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HYDRAULIC CAPACITY of CDOT TYPE C and D AREA INLETS (Installed in flat, depressed, and inclined configurations)

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This report summarizes the theoretical derivation, laboratory data collection, modeling calibration, and design application developed from the study on "Hydraulic Efficiency of CDOT Type C and D inlets". The major tasks in this project include: (1) laboratory tests on Type C and D inlets using a1/3 scale model performed at the Hydraulic Laboratory, Colorado State University, (2) development of design methods and calibration of design procedures conducted at the University of Colorado Denver. Under the UDFCD Agreement 10.07-04, this report presents the detailed derivation of governing equations for determining the flow interception capacity through an inclined Type C or D inlet, and calibration of flow coefficients used in the design equations.

TYPE C AND D INLETS

Type C and D inlets (TY C, TY D) are often installed at a low point for runoff collection from a large depressed area or in a highway median. According to the Hydraulic Design Manual issued by the Colorado Department of Transportation (CDOT), a TY C has a standard frame size of 3-ft by 3-ft with I-beam bars to support the loadings on its top. Figure 1 shows examples of TY C in a highway system.

	
Type C inlet in Highway Median	Depressed Type C Inlet

Figure 1 Example Type C Inlet Installed in Colorado Highways

A TY D inlet is formed by two TY C inlets lined in series or in parallel with a standard dimension of 3-ft by 6-ft. A TY C or D inlet is often located at the low point with a headwater ranging from 0.5 to 3 feet to increase its flow interception capacity. A depressed TY C or D inlet often entrains highway debris carried in the runoff flows. The flow eddies and swirls circulate twigs and leaves between the I-beam bars. The accumulated debris tends to clog the grate surface.

	
Laboratory Model for Inclined Type D Inlet	Laboratory Model for Flat Type D Inlet

Figure 2 Illustration of Inclined and Flat Laboratory Type D Inlet Model

As illustrated in Figure 2, a TY D inlet laboratory model is installed with an inclined angle facing the direction of inflow. It is expected that the floating debris will be pushed up along the grate surface. While the debris is accumulated in the back of a TY D grate, the front area on the grate surface remains open to intercept runoff flows.

HYDRAULIC CAPACITY AND FLOW INTERCEPTION

The capacity of at a TY C is quantified by its flow interception in terms of water volume per time. The flow rate is an integration of the flow velocity acting on the finite flow area. Although the flow continuity principle is derived using a vector approach, the integral of flow interception through an opening area is stated as:

$$Q = C_d \int v \, dA \tag{1}$$

Where Q= flow rate in L^3/T, C_d= flow coefficient, v = flow velocity in L/T, and A= flow area in L^2. The flow velocity is calculated as:

$$v = \sqrt{2gh} \tag{2}$$

Where g=gravitational acceleration, h = headwater depth on its flow area, dA, that will be formulated according to flow direction and flow hydraulics.

Weir flow around flat TY C inlet | Orifice flow entering inclined TY C inlet

Figure 3 Flow Hydraulics around Type C Inlet

As shown in Figure 3, when the water depth is too shallow to submerge the entire inlet grate, the grate operates like a weir. When the grate area is completely under water, the inlet operates like an orifice.

WEIR FLOW CAPACITY

When the inclined grate operates like a weir, water overtops three submerged sides into the inlet box, including two inclined sides and the lower base. As illustrated in Figure 4, the TY C inlet is installed with an incline angle which is formed by the inlet length, L, and box height, H_b. The coordination system is set to have *h*=0 at the water surface and x=0 at the lower grate base. The headwater depth decreases along the grate from x=0 to x=L which is the length of the grate.

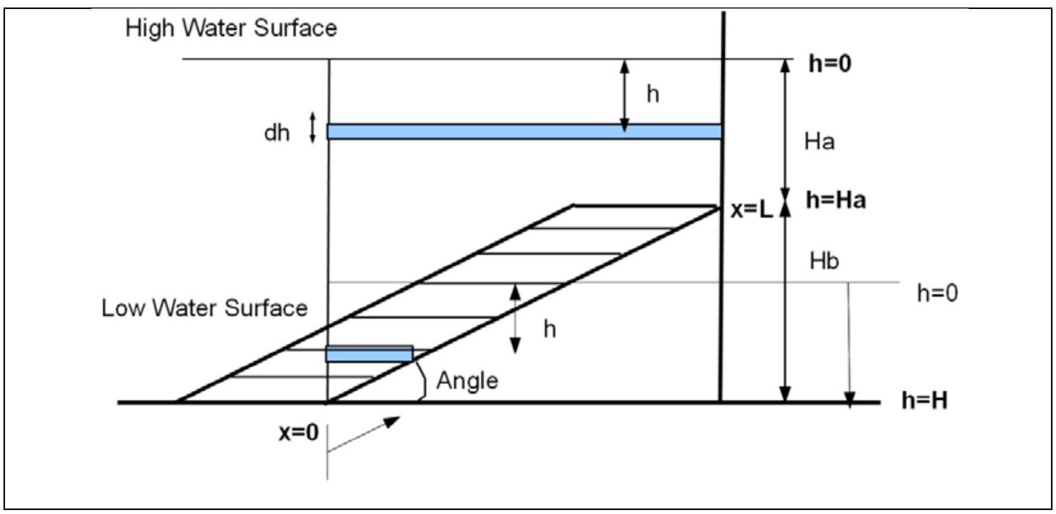


Figure 4 Illustration of Side Weir Flow

When the water depth, H, is less than H_b, the infinitesimal flow area is derived as:

$$dA = (H - h) \cot \theta \, dh \qquad \text{for } H<H_b \qquad (3)$$

Where θ = inclined angle, *dh* = thickness of infinitesimal flow area, The weir flow, Q_{ws}, overtopping the wetted length along the grate's side is integrated as:

$$Q_{WS} = nC_d \int_{h=0}^{h=H} \sqrt{2gh}(H-h)\cot\theta \, dh = nC_d \sqrt{2g} \cot\theta \int_{h=0}^{h=H} (Hh^{1/2} - h^{3/2}) dh \qquad \text{for } H<H_b \qquad (4)$$

Where dq = flow over the infinitesimal area and n= net length ratio after subtracting I-beam bar widths. Integration of Eq 4 yields:

$$Q_{WS} = \frac{4}{15} n \, C_d \sqrt{2g} \, Cot\theta \, H^{\frac{5}{2}} \qquad \text{for } H<H_b \qquad (5)$$

When the grate is completely submerged as illustrated in Figure 4, the water depth, $H>H_b$, is divided into two zones, i.e. above and below the top base of the grate as:

$$H=H_b + H_a \qquad (6)$$

Where H = water depth, H_a= surcharge depth above the top base of the grate as illustrated in Figure 4, and H_b = vertical height of inclined grate above the ground. The infinitesimal flow areas for these two zones are formulated as:

$$dA_1 = (H-h) \cot\theta \, dh \qquad 0<h< H_a \text{ for Zone 1} \qquad (7)$$

$$dA_2 = L \cos\theta \, dh \qquad H_a<h< H \text{ for Zone 2} \qquad (8)$$

The weir flow overtopping the wetted length is integrated as:

$$Q_{WS} = C_d \int_{h=0}^{h=H_a} v dA_1 + C_d \int_{h=H_a}^{h=H} v dA_2 = nC_d \int_{h=0}^{h=H_a} \sqrt{2gh} L \cos\theta dh + nC_d \int_{h=H_a}^{h=H} \sqrt{2gh}(H-h)\cot\theta dh \qquad (9)$$

Integrating Eq 9 yields:

$$Q_{WS} = \frac{2}{3} nC_d \sqrt{2g} L \cos\theta H_a^{\ 3/2} + nC_d \sqrt{2g} \cot\theta [\frac{4}{15} H^{2/5} - H_a^{\ 3/2} (\frac{2}{3} H - \frac{2}{5} H_a)]$$

$$Q_{WS} = \frac{4}{15} nC_d \sqrt{2g} L \cos\theta H_a^{3/2} + nC_d \sqrt{2g} \cot\theta [\frac{4}{15} H^{2/5} - H_a^{3/2} (\frac{2}{3} H - \frac{2}{5} H_a)]$$
$$= \frac{4}{15} nC_d \sqrt{2g} \cot\theta (H^{5/2} - H_a^{5/2}) \qquad (10)$$

Re-arranging Eq 10 yields:

$$Q_{WS} = \frac{4}{15} nC_d \sqrt{2g} Cot\theta [H^{\frac{5}{2}} - (H - H_b)^{\frac{5}{2}}] = \frac{4}{15} nC_d \sqrt{2g} H_b H^{\frac{3}{2}} Cot\theta [\frac{H^{\frac{5}{2}}}{H^{\frac{2}{3}} H_b} - \frac{(H - H_b)^{\frac{5}{2}}}{H^{\frac{2}{3}} H_b}]$$

$$Q_{WS} = \frac{4}{15} nC_d \sqrt{2g} L \; Cos\theta \; H^{\frac{3}{2}} [\frac{H^{\frac{5}{2}}}{H^{\frac{3}{2}} H_b} - \frac{(H - H_b)^{\frac{5}{2}}}{H^{\frac{3}{2}} H_b}] \qquad \text{for } H>H_b \qquad (11)$$

When $H= H_b$ or the water surface just reaches the top of inclined grate, Eq (11) is reduced to:

$$Q_{WS} = \frac{4}{15} nC_d \sqrt{2g} L \; Cos\theta \; H_b^{\frac{3}{2}} \qquad \text{for } H=H_b \qquad (12)$$

Eq 12 agrees with Eq 5 at $H=H_b$. It means that Eq's 5 and 12 provide a continuous function at $H=H_b$. The total flow, Q_{WB}, collected into the inlet is the sum of the weir flows overtopping the two wetted sides along the grate and the lower base of the grate, and. The weir flow, Q_{WB}, over the base is computed as:

$$Q_{WB} = \frac{2}{3} nC_d \sqrt{2g} \; B \, H^{\frac{3}{2}} \qquad (13)$$

Where B= base width of grate. The total weir flow, Q_W, under a water depth of H above the ground is the sum as:

$$Q_W = 2Q_{WS} + Q_{WB} \qquad (14)$$

ORIFICE FLOW CAPACITY

When the inclined grate operates like an orifice. The head water is applied to the opening area on top of the grate. As illustrated in Figure 5, when $H<H_b$, the infinitesimal flow area is defined as:

$$dA = n\ B\ dx\ \cos\theta = n\ B\ \cos\theta\ dx \tag{15}$$

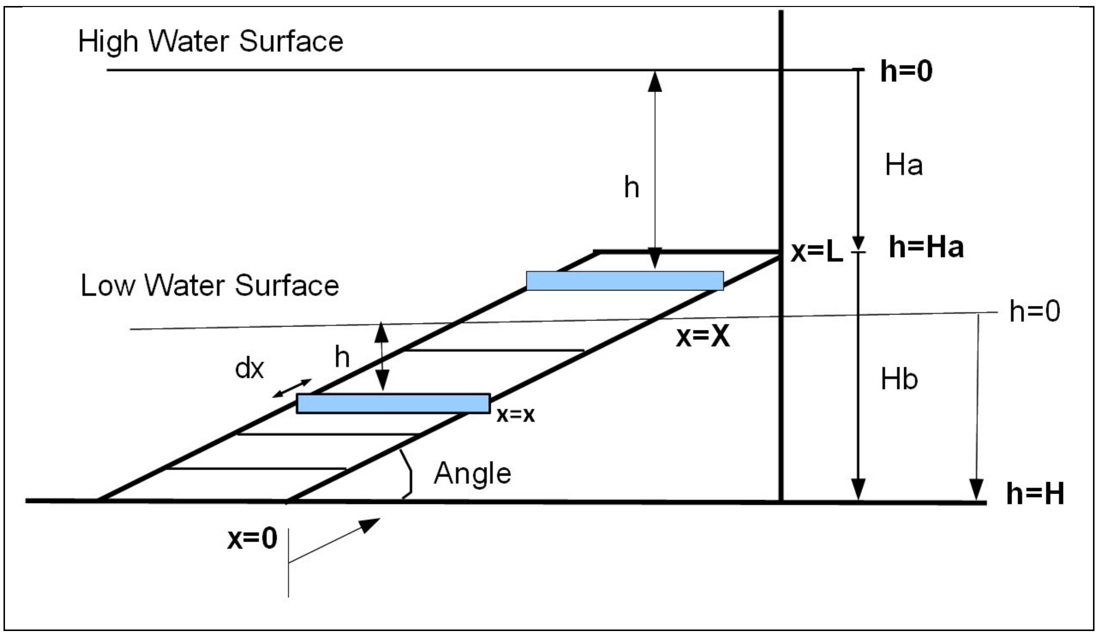


Figure 5 Illustration of Orifice Flow

in which *n* = opening area ratio on grate surface. Referring to Figure 5, the head water depth, h, is related to the wetted length along the lower portion of the grate as:

$$h = (1 - \frac{x}{X})H \tag{16}$$

where X= wetted length that varies between $0 \le X \le L$, x= integration variable that varies between $0 \le x \le X$. Substituting Eq 16 into Eq 2, the flow velocity acting on the flow area is:

$$v = \sqrt{2gh} = \sqrt{2g(1-\frac{x}{X})H} \qquad (H<H_b) \qquad (17)$$

For $H \leq H_b$, the orifice flow, Q_o, through the wetted surface area on the grate is calculated as:

$$Q_o = nC_d \int_{x=0}^{x=X} vdA = nC_d B\cos\theta\sqrt{2gH}\int_{x=0}^{x=X}\sqrt{1-\frac{x}{X}}\,dx = \frac{2}{3}nC_d B X\cos\theta\sqrt{2gH} \qquad (18)$$

Re-arranging Eq 18 yields:

$$Q_o = \frac{2}{3}nC_d BH\cot\theta\sqrt{2gH} \qquad \text{for } H\leq H_b \text{ and } \theta\geq 0 \qquad (19)$$

When *θ=0, X=L, cosθ=1*, Eq 19 is reduced to a horizontal orifice as:

$$Q_o = \frac{2}{3}nC_d BL\sqrt{2gH} \qquad \text{for } H\leq H_b \text{ and } \theta=0 \qquad (20)$$

When the grate is completely submerged, the flow depth is divided into two zones for numerical integration as: (1) above the top of the grate and (2) below the top of the grate. The headwater is expressed as

:

$$h = H - \frac{x}{L}(H-H_a) = H - \frac{x}{L}H_b \qquad (21)$$

Taking the first derivative of Eq 21 yields:

$$dh = -\frac{H_b}{L}dx \qquad (22)$$

The orifice flow through the wetted surface area on the grate is calculated as:

$$Q_o = nC_d \int_{x=0}^{x=L} B\cos\theta\sqrt{2gh}\ dx = nC_d B\cos\theta\sqrt{2g}\int_{x=0}^{x=L}\sqrt{H - H_b\frac{x}{L}}\ dx \quad (23)$$

Integration of Eq 23 yields:

$$Q_o = \frac{2}{3}nC_d BL\cos\theta\sqrt{2gH}\left[\frac{H^{\frac{3}{2}}}{H_b\sqrt{H}} - \frac{(H-H_b)^{\frac{3}{2}}}{H_b\sqrt{H}}\right] \quad (H>H_b) \quad (24)$$

When $H = H_b$ (the water surface just reaches the top of the inclined grate), Eq 24 is reduced to:

$$Q_o = \frac{2}{3}nC_d BL\cos\theta\sqrt{2gH} \quad (25)$$

Eq 19 and Eq 24 produce a continuous function at $H=H_b$.

DESIGN PROCEDURE

The opening ratio, n, is defined as the clear opening area on the grate surface as:

$$n = (1 - C\log)\frac{LB - L_b B}{LB} = (1 - C\log)\frac{L - L_b}{L} \quad (26)$$

Where Clog = clogging factor 0≤Clog≤1.0, and L_b = cumulative width of I-beam bars on grate. Eq 26 indicates that the area opening ratio is equal to the net length ratio on the grate.

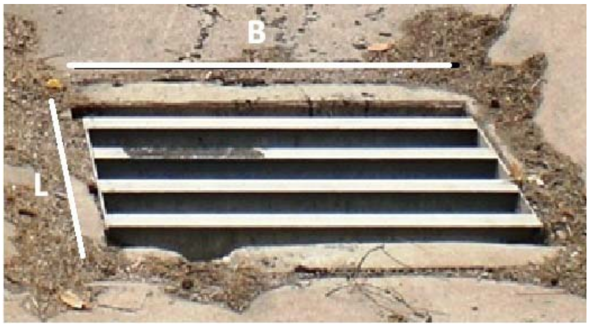


Figure 6 Net Opening Area on Type C Inlet

The governing equations derived in this report are dimensionally consistent when using the flow coefficient, C_d. Table 1 is the summary of the derived equations under various conditions.

Flow Type	Flow Overtopping Two Sides of Inclined Grate	Flow overtopping the Lower Base Width	Condition
Orifice	$Q_o = \frac{2}{3} nC_d BHCot\ \theta\sqrt{2gH} = \frac{2}{3} nC_d BXCos\ \theta\sqrt{2gH}$ Subject to: $X = \frac{H}{Sin\theta} < L$		$H<H_b$ Un-submerged
Weir	$Q_{WS} = \frac{4}{15} nC_d \sqrt{2g} Cot\theta H^{\frac{5}{2}} = \frac{4}{15} nC_d XCos\theta\sqrt{2g} H^{\frac{3}{2}}$ subject to: $X = \frac{H}{Sin\theta} < L$ $Q_W = 2Q_{WS} + Q_{WB}$	$Q_{WB} = \frac{2}{3} nC_d \sqrt{2g} BH^{3/2}$	$H<H_b$ Un-submerged
Orifice	$Q_o = \frac{2}{3} nC_d BLCos\theta\sqrt{2gH}[\frac{H^{\frac{3}{2}}}{H_b\sqrt{H}} - \frac{(H-H_b)^{\frac{3}{2}}}{H_b\sqrt{H}}]$ In case of θ=0 and Hb=0, then $Q_o = \frac{2}{3} nC_d BL\sqrt{2gH}\ if\ \theta = 0$		$H \geq H_b$ Submerged
Weir	$Q_{WS} = \frac{4}{15} nC_d \sqrt{2g} LCos\theta\, H^{\frac{3}{2}}[\frac{H^{\frac{5}{2}}}{H^{\frac{3}{2}} H_b} - \frac{(H-H_b)^{\frac{5}{2}}}{H^{\frac{3}{2}} H_b}]$ In case of θ=0 and Hb=0, then $Q_{WS} = \frac{2}{3} nC_d L\sqrt{2g} H^{\frac{3}{2}}$ $Q_W = 2Q_{WS} + Q_{WB}$	$Q_{WB} = \frac{2}{3} nC_d \sqrt{2g} BH^{3/2}$	$H \geq H_b$ Submerged

Table 1 Equations derived for inclined inlet using flow coefficient, C_d.

Comparing with the conventional approach using orifice and weir hydraulics, the equivalent orifice and weir coefficients are:

$$C_o = \frac{2}{3} C_d \tag{27}$$

$$C_w = \frac{4}{15} C_d \sqrt{2g} \tag{28}$$

Using Eq's (27) and (28), Table 1 is converted to Table 2.

Flow Type	Flow Overtopping Two Sides of Inclined Grate	Flow overtopping the Lower Base Width	Condition
Orifice	$Q_o = nC_o BHCot\theta\sqrt{2gH} = nC_o BXCos\theta\sqrt{2gH}$ Subject to: $X = \frac{H}{Sin\theta} < L$		$H<H_b$ Un-submerged
Weir	$Q_{WS} = n\,C_w Cot\theta\,H^{\frac{5}{2}} = n\,C_w XCos\theta\,H^{\frac{3}{2}}$ subject to: $X = \frac{H}{Sin\theta} < L$ $Q_W = 2Q_{WS} + Q_{WB}$	$Q_{WB} = nC_w BH^{3/2}$	$H<H_b$ Un-submerged
Orifice	$Q_o = nC_o BLCos\theta\sqrt{2gH}[\frac{H^{\frac{3}{2}}}{H_b\sqrt{H}} - \frac{(H-H_b)^{\frac{3}{2}}}{H_b\sqrt{H}}]$ In case of θ=0 and Hb=0, then $Q_o = nC_o BL\sqrt{2gH}\ \ if\ \ \theta = 0$		$H \geq H_b$ Submerged
Weir	$Q_{WS} = nC_w LCos\theta\,H^{\frac{3}{2}}[\frac{H^{\frac{5}{2}}}{H^{\frac{3}{2}}H_b} - \frac{(H-H_b)^{\frac{5}{2}}}{H^{\frac{3}{2}}H_b}]$ In case of θ=0 and Hb=0, then $Q_{WS} = nC_w LH^{\frac{3}{2}}$ $Q_W = 2Q_{WS} + Q_{WB}$	$Q_{WB} = nC_w B\,H^{3/2}$	$H \geq H_b$ Submerged

Table 2 Equations for inclined inlet using orifice coeff, Co, and weir coeff, Cw.

For a given water depth, the interception capacity, Q_c , through an inclined grate is dictated by weir or orifice flows, whichever is less as:

$$Q_c = \min(Q_w, Q_o) \text{ for a given water depth} \tag{29}$$

On the contrary, for a given design flow, the required headwater depth, H, acting on an inclined grate is determined as:

$$H = \max(H_w, H_o) \text{ for a given design flow} \quad (30)$$

Where H_w = headwater for weir flow, H_o= headwater for orifice flow, and H= design headwater.

DATA ANALYSIS

As shown in Figure 7, Laboratory tests were conducted using 1/3-scaled Type C and D inlet models (Comport et. al. 2010). According to the criteria of Froude number simulation, the flow depth in prototype is 3 times the observed flow depth in the model, and the flow rate will be enlarged 15.6 times. Both Type C and D inlets were studied in the laboratory tests. A Type D is formed using two Type C inlets in series (B=3 ft and L=6 ft in Figure 8) or in parallel (B=6 ft and L=3 ft in Figure 9). An in-parallel Type D inlet is also termed rotated Type D. Both Type C and D inlets have an area opening ratio of 0.7.

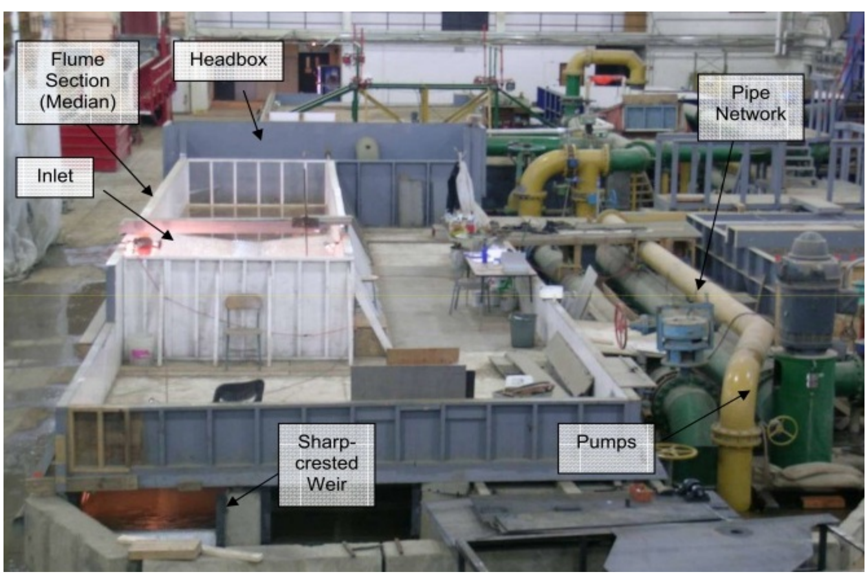
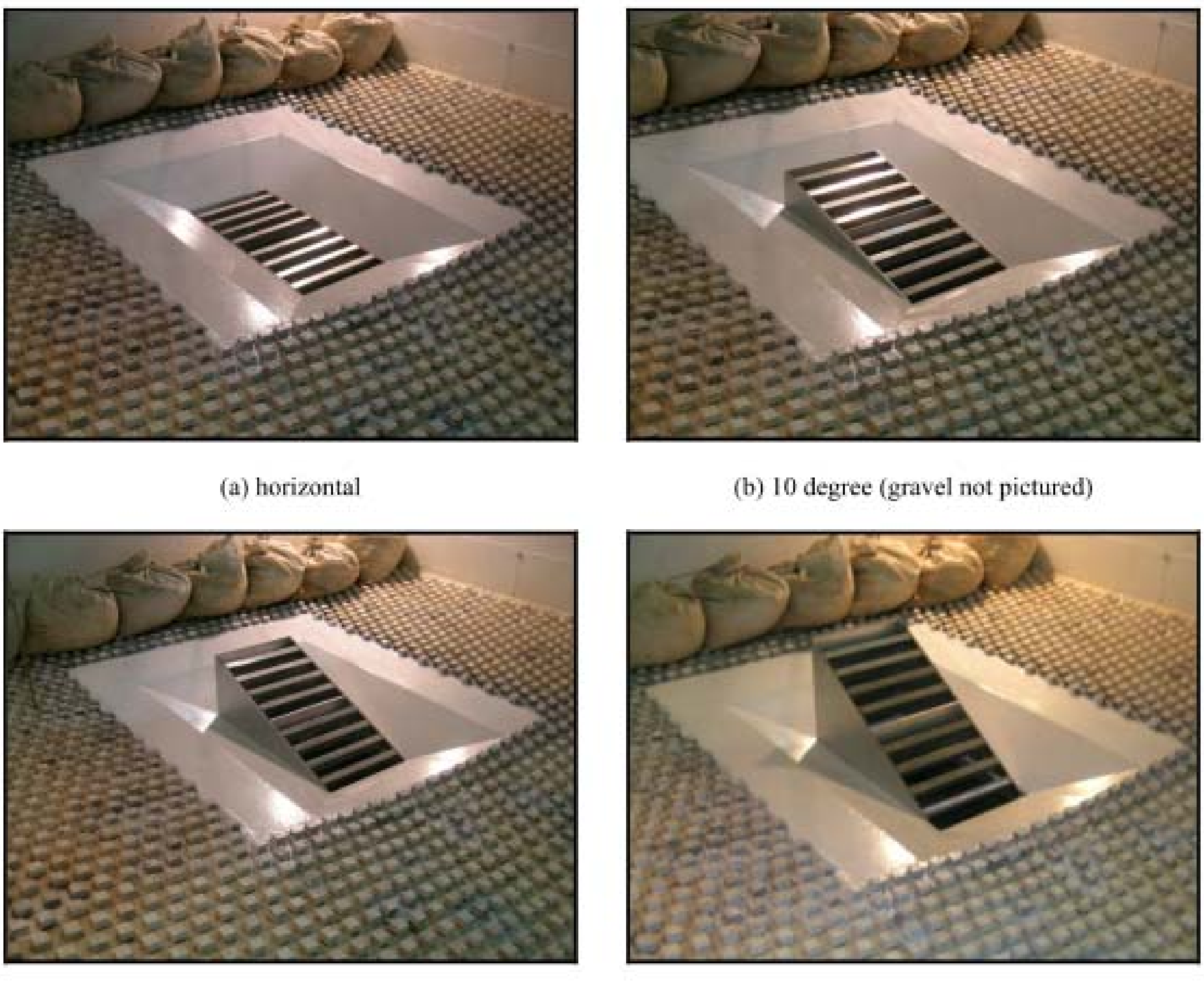


Figure 7 Laboratory Test for Type C and D Inlets

The inclined angles for this study vary from 0 to 30-degree. The model inlet was placed under a condition with or without a depression of one foot. As summarized in Appendix I, II, and III, there were 96 data sets measured at the Hydraulic Laboratory at the Colorado State University (Comport 2010). Each set of data includes flow intercepted by the model inlet and flow depth applied to the front of the model inlet. The values of flow coefficient, C_d, are derived using the least error- square method between the predicted and observed flow rates under the observed flow depths. Appendix IV presents several sample analyses of the depth-flow relationships reported from the laboratory data.



(a) horizontal

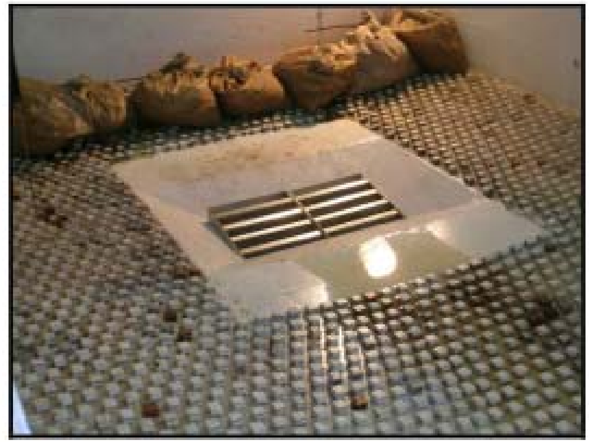
(b) 10 degree (gravel not pictured)

(c) 20 degree (gravel not pictured)

(d) 30 degree (gravel not pictured)

Figure 8 Type D Model formed with two Type C Inlets in Series

(a) horizontal



(b) 10 degree (gravel not pictured)

(c) 20 degree (gravel not pictured)

(d) 30 degree (gravel not pictured)

Figure 9 Rotated Type D Model formed with two Type C Inlets in Parallel

Figures 10 through 12 and Tables 3 through 5 present the flow coefficients for the governing equations derived in this report.

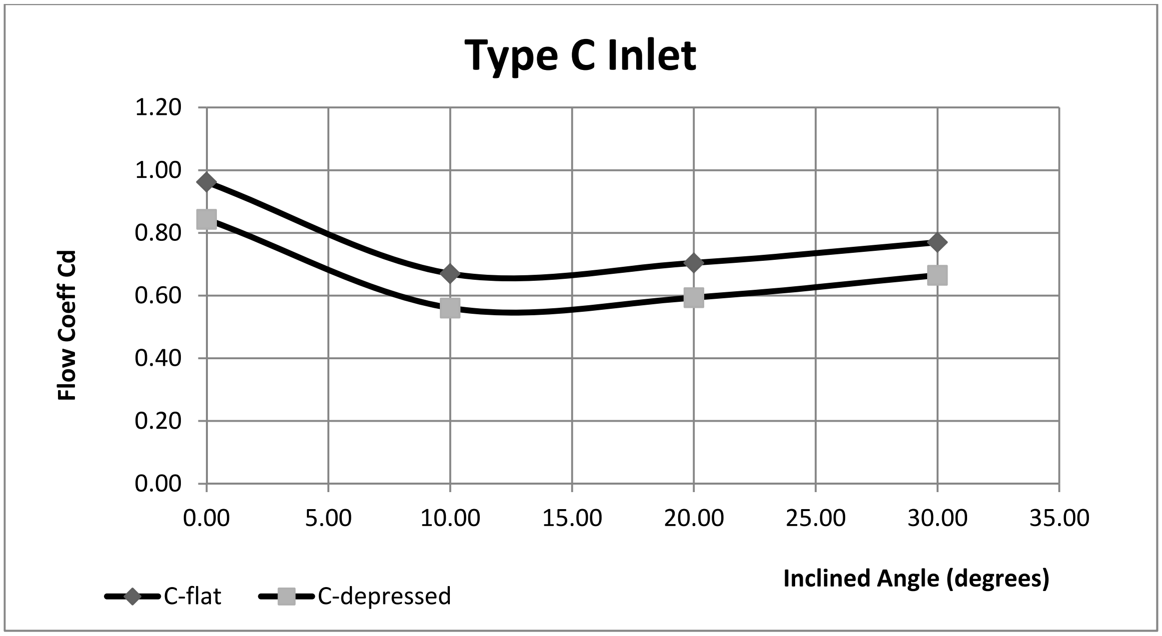


Figure 10 Flow Coefficients Derived for Inclined Type C Inlet

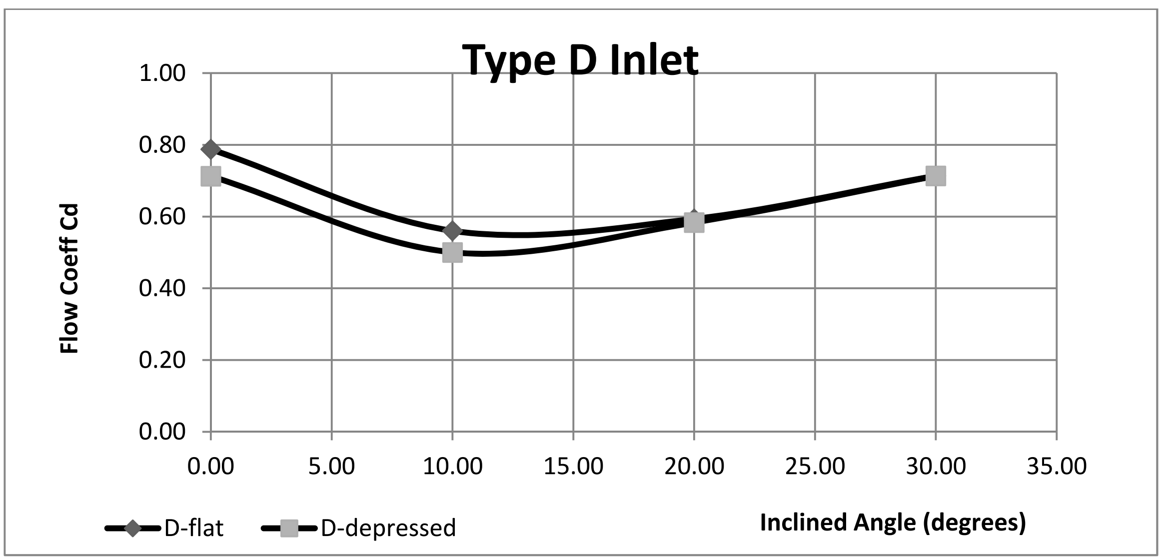


Figure 11 Flow Coefficients Derived for Type D Inlet

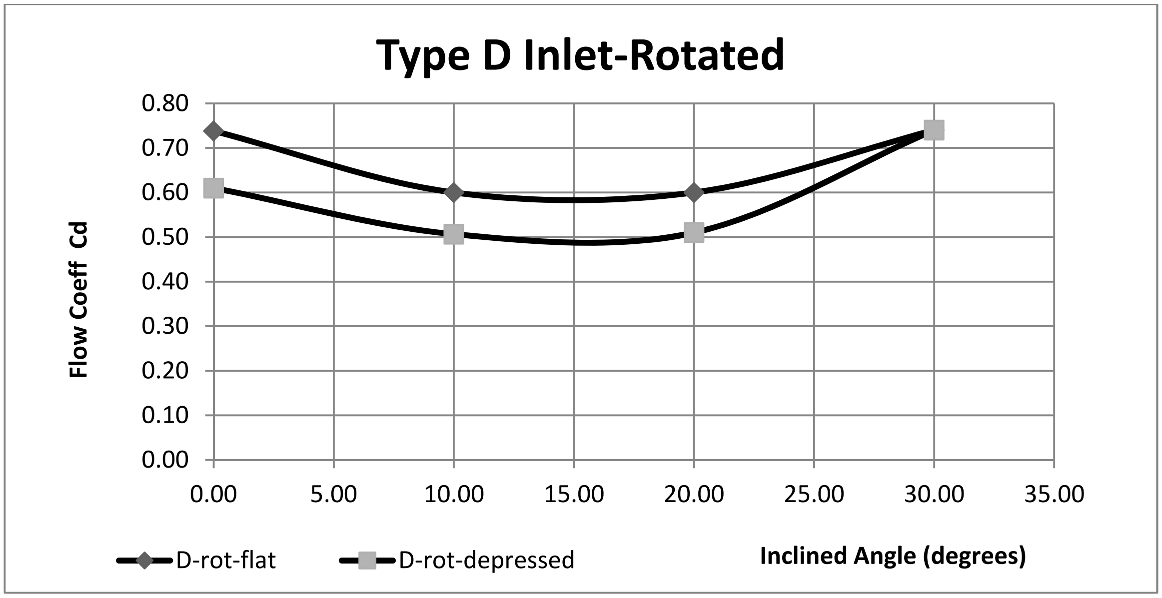


Figure 12 Flow Coefficients Derived for Rotated Type D Inlet

Type of Inlet Condition	Inclined	Angle	(degrees)		Remark
	0.00	10.00	20.00	30.00	
C-flat	0.96	0.67	0.70	0.77	
C-depressed	0.84	0.56	0.59	0.67	1-ft depression
D-flat	0.79	0.56	0.59	0.71	
D-depressed	0.71	0.50	0.58	0.71	1-ft depression
D-rotated	0.74	0.60	0.60	0.74	
D-rotated-depressed	0.61	0.51	0.51	0.74	1-ft depression

Table 3 Flow Coefficients

Type of Inlet Condition	Inclined	Angle	(degrees)		Remark
	0.00	10.00	20.00	30.00	
C-flat	0.64	0.45	0.47	0.51	
C-depressed	0.56	0.37	0.40	0.44	1-ft depression
D-flat	0.53	0.37	0.40	0.48	
D-depressed	0.48	0.33	0.39	0.48	1-ft depression
D-rotated	0.49	0.40	0.40	0.49	
D-rotated-depressed	0.41	0.34	0.34	0.49	1-ft depression

Table 4 Equivalent Orifice Coefficients

Type of Inlet Condition	Inclined	Angle	(degrees)		Remark
	0.00	10.00	20.00	30.00	
C-flat	2.06	1.43	1.51	1.65	
C-depressed	1.80	1.20	1.27	1.42	1-ft depression
D-flat	1.69	1.20	1.27	1.53	
D-depressed	1.53	1.07	1.25	1.53	1-ft depression
D-rotated	1.58	1.28	1.28	1.58	
D-rotated-depressed	1.31	1.08	1.09	1.58	1-ft depression

Table 5 Equivalent Weir Coefficients for English Units

Type of Inlet Condition	Inclined	Angle	(degrees)		Remark
	0.00	10.00	20.00	30.00	
C-flat	1.14	0.79	0.83	0.91	
C-depressed	1.00	0.66	0.70	0.79	1-ft depression
D-flat	0.93	0.66	0.70	0.84	
D-depressed	0.84	0.59	0.69	0.84	1-ft depression
D-rotated	0.87	0.71	0.71	0.87	
D-rotated-depressed	0.72	0.60	0.60	0.87	1-ft depression

Table 6 Equivalent Weir Coefficients for Metric Units

CLOGGING EFFECT

Type C and Type D inlets are susceptible to debris clogging. To be conservative, a clogging factor of 0.5 is recommended for a Type C inlet (Guo 2000C). For a Type D inlet, the decay-based clogging is recommended (Guo 2006). Namely, the first grate is subject to a clogging factor of 0.5 and the second grate may have a clogging potential of 0.25. Or, an average clogging factor of 0.375 is applicable to two grates, i.e. a Type D inlet.

	
Clogged Type D Inlet	Accumulation of Debris around Ty D inlet

Figure 13 Clogging Condition around Type D Inlet in Field

CONCLUSION

Tables 1 and 2 summarize the new formulas developed to design Type C and D inlets for highway median drainage systems. The inclined angle can be raised from 0 to 30 degrees for debris control. When the inlet is laid flat on the ground, the equations in Tables 1 and 2 are reduced to the conventional equations recommended for a horizontal inlet.

Tables 3 through 6 present the best-fitted values for flow coefficient, C_d, orifice coefficient, C_o, and weir coefficient, C_w, derived from 92 sets of laboratory data. Although the flow coefficient used in the new equations in Table 1 is dimensionless, workable with both English and Metric units, it can be converted into the conventional orifice and weir flow coefficients in Table 2. Care needs to be taken because the value of weir coefficient is unit dependent.

In comparison, a flat Type C inlet has the highest flow interception capacity compared to the inclined. To compensate the clogging effect, an inclined angle is recommended. The laboratory data indicate that there is a tradeoff between the reduction on clogging coefficient and the decrease in flow interception. With the recommended flow coefficients, the engineer can select the design parameters based on the optimal performance of the inlet under the specified condition in the field.

REFERENCES

AASHTO (2007). " Highway Drainage Guidelines, 4th Edition.

CDOT (2004) "Drainage Design Manual", Colorado of Department of Transportation, Denver, Colorado.

Comport, B.C., Cox, A. L., and Thornton C. (2010). "Performance Assessment of Grate Inlets for Highway Median Drainage", submitted to UDFCD, Denver, Colorado.

Guo, James C.Y. and McKenzie, K, and Mommandi, A. (2008) "*Sump Inlet Hydraulics*", ASCE J. of Hydraulic Engineering, Vol 135, No 1, Nov.

Guo, James C.Y. (2000A). "*Street* Storm Water Conveyance Capacity," ASCE J. of Irrigation and Drainage Engineering, Vol 126, No 2, Mar/Apr,

Guo, James C.Y. (2000B). "Street Storm Water Storage Capacity", J. of Water Environment Research, Vol 27, No 6., Sept./Oct.

Guo, James C.Y. (2006). "Decay-based Clogging Factor for Curb Inlet Design", Vol 132, No. 11, ASCE J. of Hydraulic Engineering, November.

Guo, James C.Y. (2000C). "Design of Grate Inlets with a Clogging Factor," Advances in Environmental Research, Vol 4, Elsvier Science, Ireland.

Guo, James C.Y. (1999). "Street Hydraulics and Inlet Sizing", published by WRP Company, Littleton, Colorado.

HEC 12, (1984). "*Drainage of Highway Pavements"*, US Department of Transportation, Federal Highway Administration Washington D.C., Virginia.

HEC 22 (2002) *"Urban Drainage Design Manual* , US Department of Transportation, Federal Highway Administration, Washington D.C., Virginia.

Huebner, R.S., Reed, J.R., and Henry, J.J., (1986) "*Criteria for Predicting Hydroplaning Potential*," ASCE Journal of Transportation Engineering, Vol 12, No 5, September.

Mays, L (2001) "Stormwater Collection Systems Design Handbook", published by McGraw Hill Publication Company in August.

McEnroe, M.B., Wade, P. R. and Smith, A.K. (1999). "Hydraulic Performance of Curb and Gutter Inlets", Report No. K-TRAN: KU-99-1, Kansas Department of Transportation, September.

USWDCM (2001) "*Storm Water Design Criteria Manual*," Vol 1 and 2, Urban Drainage and Flood Control District, Denver, Colorado

Appendix 1 Laboratory Data for Type C Inlet

	Laboratory		Observation			
Test	Configuration	Grate angle (deg)	Inlet Depth (ft)	Flow measured (cfs)	Prototype Inlet Depth (ft)	Prototype flow (cfs)
1	C	0	0.352	1.84	1.06	28.7
2	C	0	0.513	2.46	1.54	38.3
3	C	0	0.795	3.39	2.39	52.8
4	C	0	1.037	3.75	3.11	58.4
6	C	10	0.370	1.85	1.11	28.8
7	C	10	0.528	2.46	1.58	38.3
8	C	10	0.765	3.14	2.30	48.9
9	C	10	1.044	3.62	3.13	56.4
11	C	20	0.369	1.72	1.11	26.8
12	C	20	0.506	2.24	1.52	34.9
13	C	20	0.798	2.98	2.39	46.4
14	C	20	0.989	3.41	2.97	53.1
16	C	30	0.362	1.53	1.09	23.8
17	C	30	0.516	2.24	1.55	34.9
18	C	30	0.748	2.86	2.24	44.6
19	C	30	1.008	3.50	3.02	54.5
21	C depressed	0	0.668	1.95	2.00	30.4
22	C depressed	0	0.834	2.43	2.50	37.9
23	C depressed	0	1.089	3.60	3.27	56.1
24	C depressed	0	1.365	4.23	4.10	65.9
26	C depressed	10	0.707	1.87	2.12	29.1
27	C depressed	10	0.864	2.50	2.59	39.0
28	C depressed	10	1.118	3.43	3.35	53.4
29	C depressed	10	1.341	4.04	4.02	62.9
31	C depressed	20	0.639	2.35	1.92	36.6
32	C depressed	20	0.840	2.42	2.52	37.7
33	C depressed	20	1.098	3.25	3.29	50.6
34	C depressed	20	1.337	3.89	4.01	60.6
36	C depressed	30	0.685	2.55	2.06	39.7
37	C depressed	30	0.825	2.84	2.48	44.2
38	C depressed	30	1.078	3.25	3.23	50.6
39	C depressed	30	1.345	3.99	4.04	62.2

Appendix II Laboratory Data for Rotated Type D Inlet

	Laboratory		Observation			
Test	Configuration	Grate angle (deg)	Inlet Depth (ft)	Flow measured (cfs)	Prototype Inlet Depth (ft)	Prototype flow (cfs)
41	D rotated depressed	0	0.632	4.46	**1.90**	**69.5**
42	D rotated depressed	0	0.849	3.80	**2.55**	**59.2**
43	D rotated depressed	0	1.080	5.55	**3.24**	**86.5**
44	D rotated depressed	0	1.354	7.93	**4.06**	**123.5**
46	D rotated depressed	10	0.638	4.16	**1.91**	**64.8**
47	D rotated depressed	10	0.856	3.44	**2.57**	**53.6**
48	D rotated depressed	10	1.074	5.06	**3.22**	**78.8**
49	D rotated depressed	10	1.327	7.68	**3.98**	**119.7**
51	D rotated depressed	20	0.673	4.27	**2.02**	**66.5**
52	D rotated depressed	20	0.826	3.85	**2.48**	**60.0**
53	D rotated depressed	20	1.083	5.12	**3.25**	**79.8**
54	D rotated depressed	20	1.341	6.97	**4.02**	**108.6**
56	D rotated depressed	30	0.663	4.68	**1.99**	**72.9**
57	D rotated depressed	30	0.839	4.70	**2.52**	**73.2**
58	D rotated depressed	30	1.080	5.70	**3.24**	**88.8**
59	D rotated depressed	30	1.377	7.23	**4.13**	**112.6**
101	D rotated	0	0.334	2.55	**1.00**	**39.7**
102	D rotated	0	0.494	2.95	**1.48**	**46.0**
103	D rotated	0	0.758	4.75	**2.27**	**74.0**
104	D rotated	0	1.001	6.60	**3.00**	**102.8**
106	D rotated	10	0.354	2.45	**1.06**	**38.2**
107	D rotated	10	0.488	2.90	**1.46**	**45.2**
108	D rotated	10	0.753	4.30	**2.26**	**67.0**
109	D rotated	10	1.008	6.70	**3.02**	**104.4**
111	D rotated	20	0.332	2.07	**1.00**	**32.3**
112	D rotated	20	0.503	3.75	**1.51**	**58.4**
113	D rotated	20	0.745	4.50	**2.24**	**70.1**
114	D rotated	20	1.014	6.45	**3.04**	**100.5**
116	D rotated	30	0.353	2.45	**1.06**	**38.2**
117	D rotated	30	0.518	3.82	**1.55**	**59.5**
118	D rotated	30	0.761	5.02	**2.28**	**78.2**
119	D rotated	30	1.025	6.50	**3.08**	**101.3**

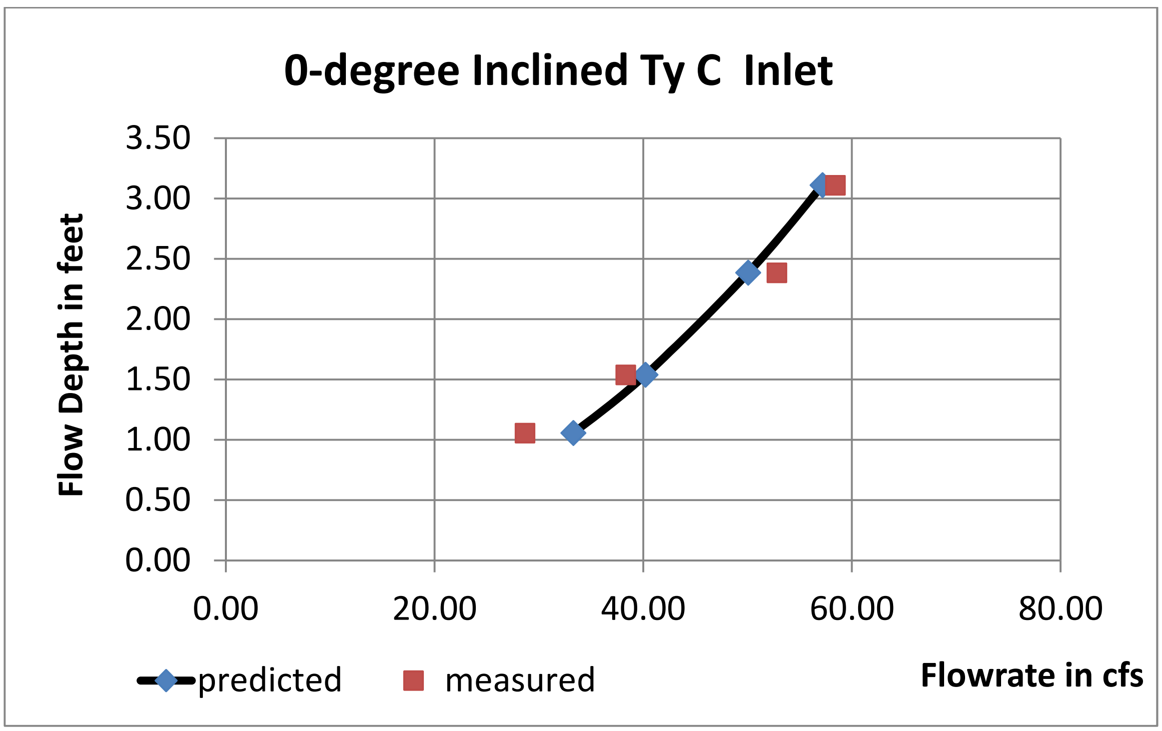
Appendix III Laboratory Data for Type D Inlet

	Laboratory		Observation			
Test	Configuration	Grate angle (deg)	Inlet Depth (ft)	Flow measured (cfs)	Prototype Inlet Depth (ft)	Prototype flow (cfs)
61	D depressed	0	0.657	4.06	1.97	63.3
62	D depressed	0	0.979	4.45	2.94	69.3
63	D depressed	0	1.075	5.11	3.23	79.6
64	D depressed	0	1.345	7.55	4.04	117.6
66	D depressed	10	0.660	3.87	1.98	60.3
67	D depressed	10	0.932	4.13	2.80	64.3
68	D depressed	10	1.094	5.32	3.28	82.9
69	D depressed	10	1.336	6.95	4.01	108.3
71	D depressed	20	0.673	3.54	2.02	55.2
72	D depressed	20	0.846	4.35	2.54	67.8
73	D depressed	20	1.085	5.36	3.26	83.5
74	D depressed	20	1.326	6.65	3.98	103.6
76	D depressed	30	0.674	3.24	2.02	50.5
77	D depressed	30	0.844	4.62	2.53	72.0
78	D depressed	30	1.101	5.55	3.30	86.5
79	D depressed	30	1.332	6.79	4.00	105.8
81	D	0	0.323	2.24	0.97	34.9
82	D	0	0.509	3.39	1.53	52.8
83	D	0	0.749	5.20	2.25	81.0
84	D	0	1.005	6.63	3.02	103.3
86	D	10	0.366	2.00	1.10	31.2
87	D	10	0.513	3.43	1.54	53.4
88	D	10	0.770	4.88	2.31	76.0
89	D	10	1.015	6.15	3.05	95.8
91	D	20	0.335	1.11	1.01	17.3
92	D	20	0.504	2.27	1.51	35.4
93	D	20	0.758	4.20	2.27	65.4
94	D	20	1.001	5.60	3.00	87.2
96	D	30	0.358	1.29	1.07	20.1
97	D	30	0.528	2.19	1.58	34.1
98	D	30	0.780	3.52	2.34	54.8
99	D	30	1.022	4.99	3.07	77.7

Appendix IV Sample Analyses for Flow Coefficients

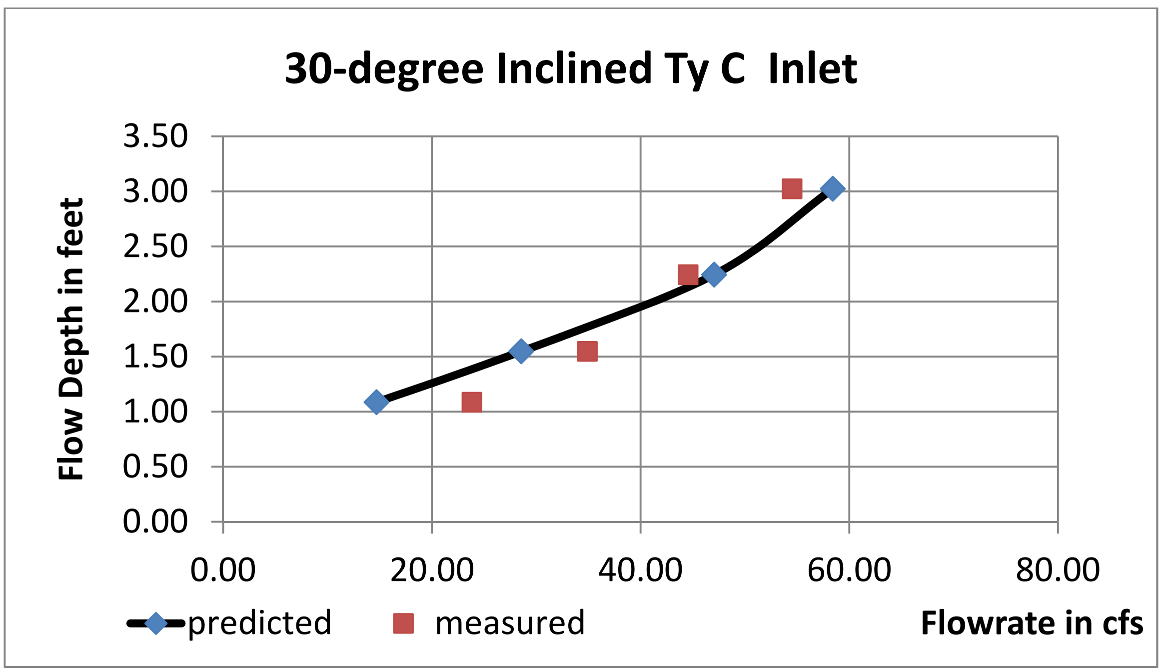
Width of Grate	B	3.00		(input)
Inclined Length of Grate	L	3.00	ft	
Opening Ratio of Grate	n	0.70		(input)
Grate Discharge Coeff	Cd	0.96		(input)
Height of Box	Hb=	0.00	ft	
Inclined Angle	@	0.00	degree	(input)
Orifice/ Weir Coeff	Co=	0.64	Cw=	2.06
Orientation	Ko=	0		

Water Depth H ft	Submerged Side Weir Length ft (X)	Inclined Left S Weir cfs	Inclined Right S Weir cfs	Base Weir cfs	Total Weir cfs	Total Orifice cfs	Predcited Flow cfs	Observed Flow cfs	Error %	Sq error cfs^2
1.06	3.00	11.73	11.73	16.76	40.21	33.32	**33.32**	**28.7**	-16.23%	21.66
1.54	3.00	20.64	20.64	29.48	70.75	40.23	**40.23**	**38.3**	-4.96%	3.61
2.39	3.00	39.81	39.81	56.87	136.49	50.08	**50.08**	**52.8**	5.19%	7.51
3.11	3.00	59.31	59.31	84.73	203.34	57.19	**57.19**	**58.4**	2.11%	1.52
										34.29



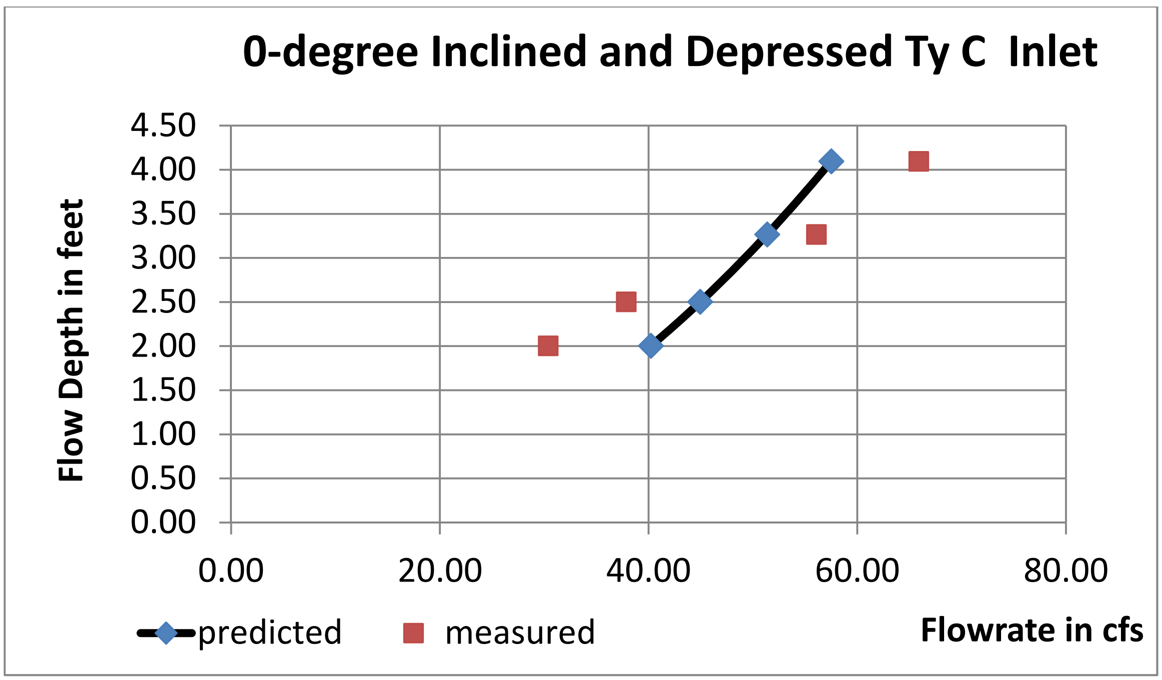
Width of Grate	B	3.00		(input)	
Inclined Length of Grate	L	3.00	ft		
Opening Ratio of Grate	n	0.70		(input)	
Grate Discharge Coeff	Cd	0.77		(input)	
Height of Box	Hb=	1.50	ft		
Inclined Angle	@	30.00	degree	(input)	
Orifice/ Weir Coeff	Co=	0.51	Cw=	1.65	
Orientation	Ko=	0			

Water Depth H ft	Submerged Side Weir Length ft (X)	Inclined Left S Weir cfs	Inclined Right S Weir cfs	Base Weir cfs	Total Weir cfs	Total Orifice cfs	Predcited Flow cfs	Observed Flow cfs	Error %	Sq error cfs^2
1.09	2.17	2.46	2.46	9.79	14.70	19.58	**14.70**	**23.8**	38.33%	83.46
1.55	3.00	5.96	5.96	16.66	28.57	33.14	**28.57**	**34.9**	18.13%	40.03
2.24	3.00	14.12	14.12	29.08	57.31	47.06	**47.06**	**44.6**	-5.60%	6.23
3.02	3.00	26.04	26.04	45.49	97.58	58.43	**58.43**	**54.5**	-7.15%	15.21
										144.93



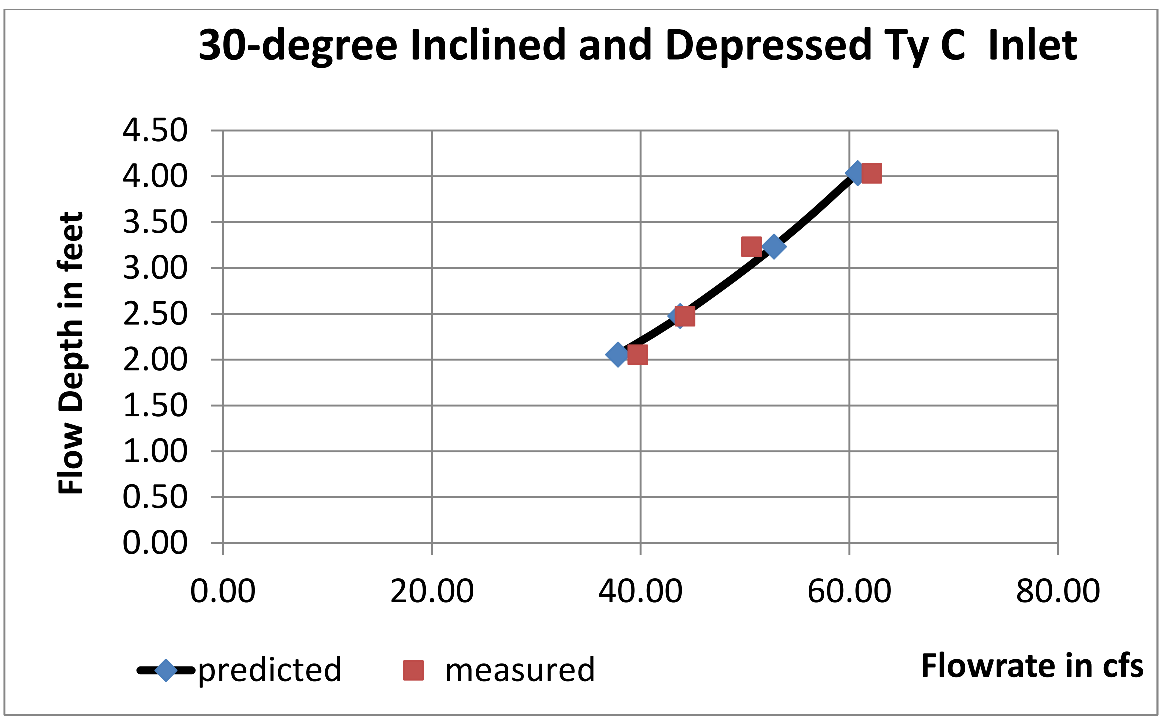
Width of Grate	B	3.00		(input)					
Inclined Length of Grate	L	3.00	ft						
Opening Ratio of Grate	n	0.70		(input)					
Grate Discharge Coeff	Cd	0.84		(input)					
Height of Box	Hb=	0.00	ft						
Inclined Angle	@	0.00	degree	(input)					
Orifice/ Weir Coeff	Co=	0.56	Cw=	1.80					
Orientation	Ko=	0							

Water Depth H ft	Submerged Side Weir Length ft (X)	Inclined Left S Weir cfs	Inclined Right S Weir cfs	Base Weir cfs	Total Weir cfs	Total Orifice cfs	Predcited Flow cfs	Observed Flow cfs	Error %	Sq error cfs^2
2.00	3.00	26.88	26.88	26.88	80.65	40.24	**40.24**	**30.4**	-32.47%	97.28
2.50	3.00	37.50	37.50	37.50	112.51	44.97	**44.97**	**37.9**	-18.77%	50.52
3.27	3.00	55.96	55.96	55.96	167.87	51.38	**51.38**	**56.1**	8.39%	22.13
4.10	3.00	78.53	78.53	78.53	235.58	57.53	**57.53**	**65.9**	12.71%	70.14
										240.08



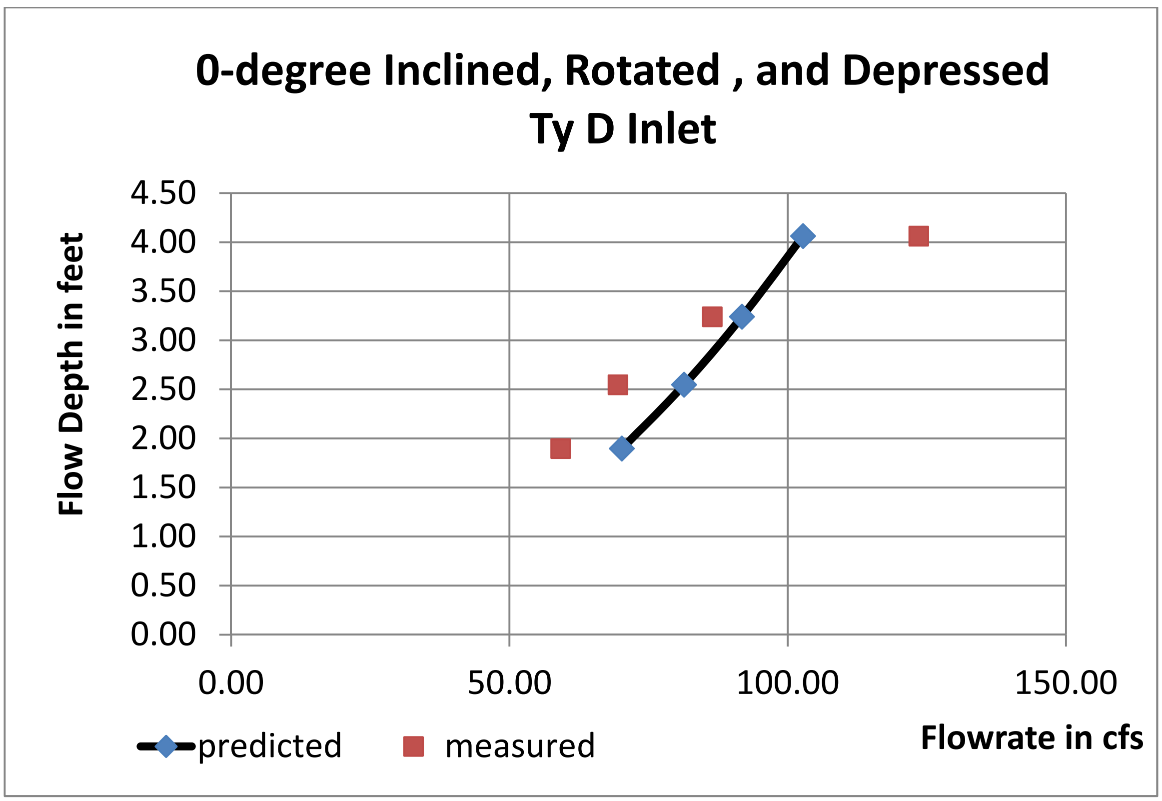
Width of Grate	B	3.00		(input)
Inclined Length of Grate	L	3.00	ft	
Opening Ratio of Grate	n	0.70		(input)
Grate Flow Coeff	Cd	0.67		(input)
Height of Box	Hb=	1.50	ft	
Inclined Angle	@	30.00	degree	(input)
Orifice/ Weir Coeff	Co=	0.44	Cw=	1.42
Orientation	Ko=	0		

Water	Submerged Side	Inclined	Inclined	Base	Total	Total	Predcited	Observed	Error	Sq error
Depth H	Weir Length	Left S Weir	Right S Weir	Weir	Weir	Orifice	Flow	Flow		
ft	ft (X)	cfs	cfs	cfs	cfs	cfs	cfs	cfs	%	cfs^2
2.06	3.00	10.05	10.05	22.01	42.12	37.85	**37.85**	**39.7**	4.73%	3.54
2.48	3.00	15.01	15.01	29.10	59.12	43.81	**43.81**	**44.2**	1.00%	0.20
3.23	3.00	25.63	25.63	43.46	94.71	52.79	**52.79**	**50.6**	-4.26%	4.66
4.04	3.00	38.78	38.78	60.57	138.14	60.81	**60.81**	**62.2**	2.17%	1.82
										10.22



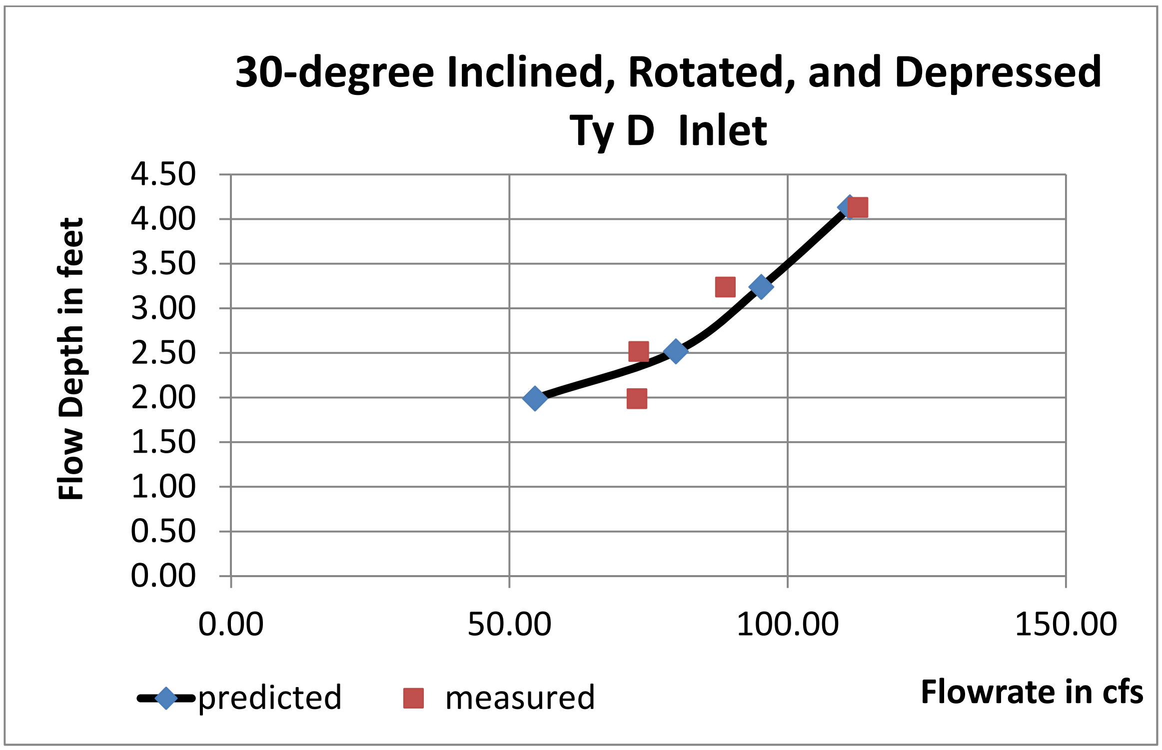
Width of Grate	B	3.00		(input)
Inclined Length of Grate	L	6.00	ft	
Opening Ratio of Grate	n	0.70		(input)
Grate Discharge Coeff	Cd	0.76		(input)
Height of Box	Hb=	0.00	ft	
Inclined Angle	@	0.00	degree	(input)
Orifice/ Weir Coeff	Co=	0.50	Cw=	1.62
Orientation	Ko=	0		

Water Depth H ft	ubmerged Si Weir Length ft (X)	Inclined Left S Weir cfs	Inclined Right S Weir cfs	Base Weir cfs	Total Weir cfs	Total Orifice cfs	Predcited Flow cfs	Observed Flow cfs	Error %	Sq error cfs^2
1.90	6.00	44.38	44.38	22.19	110.94	70.22	**70.22**	**59.2**	-18.61%	121.38
2.55	6.00	69.09	69.09	34.55	172.74	81.38	**81.38**	**69.5**	-17.10%	141.22
3.24	6.00	99.13	99.13	49.57	247.83	91.79	**91.79**	**86.5**	-6.15%	28.31
4.06	6.00	139.16	139.16	69.58	347.90	102.78	**102.78**	**123.5**	16.81%	431.52
										722.43



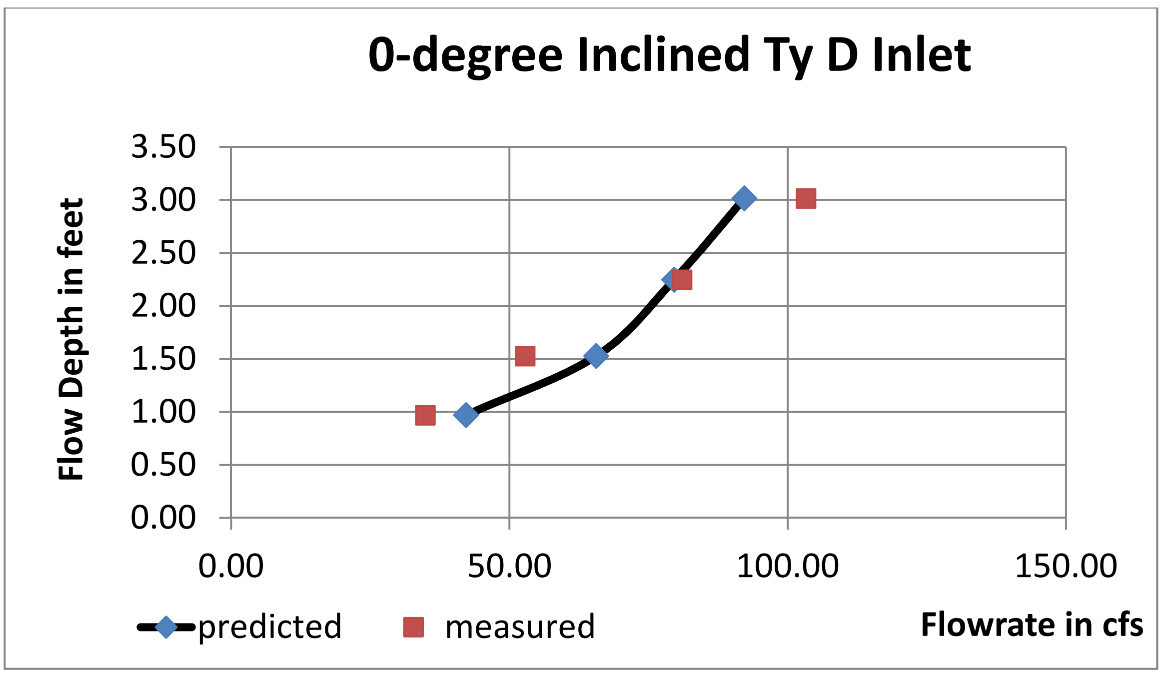
Width of Grate	B	6.00		(input)						
Inclined Length of Grate	L	3.00	ft							
Opening Ratio of Grate	n	0.70		(input)						
Grate Discharge Coeff	Cd	0.60		(input)						
Height of Box	Hb=	1.50	ft							
Inclined Angle	@	30.00	degree	(input)						
Orifice/ Weir Coeff	Co=	0.40	Cw=	1.28						
Orientation	Ko=	0								

Water Depth H ft	Submerged Side Weir Length ft (X)	Inclined Left S Weir cfs	Inclined Right S Weir cfs	Base Weir cfs	Total Weir cfs	Total Orifice cfs	Predcited Flow cfs	Observed Flow cfs	Error %	Sq error cfs^2
1.99	3.00	8.42	8.42	37.78	54.62	66.35	**54.62**	**72.9**	25.09%	334.79
2.52	3.00	14.01	14.01	53.79	81.80	79.94	**79.94**	**73.2**	-9.17%	45.08
3.24	3.00	23.18	23.18	78.55	124.90	95.27	**95.27**	**88.8**	-7.28%	41.81
4.13	3.00	36.48	36.48	113.09	186.05	111.21	**111.21**	**112.6**	1.27%	2.04
										423.72



Width of Grate	B	3.00		(input)
Inclined Length of Grate	L	6.00	ft	
Opening Ratio of Grate	n	0.70		(input)
Grate Discharge Coeff	Cd	0.79		(input)
Height of Box	Hb=	0.00	ft	
Inclined Angle	@	0.00	degree	(input)
Orifice/ Weir Coeff	Co=	0.53	Cw=	1.69
Orientation	Ko=	0		

Water Depth H ft	ıbmerged Si Weir Length ft (X)	Inclined Left S Weir cfs	Inclined Right S Weir cfs	Base Weir cfs	Total Weir cfs	Total Orifice cfs	Predcited Flow cfs	Observed Flow cfs	Error %	Sq error cfs^2
0.97	6.00	16.89	16.89	8.44	42.22	52.28	**42.22**	**34.9**	-20.97%	53.58
1.53	6.00	33.41	33.41	16.70	83.52	65.63	**65.63**	**52.8**	-24.27%	164.26
2.25	6.00	59.63	59.63	29.82	149.08	79.62	**79.62**	**81.0**	1.73%	1.96
3.02	6.00	92.69	92.69	46.34	231.71	92.22	**92.22**	**103.3**	10.72%	122.57
										342.37



Width of Grate		B	3.00		(input)					
Inclined Length of Grate		L	6.00	ft						
Opening Ratio of Grate		n	0.70		(input)					
Grate Flow Coeff		Cd	0.68		(input)					
Height of Box		Hb=	3.00	ft						
Inclined Angle		@	30.00	degree	(input)					
Orifice/ Weir Coeff		Co=	0.45	Cw=	1.45					
Orientation		Ko=	0							

Water Depth H ft	Submerged Side Weir Length ft (X)	Inclined Left S Weir cfs	Inclined Right S Weir cfs	Base Weir cfs	Total Weir cfs	Total Orifice cfs	Predcited Flow cfs	Observed Flow cfs	Error %	Sq error cfs^2
1.07	2.15	2.10	2.10	8.47	12.67	16.94	**12.67**	**20.1**	36.95%	55.15
1.58	3.17	5.55	5.55	15.17	26.27	30.34	**26.27**	**34.1**	23.00%	61.60
2.34	4.68	14.72	14.72	27.24	56.68	54.48	**54.48**	**54.8**	0.66%	0.13
3.07	6.00	28.93	28.93	40.86	98.71	81.45	**81.45**	**77.7**	-4.77%	13.74
										130.62