Cihan University-Erbil Scientific Journal (CUESJ)

RESEARCH ARTICLE

Computations of the Effects of Flat and Sloped Steps of Stepped Spillways Types on the Size of Stilling Basin Using Computational Fluid Dynamic

Pshtiwan O. Zaid, Abdulla A. Abo

Department of Water Resources Engineering, College of Engineering, Salahaddin University-Erbil, Iraq

ABSTRACT

The objective of this study was to assess the impact of stepped spillways on the dimensions of stilling basins. This goal can be reached by using the computational fluid dynamics code FLUENT, which works with the ANSYS software. The experiment's results were used to test the code. The results from the code were identical to what the first results of the experiment showed. Then, the code was used on 45 different stepped spillways, each with three different step numbers: 20, 30, and 40 steps. Then, the code was used on each of the spillways. There are three different step slopes in this area: 0°, 6°, and 12°. There were five different flows: 0.16, 0.32, 0.48, 0.64, and 0.8 m^3/s. The study found that stepped spillways with sloped steps needed a stilling basin that was 16% shorter. This was in contrast to stepped spillways featuring level steps.

Keywords: Flat steps, sloped steps, stepped spillway, stilling basin, ANSYS-fluent, computational fluid dynamics

INTRODUCTION

Adam's spillway is an important part of managing and releasing floodwaters, making sure that extra water can safely flow through during times of heavy rain. However, spillways often have problems, such as cavitation and high kinetic energy because of the strong flow discharge.[1] Aeration devices are often put on the bottom and sides of the spillway to bring air close to the surface and lower the risk of cavitation erosion.[2] The supercritical flow conditions and high speeds make the erosive potential even worse, so effective energy dissipation mechanisms are needed to protect riverbeds and foundation structures downstream. Stepped spillways have become a promising way to improve energy dissipation. These spillways break up the flow into smaller steps, which lowers river speeds, lowers kinetic energy, and raises air entrainment rates. This makes cavitation less likely.[3] Researchers like Obaid *et al.*,[4] have done experimental studies to find out what the limits are for stepped spillways. They looked at how different downstream slope angles (25°, 35°, and 45°) and step configurations (flat, pooling, porous end sills, and gabions) affect the flow. Their findings underscore the substantial impact of end sills on flow regimes, especially in prolonging the transition flow regime and enhancing stability. Recent improvements in computational fluid dynamics (CFDs) have made it possible to do detailed numerical studies of how well spillways work. For example, Zaid *et al.*,[5] used ANSYS-FLUENT to look at how well an Ogee spillway with a bucket-type energy dissipater worked hydraulically. The numerical and theoretical results were very similar. Their research highlighted the dependability of CFD in modeling intricate flow dynamics, encompassing water surface profiles, velocity distributions, and pressure metrics. In the same way, Mamand and Zaid[6] used ANSYS-FLUENT to check the flow over a rectangular sharp-crested weir by comparing experimental and numerical results. Their research underscored the precision of the renormalization group (RNG) k-epsilon turbulence model in forecasting flow characteristics, exhibiting negligible error margins.

This research seeks to numerically examine the effects of step heights and slopes on skimming flow characteristics, with a focus on energy dissipation, building upon previous studies. We will use ANSYS-FLUENT to look at forty-five different configurations with the same chute slopes but different flow conditions. The results will help improve stepped spillway designs by making them more efficient at dissipating energy and keeping the flow stable.

Corresponding Author:
Pshtiwan O. Zaid, Department of Water Resources Engineering, College of Engineering, Salahaddin University-Erbil, Iraq.
E-mail: pshtiwan.zaid@su.edu.krd

Received: January 09, 2025
Accepted: July 12, 2025
Published: September 10, 2025

DOI: 10.24086/cuesj.v9n2y2025.pp56-60

METHODOLOGY

Using the commercial code Ansys-Fluent, numerical results are compared to the experimental data for the spillway model tested experimentally, with a specific focus paid to alternating skimming flow behavior. Different spillway configurations may then be studied using the numerical code. These sections cover the proposed numerical model's definition and implementation aspects in detail. The mesh was generated using an inflation technique near the wall boundaries to accurately capture the boundary layer (see Figure 2).

Governing Equations

The RNG k–ε° turbulence model closure is used in cooperation with a set of 3D Reynolds Averaged Navier - Stokes equations in the spillway numerical model and Hirt & and Nichols' Nichols' (1981) volume of fluid (VOF) technique. The water volume fraction (α) was used to track the free surface interface (see Figure 3). For example, the model functions as a k-w model for near-wall vortices, and as a k-e model in the free stream zone (above the pseudo-bottom), where high Reynolds number formulation of the model is quite successful. Once the mass and momentum conservation equations (Eqs.1 and Eq. 2) for each phase have been solved, the fluid volume in each domain cell may be estimated to get the free surface. Values of alpha (α) are defined by VOF, and they range from 1 to 0, which corresponds to cells filled with water or fluid 1 (f1), α value of 1; and cells filled with air air (f2), α value of 0. Volume fractions αα may be expressed as $\alpha_\alpha = 1 - \alpha_w$ in each instance, because the volume of the fluid fraction sum of air and water equals one. Each time step, the advection equation for a (Eq. 3) is used to update α. Assuming that each phase is highly viscous;, the VOF model does not include air entrainment in its calculations. To get a rough idea of the free-surface location, α = 0.5 is often used.

$$\mathrm{GY}\,\nabla.\upsilon = 0 \tag{1}$$

$$\frac{\partial\rho\bar{\upsilon}}{\partial t} + \nabla.\left(\rho\overline{u}\overline{u}\right) = -\nabla p^{*} - g.x\nabla_{\rho} + \nabla.\left(\mu\nabla u\right) + \left(\nabla u\right).\nabla\mu + f \tag{2}$$

$$\frac{\partial\alpha_w}{\partial t} + \frac{\partial\alpha_w u}{\partial X_i} = 0; 0 \le \alpha_w \le 1 \tag{3}$$

Where $x = [x, y, z]$ is the Cartesian coordinates and u is the Reynolds-averaged velocity components in the x direction. There are three variables in this equation: Time (t), gravity (g), and velocity $\left(\bar{u}\right)$. $\nabla.\left(\mu\nabla\bar{u}\right) + \left(\nabla\bar{u}\right).\nabla\mu$ is a decomposition of the shear stress tensor, f is the volumetric surface tension force, and the modified pressure (p^*).

It is possible to determine in each cell the density using (Eq. 4), the dynamic viscosity using (Eq. 5), and the turbulent viscosity using (Eq. 6), which are all functions of the water volume fraction $\alpha_w \alpha_w$.

$$\rho = \alpha_w \rho_w + (1 - \alpha_w)\rho_a \tag{4}$$

$$\mu = \alpha_w \mu_w + (1 - \alpha_w)\mu_a \tag{5}$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} = \rho C_\mu \frac{k}{\omega} \tag{6}$$

In this equation, k is the kinetic energy of turbulence, ε is the energy dissipation rate of turbulence, and ω = ε/k $\omega = \varepsilon / k$ is the specific energy dissipation rate. There are specifics to each of the variables' transport equations based on the model employed for turbulence.[7]

Boundary Conditions, Properties, and Settings

Mechanical parameters of water (pw = 998.78 kg/m^3) and air (Pa = 1.225 kg/m^3) are considered in this article, respectively, as density and kinematic viscosity, respectively, of water and air. A surface tension coefficient of 0.072 kg/s^2 was applied. Second-order discretization schemes were adopted for momentum, turbulence kinetic energy, and dissipation rate, as these are important for accurately capturing swirl flows. The pressure velocity was then connected using a SIMPLE coupled phase technique. Next, we examined hydrostatic pressure for inlet and outflow, where input water velocity on the left side. At the spillway, there was a no-slip and fixed wall, as well as an atmosphere on the top. Wall functions were used to avoid fine meshes and conserve computing resources when modeling the boundary layer at the bottom of this study. The inflow water has a depth (h) and velocity (u_x) that are used as beginning conditions at t_0 our goal was to find a differential in water flow between the input and output that was <1%. The parameters k and ω, volume percent, and mass were also set as criteria (allowing a tolerance of 10^{-3} for the residual). The compatibility with the courant number may be determined under these circumstances and with the use of a time step variable. A typical cross-section of the stepped spillway used in this study is shown in Figure 4.

CODE VALIDATION

Researchers utilize numerical data from their experiments to verify their results and to develop confidence in the correctness of their forecasts. This program requires the geometry, mesh, and processing steps be pre-defined before it can be used. We attempt to verify one model numerically against the quantity of energy dissipation found experimentally by Zhang and Liu[8] To find the most efficient way to dissipate energy at high discharges, built and tested twelve spillways made of plywood. Then, to improve energy dissipation, it was modified using two block configurations and one cascade configuration, resulting in three downstream slopes with stepped faces (27°, 32°, and 40°). Our validation use one of these cases to see the accuracy of the numerical model, a model with chute slope 27°, 4 steps, step height 3 cm, step length 5.9 cm, and q = 2.25L/s as shown in Figure 1. The experimental results show that the energy dissipation is about 43%.

Applying energy equations between U/S and D/S of the stepped spillway.

$$E_o = y_o + \frac{\alpha v_o^{\ 2}}{2g} \tag{7}$$

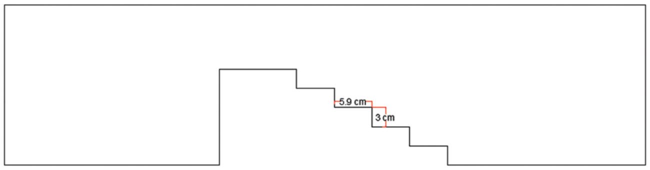

Figure 1: Stepped spillway cross-section

$$E_1 = y_1 + \frac{\alpha v_1^2}{2g} \tag{8}$$

$$\frac{\Delta E}{E_o}\% = \frac{(E_o - E_1)}{E_o}\% \tag{9}$$

Where:
E_o = U/S energy (m)
E_1 = D/S energy (m)
V_o = velocity at downstream (m/sec)
V_1 = velocity at upstream of spillway (m/sec)
α = kinetic correction coefficient, for turbulent flow, generally equal to 1.1.[9]
g = gravity acceleration (m/s^2)
$\frac{\varnothing E}{E_0}\%$ = Relative energy dissipation between U/S and D/S.

Numeric results are as follows:
$y_o = 0.225$ m
$v_o = 0.18\ m^2/s$
$y_1 = 0.024$ m
$v_1 = 1.4\ m^2/s$
$E_o = 0.2268$ m
$E1 = 0.133\ m$

$$\frac{\Delta E}{E_0}\% = 41.3\%$$

$$\%difference = \frac{Experiment - numeric}{Experiment} = \frac{43 - 41.3}{43} = 3.9\%$$

The results show a good agreement between the experiment and numeric results. The code can be used for our cases in this study.

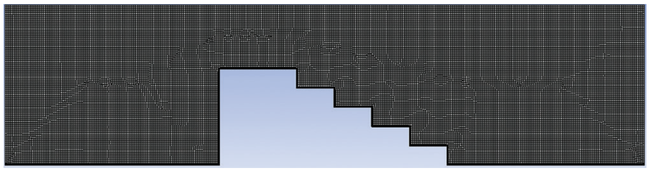

Figure 2: Spillway mesh with inflation technique

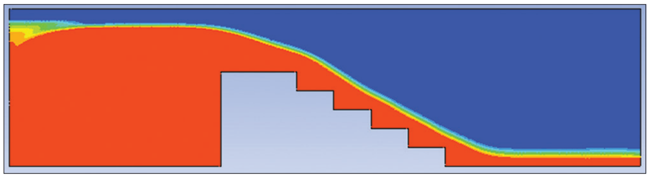

Figure 3: Water volume fraction

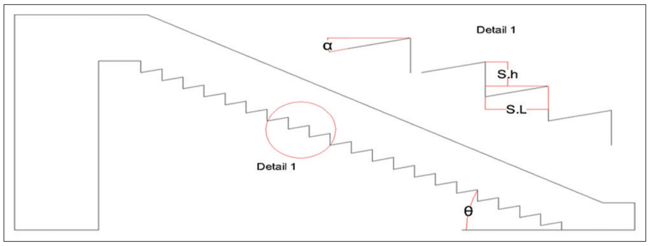

Figure 4: Typical cross-section of stepped spillway

RESULTS AND DISCUSSION

The present study quantitatively examines the impact of step height and step slope on skimming flow characteristics, with a particular emphasis on energy dissipation across forty-five distinct configurations. The setups have three different step heights (11.9 cm, 8.1 cm, and 6.1 cm) and three different step angles (0°, 6°, and 12°). They were all tested with a constant chute slope of 26° and five different discharge rates (0.16–0.8 m^2/s). The results, which are shown in Table 1, show clear patterns in the relative energy dissipation rate ($\Delta E/E_o\%$), which are very important for figuring out how stepped spillways work with water. Physical Interpretation of Flow Behavior: The data show that energy loss is very sensitive to the shape of the steps and the rate of discharge. For example, when the step angle is 0°, raising the discharge from 0.16 to 0.8 m^2/s lowers energy dissipation by about 23.5% (from 61.5% to 38%) for the 20-step setup. This trend indicates that increased discharges result in diminished relative energy dissipation, presumably attributable to the development of larger air-water interfaces and the redistribution of turbulent kinetic energy. Conversely, introducing a step angle (6° or 12°) consistently enhances energy dissipation, with the 12° angle showing the most pronounced effect. For instance, when q = 0.32 m^2/s, the dissipation rate goes up from 51.2% (0°) to 60% (12°) for the 20-step setup. This behavior can be explained by the fact that inclined steps cause more flow disruption and vortex generation, which leads to more energy loss.

Depending on equation-7-9, the numerical results are listed below:

The results and the visual data in Figures 5-7 show that sloped stepped spillways lose energy at a faster rate than flat

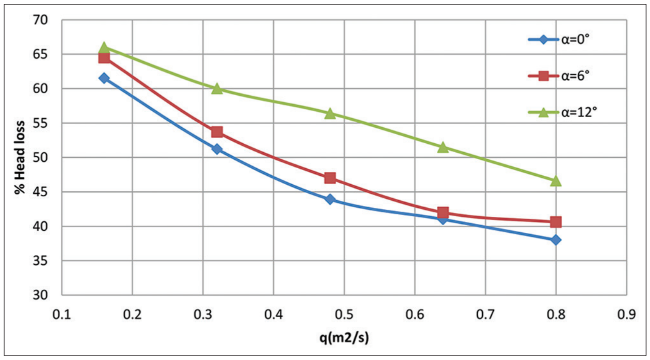

Figure 5: Discharge and relative energy dissipation relations for 20 steps

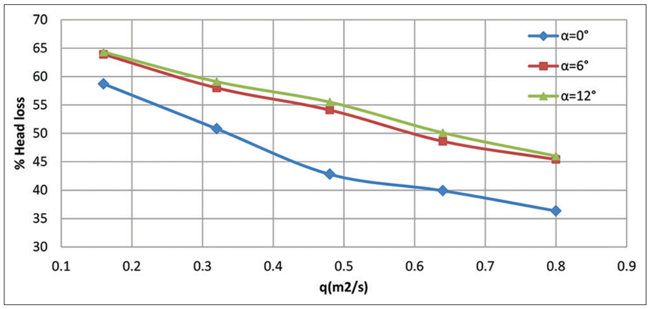

Figure 6: Discharge and relative energy dissipation relations for 30 steps

Table 1: Relative energy dissipation rate for all configurations

Steps	Step angle(α)	Step height (m)	Step length (m)	Chute angle (θ)	q (m^2/s)	$\Delta E/E_0$%
20	0	0.119	0.25	26	0.16	61.5
20	0	0.119	0.25	26	0.32	51.2
20	0	0.119	0.25	26	0.48	43.9
20	0	0.119	0.25	26	0.64	41
20	0	0.119	0.25	26	0.8	38
20	6	0.119	0.25	26	0.16	64.5
20	6	0.119	0.25	26	0.32	53.7
20	6	0.119	0.25	26	0.48	47
20	6	0.119	0.25	26	0.64	42
20	6	0.119	0.25	26	0.8	40.6
20	12	0.119	0.25	26	0.16	66
20	12	0.119	0.25	26	0.32	60
20	12	0.119	0.25	26	0.48	56.4
20	12	0.119	0.25	26	0.64	51.5
20	12	0.119	0.25	26	0.8	46.6
30	0	0.081	0.167	26	0.16	58.7
30	0	0.081	0.167	26	0.32	50.8
30	0	0.081	0.167	26	0.48	42.8
30	0	0.081	0.167	26	0.64	39.9
30	0	0.081	0.167	26	0.8	36.35
30	6	0.081	0.167	26	0.16	63.9
30	6	0.081	0.167	26	0.32	58
30	6	0.081	0.167	26	0.48	54.1
30	6	0.081	0.167	26	0.64	48.6
30	6	0.081	0.167	26	0.8	45.4
30	12	0.081	0.167	26	0.16	64.3
30	12	0.081	0.167	26	0.32	59.1
30	12	0.081	0.167	26	0.48	55.5
30	12	0.081	0.167	26	0.64	50.1
30	12	0.081	0.167	26	0.8	46
40	0	0.061	0.125	26	0.16	60
40	0	0.061	0.125	26	0.32	54.4
40	0	0.061	0.125	26	0.48	49
40	0	0.061	0.125	26	0.64	44.7
40	0	0.061	0.125	26	0.8	40.7
40	6	0.061	0.125	26	0.16	60.5
40	6	0.061	0.125	26	0.32	55.3
40	6	0.061	0.125	26	0.48	49.9
40	6	0.061	0.125	26	0.64	47
40	6	0.061	0.125	26	0.8	43.5
40	12	0.061	0.125	26	0.16	63.4
40	12	0.061	0.125	26	0.32	55.9
40	12	0.061	0.125	26	0.48	50.9
40	12	0.061	0.125	26	0.64	49
40	12	0.061	0.125	26	0.8	45

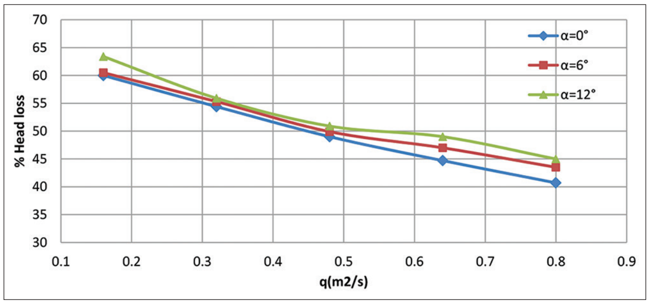

Figure 7: Discharge and relative energy dissipation relations for 40 steps

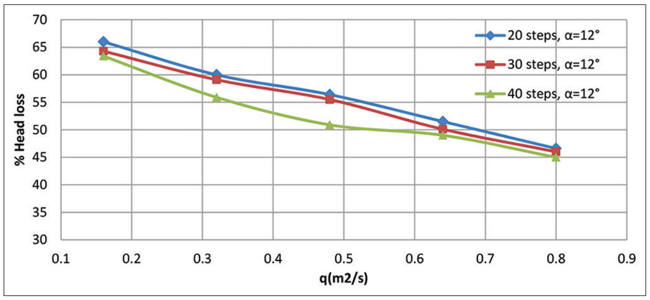

Figure 8: Discharge and energy dissipation relations for 20, 30, 40 steps and α = 12°

stepped spillways. The better performance is due to the inclined geometry, which causes more turbulent flow and more air to be entrained, which makes the overall energy dissipation more efficient. Furthermore, when the hydraulic flow conditions are the same, raising the step height makes the energy dissipation rate go up even more. This implies that, besides the slope, the geometric arrangement of the steps-particularly their height-substantially contributes to the improved hydraulic efficiency of stepped spillways.

The study showed that making the steps steeper greatly speeds up the rate at which energy is lost along the stepped spillway. The main reason for this improvement is that the flow has more gravitational force and the turbulence is stronger because of the steeper gradient. Together, these two things make energy loss more effective. The analysis also showed that lowering the number of steps can increase energy dissipation even more when the slope is at its highest. This is probably because fewer steps at a steeper angle make each step higher, which makes the hydraulic impact and energy conversion mechanisms stronger. Figure 8 clearly shows these results. It shows how the shape of the steps affects the amount of energy lost when the slope changes.

Length of Stilling Basin

$$\frac{y_2}{y_1} = \frac{1}{2}\left[\sqrt{1+8F_1^2} - 1\right] \quad (10)$$

$$F_1 = \frac{V_1}{\sqrt{gy_1}} \quad (11)$$

Length of cistern = 6 $(y_2 - y_1)$ $6(y_2 - y_1)$ (12)

Length of cistern for 20 steps, q = 0.8m²/s, and α = 0° = 5.57

Length of cistern for 20 steps, q = 0.8m²/s, and α=12° = 4.66 m

Difference between cistern length of (α = 0° and α = 12°) = 16%

CONCLUSION

This research aimed to optimize energy dissipation at high discharges, as multiple studies have shown that energy dissipation diminishes with increasing discharge. The flow rate was increased in each case. The study found that in stepped spillways, a higher ratio of flow energy dissipation is reached when the number of steps is lowered and the steep slopes are raised. This is different from flat stepped spillways. The results from all cases indicate that 20 steps and an angle of α = 12° are most effective at dissipating energy, achieving approximately 46.6% for maximum discharge. The length of the stilling basin will change depending on how much energy is lost. When energy losses go up, the length of the stilling basin will go down. The study found that for the critical case (20 steps and q_{max} = 0.8m²/s), the length of the stilling basin will go down by 16% when α = 12° instead of α = 0°.

REFERENCES

1. J. Peakall and J. Warburton. Surface tension in small hydraulic river models - the significance of the weber number. *Journal of Hydrology New Zealand*, vol. 35, no. 2, pp. 199-212, 1996.
2. H. Chanson. *Air Bubble Entrainment in Free-Surface Turbulent Shear Flows*. vol. 20. Elsevier, Netherlands, pp. 630-647, 1996.
3. N. Rajaratnam. Skimming flow in stepped spillways. *Journal of Hydraulic Engineering*, vol. 116, no. 4, pp. 587-591, 1990.
4. N. Obaid, S. Alghazali and S. M. Jasim. Experimental study on the limits of flow regimes for different configurations of stepped spillway. vol. 6, no. 6, pp. 30-40, 2014.
5. P. O. Zaid, P. O. A. Abo, A. K. Fatah and A. H. Ibrahim. Computation of hydraulic performance for ogee spillway with bucket-type energy dissipater using CFD. *The 3rd International Conference on Engineering and innovative Technology ICEIT2024 Salahaddin University-Erbil*, 2024.
6. B. S. Mamand and P. O. Zaid. The validation of rectangular sharp crested weir flow using ANSYS-FLUENT. *ZANCO Journal of Pure and Applied Sciences*, vol. 36, pp. 27-34, 2024.
7. ANSYS. *Ansys Fluent-Solver Theory Guide*. ANSYS, United States, 2021.
8. F. Zhang and H. Liu. Experimental study on energy dissipation ratio of pure steps on stepped spillway. *Shuili Fadian Xuebao Journal Hydroelectric Engineering*, vol. 34, no. 4, p. 87-100, 2015.
9. H. Rouse. Open channel flow. By F. M. Henderson. Macmillan, 1966. 522 pp. $14.95. *Journal of Fluid Mechanics*, vol. 29, no. 2, pp. 414-415, 1967.