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Numerical Modeling of Submerged Spatial Hydraulic Jumps in In-ground Stilling Basins

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ملخص عربى

يعد تصميم حوض التهدئة خلف المنشآت الهيدروليكية أمرًا بالغ الأهمية حيث أن حوض التهدئة يلعب دورًا مهمًا للغاية في تثبيت القفزة الهيدروليكية و تبديد الطاقة. في هذه الدراسة، تمت المحاكاة العددية للقفزة الهيدروليكية المغمورة المتكونة عند الاتساع الحاد في عرض القناة دخولاً لأحواض تهدئة غائرة في الأرض (ISB). اثبتت الدراسة أن أحواض التهدئة الغائرة تساعد في تثبيت القفزة الهيدروليكية و تقليل طولها.

Abstract

Design of stilling basins downstream of hydraulic structures is very critical as stilling basins have a very important role in stabilizing hydraulic jumps and dissipating energy. In this study, the effect of In-ground Stilling Basin (ISB) on submerged spatial hydraulic jumps is examined using a three-dimensional numerical model. This study shows that In-ground stilling basins help in stabilizing the hydraulic jump and make it more compact.

1. Introduction

Stilling basins for hydraulic structures have an important role in dissipating energy and in stabilizing hydraulic jumps. A type of stilling basins that is used downstream of narrow outlets of hydraulic structures is the so-called In-ground Stilling Basin (ISB). The ISB has a depressed bed with a sudden drop immediately downstream of the outlet and a sudden rise at the end of the stilling basin (Figure 1) (Meshkati et al., 2012). The sudden drop of the ISB bed is combined with sudden enlargement to full width of channel. At the downstream end, ISBs may be provided with a sill which may not span the entire width of the stilling basin (Figure 1).

Previous experimental studies of flow downstream of hydraulic structures include studies of hydraulic jumps with sudden enlargement in channel width (Rajaratnam and Subramanya, 1968; Bremen and Hager, 1993; Ohtsu et al., 1999; Zare and Doering, 2010), studies of only abrupt drop in channel bed (Rajaratnam and Ortiz, 1977; Hager and Bretz, 1986; Ohtsu and Yasuda, 1991), and studies combining both sudden enlargement and abrupt drop (Ram and Prasad, 1998; Ferreri and Nasello, 2002). The majority of these studies focused on the description of features of the hydraulic jump and prediction of the sequent depth.

Few studies deal with the combination of abrupt drop and sudden enlargement. Ram and Prasad (1998) studied analytically and experimentally the hydraulic jump in stilling basin with abrupt drop and sudden enlargement. They found that combining the sudden enlargement and abrupt drop can reduce the required tail-water level for formation of the hydraulic jump within the stilling basin. Ferreri and Nasello (2002) showed that when a drop and expansion are provided simultaneously and when the tailwater depth increases, several types of hydraulic jumps occur. Meshkati et al. (2012) experimentally studied the existence of the end sill with two lateral free spaces downstream of the ISB. They concluded that the end sill downstream of the ISB could efficiently stabilize the hydraulic jump and increase the energy dissipation.

Several factors affect the flow in ISBs including the expansion ratio $\alpha = b/B$, aspect ratio $\beta = b/h$, inlet Froude number F_r, tailwater depth ratio $Y_t = y_t/h$, ISB depth ratio $S = s/h$, ISB length ratio $l = L/h$, sill height ratio $H_e = h_e/h$, and sill width ratio $B_e = b_e/h$, in which b is outlet width, h is outlet height, s is drop height, B is ISB width, L is ISB length, h_e is end-sill height, and b_e is end-sill width (Figure 1).

This study numerically evaluates the effectiveness of In-ground Stilling Basin (ISB) as an alternative to conventional stilling basins for stabilizing the hydraulic jump, creating more compact hydraulic jump roller, and forming steady symmetric hydraulic jump. The objective is to assess the reliability of applying numerical models for simulating ISB performance.

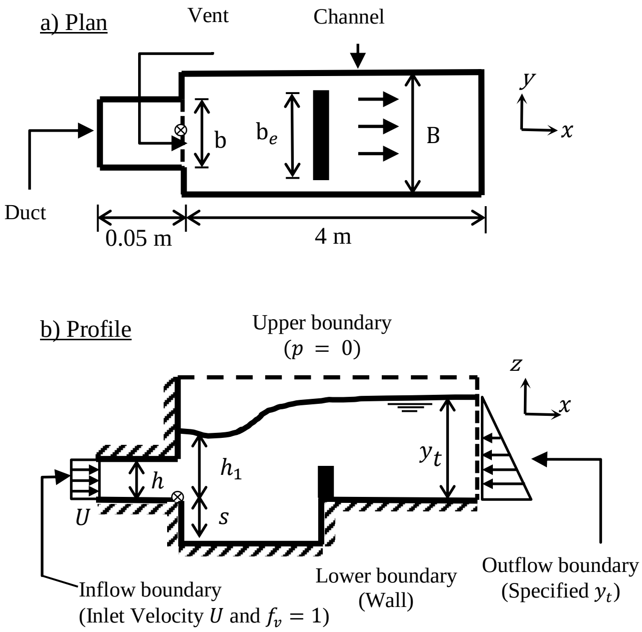

Figure (1) Schematic of a stilling basin with an end sill downstream of an abrupt expansion. Shown are the geometry and boundary conditions for the numerical domain in a) plan view and b) profile view through vent. Coordinate system x, y, and z has the origin indicated by the marker ⊗.

2. Methodology

2.1 Numerical Simulations

The ANSYS-FLUENT computational fluid dynamics model was used for the numerical simulation of flow within ISBs. Simulations were based on the incompressible continuity equation and Reynolds-averaged Navier-Stokes equations. Turbulence was parameterized using the $k - \mathcal{E}$ turbulence closure model (Mohammadi and Pironneau, 1993). The volume of fluid method was used to simulate the free water surface (Nguyen and Nestmann, 2004).

The numerical domain consisted of a horizontal rectangular channel 4.0 m long and 0.4 m wide (Figure 1). Simulations were performed for fixed values of the inlet velocity $U =$

$1.52\ m/s$, inlet width $b = 0.133m$, channel width $B = 0.4m$ expansion ratio $\alpha = 0.33$, aspect ratio $\beta \cong 5$, and inlet Froude number $F_r = 3.02$ (Table 1). Boundary conditions specified to the model included uniform velocity of xx m/s at the channel inlet and a constant tailwater depth of 0.115 m at the channel outlet.

Five numerical simulations were performed. In all simulations, the ISB length and depth were 0.8 m and 0.053 m, respectively. Simulation E0 was carried out without an end sill. For the other four simulations E1 to E4, the sill height h_e ranged from 0.0265 to 0.053 m with sill height ratio ranged from 1 to 2, and the sill width b_e ranged from 0.24 to 0.32 m with sill width ratio ranged from 9 to 12.

Table 1: Geometric and hydraulic parameters for numerical simulations

Run Code	Sill Height (h_e) (m)	Sill Width (b_e) (m)
E0	0	0
E1	0.0265	0.24
E2	0.0530	0.24
E3	0.0265	0.32
E4	0.0530	0.32

2.2 Analysis of Simulation Results

The efficiency of ISBs was assessed by three indicators which are whether the formed hydraulic jump is steady, symmetric jump or not; the reduction in the hydraulic jump roller length; and the amount of energy lost through the hydraulic jump. For assessing the symmetry of hydraulic jumps forming in the ISB, a degree of symmetry index (DSI) was computed based on the similarity of the velocity field within the two sides of the ISB (Foda et al., submitted). Energy head upstream and downstream of the ISB were used to calculate energy dissipation efficiency within the ISB. Finally, the length of the hydraulic jump was calculated by determining the extent of the jump side rollers.

3. Results and Discussion

3.1 Effect of ISB

For $L = 0.8$ m, $s = 0.053$ m, and $F_r = 3.0$, model results for run E0 with sill height of $h_e = 0$ m and sill width of $b_e = 0$ indicated the formation of a steady symmetric jump (Figure 2). In Foda et al. (submitted), a numerical simulation using the same hydraulic conditions of run E0 were carried out but without the existence of ISB (only abrupt expansion), and the generated hydraulic jump was of the oscillatory asymmetric type. This means that the ISB has an effective functionality on stabilizing the hydraulic jump.

For the same L, s, and F_r, with the existence of end sill with dimensions $b_e = 0.24$m and h_e of either 0.0265 m and 0.053 m, runs E1 and E2 produced a steady symmetric jump (Figure 3). In these runs, the side vortices associated with the hydraulic jump were similar in dimensions. For a wider sill $b_e = 0.32$ m and with the same previous hydraulic and geometric conditions, the results of simulation runs E3 and E4 also indicated the formation of a symmetric hydraulic jump.

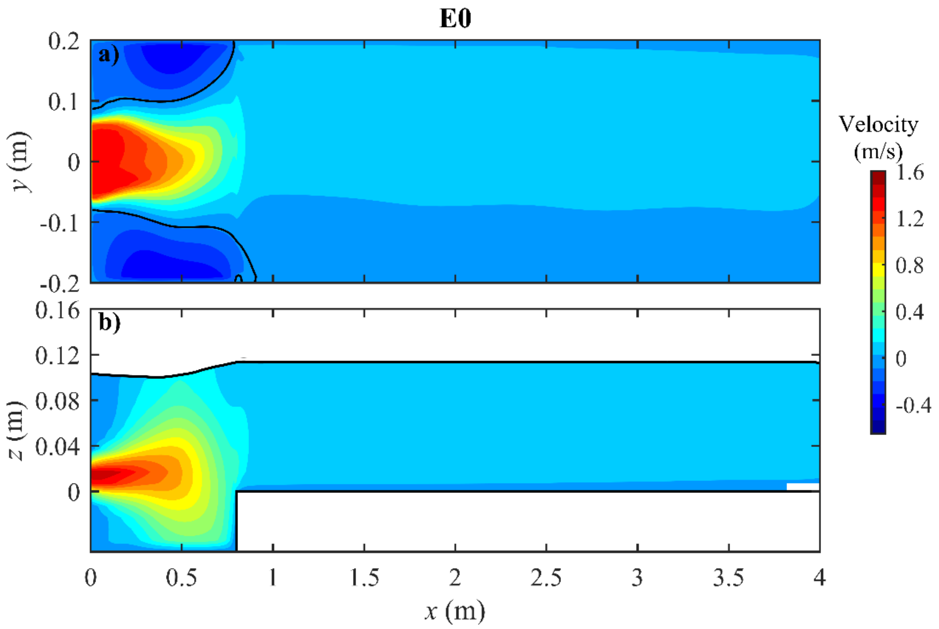

Figure (2) Distribution of longitudinal velocity over horizontal plane at height $z = 0.02$ m above bed and a longitudinal profile at $y = 0$ for run E0. Parameters were $L = 0.8$m, $s = 0.053$m, $F_r = 3.0$, $h_e = 0$ and $b_e = 0$.

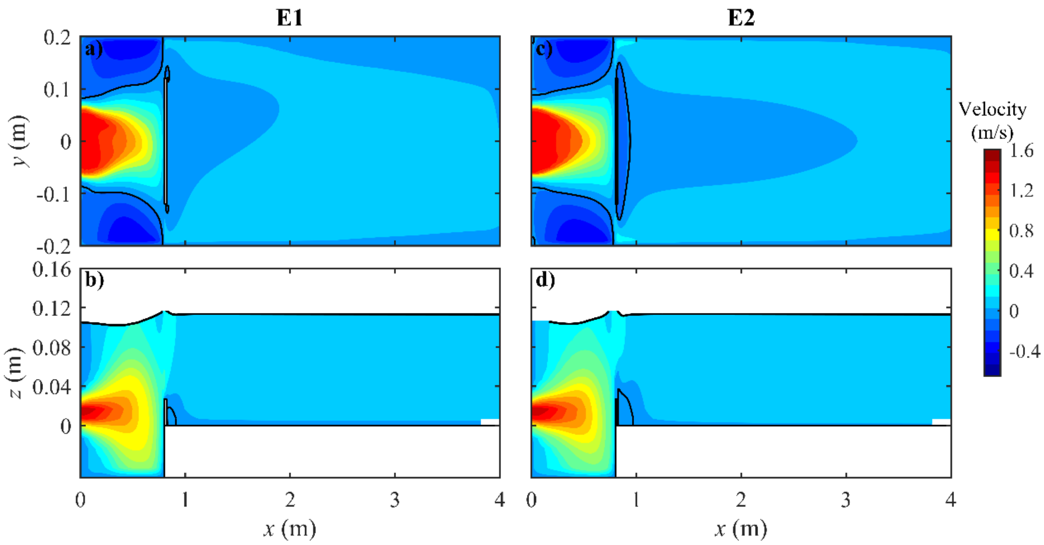

Figure (3) Distribution of longitudinal velocity over horizontal plane at height $z = 0.02$ m above bed and a longitudinal profile at $y = 0$ for run E1, and run E2.

The degree of symmetry index (DSI) for all simulations ranged between 95% and 100% (Figure 4). The lowest (DSI) value was around 95% for run E0 without end sill. For runs E1 and E3 with the same sill height and different sill widths, DSI was the same with a value of 97%. With different sill heights of 0.0265 m in run E2 and 0.053 m in run E4, DSI was the same with a value of 100%. These results indicate that the sill width does not play an important role in increasing the DSI for hydraulic jumps.

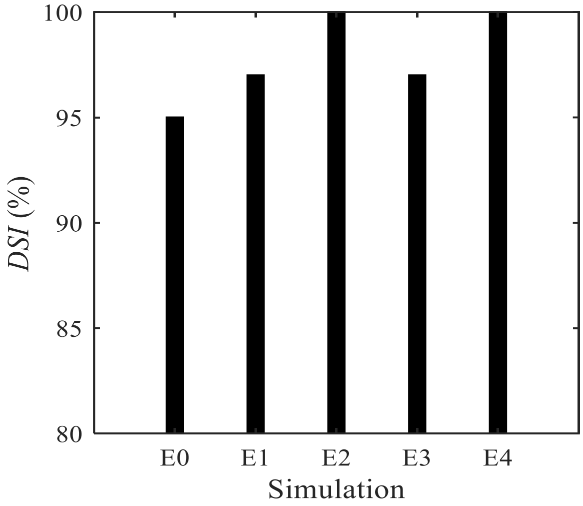

Figure (4) Degree of symmetry index for runs E0 to E4.

3.2 Roller length

For run E0 without the existence of end sill, model results indicated that jump roller length was 0.91 m. By introducing end sill with different dimensions, model results for runs E1, E2, E3, and E4 indicated that jump roller length was 0.8 m. These results indicate that the end sill plays an important role in containing the jump rollers within the boundaries of the In-ground Stilling Basin.

3.2 Energy Dissipation Efficiency

For sill height $h_e = 0$, the energy dissipation efficiency for run E0 was 0.46 (Figure 5). For sill height ratio $h_e = 0.0265$ m, energy dissipation efficiency was 0.48 for both runs E1 and E3. By increasing the sill height from $h_e = 0.0265$ to 0.053 m, energy dissipation efficiency for runs E2 and E4 was 0.49. These results indicate that the energy dissipation ratio increases by increasing the sill height ratio. The sill width ratio has no effect on energy dissipation.

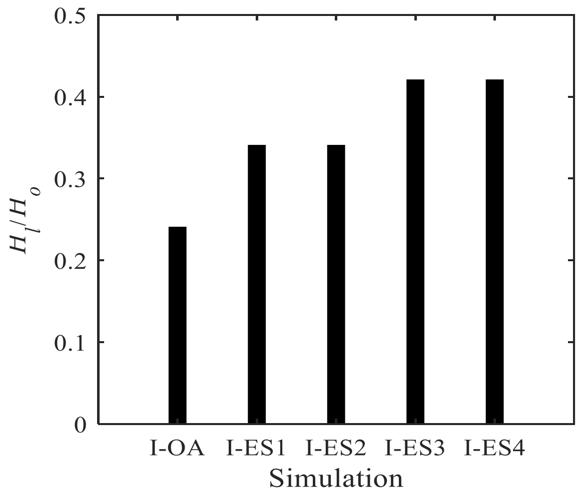

Figure (5) Energy dissipation ratio for runs E0 to E4

3. Conclusions

The In-ground stilling basin (ISB) has been numerically investigated in this study. The ISB helps in stabilizing the hydraulic jump downstream of abrupt expansions and make it more compact. The presence of end sill increases the efficiency of ISB in stabilizing the hydraulic jump and increasing the jump degree of symmetry. As a results of this study, the end sill with length of 60% of channel width gives the same performance of sill with length of 80% of channel width which helps in reducing the cost of the end sill.

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