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INVESTIGATION OF ENERGY DISSIPATION AND SEDIMENT SCOUR OVER A REGULATOR USING CFD

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Abstract

Computational Fluid Dynamic (CFD) software hold an important place in hydraulic engineering as well as in other engineering fields. Use of CFD software in the hydraulic field can also provide reliable and accurate results. Indeed, hydraulic and hydrologic factors play key roles in addition to static and dynamic loads acting on water structures. In this study, flow dynamics on a sample regulator structure are investigated by using FLOW-3D software program. The study investigates the energy dissipation on the spillway and downstream sediment scour of a regulator for different flow conditions. Thus, using of numerical methods were discussed in this respect.

Introduction

Regulators are mainly used water structures on the streams for many kinds of purposes. Engineering designs of regulators are usually conducted under static and dynamic loads, but the hydraulic and hydrological effects are not often considered during the design process. For this reason, regulators built on the loose grounds exposed to severe flow conditions over time can be damaged by local scours in the downstream region. Recently, Computational Fluid Dynamics (CFD) are frequently used to determine velocity vectors, pressure, fluid characteristics, etc. of the flows. In this sense, FLOW-3D numerical analysis software program is an important tool in terms of predicting the scour and pressure parameters that may occur in the downstream part of the river depending on the sediment and water flow rate at the base of the structures to be built on the river. The majority of the studies related to scouring and sediment transport in the literature are concerned with

scouring of sediment-free water jets. Even though there are several scours related paper exists, no similar work exists on the topic of this article in the literature.

Ghodsian et al. (2012) discuss the scour problems and their characteristics (i.e. discharge, tailwater) experimentally. Unlike many other publications related scouring, Ghodsian et al. (2012) investigated the effects of sediment-carrying water jet. As a result, it has been observed that the sediment-carrying water jet reduces the problem of scouring. In the experimental study of Dey and Sarkar (2008), the scour occurred in the downstream of an apron due to submerged-jet was investigated in terms of velocity and turbulence characteristics. Thus, as the velocity of the submerged-jet increases, the amount of scouring downstream of the apron increases. In another study by Ghodsian et al. (2006) investigates how the depth of the tailwater affected the amount of scouring. In the study, it is said that the low and high tailwater depth is related to the size of the scour. It has been determined that the scouring decreases at high tailwater depths. In another experimental study of Dey et al. (2007), the scouring of a water jet falling on a uniform spot of sand and gravel from a high point has been investigated. The article has carried out dimension analysis by specifying important parameters encountered in this process. It was observed in the article that the equilibrium scour depth increased as densimetric Froude number increased. However, the depth of scouring has been observed to decrease with increasing sediment size and tailwater depth. Some other scour related articles other than above in the literature can be stated as Doehring and Abt (1994), Pagliara et al. (2008), Balachandar et al. (2000), Kurniawan et al. (2004) and Dey and Westrich (2003).

In this study, it will be dwelled on the scour problems in the downstream of hydraulic structures. As an example, the scour at a regulator for different spillway discharges were analyzed by using CFD and discussed.

Scour in Hydraulic Structures

Scour in the downstream of hydraulic structures is one of the most important problems in the civil engineering. Large of scouring in the base of hydraulic structures may cause severe damages and even collapse the structures. Because of this, the scouring in the hydraulics structures must be forecasted and must be taken precautions. The most important reason of scour is the kinetic energy of downstream flow. This energy must be

absorbed by any energy dissipation devices i.e. baffle, sill or stilling basin. It is difficult to estimate scour phenomenon because of complex fluid-solid flow dynamics and their interactions. Therefore, to estimate scour dimensions for any hydraulic structures, experimental tests or based on them empirical formulas have been generally used up to now. However, a different experiment and formula are required for each different model, and these model and formulas give different results. In addition, these physical model experiments are quite costly and time consuming. Recently developed Computational Fluid Dynamics (CFD) techniques may be a good alternative for analyzing scour problems as used in many different areas.

In the past, many serious scouring cases had been occurred in the world. Especially, after large amount water were discharged over spillways in flood period, serious scour may occur at downstream of dams. Many dams such as Kariba Dam (Zimbabwe), Ukai Dam (India), Kilickaya Dam (Turkey), Keban Dam (Turkey) were exposed to scour after their spillways operated with high discharges (Yıldız, 2001).

Used Method

As an example, the scour at the downstream of a 2D ogee-crested regulator was analyzed by using FLOW-3D. FLOW-3D is general-purpose computational fluid dynamics (CFD) software. CFD is a computer solution technique which solves the governing equations of fluid motion (the mass conservation, momentum, and energy equations) by two or three dimensionally. These governing equations are discretized and are solved by using some numerical methods. Fluid flows can be expressed with non-linear, second-order, transient differential equations. The fluid motion is computed by solving these equations, and thus the simulation of fluid flows realized. To describe of free surface flows, the volume of fluid (VOF) method is generally used in the CFD models for simulation of free surface flows. The general mass continuity equation for fluid motion is given as below (FLOW-3D, 2014):

$$V_f \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + R \frac{\partial}{\partial y}(\rho v A_y) + \frac{\partial}{\partial z}(\rho w A_z) + \xi \frac{\rho u A_x}{x} = R_{\text{DIF}} + R_{\text{SOR}} \quad (1)$$

where; V_f is the volume of fraction open to flow, ρ is the density of fluid, R_{DIF} is a turbulent diffusion term, and R_{SOR} is a mass source. u , v , w are the velocity components in the coordinate directions (x , y , z).

The sediment scour model defined in the FLOW-3D was used to simulate scour process at the downstream of a hydraulic structure in this study. In FLOW-3D the sediment transport occurs in two ways: suspended and packed sediment. Suspended sediment moves with low concentration in fluid flow. For moving of packed sediment, the critical Shields number was empirically defined by Soulsby-Whitehouse equation as follows (Soulsby, 1997):

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

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

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

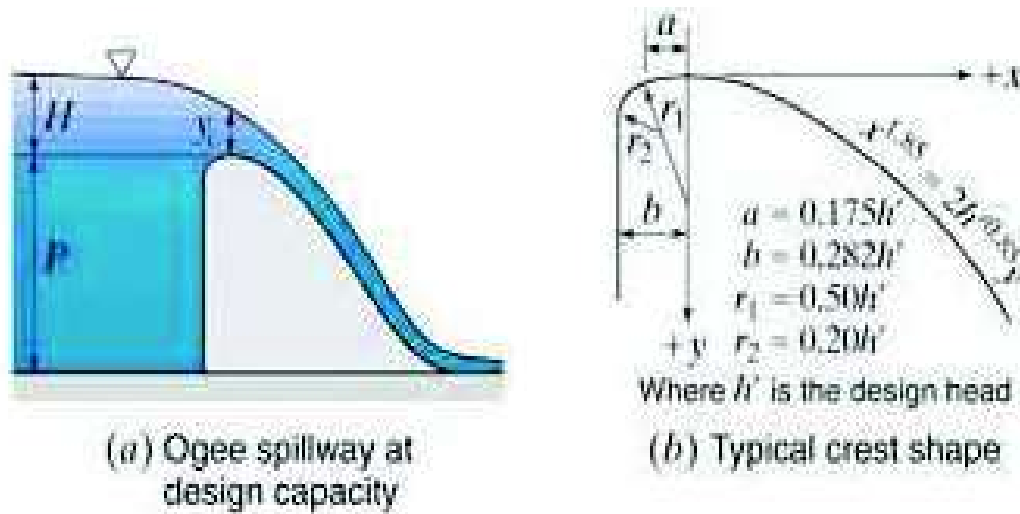
in which ρ_i is the sediment density, ρ_f is the density of fluid, d_i is the diameter of sediment, μ_f is the dynamic viscosity of fluid, $\|g\|$ is the magnitude of the gravitational acceleration. Meyer, Peter and Müller (1948) describe the volumetric bed-load transport rate as follows:

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

in which Φ_i is the dimensionless bed-load transport rate.

In this study, regulator size calculations designed by Ogee-crested were used. Ogee-crested regulator design is the most common hydraulic structure used in its own field to date (Ahmed, 2011). Characteristics of an Ogee-crested regulator types can be seen in the Fig. 1 below.

Fig. 1. Ogee-crested Regulator Types



Source: Finnemore et al., 2002, web-1)

The calculations used in the model is shown in Fig. 1 (b). In the model, height of P was chosen as 5 m. In the study, the design head (H) was taken at different values to observe the scour occurred at the regulator downstream.

Computational Domain, Mesh and Boundary Condition

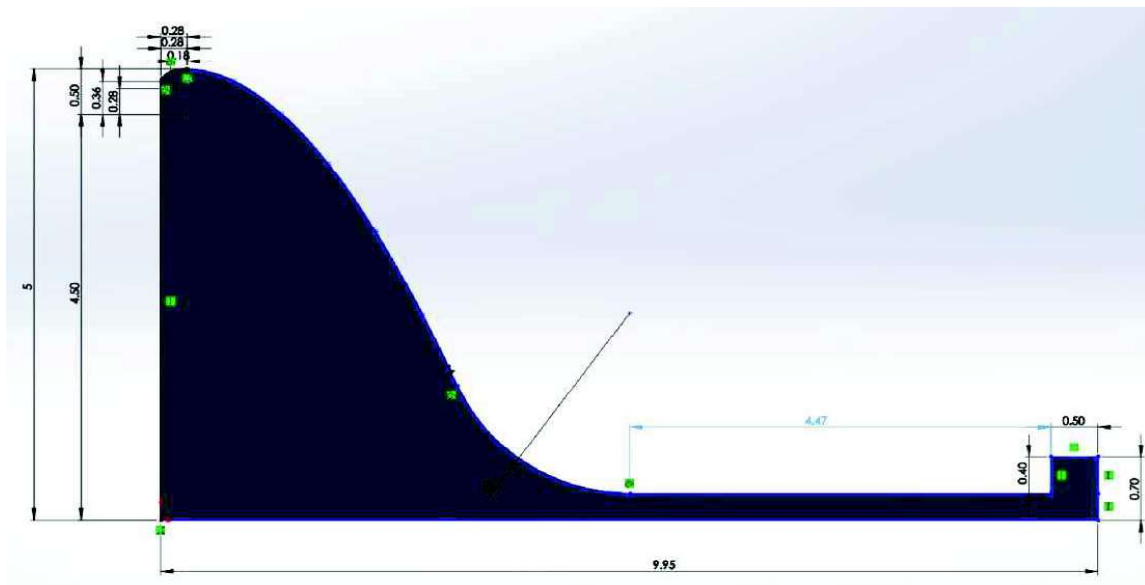
For CFD solutions, an Ogee profile was obtained for a given maximum flow rate and crest height. The stilling basin where the hydraulic jump will take place is connected by a curved arc to the basin of about 4.5 m in length. At the end of the stilling basin, an energy dispersion baffle of size 0.4x0.5 m was placed. The generated geometry is given in Fig 2. A 1.0 m thick cohesionless sand base placed at the foundation of the solid model prepared for the numerical model reaching to the downstream. 12750 high quality (max. aspect ratio = 1.00) structured mesh were used in the two-dimensional model. The RNG (Renormalized Group) turbulence model were used for considering turbulence effects on the scour. Meyer-Peter, Müller formula described above was also used for estimating of bed-load transport. The physical properties of the bed-load sediment subjected to scouring are given in Table 1:

Table 1. Physical Specifications of The Selected Sediment

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

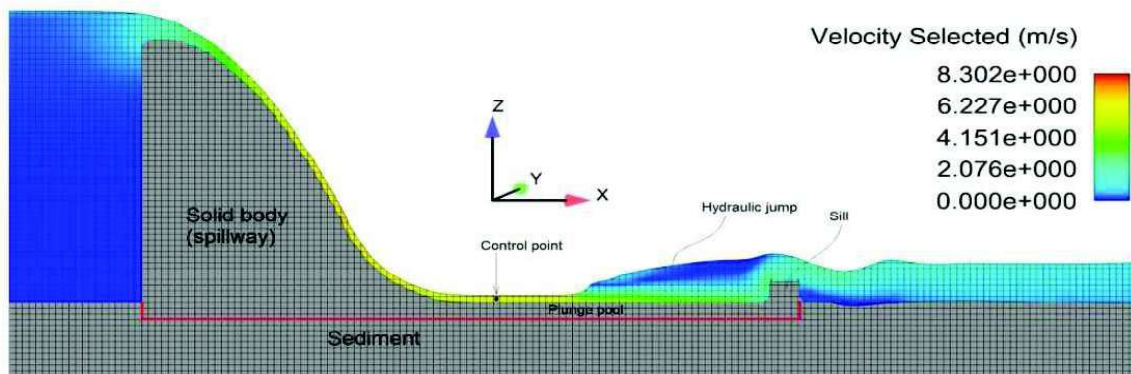
Source: own research

Fig. 2. 2D Geometry of Ogee profiles and Stilling Basin (dimensions in meter)



Source: own research

Fig. 3. Mesh Structures of Numerical Model

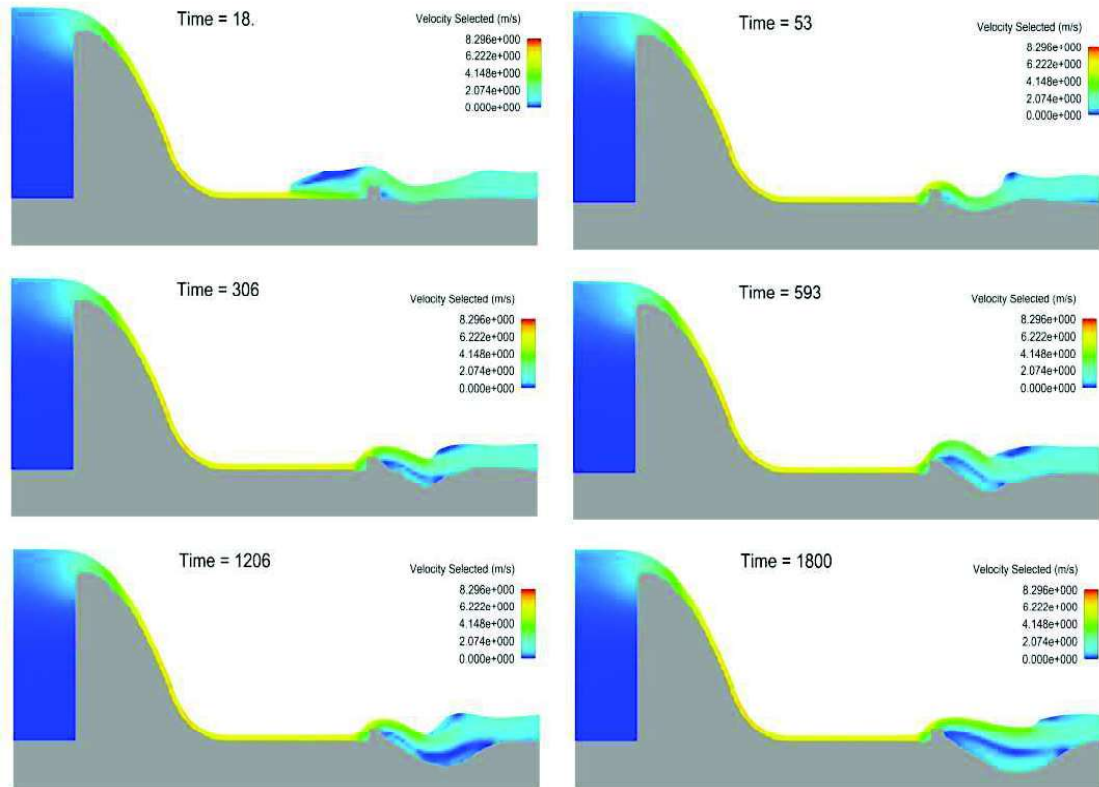


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Numerical Analysis

Numerical analyzes were carried out for different flow conditions with unit flow $q = 0.54-1.07 \text{ m}^3/\text{s}/\text{m}$ and Froude number $Fr = 5.45-6.27$ before the hydraulic jump in the stilling basin. Solutions were conducted for only 30 min. It is stated from the previous studies that a period of approximately 9-12 hours is required for scour to become stable. However, it is also known that 75% and 85% of the scouring occurs within the first half hour and one hour period. Since numerical modeling takes a considerable amount of time for 2D models, but a half-hour solution time is considered enough to give an idea of whether the scour will start and how much scour will take place. In Figure 4, flow state for $q=0.93 \text{ m}^3/\text{s}/\text{m}$ unit flow rate and the scouring developed at the downstream of the regulator by time was given. At the end of this given model, the conditions for hydraulic jump in the stilling basin are not met and therefore the scour in the downstream increases by time since the energy of the stream is not broken.

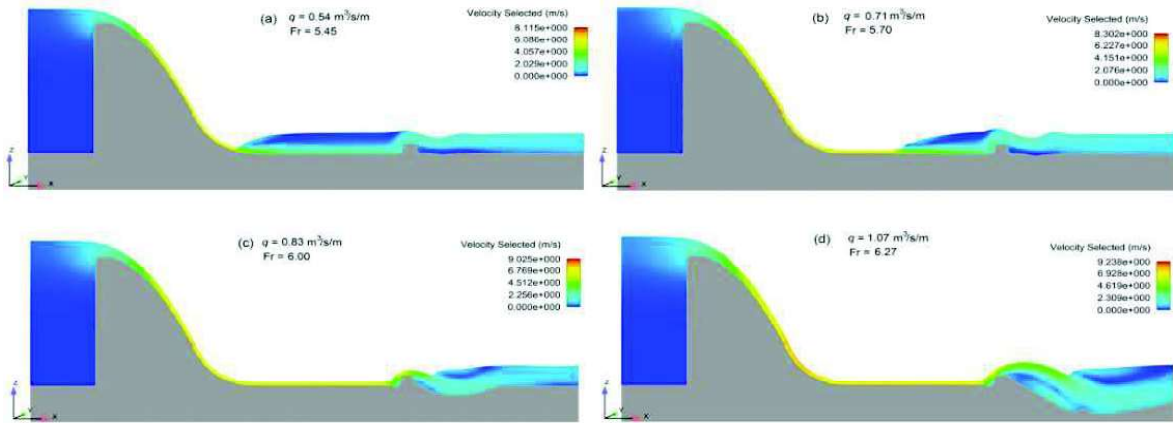
Fig. 4. Developing of Scour at Downstream of Regulator with Time ($q=0.93 \text{ m}^3/\text{s}/\text{m}$) (Time in second)



Source: own research

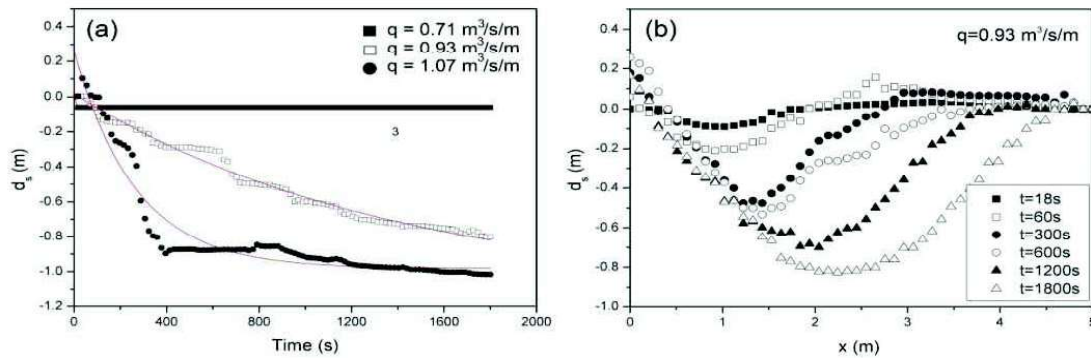
Fig. 5 shows the flow conditions and downstream scour under the different discharges. In Fig. 5 (a) and (b), the energy of the flow is broken due to hydraulic jumps in the stilling basin for $q = 0.54$ and $0.71 \text{ m}^3/\text{s}/\text{m}$. Because of this, the low-energy flow passing through the downstream region does not cause the scour. However, in Fig. 5 (c) and (d), the flow energy cannot be broken because the hydraulic jump does not occur in the stilling basin. Flow with high kinetic energy has caused scour by passing through the downstream zone.

Fig. 5. Scour at the Downstream of the Regulator for Different Flow Conditions



Source: own research

Fig. 6. (a) Variation of Scour Depth with Time for Different Froude Number, (b) Scour Profiles at Downstream of the Regulator for Different Times ($q=0.93\text{m}^3/\text{s/m}$)



Source: own research

The scour at different flow conditions and at different times are graphically presented in Fig 6. In Fig. 6 (a), almost no scouring observed over time for $q=0.71 \text{ m}^3/\text{s/m}$, but maximum scour exponentially increased over time for the unit discharges of $q=0.93$ and $1.07 \text{ m}^3/\text{s/m}$. Similar time-dependent changes in the scouring are given by Dey and Raikar (2007) and Dey and Westrich (2003). It is seen that most of the scour on these graphs takes place in the first 30 minutes. Figure 6 (b) shows the scour profiles varying over time. The amount of scouring reached 8 cm at $t = 18\text{s}$, but after 1800 s (30 min) it reached 80 cm^2 . If this value is taken as

75% of the depth of scouring from previous work, it can be estimated that the depth of stable scour is about 106 cm.

Conclusions

It is of vital importance to anticipate the scouring of the foundation and downstream of the water constructions. Many experimental investigations have been done in the past to estimate the scouring at the downstream of water structures with different purposes and designs. However, the empirical correlations and results obtained from these studies generally give different results and can give close results only the related problems. In this study, numerical analysis of the problem of scouring is emphasized and the scouring at a regulator's downstream is investigated by CFD software. As a result, it was observed that there was no scouring at downstream when the flow passing through an Ogee profile of 5 m crest height subjected to hydraulic jump in a stilling basin. On the contrary, in the flow situations where the hydraulic jump has not occurred, it has become a serious scouring process. In this study, the effects of hydraulic profile and stilling basin on the scour are analyzed by 2D numerical modeling for only one hydraulic structure. In the more extensive studies to be conducted in the future; the accuracy of the numerical analysis will be tested and more comprehensive analyzes will be conducted.

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