EFFECT OF END SILL ON SCOUR CHARACTERISTICS DOWNSTREAM OF SUDDEN EXPANDING STILLING BASINS

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ABSTRACT

Scour downstream of a hydraulic structure may endanger the whole structure after long or short run depending upon the extent of scouring processes. It is highly recommended to prevent the downstream bed from being scoured if possible or minimize the dimensions of the scour hole and force it to form away from the end of the stilling basin to increase the safety of the structure. It is believed that the end sill - when carefully designed- can have an important role to force the scour hole and reduce the extent of erosion. In this paper, the effects of using end sills in the sudden expanding stilling basins are addressed experimentally. Stilling basins with different expansion ratios of 1.54, 2.0 and 2.5 are used to collect the scour information when a sill is installed at the end of the basin. Sills of different dimensions are tested under wide range of flow conditions. The optimal sill that reduces the extent of scour downstream of the most practical sudden expanding stilling basin is recommended.

Keywords: Stilling basins, Scour, Erosion, End sill, Hydraulic structures

INTRODUCTION

Stilling basins are used mainly to protect the hydraulic structure from any expected failure due to the erosive power of the issuing high velocity jet. Man types of stilling basins were discussed in the literature, USBR [1] and Hager [2]. One of these stilling basins is the sudden expanding stilling basin. Various investigators have been observed that the flow through symmetric sudden expansion is asymmetric. Graber [3] reported some of such studies and presented an explanation of the asymmetric behavoir of the flow in symmetric sudden expansion. Graber also presented a predictive method that agreed well with the experimental observations and extended the predictive method theoretically to corrective measures up to a Froude number of 1.5. Bremen and Hager [4] conducted an extensive experimental investigation to determine the optimal configuration of the central baffle sill based on experimental optimization that improves the flow behavoir in symmetric sudden expanding stilling basins with downstream rigid bed. They performed two additional experiments using movable bed of uniform gravel of 10 mm with a thickness of 150 mm at F_1=7 and e=3.0 One experiment was conducted using smooth basin and the second one was performed using a lateral central sill of h_S=50 mm ($S=h_s/y_1$=0.63) located at X_S = 0.65 m (X_S/L_r=0.2) in addition to a 2 horizontal to 1 vertical sloping end sill designed according to USBR basin III. In the former experiment, a scour hole of depth 150 mm occurred at 500 mm and was observed after 15 minutes of operation compared to only 20 mm scour hole in the later experiment with 30% reduction in the length of the jump and the flow was symmetrical. The review of literatures indicated that very few studies on the movable bed downstream sudden expansion are available. These studies were reviewed in the study of Nashta et al. [5]. Nashta et al [5] investigated 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).

Recently, Negm et al. [6] investigated experimentally the effect of supercritical flow on maximum scour depth downstream of smooth sudden expanding stilling basins. They concluded that the scour patterns are asymmetric due to the asymmetric flow patterns. The smaller expansion ratio produces shallower maximum scour depth and vice versa. They provided the following prediction model for the maximum scour depth downstream the smooth sudden expanding stilling basin.
as a result

$$\left(\frac{Ds}{G}\right) = 1.13(F_G) - 3.59\left(\frac{H_G}{G}\right) - 28.9\left(\frac{D_{50}}{G}\right) + 0.26\left(F_G\left(\frac{B-b}{b}\right) + 2.1\right) \qquad (1)$$

Equation 1 has R^2=0.857 and SEE = 0.4476 and was developed using the multiple linear regression tool of the Neuraal Connection [7] Software.

Moreover, Negm et al. [8] extended their previous work on the smooth sudden expanding stilling basins by investigating the effect of central sill on the scour characteristics downstream of the basins under supercritical flow conditions. They concluded that the lateral central sill affects both the flow and scour patterns. The minimum scour dimensions are function of the flow parameters as H_u/G and F_G, sill parameters as X_s/L and h_s/G, expansion ratio B/b and the median soil particle ratio D_{50}/G. They used the collected experimental data along with those of Negm et al. [6] to develop a prediction model for the maximum scour depth downstream of sudden expanding stilling basins with and/or without central sill. The equation had the form:

$$\left(\frac{D_S}{G}\right) = 1.27(F_G) - 0.042\left(\frac{H_u}{G}\right) - 1.47\left(\frac{h_S}{G}\right) - 17.3\left(\frac{D_{50}}{G}\right) + 0.30\left(\frac{X_S}{L}\right) + 0.25\left(F_G\left(\frac{B-b}{b}\right)\right) + 0.687 \qquad (2)$$

Equation 2 has a coefficient of determination of 63.4% and standard error of estimate of 0.64.

As far as the authors are aware, no extensive investigation exists on characteristics of the downstream scour under the effect of supercritical flow when an end sill exists at the end of the sudden expanding stilling basin. This paper concentrates on the effect of the end sill of different heights on scour patterns and on the maximum scour downstream of sudden expanding stilling basin compared to the investigation carried out by the authors without any appurtenances in the stilling basin.

THEORETICAL BACKGROUND

Figure 1 shows a definition sketch for the phenomena under study. The maximum (max) scour depth downstreaam of the stilling basin can be expressed as follows, Negm et al. [8]

$$D_S = f(g, \rho, \rho_s, G, V_G, b, B, H_u, D_{50}, h_S) \qquad (3)$$

in which D_S is the maximum depth of scour, g is the acceleration due to gravity, ρ is the density of water, ρ_S is the density of the movable soil, G is the gate opening height, H_u is the upstream water depth, D_{50} is the mean particle diameter and V_G is the mean velocity under the gate.

Applying the Buckingham theorem with ρ, G, V_G as repeating variables, Equation 3 can be written in dimensionless form as:

$$\frac{D_s}{G} = f\left(F_G, \frac{H_u}{G}, \frac{B}{G}, \frac{b}{G}, \frac{h_S}{G}, \frac{D_{50}}{G}, \frac{\rho_s}{\rho} \right) \qquad (4)$$

In which $F_G = V_G /(gG)^{0.5}$ is the Froude number under the gate. The effect of the densities ratio is excluded because only one fluid and one soil are used during the course of experiments. Keeping in mind the properties of the dimensional analysis, Equation 4 could be reduced to

$$\frac{D_s}{G} = f\left(F_G, \frac{H_u}{G}, \frac{h_S}{G}, \frac{D_{50}}{G}, e \right) \qquad (5)$$

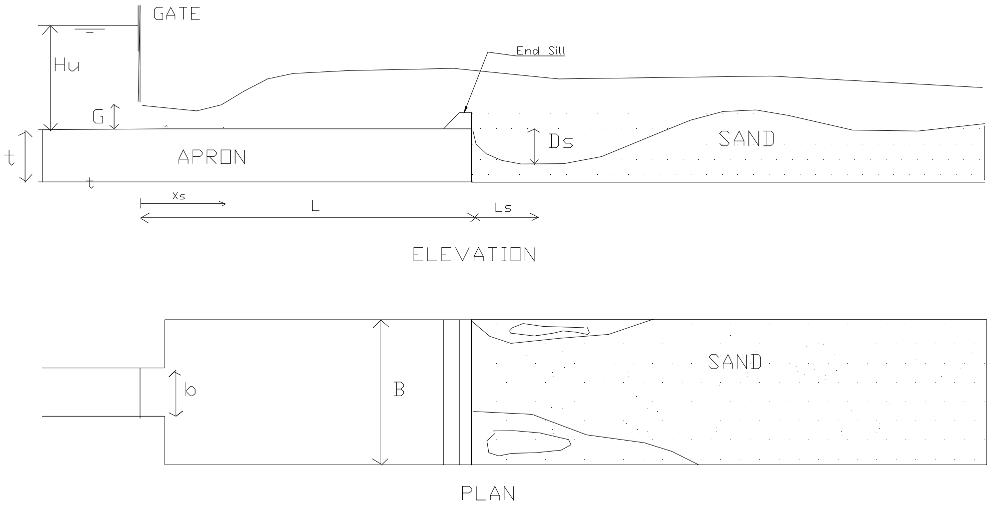


Figure 1 Definition sketch for scour downstream of sudden expanding stilling basin with end sill

EXPERIMENTAL STUDY

The experiments were carried out in a laboratory recirculating flume 0.30 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 pipe line. The stilling basin model was 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 10 cm, while the width of expanding channel was variable as 25, 20 and 15.4 cm to obtain expansion ratios of 2.5, 2.0 and 1.54 respectively.

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 (2.5m) is covered by sediment consisting of 7.5 cm sand layer of medium diameter, D_{50} = 1.77 mm. The tail gate at the end of the flume is used to control the tailwater depth. During the course of the experiments, the tail gate is kept unchanged such that the tailwater depth was about 5 cm when the expansion ratio was 2.5 and slightly less than 5.0 cm for other expansion ratio.

An end sill having 2:1 upstream slope and with vertical downstream slope designed based on the results of USBR [1]. Several heights of the same sill geometry were tested under the same flow conditions. Different expansion ratios were considered. Each expansion ratio was tested with and without end sill. Different heights of the sill were also tested viz h_s=0.0, 1.0, 1.5, 2.0, 2.5 and 3.0 cm. Range of discharges and gate openings were used such that the Froude number under the gate ranged from 1.25 to about 4.4. A total of about 129 runs were performed. In a previous study on scour characteristics downstream of sudden expanding stilling basins, the effect of time was considered, Negm et al. [6]. It was found that about 80 to 85% of the scour occurred during the first 30 minutes. Hence, in the present study, the time of each run was chosen to be 45 min. A typical run is 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 is recorded and its direction is measured. 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

Flow and Scour Patterns

Few typical flow patterns in sudden expanding stilling (e=2.0) with and without end sill are presented in Figures 2 and 3. Figure 2 shows the flow patterns for selected runs when end sill of small height (h_s=1.0 cm) is used and the corresponding flow patterns when the end sill is absent. At low Froude number (e.g. F_G=1.7), the flow patterns for both cases are mostly similar where the main jet of flow is deflected towards one of the basin sides and then flow in the same direction parallel to the center line of the basin (asymmetric flow). When the main jet reaches the movable soil, a secondary scour hole occurs at the same side and a mound occurred on the other side. Part of the flow in the secondary scour hole carries some of the soil particles back to the apron of the stilling basin. The main scour hole occurred at the same direction of the main jet of flow while the main mound is formed at the other side. This means that the asymmetric flow patter in the sudden expanding stilling basin without end sill and with end sill of small height causes asymmetric scour pattern. It is also observed that the length of scour and deposition process is longer when the end sill is not existed. These observations of the scour pattern could be noticed from Figure 4 and 5 that show the scour pattern (contour maps) due to no sill case and a case with an end sill of height h_s=1.0 cm. The observations of flow patterns and scour patterns for no sill are also similar in nature to those previously observed by Negm et al. [6].

Figure 2 also presents the flow patterns for other typical values of F_G for both cases with and without end sill. For the case of no sill, the flow in the stilling basin are mostly similar in nature to that of small Froude number. But the main jet becomes more strong leading to the formation of fast flow with lower water surface level compared to weak hydraulic jump at the small F_G. This causes a deeper and wider scour to form and still both the flow and the scour are asymmetric and the scour hole is formed in the same direction of the main jet of the flow over the apron of the stilling basin. Regarding the cases where end sills are existed at larger Froude numbers, the main jet of flow in each case is deflected downstream of the expansion section and hit one of the basin sides then flows parallel to the central line of the stilling basin up to the end of the stilling basin where it meets the end sill. The distance from the expansion section and the angle of deflection where the jet meets the basin side depends on the Froude numbr when the expansion ratio is constant. This distance increases by increasing of F_G. The presence of the end sill forces the main jet to change its direction to the other side of the flume causing a secondary scour hole near the apron and a main scour hole away from the apron along his new direction. On the other side, a minor mound is formed near the apron of the basin and the main deposition is formed in the same direction of the secondary one but away from the end of the stilling basins.

Figure 3 shows more typical flow patterns when an end sill of larger heights than 1.0 cm are used at the same expansion ratio (e=2.0) and the same F_G. The presence of sill produces flow patterns which are similar in nature to those when an end sill of small height is existed but at high Froude number. In all these cases (h_s=1.5, 2 and 2.5 and F_G>1.7), the flow patterns are asymmetric and the resulting scour patterns are asymmetric also. It is observed that the flow tends to be slightly submerged at some F_G when the height of sill exceeds the gate opening. This submergence delays the decay of the jet resulting in lower energy dissipation and hence a larger depth of scour is expected in such cases. Typical scour patterns for selected runs are presented in Figures 6 to 12 confirming these observations. Figures 5, 6, 7 and 8 show the effect of the height of sill at constant e and fixed F_G, while Figures 8, 9 and 10 are presented to show the effect of expansion ratio at constant F_G and fixed height of sill. Also, Figures 10, 11 and 12 demonstrate the effect of F_G at constant e=2 and hs=1.54.

From all the observed and the presented scour patterns, the scour hole is formed near to one side of the flume and in the same direction of the main jet of flow over the movable soil. The main scour hole is non-uniform in nature and mostly with unequal width and length. The formed scour hole near one of the flume sides (banks) is incomplete because the jet of flow is faced with the flume side (or bank of the flume) which rigid preventing a complete scour hole from being formed. On the other hand, the formed mound which is most of the cases is asymmetric in nature regarding the flume dimensions and the dimensions of the mound itself.

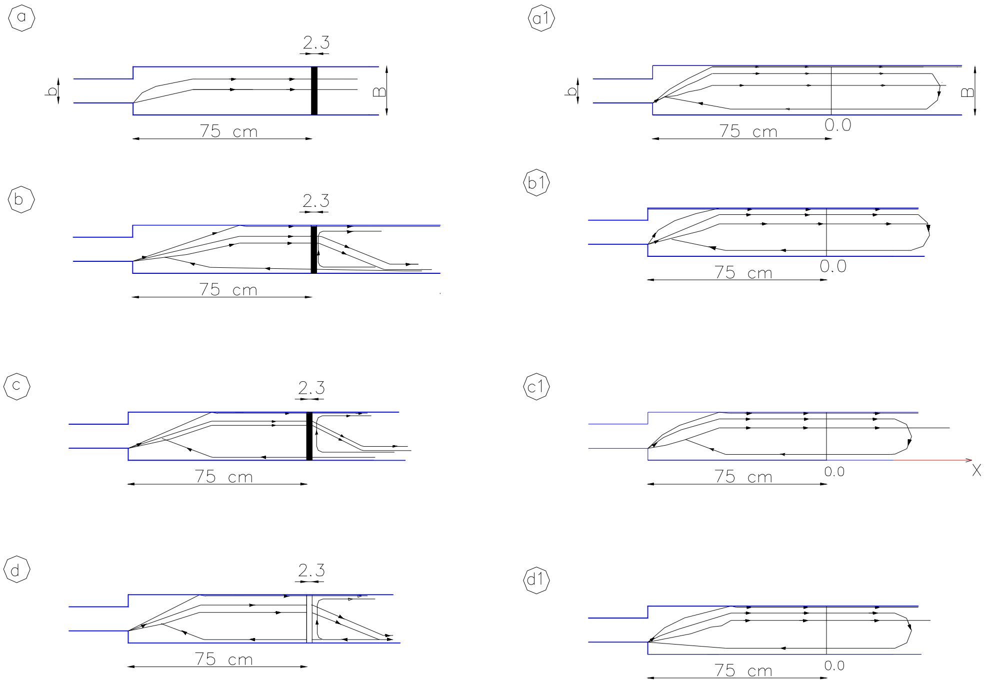


Figure 2 Typical flow patterns in sudden expanding stilling basin with and without end sill for e=2.0 and different F_G. (a) F_G=1.7, h_s=1, G=1.8, (a1) F_G=1.7, h_s=0, G=1.8, (b) F_G=2.9, h_s=1, G=1.5, (b1) F_G=2.9, h_s=0, G=1.5, (c) F_G=3.4, h_s=1, G=1.2, (c1) F_G=3.4, h_s=0, G=1.2, (d) F_G=4.4, h_s=1, G=1.2 , (d1) F_G=4.4, h_s=0, G=1.0 (All Dim. Are in cm)

Effect of Froude Number and Expansion Ratio on Ds/G (No Sill Case)

Figure 3 presents the relationship between D_s/G and the F_G for different expansion ratios of 1.54, 2.0 and 2.5 for no sill case (h_s/G=0). Also, the values due to Negm et al. [6] for no sill cases when e=2, 2.5 an 3.0 are presented. It is observed that the relative scour depth is high for high Froude number and vice versa at particular expansion ratio and this agreed well the previous observations of Negm et al. [6]. At particular Froude number, the vertical variation in the relative scour depth is due to the effect of expansion ratio where larger expansion ratio indicate deeper scour hole or larger relative depth of scour. The smallest expansion ratio (e=1.54) shows the smallest relative depth of scour at smaller Froude number while for higher Froude number, the expansion ratio e=2.0 produces smaller relative scour depth.

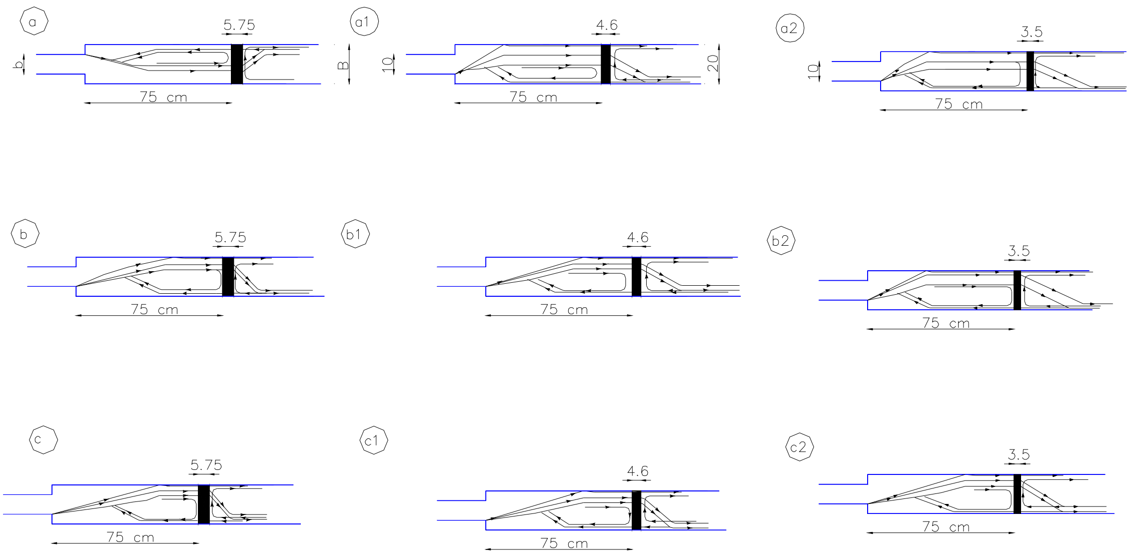


Figure 3 Typical flow patterns in sudden expanding stilling basins with end sill for expansion ratio e=2, different F_G and constant h_s (All Dim. Are in cm)
(a) F_G=1.7, h_s=2.5, G=1.8 (a1) F_G=1.7, h_s=2.0, G=1.8 (a2) F_G=1.7, h_s=1.5 G=1.8,
(b) F_G=3.4, h_s=2.5, G=1.2 (b1) F_G=3.4, h_s=2.0, G=1.2 (b2) F_G=3.4, h_s=1.5 G=1.5,
(c) F_G=4.4, h_s=2.5, G=1.0 (c1) F_G=4.4, h_s=2.0, G=1.0 (c2) F_G=4.4, h_s=1.5 G=1.0

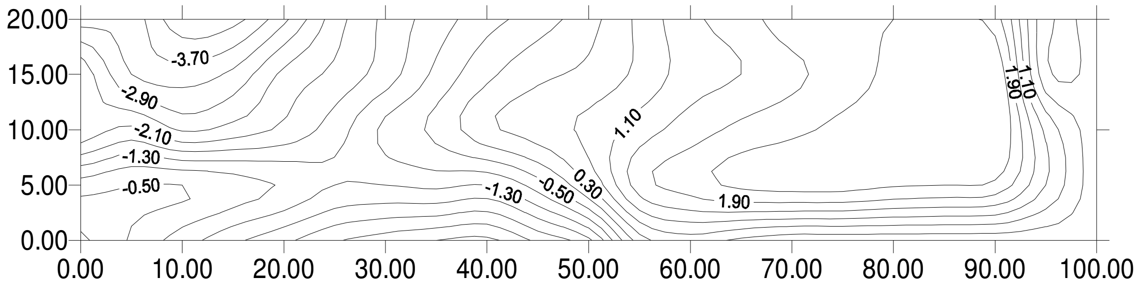


Figure 4. Scour pattern downstream sudden expanding stilling basin for e=2, h_s=0.0 and F_G=3.4

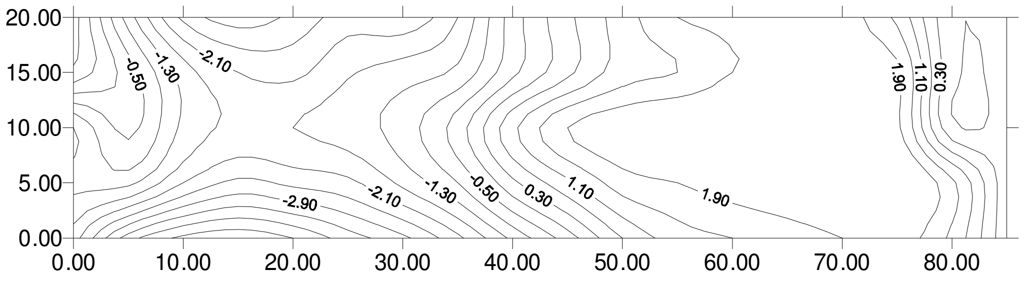


Figure 5. Scour pattern downstream sudden expanding stilling basin for e=2, h_s=1.0 and F_G=3.4

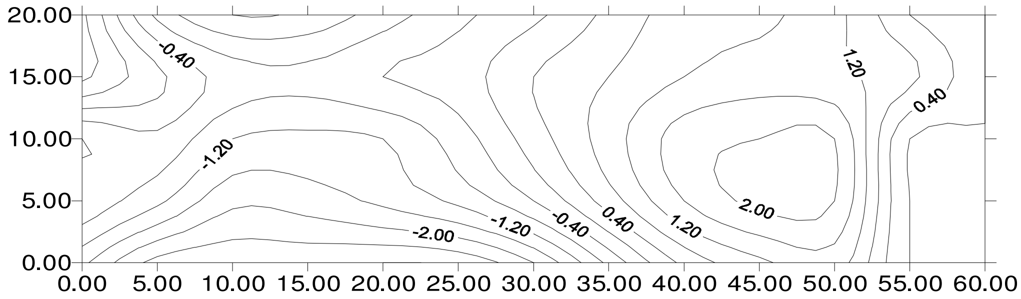


Figure 6. Scour pattern downstream sudden expanding stilling basin for e=2, h_s=1.5 and F_G=3.4

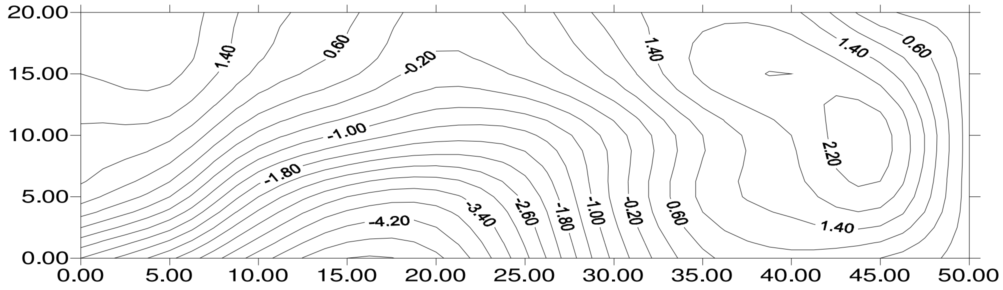


Figure 7. Scour pattern downstream sudden expanding stilling basin for e=2, h_s=2.0 and F_G=3.4

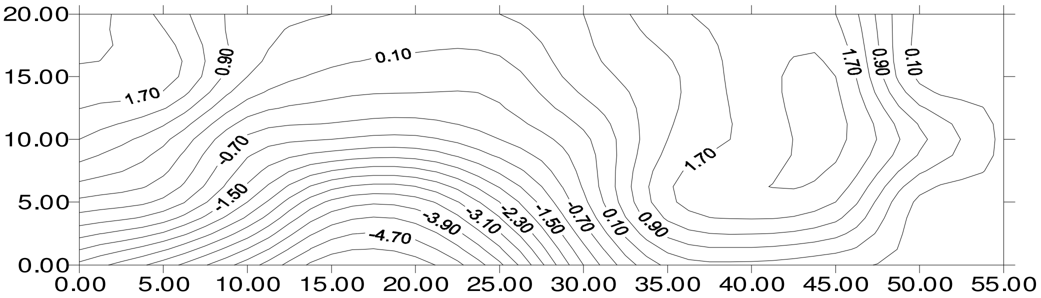


Figure 8. Scour pattern downstream sudden expanding stilling basin for e=2, h_s=2.5 and F_G=3.4

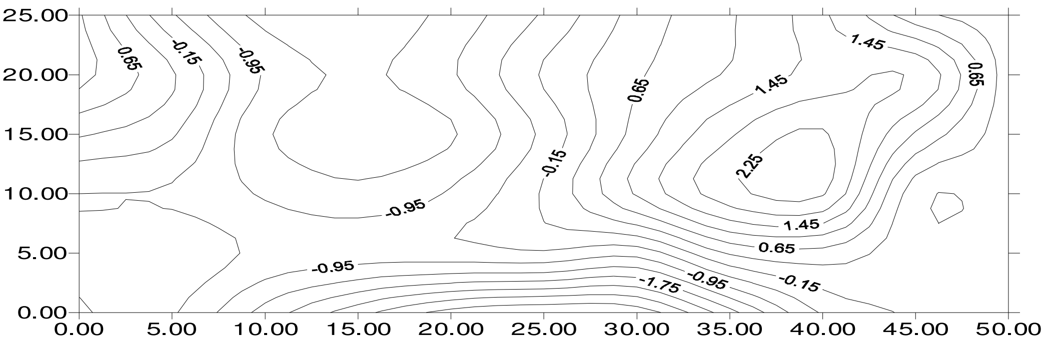


Figure 9. Scour pattern downstream sudden expanding stilling basin for e=2.5, h_s=1.5 and F_G=3.4

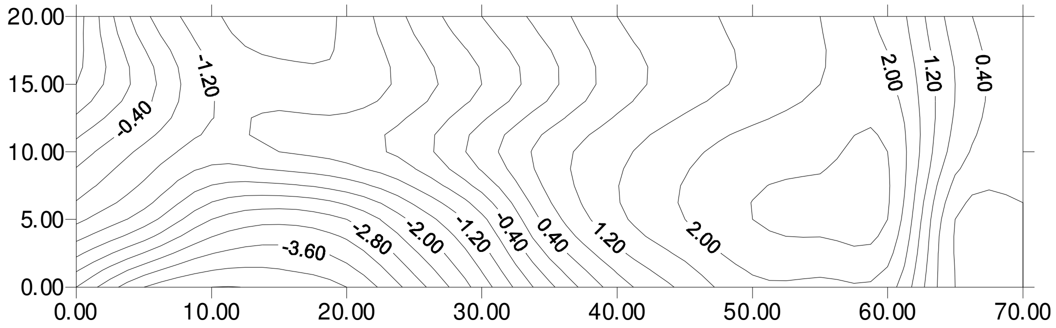


Figure 10. Scour pattern downstream sudden expanding stilling basin for e=1.54, h_s=1.5 and F_G=3.4

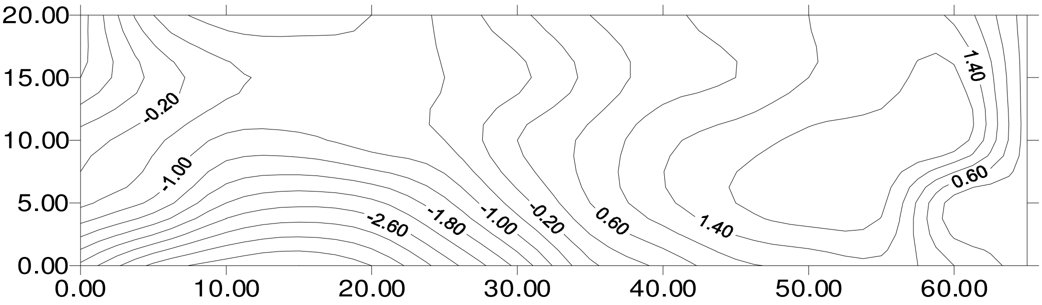


Figure 11. Scour pattern downstream sudden expanding stilling basin for e=1.54, h_s=1.5 and F_G=2.63

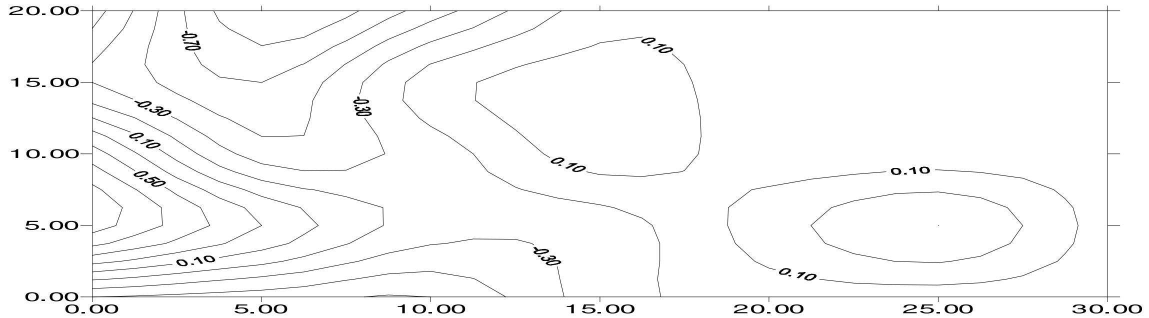


Figure 12. Scour pattern downstream sudden expanding stilling basin for e=1.54, h_s=1.5 and F_G=2.00

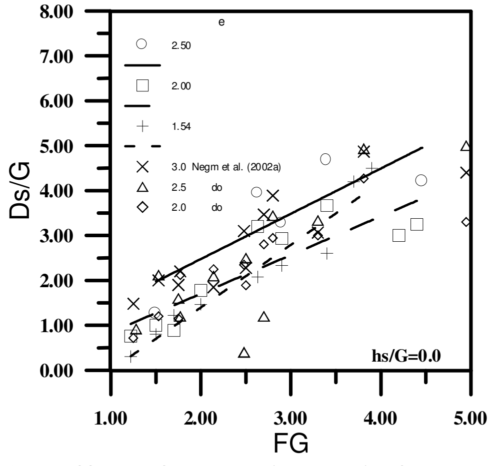
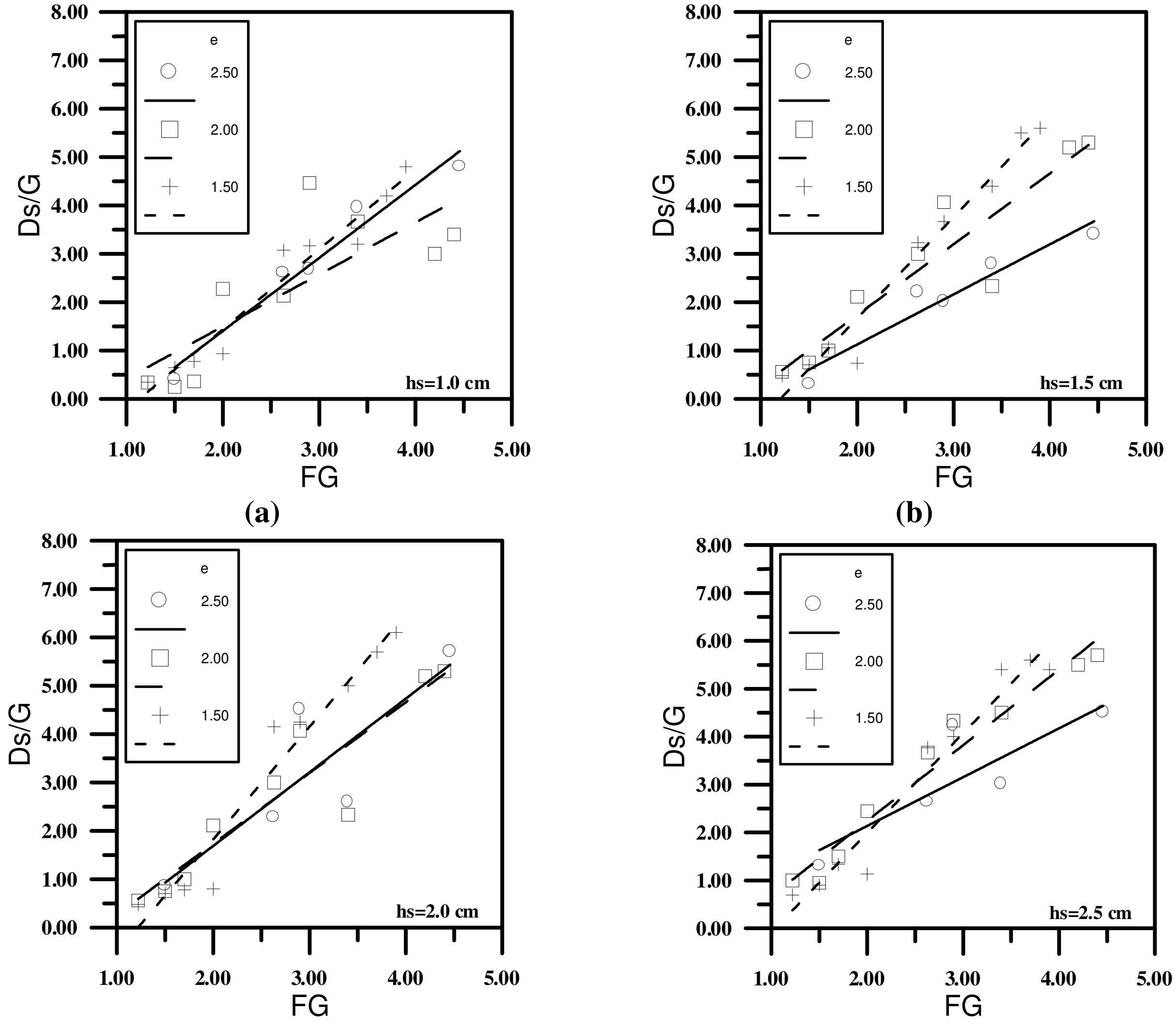


Figure 13. Effect of expansion ratio for no sill case

Effect of Froude Number And Expansion Ratio on D_s/G (Case of End Sill)

Figures 14a, 14b, 14c and 14d indicate the relationships between D_s/G and F_G for different expansion ratios at fixed height of end sill. These figures show similar trend of the variation of D_s/G with F_G at fixed expansion ratio as explained in Figure 13. However, the effect of the expansion ratio at particular F_G depends highly on the height of the end sill. In Figure 14a where the height of the sill is very small, the expansion ratio e=2 produces smaller D_s/G at $F_G>2.0$ and both e=1.54 and e=2.5 produce mostly the same values. Although, there are two runs where the value of the D_s/G are higher than any other D_s/G values and another two unexpected small values at high F_G. However, if the small values of D_s/G at the higher F_G are omitted, the trend of the line representing e=2.0 will rise up higher than the other two expansion ratios (e=154 and e=2.5) indicating that the expansion ratio e=2.5 will produce higher D_s/G as the other figures (14b, 14c and 14d) indicate at higher height of the end sill.



(a) (b)

(c) (d)

Figure 14. Effect of expansion ratio for cases with end sill, (a) h_s=1.0 cm, (b) h_s=1.5 cm, (c) h_s=2.0 cm and (d) h_s=2.5 cm

Effect of Height of End Sill at Fixed Expansion Ratio on D_s/G

As discussed above, the height of the end sill has a pronounced effect on the flow pattern in the sudden expanding stilling basin and hence on the scour pattern. The effects of height of end sill on D_s/G are presented in Figures 15a, 15b and 15c at fixed expansion ratios 2.5, 2 and 1.54. Clearly, the sill of height 1.5 cm produces the minimum D_s/G in case of e=2.5. While the no sill case produces the lowest values of D_s/G in both cases of e=2 and e=1.54 followed by the sill with height equals 1.0 cm. Consequently, the values of D_s/G depend not only on F_G but also on both e and h_s relative to the gate opening for a particular soil type. Practically, the end sill has not improve significantly either the flow pattern or scour patter.

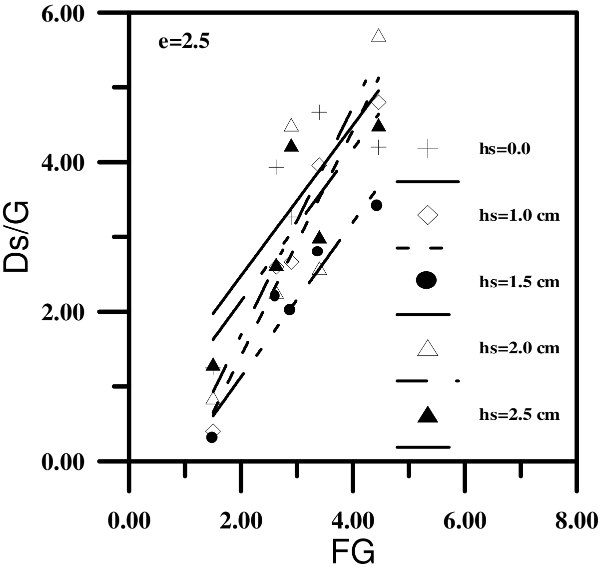


Figure 15a. Effect of height of end sill for e=2.5

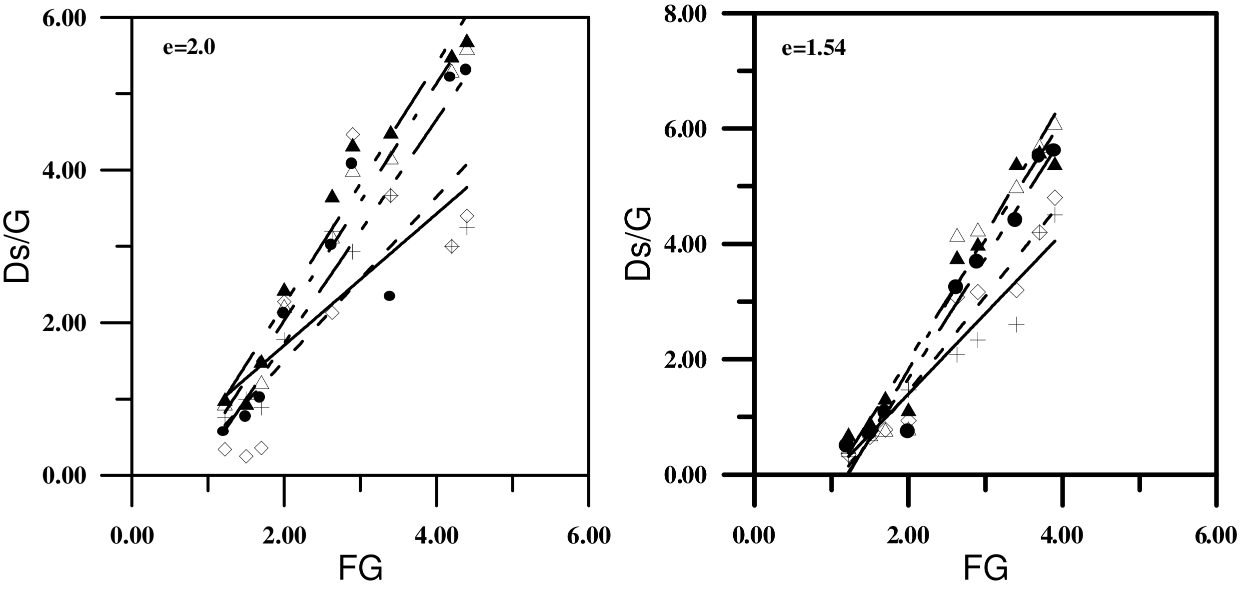


Figure 15b. Effect of height of end sill for e=2.0

Figure 15c. Effect of height of end sill for e=1.54

Estimation of Maximum Scour Depth Ratio Ds/G

Using the multiple linear regression analysis, several attempts are made to fit the data to a suitable model based on equation 2. The following equation is found to represent the data well with R2=0.83 and standard error of estimate of 0.705.

$$\frac{D_s}{G} = 7.012 + 0.496\frac{h_s}{G} + 38.92\frac{G}{H_u} + 0.375F_G - 0.702\frac{B}{b} - 100.809\frac{D_{50}}{G} \qquad (6)$$

The estimated D_s/G from Equation 6 is plotted against the measured ones in Figure 16 and the line of equality is shown on the figure. Clearly, fair agreement is obtained.

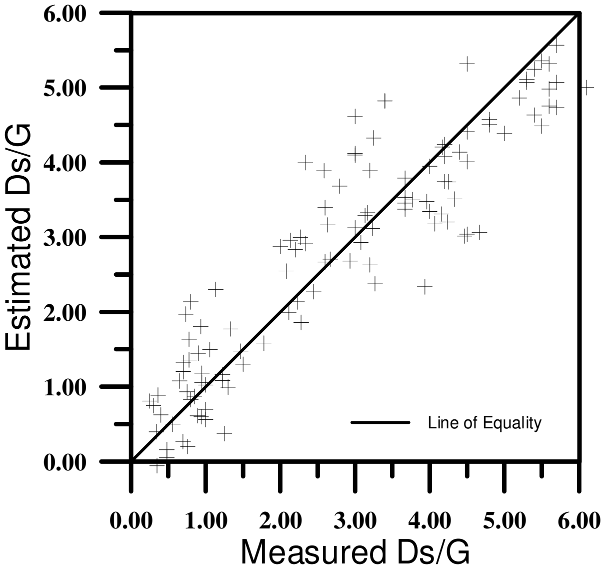


Figure 16 Comparison between estimated D_s/G and measured ones for basin with or without end sill

CONCLUSIONS

An experimental investigation was conducted to study the effect of the end sill in the sudden expanding stilling basin on the scour downstream of the basin. Three different expansion ratios and five different heights of sills were tested. Both the flow and scour patterns are discussed as affected by the flow and basin parameters. It was found that the presence of end sill changes the flow pattern slightly upstream of the sill and highly just downstream of end sill. The scour downstream of the sudden expanding stilling basins with end sill is asymmetric. The extent of scour and deposition process depends on the Froude number, the height of the end sill and the expansion ratio. When an end sill is a must, its height should be designed carefully to improve the scour pattern and to produce the minimum scour depth downstream of the basin. This height should not be more than the dominant height of the gate to avoid the deflection of the main jet of flow just downstream of the sill and hence a fully asymmetric and incomplete scour hole may be avoided. Practically, the use of end sill in sudden expanding stilling basins to reduce the scour depth is not recommended.

However, it may be useful to throw the scour hole away from the end of the basin increasing the safety of the structure. Equation 6 is developed to estimate the maximum scour depth ratio in terms of the same parameters of Equation 2.

REFERENCES

[1] U.S. Bureau of Reclamation, (1958), “Hydraulic Design of Stilling Basins and Energy Dissipators”, Engineering Monograph No. 25, Denver, Colorado.

[2] Hager, W.H. (1992), “Energy Dissipators and Hydraulic Jumps.” Kluwer Academic Publications, Dordrecht, The Netherlands.

[3] Graber, S.D. (1982), “Asymmetric Flow in Symmetric Expansion”, Journal of Hydraulics Div., Proc. ASCE, Vol. 135, No. 10, PP. 1082-1101.

[4] Bremen, R. & Hager, W.H. (1994), “Expanding Stilling Basin”, Proc. Instn Civ.Engrs Wat., Marit. & Energy, Vol. 106, No. 9, PP. 215-228.

[5] Nashta, C.F. & Swamee, P.K., and Garde, R.J. (1987), “Subcritical Flow in Open Channel Expansions With Movable Bed.”, Journal of Hyd. Research, Vol. 25, No. 1, PP. 89-102.

[6] Negm, A.M., Abdel-Aal, G.M. Saleh, O.K, & Sauida, M.F. (2002), “Effect of Supercritical Flow on Scour Characteristics Downstream of Sudden Expanding Stilling Basins”, Egyptian Journal for Engineering Science and Technology EJEST, Vol. 6, No. 1, PP. 1-13.

[7] Neural Connections. (1998), “ANNs software and user manuals”, SPSS Inc./Recognition Systems Inc.

[8] Negm, A.M., Saleh, O.K., Abdel-Aal, G.M. & Sauida, M.F. (2002), “Investigating Scour Characteristics Downstream of Abruptly Enlarged Stilling Basins”, River Flow 2002 - Proceedings of the International Conference on Fluvial Hydraulics, D.Bousmar & Y. Zech, Editors, Swets & Zeitlinger, Lisse, The Netherlands.

NOTATIONS

b	The width of channel.
B	The width of gate openning.
D_s	The max. scour depth.
D_{50}	The mean particle diameter.
e	The expansion ratio.
F_1	The Froude number of the approaching flow.
F_G	The Froude number under the gate.
G	The gate openning.
H_U	The upstream water level.
h_S	The sill height.
L	The length of apron.
L_S	The length of the max. scour depth from the apron.
L_r	The length of roller.
V_G	The mean velocity under the gate.
X_S	The distance of sill from expansion section.
y_1	The depth of approaching flow.
ρ	The water density.
ρ_S	The density of the movable soil.