EFFECT OF SILL ARRANGEMENT ON MAXIMUM SCOUR DEPTH DOWNSTREAM OF ABRUPTLY ENLARGED STILLING BASINS

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ABSTRACT

Scour downstream (DS) of hydraulic structures (HS) may endanger the safety of the structures if the necessary precuations are not considered during the design stage. Normally, different measures produce different effects on reducing the maximum scour depth DS of HS. One of the important HSs is the abruptly enlarged (or sudden expanding) stilling basins. In this paper, the effects of different arrangements of sills inside an abruptly enlarged stilling basin will be discussed. An experimental program was conducted to investigate the effects of continuous end sill, one asymmetric side side, double staggered asymmetric side sills, symmetric side sills, central sill and continuous central sill. The flow patterns were observed and the maximum scour depths were recorded. The results revealed that in most of the cases the flow patterns are asymmetric resulting in asymmetric scours. The reduction in the maximum scour depth depends on the type of arrangement of the used sill and on the flow conditions represented by Froude number. Both of the central sill with limited width and continuous central sill improved the flow patterns towards symmetric type and yielded minimized maaximum scour depth with preference to the continuous sill.

Keywords: Scour, Hydraulic structures, Stilling basins, Sudden expansion, Experimental work

INTRODUCTION

Sudden expanding stilling basins may be used effectively in dissipating the energy downstream the hydraulic structures. One disadvantage of such basins is the flow patterns inside the basin are mostly asymmetric specially at high values of Froude numbers. This asymmetric flow causes asymmetric scour downstream of the basin where the soil is erodible, Negm et al. [1]. Different measures may be used to improve the flow pattern in the sudden expanding stilling basin by forcing the flow to be symmetric and hence the expected downstream scour patterns may be improved. These methods may include the use of central sill of limited width at particular position, Negm et al. [2], one or more asymmetric side sills at certain position with particular orientation, Saleh et al. [3] and symmetric side sills at particular positions with pre-specified orientation, Saleh et al. [4]. All the above studies dealt with the supercritical flow. The effect of subcritical flow (F_1=0.48 to 0.73) in sudden expansion (e=1.5 to

4.5) on movable bed topography (sediment size is 0.28 mm) was discussed by Nashta et al. [5]. In this paper, the effect of sill arrangement on the scour characteristics DS of SESB is discussed based on experimental investigations.

THEORETICAL BACKGROUND

Figure 1 shows a definition sketch for the phenomenon under study. The maximum (max) scour depth downstreaam of the stilling basin can be expressed as follows:

$$Ds = f(g, \rho, \rho_s, G, V_G, b, B, H_u, D_{50}, h_s, x_s, L_b, W, \phi) \tag{1}$$

in which g is the gravitational acceleration, ρ is the density of water, ρ_S is the density of the movable soil, G is the gate opening, V_G is the mean velocity under the gate, b is the approaching channel width, B is the width of the expanding channel, H_u is the upstream water depth, D_{50} is mean particle diamter, h_s is the height of the sill, x_s is the position of the sill from the expanding section, L_b is the length of the basin, W is the total length of the symmetric side sills normal to the flow direction (W equals two times the length of one side sill), and ϕ is a fator to account for sill arrangement.

Selecting ρ, G, V_G as repeating variables and employing the principle of Π theorem, equation (1) can be written in dimensionless form as:

$$\frac{D_s}{G} = f\left(F_G, \frac{H_u}{G}, \frac{B}{G}, \frac{b}{G}, \frac{h_s}{G}, \frac{x_s}{G}, \frac{L_b}{G}, \frac{W}{G}, \frac{D_{50}}{G}, \frac{\rho_s}{\rho}, \phi\right) \tag{2}$$

The effect of the density ratio is excluded because only one fluid and only one soil were used during the course of experiments. Neglecting the effects of sill height and particle size (since h_s and D_{50} are both constant). Also, the effect of expansion was neglected because only one expansion ratio (e=b/B=1.54) was used. Keeping in mind the properties of the dimensional analysis, Equation (2) could be reduced to

$$\frac{D_s}{G} = f\left(F_G, \frac{H_u}{G}, \frac{W}{B}, \frac{x_s}{L_b}, \phi\right) \tag{3}$$

The validity of this equation will be checked using the collected experimental data in a forthcoming section.

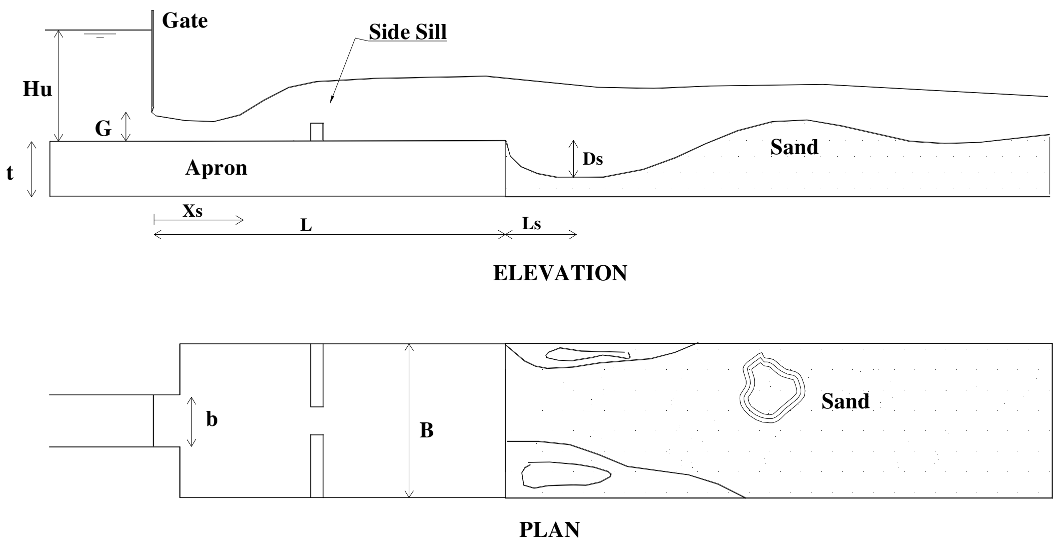


Figure 1 Definition sketch for a typical tested sill model in sudden expanding stilling basin (SESB)

EXPERIMENTAL SET-UP

The experiments were carried out in a recirculating laboratory flume 0.20 m wide, 0.25 m deep and 3.5 m long. The discharge was measured using a pre-calibrated orifice meter installed in the feeding pipeline. The stilling basin model is made from prespex of thickness 10 mm with a length of 1.25 m. The length of the approaching channel was 50 cm while the length of the apron of the expanding stilling basin is 75 cm. The width of the approaching channel was kept constant to 13 cm, and the width of expanding channel was fixed to obtain an expansion ratio of 1.54, which is close to the one normally used in practice. A control sluice gate is made from the same prespex and is used to control the upstream depth and the gate opening. The gate is installed 5 cm upstream the sudden expansion section. The rest of the flume (2.5 m) is covered by sediment consisting of 7.5 cm sand layer of medium diameter, D_{50} = 1.77 mm. The tailgate at the end of the flume is used to control the tail water depth. During the course of the experiments, the tailgate is controlled such that the tailwater depth was about 5 cm

Nine models were tested. One model is consisted of smooth SESB (no sill case). A smooth SESB with an end sill of 2:1 US slope and vertical DS face with a height of 1.0 cm represents the second model. The thrid model consisted of a single side sill of height 1.5 cm and length of 7.4 cm fixed at $0.5L_b$. Adding another side sill of the same dimensions at the position of $0.25L_b$ to the third model produced the fourth model. The fifth and sixth models, each consisted of two symmetric side sills, the width of each sill is 7.4 cm with W/B=0.74, one is fixed at x_s/L_b=0.15 and the second at x_s/L_b=0.35. The seventh and eigthth models were similar to the sixth one but with W/B=0.90 and W/B=1.0. The last model was a central sill of length 14.75 fixed at x_s/L_b=0.35 and of the same height of 1.5 cm. Since some of the tested sills consisted of two parts, the length of the sill

W is obtained by doubling the length of one part and the width ratio is therefore W/B. The selection of the models were based on previous researches conducted by the Bremen and Hager [6], Negm et al. [2], Saleh et al. [7], Saleh et al. [3,4] such that each of the tested models was optimal copmared to a specific group of sills of smilar nature.

Range of discharges and gate openings were used such that the Froude number under the gate ranged from 1.20 to about 3.9. A total of about 90 runs were performed. The time of each run was chosen to be 45 min based on previous studies, Saleh et al. [3,4,7]. A typical run consisting of leveling the movable soil, allowing a particular fixed tailwater depth in the downstream channel with the control gate in close position. The discharge was adjusted to the desired value and the gate was opened to the desired opening to obtain the required under gate Froude number. During each run the flow pattern was observed and sketched. The deflection of the supercritical jet was recorded. After about 20 minutes, the water surface profile was recorded and its direction was noticed. After 45 minutes, the control gate was closed and the pump was switched off. The topography of the movable bed was measured at each 5 cm in the direction of the flow (x direction) and in the widthwise direction or lateral direction (y direction) to enable the study of the scour pattern.

ANALYSIS AND DISCUSSIONS OF EXPERIMENTAL RESULTS

Effect of Sill Arrangement on Maximum Scour Depth

The relationship between D_s/G and F_G is shown in Figure 2 for all tested arrangements of sill. Except of the end sill, in general the sill has a significant effect on reducing the relative magnitude of the maximum depth of scour. The sill arrangement has a major effect on the relative magnitude of the maximum depth of scour, D_s/G regardless of the value of the Froude number. However, Froude number has a remarkable effect on D_s/G for a particular arrangement of sill. The values of D_s/G increases linearly with F_G for a particular sill. On the other hand, at certain F_G, the effect of sill on reducing D_s/G is increasing from the no sill case towards the continous sill (W/B=1.0) in the following order (i) no sill case, (ii) asymmetric single side sill at $x_s=0.5L_b$, (iii) symmetric side sill at $x_s=0.15L_b$ and at $x_s=0.35L_b$ (iv) asymmetric staggered side sills at $x_s=0.25L_b$ and $x_s=0.5L_b$, (v) symmetric side sill at $x_s=0.35L_b$ with W/B=0.9, (vi) central sill of width W/B=0.74 positioned at $x_s=0.35L_b$ and (vii) continous sill located at $x_s=0.35L_b$. Regarding the end sill, it increases the magnitude of the relative value of D_s/G. The values of D_s/G for end sill is larger than those of no sill case specailly for values of $F_G>2.2$ and produces similar values or lower at smaller values of F_G. Based on the present results and results by others, Saleh et al. [7] the use of end sill in SESB basin is not recommended as a tool for reducing the maximum depth of scour DS of the basin.

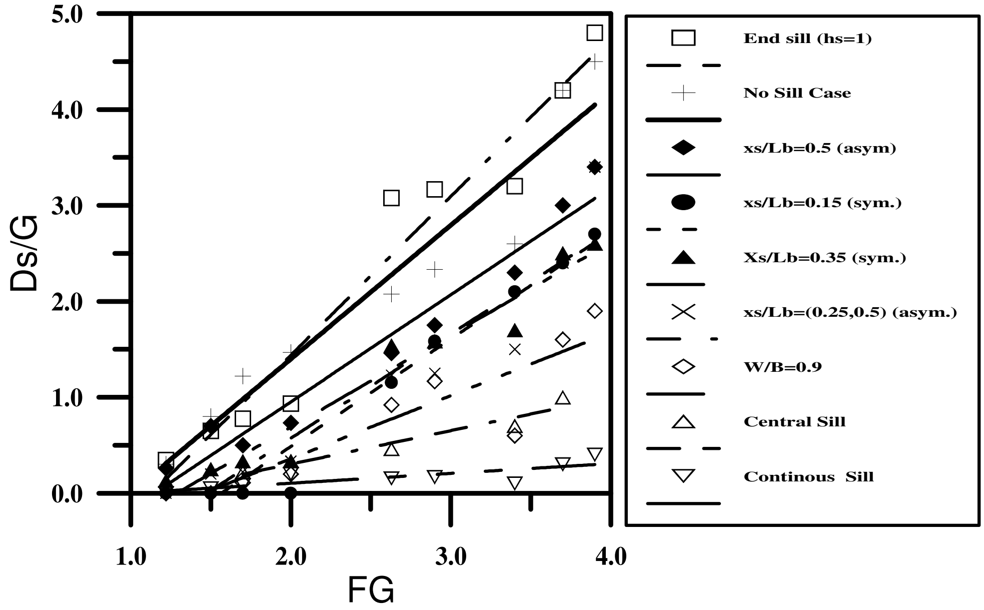


Figure 2. Relationship between Ds/G and FG for different arrangements of sill inside SESB

Effect of Sill Arrangement on Flow and Scour Patterns

Case of no sill

The results of investigating the scour patterns in SESB under different flow conditions in case of no sill for e= 1.54 indicated that the scour pattern is asymmetric as a result of asymmetric flow pattern inside the basin. The main jet of supercritical flow inside the basin may be directed towards the left or right walls of the basin. This may be attributed to the instability of the hydrostatic pressure at the sluice gate section. Figure 3a shows a typical flow pattern for e=1.54 at F_G=2.63 while Fig. 3b shows the corresponding scour pattern. It is observed that the maximum scour occurs in the same direction of the main jet and another smaller scour hole may be formed on the other side.These results corporates well with those obtained by Negm et al. [1] for expansion ratios 2.0, 2.5 and 3.0.

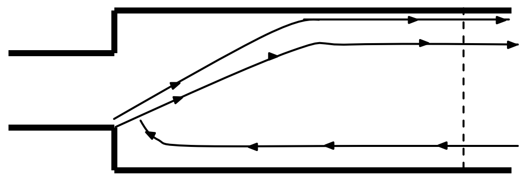


Figure 3a. Typical flow pattern for no sill case for e=1.54 at F_G=2.63

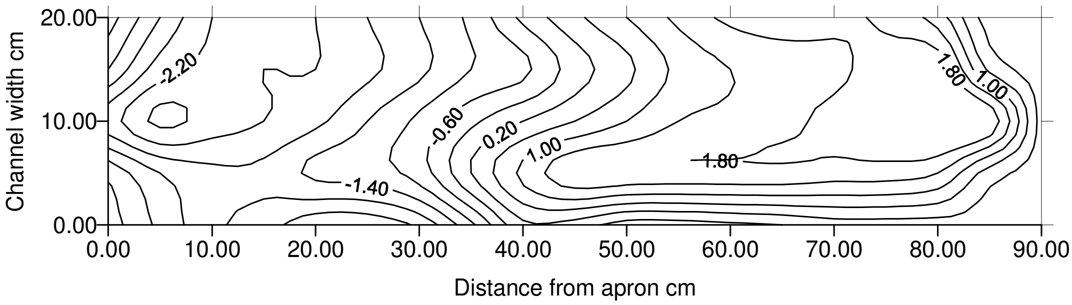


Figure 3b. Scour pattern DS of SESB with no sill for e=1.54 at FG=2.63

Case of end sill

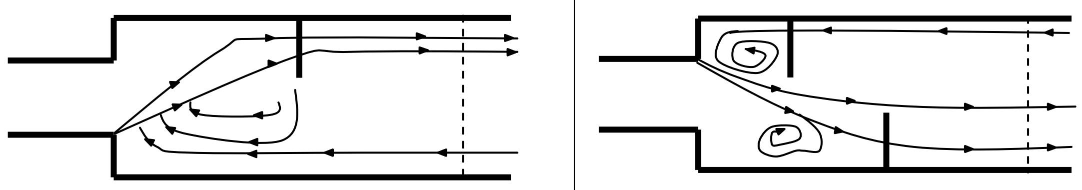
Inspection of the flow patterns and scour patterns due to the presence of end sill revealed that both of them are asymmetric ensuring that the end sill is not recommended for improving either the flow pattern or the scour pattern in or DS of SESB.

Case of asymmetric side sill

When the side sill was placed at x_s/L_b=0.5, the main jet of flow is deflected towards one of the basin sides. The deflection length for most values of the Froude number (F_G<3.4) are less than $0.5L_b$. Consequently, the flow behaves as in the case of no sill with the exception that lower values of maximum depth of scour was observed when the direction of the main jet was in the same side of the sill and vice versa. At higher values of F_G, the sill forces the jet to the opposite direction to flow parallel to the bank and causing scour which is less than that of the no sill case. Also, it was observed that a slight portion of flow is revered on the apron of the basin due to the formation of mound downstream of the SESB. In all cases of flow conditions, the observed scour patterns were asymmetric because the main jet of flow was also asymmetric. A typical flow pattern at F_G=2.63 is showin in Fig. 4a which confirms these features.

The second arrangement of asymmetric side sills was using two sills one at $0.25L_b$ and the second at $0.50L_b$ on the opposite side. It was observed that the scour was greatly reduced if compared with the case of using only one of these two sills. In this case, both sills affect the flow because the first sill forced the flow to the other side; hence, the flow was affected by the other sill. At very low

F_G, the flow is symmetric and causing little scour depth, which tends to be symmetric. Increasing the Froude number, causing the main jet of flow to change its direction to the opposite sill passing over it and flows parallel to the bank. At higher F_G=3.9, the main jet of flow was mostly symmetric up to the second sill then slightly diverted to the bank in the same direction of the second sill and flows parallel to the same bank. In all cases, the flow at the gate is partially submerged and two vortices were formed, one in front of the each side sill. A typical case of this type of flow pattern is indicated in Fig. 4b.



(a) e=1.54, F_G= 2.63, x_s=0.5L_b

(b) e=1.54, F_G= 2.63, x_s={0.25,0.5}L_b

Figure 4. A typical flow pattern for (a) single side sill at 0.5L_b and (b) two asymmetric side sills at 0.25L_b and 0.5 L_b.

On the other hand, using double side sills at (0.25 & 0.5) reduces greatly the extent of scouring and deposition process to about one times the length of the basin. It is also observed that sometimes the maximum scour depth is reduced and sometimes it is increased by using the double side sills based on the behavior of the flow in the basin over the solid apron before reaching the movable soil. If both sills affect the main jet of flow, the scour depth is reduced and may be increased if the coming flow is affected by one of the two side sills.

Case of symmetric side sills with at xs/L_b=0.15 and 0.35

For W/B=0.74 and F_G equals 1.22 to 2, the flow DS of sill is symmetric and mostly symmetric US of it with slight difference in the size and strength of the votices US of each sill. The change in the bed topography takes place for a short length of about 20% of the basin length. For higher F_G>2, the main jet of flow passes in between the two sills from the right one to the left one with the other portion of flow passing over the left sill. The length of scouring and deposition process increases upto about 55% of the basin length for F_G<3.7 and upto 85% of the basin length for F_G>3.7. The scour patterns are mostly symmetric although the values of scour is smaller than when one side sill is used and higher than when the same two sills are used in staggered arrangement at positions 0.25L_b and 0.5L_b. It is interesting to state that the flow and scour patterns in this case are not so different from those of x_s/L_b=0.15. Further increase in W/B from 0.74 to

0.90 improves both the flow and scour pattern and produces scour depths which are smaller than those of W/B=0.74 whether they are symmetric or asymmetric. Generally the flow in this case is more symmetrical than other cases and the water surface of the flow is less fluctuating. The resulting scour is symmetrical about the flume centerline with smaller values and the scour processes end at shorter distances compared to all previous cases.

Typical flow patterns for e=1.54, W/B=0.90 at (a) F_G=1.7 and (b) F_G=2.63 are preented in Figures 5a, b while Figures 6a,b presents the scour patterns for e=1.54, x_s/L_b=0.35, F_G=2.63, at (a) W/B=0.74 and (b) W/B=0.90. Comparing these patterns with that of no sill case at the same F_G indicated that the scour depth is reduced significantly and the extent of erosion is shortened due to the presence of the sill. Comparing these results with the previous ones, Saleh et al 2003c proved that the use of symmetric sill at the positions $0.35L_b$ with a lateral length of more than 70% of the flume width enhances the flow patterns and the maximum scour depth was remarkably reduced. Also, the length over which the scour and deposition process takes place was significantly shortened. Using wider sills as in the case of W/B=0.90, both the depth of the scour and the length of scouring and deposion processes are reduced more than when the width ratio of sill is greater than 0.74.

(a2)

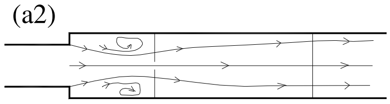


Figure 5a. Typical flow patterns for e=1.54, x_s/L_b=0.35, W/B=0.90 at F_G=1.73

(b2)

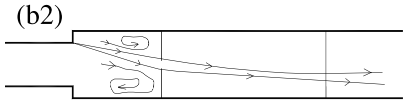


Figure 5b. Typical Flow patterns for expansion ratio e=1.5, xs/Lb=0.35 W/B=0.90, at FG=1.70

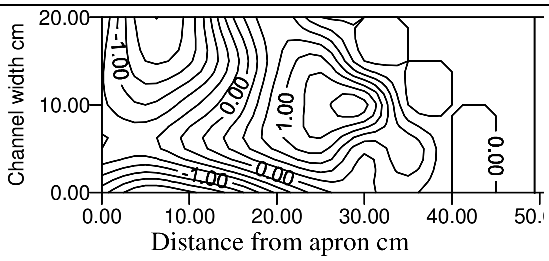


Figure 6a. Scour pattern DS of SESB with symmetric side sill of height h_s=1.50 positioned at $0.35L_b$ for e=1.54 and W/B=0.74 at F_G=2.63

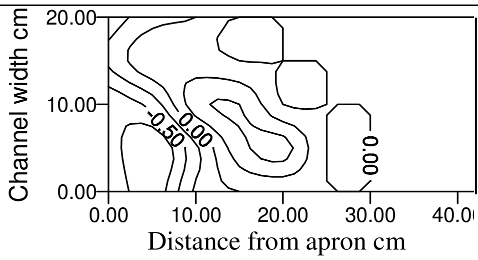


Figure 6b. Scour pattern DS of SESB with symmetric side sill of height h_s=1.50 positioned at $0.35L_b$ for e=1.54 and W/B=0.9 at F_G=2.63

Case of central sill

The water surface is nearly smooth with very little fluctuations for low values of Froude number upto about 2.0. The issuing jet from under the gate is symmetric till it reaches the sill then the main jet is distributed to cover the full width of the channel forming symmetric flow pattern with slightly higher velocity at one side than at the other one. In front of the central sill, two vortices were formed but with different strengthes. The sill causes some back effect leading to partial submergence of the gate of about 16% for F_G=1.7 and about 20% for F_G=2.0. The stronger vortix is in the same side of the higher velocities. Downstream of sill, the water surface is almost smooth. The resulting scour is very small and nearly symmetric around the channel centerline but slightly different in magnitude. The legnth of scouring and deposion processes extended to about 13% of the basin length. Further increase in the Froude number results in more turbulence at and near to the zone of the the sill but the flow in front and DS of the sill is almost symmetric. Also, a length of about $0.13L_b$ is affected DS of the SESB in this case. Further increase in F_G leads to more fluctuations in the water surface at and near the sill leading to unequal distribution of the flow over the channel width giving an indicator that the flow tends to be asymmetric for higher values of F_G>3.4. Although a length of about $0.2L_b$ of the movable soil DS of SESB is affected for F_G>3.4, the scour and deposition pattern is asymmetric forming the main scour in the same direction of the main jet of flow.

Case of continous sill

The flow in the basin for low values of F_G<2.0 is symmetric both in front of the sill and DS of it. The water surface DS the sill is smooth while US it two votices are formed which are slightly different in strength (one is weaker than the other). The gate is partially submerged by about 20% due to the effect of sill. The formed scour is very small in magnitude and the length of the scouring and deposion processes are very small about 5% of the basin length. For higher F_G>2.0, the flow at the gates becomes free. The flow coming from the expanding section forms one strong jet US of the sill which is divided again to pass over the sill with higher water surface and flows over the whole width of the channel (symmetric flow in the basin DS the sill). Also, two vortices are formed US of the sill. The vortices are longer than those due to lower F_G. The formed scour is symmertic around the centerline of the channel with smaller magintude than in the case of central sill. For the highest F_G in this paper, the scour is overall symmetric and smaller comapred to its corresponding one due to the central sill. Two typical cases of scour pattern are presents in Figures 7a,b for FG=2.63 and 3.9 respectively when W/B=1 and e=1.54.

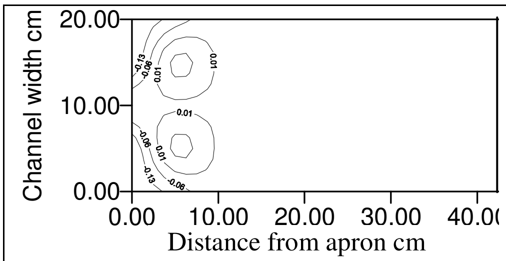


Figure 7a. Scour pattern DS of SESB with continous sill of height h_s=1.50 cm positioned at 0.35L_b for e=1.54 and W/B=1.0 at F_G=2.63

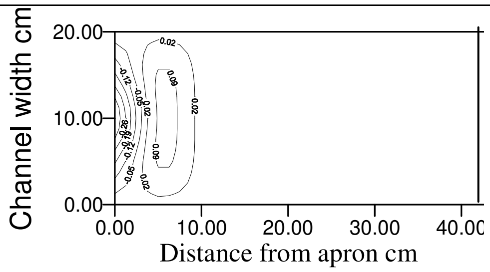


Figure 7a. Scour pattern DS of SESB with continous sill of height h_s=1.50 cm positioned at 0.35L_b for e=1.54 and W/B=1.0 at F_G=3.90

ESTIMATION OF MAXIMUM SCOUR DEPTH RATIO DS/G

Using the linear regression analysis both simple and multiple, several models were proposed and their coefficients were estimated using the experimental data. Out of all trials, it is concluded that simple linear regression model of the form of Eq. (4) is the best one due to the wide variation in the data.

$$\frac{D_s}{G} = a + b(F_G) \qquad (4)$$

where a and b are regression coefficients. Their values depend only on the value of x_s/L_b and W/B as shown in Table 1.

Table 1. Values of the regression coefficient of Eq. (4)

Sill Arrangement	W/B	x_s/L_b	Values of a, b and R^2		
			a	b	R^2
End sill	1.00	1.00	-1.871	1.655	0.952
No sill	-	-	-1.389	1.395	0.929
Asym sill	0.37	0.50	-1.280	1.117	0.957
Sym sill	0.74	0.15	-1.751	1.120	0.958
Sym sill	0.74	0.35	-1.238	0.964	0.951
Asym sills	0.74	0.25,0.5	-1.601	1.087	0.887
Sym sill	0.90	0.35	-0.955	0.658	0.833
Central sill	0.74	0.35	-0.393	0.349	0.937
Continous sill	1.00	0.35	-0.099	0.102	0.655

CONCLUSIONS

An experimental investigation was conducted in a laboratory flume to stusy the effect of sill arrangements in sudden expanding stilling basin on scour characteristics downstream of the basin. It was concluded that the use of sill inside the basin affects significantly the maximum scour depth downstream of the basin. The reduction rate depends upon the sill position, the type of arrangement of sill, the length of sill and the Froude number at particular expansion ratio. The presence of sill inside the basin affects the flow pattern in the basin and affects also the scour patter downstream of the basin. Two asymmetric staggered side sills at 0.25 and at 0.50 times the basin length is better than two symmetric side sills at the position 0.35 times the basin length. While these two symmertic sills are better than one asymmetric side sill at 0.5 times the basin length. Much better than all sills, the central sill and the continous sill at the position 0.35 times the basin length with preference to the continous sill. Both of them produces lower values of the maximum depth of scour and an improved flow and scour patterns. However, the continous yields the minimum values of the maximum depth of scour and more improved flow and scour patterns compared to all investigated sills. Emiprical formula (4) was developed to estimate the maximum depth of scour downstream of the sudden expanding stilling basin for the different tested arrangement of sills.

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