THE EFFECT OF IN-GROUND STILLING BASIN GEOMETRY COMBINED BY SLIT-TYPE END-SILL ON FLOW PATTERN AND ENERGY DISSIPATION BELOW THE FLOOD MITIGATION DAMS

M. E. Meshkati Shahmirzadi[1], Tetsuya Sumi[2] and S. A. Kantoush[3]

[1]Ph.D. Candidate, Disaster Prevention Research Institute, Kyoto University, Goka-sho, Uji-shi, 611-0011, Kyoto, Japan, (e-mail: meshkati.shahmirzadi@gmail.com)

[2]Professor, Disaster Prevention Research Institute, Kyoto University, Goka-sho, Uji-shi, 611-0011, Kyoto, Japan, (e-mail: sumi.tetsuya.2s@kyoto-u.ac.jp)

[3]Associate Professor, Faculty of Engineering and Material Science, German University in Cairo, New Cairo City, Al-Tagamoa Al-Khames, Cairo, Egypt, (e-mail: sameh.kantoush@guc.edu.eg)

Abstract: In this paper, an ecofriendly concept of stilling basin (SB) is introduced; called In-ground Stilling Basin (ISB), which can be optionally equipped with a slit type (non-continuous) end-sill at its downstream end. ISB is a non-prismatic SB with a sudden enlargement in transversal cross section and an abrupt drop in the bed at its upstream end, and is accessorized by a positive step at its downstream end, so that it creates a drop box below FMD's outlet; a geometry similar to an elongated pool below the bottom outlet. Particular interest during our study was to solve the problem of fish and sediment passages disruption in conventional stilling basin design. Thus, extended series of experiments were carried out to obtain the optimum ISB geometry (length and depth) and optimum end-sill geometry (height and width), so that be acceptable in terms of hydraulic, economic and environmental aspects. To achieve this purpose, the experiments were conducted under various hydraulic conditions such as: stilling basin length (L= 125 and 75cm), step depth (s= 5 and 15cm), end-sill height (h_e= 0, 4, 8 and 12cm) and end-sill width (b_e= 50, 40 and 30cm). Observation of the experiments showed that the forced hydraulic jump within ISB has a very complex 3D nature and highly influenced by geometry of ISB as well as end-sill. In this respect, a higher end-sill can effectively reduce the magnitude of velocity along the centerline of SB but it may be an obstacle for fish and sediment passage. However, considering two free spaces at the lateral side of end-sill shows almost equal function for velocity reduction to that of fully end-sill, providing additional positive solution for smooth fish and sediment passing.

Keywords: flood mitigation dam, stilling basin, abrupt drop, sudden enlargement, forced hydraulic jump, slit-type end-sill.

1. INTRODUCTION

Recently, enormous floods have been experienced worldwide more often than the past and it causes severe losses and damages for human being properties and civilization. Thus, developing innovative strategies is vital for protection of urban area against the massive floods. One of the well-known constructive flood control measures is Flood Mitigation Dam (FMD) which attracted much attention over past decades. FMD is defined as a dam devoted only to flood retention and retardation which its storage volume is completely dry except for a few weeks per century, while in case of flood events the flood flow can be stored temporary its inside and gradually discharge out through its gateless bottom outlet (Lempérière, 2006).

In practice, FMD's design is still facing to several problematic; and need more investigation in order to improve its design. In particular, design of stilling basin at the downstream of FMDs required to be modified. Stilling basin (SB) is a hydraulic structure aimed to dissipate the excess energy of flow and prevent the undesirable scouring at its downstream area by inducing hydraulic jump. Truncate of hydraulic jump within a limited area is not simply achievable, unless utilizing appurtenances such as fully width (continuous) end-sill with an adequate height to compact the jump, resulting in reduction of SB length and an economical design. But it should take in to account that, a fully width end-sill can negatively disrupt the fish migration and sediment transport in river system. Then, presence of fully width end-sill creates the contradictory goals for SBs.

In this paper, a new innovative concept of SB is introduced; called In-ground Stilling Basin (ISB), which can be optionally equipped with a slit type (non-continuous) end-sill at its downstream end. ISB can be defined as a non-prismatic SB with sudden enlargement in the flume width and abrupt drop in the bed at its upstream end and a positive step at its downstream end (with a height equal to abrupt drop), so that it creates a drop box below FMD's outlet; a geometry similar to an elongated pool below the bottom outlet. The schematic view and hydraulic parameters of ISB are shown in **Fig. 1.** The slit-type end-sill, indeed, is similar to the conventional fully width (continuous) end-sill as a point of view of shape; and just the length of slit-type end-sill is not equal to the width of channel and it has two free spaces in both lateral sides which can facilitates the fish and sediment passing. Both either positive step only or its combination with slit-type end-sill are intended to force hydraulic jump within ISB apron without the assistance of tail-water depth downstream. Present research thus can be considered as a subset of forced hydraulic jump studies.

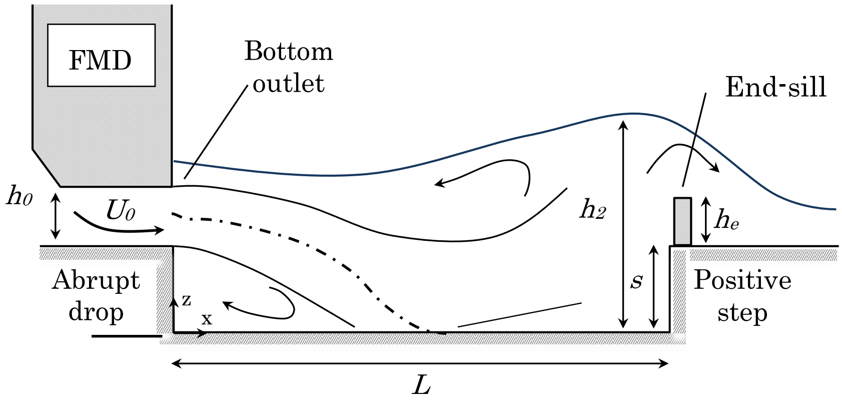

Figure 1: The schematic side view of ISB concept downstream of FMDs.

Extensive experimental studies have been completed on hydraulic jumps below the expansions which can be classified into three main categories as: hydraulic jump in case of only sudden enlargement in the flume width (Bremen and Hager, 1994; Ohtsu et al., 1999; Zare and Doering, 2011), only abrupt drop at the bed (Rajaratnam and Ortiz, 1977; Hager and Bretz, 1986; Ohtsu and Yasuda, 1991; Hotchkiss and Larson, 2005), and combination of both sudden enlargement and abrupt drop (Katakam and Rama, 1996; Frerri and Nasello, 2002) whose commonly used in the reality. The majority of above-mentioned studies have focused on the details description on hydraulic characteristics of jump as well as prediction of sequent depth. Literature review evince that a few number of papers concern the combination of abrupt drop and sudden enlargement simultaneously. Katakam and Rama (1996), expand an analytical and experimental study of the hydraulic jump in stilling basin with abrupt drop and sudden enlargement. They found that the required tail-water level to ensure the hydraulic jump within stilling basin can be reduced by combining the sudden enlargement and abrupt drop. They introduce the most common feature of hydraulic jump in case of simultaneously abrupt drop and sudden enlargement; called spatial B-jump which has relatively higher energy loss compared to either the special jump or B-jump. Frerri and Nasello (2002), provide qualitative physical explanations on sequence of different hydraulic jumps below abrupt drop combined with sudden enlargement as tail-water depth increases. They stated that, hydraulic jumps at a drop combined with sudden enlargement present very different and complex characteristics whose overall characteristics at time are mainly referable to those of drop only, at other times to those of enlargement only, while yet other times the jumps just have autonomous characteristics. Additionally, they emphasize on necessity of specific experimental investigation for each type of hydraulic jump that can occur in order to design of structure. There are some differences between the present study and exist studies in the literature. First, the approach supercritical flow after discharging out through the bottom outlet was plunged into the ISB pool (drop box) and then was encountered to a positive step as well as an end-sill at the downstream end. Second, there was no adjustment for tail-water depth at far downstream of flume. Third, the combination of positive step and the slit-type end-sill had not been examined yet.

Present study experimentally evaluates the functionality of in-ground stilling basin (ISB) as an alternative for energy dissipation of high velocity flow exiting from the FMD's bottom outlet. Particular motivation during study was to solve the problem of fish and sediment passages disruption in conventional stilling basin design. Additionally, evaluation of the functionality of ISB pool for residency of aquatic animals as a desire habitat was one of the other interest point in current research. Thus, an extended series of experiments were carried out to obtain the optimum ISB geometry (length and depth) as well as the necessary end-sill geometry (height and width) that would force and stabilize hydraulic jump for given discharge and bottom outlet dimension. Proposing a new design procedure by using the successful test outcomes is the ultimate goal of this experimental investigation which it should be valuable for practicing engineers.

2. EXPERIMENTAL INVESTIGATION

2.1. Main governing parameter definition

Fig. 2 shows the schematic side and plan views of the constructed model at Disaster Prevention Research Institute of Kyoto University (Japan) including the main hydraulic parameters involved in this study. Based on the test series, it was found that the energy loss (H_L) within in-ground SB to be dependent on the following parameters: outlet velocity at the outlet exit (U_0), outlet width (b_0), outlet height (h_0), drop height or in other words, step depth (s), SB width (B), SB length (L), sequent depth (h_2), end sill height (h_e), the width of free space at the lateral side of end-sill ($2b_e$) water density (ρ_w) and gravitational acceleration (g):

$$H_L = f(U_0, b_0, h_0, s, \mathrm{B}, L, h_2, 2b_e, h_e, \rho_w, g) \tag{1}$$

Since U_0, b_0, h_0, B, ρ_w *and* g are constant in present study, thus **Eq. (1)** could be simplified as **Eq. (2)**.

$$H_L = f(\, s, L, h_2, 2b_e, h_e) \tag{2}$$

Lastly, the relative energy loss (H_L/H_1+s) can be written as a function of four dimensionless parameters as below:

$$\frac{H_L}{H_1+s} = f(y, \beta, S, \alpha, e) \tag{3}$$

where H_1 is the total energy at the face of outlet to the ISB, y is the ratio of sequent depth to the height of outlet (h_2/h_0), β is the relative end-sill width ((B-2b_e)/B), S is the drop number ((s+h_e)/h_0), α is the aspect ratio of ISB (B/L) and e is the expansion ratio (B/b_0). It should be take into account that, the sequent depth (h_2) can be defined in **Eq. (4)** where h_c is the critical water depth over the end sill (F_r =1).

$$h_2 = s + h_e + h_c \tag{4}$$

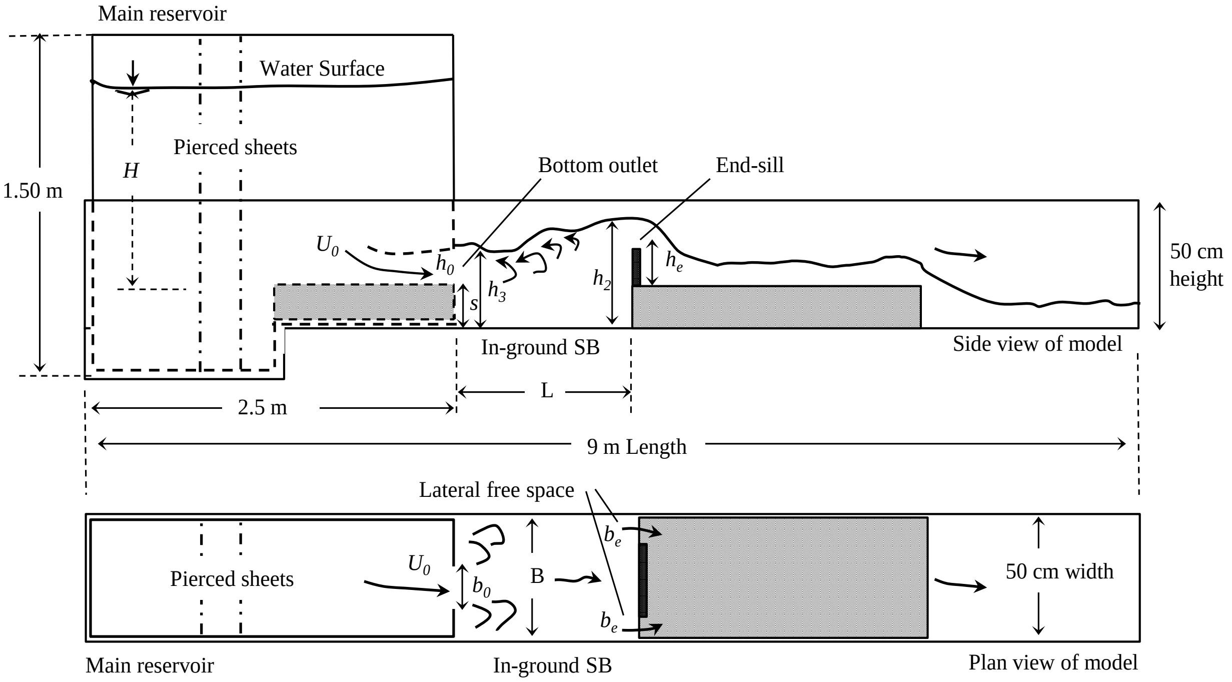

Figure 2: The schematic side and plan view (not to scale) of experimental setup.

2.2. Experimental condition and limitations

The experiments were carried out under different ISB geometries as follow: stilling basin length (L= 125 and 75cm), step depth (s= 5 and 15cm), however, the width of ISB for all experiments was the same B= 50cm equal to the width of flume. For each ISB geometry configuration, different geometry of end-sill with various heights and width has been examined systematically to obtain the optimum case as: end-sill height (h_e= 0, 4, 8 and 12cm) and end-sill width (b_e= 50, 40 and 30cm). The end-sills used in this study were uniform in both height and thickness and were placed vertically above the positive step downstream end of ISB, perpendicular to the longitudinal axis of flume. In addition to the given Froude number of supercritical flow at the bottom outlet exist (namely F_r= 5.5), only one dimension of bottom outlet (h_0= 7cm and b_0= 10cm) was examined as FMD's bottom outlet, create an expansion ratio of 5.

2.3. Experimental setup

The experiments were conducted in a horizontal rectangular flume, 0.5m width, 0.5m deep and 9m long. This flume had a transparent Plexiglas sidewall at the left side of stream flow direction which facilitates the visual access. A centrifugal pump was employed to support the recirculating water system in this study. The height of opening (h_0) was simply changeable by sliding the vertical gate up or down. Two pierced plates attached with pieces of cotton sheets were installed inside of main reservoir to attain the laminar flow before discharging out into the in-ground stilling basin (SB). Since the function of gate in this study was exactly similar to the concept of bottom outlet in FMDs; the terminology of bottom outlet was selected for the gate. The exit of bottom outlet faced to ISB structure and its entrance was located 50cm inside of main reservoir to guarantee the straight streamlines of flow approaches to exist. Flow was entered into the ISB through bottom outlet, so that a uniform supercritical flow with a thickness equal to the outlet was fall into the ISB.

An electro magnitude wave gage (EMWG) was used to measure the water depth fluctuation throughout the in-ground SB as well as the average water depth of stream-wise along the in-ground SB.

Additionally, the instantaneous 3D velocity of water body was measured in different transverse and longitudinal cross sections using electro magnitude current meter (EMCM) for each test run. For each test digital photographs were taken and visual observations were recorded using high resolution digital camera. The basic data collection procedure was the same for all of the experiments run.

2.4. Experiments program

As previously mentioned, present study aimed to untimely propose a new design guideline for stilling basin downstream of FMDs how to be hydraulically, economically and environmentally acceptable. To achieve this final purpose and to be able to propose a robust and useful design guideline, it is necessary to put efforts in organized and systematical manner. Here in the details about the experiments program was described.

The experiments were conducted in two phases of "clear water" and "clear water with movable bed". In the first phase of experiments, clear water condition, 50 experiments were carried out to select suitable geometries of ISB in which dissipation of energy and stabilization of hydraulic jump were significantly higher than others. The hydraulic criteria used to evaluate the overall efficiency of ISB geometry (from the hydraulic point of view) includes: dissipation of energy between bottom outlet section and a section at the downstream of end-sill, momentum at the downstream of end-sill, type, symmetry and stabilization of hydraulic jump within ISB, fluctuation of water surface within ISB, the maximum height of standing wave over the end-sill, stream-wise velocity reduction along the centerline of ISB, and tail water depth at the downstream of end-sill.

It should be noted that precise velocity distribution measurements have been done in several longitudinal and transversal cross sections. At least 5 minutes, 3D velocity measurement for each point was considered to create the spatial velocity distribution within ISB and obtains the variation of velocity in each point over time. This kind of measurement is needed for environmental analysis of ISB design. Velocity vectors and magnitude, and its variation in each point over time are three required indicators to answer the question of which geometry of ISB is more acceptable from the viewpoint of habitat for aquatic animals.

Moreover, total wetted perimeter and total wetted area of ISB was considered as two main indicators for selecting the more economical acceptable geometries. Then, the optimal geometry was selected between the cases that could satisfy all three terms of hydraulic, economic and environmental requirements.

3. RESULTS AND DISCUSSION

Fig. 3 plots the mean stream-wise velocity (U_{ave}) distribution along the centerline of ISB for different end-sill heights. As can be seen, in case of experiment without end-sill, the U_{ave} was remained considerably high until the end of ISB. While for the case of fully end-sill with 10cm height the lowest magnitude of U_{ave} was observed. The laboratory observation also proves the results obtained by flow velocity measurements. In case of the experiment without end-sill, the nappe flow into the ISB was visible and at the downstream of plunging point a supercritical current observed which enlarges to the whole width of flume in section 2.

The huge number of minor jumps were observed at the second downstream half of ISB and consequently considerable amount of air was entrained into the water body that is dragged far downstream of ISB. It means that the ISB length and end-sill height was not sufficient to force the jump to occupy within ISB. While by increasing the end-sill height to 10cm, the toe of the jump draws back toward the FMD and the jump stabilize within limited area of ISB.

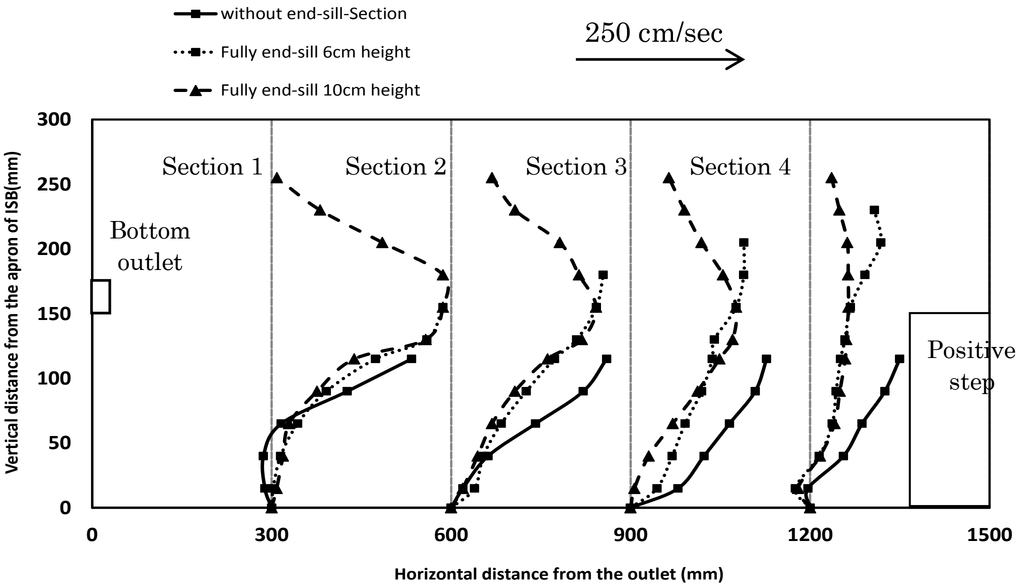

Figure 3: The mean stream-wise velocity (U_{ave}) distribution along the centerline of ISB for different end-sill heights, in case of L= 125cm, s= 15cm, F_r= 5.5.

Fig. 4 depicts the mean transversal velocity (W_{ave}) distribution on four predefined cross sections along the centerline of ISB. As can be seen, in case of fully end-sill with 6cm height, transversal reverse flow occurred in deep area of basin where close to the positive step. In this condition, the water surface was slightly tended to the left side and creates an asymmetric hydraulic jump. The oriented hydraulic jump to the left side wall hit the wall and deflected back to the center part of ISB. Then a vertical vortex was created in the section number 4.

Further increase in end-sill height to 10cm, creates two long horizontal eddies as secondary subcritical flow goes back toward the FMD in both lateral side of flume. **Fig. 5** shows the variation of the maximum stream-wise velocity (U_{ave}) along the ISB centerline. Interestingly, slit-type end-sill with 5 cm free space at both lateral side and 10cm height create a symmetric jump orthogonally to the channel axis with approximately the same velocity reduction with fully end-sill 10cm height.

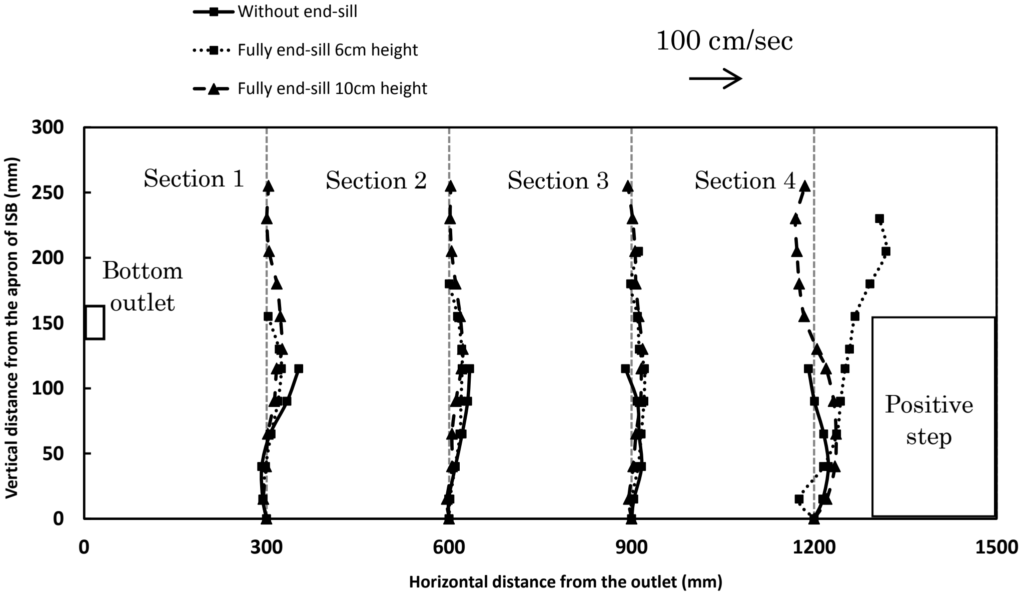

Figure 4: The mean transversal velocity (W_{ave}) distribution along the centerline of ISB for different end-sill heights, in case of L= 125cm, s= 15cm, Fr= 5.5.

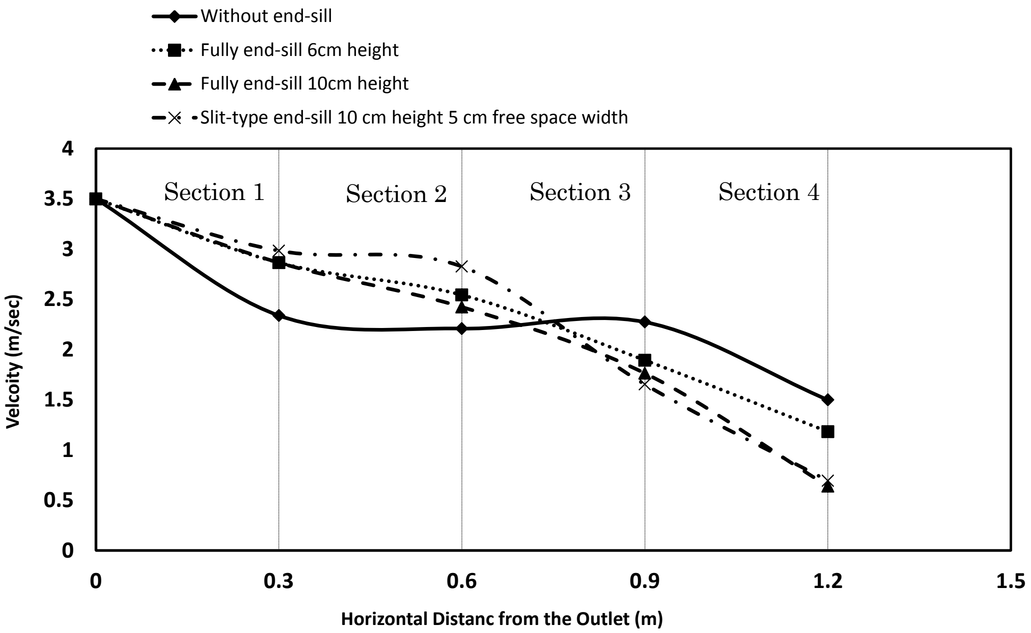

Figure 5: The variation of maximum stream-wise velocity (U_{max}) along the ISB centerline, in case of L= 125cm, s= 15cm, Fr= 5.5.

4. CONCLUSION

The new concept of stilling basin as well as end-sill for FMDs has been proposed in this study, which could be environmentally acceptable from the point views of fish and sediment passages. The velocity reduction of stream-wise flow affected by different end-sill heights and width was experimentally investigated and the following results can be concluded:

1- The presence of end-sill at the end downstream of ISB could stabilize the hydraulic jump symmetrically.

2- The taller fully end-sill can effectively reduce the magnitude of velocity within ISB compare to the shorter one.

3- Considering two free spaces at the lateral side of end-sill (slit-type) shows the almost equal function for velocity reduction with fully end-sill and positively provides additional effects for fish and sediment passing.

Bremen, R., Hager, W.H. (1994), Expanding stilling basin, Proc. ICE, Water, Maritime and Energy, Vol. 106, pp, 215-228.

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

Hager W.H. and Bretz V.N. (1986), Hydraulic jumps at positive and negative steps, Journal of Hydraulic Research, Vol. 24, No. 4, pp. 237-253.

Hotchkiss, R. and E. Larson. (2005), Simple Methods for Energy Dissipation at Culvert Outlets. Impact of Global Climate Change. World Water and Environmental Resources Congress.

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

Lempérière, F. (2006), The role of dams in the XXI century, Achieving a sustainable development target, Hydropower and Dams, Issue Three, pp.99-108.

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.

Ohtsu I. and Y asuda Y., (1991), Transition from supercritical to subcritical flow at an abrupt drop, Journal of Hydraulic Re-search, Vol. 29, No. 3, pp. 309-328.

Rajaratnam N., Ortiz V., (1977), Hydraulic jumps and waves at abrupt drops, Proc. ASCE, Journal of the Hydraulics Division, Vol. 103, No. HY4, pp. 381-394

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