COMPUTATIONS OF THE FLOWS OVER THE WEIR CHANGING FROM THE SUBMERGED TO SURFACE FLOWS

SEONGWOOK CHOI

Graduate student, Department of Civil and Environmental Engineering, Yonsei University, Seoul, Korea, csu1220@yonsei.ac.kr

SUNG-UK CHOI

Professor, Department of Civil and Environmental Engineering, Yonsei University, Seoul, Korea, schoi@yonsei.ac.kr

ABSTRACT

Flow over the embankment-type weir shows a transition from the submerged hydraulic jump to the surface flow as the tailwater depth increases. The submerged hydraulic jump induces so called "hydraulic or drowning machine" downstream of the weir and severe scour in the vicinities of the free surface and bed, respectively. The increase of the tailwater depth makes the transition to the surface flow, resulting in the dramatic change of the flow structure. This study attempted numerical simulations of the two flow regimes for the flow over the embankment-type weir using the k-ω SST model. Both submerged hydraulic jump and surface flow are simulated and computed results are compared not only with measured data but also with results by the k-ε model. Hydraulic characteristics of the two flow regimes are presented and discussed.

Keywords: Submerged hydraulic jump, embankment-type weir, re-circulation zone, flow transition, turbulence model

1. INTRODUCTION

The flow over the embankment-type weir shows four different flow regimes depending on the tail water level, namely swept-out hydraulic jump, optimum hydraulic jump, submerged hydraulic jump, and washed-out hydraulic jump with increasing tailwater level. This study investigated numerically the transition of the flow over the weir from the submerged hydraulic jump to the surface flow. For the submerged and surface flows, re-circulation zones are created in the vicinity of the free surface and bed immediately downstream of the weir, respectively. These re-circulation zones are critical in predicting the flow structure of the overflow correctly. In addition, the re-circulation zone near the free surface by the submerged hydraulic jump induces so called "hydraulic" and affects greatly bed scour.

In the present study, the k-ω SST model is used to simulate the two flow regimes. The PISO algorithm in OpenFOAM is used for velocity-pressure correlation. The time derivative terms are discretized by Euler scheme. The VanLeer scheme and Gauss linear corrected scheme are used for discretization of convection term and diffusion term, respectively. Computed results are validated against laboratory experiments by Fritz and Hager (1998). The limit condition under which the overflow changes from the submerged to surface flows is examined.

2. GOVERNING EQUATIONS AND NUMERICAL METHODS

The following Unsteady Reynolds-Averaged Navier-Stokes (URANS) equation is solved for computing weir overflows:

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\partial x_j}\left\{(\upsilon + \upsilon_t)\frac{\partial \bar{u}_i}{\partial x_j}\right\} + g_i \tag{1}$$

where $\bar{u}_i$ is time (ensemble) averaged velocity of x_i-direction, t is time, ρ is density of mixture, p is time averaged pressure, ν is kinematic viscosity, ν_t is turbulence viscosity, and g is gravitational acceleration. Turbulent viscosity can be estimated by the k-ω SST turbulence model such as

$$\upsilon_t = \frac{\alpha_1 k}{max(\alpha_1 \omega, SF_2)} \tag{2}$$

where k is turbulence kinetic energy, ω is specific dissipation rate of k, and $\alpha_1$and F_2 are model coefficients. From the k-ω SST model, k and ω can be obtained by solving the following respective transport equations:

$$\frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = \frac{1}{\partial x_j}\left\{(\upsilon + \alpha_k \upsilon_t)\frac{\partial k}{\partial x_j}\right\} + P_k - \beta^* k\omega \tag{3}$$

$$\frac{\partial \omega}{\partial t} + \bar{u}_j \frac{\partial \omega}{\partial x_j} = \frac{1}{\partial x_j}\left\{(\upsilon + \alpha_\omega \upsilon_t)\frac{\partial \omega}{\partial x_j}\right\} + \alpha S^2 - \beta\omega^2 + 2(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \tag{4}$$

where P_k is turbulence production, S is strain rate, and α_k, β^*, α_ω, α, β, and F_1 are model constants. The Volume of Fluid (VOF) method is used to predict the free surface. The VOF method solves the transport equation of volume fraction (α_F) such as

$$\frac{\partial \alpha_F}{\partial t} + \frac{\partial(\bar{u}_j \alpha_F)}{\partial x_j} = 0 \tag{8}$$

The region where α_F is between 0 and 1, which represents states fully-occupied by air and water, respectively.

For calculating the velocity-pressure correlation, pisoFoam in OpenFOAM based on the PISO algorithm is used. The time derivative terms are discretized by Euler scheme. The convection and the diffusion terms are discretized by the VanLeer scheme (Van Leer, 1974) and Gauss linear corrected scheme, respectively. All discretized terms are interpreted using the generalized geometric-algebraic multi-grid (GAMG) matrix solver.

3. COMPUTATIONAL CONDITION AND MODEL APPLICATION

The numerical models are applied to laboratory experiments by Fritz and Hager (1998). The height (H_a) and crest length (L_W) of embankment-type weir are 0.1 m and 0.3, respectively. The upstream and downstream boundary conditions of numerical models are unit discharge (q, 0.55 m^2/s) and tailwater depth (h_t, 0.3 ~ 0.39 m), respectively. For computational efficiency, the computational domain is divided by five subdomains. A total number of 140,000 cells are used for whole domain to obtain the small size of wall unit, $z^+ < 1$. For grid dependency study, a domain of 220,000 cells is also tested.

4. SIMULATION RESULTS

Figure 1 presents computed results of the free surface and the interface of the re-circulation zone for the submerged hydraulic jump. For comparisons, computed results by the k-ε model and measured data by Fritz and Hager (1998) are provided. It can be seen that both numerical models predict the free surface well. That is, the critical depth occurs near the end of the weir crest, showing the minimum flow depth after passing the crest, then the flow depth increases slightly. However, the re-circulation zone predicted by the k-ω SST model is observed to be slightly smaller than the measured data, and the re-circulation zone by the k-ε model is much smaller. Quantitatively, the length of the re-circulation zone by the k-ω SST model is 6 times the tailwater depth, while the lengths by the measurement and the k-ε model are 6.5 and 5 times, respectively. The trend in the computed results is consistent with the findings by Gumus et al. (2016). The flow accelerates along the slope of the weir, with upper interface by the re-circulation zone. At the toe of the weir, the accelerated flow is turned into a wall-jet-like flow and the hydraulic jump takes place under the re-circulation zone. Then, the flow shows a transition and recovers to an open-channel flow.

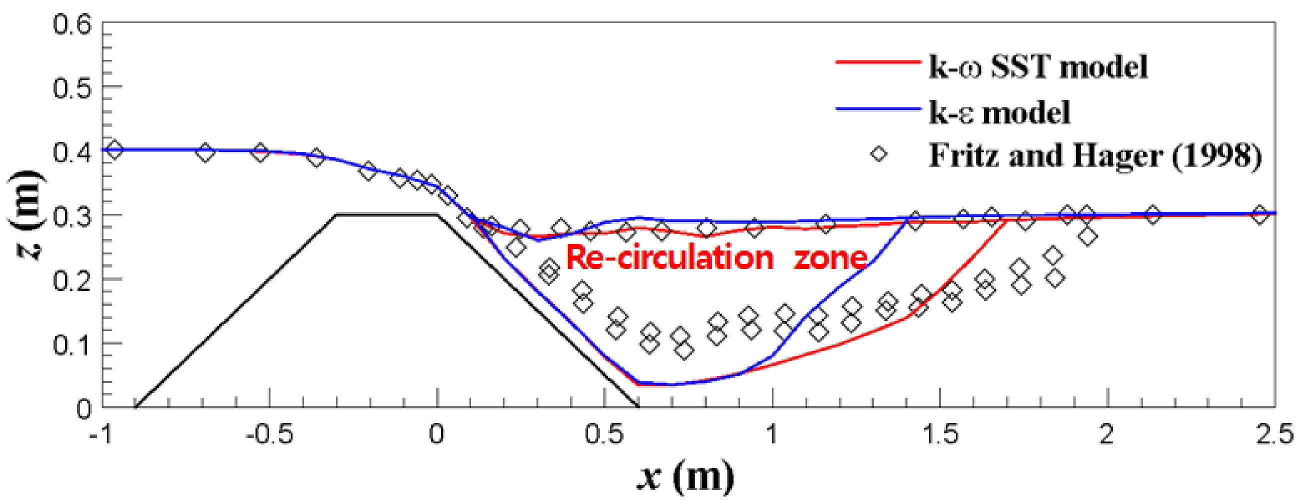

Figure 1. Free surface and interface of re-circulation zone for submerged hydraulic jump.

Figure 2 shows the same results for the washed-out hydraulic jump. The relative water depth, defined by $(H_a - h_t)/(H_a - h_0)$, in the measurement is 0.76, which is, however, too small for the washed-out hydraulic jump to take place in the computations. So a value of 0.9 for the relative water depth is used in the numerical simulations using both models. The free surface predicted by the numerical models show a slight decrease while passing the weir crest and it becomes constant. Whereas the measured free surface exhibits fluctuations. It can be seen that the re-circulation zone computed by the k-ω SST model is similar to the measured data. However, the re-circulation zone by the k-ε model is much smaller. The flow, after passing the weir crest, shows characteristics of a shear flow over the re-circulation zone, and becomes an open-channel flow after passing the re-circulation zone.

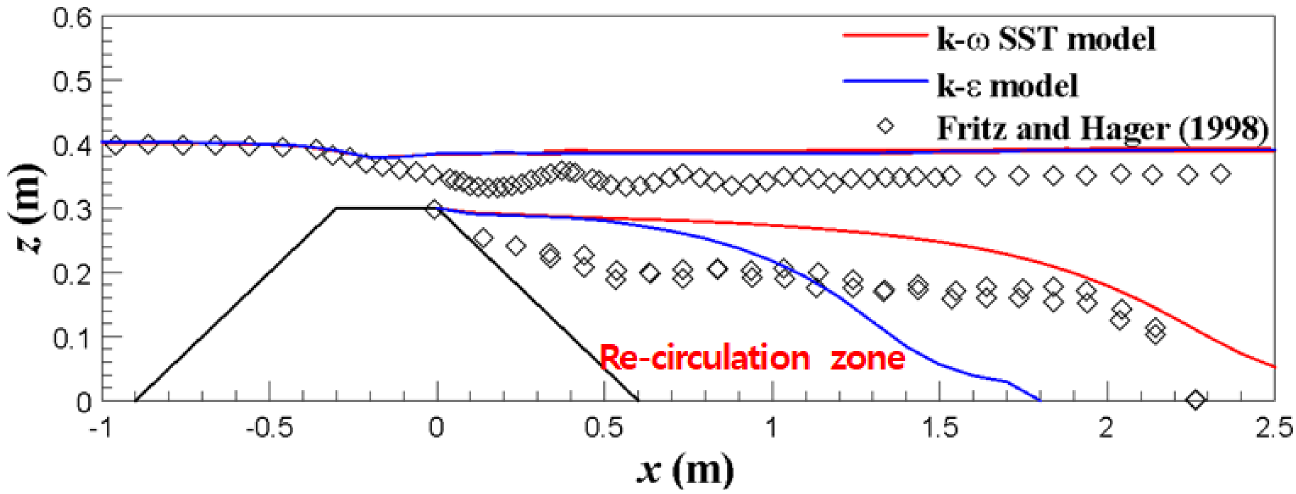

Figure 2. Free surface and interface of re-circulation zone for washed-out hydraulic jump.

5. CONCLUSIONS

This paper presented simulation results for the submerged hydraulic jump and washed-out hydraulic jump over the embankment-type weir. The k-ω SST model was used for the URANS computation. The computed results were compared with the results by the k-ε model, as well as measured data by Fritz and Hager (1998). It was found that the k-ω SST model predicts the free surface and re-circulation zone more or less correctly for the submerged hydraulic jump. However, the transition to the washed-out hydraulic jump was observed to take place at a higher value of relative water depth in numerical simulations, compared to the laboratory experiments. For the washed-out hydraulic jump, the k-ω SST model appeared to predict the re-circulation zone appropriately, but failed to predict the fluctuating free surface.

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