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# The Effect of End-sill Geometry on Functionality of In-ground Stilling Basin

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## Synopsis

In practice, design of stilling basin downstream of Flood Mitigation Dams (FMDs) is still facing several problems such as blockage of sediment passage and fish migration; and thus, it is necessary to improve its design. In this paper a new concept of stilling basin for FMDs is introduced; called In-ground Stilling Basin (ISB). Present study mainly focuses on experimental investigation on end-sill geometry at the end downstream of ISB. As results, several unique outcomes of experimental investigations have been obtained to improve the performances of FMDs as well as facilitate the fish and sediment passage.

**Keywords**: flood mitigation dam, stilling basin, bottom outlet, end-sill.

## 1. Introduction

Recently, huge 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 problems; 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 concept of SB for FMDs is introduced; called In-ground Stilling Basin (ISB). ISB can be defined as a non-prismatic SB with a sudden transversal enlargement combined with a vertical abrupt drop at its upstream end where the bottom outlet of FMD is located. A positive step (an abrupt rise) at ISB's downstream end, also, has been added to its geometry. The height of positive step is exactly equal to abrupt drop, so that it

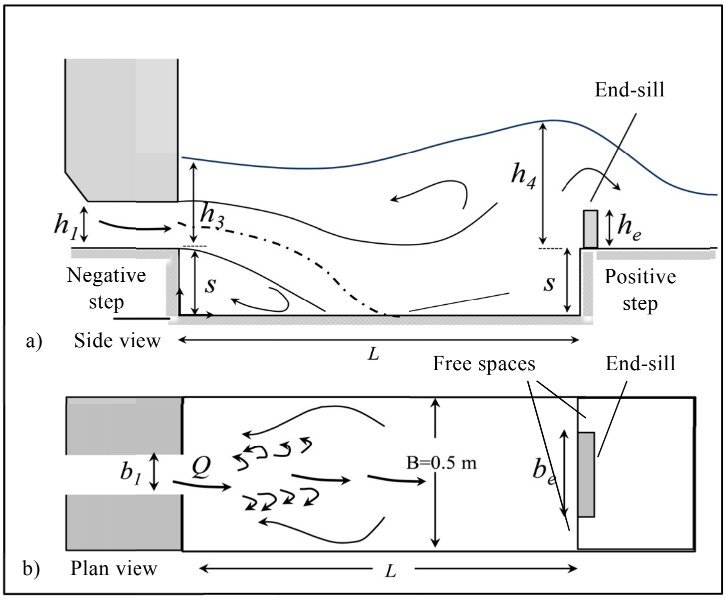

Fig. 1 The schematic side and plan view of ISB downstream of FMD.

Creates an empty drop box below FMD, similar to the shape of an elongated pool. A slit-type end-sill, optionally, can also be added above the positive step as means of insuring the formation of jump and control its position within ISB. The slit-type end-sill is similar to fully width (continuous) end-sill with a tiny difference as it has two free spaces at the lateral sides which may positively facilitates the fish migration and sediment passing. The schematic view of the ISB and the hydraulic parameters tested are shown in Fig. 1. Either considering only positive step at the downstream end of ISB or its combination with slit-type end-sill are intended to force the hydraulic jump within ISB's apron without the assistance of tail-water depth downstream. Present research, thus, can be considered as a subset of forced hydraulic jump studies.

## 2. Background

Extensive experimental studies have been devoted to the study of hydraulic jumps in non-prismatic stilling basin which can be classified into three main categories as: hydraulic jump in case of only sudden enlargement in the flume width (Rajaratnam and Subramanya, 1968; 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; Kawagushi and Hager, 1990; 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 further downstream of ISB. Third, the combination of positive step and the slit-type end-sill have not been examined yet.

Present study experimentally evaluates the functionality of in-ground stilling basin (ISB) as an alternative of conventional stilling basin on 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, functionality assessment of ISB 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.

## 3. Experimental investigation

### 3.1 Definition of main governing parameters

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. Functionality of an ISB can be discussed in two different aspects, hydraulic functionality (*HF*) and ecological functionality (*EF*). To evaluate the hydraulic functionality of an ISB different hydraulic criterion can be utilized i.e. velocity reduction along the ISB, energy dissipation within ISB, water level fluctuation inside the ISB and flow condition downstream of ISB. Based on the literature review and preliminary experiments, it was found that the hydraulic functionality (*HF*) of ISB may depend on the following parameters: the outlet velocity at the bottom outlet exit ($U_0$), the bottom outlet width ($b$), the bottom outlet height ($h_1$), the drop height or in other words, step depth ($s$), the ISB width ($B$), the ISB length ($L$), the sequent depth ($h_4$), the end-sill height ($h_e$), the end-sill width ($b_e$), the water density ($\rho_w$) and the gravitational acceleration ($g$):

$$HF = f(U_0, b, h_1, s, B, L, h_4, h_e, b_e, \rho_w, g) \tag{1}$$

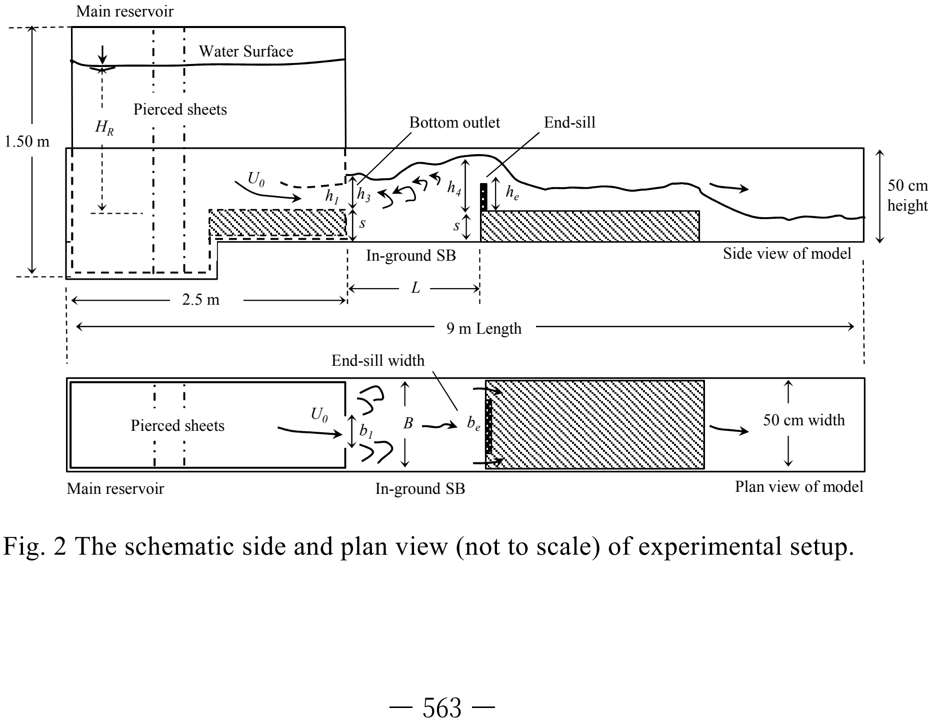

Fig. 2 The schematic side and plan view (not to scale) of experimental setup.

The relative hydraulic functionality (RHF) can be written as a function of eight dimensionless parameters as below:

$$RHF = f(Fr, Y, Y_3, \gamma, S, \delta, \alpha, \beta) \tag{2}$$

where $Fr$ is the Froude number at the bottom outlet exit, $Y$ is the ratio of sequent depth to the bottom outlet height $h_4/h_1$, $Y_3$ is the degree of submergence or in other words the ratio of water depth at the face of bottom outlet to the bottom outlet height $h_3/h_1$, $\gamma$ is the relative end-sill width $b_e/B$, $S$ is the drop number $(s+h_e)/h_1$, $\delta$ is the ratio of end-sill height to the end-sill position $(s+h_e)/L$, $\alpha$ is the expansion ratio $B/b$ and $\beta$ is the aspect ratio $L/B$. It should be take into account that, the sequent depth ($h_4$) can be defined in Eq. (3) where $h_c$ is the critical water depth over the end sill ($Fr$ =1).

$$h_4 = s + h_e + h_c \tag{3}$$

### 3.2 Experimental condition and limitations

The experiments were carried out under different ISB geometries as follow: ISB length ($L$= 75, 100 and 125 cm), step depth ($s$= 5, 10 and 15 cm), however, the width of ISB for all experiments was the same $B$= 50 cm equal to the width of flume. For each ISB geometry configuration, different geometry of end-sill with various heights ($h_e$= 0, 4, 8 and 12 cm) and width ($b_e$= 50, 40 and 30 cm) has been systematically examined to obtain the optimum case. The end-sills used in this study were made by plywood and were uniform in both height and thickness. The end-sills were placed vertically above the positive step and perpendicular to the longitudinal axis of flume. The end-sill with two free spaces located at the downstream end of ISB was shown in Fig. 3. In addition to the three different Froude number of supercritical flow at the bottom outlet exist (namely $Fr$= 3, 4.3 and 5), only one dimension of bottom outlet ($h_1$= 5 cm and $b_1$= 10 cm) was examined, thus, creates an expansion ratio of 5.

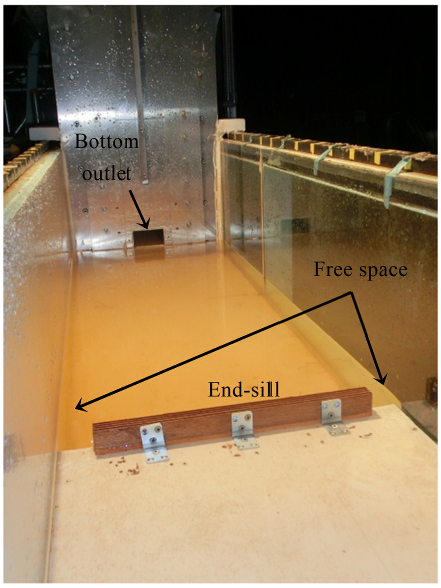

Fig. 3 The front view of end-sill with two free spaces at its both sides.

### 3.3 Experimental setup

The experiments were conducted in a horizontal rectangular flume, 0.5 m width, 0.5 m deep and 9m Long. This flume had a transparent Plexiglas sidewall which facilitates the visual access. A centrifugal pump was employed to support the recirculating water system in this study; by pumping up the water into the supply tank from the underground sump. Volume rates of flow were regulated by a valve located between the underground sump and the supply tank. The supply tank was located at the upstream of the flume and equipped by a calibrated 90 degree V-notch weir.

To measure the water head above the V-notch weir a point gage was used, and then average time-volume method was utilized for five reading for each flow rates to obtain the relationship between water head and the pertinent discharge. The water over the V-notch weir, then, was fall into a hexahedral shape tank constructed at the beginning and inside of the flume; named main reservoir. The main reservoir was representative of FMD and it was equipped by a low level vertical gate at its downstream end. The opening height of discussed low level gate could be simply adjusted by sliding the vertical gate up or down. The exit of the low level gate was faced to the ISB, whereas its entrance was located 50 cm inside of the main reservoir to guarantee the straight streamlines of flow approaches to the exit. Since the function of low level gate in this study was exactly similar to the concept of bottom outlet in FMDs; the terminology of bottom outlet was selected for that.

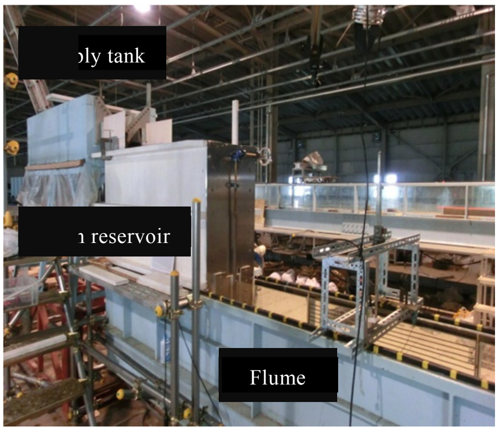

Fig. 4 The model setup used in this study.

Additionally, two pierced plates were installed inside of the main reservoir to attain the laminar outflow discharge into the ISB; so a uniform supercritical flow with a thickness equal to the bottom outlet was fall into the ISB. The photography of constructed model setup was shown in Fig 4.

### 3.4 Experimental measurements

The measurements in all experiments were taken 15 minutes after the pump started to re-circulating water throughout the model. Water head in supply tank ($h_w$) and water depth in the main reservoir ($h_r$) were measured and controlled several times during the experiment, using respectively point gauge and piezometer tube, to ensure a constant discharge and upstream water depth for steady state compliance. The basic data collection procedure was the same for all of the experiments run.

#### (1) Hydraulic jump properties

For each test digital photographs were taken from both side and plan view of ISB and visual observations were recorded using high resolution digital camera. Thus, the main characteristics of hydraulic jump were acquired through the image treatment.

#### (2) Water depth and fluctuation

The water level meter (ACH-300RS produced by JFE_ADVANTEC) was used to measure the mean water depth and its fluctuation throughout ISB. The red dots in Fig 5 indicate the points in which water level were measured. A sampling frequency was set to 50 HZ and the number of sample taken for each run was around 35000 to cope with the application of Fast Fourier Transform (FTT) in energy spectrum calculation.

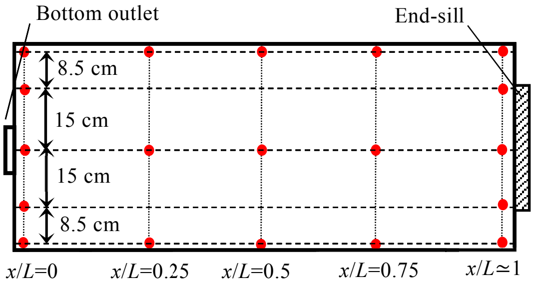

Fig. 5 The points in which water level were measured throughout ISB.

#### (3) Velocity measurements

Using an electro-magnetic current meter (ACM-3RS produced by JFE_ADVANTEC) the stream-wise instantaneous 3D velocity was measured in four different cross sections for each test run. At every section the velocity was measured at 3 cm interval. The sampling frequency was set to 50 HZ. The red dots in Fig 6 show the points where velocity profile distributions were measured. Fig. 7 shows the water level meter and electro-magnetic current meter in a position close to the end-sill.

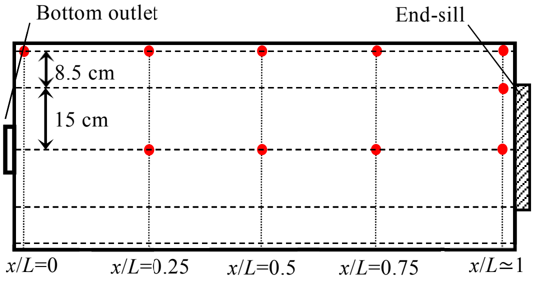

Fig. 6 The points in which velocity profile were measured throughout ISB.

#### (4) Flow condition downstream of ISB

The mean velocity and the water depth distribution at a specific cross section downstream of ISB were taken (4 meter farther downstream of bottom outlet section) where uniformly distributed flow was re-established in channel. These data were useful in determining the energy loss in ISB.

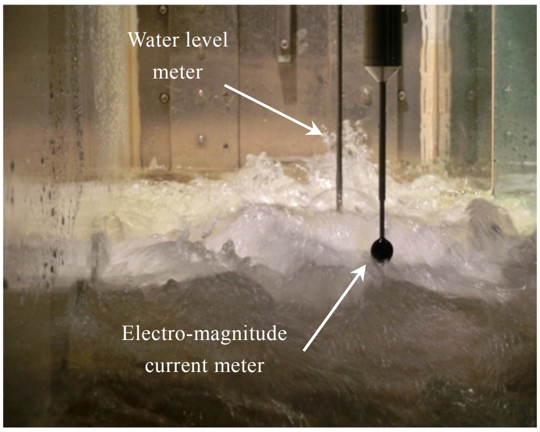

Fig. 7 The water level meter and electro-magnetic current meter used in this study.

### 3.5 Experiments program

As previously mentioned, present study aimed to ultimately 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 of the experiments program was described.

The 50 experiments were carried out in "clear water" condition to select optimum geometry 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. 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 view point of habitat for aquatic animals.

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

## 4 Results

### 4.1 The effect of end-sill height on hydraulic functionality of ISB

To identify the effect of end-sill height on hydraulic functionality of ISB, four tests were designed in which all parameters were constant and only the end-sill height varied. Table 1 shows the geometric and hydraulic variables of designed tests for this section. In order to investigate the effectiveness of different ISB geometry in flow velocity reduction, the normal stream-wise velocity ($U_{ave}/U_0$) along the centerline of ISB is plotted against the normal distance from the bottom outlet section ($x/L$). Fig. 8 plots the normal stream-wise velocity ($U_{ave}/U_0$) distribution along the centerline of ISB for different end-sill heights. As can be seen, in case of experiment without end-sill (E1), the $U_{ave}/U_0$ was remained considerably high until the end of ISB. While for the cases E3 and E4, respectively 8 and 12 cm end-sill height the lowest magnitude of $U_{ave}/U_0$ was observed at the end of ISB.

Table 1: The designed geometric and hydraulic variables for section 4.1.

| Case | *Q*(lit/sec) | *Fr* | $h_1$(cm) | $b_1$(cm) | *L*(cm) | *s*(cm) | $h_e$(cm) | $b_e$(cm) |
|---|---|---|---|---|---|---|---|---|
| E1 | 15 | 4.3 | 5 | 10 | 100 | 15 | 0 | 50 |
| E2 | 15 | 4.3 | 5 | 10 | 100 | 15 | 4 | 50 |
| E3 | 15 | 4.3 | 5 | 10 | 100 | 15 | 8 | 50 |
| E4 | 15 | 4.3 | 5 | 10 | 100 | 15 | 12 | 50 |

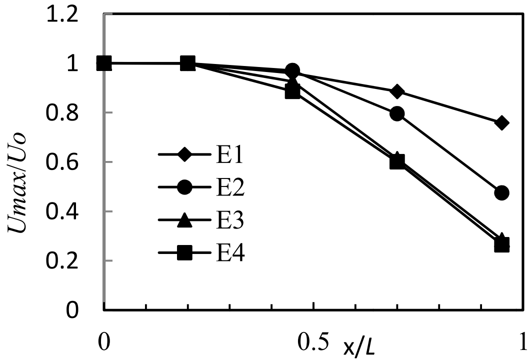

Fig. 8 The normal stream-wise velocity ($U_{ave}/U_0$) reduction along the centerline of ISB.

Additionally, this figure indicates that increasing the height of end-sill from 8 to 12 cm (E3 to E4) has not any significant effect on velocity reduction along the ISB. The laboratory observation also proves the results obtained by flow velocity measurements. In case of the experiment without end-sill, E1, the jet skims on the surface of stagnant water within ISB and a supercritical current observed which enlarges to the whole width of flume in the second half of the ISB. Then, a 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 (Fig. 9). It means that the ISB length and end-sill height was not sufficient to force the jump to occupy within ISB. Whereas, by increasing the end-sill height to 8 cm, the toe of the jump draws back toward the bottom outlet section and the jump stabilize within limited area of ISB (Fig. 10).

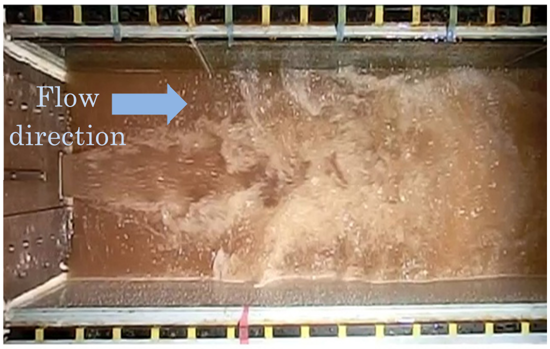

Fig. 9 The flow pattern within ISB for case E1. ($Fr$= 4.3, $Q$=15 lit/sec, $L$=100 cm, $s$= 15 cm, $h_1$=5 cm, $b_1$= 10 cm, $b_e$= 50 cm, $h_e$= 0).

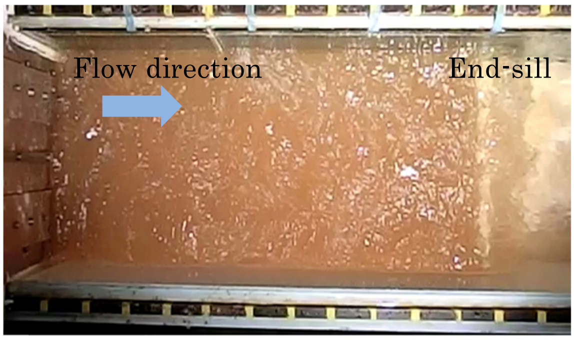

Fig. 10 The flow pattern within ISB for case E3. ($Fr$= 4.3, $Q$=15 lit/sec, $L$=100 cm, $s$= 15 cm, $h_1$=5 cm, $b_1$= 10 cm, $b_e$= 50 cm, $h_e$= 8 cm).

As can be seen in Fig. 11, by increasing the end-sill height from 0 (case E1) to 8 cm (case E3) the energy loss within ISB continuously increased. While further increase of end-sill height, adversely decreases the energy dissipation (case E4). The following equation was used to calculate the relative energy loss below the FMD due to submerged jump:

$$\frac{\Delta H}{H_1} = \frac{\left(\frac{U_0^2}{2g}+h_3\right)-\left(\frac{U_5^2}{2g}+h_5\right)}{\frac{U_0^2}{2g}+h_3} \qquad (4)$$

where $\Delta H$ is the differential of head loss between bottom outlet section and a section 4 meter further downstream of FMD, called section 5, where the flow velocity distribution is homogenous there. $U_5$ and $h_5$ are respectively the average velocity and the average water depth in section 5. $H_1$ is the total head at the toe of submerged jump at the upstream end of ISB.

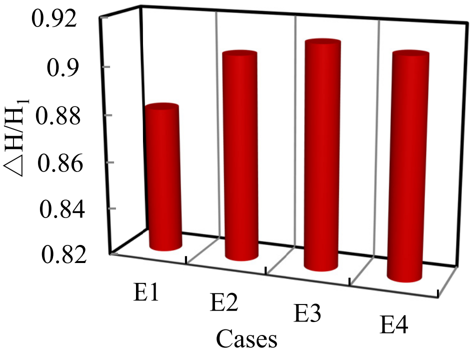

Fig. 11 The variation of relative energy loss versusthe different end-sill height. (E1 :$h_e$=0 cm, E2 : $h_e$=4 cm, E3 : $h_e$=8 cm, E4 : $h_e$=12 cm).

### 4.2 The effect of end-sill width on hydraulic functionality of ISB

To clarify the effect of end-sill width on hydraulic functionality of ISB, six tests were designed in which all parameters were constant and only the end-sill height and width varied. The designed geometric and hydraulic variables of tests for this section are tabulated in Table 2. Fig. 12 illustrates the normal stream-wise velocity ($U_{ave}/U_0$) reduction against the normalized distance from the bottom outlet section ($x/L$) for two different end-sill heights, (E2, E5 and E6 with 4 cm end-sill height and E3, E8 and E9 with 8 cm end-sill height).

As can be seen, in case of experiment with lower end-sill height (E2, E5 and E6), the less velocity reduction occurred compare to the cases with higher end-sill height (E3, E8 and E9). Additionally, considering two free spaces at the both side of end-sill slightly reduced the functionality of ISB for velocity reduction, however the magnitude of $U_{ave}/U_0$ has not been changed considerably at the downstream end. Thus, free spaces at both side of end-sill can effectively facilitate the fish and sediment passage while it has not significant impact on function of ISB.

Fig. 12 also shows that the lower end-sills are more sensitive against the free space width rather than higher end-sills. The result of energy loss calculation for designed test in this section was shown in Fig. 13. As can be seen, the result obtained by Eq. (4) is in good agreement with velocity reduction analysis along the ISB. Higher end-sill could dissipate more energy than the lower one and decreasing the end-sill width reduced the function of ISB.

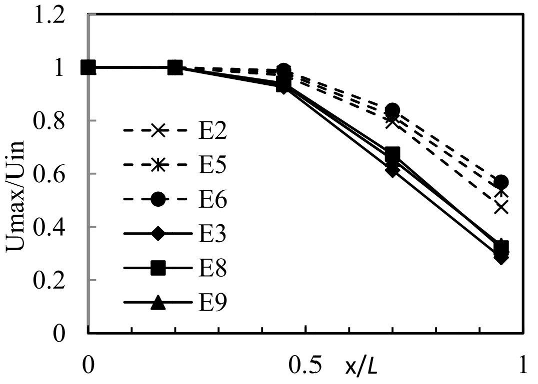

Fig.12 The normal stream-wise velocity ($U_{ave}/U_0$) reduction along the centerline of ISB.

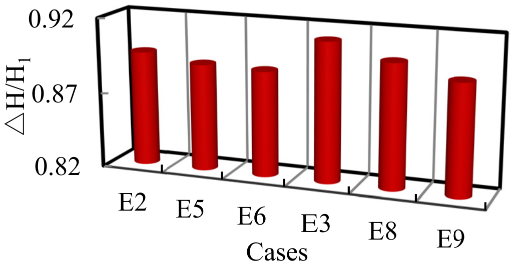

Fig. 13 The variation of relative energy loss versus the different end-sill height. (E2: $h_e$=4 cm, $b_e$=50 cm ;E5: $h_e$=4 cm, $b_e$=40 cm ;E6: $h_e$=4 cm, $b_e$=30 cm ;E3: $h_e$=8 cm, $b_e$=50 cm ;E8: $h_e$=8 cm, $b_e$=40 cm ;E9: $h_e$=8 cm, $b_e$=30 cm ).

Table 2: The designed geometric and hydraulic variables for section 4.2.

| Case | *Q*(lit/sec) | *Fr* | $h_1$(cm) | $b_1$(cm) | *L*(cm) | *s*(cm) | $h_e$(cm) | $b_e$(cm) |
|---|---|---|---|---|---|---|---|---|
| E2 | 15 | 4.3 | 5 | 10 | 100 | 15 | 4 | 50 |
| E5 | 15 | 4.3 | 5 | 10 | 100 | 15 | 4 | 40 |
| E6 | 15 | 4.3 | 5 | 10 | 100 | 15 | 4 | 30 |
| E3 | 15 | 4.3 | 5 | 10 | 100 | 15 | 8 | 50 |
| E8 | 15 | 4.3 | 5 | 10 | 100 | 15 | 8 | 40 |
| E9 | 15 | 4.3 | 5 | 10 | 100 | 15 | 8 | 30 |

## 5 Conclusions

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. On the basis of present study following conclusions are arrived at:

(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.

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# 潜り跳水式減勢工の減勢効果に及ぼすエンドシル形状の影響

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## 要　旨

流水型ダム下流に設置される減勢工の設計には，土砂や魚類の安全な通過のための課題が残されており，改善が求められている。本研究では，河川環境に対する適合性を高めるために，ダム直下を潜り跳水式とした新しい減勢工形式について，その考え方と水理設計上の課題について検討を行った。ここでは，減勢工下流に設置されるエンドシル高さと形状に着目して水理実験を行った。その結果，減勢機能を満足しつつ，土砂や魚類の通過機能も満たすことが可能な減勢工形状を結果を得ることができた。

**キーワード**: 流水型ダム，減勢工，底部洪水吐，エンドシル