5th International Symposium on Hydraulic Structures Brisbane, Australia, 25-27 June 2014
Hydraulic Structures and Society: Engineering Challenges and Extremes
ISBN 9781742721156 - DOI: 10.14264/uql.2014.33

Energy Dissipation within In-Ground Stilling Basin

M.E. Meshkati Shahmirzadi[1], T. Sumi[1] and S.A. Kantoush[2]
[1]Disaster Prevention Research Institute
Kyoto University
Gokasho, Uji, Kyoto, 611-0011
JAPAN
[2] Civil Engineering Department
The German University of Cairo
EGYPT
E-mail:meshkati.shahmirzadi@gmail.com

Abstract: *We investigated the hydraulic characteristics of an in-ground stilling basin (ISB) below a flood mitigation dam (FMD). The ISB structure is adapted to be ecologically transparent for fish migration and sediment transport through consideration of two lateral free spaces at the ISB end. We attempted to assess the energy dissipation performance of ISB by considering the interdependence between ISB geometry and flow pattern. The experimental results evidence there is a significant correlation between flow patterns and ISB geometry.*

Keywords: *In-ground stilling basin, energy dissipation, flood mitigation dam, eco-hydraulic structures.*

1. INTRODUCTION

Flood mitigation dams (FMDs) in the normal condition permits the flow pass through the bottom outlet unobstructed. Meanwhile, a large percentage of river inflow can be temporarily stored within the reservoir during the flood events (Sumi, 2008). Stilling basin, thus, is vital to dissipate the energy of outflow from FMDs to protect downstream reaches from unfavorable degradation and side bank erosions (Hager, 1992). However, the function of stilling basin in FMD is not only to dissipate the excess energy of the outflow, but also to let the sediment and fish pass through the structure unopposed (Meshkati Shahmirzadi & Sumi, 2013). Figure 1a and b depict the Masudagawa FMD in Shimane prefecture, Japan and its stilling basin, respectively. Tall and full width end-sill at the end downstream of stilling basin brings contradictory goals for FMDs. On the one hand, tall and full width end-sill can positively confine the hydraulic jumps within a limited area that finally lead to an economical design. On the other hand, a tall full width end-sill itself negatively acts as an obstacle for sediment supply and fish migration; and it would increase the deposition of sediment within stilling basin that would build up over time. In order to decrease necessary end-sill height and to keep the suitable water depth during the normal river condition, an in-ground stilling basin (ISB) can be an alternative for the conventional stilling basins. Additionally, lateral free spaces in end-sill may increase the sediment sluicing and fish migration rate.

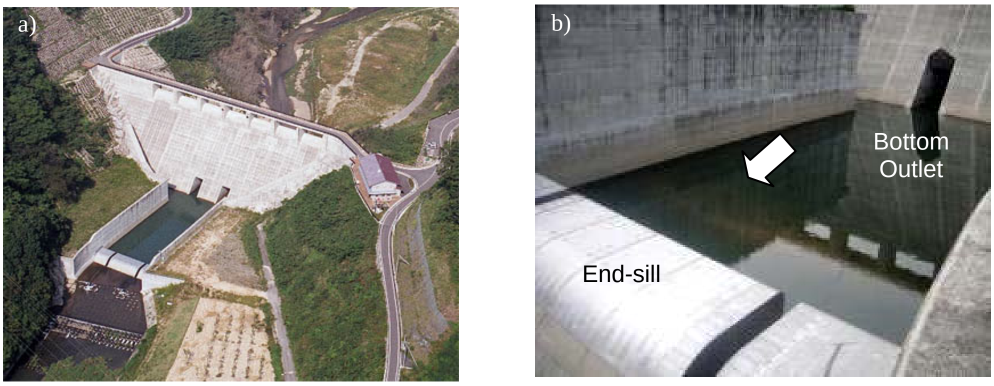


Figure 1a and b– Masudagawa FMD and its stilling basin

In spite the fact, there are enormous numbers of researches on hydraulic jumps within stilling basin (Sumi & Nakanishi, 1991; Chanson & Montes,1995; Katakam & Rama, 1998; Ohtsu et al., 1999; Larson, 2004; Pagliara et al., 2008; Zare & Doering, 2011), 3D nature of energy dissipation process at the presence of forced hydraulic jumps within simultaneous combination of sudden lateral enlargement, abrupt drop and end-sill is not yet solved in the literature. Fulfilling the gap of knowledge under this topic was the major motivation to conduct this investigation. Present research is unique due to covering a various geometrical and hydraulic variables such as Froude number (Fr_1), normalized ISB length (L/B), normalized ISB depth (s/h_1), normalized end-sill height (h_e/h_c) and normalized free space width ($1-(b_e/B)$). The governing absolute parameters e.g. h_1, h_c, b_e and B are defined in section 2. In the present study we aim to assess the interaction between ISB structure geometry and the energy dissipation within ISB. The possible hydraulic jumps types within ISB are classified based on their surface pattern and water surface profile. Finally, the most effective ISB geometry structure was presented in term of higher velocity reduction, and better stability and symmetry of the flow patterns.

2. EXPERIMENTATION

Figure 2 provides the schematic plan and side view of our physical model and the main governing parameters considered in this study. The range of Froude numbers (Fr_1 ($Fr_1=U_1/(gh_1)^{0.5}$, U_1 is the outflow velocity from the bottom outlet in FMD, g is the gravitational acceleration and h_1 is the bottom outlet opening height) that we examined was from 2.8 to 5.1. The corresponding values of the critical depth (h_c) were obtained through $((Q/B)^2/g)^{1/3}$, where Q is the outflow discharge from FMDs bottom outlet and B is the width of channel. As the width of the bottom outlet in FMDs are considerably smaller than the width of the downstream river channel, it creates a small but sudden expansion ratio. The value of this ratio ($k=b_1/B$, b_1 is the width of bottom outlet) ranges from 0.1 to 0.3 in real life. Thus, we selected a given ratio for our physical model equal to 0.2, representing the actual average value of the expansion ratios in FMDs. Experiments were carried out under different geometrical and hydraulic conditions as: ISB length (L= 75, 100 and 125 cm), ISB depth (s= 5, 10 and 15 cm), different geometry of end-sill with various heights (h_e= 0, 4, 8, 12 and 13.5 cm) and various widths (b_e= 50, 40, 30, and 20 cm) has been examined. However, the width of ISB itself for all experiments was the same B= 50 cm equal to the width of flume; in addition to only one dimension of bottom outlet (h_1= 5 cm and b_1= 10 cm).

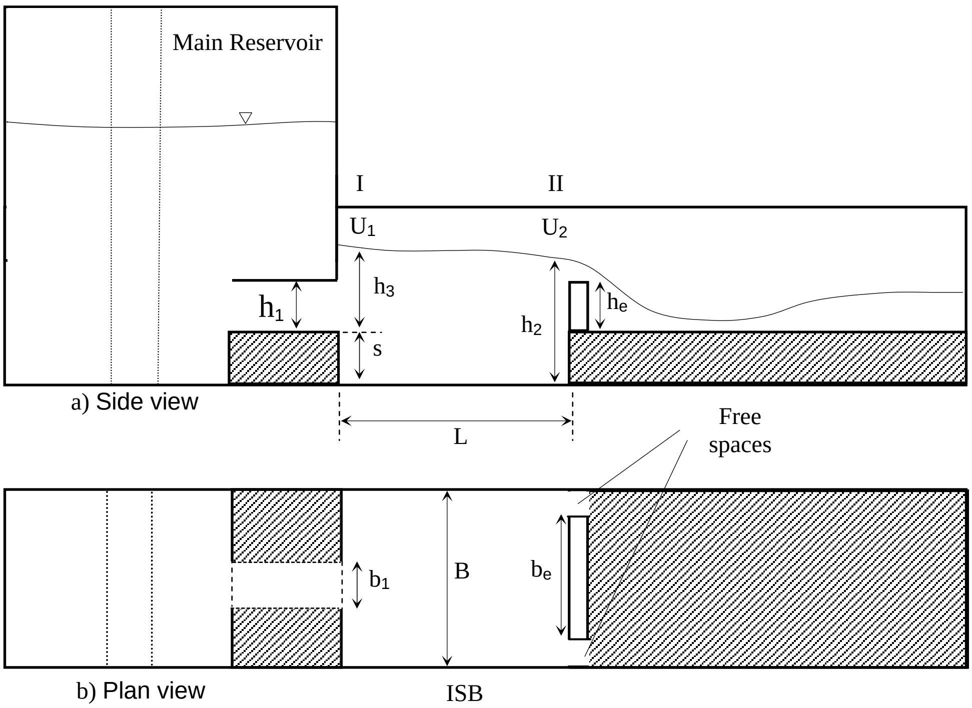


Figure 2 – The schematic side and plan view of physical model

3. RESULTS AND DISCUSSION

3.1. Analysis of Non-dimensional Governing Parameters

This section aims to identify the effect of various combinations of ISB geometries on ISB performance. The effect of different geometrical parameters on velocity reduction has been investigated. It is noteworthy to mention about the formulation of the naming system for each test configuration in the present research. In legend box of each figure three successive capital letters can be seen. The naming system is very simple to learn and useful to be used for comparison of the different cases easily. The three capital letters e.g. MMM, give in succession qualitative description of the length of ISB, height of end-sill and ISB depth respectively. 'M' in the example just shown refers to a medium value. To give a further example, LTD is the case where a **L**ong ISB, **T**all end-sill height and **D**eep ISB has been examined. The table below provides the definition of each abbreviation used here in this study and its relevant values.

Table 1- The definitions of the qualitative abbreviations used in the present study

Abbreviation	Meaning	Example	Relevant normalized		
			ISB length	ISB end-sill height	ISB depth
S	Short, Small, Shallow	Short ISB length, Small end-sill height, Shallow ISB depth	1.5	0.8	1
M	Medium	Medium ISB length, Medium end-sill height, Medium ISB depth	2	1.7	2
D	Deep	Deep ISB depth	-	-	3
T	Tall	Tall end-sill height	-	2.8	-
T'	Very tall	very Tall end-sill height	-	3	-
N	Nothing (without)	No end-sill	-	0	-
L	Long	Long ISB length	2.5	-	-

3.1.1. The Effect of Normalized End-sill Height

To identify the effect of end-sill height on performance of ISB, three series of tests were designed in which all parameters were constant and the end-sill height and ISB depth varied (Figure 3). In case of the experiment without an end-sill (e.g. MND or MNS), the normalized velocity reduction remained very low around 25%; when even increasing the ISB depth could not considerably improve the ISB performance. While for the cases with a taller end-sill (M, T and T'), the magnitude of normalized velocity reduction increased up to 60% of the initial velocity.

However, this figure indicates that increasing the height of the end-sill from T to T' (from tall to very tall) did not enhance the performance of ISB regarding velocity reduction. Thus, it can be concluded that although a taller end-sill could dissipate more energy than the shorter, increasing the end-sill height above an optimum value has no enhancement on the performance of ISB. The normalized end-sill height, h_e/h_c, greater than 2 may be can provide an acceptable velocity reduction around 60 to 70% within ISB. Furthermore, as can be seen in Figure 3, for a constant normalized end-sill height, h_e/h_c, deeper ISB e.g. M(X)D and M(X)M just slightly increased the normalized velocity reduction in comparison with M(X)S. Therefore, deepening the stilling basin may not be economically justified since it does not lead to a significant impact on energy dissipation within ISB.

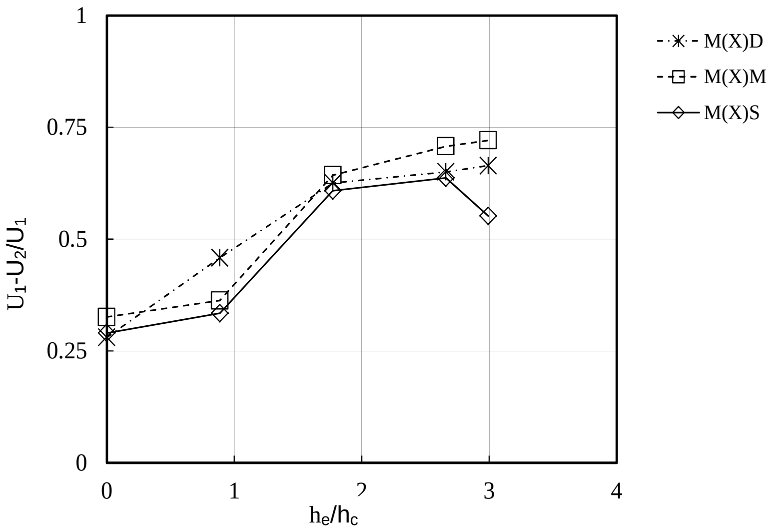


Figure 3- The variation of normalized velocity reduction versus the normalized end-sill height

3.1.2. The Effect of Normalized ISB Length

Figure 4 illustrates the variation of normalized velocity reduction versus the normalized ISB length for different combinations of end-sill height and ISB depth where Fr_1= 4.3. The normalized velocity reduction is defined as U_1-U_2/U_1 between sections I and II (see in Figure 1). U_1 is the initial bottom outlet velocity and U_2 is the largest average velocity measured just upstream of the end-sill. This figure illustrates the ISB performance regarding velocity reduction consistently enhanced by increasing the ISB length, in particular in case of taller end-sill height. In general, in presence of taller end-sill (e.g. (X)TM and (X)TD) the rate of velocity reduction was relatively larger compared to those cases with shorter end-sill height (e.g. (X)SM and (X)SD). Therefore, by considering a medium height to tall end-sill we may are allowed to reduce the ISB length. Reduction of the ISB length is cost effective. Moreover, the longer the ISB, the higher possibility for formation of periodic and instable submerged jump within ISB, which is not favorable for hydraulic structure designers. The formation of different flow pattern within ISB as function of ISB geometry is discussed later in this paper. Considering the economical aspects in design as well as our desire to have a steady stable flow pattern within ISB, a medium normalized ISB length equal to 2 (L/B=2) is preferred. A very short ISB may not be adequate to be considered for design, L/B=1.5, due to their relatively low normalized velocity reduction, less than 60%, when a medium end-sill height is installed at their downstream (Figure 4). In presence of a short ISB the plunging jump into ISB has not enough space to be fully developed. Hence, the hydrodynamic force may cause failure of structure in case of extreme flood events.

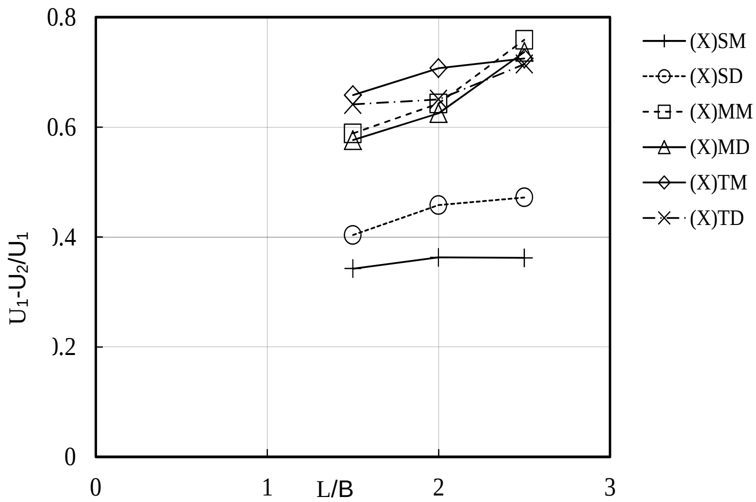


Figure 4- The variation of normalized velocity reduction versus the normalized ISB length

3.1.3. The Effect of Drop Number

The effect of drop number s/h_1 has been studied herein. Based on the classification of Ohtsu and Yasuda (1991) on drop types, the drop numbers that we examined in this study fall into lowe drops, 0.5~1.5 $\leq s/h_1 \leq$8~9. Figure 5 depicts the normalized velocity reduction within ISB for different drop numbers. The ISB performance displayed two different behaviors with an increase in drop number. In case of a shorter end-sill height e.g. MS(X), by increasing the drop number the ISB performance regarding velocity reduction is improved. However, for taller end-sills (MM(X) and MT(X)), in general, by deepening the ISB no significant effect on ISB performance was found.

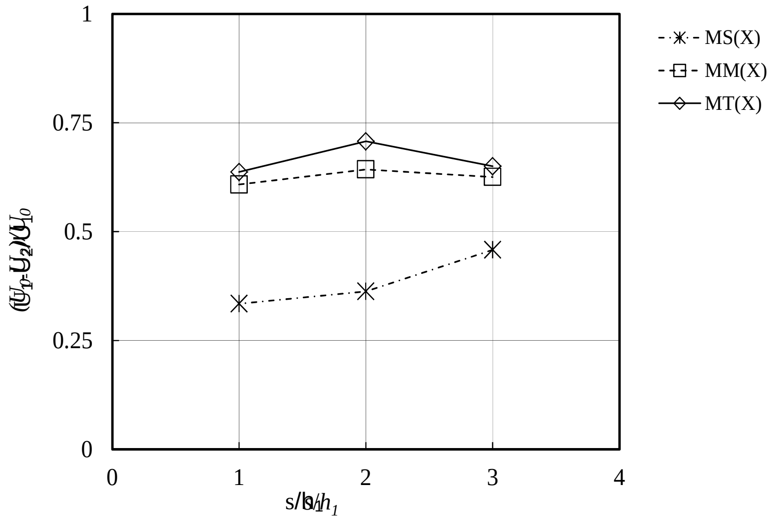


Figure 5- The variation of normalized velocity reduction versus drop number

3.1.4. The Effect of Relative End-sill Width

To clarify the effect of free spaces (b_e, end-sill width) on velocity reduction along the ISB two groups of tests are designed in which all parameters were constant and only the end-sill width was varied. The first group of experiments concerned the effect of free spaces on performance of those ISB with a medium end-sill height (MMM) and the second group of experiments with a taller end-sill (MTM). Figure 6 shows the variation of normalized velocity reduction with normalized free space width.

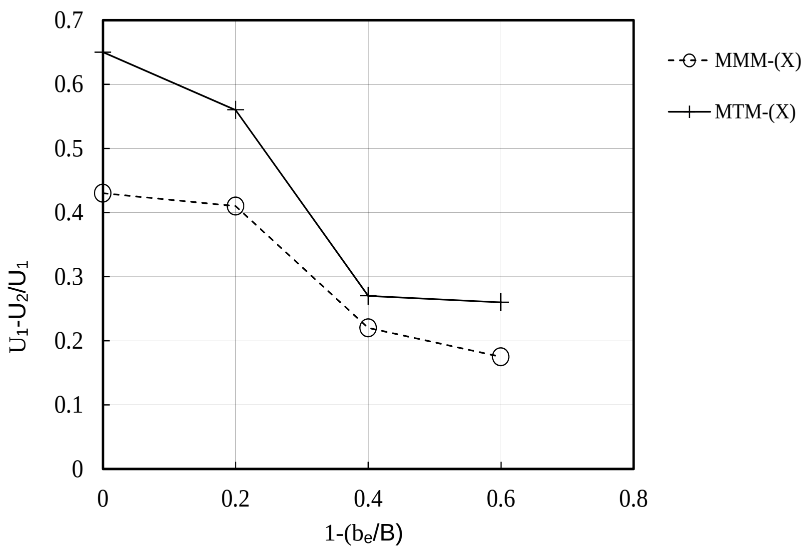


Figure 6- The variation of normalized velocity reduction versus the degree of end-sill width

Considering two free spaces at both sides of the end-sill weakened the performance of ISB for velocity reduction; however, the general trend reveals that selecting a taller end-sill with free spaces may provide a better performance in velocity reduction than a full end-sill with no free spaces. Thus, a taller end-sill with 20% free space of whole channel width in addition to facilitating the fish passage can offer better ISB performance.

3.2. Velocity Reduction Performance within ISB

Figures 7a and b presents a general and 3D view of ISB performance with regard to velocity reduction for all the successful experiments in this study. The horizontal plane in Figure 7a shows the normalized end-sill height, h_e/h_c, versus the normalized ISB length, L/B. However, the horizontal plane in Figure 7b produces the interaction between the normalized end-sill heights, h_e/h_c, with the drop number, s/h_1. The vertical axis in both discussed figures represents the normalized velocity reduction, U_1-U_2/U_1, between section I and II that is also quantified by the color shading.

Figures 7a illustrates, in an overall view, the combination of medium end-sill height, $1.5<h_e/h_c<2.5$, with medium ISB, L/B=1.5, leads to larger reduction of initial velocity about 60 to 70% of U_0. However, as can be seen in Figure 7b some amount of drop number can contribute to reduce the necessary end-sill height since that the combination of $(h_e/h_c, s/h_1)=(2,2)$ showed the same performance in velocity reduction as $(h_e/h_c, s/h_1)=(2.5,1.5)$.

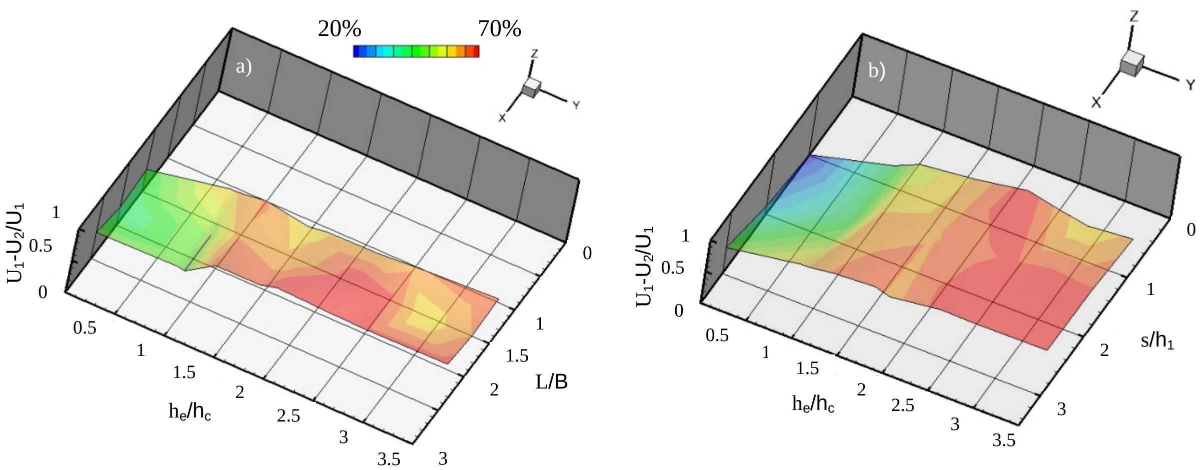
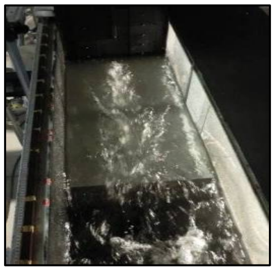


Figure 7a and b- 3D view of normalized velocity reduction within ISB

3.3. Flow Pattern Detection

We utilized electric magnetic velocity meter, LSPIV technique and laboratory observation. The possible hydraulic jumps types within ISB classified into 4 major flow patterns as: B-jump, U-jump, Periodic submerged jump and Steady submerged jump. The definition of the different type of jumps that we observed in the current study is well described in the past (Ferreri and Nasello, 2002). Table 2 summarizes the flow patterns with names, characteristics and ISB structure geometry that is required to form each flow pattern. Ferreri and Nasello (2002) pointed out through the mutual effect of a drop and an enlargement, a fully 3D and complex overlapping effect has been detected that in individual presence of each of these measures has not been detected. Katakam & Rama (1998), but, noted that in case of low drop number conditions, which is introduced earlier, the flow patterns within ISB is much referable to those that is observed in only sudden enlargement. In contrary, we found that due to the presence of positive step at ISB downstream, the jump types are more referable to those have been detected in only drop cases and not in an enlargement. Combination of drop and positive step creates a stilling basin homogenous with a box or a pool below the dam. This box increases the complexity of flow field within ISB through providing the condition in which plunging jet into ISB faces to two different areas with higher and lower shear stress as well as by producing the lateral reverse flow within ISB. We called this effect as box effect. Box effect solves the huge periodicity issues that stilling basins with small expansion ratio are generally faced e.g. stilling basin downstream of FMDs. Although, the influence of drop number, s/h_1, on velocity reduction was found to be not significant, it plays an important role in defining the flow pattern within ISB with the aid of positive step.

Table 2 – Summary of major flow patterns that observed in ISB and its characteristics

Class Number	Jump Characteristics	ISB geometry Characteristics	Photograph
1	B-jump, Symmetric, In-sufficient velocity reduction.	When there is no end-sill downstream of the ISB and the ISB depth is shallow.	
2	U-jump, Symmetric, In-sufficient velocity reduction.	When there is a medium height of end-sill downstream of the ISB and ISB depth is shallow.	
3	Periodic submerged jump, Unstable, Medium velocity reduction.	When there is a medium end-sill height downstream of the ISB and ISB length is relatively long, as well as in case of higher Fr numbers.	
4	Steady submerged jump, Stable, High velocity reduction.	When there is a tall end-sill downstream of the ISB and ISB length is relatively short.	

Moreover, we realized that the taller end-sill height and the shorter ISB length may be the suitable geometry; since it could provide steady symmetric submerged jump with a higher dissipation of energy. A taller end-sill and shorter ISB length confides the jump and provides a sequent depth that leads to formation of a complete jump. It is in consistent with the discussed results in section 3.1.3., where it was shown that the higher rate of velocity reduction occurred when there was a taller end-sill at ISB downstream. However, a very tall end-sill didn’t show any benefit in velocity reduction. Regarding ISB length, the relatively long ISB negatively increased the periodicity and instability of the flow within ISB. Therefore, a long ISB, in spite the fact that it showed higher velocity reduction performance, is not a favorable option for design purposes.

4. CONCLUSION

We systematically investigated the influence of different geometry of in-ground stilling basin (ISB), e.g. ISB length, ISB depth, on the flow pattern and its performance in energy dissipation. Following conclusions are presented as the main outcomes of this study:

a) A taller end-sill provides better ISB performance with regard to energy dissipation and it induces the steady symmetric jump within ISB. However, end-sill height larger than optimum range, $1.5<h_e/h_c<2.5$, showed no more benefit regarding with velocity reduction.

b) The longer ISB, the better velocity reduction. However, long ISBs increase the periodicity and instability of the flow. Therefore, combination of a medium end-sill height, $1.5<h_e/h_c<2.5$, with a medium ISB length, L/B=2, is recommended for design purposes. It should take into account that it is vital to avoid both very tall end-sills and long ISBs, considering the economical aspects.

c) Deepening ISB slightly improves the velocity reduction within ISB while further increase in depth showed no more benefits, in particular in case of medium to tall end-sill. We highly recommend a medium ISB depth for design, $s/h_1=2$, since it allows a considerable reduction in end-sill height. Additionally, drop number in combination with positive step at ISB downstream provides a 3D influence on flow filed, which is called box effect. Box effect on flow within ISB positively stabilizes the flow.

d) Considering two lateral free spaces with a width up to 10% of the channel width, showed approximately same performance in velocity reduction with no free space condition. A taller end-sill with lateral free spaces showed higher velocity reduction than medium end-sill height with no free space. Hence, considering a relatively tall end-sill height with two lateral free spaces at the end of ISB may grantee an efficient velocity reduction during flood events and also facilitate fish passage in the normal river flow condition.

5. REFERENCES

Chanson, H., and Montes, J.S. (1995), *Characteristics of Undular Hydraulic Jumps Experimental Apparatus and Flow Patterns*, Jl of Hydraulic Engineering, ASCE, Vol. 121, pp. 129-144.

Ferreri, G.B., and Nasello, C. (2002), *Hydraulic jumps at drop and abrupt enlargement in rectangular channel*, Jl of Hydraulic Research, Vol.40, No.4, pp.491-504.

Hager, W. H., 1992. *Energy Dissipators and Hydraulic Jump*, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Katakam V.S.R., Rama P. (1998), *Spatial B-jump at sudden channel enlargements with abrupt drop*, Jl of Hydraulic Engineering, Vol.124, No.6, pp.643-646.

Larson E. A. (2004), *Energy dissipation in culverts by forcing a hydraulic jump at the outlet*, Thesis on Master of Science in civil engineering, Washington State University, USA.

Meshkati Shahmirzadi, M. E., and Sumi, T. (2013), *Hydraulic Design of In-ground Stilling Basin under Submerged Jump Condition in Flood Mitigation Dams*, Jl of Japan Society of Civil Engineering, Vol. 69, pp. 79-84.

Ohtsu, I., Yasuda, Y., and Ishikawa, M. (1999), *Submerged hydraulic jumps below abrupt expansions*, Jl of Hydraulic Engineering, Vol. 125, No. 5, pp. 492-499,.

Ohtsu, I., and Yasuda, Y. (1991), *Transition from supercritical to subcritical flow at an abrupt drop*, Jl of Hydraulic Research, Vol. 29, No. 3, pp. 309-328.

Pagliara, S., Das, R. and Palermo, M. (2008), *Energy Dissipation on submerged block ramps*, Jl of Irrigation and Drainage Engineering.

Sumi, T., (2008), *Designing and Operating of Flood Retention Dry Dams in Japan and USA*, Proc. of ICHE Conference on Hydro-Science and Engineering, Nagoya, Japan.

Sumi, T. and Nakanishi, T. (1991), *Characteristics of Hydraulic jump type energy dissipators below abrupt symmetrical expansion*, Civil Eng. Jl, 33-6, pp.21-27.

Zare H. K. and Doering J. C. (2011), *Forced hydraulic jumps below abrupt expansions*, Jl of Hydraulic Engineering, Vol. 137, No. 8, pp. 825-835.