Characteristics of Submerged Flow Below Gate With Sill in Non-Prismatic Channels

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Abstract

The characteristics of submerged flow below vertical gate with sill upstream of horizontal diverging channel reach are analyzed based on experimental investigation. The experimental program is conducted in a laboratory flume with 10 cm wide, 31 cm deep and 3.0 m long. A diverging channel reach with fixed length and constant divergence angle is used. Polygonal sills with constant height, constant upstream slope and variable downstream slope are used under the gate. These sills are tested under wide range of similar submerged flow conditions to investigate the effect of sill slope on the flow characteristics. Also, a particular sill is tested under different heights to address the effect of sill height on the flow characteristics. Both the effects of submergence and the under-gate Froude number on the flow below the gate are discussed. Different flow regimes are considered (Supercritical, critical and subcritical flow). It is found that the presence of sill under the gate upstream of diverging channel reach has a remarkable effect on the discharge coefficient of the gate. It is noticed that the submergence ratio and the upstream head ratio are not able to explain the observed variations (or scatter of data) in the discharge coefficients. These variations or scatters are completely explained by the under-gate Froude number and the differential head ratio.

1 Introduction

Gates are used in open channels to control the flow and measure its rate. Gates may be free or submerged according to the extent of the water depth downstream the gate relative to the gate opening. They may be used in prismatic or in non-prismatic channels. Studies on flow characteristics below gates with sill in prismatic channels are mostly covered in Negm (1995) and recently in Negm et al. (1998, 1999) and Negm (2000a). Also, the characteristics of flow below gates without sill in non-prismatic channels were studies by Negm et al. (2000a,b) for free flow and by Ibrahim (2000) and Negm (2000b) for submerged flow.

On the other hand, the hydraulic jump characteristics in non-prismatic channels were investigated by many investigators, Arbhabhirama and Abella (1972), Arbhabhirama and Wan (1975), Khalifa and Mcorquodale (1979), France (1981), Hager (1985), Abdel-Aal et al. (1998), Rageh (1999), and

Abdel-Aal (1999, 2000). A review of these studies and others are found in Negm (2000a). It was found that the radial basin is proved to be more effective in dissipating the energy than the rectangular one. Therefore, it is preferred to use the gradual expanding stilling basins (or radial basins) to ensure more safety of the hydraulic structures against failure and to be more economic. This study investigates the discharge characteristics of gates with sill upstream of radial diverging channel reach (radial stilling basin). However, Regarding the submerged flow below gate in radial basin, Ibrahim (2000) analyzed the experimental data of supercritical submerged flows at fixed F_G=1.806, 1.462, 1.255 and 1.018 with F_G being the under-gate Froude number ($=\sqrt{(q^2/gG^3)}$, q is the discharge per unit width; g is the acceleration due to gravity; G is the gate opening). A prediction equation is developed for the discharge coefficient C_d in terms of F_G and the differential head on the gate $\Delta H / G$ in the form:

$$C_d = \frac{0.001545 + 0.7063 F_G}{\sqrt{\frac{\Delta H}{G}}} \tag{1}$$

Equation (1) is developed for the following ranges of the parameters: $1.02 \leq F_G \leq 1.81$, $5 \leq H_1/G \leq 20$, $0.5 \leq \Delta H/G \leq 9.0$, $0.25 \leq X/L \leq 1$, $2 \leq S \leq 12$.

It was concluded that the discharge coefficients attain their maximum values when the lateral sill is constructed at a distance of ¾ of the basin length from the gate. Negm (2000b) extended the study of Ibrahim by analyzing the experimental data of subcritical flow below gate in radial basin with sill with the same experimental configuration as those of Ibrahim. A generalized equation for the discharge coefficient for the full range of submerged flow (supercritical, critical and subcritical flows) is developed and is compared by that of supercritical and subcritical flows. The developed equation is:

$$C_d = \frac{0.70749 F_G}{\sqrt{\frac{\Delta H}{G}}} \tag{2}$$

Eq.(2) is developed for the following ranges of the investigated parameters: $0.2858 \leq F_G \leq 1.81$, $0 < H_1/G \leq 20$, $0 < \Delta H/G \leq 9.0$, $0.25 \leq X/L \leq 1$, $2 \leq S \leq 12$. Comparison between Eq.(2) and Eq.(1) shows that Eq.(2) predicts C_d with sufficient accuracy.

Recently, Negm (2000a) compared the performance of rectangular and radial stilling basins from both hydraulic jump and discharge characteristics point of views. It was concluded that the radial basin is more efficient regarding the whole characteristics.

2 Theoretical Background

Figure 1 shows a typical definition sketch for submerged flow below gate with sill. Applying the principles of dimensional analysis, the following functional relationship for coefficient of discharge of the submerged silled gate, C_d, can be proved as:

$$C_d = f_1\left(\frac{H_1}{G},\frac{\Delta H}{G},F_G,\frac{H_t}{G},\theta,DSS,USS\right) \qquad (3)$$

in which C_d is the discharge coefficient of gate; F_G, the under-Froude number, $\sqrt{(q^2/gG^3)}$, q is the discharge per unit width; g is the acceleration due to gravity; G is the gate opening, H_1 is the upstream water depth, $\Delta H = H_1 - H_2$ is the differential head on the gate with H_2 the water depth just downstream the gate, H_t is the tailwater depth, DSS is the downstream slope of the sill, θ is the angle of divergence of the radial basin, USS is the upstream slope of the sill. The angle of divergence and USS are kept constant, their effects will be excluded from Eq.(3) which becomes:

$$C_d = \psi\left(F_G,\frac{H_1}{G},S,\frac{\Delta H}{G},DSS\right) \qquad (4)$$

The discharge coefficient (C_d) of gate with sill for submerged flow (Fig. 1) is computed based on the following equation:

$$C_d = \frac{Q}{Gb\sqrt{2g\Delta H}} \qquad (5)$$

in which b is the width of the flume at the gate location.

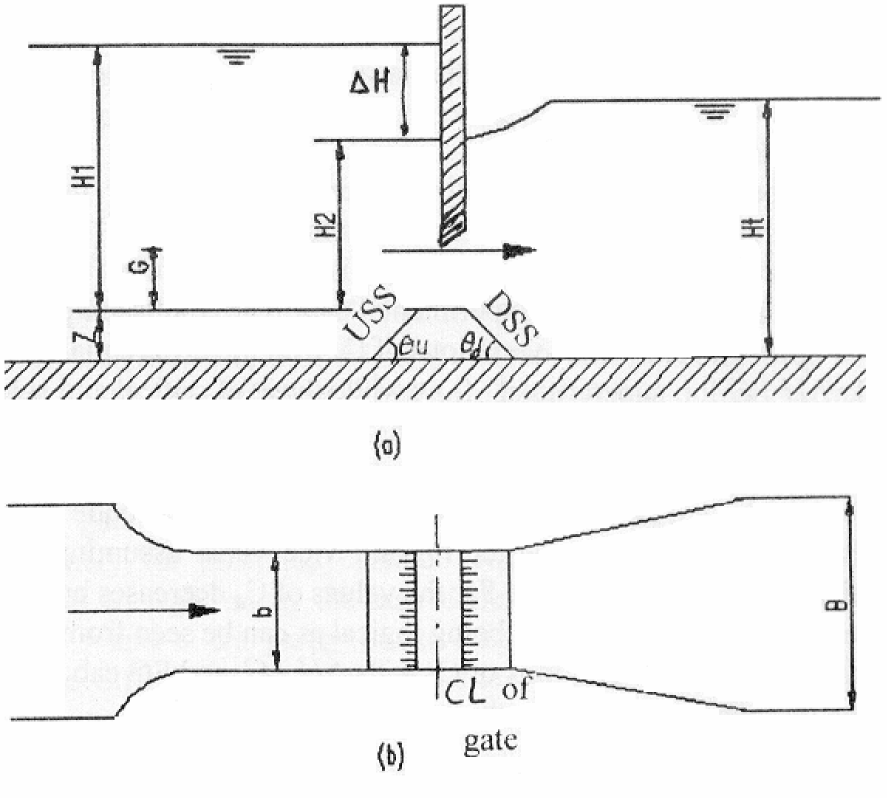

Figure 1: Definition sketch for submerged flow below gate US horizontal radial stilling basin with sill under gate

3 Experimental Arrangement

A glass sided tilting re-circulating flume of 3.0 m long is used to conduct the experiments of the present study. The flume bed is 10 cm wide, 31.8 cm deep and 3 m long. The water depths are measured by means of point gauges mounted on instrument carriages. The discharge is measured by means of a pre-calibrated orifice meter. The flume has a vertical sluice gate which was made from an aluminum plate, 5 mm thick with a sharp beveled lower edge to control the upstream water depth. The flume is supplied by the water which comes from a self-contained sump tank. The tailwater is controlled by means of the tail gate which is located at the downstream end of the flume. Trapezoidal sills of varying heights (0, 1.0, 1.5 and 2.0 cm) with vertical upstream face (θ_u=90) and sloping downstream face with different slopes of θ_d=90, 45, 18.43, 11.30 and 8.4 are tested under the same submerged flow conditions. The basin has a small divergence angle ($\theta = 1.61°$) such that the width of the flume at the gate is 7 cm. The distance from the gate to the end of the basin is 105 cm. The sill is made from smooth painted wood. The gate is fixed at the center line of the top width of the under-gate sill which is 2 cm wide. Tests covered the following ranges of flow and sill parameters: $0.286 \leq F_G \leq 2.098$, $2.0 \leq H_1/G \leq 19.0$, $0 < \Delta H/G \leq 8.9$, $2.0 \leq S \leq 13.0$. The measurements of submerged flow include the water depths upstream and downstream the gate as well as the tailwater depth and the discharge. Different submergence were obtained by varying the tailwater depth at constant discharge and fixed gate opening.

4 Results and Discussions

The discharge below silled-gates is directly proportional with the discharge coefficient. Therefore, it is taken as an indicator to study the effect of the different parameters on the discharge. Eq.(5) is used to calculate the discharge coefficient, C_d, for all collected experimental data. The results are presented in Figure 2. Figure 2(a) shows the variations of C_d with the differential head ratio, $(H_1-H_2)/G=\Delta H / G$ for supercritical flow while those of critical and subcritical flows are presented in Figure 2(b). Both figures indicate the same trend of variations of C_d with $\Delta H / G$ for supercritical, critical and subcritical flows. It is clear that the data are grouped according to the under-gate Froude number, F_G with higher values of C_d for larger F_G and vice versa assuming the same differential head ratio. At the same F_G, the values of C_d decreases by increasing the differential head ratio which is being logical as can be seen from Eq.(5). An equation to describe the variations of C_d with $\Delta H / G$ and FG can be obtained by using the regression analysis. Such equation takes the form:

$$C_d = \frac{0.707 F_G}{\sqrt{\frac{\Delta H}{G}}} \tag{6}$$

Equation (6) fits the data well with a tolerance of ± 0.0015 for all flow cases.

Eq.(6) is also useful in estimating an accurate C_d if an average value is known to estimate Q, then F_G could be calculated to enter Eq.(6) in order to improve the estimation of C_d which in turn is used in another iteration. The procedure is continued till the required accuracy is attained.

The effect of the downstream slope of the sill can be traced by careful inspection of Figures 2(a) and (b). For supercritical flow, the sill with downstream slope of 1V:5H (θ_d=11.30) improves the discharge coefficient of the gate as it indicates the highest vales of C_d at all F_G>1.0. For critical flow, the sill with vertical both upstream and downstream faces produces the highest values of C_d. As the flow changes to subcritical flow, the role if sill on C_d is changed as it affects the C_d negatively (C_d is reduced compared to the case of no sill under the gate). These results can also be deduced from Figures 3 and 4. Figures 3 and 4 are reproduced from Figures 2 (a) and (b) for supercritical and subcritical flows. Each plot demonstrates a case where F_G is kept constant and both the downstream slope of sill and the submergence are variable. Clearly, the role of the downstream slope of sill is affected greatly by the under-gate Froude number and is slightly affected by the submergence, S. For each particular F_G value, the data is being grouped with the submergence where C_d values at smaller S correspond to lower H_1/G values, i.e., the values of submergence increase on each plot from left to right.

It may be interested to investigate the effect of submergence on the discharge characteristics in terms of C_{dh} as studies earlier by Henry (1950) for gate without sill in rectangular prismatic channel. According to Henry, C_{dh} is calculated as follows:

$$C_{dh} = \frac{Q}{Gb\sqrt{2gH_1}}$$

The variations of C_{dh} with H_1/G at θ_u=90 and θ_d=45.0 and different submergence of 2.0, 3.0, 4.0, 5.0, 6.0 and 7.0 are shown in Figures 5 and 6. Also, indicated on the figures the values of no sill at S=7.0 in diverging channel due to Negm (2000a) and those due to Swamee (1992) for no sill at S=7.0 in rectangular prismatic channel. Clearly the trend of variations of C_{dh} with H_1/G and S for silled gate in diverging channel (non-prismatic) is similar to that obtained by Henry for prismatic channel. The values of the submergence increase from left to right as in the case of Henry diagram. The scatter of the data on Figures 5 and 6 are partly due to change of case of flow and may be partly due to the difficulties in measuring the water depth using the ordinary point gauge. An equation to describe the family of curves of figures 5 and 6 could be developed as that presented in Negm (2000a).

On the other hand, Figure 8 presents the variations of C_{dh} with H_1/G at S=4.0 and variable downstream slopes of sill. Again it could be stated that the discharge coefficient is higher for the sill having downstream slope of 1:5 specially at large values of F_G (upper zone of the curve).

Figure 9 compares the presents results for no sill (at S=4.0 and S=7.0) with those of Negm (2000a) for no sill in diverging channel reach (non-prismatic channel reach) and those of Swamee (1992) for gate without sill in prismatic channel. Clearly, the results are comparable and trends are similar.

5 Conclusions

An experimental investigation is conducted in a laboratory flume using sills of different downstream slopes and constant upstream slope to investigate the effects of both the DSS of sill and the submergence on the discharge coefficient of gate with sill when used in diverging channel reach. The results indicated that the effect of DSS of sill on the discharge is affected by the regime of flow or the under-gate Froude number. Therefore, the selection of the sill to be used under the gate in diverging channels should depend upon the dominant under-gate Froude number during the operation conditions of the gate or the structure involving gates. If supercritical submerged flow is prevailed, the sill with 1:5 downstream slope is preferred while the sill with both vertical upstream and downstream faces increases the discharge coefficient for subcritical submerged flow in diverging channels. The role of submergence is not clear in Figure 2 as more or less tailwater is directly affects the differential head ratio. However, the effect of submergence on C_{dh} is very clear when analyzed in terms of H_1/G. The values of H_1/G are higher for high submergence and hence the discharge coefficient is greater for higher submergence at the same H_1/G. Furthermore, the discharge coefficients values are grouped according to $\Delta H / G$ and F_G (Fig.2) or according to H_1/G and S (Figures 5 and 6).

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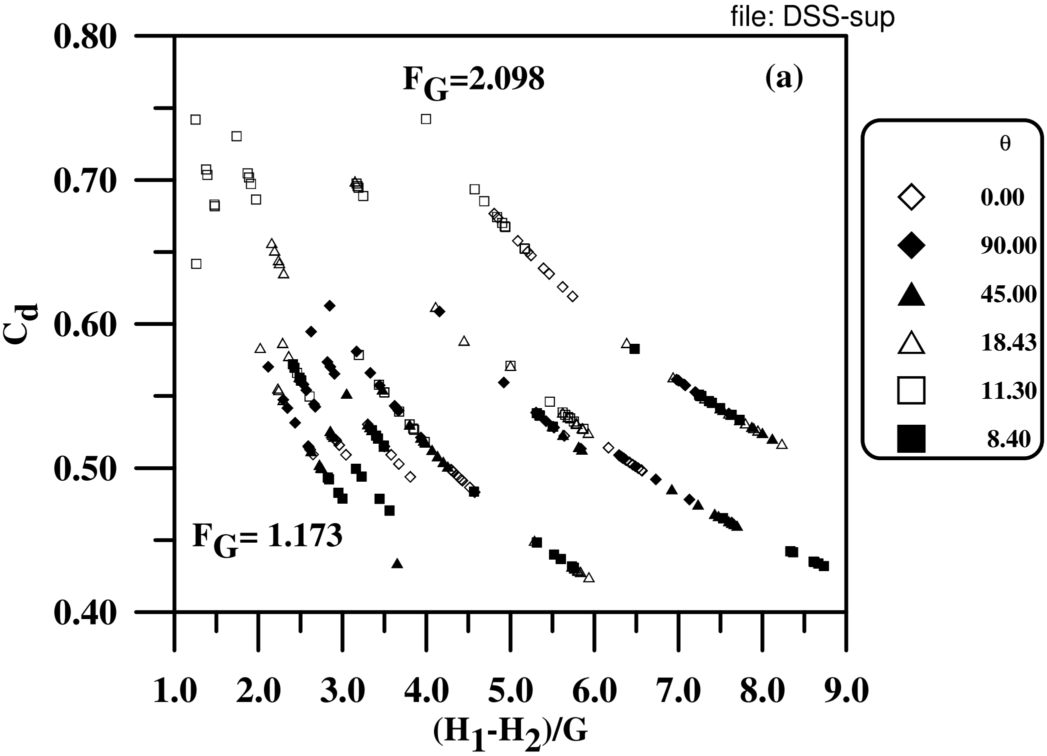
NOTATIONS

b	width of the flume at the gate location (7 cm)
B	Width of the flume at the end of the basin (10 cm)
C_d	the coefficient of discharge of silled submerged sluice gate
C_{dh}	discharge coefficient according to Henry
F_G	Froude number under gate
G	gate opening height above sill level
g	acceleration due to gravity
ΔH	effective head in the submerged flow case (upstream head, H_1 - downstream head, H_2)
Q	discharge passing through the flume
H_1	upstream water depth
H_2	depth of water just downstream the gate
S	submergence ratio, H_t/G
H_t	tail water depth
θ	the angle of divergence of the basin
DSS	downstream slope of sill or θ_u in degrees
USS	upstream slope of sill or θ_d in degrees



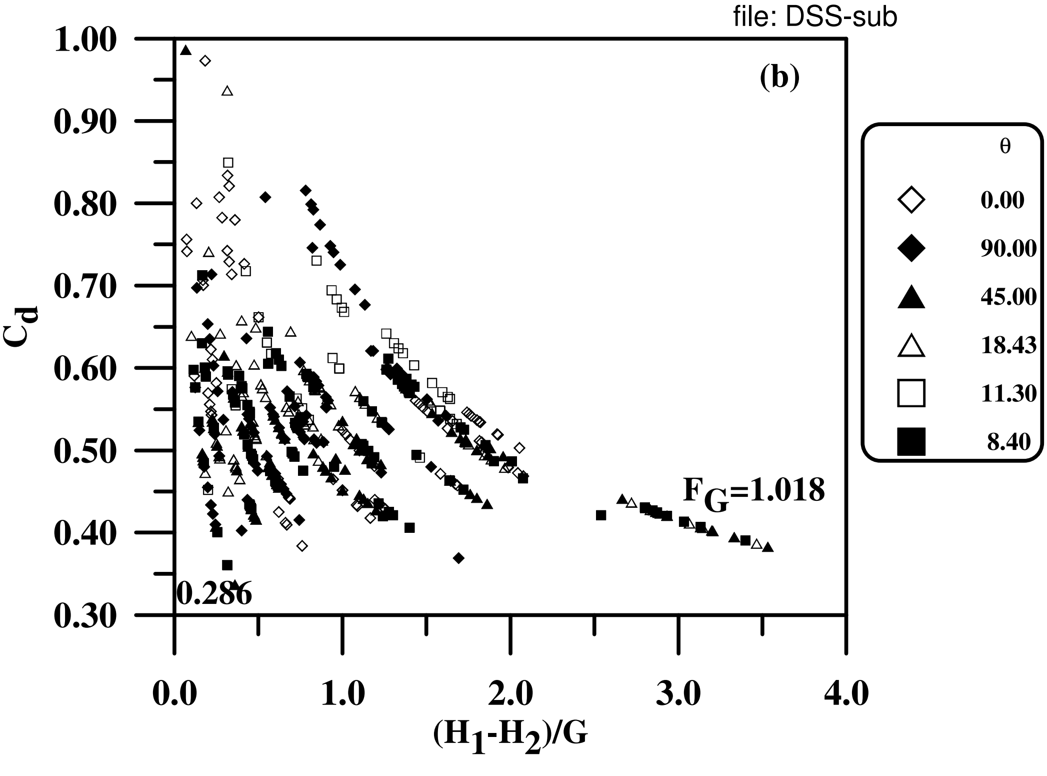


Figure 2. Variations of C_d with $(H_1-H_2)/G$ for (a) supercitical flow and (b) subcritical flow below silled-gate upstream of radial stilling basin

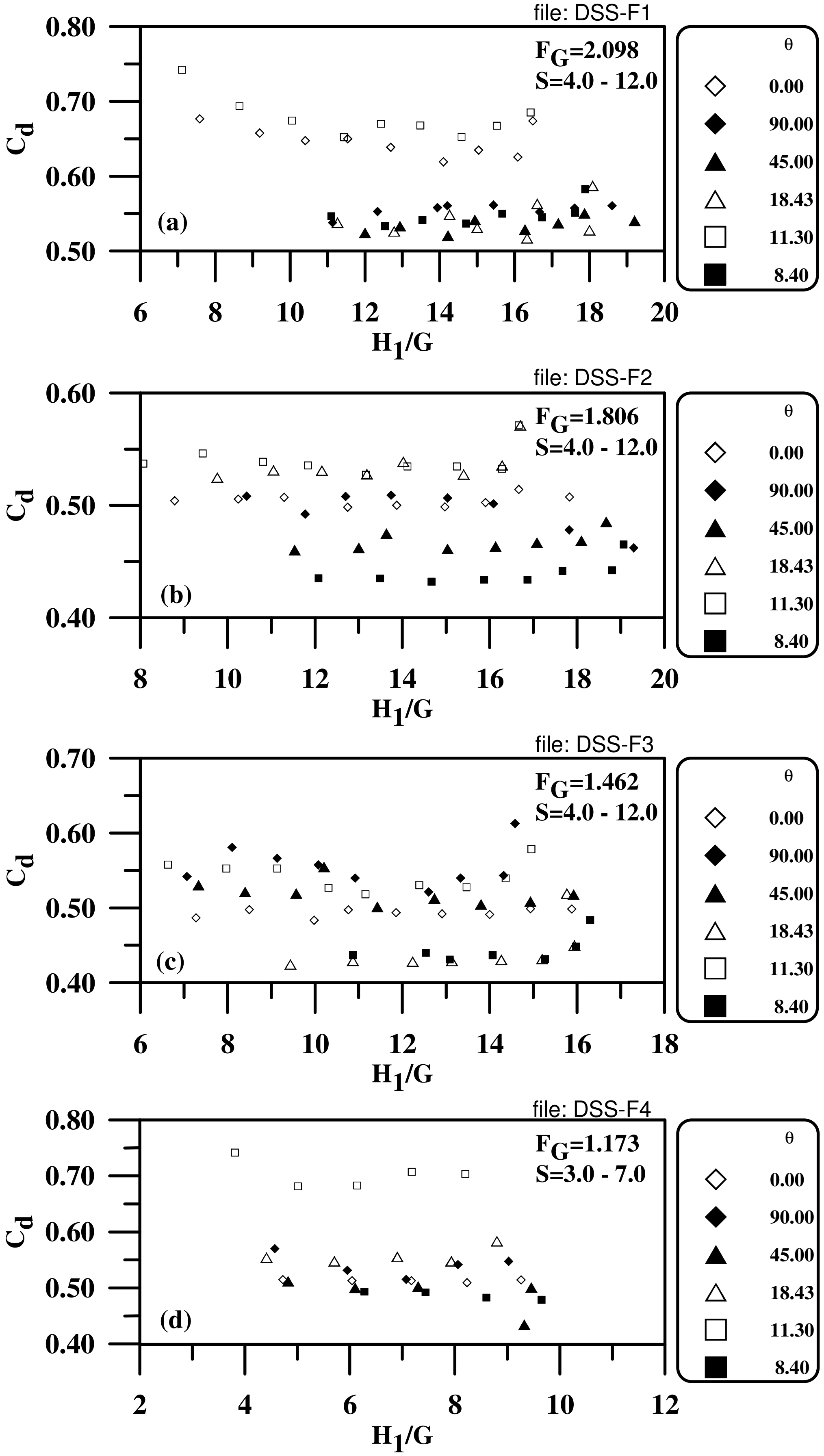


Figure 3. Variations of C_d with H_1/G for supercitical flow

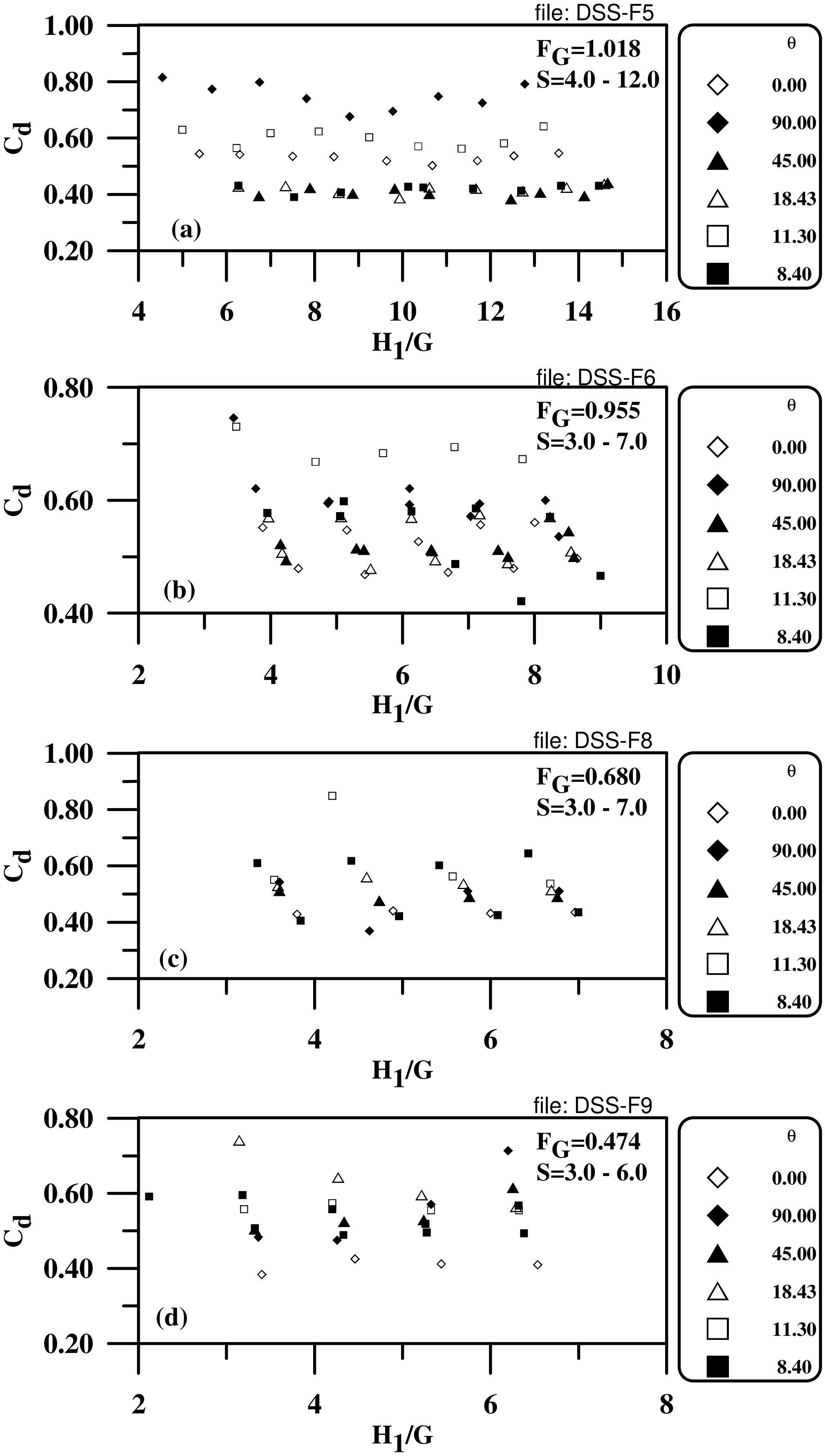


Figure 4. Variations of C_d with H_1/G for (a) critical and (b,c,d) subcitical flow

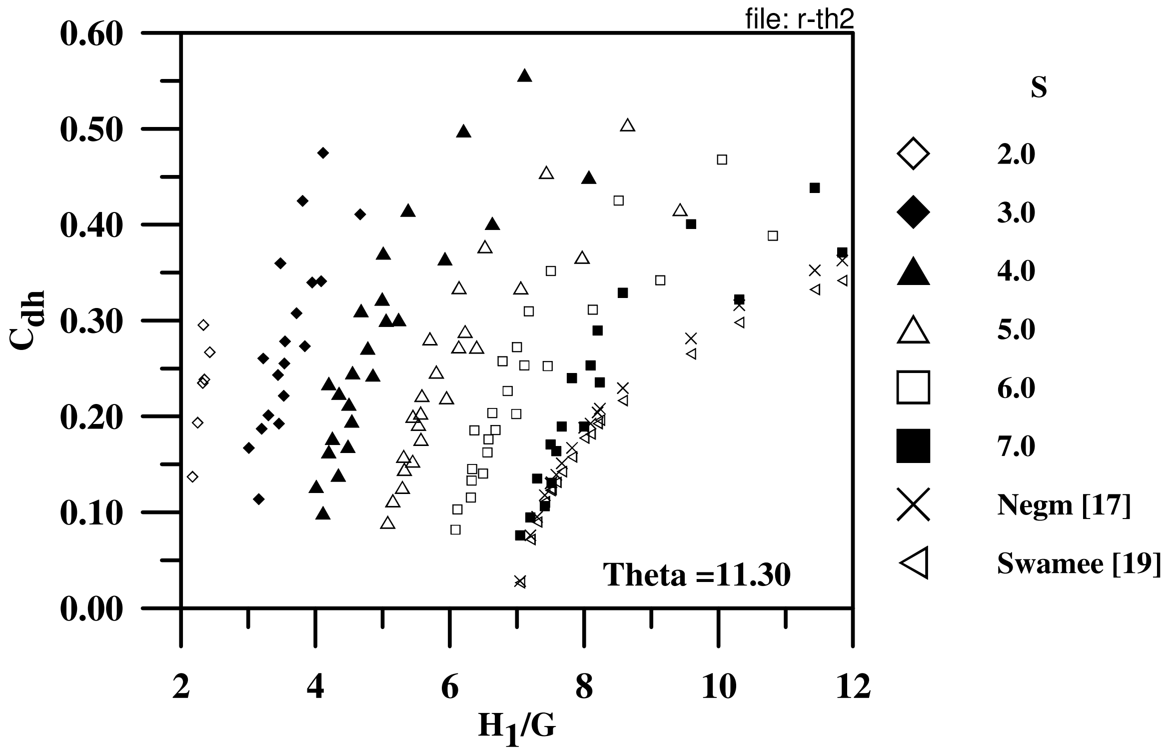


Figure 5. Variations of C_{dh} with H_1/G for different S at θ=11.3

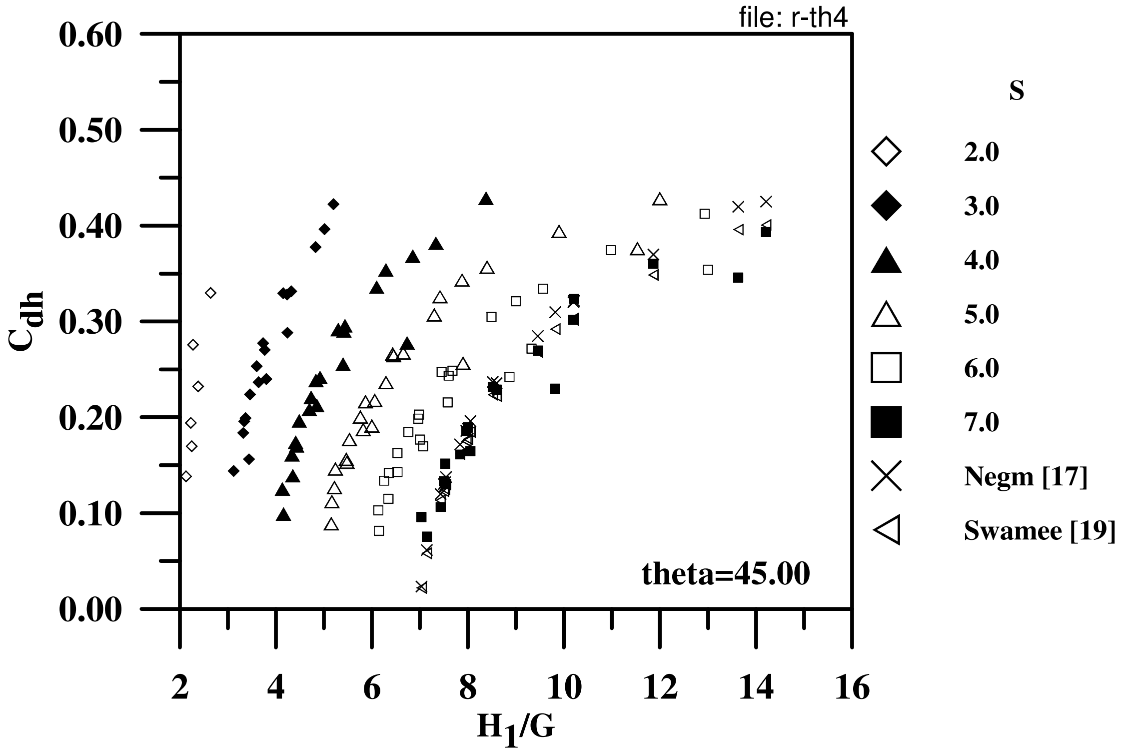


Figure 6. Variations of C_{dh} with H_1/G for different S at θ=45

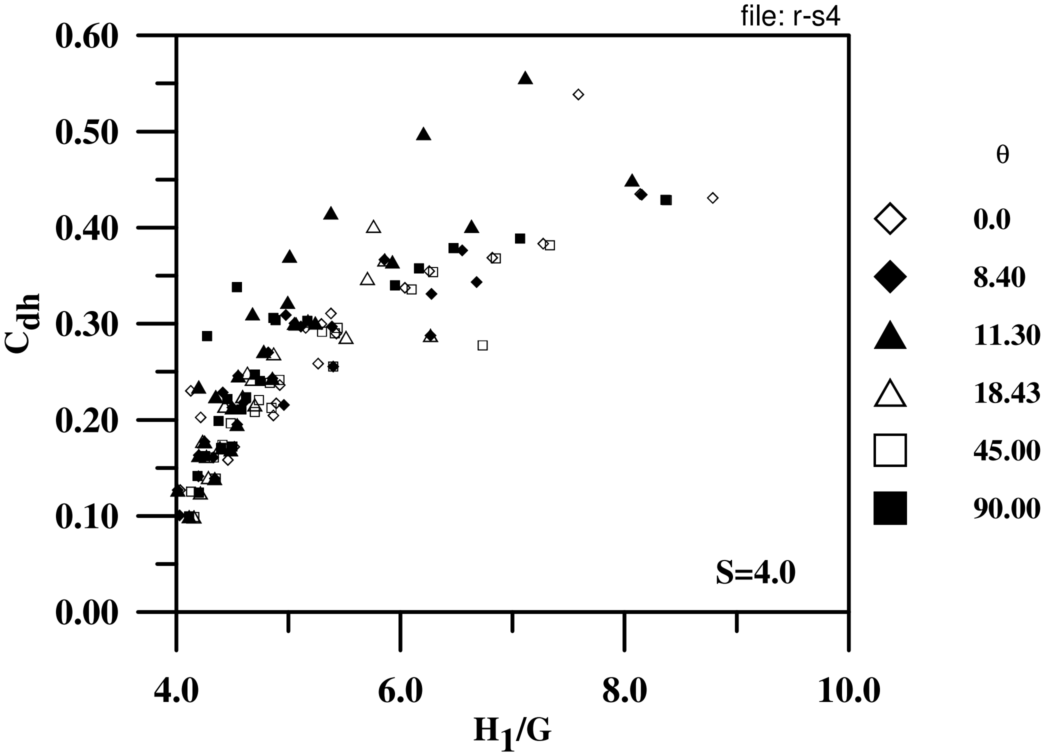


Figure 7. Variations of C_{dh} with H_1/G for different sills at S=4.0

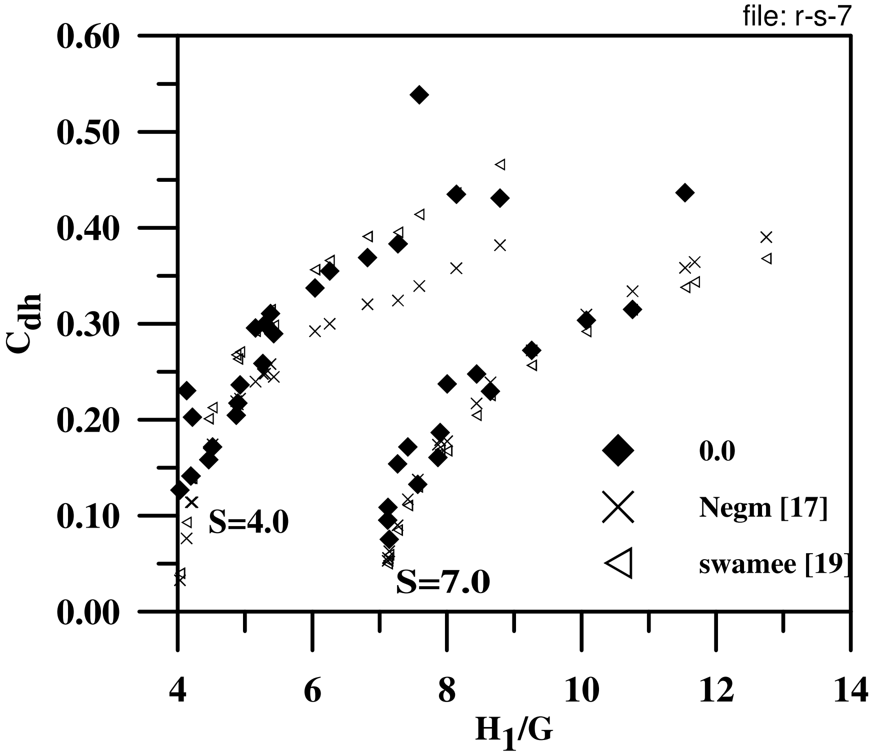


Figure 8. Comparison between present results and other authors results of radial and rectangular stilling basins