Effect of Submergence and Slopes of Polygonal Under-Gate Sill on Discharge Characteristics of Submerged Subcritical Flow

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ABSTRACT: The experimental results of testing under-gate polygonal sills of different slopes were presented. The laboratory tests on each sill were conducted under comparable variable tailwater conditions at the same discharge. Only submerged subcritical flow below the gate was considered. The effects of both slopes (US and DS) of sill and submergence ratio on discharge characteristics below submerged silled sluice gate were discussed. The analysis of the results showed that the data were grouped according to the relative differential head and the under-gate Froude number. The submergence effect could be easily addressed if the results are analyzed in terms of discharge coefficient as computed by Henry (1950). The presence of submergence increased the discharge coefficient of the gate. The results of no sill were compared to those of other authors and fair agreement was found.

Keywords: Hydraulics, free surface flow, gates, sills, discharge coefficient, hydraulic structures.

1. INTRODUCTION

Different types of gates were used in hydraulic structures to control and regulate the flow through structures. The characteristics of flow below sluice gates were discussed by many reserachers, like Henry (1950), Anwar (1964), Rajaratnam & Subramanya (1967), Rajaratnam (1977), Rajaratnam & Subramanya (1977), Talaat (1988), Abdel-Hafiz & Elotla (1989) and Ohtsu & Yasuda (1994). The studies related to flow below gate with were reviewed in the first part of this paper the same authors, and is presented here again for the benefit of EJEST readers.

A sill downstream of sluice gate or a sill located in stilling basins is used to dissipate the energy and to stabilize the flow while the sill under the gate is used commonly to reduce the height of the gates and consequently their weights. Most of the studies regarding the former sill type were reviewed and listed in Alhamed et al. (1996) and in Negm et al. (1995)

According to the Egyptian practice in the design of hydraulic structures, sills may be constructed under sluice gates to meet certain specific design criterion. For example, when the gate height exceeds some particular limit, double or triple leaf gates are recommended. In the cases where construction of double or triple leaf gates is not desirable for economic reasons or when the increase of the height is not big, a sill is constructed under the gate to reduce its height to meet the design criterion of single leaf gate. The use of the under-gate sill affects the flow behavior below and downstream of the gate. Sills may improve or dis-improve the discharge characteristics below the gate. Recent studies on the under-gate sill include, El-Saiad et al. (1991a,b), Negm et al. (1993a, b, c, 1998, 1999) and Negm (1994, 1995, 1998).

Most of the existing investigations concerning under-gate sill dealt with the coefficient of discharge, which were carried out by Ranja Raju and Visavadia (1979), Ranga Raju (1981), Salama (1987), Negm et al. (1993, 1995, 1998), Negm (1998). A list of most of the studies related to under-gate sill can be found in the works by the first author.

On the other hand, El-Saiad et al. (1991a,b), Negm and El-Saiad (1993) and Negm (1994) dealt with submerged flow below sluice gates. Other studies dealt with the effect of the gate or sill configuration on the flow below the gate, USBR (1960), Abdel-Salam et al. (1990) and Negm et al. (1993,1998). Also, regarding the free and submerged flow some studies are available in the literature, Salama (1987) and Negm (1995).

Recently, the flow characteristics for submerged flow below sluice gate with sill of USS of 1:1 and DSS of 1:5 based on laboratory experiments were presented and discussed by Negm et al. (1998). They stated that the discharge coefficient was affected by differential head-gate opening ratio, $\Delta H/G$, upstream head gate opening ratio, H_1/G, sill parameters Z/b, Z/B and the tailwater depth-gate opening ratio, H_t/G (G is the gate opening height; H_1 is the effective upstream water depth $=H-Z$; ΔH is the differential head on the gate (upstream head - downstream head), H_t is the tailwater depth, Z is the height of the sill, b is the top width of the sill and B is the bottom width of the sill). It was found that the rate of change of the discharge coefficient is large for submerged subcritical flow, and mostly constant for supercritical submerged flow. Also, Negm (1998) discussed the effect of the supercritical free flow on the characteristics of free hydraulic jump downstream of a sluice gate with the same sill shape as for submerged flow. Also, effects of different parameters on discharge coefficient of sluice gate provided with such sill were discussed and presented. The effect of regime of flow on discharge characteristics below sluice gate with sill of USS =1:1 and DSS=1:5 was discussed by Negm et al. (1999).

The critical evaluation of the review showed that all the available studies on the under-gate sill investigated had a limited range of under-gate Froude number while the effect of variable tailwater had not investigated yet. Therefore this study comes to cover this shortage in the literature using different sills under wide range of subcritical flow conditions.

2 THEORETICAL BACKGROUND

Figure (1) shows a typical definition sketch for submerged flow below a sluice gate with a sill. Applying the principles of dimensional analysis, the following functional relationship for coefficient of discharge of the submerged silled sluice gate, C_d, could be proved as, Negm et al. (1998):

$$C_d = \psi_1\left(\frac{H_1}{G}, \frac{\Delta H}{G}, F_G, S, \frac{b}{G}, \frac{B}{G}, \frac{Z}{G}, DSS, USS, \phi\right) \quad (1)$$

in which C_{ds} is the discharge coefficient of silled sluice gate; S is the submergence ratio (H_t/G); Ht is the tailwater depth; G is the gate opening; F_G, the Froude number below the gate, $\sqrt{(q^2/gG^3)}$, q is the discharge per unit width; g is the acceleration due to gravity; DSS is the downstream slope of the sill which is sometimes expressed as θ, USS is the upstream slope of the sill and ϕ is a sill shape factor. Equation (1) can be expressed as follows:

$$C_d = \psi_2\left(F_G, \frac{H_1}{G}, S, \frac{\Delta H}{G}, \frac{Z}{B}, \frac{Z}{b}, \frac{Z}{G}, USS, DSS, \phi\right) \quad (2)$$

The discharge coefficient (C_d) of sluice gate with sill for submerged flow is computed using the following equation:

$$C_d = \frac{Q}{GW\sqrt{2g(H_1 - H_2)}} \quad (3)$$

in which W is the width of the flume.

3 EXPERIMENTAL WORK

A glass sided tilting re-circulating flume of 9.0 m long was used to conduct the experiments of the present study. The flume bed was 30.5 cm wide and 30.5 cm deep. Figure (2) shows the flume and the location of test section. The water depths were measured by means of point gauges mounted on instrument carriages. The discharge was measured by means of a pre-calibrated V-notch. The flume had a 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 tailwater was controlled by means of the tail gate, which is located at the downstream end of the flume. The effect of sill height was studied by Negm (1994, 1995). El-Saiad (1991) proved that the optimal b/Z ratio was 1. For these reasons the sill height as well as the top width of sill were kept constant in the present study as b=Z=5 cm. Three sets of under-gate sills were tested. Each sill of set No. 1 had a vertical upstream face and sloping downstream face. Four slopes were tested, namely, 90o, 45o, 18.43o and 11.31. Each sill of the second set had a sloping upstream face with 45o and sloping downstream face as in set No. 1. Sills of the third set had vertical downstream face with sloping upstream face with slopes of 90°, 45°, 18.43° and 11.31°. Table (1) presents the dimensions of the tested sills of the three sets. Figure All sills were tested under different discharge and variable tailwater conditions. Sills were made from plastic-coated wood. The gate was fixed at the centerline of the top width of the under-gate sill. Tests cover the following ranges of flow and sill parameters: $0.522 \le F_G \le 1.44$, $0.25 \le \Delta H/G \le 2.75$, $2.5 \le H_1/G \le 7.0$, $3 \le S \le 7$ $11.30 \le \theta_U \le 90$, and $11.30 \le \theta_d \le 90$. The measurements of submerged flow include the water depths upstream and downstream the sluice gate as well as the tailwater depth. Different tailwater depths at constant discharge were recorded. Table (1) shows the shapes and dimensions of tested models.

4. EXPERIMENTAL RESULTS OF NO SILL CASE

The data collected for gate without sill was used to calculate the discharge coefficient according to the equation used by Henry (1950).

$$C_{dn} = \frac{Q}{GW\sqrt{2g\,H_1}} \qquad (4)$$

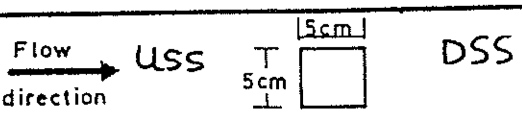
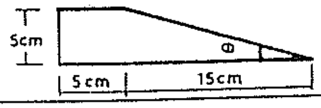
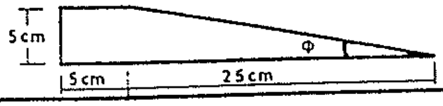
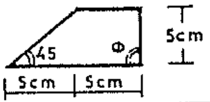
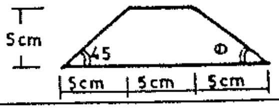
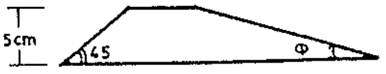
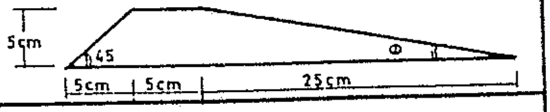
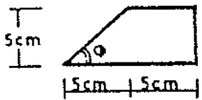
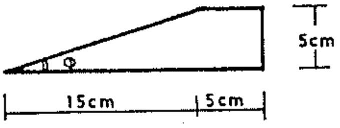
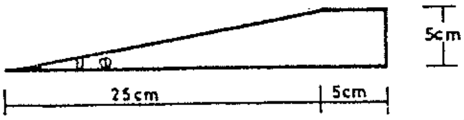
The calculated discharge coefficients were compared with Henry curves as shown in Fig. (2) for selected submergence ratios of 4,5,6, and 7. Also shown on the figure the results due to Alhamid et al. (2001) for supercritical flow. Figure (2) showed fair agreement between present and those of Henry's (1950). Also, the present results of subcritical and critical submerged flows matched well with those of Alhamid et al. (2001) for supercritical flow.

5. RESULTS AND DISCUSSIONS

5.1 Variations of C_d with $\Delta H/G$, F_G and sill slopes

The calculated discharge coefficient, C_d, according to Eq. (3) for the three sets were plotted in Figures (3), (4) and (5) versus the differential head ratio, $\Delta H/G$, for different slopes of the sills and constant values of F_G. These figures indicated that under-gate sill played an important role on flow characteristics. It was clear that some sills increased the discharge coefficient and others decreased the discharge coefficient compared to the gate without sill. For set No. 1, the sill with DSS angle of 45° produced C_d values which were higher than other cases for subcritical flow while the sill with DSS angle of 90° was optimal for the supercritical flow, Alhamid et al. (2000). For set No. 2, the sill with DSS angle of 45° followed by that of DSS angle of 11.30° produced the highest coefficient of discharge. For subcritical flow the DSS angle of 45° was effective while that of 11.30° was more effective when the flow was critical or supercritical. The third set indicated the sill with both vertical upstream and downstream faces (USS angle of 90° and DSS angle of 90°) gave the highest values of C_d. An important feature of Figures (3) through (5), is that all C_d values wee grouped according to F_G regardless of other flow or sill parameter which indicated the significant effect of the differential head ratio on the discharge coefficient of the

Table 1 Shape and dimension of tested sills.

Set No.	Sill Height Z (cm)	USS θ	DSS θ	Sahpe and Dimensions
1	5	90°	90°	
1	5	90°	45°	
1	5	90°	18.43°	
1	5	90°	11.31°	
2	5	45°	90°	
2	5	45°	45°	
2	5	45°	18.43°	
2	5	45°	11.31°	
3	5	90°	90°	
3	5	45°	90°	
3	5	18.43°	90°	
3	5	11.31°	90°	

submerged flow. Any of the three figures could be described by the following equation with deviation of less than 0.5%:

$$C_d = \frac{0.707 F_G}{\sqrt{\frac{\Delta H}{G}}} \qquad (5)$$

5.2 Variations of C_d with H_1/G and other parameters

Figure (6) shows the variation of C_d with H_1/G at constant F_G and different slopes of sill. Also, Figure (7) indicated the variation of C_d with H_1/G at constant S of S=6 (set no. 1), S=4 (set no.2) and S=5 (set no 3) and different slopes of sill. Both figures (6) and (7) showed that the discharge coefficient was also affected by the submergence ratio rather than the slope of the sill but the figures proved that the H_1/G and S or F_G could not explain the variations of C_d as high scatter was observed.

5.3 Effect of Submergence

The effect of submergence was better analyzed in terms of C_{dh} of Eq.(4). Figures 8 (a,b,c,d) present the variation of C_{dh} with H_1/G for different values of S, at constant slope of the sill for set no.1. Similarly, Figures (9) and (10) showed the same for sets no.2, and no.3 respectively. The figures showed a similar trend of the variation as those of Henry diagram. The discharge coefficient, C_{dh}, was increased by increasing H_1/G at constant both S and the sill slope. The figures indicated that C_{dh} was increased by decreasing the submergence at constant H_1/G. In fact, higher submergence created more upstream water depth as tailwater depth was increased at constant gate opening and same level of discharge as a result of energy transfer from kinetic energy to potential energy.

5.4 Effect of DSS of Sill

The values of C_{dh} at constant S and variable slopes of the sill were presented in Figure (11) versus the values of H_1/G for set no. 1 and in Figure (12) for set no.2. Clearly, the slope of the sill had remarkable effect on C_{dh} at the same S and H_1/G. The trend of the data due to sills were similar to that of no sill. From these figures, one could state that the effect of the slope of the sill was affected by the submergence ratio. However, for the set no.1, the sill with DSS angle of 45° may be considered as optimal and the one that has DSS angle of 45° could be considered as the optimal one for the second set. Although the sill with DSS angle of 11.30° showed an increase in C_{dh} at S=6,4.

5.5 Effect of USS of Sill

Regarding the sills with constant DSS and variable DSS of the sill (set no.3), the results were presented at constant S and variable DSS in Figure (13). From which it could be stated general trend is similar to that of set no.1 and set no.2. However, the sills with DSS angle of 90° and 45° may be considered as equally attracted as both of them were produced nearly equal coefficient of discharges.

6. CONCLUSIONS

Experimental results of mainly subcritical submerged flow below gate with polygonal sill was presented. The sill had a constant height and different slopes of the sills. A total of 10 sills were tested with the following experimental limitations: $0.522 \leq F_G \leq 1.44$, $0.25 \leq \Delta H/G \leq 2.75$, $2.5 \leq H_l/G \leq 7.0$, $3 \leq S \leq 7$ $11.30 \leq \theta_u \leq 90$, and $11.30 \leq \theta_d \leq 90$. The analysis was carried out based on Eqs.(3) and (4). The analysis and discussions of the experimental data of the present study recommended the following conclusions:

1- The discharge coefficients for submerged flow below gate with or without sill were correlated well with the differential head ratio and the data form a family of curves with under-gate Froude number as a third parameter. An equation was presented to describe such curves with high accuracy.
2- Both submergence ratio and the slope of the sill played an important role on the variations of the discharge coefficients.
3- The effect of the slope of the sill on the discharge coefficients was affected with by the state of flow. The sill that may be considered as an optimal for subcritical flow may not be for supercritical flow.
4- Assuming less construction costs were desired, the sill with vertical both upstream and downstream faces may be adopted as the optimal one as the discharge coefficients for this sill were close to those of other sills. Also, for less separation downstream from the sill, the sill with vertical upstream slope and DSS angle of 45° is optimal and economic compared to other sills. If sediment was expected US from the sill, the sill with USS of 45° and with DSS of 11.3° would perform much better.

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NOTATIONS

b	top width of sill.
B	Bottom width of sill.
C_{ds}	the coefficient of discharge of silled submerged sluice gate.
DSS	downstream slope of sill.

F_G	Froude number under gate.
G	gate opening height above sill level.
g	acceleration due to gravity.
H	total upstream water depth.
H_1	effective upstream water depth, H-Z.
ΔH	effective head in the submerged flow case (upstream head - downstream head).
Q	discharge passing through the flume.
q	discharge per unit width passing through the flume.
USS	upstream slope of sill.
W	width of the flume.
h_t	tail water depth.
Z	height of sill.
θ_D	the angle of the DSS of the sill.
θ_U	the angle of the USS of the sill.
ϕ	sill shape factor.

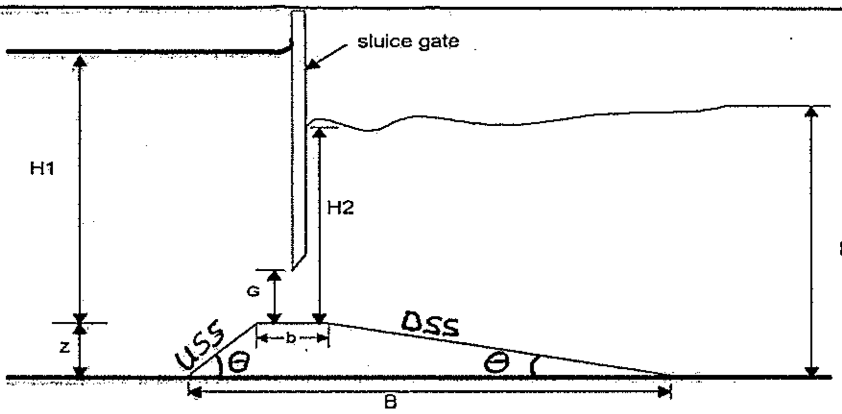


Fig. (1) Definition sketch for submerged flow, below sluice gate with a sill.

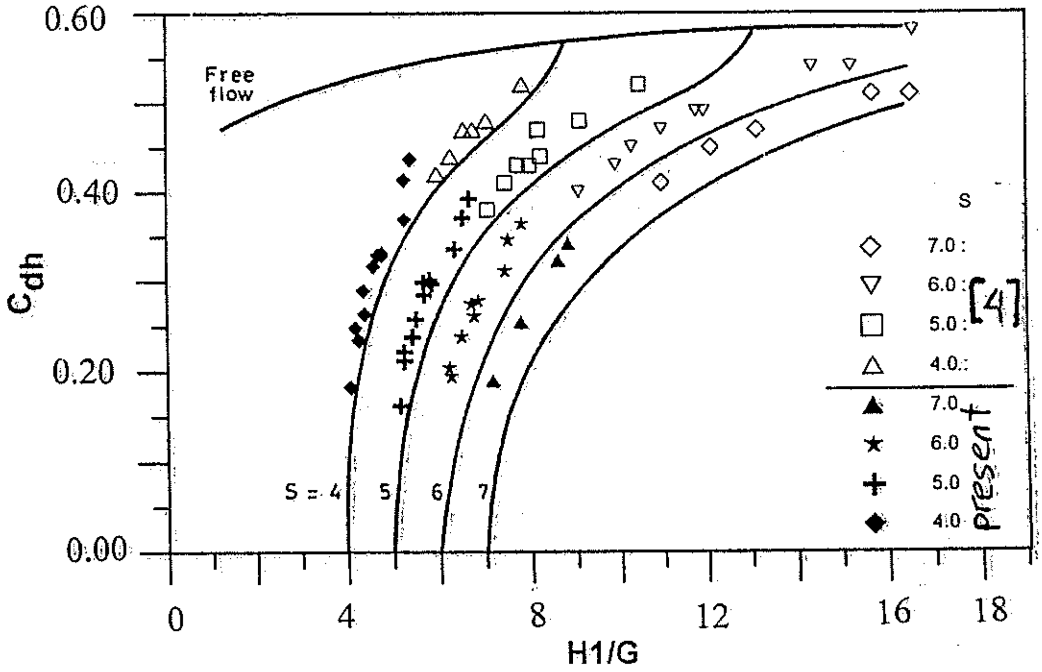


Figure 2. Comparison between present results (Eq.4) for subcritical flow, Henry curves [8] and Alhamid et al. [4] for supercritical flow, for gate without sill (no sill cases).

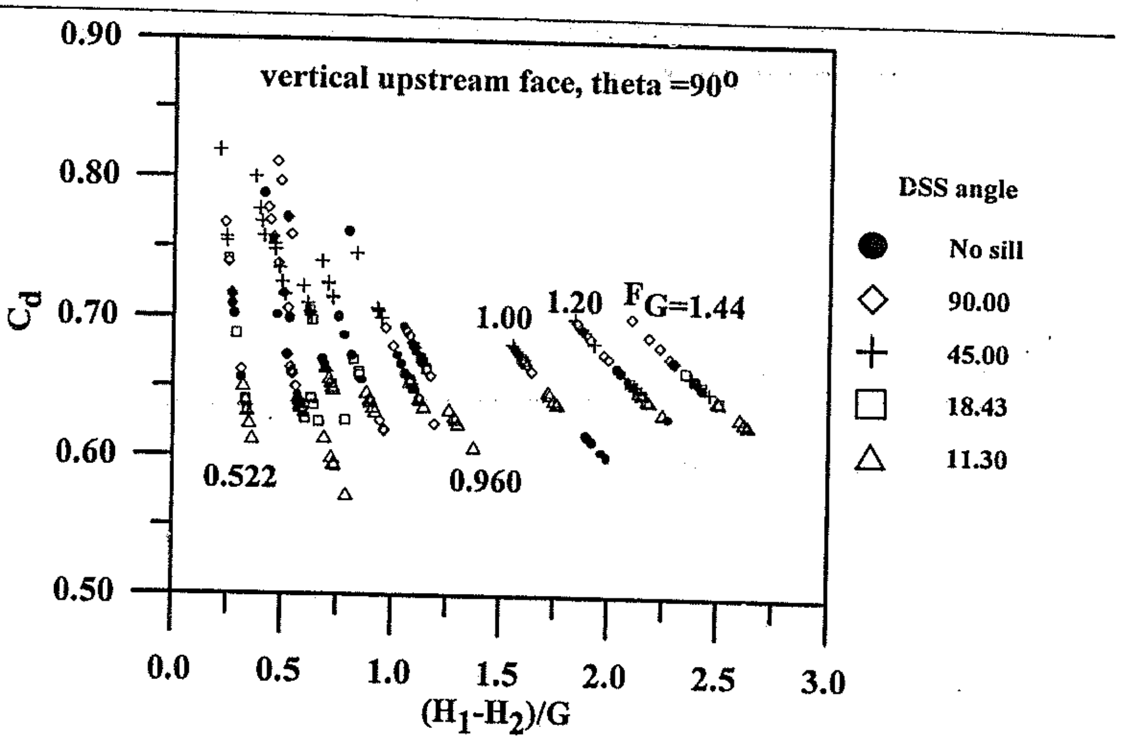


Figure 3. Variation of C_d with $(H_1-H_2)/G$ for sills of set No. 1 (vertical upstream face and varying downstream slopes)

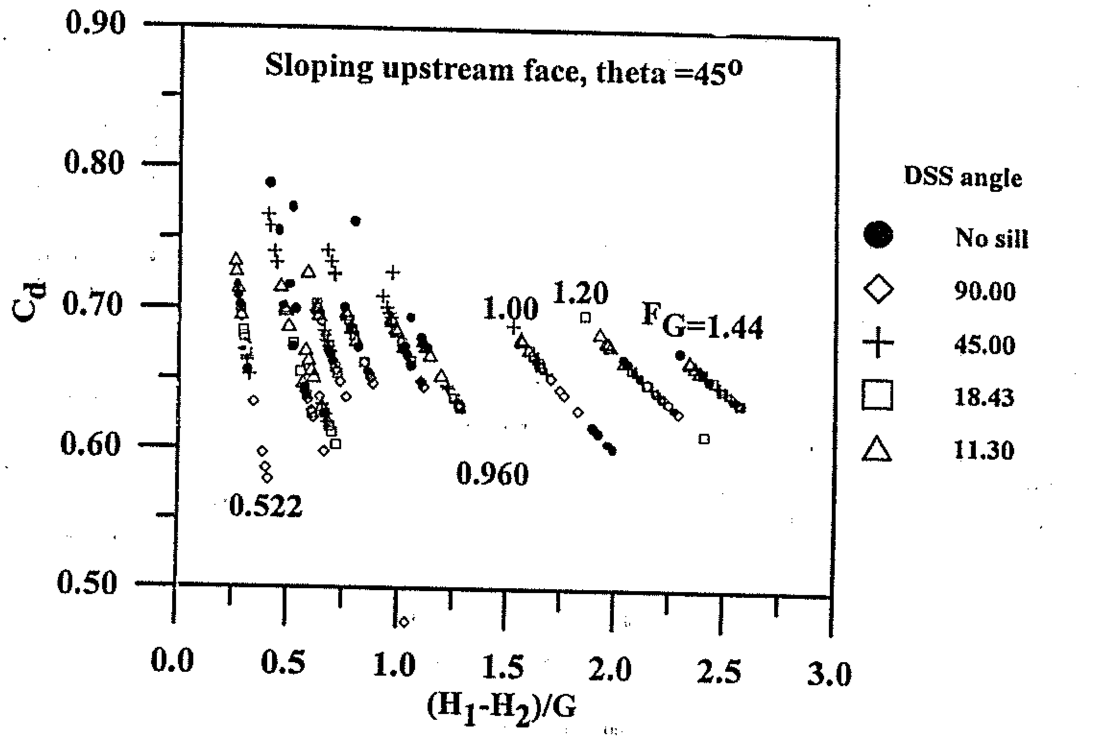


Figure 4. Variation of C_d with $(H_1-H_2)/G$ for sills of set No. 2 (sloping upstream face and varying downstream slopes)

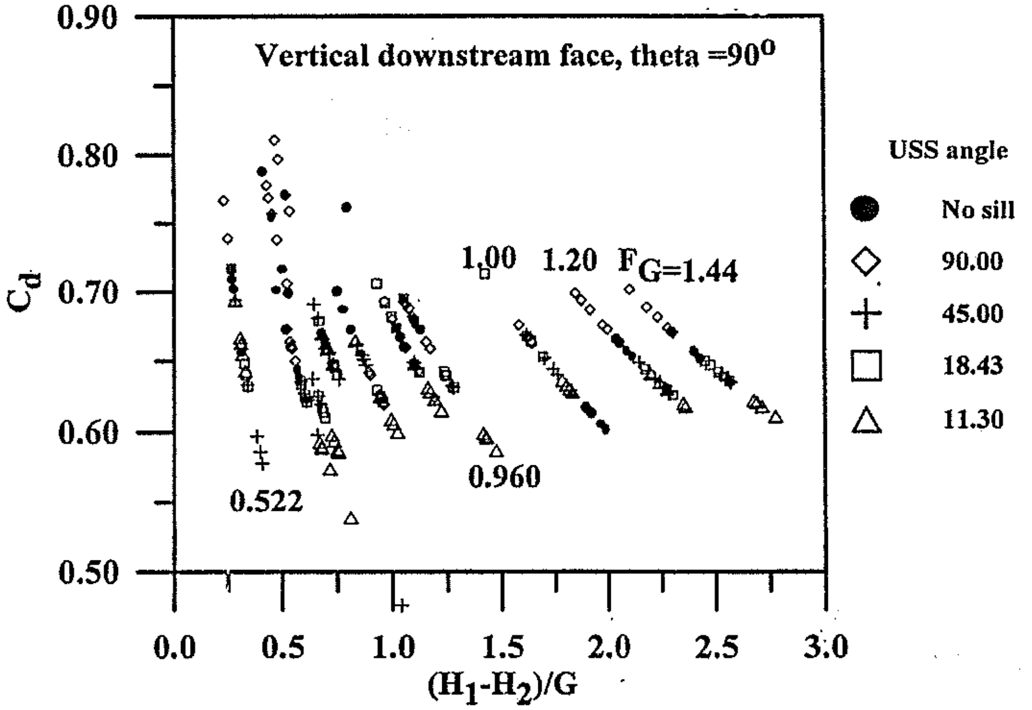


Figure 5. Variation of C_d with $(H_1-H_2)/G$ for sills of set No. 3 (vertical downstream face and varying upstream slopes)

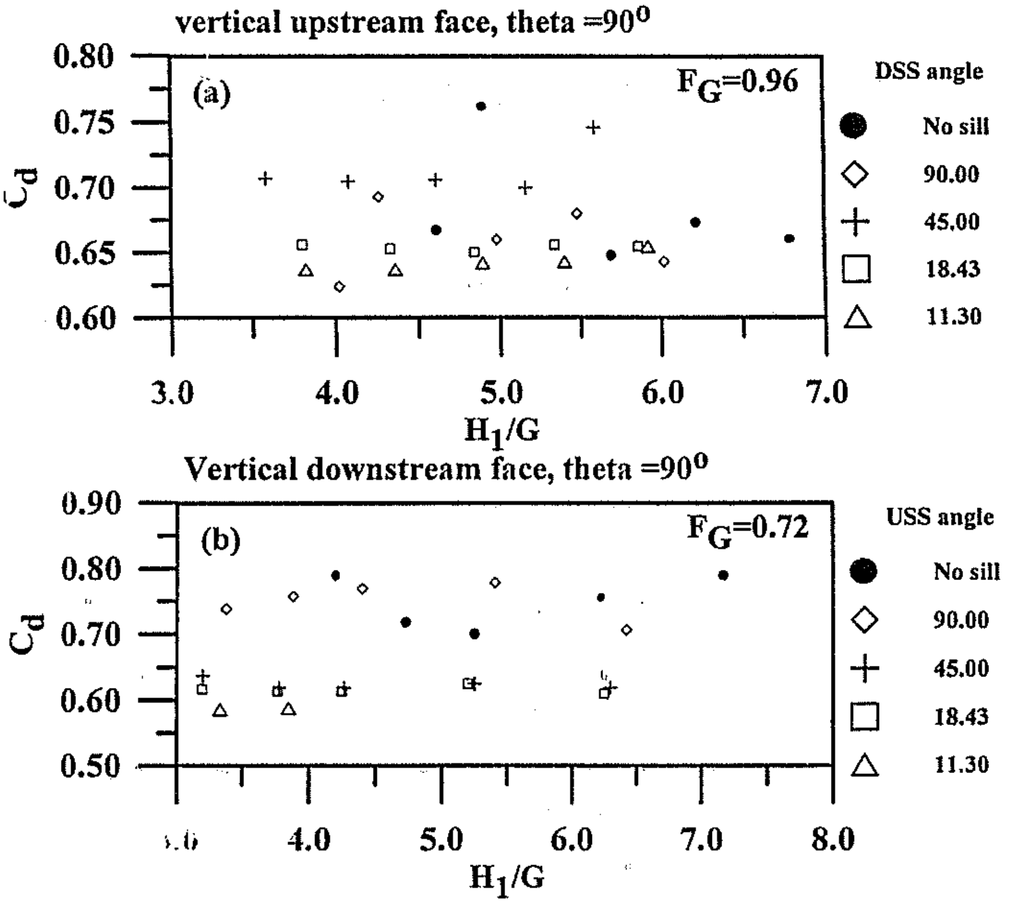


Figure 6. Typical variations of C_d with H_1/G at constant F_G and Varying slopes of sill for (a) set No. 1 at F_g=0.96 and (b) set No. 3 at F_G=0.72

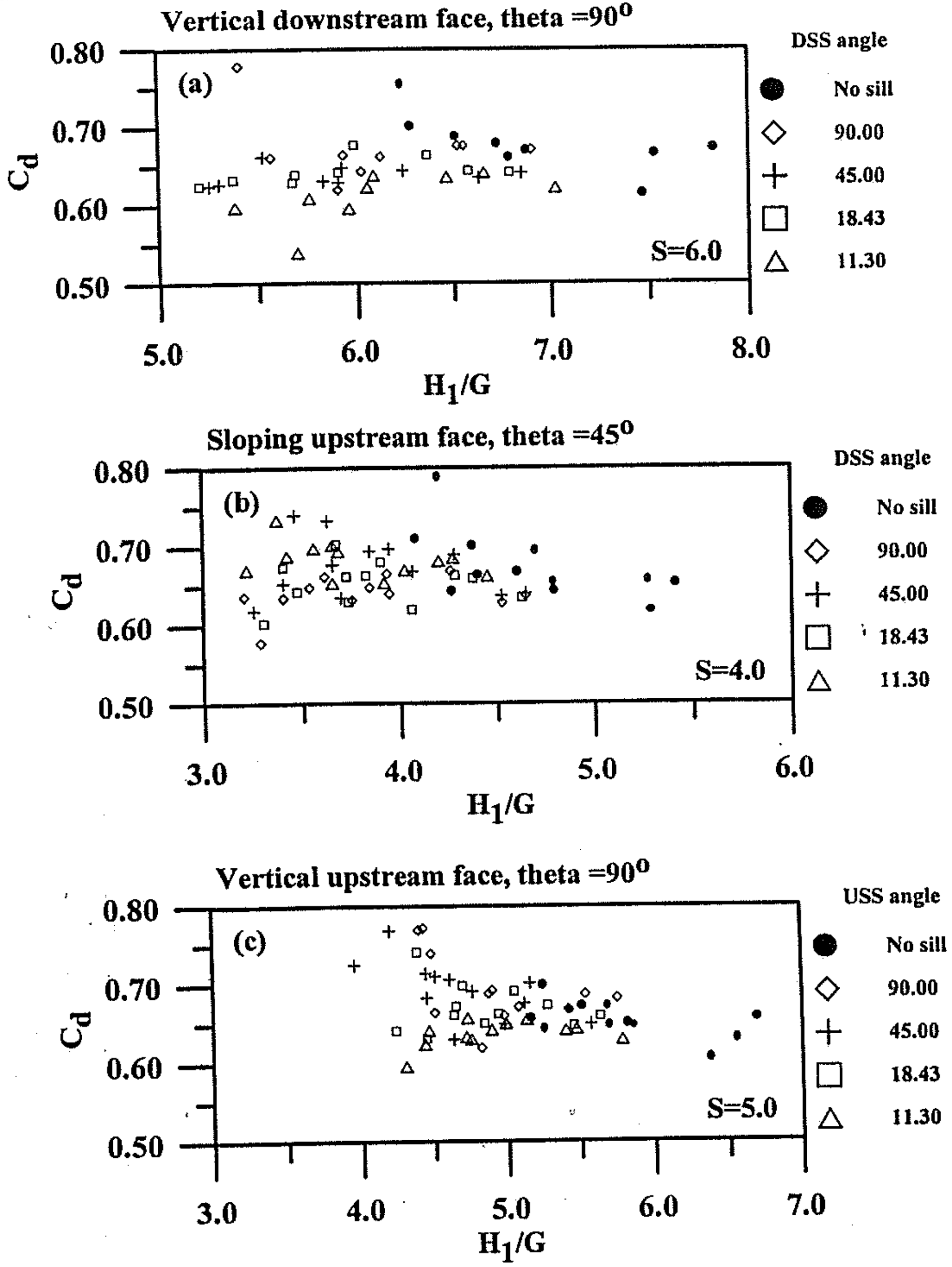


Figure 7. Typical variation of Cd with H1/G at constant S and Variable slopes of sills for (a) set No. 1 at S=6.0, (b) set No 2 at S=5.0, (c) set No. 3 at S=4.0.

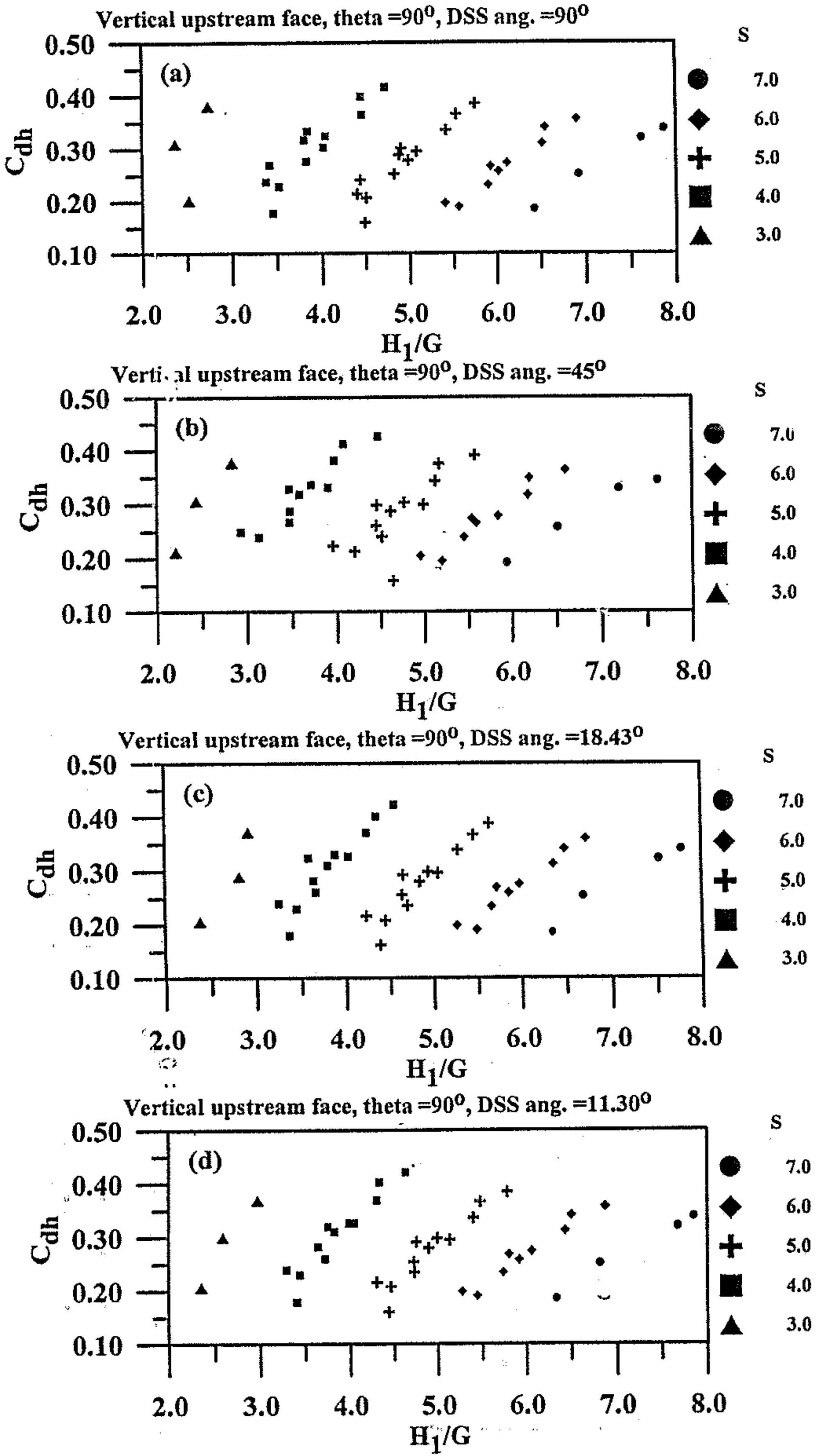
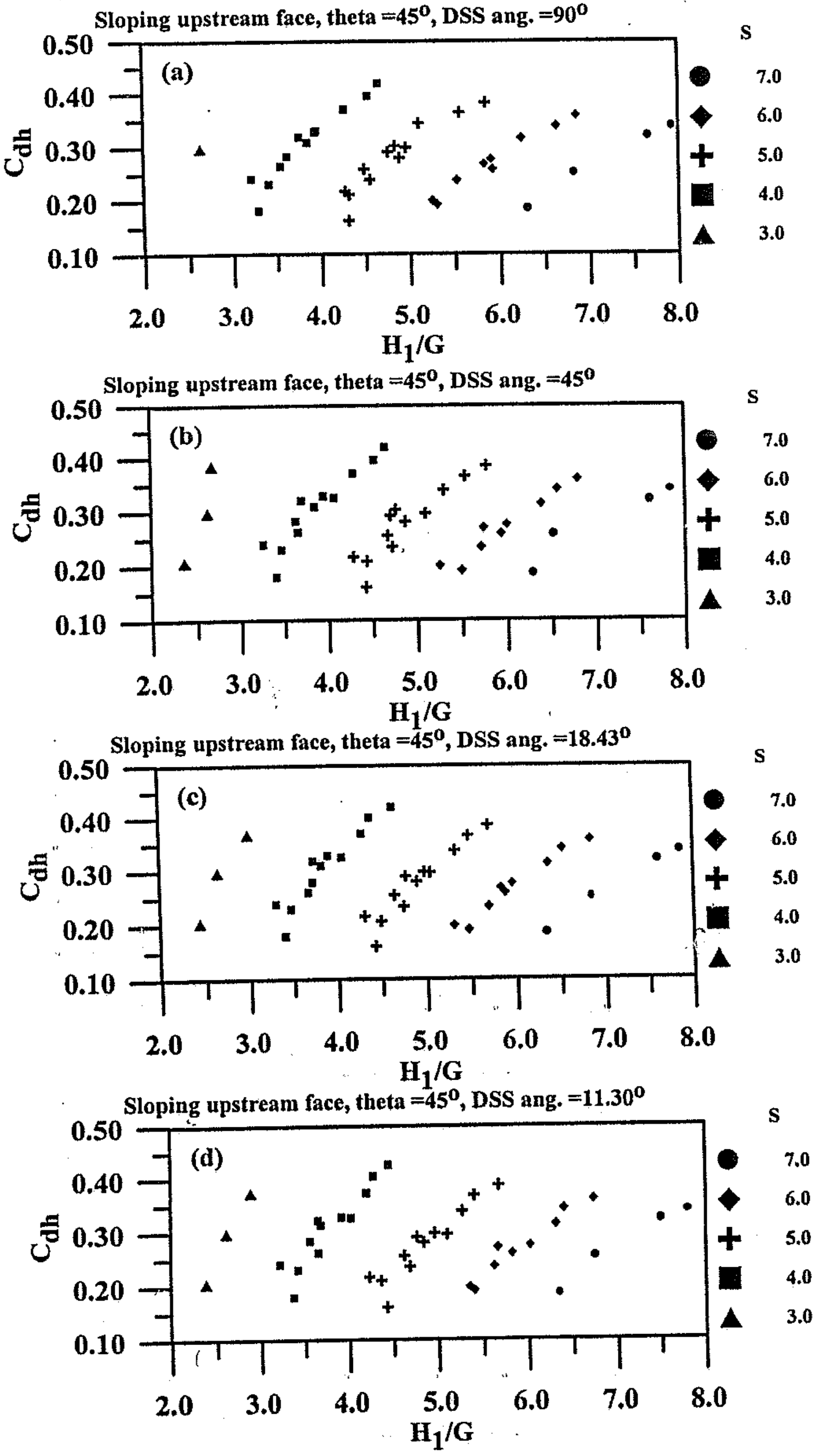


Figure 8. Effect of submergence on discharge coefficient, C_{dh}, for set No. 1


Sloping upstream face, theta =45°, DSS ang. =90°

Sloping upstream face, theta =45°, DSS ang. =45°

Sloping upstream face, theta =45°, DSS ang. =18.43°

Sloping upstream face, theta =45°, DSS ang. =11.30°

Figure 9. Effect of submergence on discharge coefficient, C_{dh}, for set No. 2

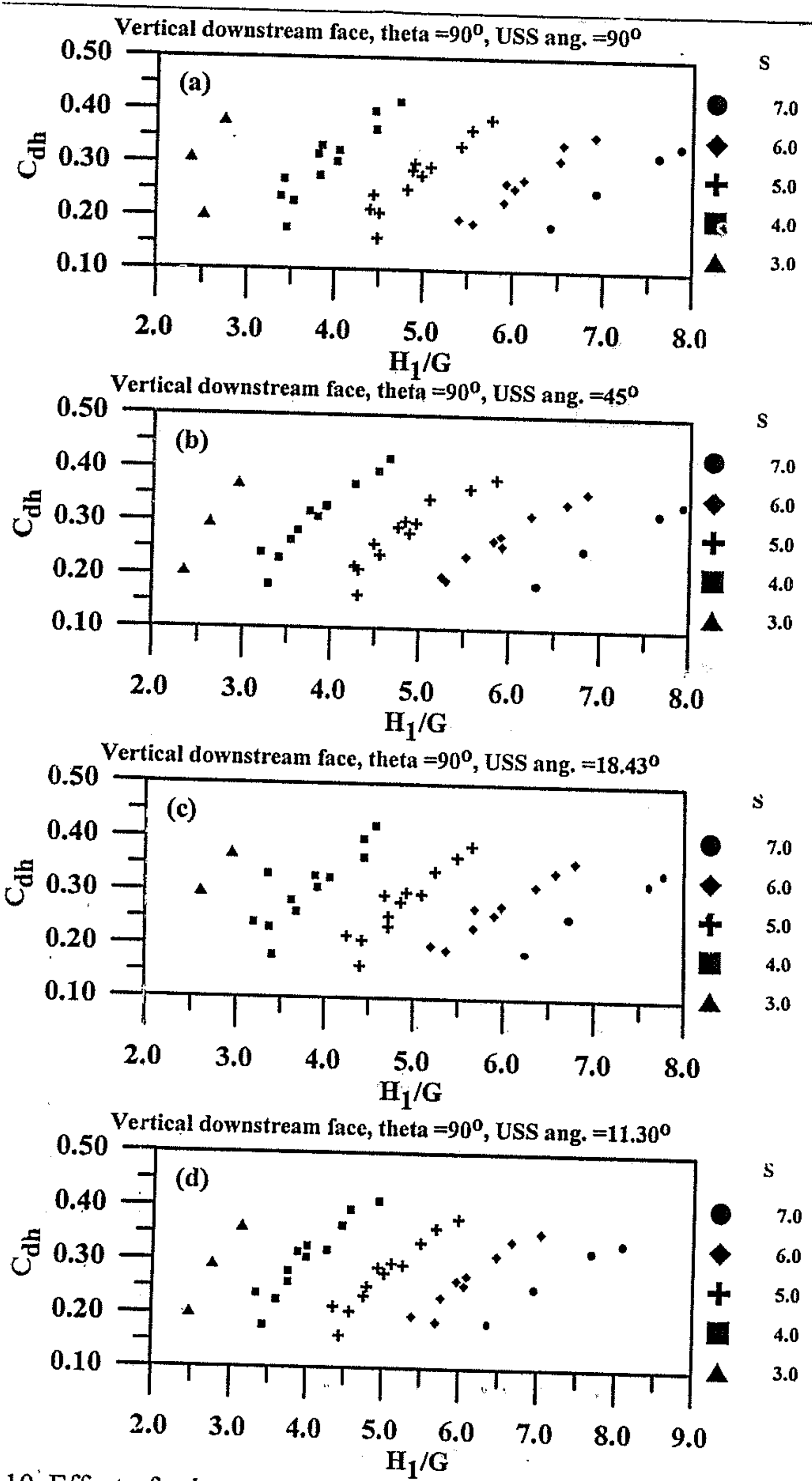


Figure 10. Effect of submergence on discharge coefficient, C_{dh}, for set No. 3

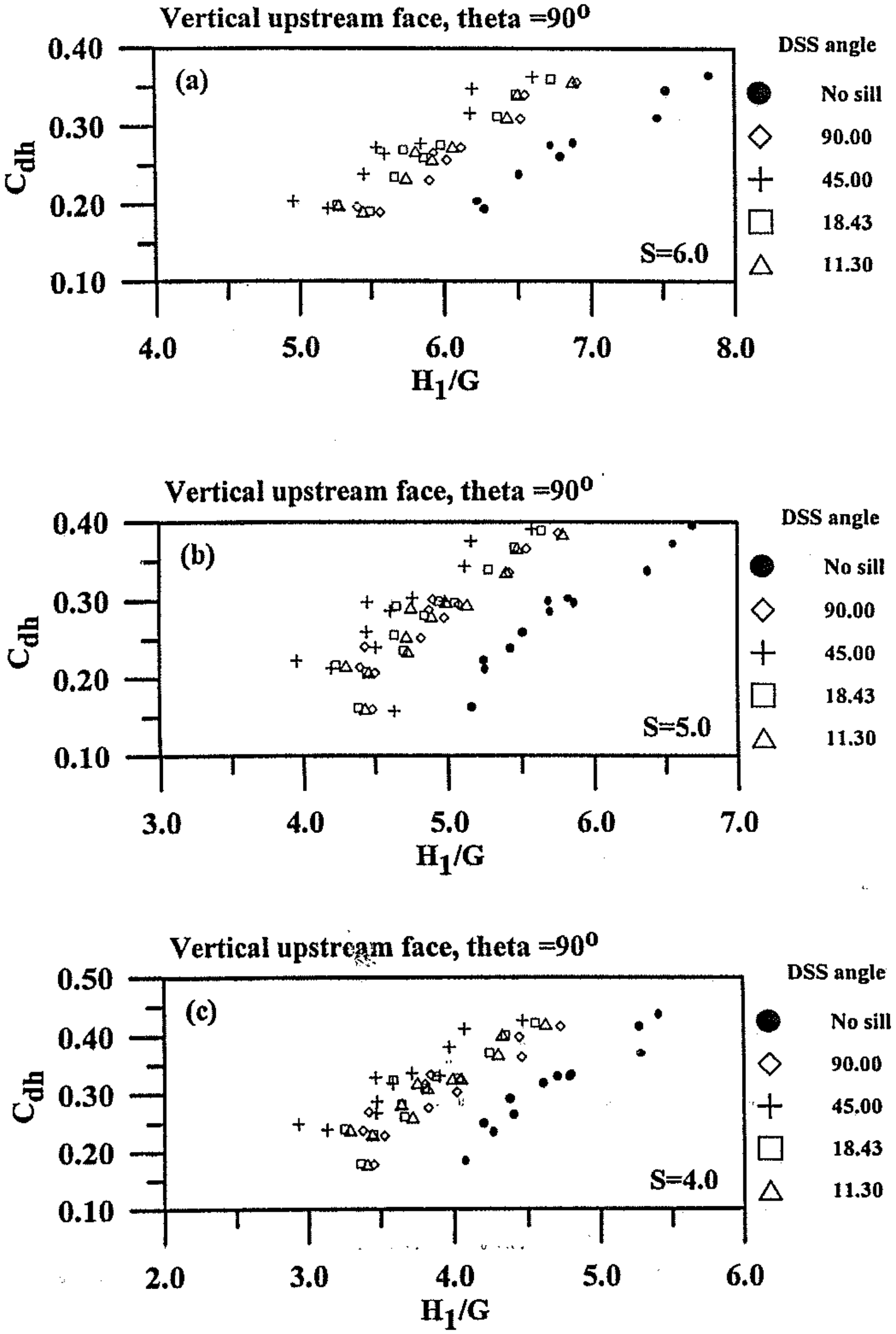


Figure 11. Effect of DSS of sill at constant S and fixed USS of sill for set No. 1

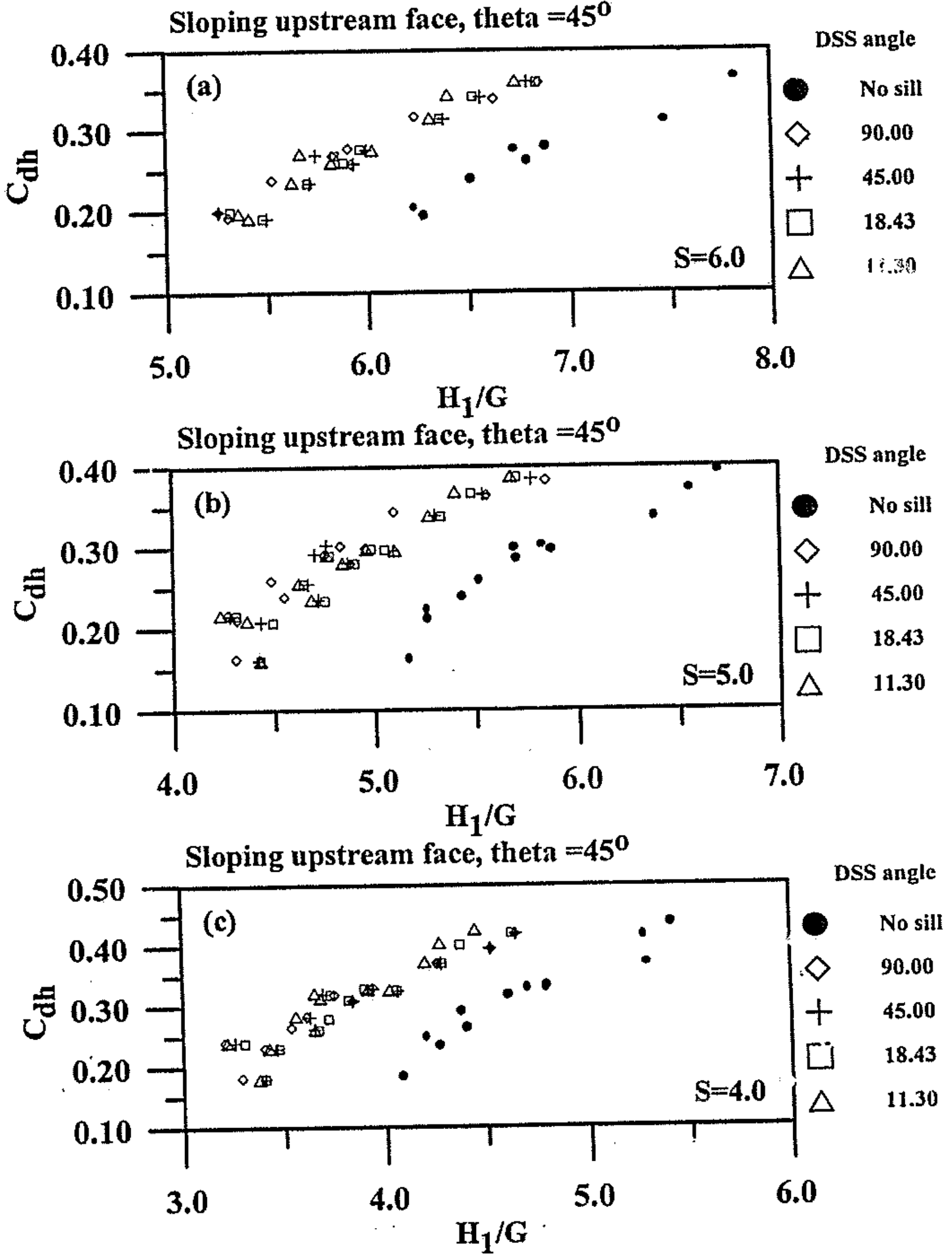


Figure 12. Effect of DSS of sill at constant S and fixed USS of sill for set No. 2

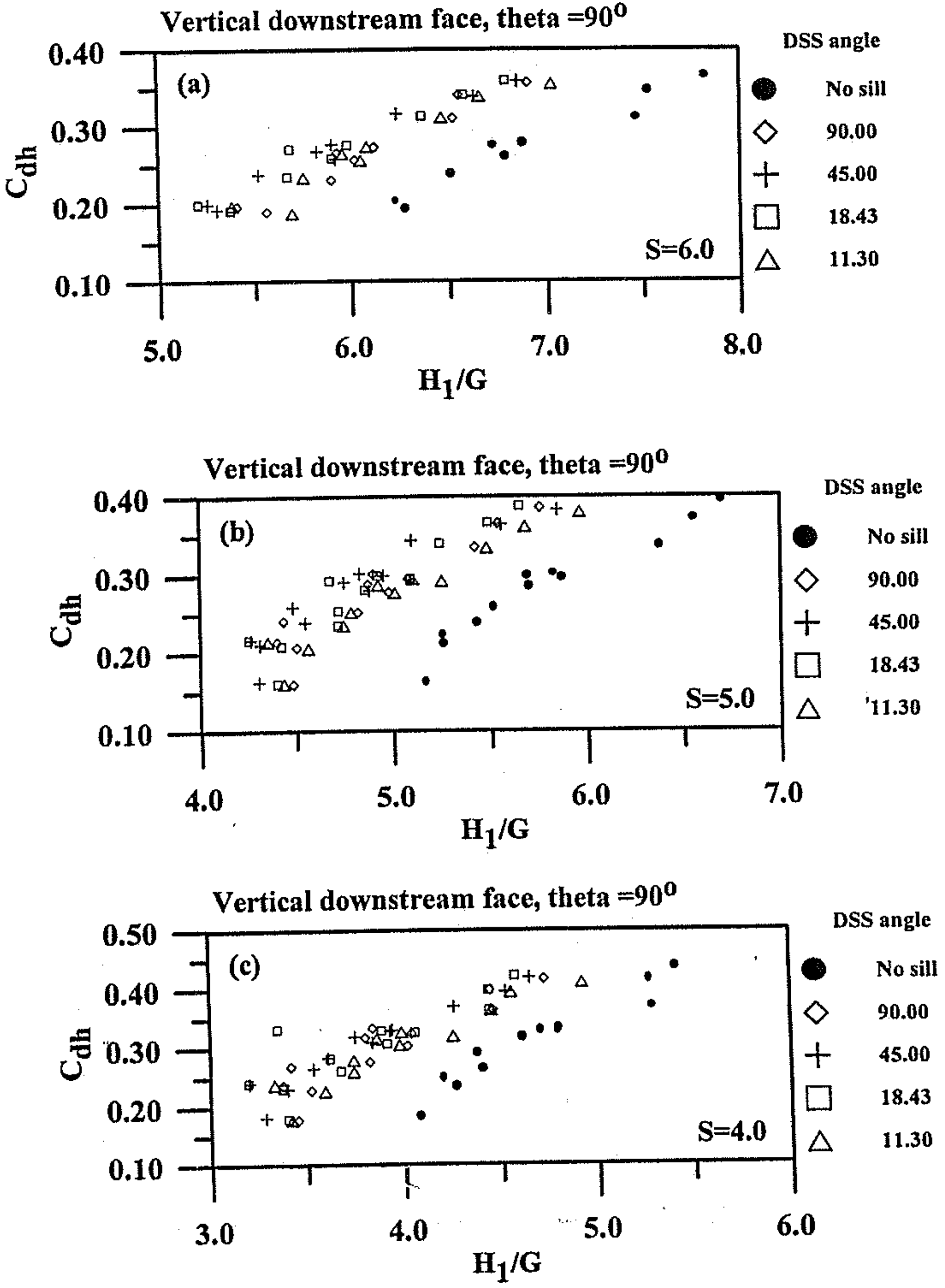


Figure 13. Effect of USS of sill at constant S and fixed DSS of sill for set No. 3, (a) S=6.0, (b) S=5.0 and (c) S=4.0

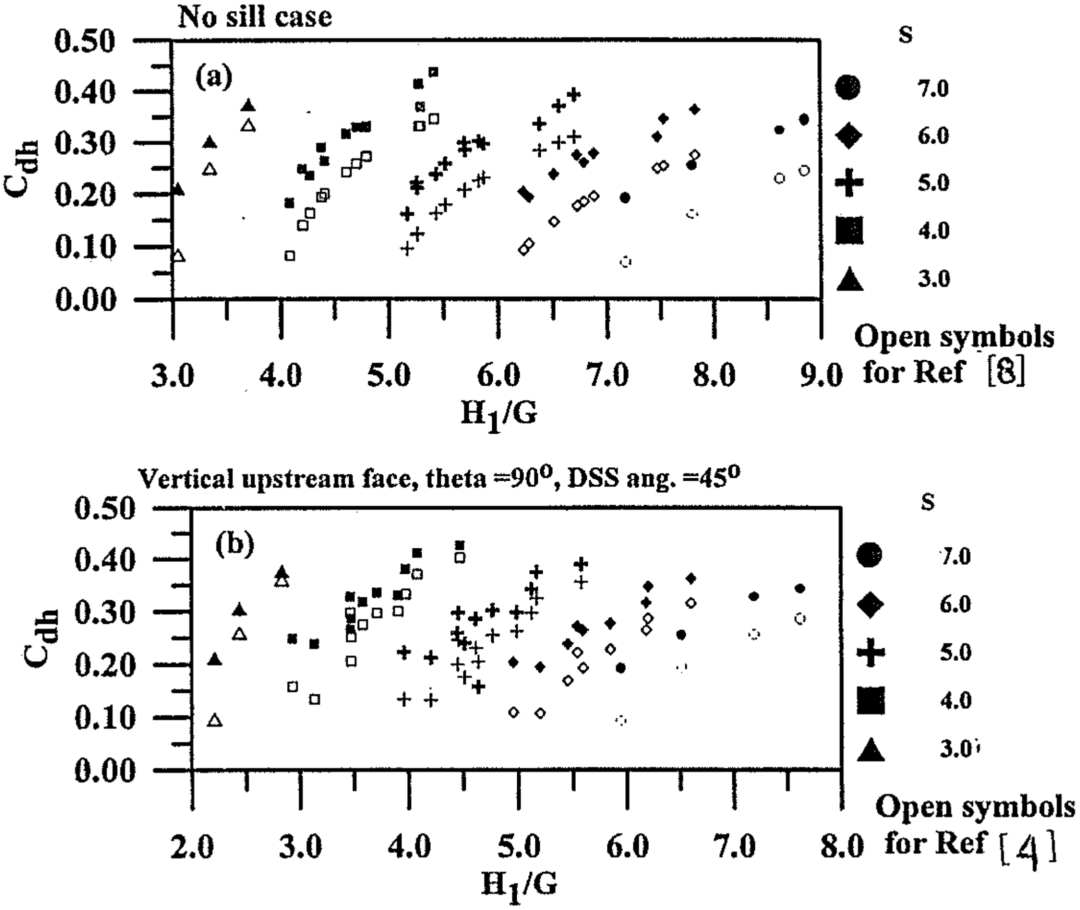


Figure 14. Comparison between results of present study and other authors results, (a) no sill case and (b) for gate with sill of vertical upstream face and 1:1 downstream face, at varying submergence ratios.