Generation of hydraulic jump with sill

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Abstract
One of the most extensively investigated phenomena in hydraulic engineering is the hydraulic jump. Numerous investigators have studied it over the past century. Thus, stilling basins with hydraulic jump remain as the most favorite choice of designers for energy dissipaters below spillways and outlets. A properly designed of hydraulic jump stilling basin can ensure 60–70% dissipation of energy in the basin itself. In this study, experiments are conducted to evaluate effects of a perforated sill with circular holes on the length of hydraulic jump and its position in a stilling basin.

A series of perforated sills with different heights and ratio of \( \frac{A_o}{A} = 0.5 \) (\( A_o \) is total area of circular holes and \( A \) is area of sill) were placed at three tailwater depth ratio \( \frac{H_o}{H} \) along a stilling basin. The hydraulic characteristics of forced jump due to perforated sill were measured and compared with the classical hydraulic jump under variable discharges. Results of experiments confirmed significant effect of the perforated sill on dissipation of energy and reduction the length of basin. Also a new relationship was developed between the height of a perforated sill and length characteristic of stilling basin according to internal flow features.

Key words: forced hydraulic jump, End sill, stilling basin

1. Introduction
Dissipation of the kinetic energy generated at the base of a spillway is essential for bringing the flow into the downstream river to the normal condition in as short of a distance as possible. This is necessary, not only to protect the riverbed and banks from erosion, but also to ensure that the dam itself and adjoining structures like powerhouse, canal, etc. are not undermined by the high velocity turbulent flow. For this purpose, energy dissipaters must be used which performs the energy reduction by converting the kinetic energy into turbulence and finally into heat. The dissipation of energy can be achieved by a variety of devices such as free jets and trajectory buckets, Roller buckets, Impact type energy dissipaters and Hydraulic jump stilling basins. Stilling basins with hydraulic jump include horizontal aprons and basins equipped with energy dissipating appurtenances is the most common type of energy dissipaters for the spillways and effects up to 60% dissipation of the energy entering the basin, depending on the Froude number of the flow. The most widely used standard designs of stilling basins with horizontal aprons have been evolved by USBR. To ensure that a stilling basin performs its function efficiently (i.e. dissipation of energy is occurred properly), in all the designs involving
horizontal aprons, USBR recommended to place the basin floor at a depth corresponding to $y_2$ below the available tail water elevation. Otherwise sweep out of the hydraulic jump from the basin takes place and as a result, scouring of downstream riverbed will occur. This, sometimes may result in a basin deeply placed below the average river bed and may also involve excessive rock excavation. There may then be a temptation to provide the basin invert at a higher elevation resulting in deficiency of tailwater depth, with an attempt to compensate the same by inclusion of appurtenances like continues or perforated sill. Such appurtenances essentially control the location of hydraulic jump and force it to develop closer to the inlet structure and are hence reduce the sequent depth and increase the energy dissipation. Also use of sill permit to shortening the basin and acts as a safety factor against sweep out of the jump.

The first studies to produce and control the forced hydraulic jump in a horizontal stilling basin by a sill have been done by Shukry (1957). He showed that the configuration of flow pattern over the sill is dependent on approaching Froude number, the distance of sill from toe of the hydraulic jump, the relative height of sill and the tailwater depth.

Rands (1957) provided an extensive classification of flow types over a sill, which is based on the height of the sill ($H$) and the tailwater depth ($y_2$) relative to the inflow depth ($y_1$), and approaching Froude number ($F_1$).

Hager and Bretz (1988) represented a formula that determines the height of the sill and its position in the stilling basin for different types of the hydraulic jump regarding to the approaching Froude number ($F_1$) and the tailwater depth ($y_2$).

Hager (1992) classified the jump over a vertical sill into A-jump, B-jump, minimum B-jump, C-jump and D-jump.

The A-jump is corresponding to the classical hydraulic jump. By decreasing the tailwater depth, toe of jump moves toward the sill and a B-jump occurs. As the tailwater depth decreases more, the distance between the toe of the jump and upstream sill face is further reduced. A further characteristics of such flow, referred to as minimum B-jump, is the formation of a second roller at the downstream sill zone and a C-jump is characterized by having the maximum difference between the depth of flow over the sill and the tailwater depth. D-jump initiates when flow is disturbed more and roller waves can reach the bed and scouring becomes expectable.

Rajaratnam et al. (2000) conducted laboratory experiments to show that screens or porous baffles with a porosity of about 40% could be used in place of solid baffles as effective energy dissipaters below small hydraulic structures.

When a supercritical flow passes through such a screen, resistance, forces a hydraulic jump to form upstream of the screen, as shown in Figure 1. The flow downstream of the screen is also supercritical, but with a Froude number in the neighborhood of 1.65. It was also found that the tail water depth, $y_2$, required to form a jump for this situation was about 0.5 times the subcritical sequent depth corresponding to the flow with Froude number $F_1$.

![Figure 1. Screen-type energy dissipater (Rajaratnam et al. 2000)](image-url)
The energy loss, \( \Delta E \), caused by the screen is:

\[
\Delta E = \frac{\left( \frac{y_1}{v_f^2 z_2} - \frac{y_1}{v_f^2 z_2} \right)}{y_1 + \left( \frac{v_f^2}{z_2} \right)}
\]  

(1)

The screens would have to be constructed of concrete with uniformly distributed holes and could be placed at about 2\(y_2\) from the structure, producing a supercritical stream. A further length of apron of about 0.7\(y_2\) and it would need only 50% of the tail-water depth otherwise required.

Debabeche and Achour (2007) studied the effect of a continuous sill on hydraulic jump in a triangle channel.

A numerical simulation of minimum B-jumps in horizontal rectangular channels having an abrupt drop is given by Tokyay et al. (2008). Before that, A-type jump at a positive step was simulated numerically by Altan-Sakarya and Tokyay (2000).

Alikhani et al. (2010) represented design criteria for estimating of the stilling basin length without consideration of tailwater where a continuous sill is located at the downstream end of the basin. They created and tested forced hydraulic jumps using a single continuous sill with variable height and position in a stilling basin. Based on their experiment results, a relationship was established between the most effective dimensionless parameters such as inflow Froude number, ratios of \( \frac{L_B}{y_2} \) and \( \frac{h}{y_1} \) to \( \frac{h}{y_2} \), to design a sill-controlled stilling basin. They developed the design criteria for B-jump with inflow Froude numbers \( F_1 = 4-12 \) and \( \frac{h}{y_2} = 2-8 \). Comparison of forced jump results of their study with free jump relationships confirm up to 30% reduction in length of stilling basin. They found that for LB smaller than 3\( (y_2 - y_4) \), the jump plunged downstream of the sill and scouring may be unavoidable, while for larger values than 5\( (y_2 - y_4) \) the effect of the sill was not significant.

![Figure 2. Sill-controlled stilling basin (Alikhani et al. 2010)](image)

Review of literature reveals that because of a continuous sill across a stilling basin is the simplest type of appurtenances to control of hydraulic jumps, almost all before researches were focused on the forced hydraulic jump due to a continuous sill. In this study, a perforated sill was investigated as an alternative to the continuous sill and the characteristics of hydraulic jump in the proposed perforated sill basin was compared with classical hydraulic jump. The concept of the perforated sill is based on the theoretical work of Rouse et al. (1958) for energy dissipation through discontinuity layers.
2. Materials and methods

1.1. Theory
Consider a stilling basin at the end of a chute in which a perforated sill located a distance of $L_s$ from the entrance is used to develop a forced hydraulic jump (Figure 4). The effective hydraulic parameters are shown in the figure.

The following functional relationship among significant parameters is used to characterize the forced hydraulic jump due to the presence of a perforated sill in a rectangular stilling basin:

$$f = \left( h, y_1, \nu, \nu_t, L_s, L, A_0, A_s, \ell, g, \rho, \mu \right) = 0$$  \hspace{1cm} (2)

Where; $h$ is the height of sill, $y_1$ and $\nu$ are depth and average velocity of the supercritical flow, $y_1$ is the tailwater depth, $L_s$ is the distance from the beginning of the stilling basin to the upstream face of the sill, $L$ is the length of the stilling basin, $A_0$ is the total area of circular holes, $A_s$ is the area of sill face, $\ell$ is channel slope, $g$ is gravity, $\rho$ and $\mu$ are water density and viscosity respectively.

Assuming a horizontal stilling basin ($i = 0$) and fully turbulent flow independent of Reynolds number, the dimensionless parameters are summarized as:

$$f = \left( \frac{h}{y_1}, \frac{\nu}{y_1}, \frac{\nu_t}{y_1}, \frac{L_s}{L}, \frac{A_0}{A_s}, \frac{\ell}{\nu}, \frac{g}{\nu}, \frac{\mu}{\nu}, P_1 \right) = 0$$  \hspace{1cm} (3)
In the other hands, the flow depths $y_1$ and $y_2$ at the extremities of a classical hydraulic jump are conventionally related by the classical Belanger’s equation based on force momentum balance in a rectangular channel, which neglects bottom shear forces:

$$Y^* = \frac{y_1^2}{y_2} = \frac{1}{3} \left[ \left( 1 + 8 F_1^4 \right)^{\frac{3}{5}} - 1 \right] \quad (4)$$

Where, $Y^*$ is the sequent depth of classical hydraulic jump. For $F_1 > 2$, the sequent depth ratio can be approximated as follows,

$$Y^* = \sqrt{2} F_1 - \frac{1}{2} \quad (5)$$

Based on experimental observations of Hager (1992), the following relation was found when a continuous sill is located in front of the hydraulic jump.

$$y = \frac{y_2}{y_1} = Y^* - Y^*_2 \quad (6)$$

Where the sill effect compared to a classical jump ($Y^*_2$) is expressed by the following relationship.

$$Y_2 = \alpha S^\beta \quad (7)$$

The coefficients ($\alpha, \beta$) depend on the type of hydraulic jump. According to Equation 7, the maximum amount of $Y_2$ can be obtained by increasing the height of the continuous sill. If the height of the continuous sill (h) becomes larger than a limit value $S_L$, the sill flow is changed into weir flow. The following relationship is suggested for the limited value of $S_L$ (Hager 1992).

$$S_L = \frac{1}{6} F_1^{1.445} \quad (8)$$

For a given $F_1$, the relative height of sill must be smaller than $S_L$.

Also the length of roller for classical hydraulic jump is given by the following expressions by Hager et al. (1990):

$$\frac{L_h}{y_2} = -12 + 160 \tanh \left( \frac{F_1}{20} \right) \quad \text{For } \frac{y_2}{B} \leq 0.1 \quad (9)$$

$$\frac{L_h}{y_2} = -12 + 100 \tanh \left( \frac{F_1}{12.2} \right) \quad \text{For } 0.1 \leq \frac{y_2}{B} \leq 0.7 \quad (10)$$

Where B is width of stilling basin. Equations (9) and (10) can be approximated as follows, Hager (1992):

$$\frac{L_h}{y_2} = -12 + 8 F_1 \quad (11)$$

USBR (1955) after many experiments, represented a graph to determine the length of free hydraulic jumps in rectangular channels. According to USBR (1955), for Froude number in ranges of 4.5 to 17, the length of hydraulic jump can be assumed as:
2.2. Experiments

Experiments were carried out in a horizontal rectangular flume with 0.3 m wide, 0.45 m deep and 10 m long with glass walls and metal frame in the Research Institute of the Ministry of Power of Iran. A perforated sill with ten heights of 1, 2, ..., 10 cm with one row of circular holes that inserted at distances from 0.2 m up to 1.3 m was tested at different discharges in range of 8 to 30 lit/s. The total surface area of the holes was 50% of the total surface area of sill (\( h \cdot B \)), where \( h \) is the sill height and \( B \) is the channel width. Experiments were performed for different Froude numbers in ranges of 4.5 to 16.7 and different sill locations. The tail water depth was controlled by a tailgate located at the downstream of flume and experiments were done under three tailwater ratio depth of 0.8, 0.9 and 1. Discharges were measured with a V notch that located at downstream of the flume. The water level and depth in the flume were measured with a point gauge comparable accuracy of \( \pm 1 \) mm. A tailgate at the downstream of the flume controls the tailwater depth.

Experiments were conducted to develop the design criteria for estimation of stilling basin length for the forced jump as result of a perforated sill in a horizontal basin. Circular perforations extending along the width of the sill, allow flow to pass through the sill. The performance of the forced hydraulic jump with perforated sill was compared with the free hydraulic jump.

3. Results and discussions

This study is mainly concerned on development of design criteria for the stilling basin equipped with a perforated sill. Regarding on theoretical analysis and experimental researches, it appears that hydraulic jump characteristics in the mentioned basin is highly dependent on the sill height (\( h \)), position of perforated sill from entrance of basin (\( L_s \)) and the length of basin (\( L_b \)).

Further experiments continued to find relations thereby establishing a relationship between perforated sill height and the length of the basin for creating a forced hydraulic jump. Accomplishing the experiments, it is known that the height of the sill is highly dependent on internal flow features, such that by making little changes in velocity (\( V_s \)) and depth (\( y_s \)) of approached flow, the required sill height for controlling the jump would changes. Thus, further analyses are concentrated on finding dimensionless relations between sill height (\( h \)), distance of perforated sill from inlet the basin (\( L_s \)) and length of stilling basin (\( L_b \)) with the internal flow features.

3.1. Relative length of jump

The relationship between \( L_s/y_s^2 \) with Froude number of the forced hydraulic jump due to a perforated sill at \( A_0/A = 0.5 \) is presented in Figure 5.a. with three ratio of tailwater depth (\( T/W/y_2^2 \)). Experiments show that the position of perforated sill is highly depended on the inflow characteristics and the tailwater depth, so that when \( F \) is kept constant, decreasing the tailwater depth causes the hydraulic jump attempt to moving towards the end of basin and toe of jump closes to upstream face of sill, As a result, ratio of \( L_s/y_2^2 \) decreases. But when the ratios of \( L_s/y_2^2 \) where compared, an inverse result was obtained for the same condition. Because this phenomena, produces a increase in the length of hydraulic jump and vice versa as strong rollers are formed at rear face of perforated sill leading to increasing in the length of stilling basin (\( L_b/y_2^2 \)). Comparing with classical hydraulic jump, figures shows significant effect of the perforated sill on the reduction of hydraulic jump, thus the length of basin compare with classical hydraulic jump can reduce up to 40%. (Figure 5b).

On the other hand, in a constant of \( F \), by increasing in tailwater depth, the ratio of \( h/y_2 \) is reduced.(Figure 5c)
Figure 5. Perforated sill stilling basin characteristic
3.2. Relative energy loss

Figures 6 presents the variation of the relative energy lose ratio $\Delta E/E_1$ with Froude number $F_1$ for forced hydraulic jump due to a perforated sill for three ratios of $Tw/y_2^*$ and $A_3/A$ equal to 0.5. When $F_1$ is kept constant, the $\Delta E/E_1$ increases with the decrease of $Tw/y_2^*$. Also, the relationship between $\Delta E/E_1$ and $F_1$ shows that like to free hydraulic jump, when the ratio of $A_3/A$ is constant, by increasing the Froude number $F_1$, the relative energy lose $\Delta E/E_1$ increases.

![Figure 6. Perforated sill-controlled stilling basin.](image)

Figure 6 shows that for all range of $F_1$, the perforated sill has a significant effect on lose of energy respective to free hydraulic jump.

In figure 7, result of this study to optimizing the stilling basin with a perforated sill was compared with previous studies that concerned on stilling basin with continuous sill.

![Figure 7. Comparison results of perforated sill and continuous sill](image)

**Conclusions**

In this study, experiments were conducted to propose a design criteria for forced hydraulic jump due to a perforated sill in the stilling basin when the ratio of $A_3/A = 0.5$. The purpose was to estimate the efficient sill height and distance from entrance of the basin to reduce the jump and basin length, thus cost. Design criteria is basically developed for inflow Froude numbers $F_1 = 4.5$-16.7 and $h/y_1 = 1$-6. Accomplishing the experiments, it is known that the height of the sill is highly dependent on internal flow features, such that by making little changes in velocity ($y_2$) and depth ($y_1$) of approached flow,
of the required perforated sill height for controlling the jump would change. Based on the internal flow features, design considerations for perforated sill stilling basins were presented and a relationship between the most effective dimensionless parameters such as inflow Froude number, ratios of $\frac{L_{f}}{y_{1}}$ and $\frac{h_{f}}{y_{1}}$ as main parameters in equation 3 is constructed to help design of a perforated sill stilling basin. Experiments proved that presence of the perforated sill in the basin has a significant effect on the hydraulic jump characteristics. It is found that perforated sill causes more energy losses in the forced jump compare with classical hydraulic jump. In addition, perforated sill decreases the length of hydraulic jump and the tailwater depth required compare with free jump. Comparison of forced jump results of this study with free jump relationships confirm up to 40% reduction in length of stilling basin where the perforated sill is there to control the jump.

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References


Notations
$F_{1}$: approaching Froude number, $g$: acceleration due to gravity, $h$: height of perforated sill, $i$: channel slope, $L_{f}$: length of stilling basin, $L_{j}$: length of hydraulic jump, $L_{k}$: length of roller for classical hydraulic jump, $m$: water viscosity, $\rho$: water density, $S$: relative sill height, $y_{1}$: average velocity of supercritical flow, $y_{s}$: distance from toe of the jump to upstream sill face, $y_{f}$: depth of supercritical
flow, $y^f$; sequent depth of forced hydraulic jump, $y^c$; sequent depth of classical hydraulic jump, $y^c$; maximum depth of flow over the continuous sill, $y^c$; tailwater depth, $Y$; sequent depth ratio for forced hydraulic jump, $y^f$; sequent depth ratio for classical hydraulic jump, $y^c$; maximum depth ratio for forced hydraulic jump, $y^f$; depth effect of sill, $A$; area of sill face, $A_{total}$; total area of holes of the sill, $E_{total}$; special energy of supercritical flow, $E_{flow}$; special energy of subcritical flow, $E_{sub}$; relative energy lose of hydraulic jump, $T_{rel}$; tailwater depth, $B$; width of channel.