Flow Under a Submerged Gate With a Circular- Crested Sill

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Abstract

The under gates sills are commonly used in irrigation structures for economical reasons. The aim of this research is to investigate the effect of the presence of circular-crested sills with different radii under submerged vertical sluice gates on the discharge coefficients, in case of supercritical flow condition.

For this purpose a series of lab experiments were conducted. The analysis of the results showed that for circular-crested sills the main factor that affects the discharge coefficient is B/Z (B= bottom width of the sill, Z= sill height). So, the circular-crested sill has a bigger discharge coefficient than the flat top sill only if B/Z of the circular-crested sill is smaller than that of the flat top one. A design chart was developed to calculate the discharge coefficient of circular-crested silled gates. Also, the results of the flat top sill case were compared to other authors' results and there were good agreement between them.

***Key Words*:** circular- crested sill, discharge coefficient, submerged flow, vertical gate

1. INTRODUCTION

The under gate sill is commonly used in irrigation structures to reduce the gate height and consequently its weight, so the required lifting force is minimized. Consequently this reduces the gate cost. Sills may improve or disimprove the flow characteristics below and downstream the gate depending on the sill geometry.

Many investigators dealt with the effect of sills on the flow characteristics. Some of these studies dealt with the free flow (e.g. Abdelaal1990; Negm et al. 1995&1993b; Ranja Raju et al.1979; Ranja Raju 1981; Saleh et al.1996). Negm et al. (1993.a) investigated the effect of the sill crest shape on the length of the free hydraulic jump and on the discharge coefficient C_d in the case of supercritical free flow conditions. Salem (1990) investigated the effect of the flat top sill and the curved top one located under radial gate with different heights under different flow conditions. It was found that the curved top sill increased the C_d by about 12% more than that caused by the flat top one when used with radial gate. Saad (2007) investigated the effect of circular-crested sill shapes under sluice gate on supercritical free flow characteristics**.** It was found that, the factor that affects the C_d value is the geometric shape of the sill, and there is no effect of the sill curvature on the characteristics of the hydraulic jump.

Other studies dealt with the submerged flow (El-Saiad 1990; El-Saiad et al.1991a; El-Saiad et al.1991b; Negm 1995&1998; Negm et al.2001; Salama 1987). Salama (1987) tested three models of sills with different downstream slopes and vertical upstream face. He found that the C_d under gate is increased by constructing a sill and the discharge increases by a ratio of 24%. Also, he concluded that for downstream sill slope of 3:1 the C_d increased by about 5% than for slope of 1:1. El-Saiad (1990) studied the effect of a silled gate under submerged flow conditions on the C_d using trapezoidal flat top sills with different downstream slopes and different heights. The study showed that the C_d increases by increasing downstream slope of sill from 1:1 to 9:1 for b/Z=1.5, 3 (b= top width of the sill, Z= sill height). Also the study showed that the best sill that gives maximum C_d with b/Z=1 is the one which has a downstream slope of 5:1. Negm (1998) investigated the effect of the sill parameters Z/b and Z/B (B= bottom width of the sill) on flow below submerged gate with sill. Generally speaking, it has been found that the sill under the gate increases the C_d of the gate and the rate of increase depends on the configuration of both the sill and the gate as well as on both the sill and flow parameters. Also, most of the studies recommended the use of an optimal sill of 5:1 downstream slope (Negm 1995).

The present study investigates the effect of the presence of circular-crested sills with different radii and constant heights, upstream and downstream slopes under vertical sluice gates on the discharge coefficient in case of submerged supercritical flow condition.

2. THEORETICAL APPROACH

By applying the theory of dimensional analysis, the following functional relationship for C_d in case of submerged flow under circular –crested silled sluice gate, Fig.(1) is developed:

$$C_d = \Phi\left(F_G \ , \sqrt{\frac{\Delta H}{G}}, \frac{Y_t}{G}, \frac{B}{Z}\right) \qquad (1)$$

Where

B : bottom width of the sill

C_d : coefficient of discharge

F_G : Froude number under the gate which is given by

$$F_G = \frac{Q}{W\,G\sqrt{g\,G}} \qquad (2)$$

G : gate opening

g : acceleration due to gravity

ΔH : the difference between the upstream and downstream water levels

Q : discharge passing through the flume

W : width of the flume

Y_t : tail water depth

Z : sill height

Φ : arbitrary function

The discharge coefficient of a sluice gate with submerged flow can be calculated as follows:

$$C_d = \frac{Q}{W\,G\sqrt{2\;g\;\Delta H}} \qquad (3)$$

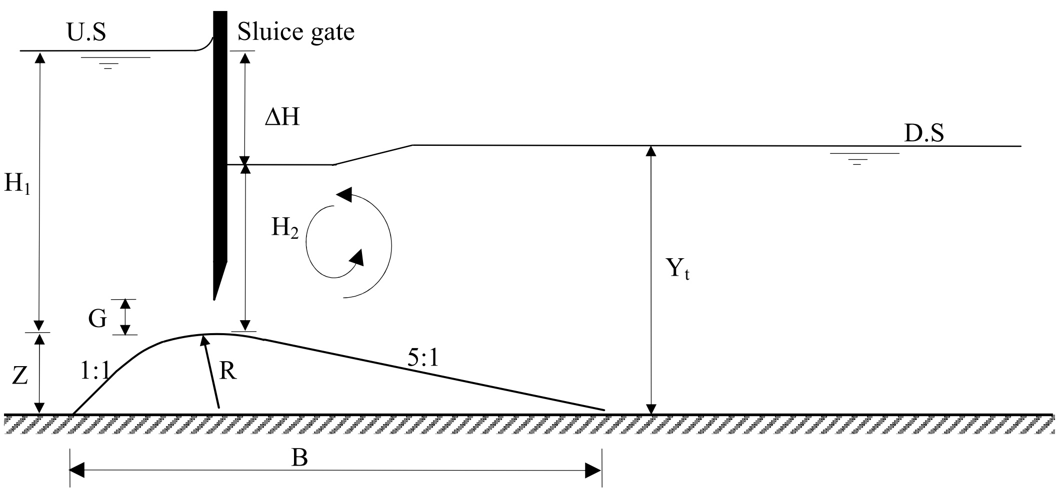

Figure 1: Sketch of Experimental Setup

3. EXPERIMENTAL SETUP

The experimental work of the present study was investigated in the hydraulic laboratory of the faculty of Engineering in Ain Shams University. A plexiglass, re-circulating, tilting flume of rectangular cross section was used. The flume is 250 cm long, 15 cm wide and 30 cm deep with an inlet part of 76 cm depth. The flume has transparent walls which facilitate the direct observation of the flow. A vertical gate with a sharp beveled lower edge fixed at the inlet section was used to control the upstream flow depth using a hand driven gear system for opening and closing the gate. The water depths were measured by means of point gauges mounted on instrument carriers with 1 mm accuracy. The discharge was measured by a pre-calibrated orifice meter.

The experiments were conducted using seven models of sills. One of them has a flat top (with 3 cm width) and the others are circular-crested with different radii. All of them have the same height (Z=3 cm), same upstream slope (U.S.S= 1:1) and same downstream slope (D.S.S= 5:1). Four models of the circular- crested sills (R= 2, 4, 6, 8 cm) have upstream and downstream slopes tangential to the circular crest. So, the models have smooth crests. The other two models (Ra= 2, 4 cm) have a tangential downstream slope to the crest, but the upstream slope is not tangential to the circular crest. So, the upstream slope is abruptly attached to the crest as shown in Fig.2 to produce smaller base length than the other models with the same radii. The sluice gate was located at the summit of the circular-crested sills and at the center line of the flat top one.

Each model was tested with four different gate openings (G = 1.5, 2, 2.5, 3cm), and each gate opening was tested with five different discharges. For each run, a specified gate opening is set and a certain flow is allowed to path through the flume. The tail gate is adjusted to provide submerged flow case. After attaining stability conditions, the upstream, downstream and tail water depths were measured. The discharge and the gate opening were recorded.

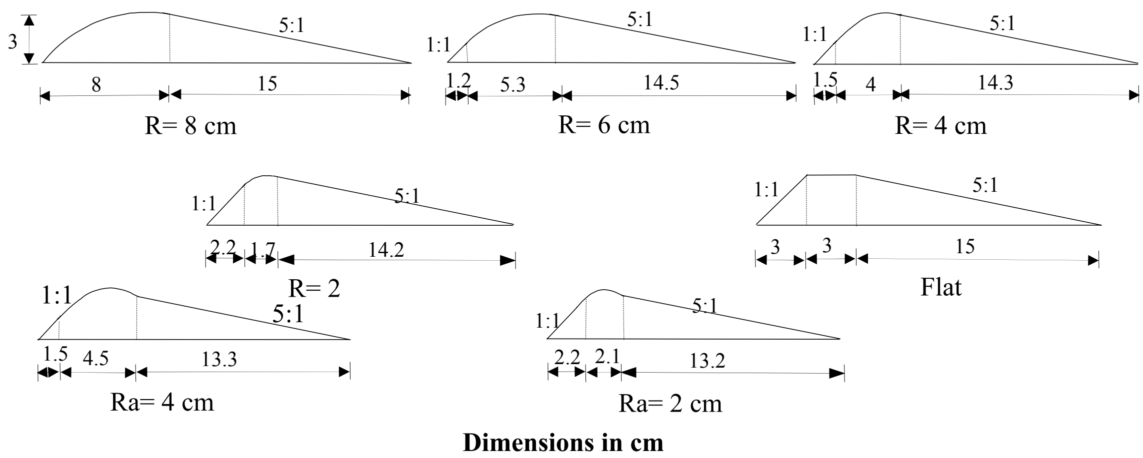

Figure 2: Shapes of the tested models

4. RESULTS AND ANALYSIS

Comparing the relation between the relative differential head $(\Delta H/G)^{0.5}$ with C_d and F_G for flat sill case of this study and that obtained by El-Said (1990) (Fig.(3 a,b)), the figure shows a good agreement between the two studies. Also, it is obvious from the figure that the present study used a bigger range of $(\Delta H/G)$.

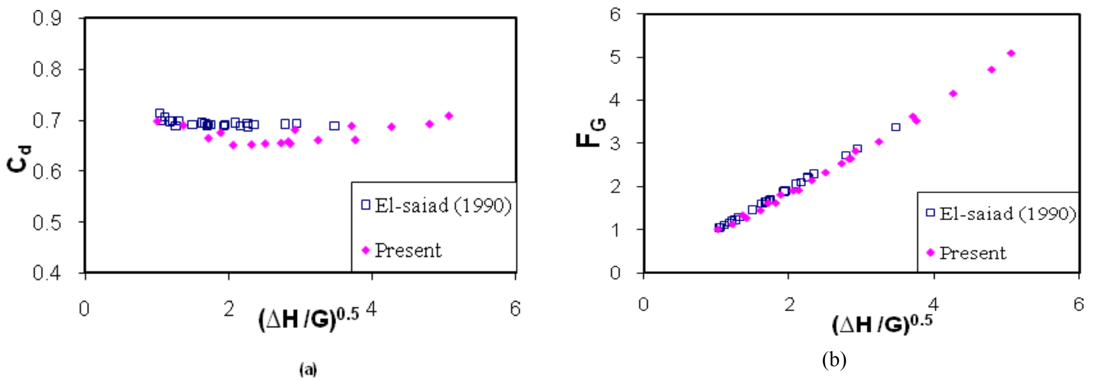

Figure 3: Verification of the relations for Supercritical submerged flow of the flat- silled gate case

In Fig.(4), the relation between $(\Delta H/G)^{0.5}$ and C_d for the two types of the tested crest shapes is compared. Also, average lines of the data sets are drawn. It is found that for smooth crested shape (R= 2,4,6,8) the value of C_d increased by decreasing the crest radius and consequently decreasing the sill bottom width B. Also, the same relation can be concluded for sills with abrupt change in the crest (Ra=2, 4). It is obvious from the figure that C_d values produced with sills of abrupt change in crest (Ra= 2,4) are bigger than those produced with smooth crest, in spite of they have the same crest radii. So, as B/Z of the sill decreased the value of C_d of the sill increased as shown in the figure. The figure indicates that the circular- crested sills produce C_d values bigger than that of the flat-crested one only if B/Z of the circular- crested sill is equal or smaller than that of the flat- crested one (R=2,4,6 , Ra=2,4). When B/Z of the circular-crested sill is bigger than that of the flat sill (R=8) C_d value of the circular-crested sill is smaller than that of the flat one. When the circular and flat crested sills have same B/Z (R=6), values of C_d of the circular crested sill are bigger than that of the flat one by small amount, as shown in the figure.

The increase in C_d with decreasing the value of B/Z may be due to the decrease in the wetted perimeter of the sill and consequently the energy loss decreases. This leads to minimizing the differential head (ΔH), and in turn C_d increases at constant F_G.

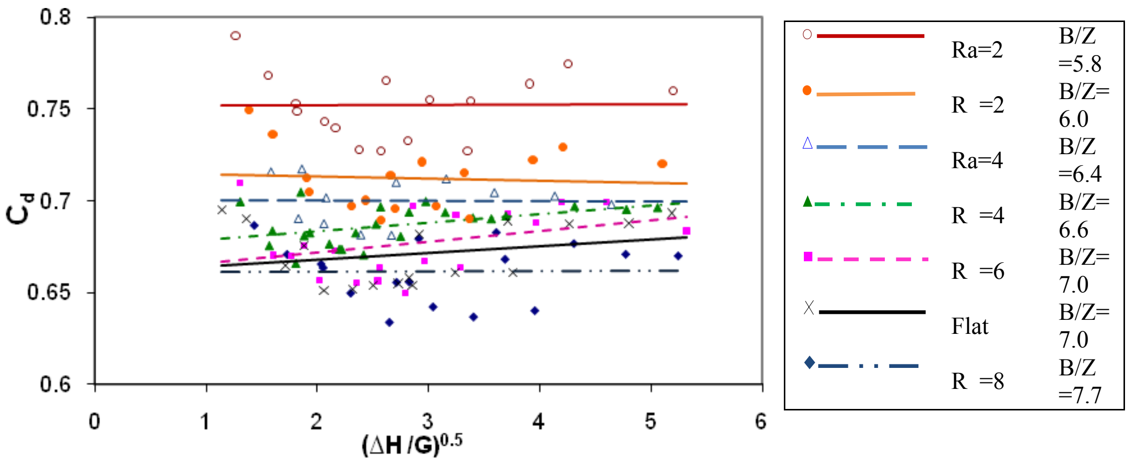

Figure 4: Relation between C_d and $(\Delta H/G)^{0.5}$ for sills with different crest shapes and radii

The relation between C_d and submergence ratio (Y_t/G) for circular-crested sills and the flat-crested one is plotted for both the two types of the tested crest shapes as shown in Fig.(5). The figure shows that for $Y_t/G < 4.8$, C_d decreases rapidly with increasing Y_t/G, while for larger values of Y_t/G, C_d is affected slightly by increasing Y_t/G. It is obvious from the figure that for any value of Y_t/G, C_d increases by decreasing B/Z value.

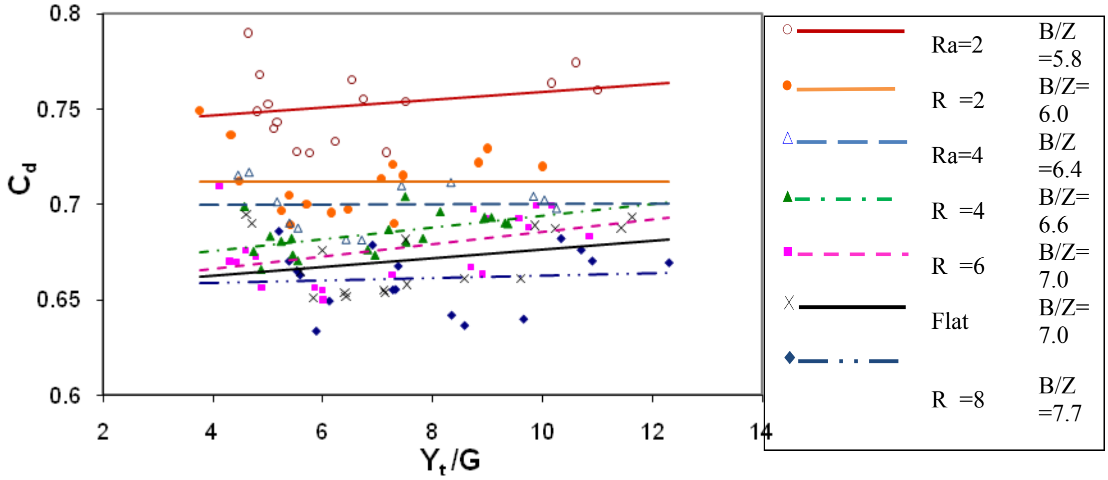

Figure 5: Relation between C_d and Y_t/G for sills with different crest shapes and radii

Fig.(6) shows the relation between C_d and Froude Number under the gate F_G. The figure indicates that at low F_G ($F_G < 1.6$) the decrease in C_d by increasing F_G is rapidly and for $F_G > 1.6$, C_d is not affected much by increasing F_G. It is obvious that at constant F_G value, C_d increases by decreasing B/Z value.

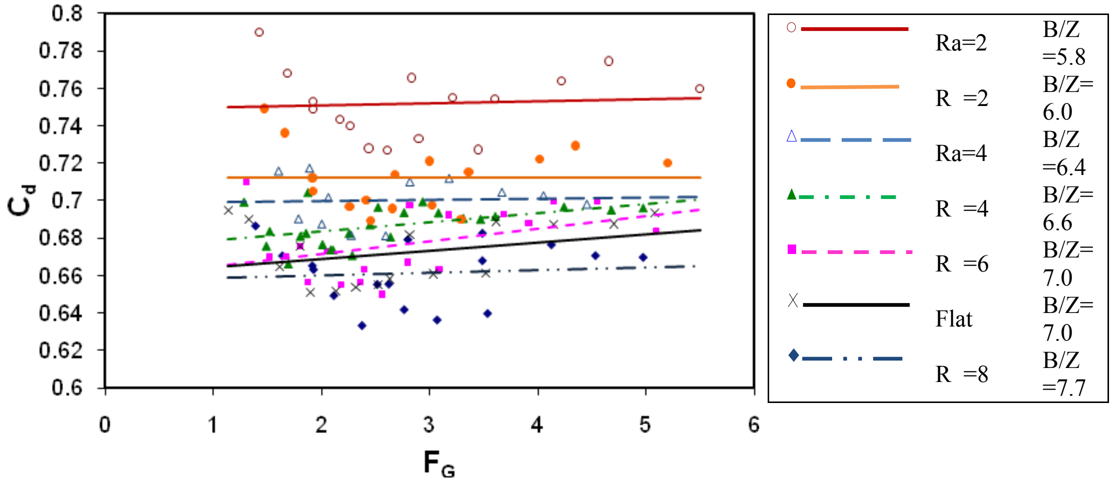

Figure 6: Relation between C_d and F_G for sills with different crest shapes and radii

Table 1 represents the average percentage of increasing in C_d (the reference is the average value of C_d of the flat-crested sill) with the experimental data range.

Table 1: % Increase in C_d with the experimental data range

Crest radius (cm)	% decrease in B/Z	Average percentage of increasing in C_d
Ra =2	17.1	12
R =2	14.3	6
Ra =4	8.6	4
R =4	5.7	2.2
R =6	0.0	0.5

The relation between $(\Delta H/G)^{0.5}$ and F_G for flat sill case and all tested models is plotted in Fig.(7a). This relation can be expressed as

$$F_G = A \sqrt{\frac{\Delta H}{G}} \tag{4}$$

Where A is a constant and its value was estimated by the least square technique as given in table 2.

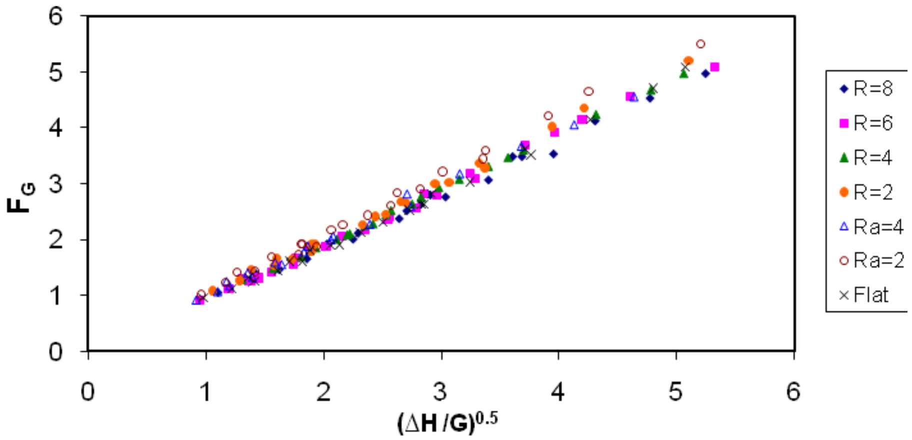

Figure 7(a): Relation between F_G and $(\Delta H/G)^{0.5}$ for sills with different crest shapes and radi

Table 2: Values of constant A

Crest shape	A	B/Z
Flat top	0.955	7.0
R = 8 cm	0.933	7.7
R = 6 cm	0.961	7.0
R = 4 cm	0.976	6.6
R =2 cm	1.000	6.0
Ra=4 cm	0.988	6.4
Ra= 2 cm	1.056	5.8

Talaat (1988) proved theoretically that A = 0.863 for no sill case. Comparing the values of A from table (2) with the value obtained by Talaat, we can conclude that at constant F_G, $(\Delta H/G)^{0.5}$ is bigger for no sill case than that obtained for silled cases, and this is normal because the value of C_d for no silled case is smaller than its value for any silled case of this study. It is obvious from Fig.(7.a) that for constant F_G, $(\Delta H/G)^{0.5}$ with circular-crested sills is bigger than that of the flat-crested one only if B/Z of the circular- crested sill is smaller than that of the flat- crested one (R=2,4 , Ra=2,4). Also the relations of F_G and $(\Delta H/G)^{0.5}$ for the flat-crested sill case and that of circular-crested sill with same B/Z (R=6) are nearly coinciding.

Fig. (7.b) can be used as a design chart to predict the discharge passing under a submerged gate with circular-crested sill with the tested range. By knowing the relative differential head $(\Delta H/G)^{0.5}$, F_G can be estimated from the chart. Then using equation (5.b), C_d can be estimated as follows

$$F_G = \frac{Q}{W\,G\sqrt{g\,G}} = C_d\sqrt{2\frac{\Delta H}{G}} \qquad (5.a)$$

$$\therefore C_d = \frac{F_G}{\sqrt{2\frac{\Delta H}{G}}} \qquad (5.b)$$

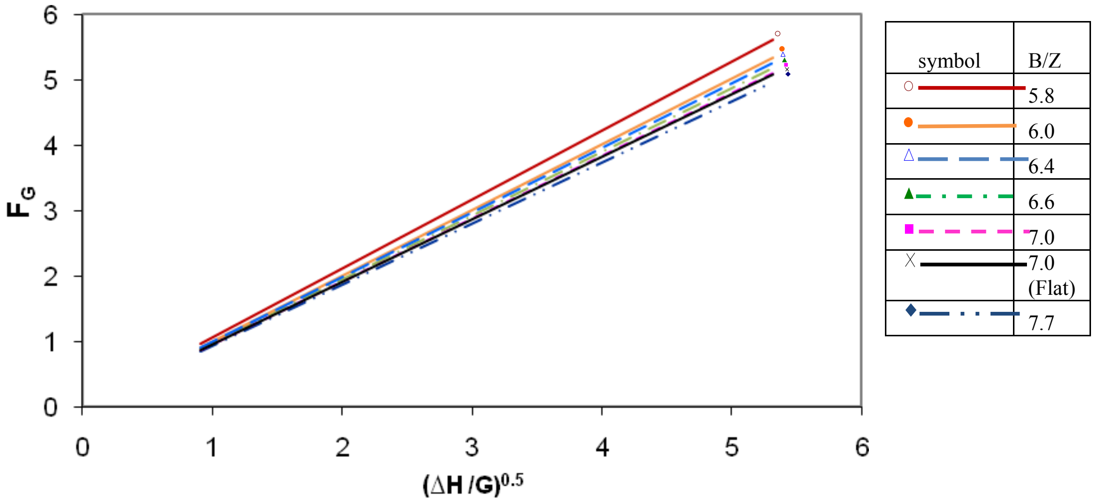

Figure 7(b): Chart between F_G and $(\Delta H/G)^{0.5}$ for sills with different crest shapes and radii

Based on the average values of the coefficient of discharge , within the experimental range, another chart between the percentage change in the discharge coefficient of the circular- crested silled gate cases with changing the percentage of B/Z (the reference is the flat-crested sill) is plotted in Fig.(8).

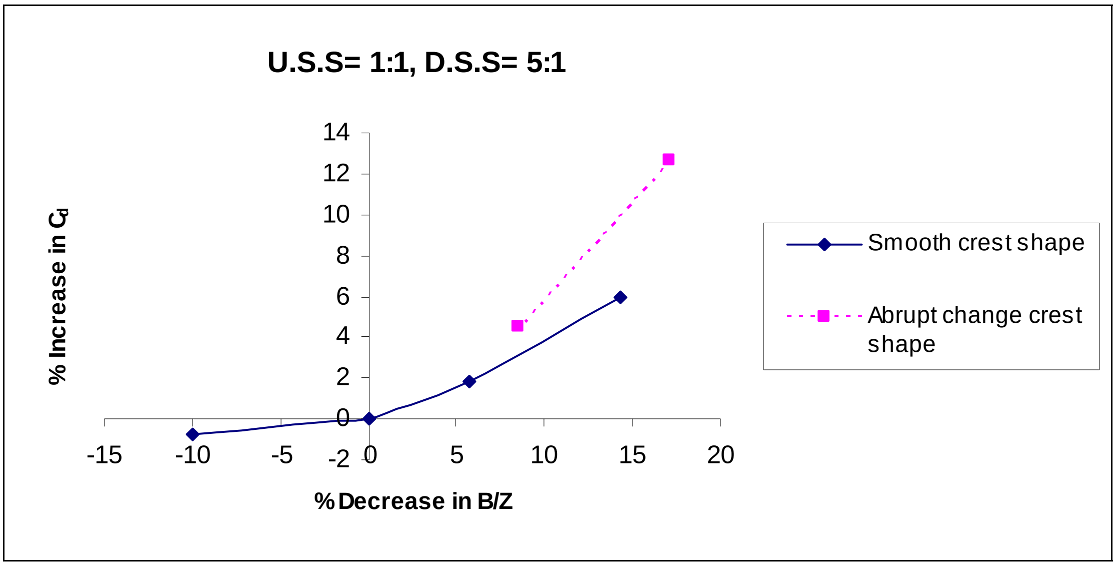

Figure 8: Chart between percentage change in C_d and percentage change in B/Z for circular-crested silled gates

5. CONCLUSION

In the present study, characteristics of supercritical flow under a submerged sluice gate with circular-crested sills were investigated over a wide range of ΔH/G ($1.2 \leq \Delta H/G < 28$). The study used two types of the crest shapes, smooth and abrupt change shape.

It is found that, for the range of experiments

- The main factor that affects the discharge coefficient is B/Z.
- The circular-crested sill produces a bigger discharge coefficient than the flat-crested sill only if B/Z of the circular-crested sill is equal or smaller than that of the flat-crested one.
- The models with abrupt change in crest produce C_d values higher than those obtained by the smooth crested ones which have same radii, because the models with abrupt change in crest have B/Z smaller than that of the smooth crested ones.

A design chart was developed to calculate the discharge coefficients of circular-crested silled gates for the investigated range by knowing the gate opening and the differential head values. Also, another design chart to calculate the percentage increase in the discharge coefficient for all models was developed.

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7. SYMBOLS

A	: constant
b	: top width of the flat sill
B	: bottom width of the sill
C_d	: coefficient of discharge

D.S.S	: downstream slope of the sill
F_G	: Froude number under the gate
G	: gate opening
g	: acceleration due to gravity
H_1	: effective upstream water depth
H_2	: downstream water depth
ΔH	: differential water head= (H_1-H_2)
Q	: Discharge passing through the flume
R	: curvature radius of the smooth crest
Ra	: curvature radius of the abrupt change crest
U.S.S	: upstream slope of the sill
W	: width of the flume
Y_t	: tail water depth
Z	: sill height
Φ	: arbitrary function