Mansoura Engineering Journal, (MEJ), Vol. 24, No. 2, June 1999.

FLOW CHARACTERISTICS OF UNDER-GATE SILL FOR DIFFERENT FLOW REGIMES

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خصائص السريان تحت البوابات ذوات الأعتاب لحالات السريان المختلفة

خلاصـــــة:

يتناول هذا البحث تحليل مجموعة كبيرة من البيانات المعملية عن السريان تحت البوابات ذوات الأعتاب لحالات السريان المختلفة والتي تشمل السريان الحر فوق الحرج والسريان المغمور فوق الحرج وتحت الحرج والحرج. وقد استخدمت في التجارب المختارة مجموعة من الأعتاب ذوات الشكل شبه المنحرف والمتباينة الميول الأمامية والخلفية. وقد تم التركيز في هذا البحث على عتب ذو ميل خلفي ٥ أفقي : ١ رأسي حيث أثبتت الدراسات السابقة أنه أفضل عتب شبه منحرف الشكل يمكن استخدامه لتحسين خواص السريان الحر والمغمور. ولقد تبين من تحليل البيانات ومناقشة النتائج أن معامل التصرف للبوابات ذوات الأعتاب يعتمد ليس فقط على متغيرات السريان ومتغيرات العتب وإنما حالة السريان لها أثر كبير على قيمة معامل التصرف وبالتالي التصرف ذاته. ولقد تم استخدام طريقة التحليل الإحصائي لاستنتاج معادلات لحساب معامل التصرف في الحالات المختلفة.

ABSTRACT

The objective of the present study is to analyze a collected experimental data due to construction of a sill with a known shape under a sluice gate for both free and submerged flows. The previous studies proved that the trapezoidal sill having a downstream slope of 5:1 improves the discharge coefficient below the gate and minimizes the jump length formed downstream the gate, compared to the other downstream slopes. Therefore, data collected from large series of experiments on the under gate-sill of this particular downstream slope were analyzed. Regarding the submerged flow case, both of the subcritical and supercritical flows were considered. The discharge coefficient of the sluice gate has been taken as the main criterion for the flow below the gate. The selected experiments have been conducted on a laboratory flume, testing sills of different heights under a wide range of flow conditions. The dimensional analysis was used to correlate the discharge coefficient to the other relevant flow and sill parameters. Dimensionless equations in terms of flow and sill parameters, computing the under gate discharge coefficient in the cases of free and submerged flows, were developed using the multiple linear regression analysis. The discharge coefficient and consequently, the flow discharge below the sluice gate with sill using the developed equations were compared to the experimental data. The developed equations proved a good reliability and a high accuracy.

Accepted June 1, 1999

INTRODUCTION:

The sluice gates are used in irrigation works to control the discharge downstream and the water level upstream. According to the level of water downstream, the flow is classified into either free flow or submerged flow. Both the free and submerged flows below sluice gates on horizontal level floors were studied extensively [1-8]. In many cases, the irrigation engineer has to select between designing double/ triple leaf gates or a single / double leaf gates with sill constructed below it. The selection of designing gates with sill reduces the costs of the gate material as well as the construction costs. Also the power requirements are minimized. The effects of constructing sills under sluice gates on the flow were investigated by numerous researchers. Some of these studies dealt with the free flow, Ranja Raju and Visavadia [9], Ranga Raju [10], Negm et al. [11] Abdelaal [12] and recently Negm, et al. [13]. While others dealt with the submerged flow, El-Saiad, et al. [14-16], Negm, and El-Saiad [17], and Negm, et al. [18]. Other studies dealt with the effect of the gate or sill configuration on the flow below the gate, [19-21]. Also, regarding the free and submerged flow some studies are available in the literature, Salama [22] and Negm [23]. Most of these studies recommended the use of sill having 5:1 downstream slope. The effect of the relative height (Z/G. Z is the sill height and G is the depth of gate opening) of the under-gate sill with downstream slope of 5:1 was studied by Negm [17] for subcritical submerged flow.

Generally speaking, it has been found that the sill under the gate increases the coefficient of discharge 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 [23]. However, still little information is available on the effect of the relative height of sill under the gate on the flow below sluice gates with sill in both cases of free and submerged flows below gates when the optimal sill is in use. Therefore, the present study aims at investigating the effect of presence a sill under vertical sluice gate with different sill relative heights (Z/G) and optimum downstream slope of trapezoidal sill of 5:1 on the discharge coefficient of sluice gate. Both cases of free and submerged flow conditions are tested experimentally under different flow regimes in order to provide more information about the interacting effect of the relative height of sill with the flow parameters. Also, equations for computing the coefficient of discharge of the silled sluice gate are developed for different flow regime conditions when either free or submerged flow is prevailing.

THEORETICAL BACKGROUND:

Figure (1) shows a typical definition sketch for both the free and submerged flow below a sluice gate with sill. Applying the principles of the dimensional analysis, the following functional relationship for the discharge coefficient of the submerged silled sluice gate, C_{ds}, can be written as:

$$C_{ds} = \psi\left(F_G, \frac{H_1}{G}, \frac{Y_t}{G}, \frac{\Delta H}{G}, \frac{Z}{G}, DSS, USS, \frac{Z}{B}\right) \tag{1}$$

As the DSS and USS are kept constant to 5:1 and 1:1 respectively, their effect can be excluded from Eq. (1) to be:

$$C_{ds} = \psi\left(F_G, \frac{H_1}{G}, \frac{Y_t}{G}, \frac{\Delta H}{G}, \frac{Z}{G}, \frac{Z}{B}\right) \qquad (2)$$

Regarding the free flow below silled sluice gates, Eq. (2) is valid if the effects of Y_t/G and H/G are dropped. Thus, The discharge coefficient for free and submerged flows below the sluice gate can be calculated from the following equation:

$$C_{ds} = \psi\left(F_G, \frac{H_1}{G}, \frac{Z}{G}, \frac{Z}{B}\right) \qquad (3)$$

or

$$C_{ds} = \frac{Q}{WG\sqrt{2g(H_1 - H_2)}} \qquad (4)$$

where W is the flume width and H_2=0 for free flow.

The effect of Z/B was studied by Negm, et al. [18] for submerged flow and by Negm [24] for free flow.

EXPERIMENTAL PROGRAMME:

A glass sided tilting re-circulating flume of 3 m long was used to conduct the experiments. The flume bed is 10 cm wide and 20 cm deep. The water depths were measured by means of point gauges mounted on the instrument carriage. The discharge was measured by means of a pre-calibrated V-notch. The flume is equipped with a sluice gate to control the upstream level and with a tailgate to control the tailwater level. The sill models were made from plastic material. The gate was located at the center of the flat top of the 3cm wide sill. The sills having three different heights, (Z=1,2 and 3 cm), were tested under different flow regimes.

For each tested model, a specific gate opening was set and a certain flow rate was allowed to run through the flume. The tailgate was controlled to create free or submerged flow below the gate. After attaining the stability conditions, (the upstream depth remains unchanged), the depths upstream and downstream of the gate were measured. The discharge and the gate opening were recorded. Different discharges and different gate opening heights were considered. This test procedure was repeated for each model.

The data for the submerged flow below gates with sill of heights 1, 2, and 3 cm, DSS=5:1, USS=1:1 and b=3 cm, are collected from [13,14,17,18] and from [13,15] for a gate without sill. For the free flow the data for the same sills are collected from [11,23] and for the case of no sill from [12]. Also, data [22] for DSS=3:1 and vertical upstream face are included for comparison. Moreover, the curve of no-sill from [9] is included as well as data concerning sluice gate located on a raised crest (weir) of DSS=5:1 is considered for the comparison.

For the submerged flow, the obtained relative heights of sill are (Z/G=0, 0.167, 0.222, 0.333, 0.444, 0.500, 0.667 & 1.0) for the subcritical flow while for the supercritical flow, the relative heights are (Z/G=0, 0.667, 1.0, 1.33, 2.0 & 3.0). For the free flow the height ratios are (Z/G=0, 0.33, 0.4, 0.5, 0.677, 0.8, 1, 1.2, 1.33, 1.5, 2 & 3). In addition, some relative heights (Z/G=0.556, 0.714 & 1) are taken from [22], and (Z/G=30 & 12) are taken from [9].

ANALYSIS AND DISCUSSIONS

The variations of the discharge coefficient for the sluice gate with sill, C_{ds}, or without sill, C_d, for free and submerged flow are presented in Fig. (2). It seems that there are large variations in C_{ds} which are due to:

1- different flow regimes are considered, i.e. (supercritical free flow, submerged subcritical flow and submerged supercritical flow).

2- different investigated ranges for each flow regime:

   a. for supercritical free flow, the ranges of the parameters are: $1.2<F_G<5$ and $2.5<H_1/G<20$.

   b. for submerged subcritical flow, the ranges of the parameters are: $0.3<F_G<0.95$, $1.2<H_1/G<4$, $0.3< H/G<1$ and $1.3<Y_t/G<3$.

   c. for submerged supercritical flow, the ranges of the parameters are: $1.2<F_G<3.5$, $2.5<H_1/G<16.5$, $1.2< H_1/G<3$ and $2.2<Y_t/G<8$.

3- wide range of the tested relative height of sill which is $0<Z/G<3$ for supercritical free flow, $0<Z/G<1$ for submerged subcritical flow and $0<Z/G<3$ for submerged supercritical flow.

Figs. (3), (4) and (5) were prepared out of Fig. (2) to show the variation of the discharge coefficient with F_G and H_1/G for supercritical free flow and with F_G, H/G, Y_t/G and H_1/G for both submerged subcritical and supercritical flows respectively. From these figures, the following main features can be observed:

1- The C_d values of the sluice gate without sill are less than the corresponding ones of the gate with sill in most cases, corroborating with other studies [9,12,14-16, 17, 18, 22, 23].

2- The C_{ds} is increasing nearly linearly with the increase of H_1/G up to $H_1/G<12$ and then the variations become smaller. These variations are mainly due to the effect of F_G, H_1/G and Z/G. Typical cases for $Z/G=3$ and $Z/G=1.2$ are shown in Figs. (3a) and (3b). Figure (3a) presents the relationship between C_{ds} and F_G with H_1/G as a third parameter, while Fig. (3b) shows the relationship between C_{ds} and H_1/G with F_G as a third parameter. Fig. (3) indicates that, at constant Z/G, the rate of increase in C_{ds} depends upon the values of both H_1/G and F_G.

3- Figs. (4a) to (4d) are presented to show the variation of C_{ds} with F_G, (Fig.4a), with H/G, Fig. (4b), with Y_t/G, Fig. (4c), and with H_1/G, Fig. (4d), for a particular $Z/G=0.667$. Fig. (4) proved that C_{ds} of the subcritical submerged flow below sluice gate with sill is a function of the parameters of Eq. (2), therefore Eq. (2) is justified for submerged subcritical flow below silled sluice gate. From these figures, it is observed that C_{ds} of the submerged subcritical flow decreases, with a very steep rate, with the increase of H_1/G up to $H_1/G=2.75$, Fig. (4d). For higher values of H_1/G, the rate of increase in C_{ds} is negligible as the flow becomes supercritical, $F_G>1$, Fig. (5a).

4- Similarly, Figs. (5a) to (5d) indicate the variation of C_{ds} with F_G, Fig. (5a), with H/G, Fig.(5b), with Y_t/G, Fig. (5c), and with H_1/G, Fig. (5d) all for $Z/G=3$. Fig. (5) shows that C_{ds} of the supercritical submerged flow below sluice gate with sill is a function of the parameters of Eq. (2), therefore Eq. (2) is justified for submerged supercritical flow below sluice gate with sill. From Fig.(5), it could be stated that C_{ds}'s for $F_G>1$ seem to be nearly constant with a slight decreasing rate as H_1/G increases.

5- General speaking, it may be stated that the variation of C_{ds} in the submerged flow case are due to the effect of the combined variations of F_G, H_1/G, H/G, Y_t/G and Z/G. The effect of the first four parameters is significant in the subcritical flow regime while it is not in case of the supercritical flow regime. In both cases the effect of Z/G on C_{ds} is significant and clear.

For three different flow regimes, Fig. (6) shows the variations of the average C_{ds} (for each Z/G value regardless of the values of the flow parameters) with Z/G for free and submerged flow below sluice gate with a sill. This figure shows the following observations:

1- The C_{ds} increases with the increase of Z/G for the three investigated flow regimes.
2- The submerged flow produces higher values of C_{ds} than the corresponding ones in case of the free flow for the same values of Z/G.
3- The C_{ds} values for submerged supercritical flow are less than those of the subcritical submerged flow for the same values of Z/G.

The above discussions indicate that the C_{ds} is a function of all the parameters of Eq. (2) for submerged flow and of Eq. (3) for the free flow. Therefore, the experimental data are used to provide dimensionless general equations for predicting C_{ds} for each flow regime, when a sill of DSS=5:1 and USS=1:1 is used under the gate, as follows:

- **For free flow:**

$$C_{ds} = a_o + a_1 F_G + a_2 \frac{H_1}{G} + a_3 \frac{Z}{G} \tag{5}$$

with $a_o=0.369$, $a_1=0.193$, $a_2=-0.027$, $a_3=-0.001$, $R^2=0.966$ and SEE=0.01. For $Z/G=0.0$, $a_o=0.366$, $a_1=0.24$, $a_2=-0.042$, $a_3=0.0$, $R^2=0.978$ and SEE=0.013.

- **For submerged subcritical flow:**

$$C_{ds} = a_o + a_1 F_G + a_2 \sqrt{\frac{\Delta H}{G}} + a_3 \frac{Y_t}{G} + a_3 \frac{Z}{G} \tag{6}$$

with $a_o=0.766$, $a_1=1.40$, $a_2=-1.555$, $a_3=-0.228$, $a_4=0.225$, $a_5=0.219$, $R^2=0.953$ and SEE=0.01. For $Z/G=0.0$, $a_o=0.725$, $a_1=1.386$, $a_2=-1.459$, $a_3=-0.200$, $a_4=0.194$, $a_5=0.0$, $R^2=0.971$ and SEE=0.005.

- **For submerged supercritical flow:**

Eq. (6) is valid with the following values of the coefficients: $a_o=0.681$, $a_1=0.349$, $a_2=-0.344$, $a_3=-0.001$, $a_4=0.003$, $a_5=0.001$, $R^2=0.897$ and SEE=0.006. For $Z/G=0.0$, $a_o=0.636$, $a_1=0.452$, $a_2=-0.406$, $a_3=0.001$, $a_4=-0.001$, $a_5=0.0$, $R^2=0.947$ and SEE=0.001.

Based on Eqs. (5) and (6), Fig. (7) is plotted to show the degree of agreement between the predicted and the measured C_{ds}. These equations are more practical than those developed previously [17]. In the present study, one equation with a good degree of accuracy of error (±2%), is presented for all Z/G values while in the past studies, the equations need coefficients for each particular Z/G. It could be clear that the accuracy is the same for both the past as well as present equations. This is due to the inclusion of new parameters in the present equations, Eqs. (5) and (6).

Eqs. (5) and (6) need trial and error as F_G is not known which means that a trial value is needed. In order to estimate C_{ds} and hence Q quickly but roughly, single variable equations relating C_{ds} with Z/G based on Fig. 6 are developed as follows:

- **For free flow with or without sill:**

$$C_{ds} = a + b\frac{Z}{G} \tag{7}$$

where a=0.582 and b=0.042 for gate without sill with $R^2=0.74$, while for gate with sill they are 0.572, 0.048 with $R^2=0.83$.

- **For submerged subcritical flow with or without sill:**

$$C_{ds} = 0.583 + 0.059\frac{Z}{G} \qquad \text{with } R^2 = 0.91 \tag{8}$$

- **For submerged supercritical flow with or without sill:**

$$C_{ds} = 0.644 + 0.016\frac{Z}{G} \qquad \text{with } R^2 = 0.88 \tag{9}$$

Estimation of C_{ds}, using these equations, yields an error of about ±5% and slightly higher values in very few cases. Figs. (8a) to (8c) present a comparison between the estimated C_{ds} and the measured ones for the analyzed Z/G values in the present study (as a third parameter) for free flow, submerged subcritical flow and submerged supercritical flow respectively. The solution of Eqs. (5) and (6) needs trial and error procedure, with a first trial based on Eqs. (7), (8) and (9) to obtain an initial value for the under-gate Froude number.

CONCLUSIONS

A selected large series of experimental data concerning the flow below a sluice gate with sill having a downstream slope of 5:1, upstream slope of 1:1 and different relative heights are analyzed for different flow regimes. It has been found that the discharge coefficient and consequently the flow discharge below the gates with sill were affected by a number of parameters depending on the flow regime below the gate.

For the supercritical free flow, the C_{ds} is a function of H_1/G, F_G and Z/G as indicated by Eq. (3) while for the submerged flow, it is a function of H_1/G, F_G, H/G, Y_t/G and Z/G as in Eq. (2). In the submerged flow case, the relative effect of these parameters depends on whether the flow is subcritical, critical or supercritical. The dimensional analysis was used to correlate the discharge coefficient to the other relevant flow and sill parameters. Dimensionless equations in terms of flow and sill parameters, computing the under gate discharge coefficient in the cases of free and submerged flows, were developed using the multiple linear regression analysis. The discharge coefficient and consequently, the flow discharge below the sluice gate with sill using the developed equations were compared to the experimental data. The developed equations proved a good reliability and a high accuracy.

Also, single variable equations are presented for the quick and rough estimation of the C_{ds} in terms of Z/G only, to obtain an initial value of F_G.

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NOMENCLATURE

a	regression constant (with suffix of o,1,2,3,4, and 5);
b	top width of sill.
B	bottom width of sill.
C_d	the coefficient of discharge of the sluice gate without sill;
C_{df}	the coefficient of discharge for free flow
C_{dm}	the measured C_d or C_{ds};
C_{dp}	the predicted C_d or C_{ds};
C_{ds}	the coefficient of discharge of silled 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_1	upstream water depth or effective head in free flow case;
H	effective head in the submerged flow case (upstream head - downstream head);
Q	discharge passing through the flume;
R^2	multiple correlation coefficient of determination of the regression equations;
SEE	the standard error of estimate of the regression equations;
USS	upstream slope of sill;

W	width of the flume;
Y_t	tail water depth;
Z	height of sill; and
ψ	an arbitrary function.

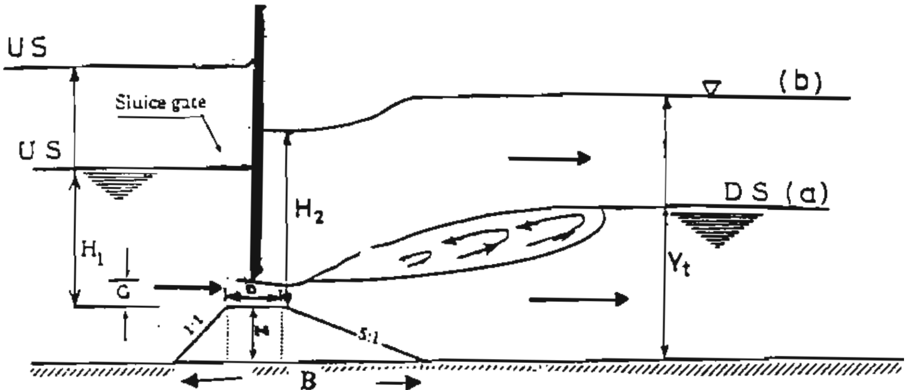

Fig. 1. Definition sketch for (a) free flow (b) submerged flow, below sluice gate with sill

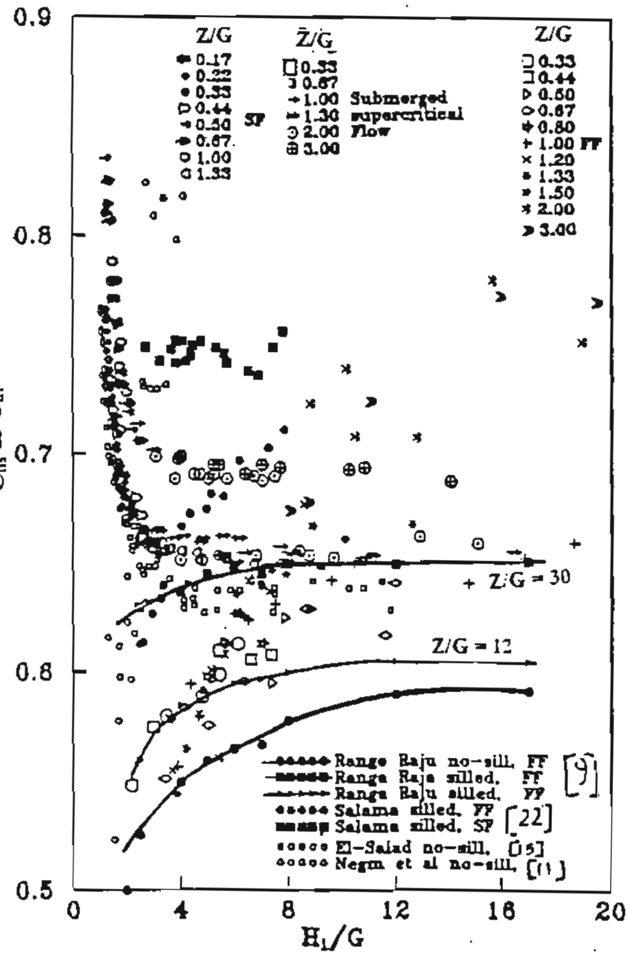

Fig. (2) Variations of both of C_{ds} & C_{df} with H_1/G for silled and non-silled gates in case of free and submerged flows.

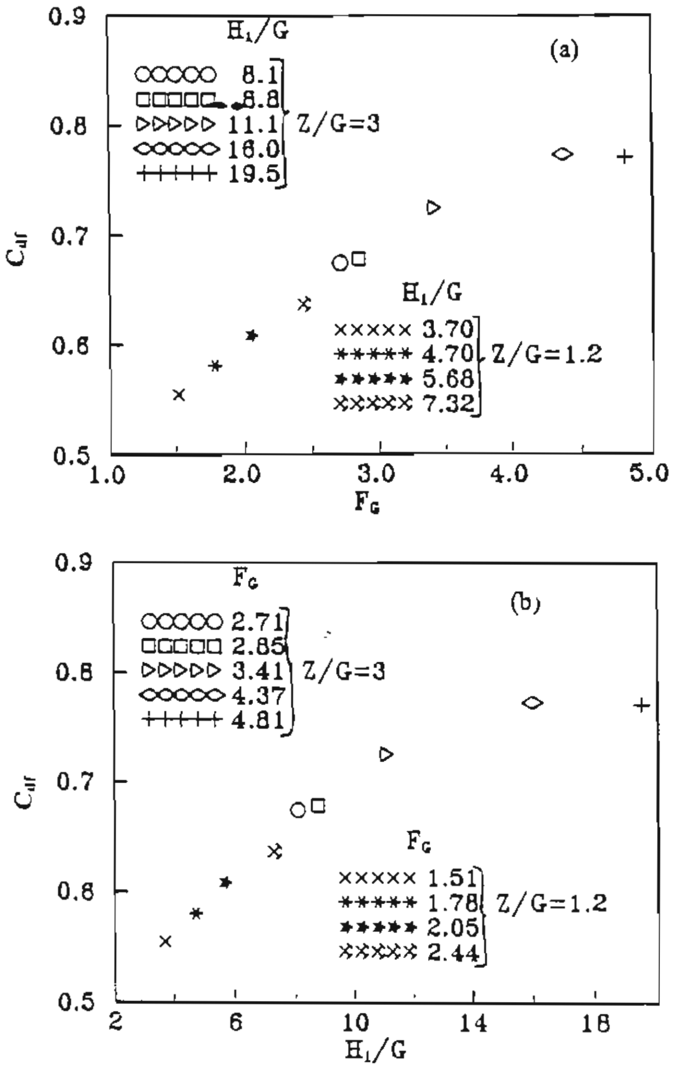

Fig.3: Typical variations of (a) C_{df} with F_G and H_l/G as third parameter (b) C_{df} with H_l/G and F_G as third parameter, for supercritical free flow at Z/G=3 and Z/G=1.2.

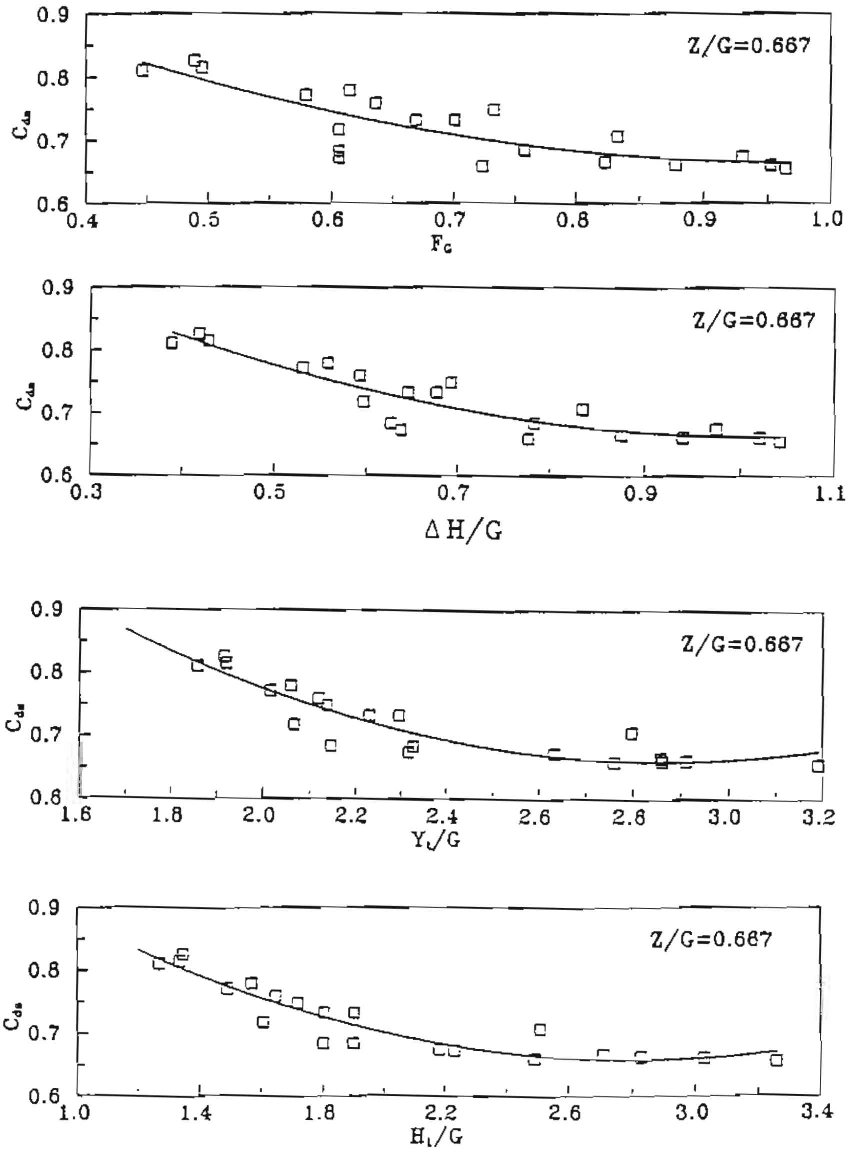

Fig.4: Typical variation of C_{ds} with (a) F_G (b) $\Delta H/G$ (c) Y_t/G and (d) H_1/G, for subcritical submerged flow at Z/G=0.667.

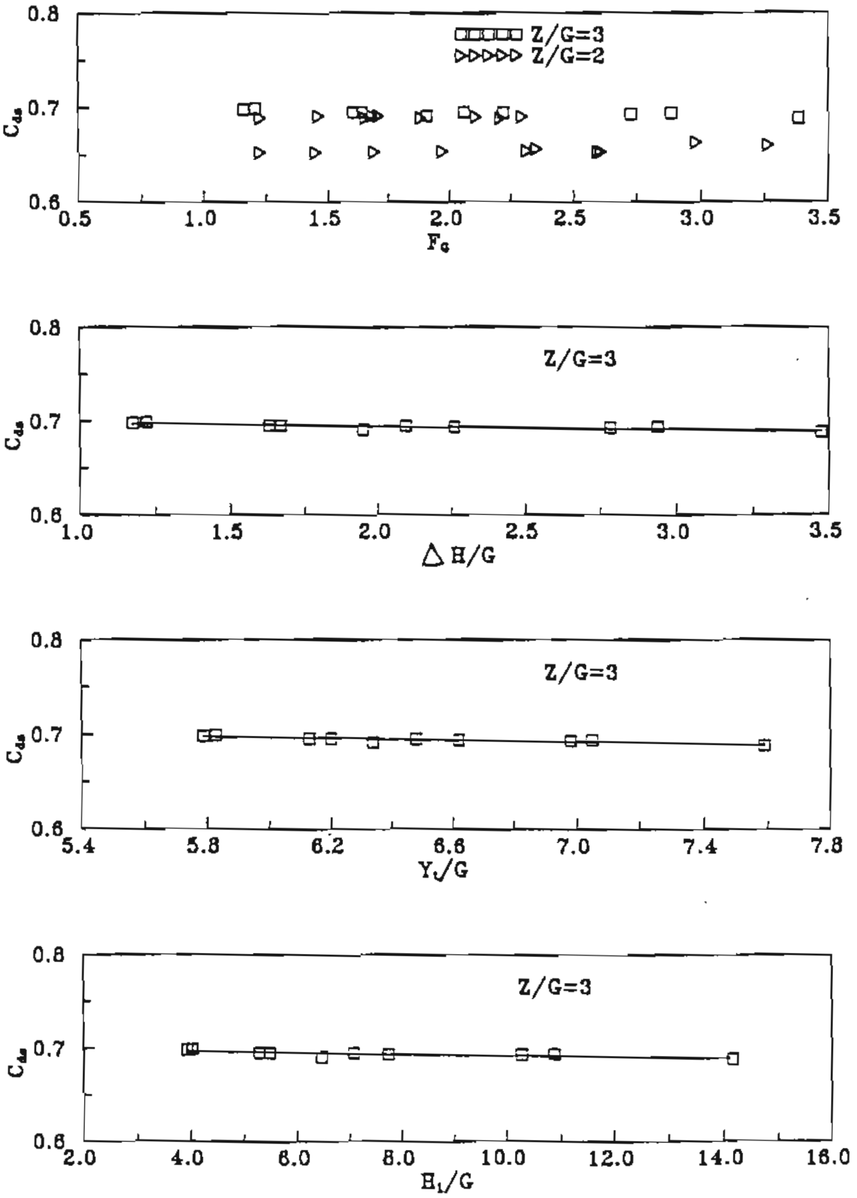

Fig.5: Typical variation of C_{ds} with (a) F_G (b) $\Delta H/G$ (c) Y_t/G and (d) H_1/G, for supercritical submerged flow at $Z/G=3$.

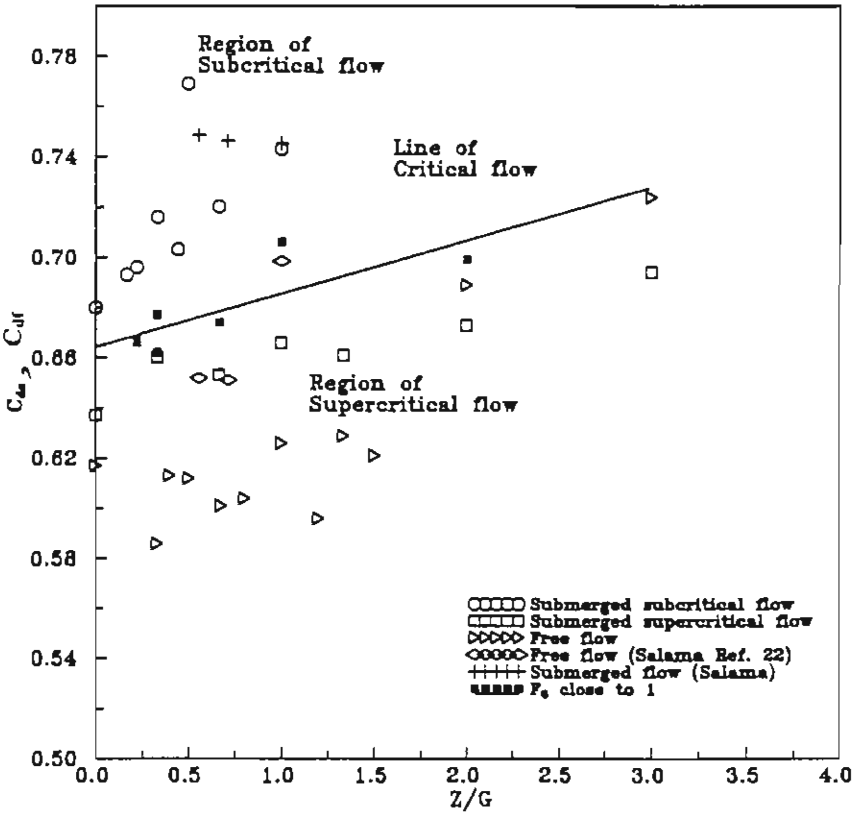

Fig.6: Variation of C_{ds} and C_{df} with Z/G for different flow regimes.

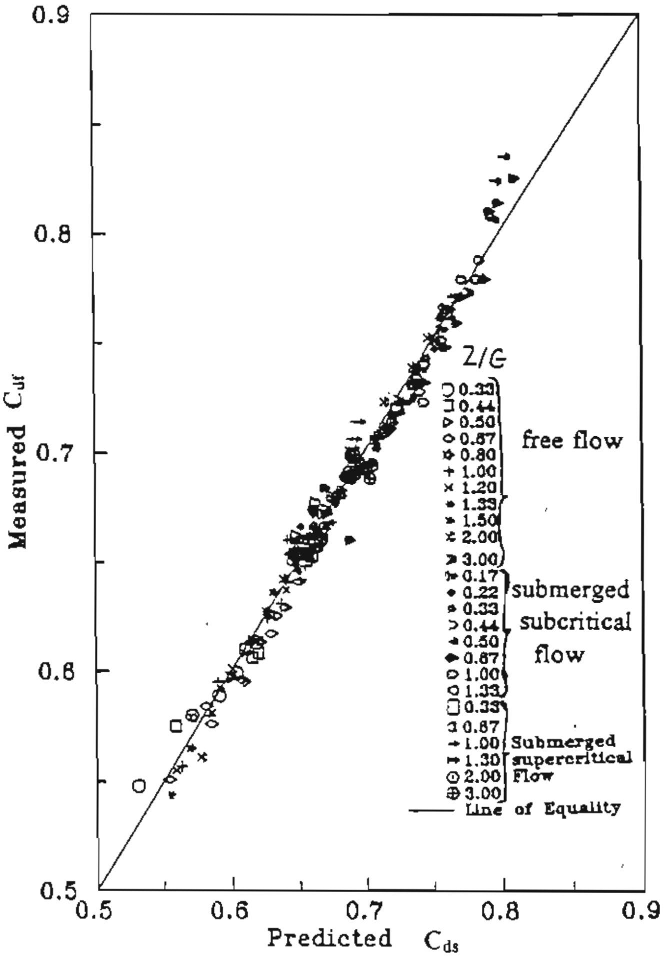

Fig. (7) Comparison between the measured C_{df} and the predicted C_{ds} using Eqs. (5) and (6).

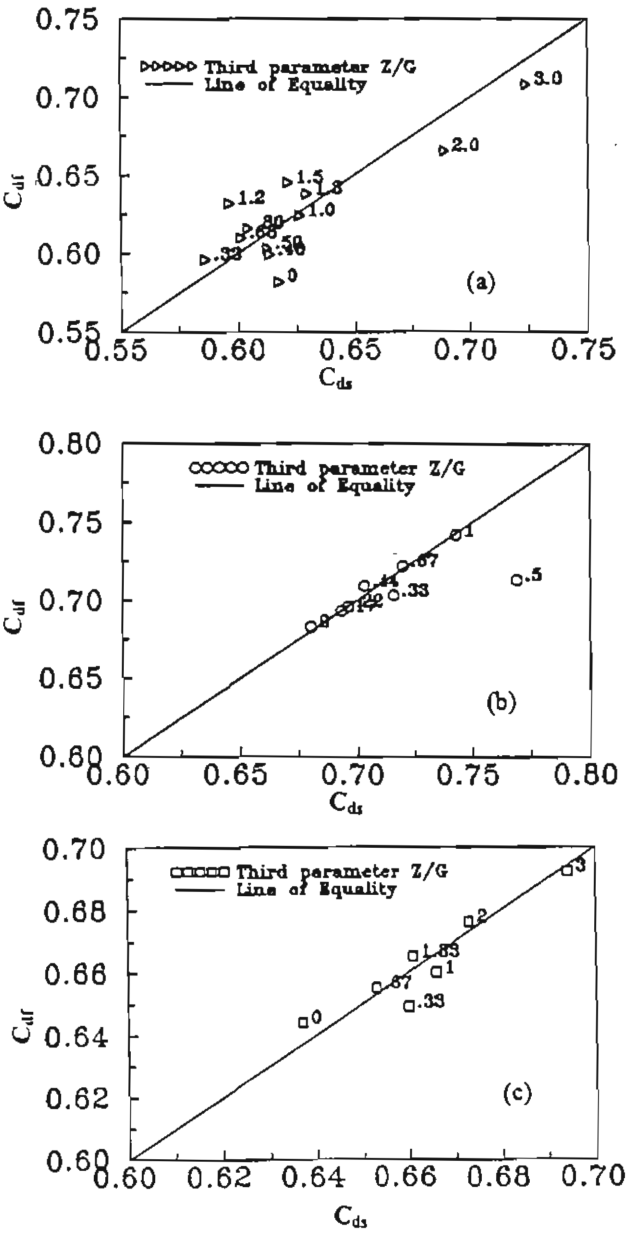

Fig. (8) Comparison between the measured C_{df} and the predicted C_{ds} Of (a) supercritical flow Eq. (7), (b) submerged subcritical flow Eq. (8)and (c) submerged supercritical flow Eq. (9)