{\partial \tau_{\mathrm{ij}}}{\partial \mathrm{x_j}} + \mathrm{f_i}, \tag{7}$$

$$\frac{\partial}{\partial \mathrm{x_i}}(\mathrm{u_i A_i}) = 0, \tag{8}$$

where u_i is the velocity component in i direction, x_i and x_j are Cartesian coordinates, p is the pressure, ρ is the water density, f_i is the body force, τ_{ij} is the Reynolds stress, and A_i is the fractional area in i direction. The fractional area is taken as 1 for an incompressible fluid. The Reynolds stress within $k-\varepsilon$ model can be defined as:

$$\tau_{ij} = -\rho u_i^{`} u_j^{`} = 2\rho v_t S_{ij} - \frac{2}{3}\rho k \delta_{ij}, \tag{9}$$

where v_t is the eddy viscosity, $u_i^{`}$ and $u_j^{`}$ are the fluctuating velocity components, S_{ij} is the strain-rate tensor and δ_{ij} is the Kronecker delta. Empirical definitions of v_t, S_{ij}, and δ_{ij} are given in the following equations.

$$v_t = C_\mu \frac{k}{\varepsilon}, \tag{10}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \tag{11}$$

$$\delta_{ij} = \begin{Bmatrix} 1 & if\ i = j \\ 0 & if\ i \neq j \end{Bmatrix}, \tag{12}$$

where $C_\mu = 0.09$ for standart $k-\varepsilon$ model [28].

Some sample numerical solution of (L_s) and non-aerated (L_{ts}) trajectory lengths are conducted and shown in Figure 8.

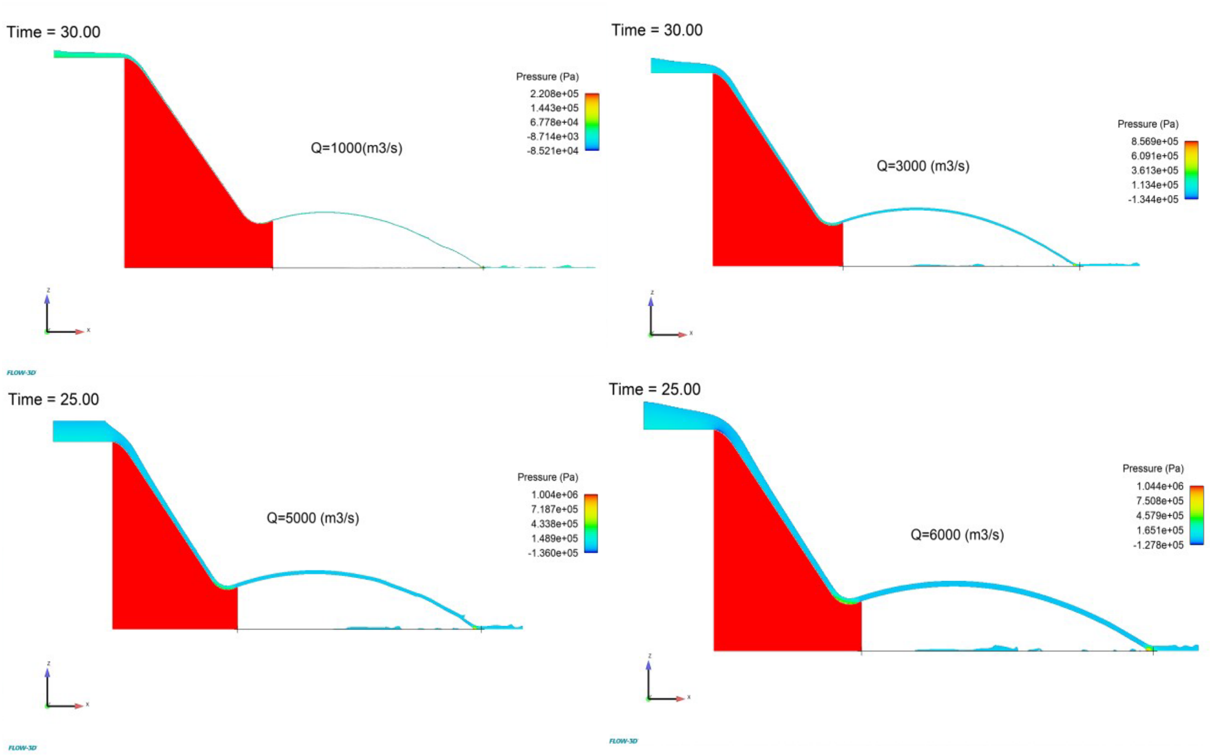

Figure 8. Sample numerical solutions of ski jump jets in prototype scale

3. The Research Findings and Discussion

Experiments were performed for 6 different discharges and measured data is converted to prototype values using Froude similarity as shown in Table 2.

Table 2. Prototype data describing the experimental cases

Q (m^3/s)	h (m)	V_j (m/s)
200	0.19	27.05
300	0.25	31.01
400	0.31	33.46
500	0.37	35.13
600	0.43	36.33
700	0.49	37.24

Benefiting from the experimental data obtained from the experimental study conducted in METU and calculated data provided by Kawakami [24], necessary data projections are computed depending on the equations and correlation coefficients from the trendlines of the existing data as shown in Figure 6. Discharge values are determined with some intervals from 200 m^3/s to 10000 m^3/s. Then all required data shown in the Equations 3, 4 and 6 are projected to calculate by empirical equations and to simulate with Flow 3D software [22]. It is possible to calculate the head loss due to air resistance for the higher discharges coming from the flip bucket with the equations obtained from the provided experimental and numerical data. By using all available information given above, head loss due to air resistance is calculated with the given formulas and simulated with the software (Figure 9).

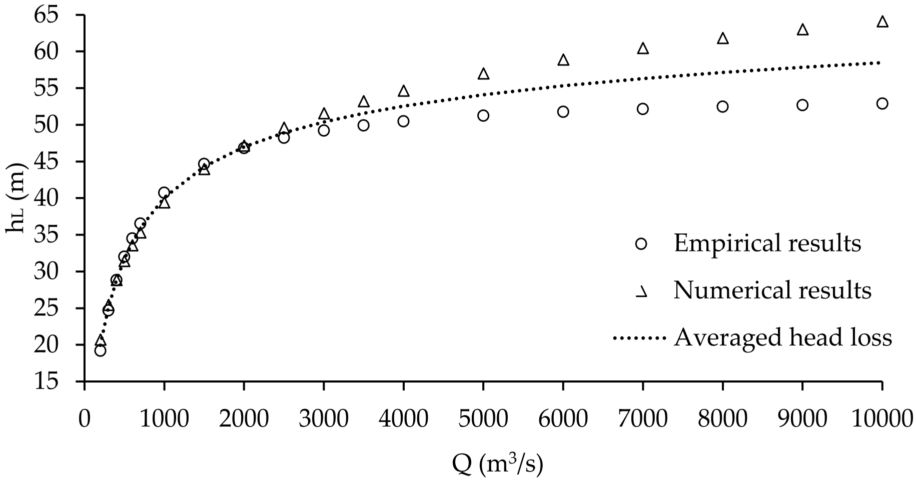

Figure 9. Head loss (energy dissipation) estimation of water jets at prototype scale due to air resistance with respect to discharge

It can be clearly seen from the revealed results in Figure 9 that the amount of energy dissipation is increase up to a certain discharge value and there is no significant increase after this value for both empirical and numerical solutions. It can be said that the energy dissipation (head loss) due to air resistance is stabilized after a certain level.

4. Conclusions

Preventing of scour at the downstream of the dam body and river bed has always been a significant phenomenon for the researchers. This study revealed a novel energy dissipation scale for ski jump jets at prototype level. The scale is obtained by comparing the experimental, empirical and numerical studies. Energy dissipation level can then be calculated by using the equation which is a function of discharge only. As given in Fig. 9, head loss due to air resistance follows a slight increase after a certain discharge level for both empirical and numerical solutions. The thickness of the released water body can cause a prevention of air intrusion into whole water jet. The empirical equation obtained from the average of conducted studies can be given as;

$$h_L = 9.6728\ln(\mathrm{Q}) - 28.417, \tag{13}$$

The regression coefficient, (R^2) of the equation is 0.9848. It should be pointed out that the Equation 13 is only valid for ski-jump jets to estimate the impingement point of the jet and the amount of head loss due to air resistance. The proposed equation can be inspected and validated for other types of energy dissipators by manipulating the required parameters. Although, high energy dissipation levels can be observed for low discharge values, the head loss follows a logarithmic trendline for high discharges (Figure 9). This trend can create a precise calculation opportunity to designers and engineers for design discharges reaching up to 10000 m^3/s.

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