Echo-Friendly Adaptation Design for Stilling Basin of Masudagawa Flood Mitigation Dam

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Abstract

During past decades the number of huge floods occurred at the urban area worldwide sharply increased. In order to survive the urban areas against the floods, it could be necessary to consider Flood Mitigation Dams (FMDs). One of the important energy dissipating structures is stilling basin (SB) downstream of FMD. Combining sudden enlargement and abrupt drop would create the non-prismatic type of SB similar to a pool downstream of FMD, named Inground SB. In this paper a new updated design is proposed for SB downstream of Masudagawa FMD; according to the In-ground SB concept. The relative energy loss of the proposed In-ground SB is 2.5 larger than the original Masudagawa SB design. Moreover, the end-sill height (D) was slightly decreased in the modified design.

Introduction

Urbanization creates the sharp growth in the value of property and the number of infrastructures at the flood plain areas. Recently, huge floods experienced even more of past at the urban area. In order to survive urban areas against the flood, it could be necessary to consider Flood Mitigation Dams (FMD). The definition of FMD is gateless outlet dam designed only for the purpose of flood control whose bottom outlets are installed at the original bed level of river.

One of the important energy dissipating structures is stilling basin (SB) downstream of FMD. There are several problems in the present design of SB: a) low efficiency of energy dissipation; b) blocking the fish passage and sediment transport by the end-sill; c) high cost. Therefore, modify and update the SB design of FMD has become important for future research. To reach the solution for these problematics, a new concept of SB is introduced in this paper; named In-ground SB.

In-ground SB is such a stilling basin with cross section enlargement and abrupt drop simultaneously after bottom outlet. In-ground SB is similar to a pool just below the FMD. Despite of extensive studies on hydraulic jump in SB (Hager and Bretz, 1986; Ohtsu and Yasuda, 1991; Moosa et al., 2003; Sumi and Nakanishi, 1991), a few research investigated the hydraulic jump within In-ground SB. The most similar study about the In-ground SB concept was conducted by Katakam and Rama (1998). Masudagawa FMD completed in 2007 is a good example for FMD in Japan. SB of Masudagawa FMD was designed by hydraulic classical jump approach. To obtain the required tail-water depth, an end-sill was equipped at the downstream of SB. Two slits were installed at the end-sill for flushing sediments and achieve fish passage functions (Kantoush and Sumi, 2010).

This paper presents a new concept for SB downstream of FMD, named In-ground Stilling Basin and the main governing parameters, then, proposes the new updated design for SB downstream of Masudagawa FMD, by applying the Katakam and Rama's approach. The new design and the existing on of Masudagawa SB are compared from the viewpoints of FMD outlet dimensions and SB dimensions.

In-ground SB concept

The classical SB consists of prismatic, rectangular and nearly horizontal basin which is designed by implementing classical hydraulic jump approach. This kind of SB needs a relatively high downstream tail-water depth to ensure transition from supercritical to subcritical flow and reduce the erosion at the downstream river bed. By combining sudden enlargement and abrupt drop, the non-prismatic type of SB is created similar to a pool downstream of FMD as shown in Figure 1. This type of SB can simplify sediment and fish transports where the SB bed is covered by large rocks and boulders naturally or artificially.



Figure 1: The schematic view of In-ground SB downstream of FMD.

Definition of Main Parameters

When a drop is combined with an enlargement, the typical hydraulic phenomena of each measure overlap, reciprocally influencing each other, and produce hydraulic jumps whose overall characteristics are very complicated (Ferreri and Nasello, 2002). An experimental research has started at Disaster Prevention Research Institute (DPRI) of Kyoto University, aiming to study on the flow pattern of hydraulic jump in the In-ground SB. Figure 2 shows the schematic side and plan views of the constructed model and the main hydraulic parameters involved in this study. Energy loss (H_L) in the In-ground SB in clear water phase may depends on parameters such as: outlet velocity at the bottom outlet (U_0), width of outlet (b), height of outlet (h_0), step depth (s), width of SB (B), length of SB (L), sequent depth (h_2), end-sill height (D), water density (ρ_w) and gravity acceleration (g):

$$H_{L} = f(U_{0}, b, h_{0}, s, B, L, h_{2}, D, \rho_{w}, g)$$
(1)

Thus, the relative energy loss (H_L/H_1+s) may be written as a function of the following dimensionless parameters:

$$\frac{H_L}{H_1 + s} = f(F_1, y, \gamma, \beta, S, \alpha, \delta)$$
(2)

where H_1 and F_1 are respectively total energy and Froude number at the face of bottom outlet to the SB, y is the ratio of sequent depth to the height of outlet (h_2/h_0) , y is the ratio of outlet width to the outlet height (b/h_0) , β is the expansion ratio (B/b), S is the drop number or in other word ratio of step depth to the bottom outlet height (s/h_0) , α is the aspect ratio of SB (B/L), and δ is the relative end-sill height (D/B). Moreover, the sequent depth (h_2) can be defined as in Eq. (3) where h_c is the critical water depth over the end-sill (Fr =1).

$$h_2 = s + D + h_c \tag{3}$$



Figure 2: The schematic side and plan views of the constructed model.

Katakam and Rama's approach to design of SB

As above mentioned, the most similar research to our In-ground SB concept was carried out by Katakam and Rama (1988). Equation 4 was proposed by them to calculate the ratio of sequent depth to the height of outlet:

$$y = \frac{2F_1^2\left(y - \frac{1}{\beta}\right)}{\beta\left\{y^2 - \left[(S+1)^2 - \left(\frac{\beta-1}{\beta}\right)\right]\right\}}$$
(4)

Furthermore, Equation 5 was proposed to calculate the relative energy loss in the In-ground SB. The output of this equation could be one of the reliable criteria to found the optimal design of SB.

$$\frac{H_L}{H_1 + s} = 1 - \left[\left(y + \frac{F_1^2}{2y^2 \beta^2} \right) / \left(1 + s + \frac{F_1^2}{2} \right) \right]$$
(5)

Masudagawa FMD and SB

Masudagawa FMD was completed in 2007, Japan. This dam is designed with probable flow rate of 100 years return period ($Q_{peak of flood} = 640 \text{ m}^3/\text{sec}$) at the Masuda River. Two gateless bottom outlet ($h_0 3.4 \times b4.4 \times 2$) and overflow spillways are installed. For energy dissipation, a conventional hydraulic jump type SB with an end-sill (D = 3 m) was designed where two slits are installed for self-sediment flushing from the SB as shown in Figure 3. Design of Masudagawa SB is very close to the presented In-ground SB concept; because the bed level of SB in Masudagawa FMD is located 4 m lower than the level of its bottom outlet where a pool below this FMD is formed. But, there are three main differences between Masudagawa SB design and In-ground SB concept: first, the bottom outlet of Masudagawa FMD is connected to SB by a ramp (not abrupt drop). Second, there is an end-sill at the downstream end of Masudagawa SB while in the In-ground SB concept intend to eliminate this end-sill. Third, the original river bed elevation at the downstream area of In-ground SB concept would level with its bottom outlet, in contrast to Masudagawa SB design. This is noteworthy to mention that, the width of SB was designed according to the width of the downstream river channel (B=30 m). Detail design of Masudagawa FMD is shown in Figure 4.



Figure 3: Bottom outlet and SB of Masudagawa FMD.



Figure 4: Detail design of Masudagawa FMD.

Results and Discussion

In this section, the new design (re-design) for Masudagawa SB is presented by implementing the Katakam and Rama's approach. The re-design of SB was conducted by considering flood peak of 100 years return period ($Q_{peak of flood}=640 \text{ m}^3/\text{sec}$) passed through one bottom outlet and not two bottom outlet as the original one. Several scenarios are investigated in this study including different geometries of SB and various outlet dimensions for four flood discharge return periods 35, 50, 75 and 100 years. To re-design of SB, Equation 4 was used to calculate the ratio of sequent depth (h_2) to the bottom outlet height (h_0). Then, by substituting the sequent depth (h_2) in Equation 3, the end-sill height (D) was obtained. The relative energy loss predicted by Equation 5 and the end-sill height (D) are two key criteria for assessing the design.

Figure 5 shows the variation of drop number (s/h_0) versus the relative end-sill height (D/B), for different geometry of SB. As illustrated in Figure 5, for a given geometry of SB and specific dimension of bottom outlet, by increasing the drop number (s/h_0) the relative end-sill height (D/B) decreased. In other words, increasing the step depth (s) allows reducing the end-sill height and consequently facilitates the fish migration. By contrast, the greater drop number (s/h_0) would slightly reduce dissipation of energy in the SB which it could be neglected. The values of relative energy loss (REL) in In-ground SB concept were almost same for all scenarios which its average was equal to %55. For a given drop number (s/h_0) in Figure 5, the lowest relative end-sill height (D/B) occurred when the width of bottom outlet (b) is greater than the height of bottom outlet (h_0) , horizontal rectangular shape, $b/h_0 > 1$.



Figure 5: Variation of drop number (s/h0) versus the relative end-sill height (D/B) for different geometry of SB and different bottom outlet dimensions.



Figure 6: Variation of drop number (s/h0) versus the relative energy loss for different geometry of SB and different bottom outlet dimensions.

In other side, when the width of bottom outlet (*b*) is smaller than height (h_0), the relative energy loss was increased, vertical rectangular shape, $b/h_0 < 1$. Therefore, it is necessary to find the optimal step depth (*s*) in order to satisfy both conditions of smaller end-sill height (*D*) and more dissipation of energy (REL) within SB. One practical solution could be equipping SB apron with rocks and boulders to create greater dissipation of energy, while simultaneously increasing the drop number (s/h_0) and increasing the bottom outlet width (*b*) to reduce the end-sill height (*D*). Table 1 shows the comparison between Masudagawa SB design with its re-design conducted according to Katakam and Rama's approach. As can be seen in Table 1, the relative energy loss in In-ground SB is 2.5 times larger than the original SB of Masudagawa FMD, and the end-sill height (*D*) is slightly decreased. Hence, the Inground SB concept could have more advantages than other types of SB.

Figure 6 shows the variation of drop number (s/h_0) versus the relative end-sill height (D/B), for different flood return period (in other words different Froude number) when the geometry of In-ground SB and dimensions of bottom outlet are constant. As can be seen in this figure, for a given drop number (s/h_0) , the longer end-sill height is needed for greater Froude number. Evidently, the flood discharge design, or put differently, flood return period has a key role in design criteria how shorter flood return period could ensure the smaller end-sill height (D).

As mentioned above, the Katakam and Rama's approach maybe is the only research that considered the In-ground SB concept. However, the proposed equations cannot directly be used for design purpose, mainly because no attempt was made to predict the jump length. One of the other drawbacks of Katakam and Rama's approach is using the narrow range of database to develop their empirical equations. Especially the effect of geometry of SB (step depth, width of SB) on flow pattern field was not well considered.

Cases	SB width (B)	Bottom outlet dimensions	Step depth (s)	End-sill height (D)	Relative energy loss (REL)
Masudagawa FMD	30 m	$[h_0 3.4 \times b 4.4 \text{ m}] \times 2$	Ramp 4 m	3 m	%18
Re-design In-ground SB	30 m	$[h_0 3.5 \times b 8.5 \text{ m}] \times 1$	Abrupt 6 m	2.2 m	%46

Table 1: Comparison between Masudagawa SB design and re-design proposed in this study.

Conclusions and future challenges

The new concept of SB has been proposed in this paper, which it was analogous to a pool below the FMD and is named In-ground SB. This type of SB involved sudden expansion and abrupt drop simultaneously. Katakam and Rama's approach is used to re-design of Masudagawa SB. Increasing the drop number (s/h_0) and installing the wider bottom outlet (horizontal rectangular shape, $b/h_0>1$), positively reduce the end-sill height (*D*). Re-design of Masaudagawa FMD according to the In-ground SB concept led to 2.5 times more energy dissipation and 25% reduction of the end-sill height (*D*). Similarly, flood return period could be one of the main design criteria so that short term flood return period may reduce the endsill height (*D*).

Taking into account the eco-friendly features of In-ground SB and unknown factors in this concept, further study is needed to propose new design guidelines for SBs. Current experimental research at DPRI aiming to evaluate several new ideas as following: a) Identifying the effect of wide range of bottom outlet and SB dimensions on flow pattern within In-ground SB. b) Installing some separate piers (cylindrical baffles) instead of end-sill to eliminate the obstacle against fish and sediment passage. c) Considering additional outlets above the main bottom outlet to create waterfall into the SB to break the hydraulic jump and dissipate energy of flow. d) Increasing the roughness of SB apron and SB training walls.

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