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## **STREET INLET IN SUMP**

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### ***Abstract***

Sump inlets are used to collect storm water on the streets or to release stored water in detention basins. The complication of sump inlet hydraulics is manifested by the unclear intermingling process between weir and orifice flows and the vortices in the flow pattern. Over the years, the capacity of a sump inlet has been assumed to be either weir or orifice flow, whichever is smaller for a given water depth. Although this practice might not result in a failure to the storm drain, it has led to randomly oversize or undersize inlets. This paper presents a laboratory investigation of the interception capacities of several different types of sump inlets, including bar and vane grates, and 3- and 5-ft curb opening inlets. The observed data revealed significant differences from the recommended HEC 22 design procedure. In this study, new formulas and procedures are developed with the coefficients calibrated by the laboratory data. In comparison, this new method well agrees with the observed data and can consistently size the various types of inlets according to the design condition.

***Key words:*** Street hydraulics, Sump inlet, Grate, Curb-opening, Combination, Type 13, and Type 16.

## **INTRODUCTION**

Water on the street generates potential safety hazards - such as hydroplaning - to moving vehicles (Agrawal et. al. 1977). The principal concern in street drainage is to remove storm water from the street as quickly as possible (Huebner et. al. 1986). The geometry of a street's cross section plays a key role in storm water drainage design. In general, storm water on the street is modeled as a wide, triangular channel that has variable depths across the tapered street gutter, with a deeper depth at the face of the curb and zero depth at the roadway shoulder or driving lane. The street hydraulic conveyance capacity (SHCC) is proportional to the longitudinal slope (McEnroe et. al. 1999) while the street hydraulic storage capacity (SHSC) is related to the gutter geometry (Guo 2000A). Stormwater on the street flows away from the street crown toward the curb. The street gutter then collects the stormwater and conveys it downstream to the inlets. To provide positive drainage by gravity, a recommended minimum longitudinal grade for a street is (+/-) 0.50% (AASHTO, 1990). However, low points are created where a roadway segment of positive grade joins with a segment of negative grade. Likewise, a sump is usually created at a street corner that is confined by street curbs and crowns (Guo 2000B). Hydraulically, inlets are classified into two categories: in-sump and on-grade. In current practice, most street drainage criteria were developed for the SHCC. For instance, the allowable water spread and inlet interception capacity are solely determined by the water flow on a sloping street (USWDCM 2001). At a sump condition, where total interception is required, an inlet is assumed to operate like either a weir or an orifice (HEC 12). The demarcation between weir and orifice flows is not well understood. As a result, drainage manuals simply suggest that for a given flow depth, the sump inlet capacity is selected as the smaller value between orifice flow and weir flow (USWDCM 2001).

Over the years, the Colorado Department of Transportation and metro Denver governments have jointly spent millions of dollars to install inlets on streets and highways (CODT 2004). The field reports in-

dicating that some of the sump inlets were found to be unnecessarily long while others were inadequate. It has become an increasing concern as to how to properly design a sump inlet according to the flow nature (Guo 2006). This study was conducted as an attempt to refine the current design methods for sump inlets. A 1/3-scale laboratory model was built in a 3.5-meter flume that was used to simulate the street flow around a sump inlet. Several sets of data were collected for grate, curb opening, and combination inlets. In this study, it was found that the current design procedure applies inconsistent parameters to size an inlet under various sump conditions. Based on the laboratory data from this study, the procedure for sump inlet design has been significantly revised and all design parameters have been consistently calibrated and then recommended for sizing various types of street inlets.

## FLUME TESTS FOR SUMP INLET

As recommended, an inlet must be installed wherever the water spread exceeds the allowable limit on a sloping street (CDOT 2004). The major parameters for a street section include street width, water spread, gutter width, gutter depression, and slopes. In an urban area, a straight street section has a uniform transverse slope while a composite cross section includes an additional gutter depression. The street transverse slope is a compromise between drainage efficiency, driver comfort, and vehicle stability. Anderson (1993) outlined various roadway cross sections and the necessary parameters involved in the determination of a transverse slope. As recommended, the transverse slope is recommended to be 1 or 2.0% on roadway pavements (Mays 2001). At a sump, the accumulated water volume is dictated by the incoming street flow and the inlet interception. The water depth and the inlet size are the key factors to determine the flow interception.

In the laboratory, a 3.5-m wide flume was built to model the street curb and gutter on a longitudinal slope of 1.0% and a transverse slope of 1%. All model parameters were determined using Froude number similarity with a length scale of 1/3. A sump was created 3.5-m upstream of the closed end of the flume. The water depth at the sump reflects the equilibrium condition between the inflow and the outflow. Inlets modeled in the laboratory tests include: (1) Bar grate (Type 13 inlet), (2) Vane grate (Type 16 inlet), (3) 3-ft Curb-opening, (4) 5-ft Curb-opening (Type R inlet), (5) Combination 13 using a bar grate and 3-ft curb opening, and (6) Combination 16 using a vane grate and 3-ft curb-opening. Their prototype dimensions are listed in Table 1 and construction details can be found elsewhere (Standard Plan 2001, Standard Details 1994). Photo 1 is the prototype Combination 13 inlet using a bar grate and 3-ft curb-opening inlets.

Grate Dimension	Bar Grate	Vane Grate	5-ft Curb-opening	3-ft Curb-opening	Combination 13	Combination 16
Length in ft	2.96	2.96	5.0	3.0	2.96	2.96
Width in ft	1.58	1.65	N/A	N/A	1.58	1.65
Opening Height in ft			0.5	0.5	0.5	0.5
Steel Bar in ft	0.14				0.14	
Vane angle in degrees		45				45

Note: one foot = 0.305 meter

Table 1 Prototype Dimensions of Inlets Investigated in Laboratory Tests

The water depth at the curb face in the model gutter was measured by a point gauge that was located 2.2 m upstream of the model inlet. Usually, a sump inlet on a residential street is allowed to have a ponding water depth up to 0.72 cm (18 inches) on a 2.4 cm (6-inch) curb. Therefore, the range of water depth in the model gutter was measured up to 2.4 cm in the model, or 0.72 cm in the prototype. For each run, water flow was circulated from a pump through the flume, and then intercepted by the sump inlet. Before a measurement was taken, the system was first operated to establish a steady state. For each run, the water depth and discharge were recorded for analyses. When water was shallow in the model gutter, the flow smoothly overtopped the edges of the model grate (Photo 2). When the water depth was close to the curb height, the grate surface area was about to be completely submerged. The flow began to form vortices along the edges of the grate (Photo 3). As soon as the curb was submerged, a large single vortex

was formed, dominating the flow pattern. This is obviously an indication of orifice flow because a strong suction was developed on the grate surface (Photo 4).



Photo1 Illustration of Combination 13 Inlet



Photo 2 Weir Flow through Model Vane Grate



Photo 3 Mixing flow through Model Vane Grate



Photo 4 Orifice flow through Model Vane Grate

### SUMP GRATE and CURB-OPENING HYDRAULICS

The analyses of data suggest that the flow through a sump inlet is varied with respect to the ponding depth and continuously changes from weir flow, through mixing flow, to orifice flow when the water becomes deep enough. A grate is formed by steel bars or vanes. Therefore, the original formulas for orifice and weir flows are modified with weir length or area opening ratios as:

$$Q_w = N_w C_w \sqrt{2g} (2W_g + L_g) d^{3/2} \quad \text{for weir flow through grate} \quad (1)$$

$$Q_o = N_o C_o \sqrt{2g} W_g L_g d^{\frac{1}{2}} \quad \text{for orifice flow through grate} \quad (2)$$

Where  $Q_w$  = weir flow,  $Q_o$  = orifice flow,  $W_g$  =grate width,  $L_g$  =grate length,  $d$ =water depth,  $N_w$ = weir length opening ratio after subtracting steel bars,  $N_o$  = orifice area opening ratio,  $C_w$  = weir discharge coefficient, and  $C_o$  = orifice discharge coefficient. Similarly, the modified weir and orifice formulas for a curb-opening are:

$$Q_w = C_w \sqrt{2g} L_c d^{3/2} \quad \text{for weir flow through curb opening} \quad (3)$$

$$Q_o = C_o \sqrt{2g} L_c H_c d^{\frac{1}{2}} \quad \text{for orifice flow through curb opening} \quad (4)$$

Where  $L_c$  = length of curb-opening and  $H_c$ = height of curb-opening. The transient process between weir and orifice flows is termed mixing flow that is modeled as:

$$Q_m = C_m \sqrt{Q_w Q_o} \quad \text{for mixing flow} \quad (5)$$

Where  $Q_m$ = mixing flow and  $C_m$  = mixing flow coefficient. In practice, for the given water depth, it is suggested that the interception capacity be the smallest among the weir, orifice, and mixing flows as:

$$Q_p = \min(Q_w, Q_m, Q_o) \quad (6)$$

Where  $Q_p$  = predicted interception capacity. A grate inlet has three parameters that need to be calibrated, including  $C_w$ ,  $C_m$ , and  $C_o$ ; so does a curb-opening. In this study, the calibration process is implemented by the least square method as:

$$E = \min \sum_{i=1}^{i=n} [Q_e(i) - Q_p(i)]^2 \quad (7)$$

Where  $E$  = sum of squared errors and  $Q_e$  = measured interception capacity. The solution for Eq. 7 is formulated under the following conditions:

$$\frac{\partial E}{\partial C_w} = 0 \quad \text{subject to } C_w < 1.0 \quad (8)$$

$$\frac{\partial E}{\partial C_o} = 0 \quad \text{subject to } C_o < 1.0 \quad (9)$$

$$\frac{\partial E}{\partial C_m} = 0 \quad \text{subject to } C_m < 1.0 \quad (10)$$

In this study, the numerical process of the least square method was executed using the solver in Microsoft Excel Software. For instance, Figure 1 presents the comparison between the observed and the predicted interception capacities for the bar grate. As shown in Figure 1, the HEC22 procedure is found to consistently over-estimate the grate capacity. In general, Eq 6 gives good agreement with the observed data, except for shallow water depths. In fact, the shallow gutter flow is more like a wide open channel flow that overtops the grate edges under a M2 profile (Chow 1959). The parameters for the model bar grate were calibrated using Eq's 1, 2, 5, and 6. As listed in Table 1,  $C_o = 0.67$  and  $C_w \sqrt{2g} = 2.38$  and the model bar grate has an open-area ratio of 44%, or 56% of the grate surface area occupied by steel bars. Figure 2 is the comparison between the observed and the predicted capacities for the model vane grate. Under the condition of no clogging, the HEC22 procedure overestimates the capacity of a vane grate until the water depth becomes adequately deep. A vane grate is shaped with the highest hydraulic efficiency to intercept the gutter flow. The model vane grate is formed with curved blades that have an inclined angle of 45 degrees. The open-area ratio for a vane grate varies with respect to the direction of flow. In this study, two variables,  $N_w$  in Eq 1 and  $N_o$  in Eq 2, were introduced to the least square method. As shown in Table 2, only 62% of the wet perimeters around the three edges of the model vane grate remained open to intercept weir flows while only 31% of the surface area of the vane grate remained open for orifice flows.

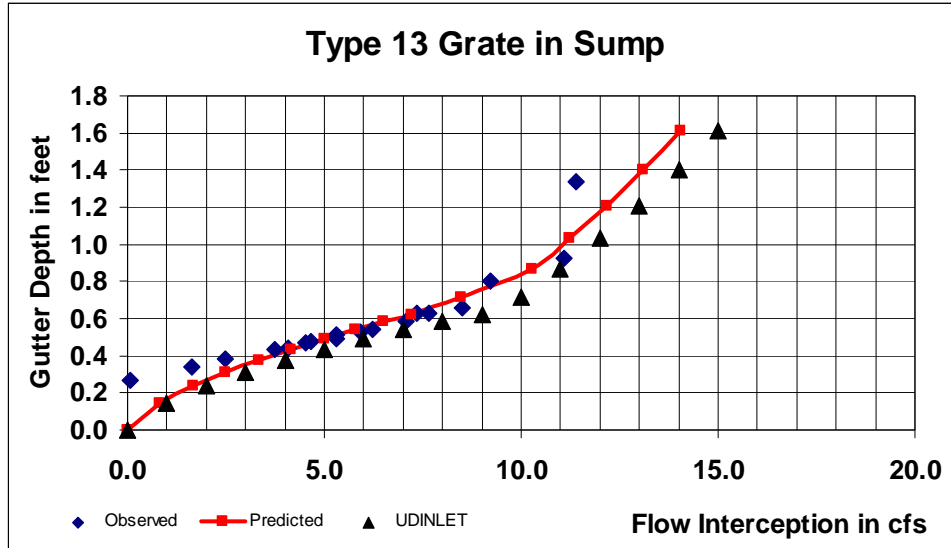


Figure 1. Comparison between Observed and Predicted data for Bar Grate.

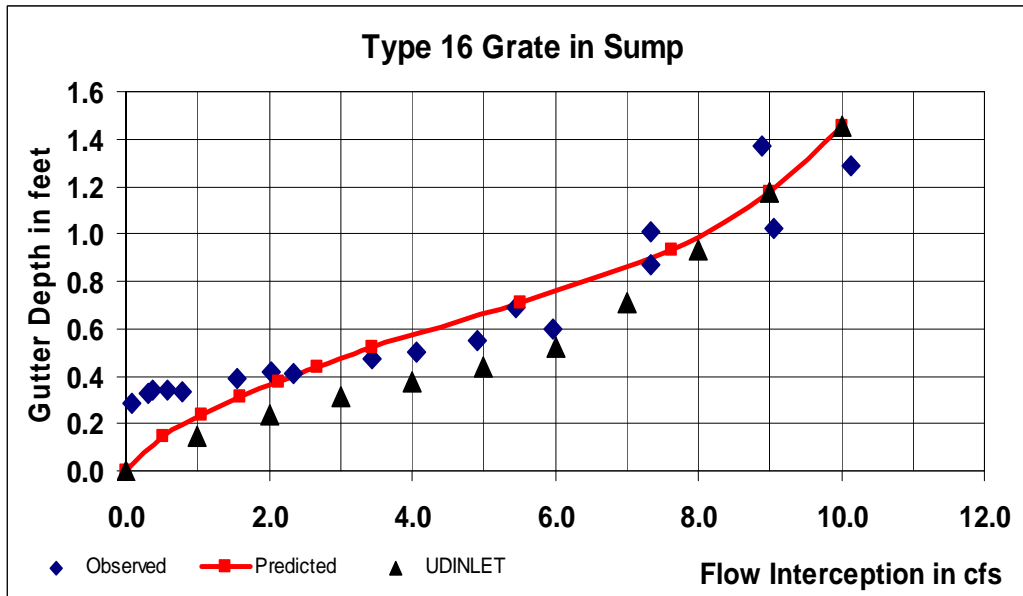


Figure 2. Comparison between Observed and Predicted data for Vane Grate.

Figure 3 and 4 present the performance curves for 3-ft and 5-ft curb opening inlets. A curb opening acts like a side weir. As shown in Table 2, the data reveal that a curb opening is a more efficient weir than the grate because both 3-ft and 5-ft curb opening have a higher value for  $C_w$ . In comparison, the HEC-22 procedure overestimates the capacity of a curb-opening inlet when water depth is shallow, and then becomes underestimating when water depth exceeds 18 cm. On the contrary, the proposed new equation agrees with the observed well.

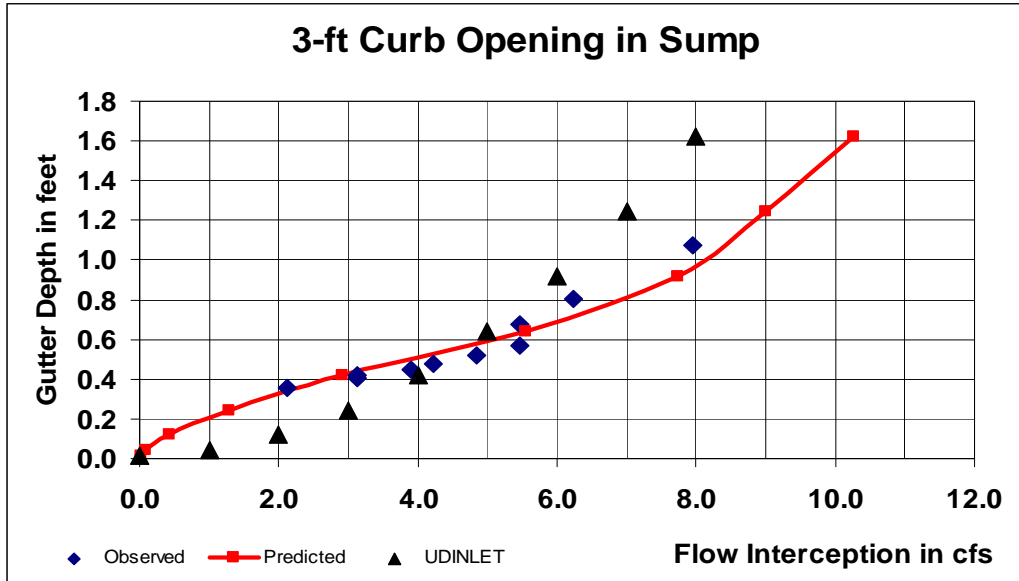


Figure 3. Comparison between Observed and Predicted data for 3-ft Curb Opening.

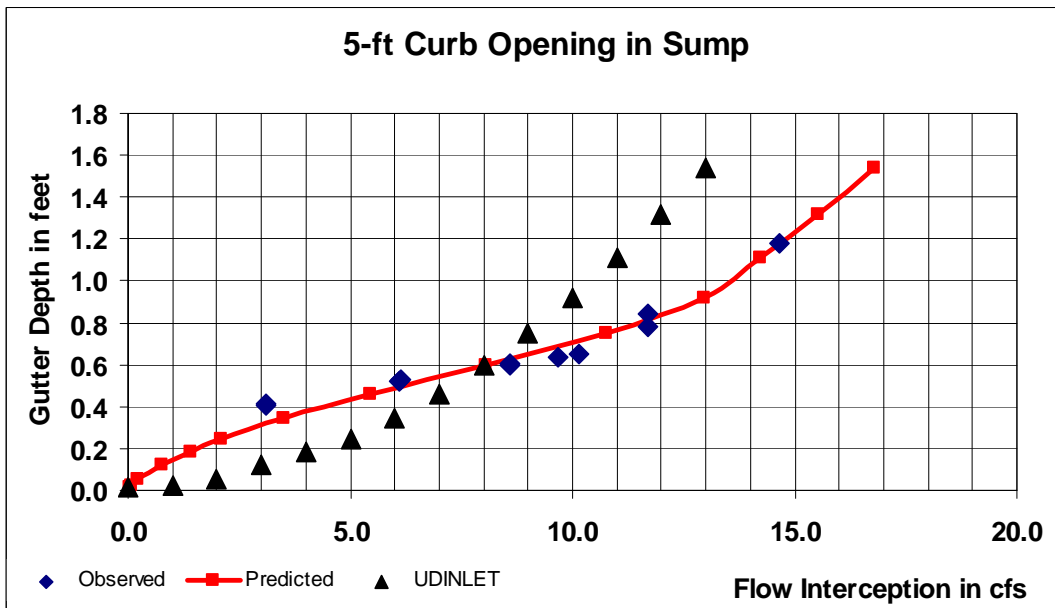


Figure 4 Comparison between Observed and Predicted data for 5-ft Curb Opening.

Type of Inlet	$C_o$	$C_w \sqrt{2g}$	$C_m$	$N_w$	$N_o$
Bar Grate	0.67	2.38	0.93	1.00	0.44
Vane Grate	0.67	2.38	0.93	0.62	0.32
3-ft Curb Opening	0.67	3.58	0.93	1.00	1.00
5-ft Curb Opening	0.67	3.51	0.93	1.00	1.00

Table 2 System Variables for Grate and Curb Opening Inlets

## SUMP COMBINATION INLET HYDRAULICS

A combination inlet consists of a horizontal grate placed in the gutter and a vertical curb opening inlet on the curb face. The advantage to adopt a combination inlet is to reduce the risk of being completely clogged by debris. For instance, if the grate becomes clogged, the curb opening remains functional or vice versa. When water flows through a combination inlet, the grate intercepts the shallow flow. As a result, the curb opening will not function until the grate is submerged. Different approaches were developed to size a combination inlet. For instance, it has been recommended that the capacity of a combination inlet be the larger interception between the grate and the curb opening or a reduction on the algebraic sum of the total interception (Guo 1999). However, no clear recommendation has ever been made or verified for such a capacity reduction. In practice, the street flow is first intercepted by a grate as if the curb opening did not exist, and then the remaining flow is applied to the curb opening inlet as if the grate did not exist (USWDCM 2001). Nevertheless, the hydraulics of a combination inlet remains unclear even though hundreds of combination inlets have been installed in metro areas every year.

In this study, a new approach was formulated to model the interception capacity of a combination inlet. It is suggested that a reduction factor be applied to the algebraic sum of the total interception as:

$$Q_i = Q_g + Q_c - K\sqrt{Q_g Q_c} \quad (11)$$

Where  $Q_i$  = interception capacity for combination inlet,  $Q_g$  = interception for grate,  $Q_c$  = interception for curb opening, and  $K$  = reduction factor. The value of  $Q_g$  is determined using Eq 6 aided with Eq's 1, 2, and 5. The value of  $Q_c$  is also determined using Eq 6 aided with Eq's 3, 4, and 5. Two combination inlets were investigated in the laboratory. Combination 13 inlet is composed of a horizontal bar grate and a 3-ft long curb opening. Similarly, Combination 16 inlet was formed with a vane grate and 3-ft long curb opening. Having collected several sets of data, the least square method was set up to minimize the squared errors using the reduction factor,  $K$ . It was found that  $K=0.45$  for Combination 13 inlet as shown in Fig 5, and  $K=0.31$  for Combination 16 inlet as shown in Fig 6. A higher reduction factor implies that the higher interference between the grate and the curb opening. For instance, the vane grate is more susceptible to inundation because of its low area-open ratio. As a result, the vane grate is more likely to operate under high water depths or both the vane grate and its curb opening can constructively function together. On the contrary, a bar grate in the Combination 13 inlet can intercept the majority of the gutter flow. Its curb opening is therefore not fully utilized till the bar grate is submerged under an overwhelming inflow. The HEC22 procedure assumes that the grate and curb opening can independently work. As a result, it consistently overestimates the capacity of a combination inlet. In this study, a capacity reduction is introduced to Eq 11. Of course, the value of  $K$  is a lumped, average parameter representing the range of observed water depths in the laboratory. During the model tests, it was observed that when the grate surface area is subject to a shallow water flow, the curb opening intercepted the flow at its two low corners, or it did not behave as a side weir to collect the flow along its full length. Under a deep water flow, the vortex circulation dominates the flow pattern. As a result, the central portion of the curb opening seems to more actively draw water into the inlet box. Although Eq 11 appears simple for use, it best represents the range of the observed data.

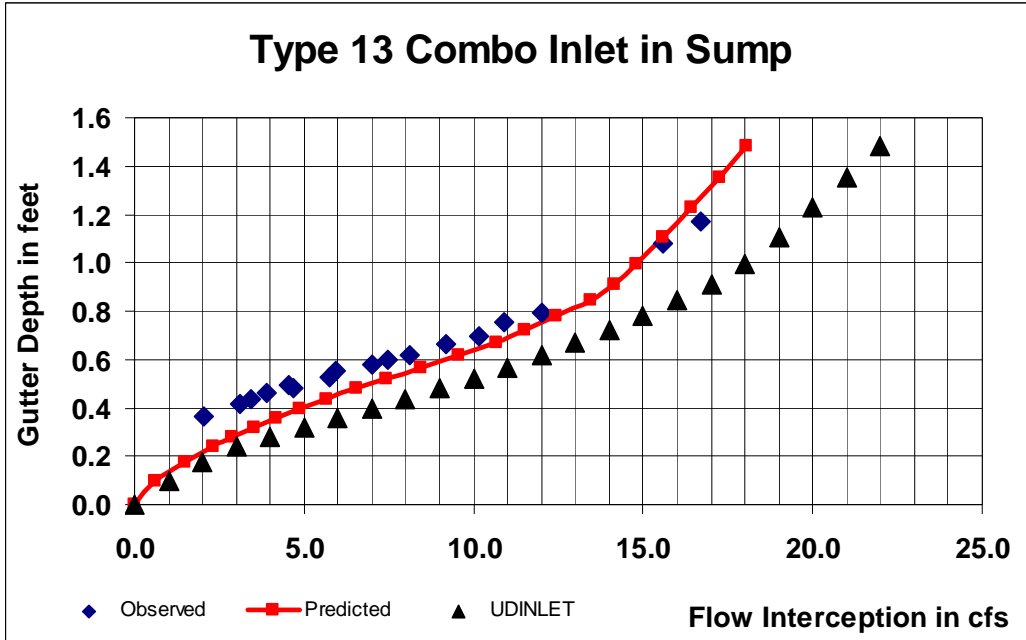


Figure 5. Comparison between Observed and Predicted data for Combination 13 Inlet.

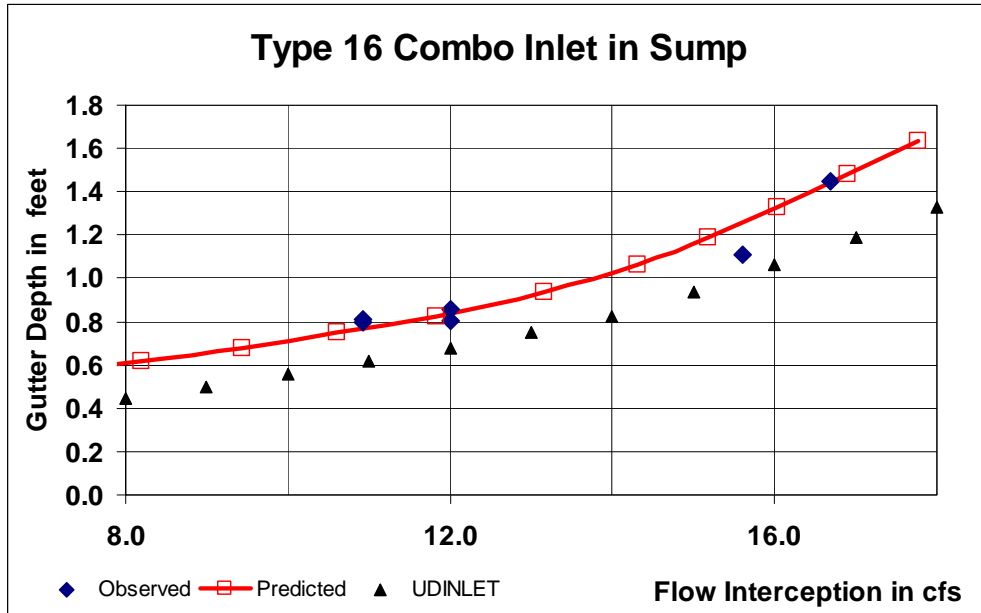


Figure 6 Comparisons between Observed and Predicted data for Combination 16.

**CONCLUSION**

- (1) The model tests were conducted in a 3.5-m wide flume to investigate the nature of the sump flow and the interception capacities of grate and curb opening inlets. It is confirmed that the capacity of a sump inlet increases with respect to water depth, starting with weir flow and then switching to orifice flow. In between, a transient mixing flow exists. In this study, the mixing flow coefficient is found to be 0.93 for both the grate and the curb opening inlets investigated.

- (2) The calibration results in a value of 0.67 for orifice discharge coefficient, 2.38 for the variable of  $C_w \sqrt{2g}$  when using a grate inlet. In comparison, the curb opening is more efficient as a weir flow because it has a value of 3.51 to 3.58 for  $C_w \sqrt{2g}$ .
- (3) The HEC 22 procedure generally follows the increasing relationship between inlet capacity and water depth. However, it tends to overestimate the capacities for both grate and combination inlets. Curb opening is found to have a higher weir coefficient than that for a grate. The HEC22 tends to overestimate the capacity of a curb opening inlet under a shallow water depth and then underestimates it for deep depths.
- (4) Vane grate was invented to be safe for bicycle and to be efficient for flow interception. The laboratory data indicate that the interception capacity of a vane grate is only 75 to 80% of bar grate. The width of inclined vanes significantly reduces the area and width opening ratios. As a result, the efficiency of a vane grate is substantially compromised by its safety. In comparison, a combination inlet with a bar grate has a higher reduction factor than that using a vane grate.
- (5) All cases investigated in this study were under no clogging condition. It has been recommended that a clogging factor be applied to the grate area when the grate operates as an orifice or to the wet perimeter when the grate operates as a weir (Guo 2000C, 2006).

## APPENDIX I. REFERENCES

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## **APPENDIX II. REFERENCES**

$C_o$  = orifice discharge coefficient

$C_m$  = mixing flow coefficient

$C_w$  = weir discharge coefficient,

$d$ =water depth,

$E$  = sum of squared errors

$H_c$ = height of curb-opening

$K$ = reduction factor

$L_c$  = length of curb-opening

$L_g$  =grate length

$N_o$  = orifice area opening ratio

$N_w$ = weir length opening ratio after subtracting steel bars

$Q_e$  = measured interception capacity

$Q_c$  = interception for curb opening

$Q_g$  = interception for grate

$Q_m$ = mixing flow

$Q_o$  = orifice flow,

$Q_p$  = predicted interception capacity

$Q_t$  = interception capacity for a combination inlet

$Q_w$  = weir flow,

$W_g$  =grate width,