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Effect of Vertical Screen on Energy Dissipation and Water Surface Profile Using Flow 3D

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ABSTRACT

Dissipating the energy downstream hydraulic structures is the main concern of hydraulic engineers when designing such structures. Many authors examined the dissipation of energy downstream hydraulic structures in the laboratory by using different tools such as stilling basins, blocks, increasing the bed roughness and using pendulum sills. Most authors studied how to dissipate the energy experimentally while few used mathematical models. Mathematical models are less expensive and time consuming than experimental work. In this study, Flow 3D software is used to examine the effect of installing a vertical screen downstream hydraulic structure as an energy dissipater device. In order to verify results of the mathematical model, a comparison between an experiment carried out in a flume in the hydraulic laboratory at Zagazig University and Flow 3D software results, has been carried out. After verification, water surface profile was studied using the mathematical model and also energy dissipation under different flow conditions.

1. Introduction

Energy dissipation downstream hydraulic structures is one of the main targets of the hydraulic structures designers. Control structures are structures provided by a device such as a gate to control the flowing water. Downstream hydraulic structures, a hydraulic jump (free or submersed) is formed in which the supercritical flow is transformed to subcritical flow combined with energy dissipation. Design engineers always provide the structures with a device to increase energy dissipation downstream the structure. There have been theoretical and experimental studies to understand the energy transformation process and consequently the applications of energy dissipaters [1-4].

In this study flow 3D software is used to study the effect of using vertical screen with fixed height and width and number of holes as a device to dissipate energy and to study its effect on water surface profile. The software model is verified by comparing with experimental test carried out in a flume located at the hydraulic laboratory-water and water structure engineering department- Zagazig university. Flow 3D software results is very close to the experimental results with maximum deviation of 13%. After verification of the software, the location, height and width of screen is fixed as recommended by Suzan et al. (2021) [5]. Series of tests are carried out with different Froude Number and gate opening in order to

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study the effect of screen on energy dissipation and on the water surface profile.

2. Literature review

The main requirement demanded downstream hydraulic structures is the dissipation of water energy. This can be attained by expansions as by France (1981) [6], steps and roughened bed as by Bejestan and Neisi (2009) [7], pendulum sills as by Aya O. K [8]. (2018), Samah et al, (2019) [9] or using screen as by Suzan et al, (2021) [5].

The screen shape was studied Rajaratnam and Hurtig (2000) [10], experimentally showed that a single wall or a double wall screens with 40% porosity are effective in energy dissipation through small hydraulic structures and better than classical hydraulic jumps.

Cakir (2003) [11], experimentally for Froude numbers range of 5 to 18, porosity ratios were 20% to 60%, and different screen locations. energy dissipation was better than classical jumps.

Balkiş (2004) [12], Studies energy dissipation using inclined screen. 40% screen porosity with different Inclination angle, screen thickness with different locations with 100 times range from the gate. The screen inclination results have an insignificant effect on the energy dissipated compared to vertical screens.

Bozkus et al. (2006) [13], studied the jump behavior for triangular and circular screens experimentally and studying the effect on the hydraulic jump characteristics and the energy dissipation. The experimental work showed that vertical and inclined screens dissipate energy more than classic jump for studied Froude numbers that were 7.5 to 25.5.

Bozkus et al. (2007) [14], studied the effect of Vertical screen, it was found that the vertical screen was more effective from the energy dissipation point of view.

Mahmoud et al. (2013) [15], experimentally studied screen with circular and square holes through experimental. He concluded that the performance of the screen decreases with increasing of Froude number for both types of holes. The results also showed that the screen with square holes dissipate energy better than that with circular holes.

Sadeghfam et al. (2014) [16], studied experimentally the double screens for variable Froude number, screen arrangements, and screen porosity. The studied Froude numbers were in the range 2.5 to 8.5, porosity ratios were 40% to 80%, and distances of double screens between 1 and 5 centimeters. The double screens jump dissipated more energy. specially The double screen of 40% porosity. Hence, Froude number was found to be the most effective parameter,

Fathi-Moghadam et al. (2017) [17], used mathematical models to simulate the perforated sill as method to control the hydraulic jump.

Rasoul et al, (2017) [18], analyzed numerically the behavior of flow through screens to study the water surface profile and energy dissipation.

The supercritical Froude number varied in the range of 2–10 and screens with porosities of 40% and 50%. Numerical water surface profiles and energy dissipation were validated by author’s experimental data. They derived a set of equations in terms of depth ratio of hydraulic jump through the perforated screen for submerged and free hydraulic jump.

Abbaspour et al. (2019) [19], examined the hydraulic jump characteristics on the reverse bed with porous screens. The study results showed that the adverse stilling basin with screens having the ability to dissipate energy greater than that corresponding stilling basin without screen The screen porosity was studied by Daneshfaraz et al. (2019) [20], to determine and select the best screen porosity that improve the characteristics of the hydraulic jump in the prismatic stilling basins. It was found that a screen porosity of 40% to 50% gave energy loss more than that of other porosities.

El-Tohamy E. (2019) [21], examined by using both experimental and using Flow 3D the improvement of performance of Gabion spillways under different flow conditions. He concluded that Flow-3D program gives results with ±5% error in upstream depth and energy dissipation. This ratio indicates accepted accuracy to use this program in similar cases simulations.

Rasoul Daneshfaraz et al, (2021) [22], investigated the effect of dual horizontal screens on a vertical drop equipped with experimentally. the relative critical height was ranged from 0.077 to 0.242. no effect for the relative screens distance on the residual energy. The results also showed that the dual screens cause subcritical flow instead super critical of downstream the drop.

Rasoul Daneshfaraza et al. (2021) [23], investigated experimentally the effect of vertical screens pore size on energy dissipation located at the downstream of vertical drop.

3. Experimental Setup

In order to verify the Flow 3D software, experimental tests were performed in a re-circulating flume of 0.30 m in width, 0.468 m in depth and 15.6 m in length with working section of 12.50 m in length as shown in photo (1). A centrifugal pump lifts the water from a sump tank to the flume inlet. The discharge of the flume is measured by a calibrated orifice meter. To adjust the required tail water depth, the tail gate can be gradually screwed until the considered depth. A point gauge was used to measure the water levels with an accuracy of ±0.1 mm.

Photo (1) Photo 1 Used flume

Screens 22 centimeter in width and 3 centimeter height having 24 holes of 1.00 centimeter diameters and with relative holes' area 0.285 cm2 were used to compare the water surface profile resulting from both the experimental work and Flow 3D model. The vertical screen model was built from clear Perspex, then placed at a distance of 10 centimeters from the gate in a sudden expanding stilling basin with a constant expansion ratio (e=1.35) downstream the vertical gate. The water level is measured along the centerline of the flume.

The comparison between the experimental and Flow 3D results as shown in figure 1, showed that the difference between both results did not exceed **14%** from which one can consider the results from Flow 3D is acceptable.

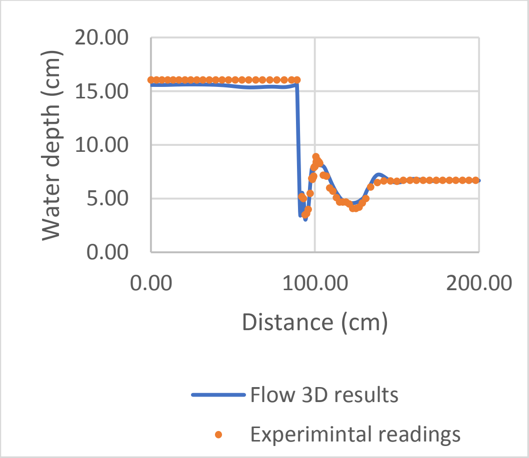

Figure 1 comparison between experimental and Flow 3D results

4. Materials and Methods

Flow-3D provides a complete and versatile computational fluid dynamics (CFD) simulation platform for engineers investigating the dynamic behaviour of liquids and gas in a wide range of industrial applications and physical processes. Flow-3D focuses on free surface and multi-phase applications. Flow-3D delivers high accuracy simulation results faster by using the industry-leading algorithm True VOF. Flow 3D software solves numerically the Naiver-Stokes equation by finite volume method. A pioneering volume of fluid tracking method, True volume of fluid continues to set the industry standard for flow accuracy since its inception since 1976.

A three-dimensional model was prepared for the case study flume and screen. All stages of model construction were conducted in AUTOCAD 3D. The used units in the model is (centimeter in lengths, gram in masses and second in times).

5. Equations Software Flow 3D

Continuity equation in three-dimensional Cartesian coordinates (x, y, z) is given by:

$$v_f \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(uA_x) + \frac{\partial}{\partial x}(vA_y) + \frac{\partial}{\partial x}(wA_z) = \frac{P_{SOR}}{\rho} \tag{1}$$

Where, $(u,\ v,\ w)$ are the velocity components in the coordinate directions axis (x, y and z). (A_x, A_y and A_z) are cross-sectional areas of flow in the coordinate (x, y and z) directions,ρ is density and P_{SOR} is the source term and v_f is the volume fraction of the fluid.

Three-dimensional momentum equations are given by:

$$\frac{\partial u}{\partial t}+\frac{1}{v_f}\left(uA_x\frac{\partial u}{\partial x}+vA_y\frac{\partial u}{\partial y}+wA_z\frac{\partial u}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial P}{\partial x}+G_x+f_x \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{1}{v_f}\left(uA_x\frac{\partial v}{\partial x}+vA_y\frac{\partial v}{\partial y}+wA_z\frac{\partial v}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial P}{\partial x}+G_y+f_y \tag{3}$$

$$\frac{\partial w}{\partial t}+\frac{1}{v_f}\left(uA_x\frac{\partial w}{\partial x}+vA_y\frac{\partial w}{\partial y}+wA_z\frac{\partial w}{\partial z}\right)=-\frac{1}{\rho}\frac{\partial P}{\partial x}+G_z+f_z \tag{4}$$

Where, P is the pressure of the fluid, (G_x, G_y and G_z) are body acceleration in the coordinate direction (x, y, and z), and (f_x, f_y and f_z) are viscosity accelerations in the coordinate direction (x, y and z).

In order to model a free surface, the boundary between water and air, the volume of fluid function (F) should be defined to meet the following governing equation, If F (x, y, z, t) is equal to 1, the control volume will be full of fluid, and if F is equal to 0, no fluid will exist in a control volume. Furthermore, in the case of a free water surface, F is shown to have a value between 0 and 1. Applying function F to the equation:

$$\frac{\partial}{\partial t}+\frac{1}{v_f}\left[\frac{\partial}{\partial x}(FA_xu)+\frac{\partial}{\partial y}(FA_yv)+\frac{\partial}{\partial z}(FA_zw)\right]=0 \tag{5}$$

6. Turbulence Models

Flow 3D offers several types of turbulence models such as: Mixing length model, k-ε equation, RNG model and large eddy simulation model. Turbulence models that have been recently proposed are based on Reynolds averaged Navier–Stokes equations. This approach involves statistical methods in order to extract an averaged equation related to the turbulence quantities.

7. Numerical Simulation Algorithm

The equation discredited using a finite difference method, whereas, a Flow-3D adopts a finite volume method using a finite difference method plus a Fractional Area and Volume Obstacle Representation method. The calculation is carried out based on a grid unit. That is, the velocity can be computed for the given pressure at each grid and using the velocity, the value of a pressure equation in the form of a Poison equation can be calculated. Then, the velocity can be adjusted to the computed value. The volume of fluid method for Flow-3D adopts accurate pressure and kinetic boundary conditions and describes movement between two fluids using a special numerical difference method in order to prevent the boundary face from smearing. A difference equation of the governing equation can be solved with an explicit method except for pressure terms of momentum equation and flow velocity term of a continuity equation.

8. Boundary and initial conditions

The boundary conditions were defined as walls in the bed and both sides, volume flow rate in the upstream varied in each model to simulate experimental discharge which taken as (6, 7, 8.29, 9.03, 9.99, 11 and 12 l/sec) in this work, gate opening (which taken as 1.0, 1.75 and 2.5 centimetre) and tail water depth at the downstream which fixed as 17 centimetres in this work.

9. Results and discussion

The results include both the water surface profile along the centreline of the flume and the relative head losses in the energy due to the screen located at fixed selected location and height as followings:

9.1 Water surface profile

For the water surface profile and for the seven selected discharges, it is found that due to using the screen to dissipate energy the water surface profile just downstream the gate is decreased compared to the normal water level at the tail, then the water level increased to be higher than the tail water level. The water surface start to be normal without the effect of the screen after a distance depending on the gate opening for gate opening 1 centimetre the distance for water to be stable is 7.0 the tail water depth (as shown in figure 2).

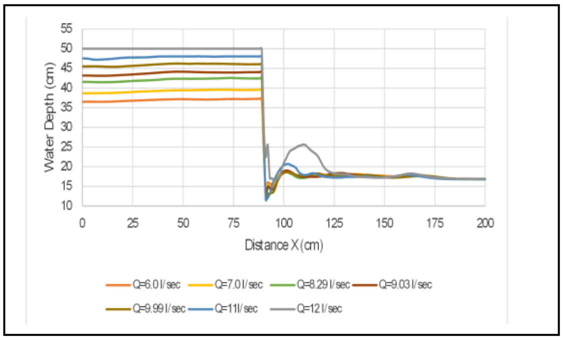

Figure 2 Water Surface profile with different discharges at gate opening 1 cm

For gate opening 1.75 centimetre the distance for water to be stable is 8.25 the tail water depth (as shown in figure 3).

For gate opening 2.50 centimetre the distance for water to be stable is 9.50 the tail water depth (as shown in figure 4).

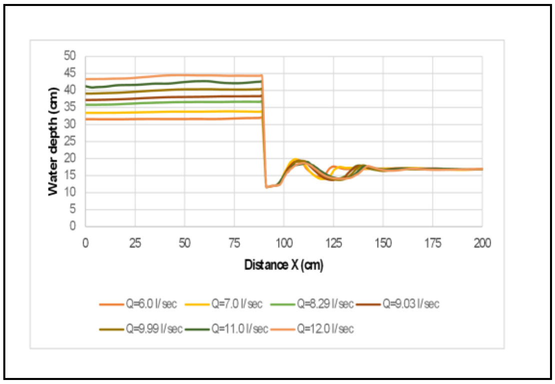

Figure 3 Water Surface profile with different discharges at gate opening 1.75 cm

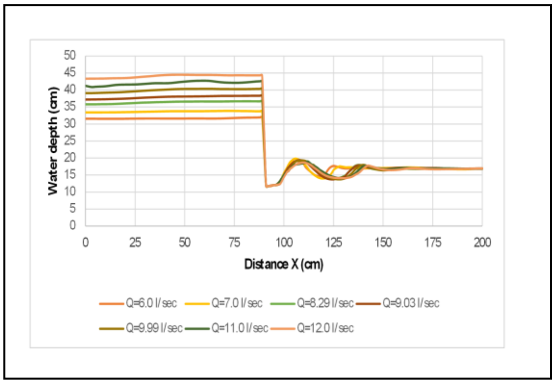

Figure 4 Water Surface profile with different discharges at gate opening 2.5 cm

9.2 Froude Number

It is well understood that for the same discharge in the flume as the water depth decreases Froude number increases

Froude number start to be constant along the canal centreline when the water surface profile starts to become constant. Figure 5 through figure 7 show that the distance in which Froude number is constant which is 7, 8.25 and 9.5 times the tail water depth.

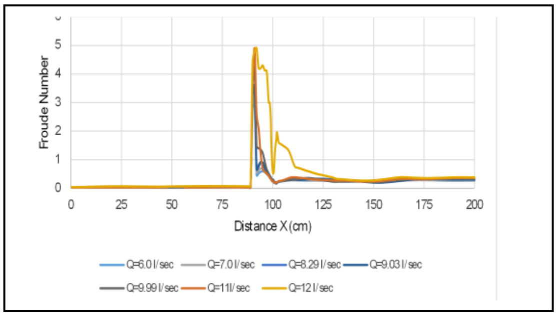

Figure 5 Froude Number with different discharges at gate opening 1.0 cm

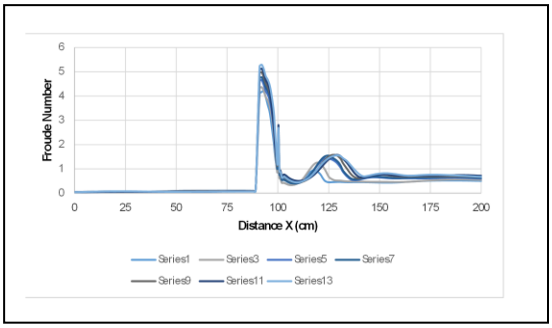

Figure 6 Froude number with different discharges at gate opening 1.75 cm

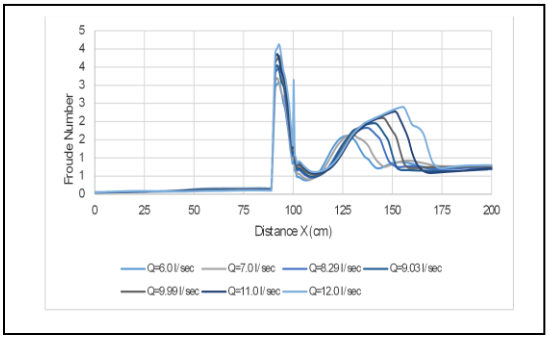

Figure 7 Froude number with different discharges at gate opening 2.5 cm

10. **Effect of head losses**

As shown in figure 8, the relative head losses are affected by the gate opening and as the gate opening increases the relative head losses are increased.

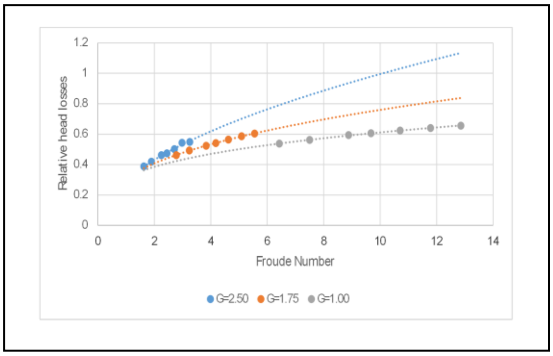

Figure 8 Relative head loss with Froude number For different gate opening

11. **Conclusions and recommendations**

From the experimental work it is clear that using a screen downstream vertical gate is an effective tool to dissipate energy. The only disadvantage of the screen as an energy dissipation tools is its effect on the water surface profile. It was concluded that the water levels increase according to the gate opening as it reached 20% of the tail water depth for gate opening 2.50 centimetres and 40% for small gate opening 1.0 centimetre.

Notations

CFD	Computational fluid dynamics
VOF	Volume of fluid
cm	Centimetre

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