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Effects of different shaped baffle blocks on the energy dissipation and the downstream scour of a regulator

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ABSTRACT

The scouring problem caused by the flow movement in the downstream areas of hydraulic structures is an issue that keeps its actuality. In order to prevent these scouring to occur in the downstream, various typed energy dissipaters are placed on the downstream of the hydraulic structures. Factors such as sediment type, the velocity of the stream, and flow regime play an important role in scouring. In order to prevent scouring, the flow's energy must be dissipated before meeting the sediment. In this study, it is aimed to reduce the amount of scour occurred at the downstream of the weir by using energy dissipaters with different geometries. The flow and scouring events on the weir were modeled in two dimensions using Computational Fluid Dynamics (CFD). The findings were compared for different downstream conditions and the results were discussed in this respect.

1. Introduction

Scouring is a serious problem that occurs when hydraulic projects are not designed correctly. This problem can often be seen in cases where flow is transferred from a high energy point to a downstream. Energy breaker basins are being constructed in the downstream to prevent this scouring. However, in some cases these basing alone are not sufficient. In order to avoid this situation, different types of sill and baffle structures are placed in the basins. These structures, by breaking the energy of the flow in the basin, can greatly prevent the sediment behind the structure to be scoured. When the relevant articles in the literature are look over, it is revealed that the scouring problem is a present problem, and it is a subject that should be emphasized especially in hydraulic structures.

Emiroğlu et al. (2017) uses different shaped antivortex structures into a trapezoidal labyrinth weir to improve the discharge capacity of weir and to determine their effects on scour occurrence. In the article which different types of antivortex are tested, the design that provides the best discharge rate was determined. In addition, in the article, it has been observed that use of antivortex in weirs reduces the maximum scour depth.

Xiong et al. (2014) states that the main reason for the collapse of the bridges on the river is scouring. The article points out that 60% of the 1000 bridges located in the United States of America were demolished due to scour in past 30 years. This also shows how the issue is serious. The article reveals the level of the problem and presents a model that is intended to be implemented the numerical analysis. This model guides researchers in order to get more accurate results in the numerical environment. The comparative results with the experiments also show that the model used is compatible with the experimental results.

Referring to the importance of experimental studies, Aydın and Işık (2015) explained the topicality, advantages and disadvantages of advanced CFD software on examples.

In the study done by Tao and Yu (2014), the flow conditions at the bridge piers with different geometric shapes are numerically investigated. In the study, vortex occurrence, velocity counters and shear stress forces are determined and

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compared. The scouring caused by the forces acting on the bridge piers are also examined. The findings are discussed.

This study is a continuation of the study conducted by Aydın et al. (2017) using the numerical method to examine the amount of scour occurring in the downstream of an Ogee type regulator. In the Aydın et al. (2017), a sill structure of 50x40 cm was placed at the end of the stilling basin in the downstream zone of the regulator. Despite this placed sill, scouring rates were observed at high flow in the downstream zone of the regulator. In this study, baffles were placed in the stilling basin of the regulator and baffles were placed in different shapes and the scouring status was re-examined.

2. Method

In this article, a computational fluid dynamic (CFD) method, FLOW-3D, which is the same method used at Aydın et al. (2017) was used. FLOW-3D is a widely used tool to simulate fluid dynamics in many engineering branches. FLOW-3D solves the equations of fluid motion such as, mass protection, momentum and energy equations in two or three dimensions. CFD models usually use the volume of fluid (VOF) method when defining free surface flows. The general mass continuity equation for fluid motion is given as below (Flow-3D, 2014):

$$V_F\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}(\rho uA_x)+R\frac{\partial}{\partial y}(\rho vA_y)+\frac{\partial}{\partial z}(\rho wA_z)+\xi\frac{\rho uA_x}{x}=R_{\mathrm{DIF}}+R_{\mathrm{SOR}} \qquad (1)$$

where;

V_f is the volume of fraction of open to flow,

ρ is the density of fluid,

R_{DIF} is a turbulent diffusion term,

R_{SOR} is a mass source,

u, v, w are the velocity components in the coordinate directions (x, y, z).

In this study, to simulate the scour process, sediment scour model defined in the FLOW-3D was used. There are two process to do it by FLOW-3D. They are called suspended and packed sediment. Suspended sediment is able to move at low concentrations in the fluid flow. For the packed sediment, the critical Shields number was empirically defined by Soulsby-Whitehouse equation as follows (Soulsby, 1997):

$$\theta_{\mathrm{cr},i}=\frac{0.3}{1+1.2d_{*,i}}+0.055\left[1-\exp\left(-0.02d_{*,i}\right)\right] \qquad (2)$$

where;

$d_{*,i}$ is a dimensionless parameter and computed as below:

$$d_{*,i}=d_i\left[\frac{\rho_f\left(\rho_i-\rho_f\right)\|\mathbf{g}\|}{\mu_f^2}\right]^{\frac{1}{3}} \qquad (3)$$

where;

ρ_i is the sediment density,
ρ_f is the density of the fluid,
d_i is the diameter of sediment,
μ_f is the dynamic viscosity of fluid,
$\|g\|$ is the magnitude of the gravitational acceleration.

Volumetric bed-load transport rate defined by Meyer-Peter and Müller (1948) is:

$$q_{b,i}=\Phi_i\left[\|\mathbf{g}\|\left(\frac{\rho_i-\rho_f}{\rho_f}\right)d_i^3\right]^{\frac{1}{2}} \qquad (4)$$

where;

Φ_i is the dimensionless bed-load transport rate.

3. Computational Domain, Mesh and Boundary Conditions

Preferred regulator which is the source for this article, has been designed giving a maximum flow rate. The regulator is connected to the stilling basin with a 4.5 m diameter curved arc. A sill structure of 40x50 cm was applied at the end of the stilling basin. Regulator geometry used in the previous study was transferred to the numerical environment without changing the mesh and boundary conditions. The crest height was taken as 5 m. The threshold structure at the end of the regulator is also left at the same place. The newly added baffles are located 6 m away from the regulator. Figure 1 illustrates the 2D geometry of ogee profile and stilling basin with dimensions. As shown in Figure 2, baffles with different geometries (rectangular, stepped, right triangular and equilateral triangles) were placed in the stilling basin. The ground material used to determine the amount of scouring is a 1.0 m thick cohesionless sand. In the 2 dimensional modeled study, 12750 high qualities (max. aspect ratio = 1.00) mesh were used. In order to observe turbulence effects more effectively, RNG (Renormalized Group) turbulence model was preferred. In order to estimate the bed-load transport, Meyer-Peter, Müller formula described with equation (4) was also used. The physical specifications of the bed-load sediment are given in Table 1:

Table 1. Physical specifications of the sediment

Sediment Characteristics	Values
Species bed-load	Coarse sand
Species diameter (m)	0.005
Sediment Density (kg/m^3)	2400
Critical Shields number	0.05
Angle of response (degree)	32

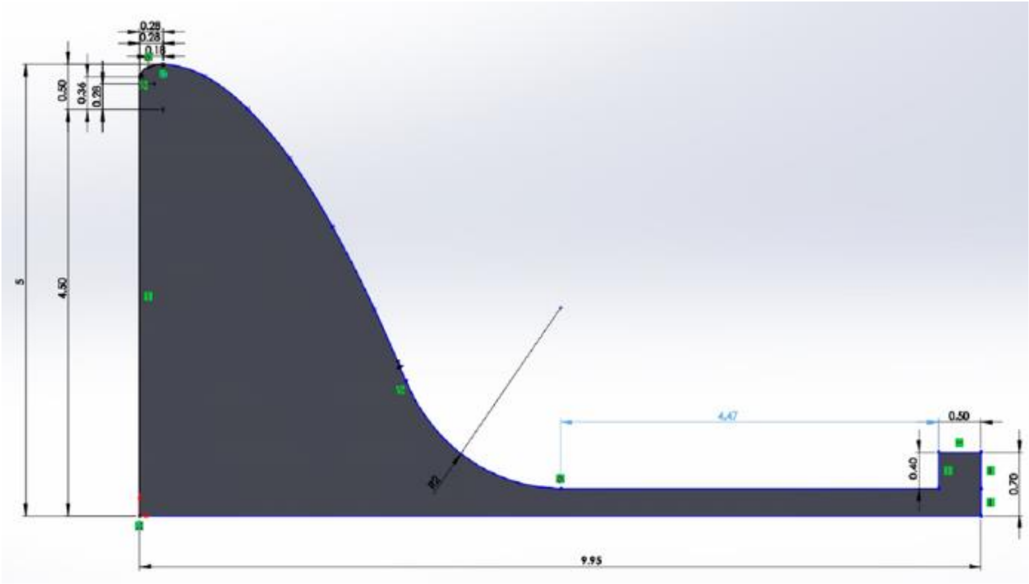


Figure 1. 2D geometry of ogee profile and stilling basin (dimensions in meter) (Aydın et al. 2017)

No-Baffle

Baffle Type I

Baffle Type II

Baffle Type III

Baffle Type IV

Baffle Type V

Figure 2. Selected baffle geometries on stilling basins

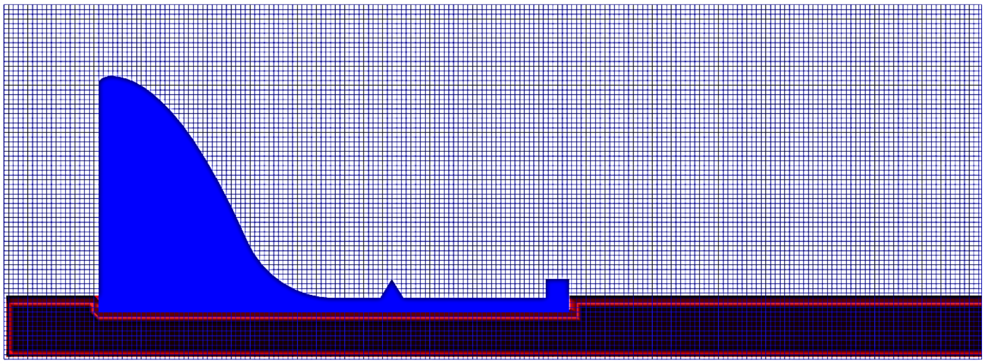
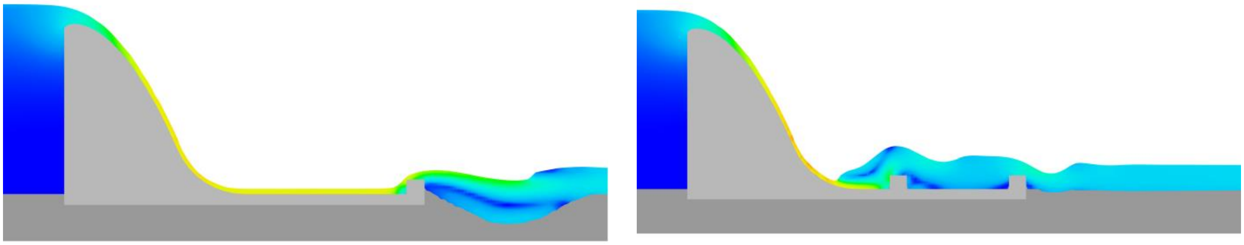


Figure 3. Mesh structures of the numerical models

4. Numerical Analysis

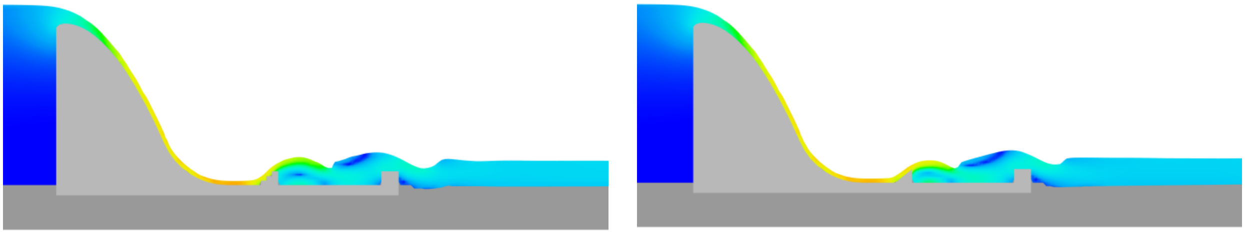
Numerical analyzes were carried out for different flow conditions. For the study, unit flows q = 0.93 and 1.07 $m^3/s/m$ were studied as the previous study. These flow rates are the values at which the highest number of scours are observed before the baffle is placed.

Solutions were conducted for 1800 sec. In the light of the information obtained from previous studies, it is known that a period of approximately 9-12 hours is necessary for the scouring to reach a stable level. In addition, it is known that 75% and 85% of the scouring takes place in the first half-hour and one-hour period. Since numerical modeling takes an important time for 2D models, a half-hour solution time is considered sufficient to give an idea of how the scouring will begin and how much it will be scoured. In Figures 4 and 5, the unit flow rates for the $q=0.93\ m^3/s/m$ and $q=1.07\ m^3/s/m$, and the scouring time developed over time in the sediment at the downstream of the regulator is given. As shown in Figures 4a and 5a, for no-baffle condition, the hydraulic jump in the stilling basin had not been met and therefore the scour in the downstream increases by time since the energy of the stream has not been dissipated. In types I, IV and V, the hydraulic jump occurs after before the baffles while no-hydraulic jump for type II and Type III. Additionally, for type II, the hydraulic jump occurs in stilling basin between the sill and baffle while any hydraulic jump is not observed in Type III condition for 1.07 $m^3/s/m$ as shown in Fig. 5. The situations show that the stepped upstream face of the type II baffle (Fig. 5c) is more effective than the smooth face of the type III with respect to energy dissipation for relatively low discharge. Among the all baffle types, the type IV presented the best performance when considering hydraulic jump which ensures energy dissipation effectively. Although the all baffle types with a sill present an effective protection with regard to the scour downstream of the structure, the best protection is also provided by type IV. The effect of baffles on the downstream scour can be clearly seen in these figures when comparing with no-baffle condition.



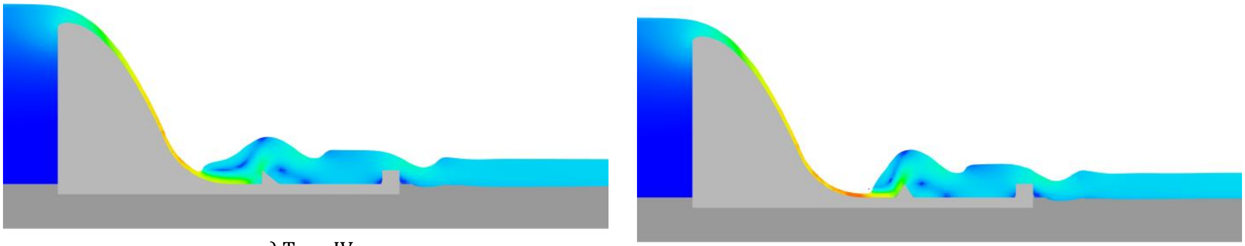
a) No-baffle

b) Type I



c) Type II

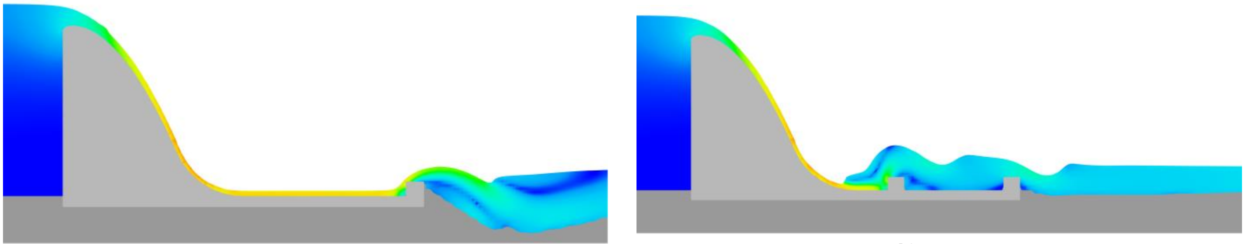
d) Type III



e) Type IV

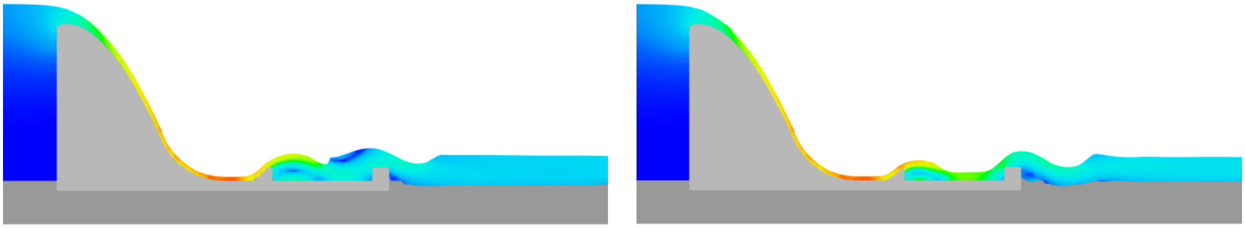
f) Type V

Figure 4. Developed scour at downstream of regulator for $q=0.93\ m^3/s/m$



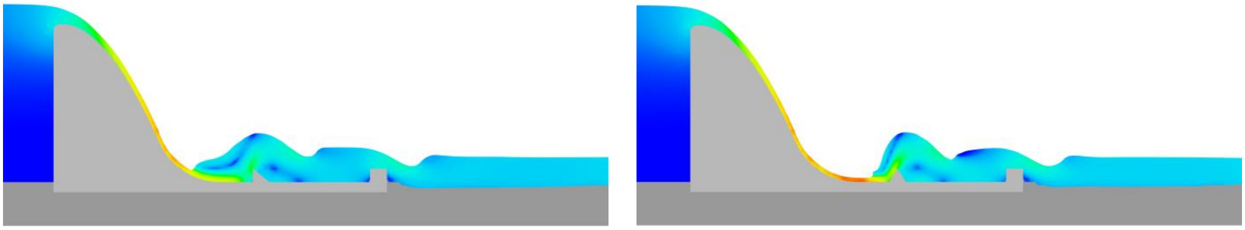
a) No-baffle

b) Type I



c) Type II

d) Type III



e) Type IV

f) Type V

Figure 5. Developed scour at downstream of regulator for q=1.07 m³/s/m

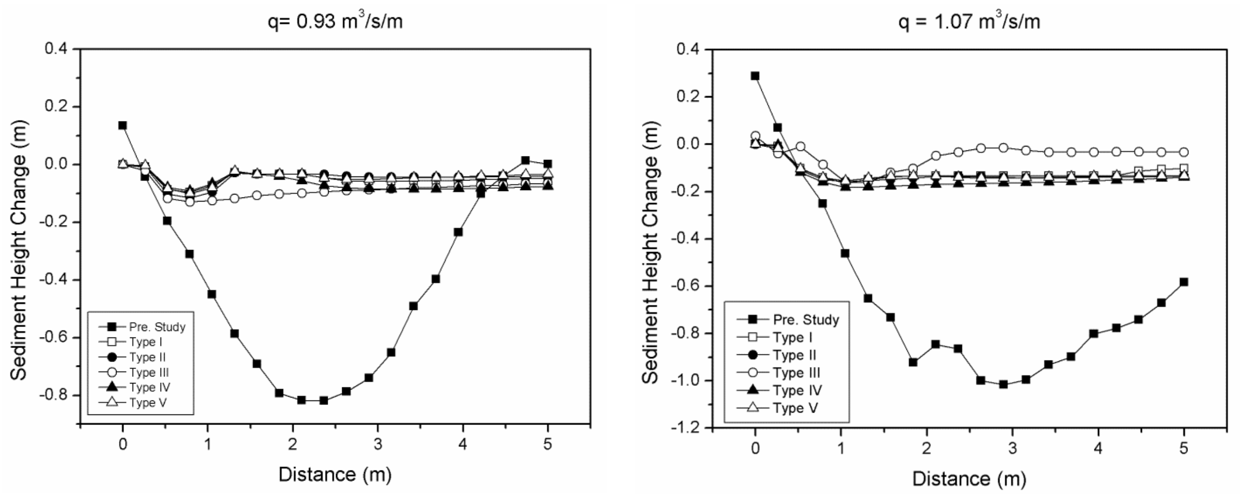


Figure 6. Equilibrium scour profiles at downstream of the flows along the 5-meter long

To show the effects of the baffle types on the scouring more clearly, the equilibrium scours profiles downstream of the sill were plotted in Figure 6. From the figure, the energy of the flow is dissipated due to hydraulic jumps in the stilling basin for q =

0.93 and 1.07 $m^3/s/m$. For this reason, scouring does not occur since the low-energy flow passing through the downstream region. However, in the no-baffle condition, the flow energy could not be dissipated because the hydraulic jump does not occur in the stilling basin as seen in the figures. That's why, flow with high kinetic energy has caused scour by passing through the downstream zone. The results show that the baffles blocks reduced the scouring by approximately 80% to %90 regarding the no-baffle condition.

4. Conclusions

The energy dissipation and scouring occurrence at the downstream of the hydraulic structures are very important for the structure safety. In this study, the effects of different types of baffle blocks placed on the stilling basin of a regulator's energy dissipation and scouring were investigated by using CFD analysis. The results obtained from the study were outlined as follows:

1. The baffle blocks of all types considerably prevent the scouring downstream of the structure. The most effective baffle shape is found Type IV which has a triangular shape with vertical upstream face.
2. Type IV is also the best energy dissipater among the all used shapes due to generating hydraulic jump at the downstream.
3. The Type III is the most ineffective with regards to generating hydraulic jump as well as energy dissipation.
4. The results from the CFD analyses show that the baffles blocks used with a sill reduced the scouring by approximately 80% to %90.
5. The study shows that the Computational Fluid Dynamics (CFD) technics can be useful to design the hydraulic structures and analyze them easily according to experimental studies.

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