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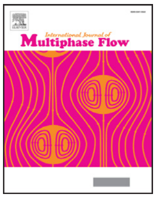

Comparison of methods to estimate the scour downstream of a ski jump

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ABSTRACT

This study analyzes the expected depth and scour shape in the Toachi River (Ecuador) as a result of the construction of the Toachi Dam in order to avoid problems with progressive scour. The dam has a maximum height of 59 m to the foundations. The free surface weir ends in a ski jump and has been designed to operate with a peak discharge of 1213 m^3/s. As each method has its limitations, the scour is studied with four complementary procedures: 1) a 1:50 Froude scale similitude laboratory model used as validation case; 2) 36 empirical formulae derived from models and prototypes; 3) a semi-empirical methodology based on pressure fluctuations-erodibility index; and 4) FLOW-3D numerical simulations. The expected scour depth is 6.65 m for the design flow. The results are close to the physical model. In the numerical analysis, turbulence is treated using the three RANS approaches. The choice of the turbulence model and the bed load coefficient in the Meyer-Peter & Müller formula are of great importance. The best results were obtained using the RNG k-ε turbulence model and a bed load coefficient below 7.

1. Introduction

Ski jumps are economic ways to dissipate energy for high-speed flows when the geological site conditions are favorable. The air-water jet travels through the atmosphere and eventually strikes into a plunge pool (Annandale, 2006; Castillo et al., 2015b). The hydraulic energy is dissipated in several steps: this entails spreading of the jet (aeration and atomization during the flight), air entrainment by the entering jet, diffusion in the pool, and finally the impact on the pool bottom.

Scour patterns are not yet fully understood, and the downstream receiving water course may be affected. The semi-empirical method (erodibility index) is based on an erosive threshold that relates the magnitude of relative erosion capacity of water and the relative capacity of a material to resisting scour. The method considers as relevant parameters the rock matrix strength, the block size, the interparticle/block friction, and the relative shape and orientation of any ground material (Kirsten, 1982; Kirsten et al., 1996; Annandale, 1995, 2006; Anton et al., 2015). Thus, discontinuity patterns play an important role in scour development. The characterization in the field of the patterns of discontinuity and the existence of several fracture sets with different orientations is very important, since these patterns results in the formation of bedrock blocks that are susceptible to removal by plucking and probable block topple (Anton et al., 2015). The limitations of plunge pools include large scour depth, their sufficient distance from other hydraulic structures to inhibit structural damage and control of the spray action (Pagliara et al., 2004b).

As several factors related with scour may be significant and complicated to know, comparison studies with different methodologies are required (Castillo et al., 2015a). In this study, the scour downstream of the Toachi Dam has been analyzed. In order to avoid a regressive erosion to the dam foundation and problems of destabilization in the riverbanks, a pre-excavated stilling basin is considered. Additionally, the design must prevent damage in the natural environment located downstream of the dam. The validation case is a physical model at 1:50 scale of the Toachi Dam spillway and scour. Two analytical approaches (empirical formulae and a semi-empirical methodology based on the erodibility index) have been evaluated, as well as a numerical analysis using FLOW-3D.

2. Dam characteristics

The Toachi Dam is located in the South-West of the city of Quito in Ecuador. It is a concrete dam with a maximum height of 59 m to the foundations. The top level has 10 m of thickness and a length of 170.5 m. It is located at an altitude of 973 m above sea level. The upstream and downstream embankment side slopes are 0.3/1.0 and 0.7/1.0 (horizontal/vertical), respectively.

The reservoir collects water from the basins of the Toachi and Sarapullo rivers. It has a total volume of 8 hm^3 with normal maximum water level located at 973 meters. At this level, the

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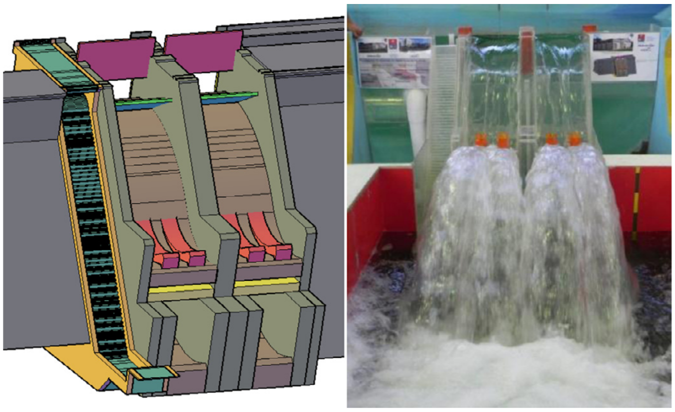

Fig. 1. Three-dimensional view and physical model of the Toachi Dam (EPN, 2013).

Fig. 2. 1:50 scale physical model of the Toachi ski jump (EPN, 2013).

reservoirs have a length of 1.3 km in the Sarapullo River and 3.2 km in the Toachi River.

The dam has two Creager spillways controlled by gates. The spillways end in a ski jump and they have two baffles to divide the flow. The design flow matches a 1000-year return period (1213 m^3/s) with an energy head of 7.50 m (Hidrotoapi, 2010). There are two bottom outlets whose combined capacity is 800 m^3/s. The dam also has a stepped spillway for the Sarapullo River with a design flow of 40 m^3/s (Fig. 1).

The pre-excavated stilling basin is located downstream of the dam. This basin is 105 m long, 68 m wide and 10 m deep. The stilling basin is filled with rock-fill of 1.02 m characteristic diameter. Downstream of the stilling basin, there are 10 m of rock-fill joined by concrete before the transition to the Toachi River (EPN, 2013).

The rock-fill material has the following characteristics: Specific weight $=24$ KN/m^3; internal friction of the granular material $=36°$; Standard Penetration Test (SPT) $=80$; d_{84} = material size in which 84% in weight is smaller $=1.20$ m; d_{50} = material size in which 50% in weight is smaller $=1.02$ m. The erodible layer is 10 m.

3. Physical model setup

The physical model was built with a Froude scale 1:50 in the Centro de Investigaciones y Estudios en Recursos Hídricos (CIERHI) of the Escuela Politécnica Nacional (EPN), in Ecuador. To scale the surface roughness of the dam, the spillway was made of acrylic (Fig. 2). The river bed was modeled considering a uniform crushed gravel size whose mean value was 0.020 m in the scale model (1.00 m in the prototype). The mobile bed in the plunge pool was 2.10 m long and 1.36 m wide in the model (105 m long and 68 m wide in the prototype). The erodible layer was 0.40 m depth.

The scour downstream of the dam was analyzed by using different flows according to the hydrology report of the Toachi-Pilaton Dam (Hidrotoapi, 2010). Each test was carried out during 90 min. After that time, researchers assumed that the scour had reached the equilibrium shape (EPN, 2013). The scour generated a mound centered in the middle of the stilling basin, while the laterals maintained the original ground level. The maximum elevation of the mound was 0.90 m over the initial ground level.

Table 1 summarizes the maximum scour depth below the original bed (Y_s) and the distance from the dam to the maximum scour (D). The maximum scour $Y_s=7.15$ m was obtained for the flow of 999 m^3/s. The design flow (1213 m^3/s) generated a bigger water cushion depth in the plunge pool (Y_0). Hence, the maximum scour depth for this flow (6.65 m) was smaller than with the smaller flow. The maximum scour distance, 64.20 m, was obtained with the design flow.

4. Empirical formulae

There are several empirical formulae to analyze the maximum scour depth into a plunge pool. Most of the equations were obtained by dimensional and statistical analysis of data obtained in Froude scale reduced models, with few formulae based on prototypes and many obtained for the ski-jump. Pagliara et al. (2004a) compare the results of known formulae with their laboratory studies. They consider that several of the formulae are dimensionally incorrect. Another complication is the lack of the application ranges of these formulae.

Following Castillo & Carrillo (2016), 36 formulae have been examined. The formulae employed by several authors obtained from dimensional analysis may be expressed in a general expression:

$$Y_s + Y_0 = k\frac{q^a H^b Y_0^c z^d}{g^e d_m^f d_{85}^h d_{90}^i} \qquad (1)$$

where Y_0 is the tailwater depth, k an experimental coefficient, q the specific flow, H the energy head, g the gravity acceleration, d_m the average particle size of the bed material, d_{85} the bed material size in which 85% is smaller in weight, and d_{90} the bed material size in which 90% is smaller in weight. The other variables are shown in Fig. 3.

Table 2 shows the parameters obtained for 26 different scour formulae that match with Eq. (1). Besides this, Table 3 shows 10 additional scour formulae whose expressions do not match with Eq. (1).

Fig. 4 shows the results obtained with the 36 formulae at prototype scale. The mean values +/−1 standard deviation is also indicated.

After removing those formulae with values that fall beyond the +/−1 standard deviation threshold, Fig. 5 shows the mean value +/− 1 standard deviation values obtained, together with the scale model results. From the simplified expression, Damle-B (1966), Chian Min Wu (1973), Martins (1973), Martins-B, 1975, Taraimovich (1978), INCYTH-LHA, 1982, and Mason and Arumugan, 1985 are the formulae whose values are closest to the mean value. From the general expressions, Jaeger (1939), Mirskhulava (1967), Veronese modified (1994), D'Agostino (1994), and Bombardelli & Gioia (2006) are the formulae with values in the same range. If the mean value for the design flow (1213 m^3/s) were considered, the scour could reach a depth of 7.95 m. However, if the mean value +0.50 standard deviation were taken into account, then the same flow would scour 11.50 m. The values obtained in the physical model fall in the mean value +/−1 standard deviation and are quite similar to the mean values calculated.

5. Semi-empirical formulae

Scour in turbulent flow is not a shear process. It is caused by turbulent and fluctuating pressures (Annandale, 2006). Pagliara et al. (2004a) observed that the maximum scour depth may be significantly larger for dynamic flow conditions than for