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Design of Street Curb Opening Inlet Using Decay-Based Clogging Factor

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Abstract: *The current design procedure for sizing a single-unit curb opening inlet has been expanded to multiple-unit inlet designs. The decay function derived in this study can consistently convert a single-unit clogging factor to its multiple-unit clogging factor. The design procedure is then revised to apply the clogging factor to the length of on-grade inlets or to the opening area of sump inlets. The revised equation provides a consistent basis for comparison among various inlet sizes on continuous grade or in sump.*

Key Words: *Storm Water, Street, Inlet, Clogging Factor, Grate, Curb Opening.*

INTRODUCTION

Water on the pavement slows traffic and contributes to accidents from hydroplaning and loss of visibility from splash and spray (Agrawal et al. 1977). In 1979, the Federal Highways Administration published a technical guide for design of urban highway drainage, and then updated it in 1984 into *Hydraulic Engineering Circular No. 12* (FHWA, 1984), entitled "*Drainage of Highway Pavement*". HEC 12 summarizes a semi-theoretical method developed for estimating street hydraulic capacities and the procedures to size street inlets. In 1996, *Hydraulic Engineering Circular No. 22 (*Brown et al, 1996) was published to refine the design procedures stated in HEC 12. Street inlet designs must take street hydraulics, inlet geometries, and debris clogging effects into consideration. Although HEC 22 procedures are considered to be the recommended technical guideline for street inlet designs, it does not address how to incorporate urban debris clogging problems into the design of street inlets. Therefore, an empirical approach has been developed by treating a debris clogging factor as a flow interception reduction factor that can be directly applied to the no-clogging interception capacity of a street inlet. This approach has been widely accepted and used in street drainage designs (*CDOH 2000, CCRFCD 1999*). Over the years, it has been found that such a simplified approach tends to overestimate the length of an inlet. For instance, assume that the length of a non-clogging inlet is sized to have an interception of 10 cfs. Under a 50% of clogging factor, the engineer has to either double the length calculated by the HEC 22 procedure or let a carry-over flow of 5 cfs move toward the immediately downstream inlet. Mathematically, regardless of how long the inlet is, applying a 50% reduction to the inlet capacity will always leave a half of the street flow as the carry-over flow. Such as a mathematical discrepancy directly results from expanding the use of the clogging factors developed for single units to multiple units. Often at street interceptions or low points where the street flow must be completely collected, the current conveyance-based empirical approach becomes insufficient in coping with the transition from the sloping to the sump street sections (Guo 2000b). For instance, the curb opening inlet on 23rd Street upstream of the Coors Field Stadium in Denver, Colorado becomes 30 feet long in order to achieve a nearly 100% storm runoff capture. In this study, a decay function was developed to expand a single-unit clogging factor into a series of multiple-unit clogging factors. The decay function defines the marginal effect when increasing an inlet unit; in other word, the first inlet unit has the highest flow collection and the last inlet unit has the least flow collection.

A secondary problem relates to the aforementioned uniform application of methods to all inlet units, the current practice has led to a serious discrepancy among on-grade inlet designs. For instance, the runoff interception by a two-grate inlet under a 50% clogging factor becomes 20% less than that of a single-grate inlet under no clogging (Guo, 2000c). In this study, it was found that the capacity consistency among various inlet clogging conditions must be separately established for sump or on-grade inlets. For a sump inlet, the clogging effect is linearly proportional to the inlet opening area; but for an on-grade inlet, the clogging effect is linearly proportional to the inlet length. The currently practice complies with the former only, but becomes inconsistent for the later. Therefore, the clogging factor is no longer a reduction factor to the flow interception. Rather, it is a reduction to the effective inlet opening area or length. The revised method presented in this paper eliminates the excessive length when an inlet has to accomplish a completion collection and provides a consistent basis for comparisons among various clogging conditions.

DECAY CLOGGING FACTORS

Selection of a clogging factor reflects the condition of urban debris at the project site. In this respect, the grate is more susceptible to flat debris such as news papers and plastic bags. There are also situations where curb inlets can be easily blocked by plastic bottles, paper boxes. As a common practice of many municipalities for urban storm water drainage, a single-grate inlet is designed under the assumption of 50% clogging and a curb opening inlet is sized with a 10% clogging (*CDOH 2000*). These recommendations were developed for inlets with a single unit. When the situation requires multiple units for a large amount of storm water collection, the current practice is to linearly apply the single-unit clogging factor to a multiple-unit inlet. As a result, for an inlet hydraulically sized to have three units, a total of six units shall be installed because of the assumption of 50% clogging. When uniformly applying a clogging factor of 50% to all the inlet units, the inlet in this example becomes excessively long.

During a storm event, street inlets are usually loaded with debris carried by the first flush runoff volume. For instance, the first 0.5 inch in a storm event or the storm water quality control capture volume can be an approximation of the first flush runoff volume (Guo and Urbonas in 2002, Guo and Hughes in 2002). Since the amount of debris is largely associated with the first flush volume in a storm event, the clogging factor applied to a multiple-unit inlet can be decreased with respect to the length of the inlet. Figure 1 presents a typical case of debris distribution observed in the field. It shows that the first inlet unit catches the most of debris; the second unit catches approximately 50% of that loaded in the first. Such a decay process on the clogging effect is described as (Guo 2000c):

$$C = \frac{1}{N}(C_o + eC_o + e^2 C_o + e^3 C_o + \ldots.. + e^{N-1} C_o) = \frac{C_o}{N} \sum_{i=1}^{i=N} e^{i-1} \tag{1}$$

in which C = multiple-unit clogging factor, C_o = single-unit clogging factor, N = number of inlet units, and e = debris decay ratio less than unity. The value of debris decay ratio is local and empirical.

Figure 1 Typical Observation of Debris Distribution in Field

Eq 1 implies that the runoff interception capacity of a street inlet is not linearly increased with the number of units, but exhibits a diminishing return for every added unit. When N becomes large, Eq 1 converges to:

$$C = \frac{C_o}{N(1-e)} \tag{2}$$

For instance, when e = 0.5 and C_o=0.5, Eq 2 shows that the limiting value is: C = 1.0/N. In other words, the equivalent clogging amount for this case is one unit out of N units, not 50% of N units to be clogged. Eq 2 preserves the recommended clogging factor for a single-unit inlet that applies to the first unit, and then decays on the clogging effect for a serial of inlets downstream. Eq 2 was tested in the City of Denver around the Coors Field Stadium area (UDFCD 2001). It was recommended that e=0.25 for curb-opening inlets and e=0.5 for grate inlets. Eq 2 is then plotted in Figure 2 for multiple-unit inlet designs.

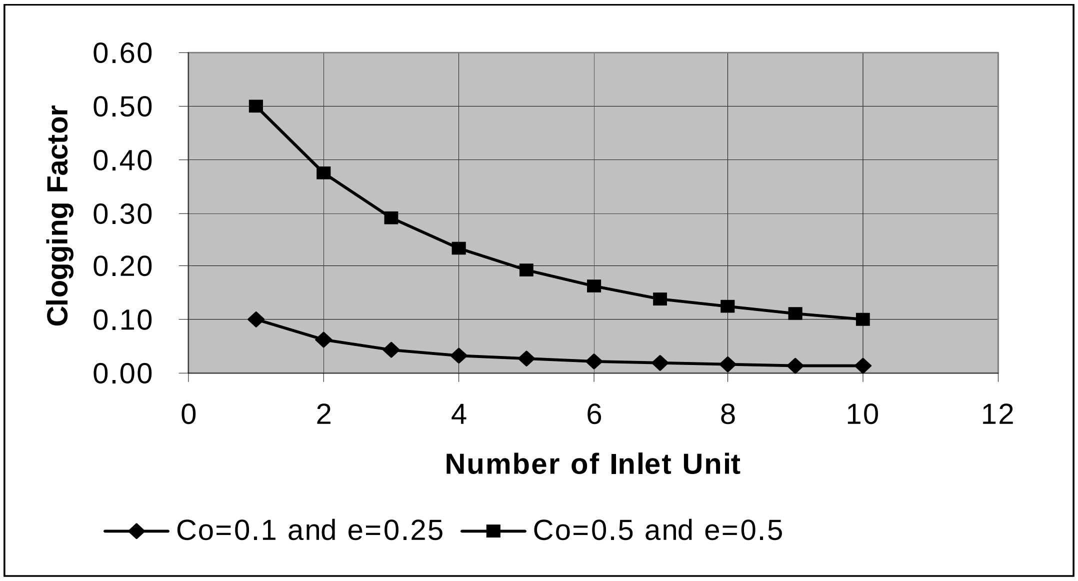

Figure 2 Decay Clogging Factors for Multiple-Unit Inlets

Figure 2 indicates that the clogging factor of 0.5 for a single unit is reduced to 0.2 for five inlet units. For this case, the current practice would install 10 units under the assumption of the first 5 units to be clogged while the decay function will only clog the first one out of five units. Although Eq 1 offers a rational basis to quantify inlet clogging effects, it does not yet improve the inconsistency among the predicted inlet capacities by current practice. In this paper, the design procedure for curb opening inlets is employed as an example for illustrating the proposed improvements.

ON-GRADE CURB OPENING INLETS

Street hydraulic capacity depends on the street longitudinal slope, transverse slope, surface roughness, and water spread (Guo 2000a, 2000b). As shown in Figure 3, a street is often designed to have a gutter depression in order to increase the storm water conveyance capacity.

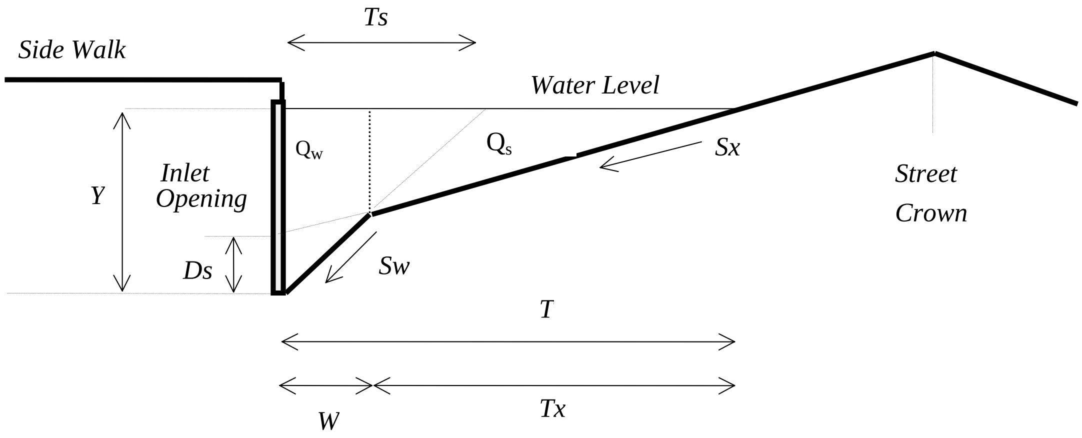

Figure 3 Illustration of Water Flow on Street

Water flowing on a street can be divided into the gutter flow which is carried within the gutter width, and the side flow which is carried by the street. Mathematically, the side flow can be described by the triangular open channel flow as (Brown et al. 1996):

$$Q_x = \frac{K_n}{n} S_x^{1.67} T_x^{2.67} \sqrt{S_o} \tag{3}$$

in which Q_x = side flow rate, S_x = street transverse slope, S_o = street longitudinal slope, T_x = water spread width in Figure 3, n = Manning's roughness, Y= water depth in gutter, and K_n= dimensional conversion factor, 0.56 for English unit or 0.375 for SI units. Referring to Figure 3, the equation for the gutter flow was derived as (Guo 2000a):

$$Q_w = \frac{K_n}{n} S_w^{1.67} [T_s^{2.67} - (W - T_s)^{2.67}] \sqrt{S_o} \tag{4}$$

in which Q_w = gutter flow rate, T_s = water spread in Figure 3, S_w = gutter crossing slope, and W = gutter width. The total flow on the street is equal to:

$$Q_s = Q_w + Q_x \tag{5}$$

in which Q_s = design flow on street. From the street geometry, the gutter crossing slope is calculated as:

$$S_w = S_x + \frac{D_s}{W} \tag{6}$$

in which D_s = gutter depression. Aided by Eq's 3 and 4, the ratio of gutter flow to street flow is defined as:

$$E_o = \frac{Q_w}{Q_s} \tag{7}$$

in which E_o = ratio of gutter flow to street flow. When a curb opening inlet is installed on a continuous grade, the required length to collect the design flow on the street is computed by side weir hydraulics as (Brown et al. 1996):

$$L_t = K_L Q_{\mathrm{s}}^{0.42} S_o^{0.30} \left(\frac{1}{nS_e}\right)^{0.6} \tag{8}$$

$$S_e = S_x + S_w . E_o \tag{9}$$

in which L_t = required opening length for complete collection, S_e = equivalent transverse street slope, K_L = unit conversion factor, 0.60 for feet and second units or 0.817 for SI units. For a curb opening inlet with N units, the interception capacity without considering clogging is estimated as:

$$Q_o = Q_{\mathrm{s}}\left[1 - \left(1 - \frac{L}{L_t}\right)^{1.80}\right] \quad \text{without clogging} \tag{10}$$

$$L = NL_i \tag{11}$$

in which Q_o = flow intercepted without clogging, L_i = unit length, and L= total non-clogged length. Considering the clogging effect, the actual interception is reduced to (*CDOH 2000, CCRFCD 1990, City of Denver 2000*):

$$Q_i = (1-C)Q_o \quad \text{with clogging} \tag{12}$$

in which Q_i = flow intercepted with clogging. The above procedure first applies the entire inlet length to Eq 10 and then linearly reduces the amount of the flow intercepted using the single-unit clogging factor as stated in Eq 12. This practice always results in a residual flow on the street and causes a discrepancy among the predicted and actual inlet capacities. In this study, the above procedure is modified by applying the clogging factor to the inlet length as:

$$L_e = (1-C)NL_i \tag{13}$$

The multiple-unit clogging factor in Eq 13 can be derived from the single-unit clogging factor using Eq 1. Let L=L_e. Eq 10 becomes:

$$Q_i = Q_s\left[1 - \left(1 - \frac{L_e}{L}\right)^{1.8}\right] \tag{14}$$

Substituting Eq 13 into Eq 14 yields:

$$Q_i = Q_s\left\{1 - \left[1 - \frac{(1-C)NL_i}{L_t}\right]^{1.8}\right\} \tag{15}$$

As expected, Eq 15 exhibits a one-to-one relationship between Q_i/Q_s and L_e/L_t, implying that Eq 15 provides a consistent basis between inlet interception capacities and effective inlet lengths under various clogging conditions. In other words, Eq 15 predicts that five units under a clogging factor of 0.2 will have the same capacity as four units under no clogging. Such consistency is critically important when the project needs to examine various alternatives for inlet selections. When the effective length of the inlet becomes adequately long, Eq 15 gives a complete collection and leaves no carry-over flow on the street.

SUMP CURB-OPENING INLET

A sump area is formed at the low point of a depressed roadway or at a street intersection confined by street crowns. The storage capacity in a sump area depends on the street side slope and allowable water spread (Guo 2000b). A sump area receives water flows from all directions. With a street curb as illustrated in Figure 4, debris is usually accumulated along the upstream and downstream portions of the depressed pan. In other words, the clogging factor shall apply to the curb opening length.

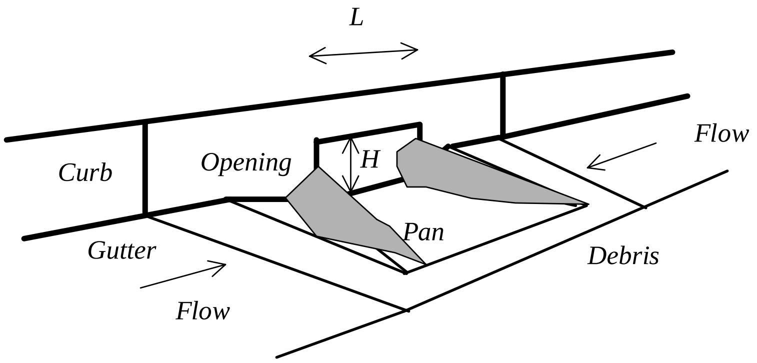

Figure 4 Illustration of Flows and Debris Around A Curb Opening Inlet

Hydraulically, a sump inlet may operate like a weir or an orifice, depending on the water depth (Guo 1997). Under a shallow depth, a sump curb-opening inlet operates like a weir. With a complete collection, i.e. $Q_o=Q_s$, the current practice calculates the required water depth under no clogging as:

$$Q_o = Q_s = \frac{2}{3} C_d \sqrt{2g} L Y_s^{1.5} \qquad (16)$$

in which C_d = discharge coefficient such as 0.60, g = gravitational acceleration, and Y_s= water depth required without clogging factor. Of course, considering the potential clogging, the current practice applies Eq 12 to make an adjustment to Eq 16. In this study, let $L=L_e$. Aided by Eq 13, Eq 16 is modified to:

$$Q_i = (1-C)Q_o = (1-C)\left(\frac{2}{3} C_d \sqrt{2g} N L_i Y_s^{1.5}\right) \qquad (17)$$

Eq 17 calculates the required water depth for completion collection with clogging. When the water depth gets deeper, a curb opening inlet operates like an orifice that can be modeled as:

$$Q_o = Q_s = C_d H N L \sqrt{2g(Y_s - 0.5H)} \qquad (18)$$

in which H = height of curb opening. In this study, let $L=L_e$. Substituting Eq 13 into Eq 18 yields:

$$Q_i = (1-C)Q_o = (1-C)\, C_d H N L_i \sqrt{2g(Y_s - 0.5H)} \qquad (19)$$

Both Eq's 17 and 19 appear to agree with the current practice described by Eq 12. The major difference is the decay nature of multiple-unit clogging factor that has been incorporated into the weir and orifice formulas. The transition of a sump inlet from weir to orifice flow is not clearly defined yet. In practice, Eq 16 shall be used when $Y \leq H$. For a submerged case, Y>H, the interception capacity of a sump inlet is dictated by either Eq 16 or 18; whichever is smaller.

DESIGN EXAMPLE

The street cross section for the design example is illustrated in Figure 5. The longitudinal and transverse slopes are 0.01 and 0.02. The Manning’s roughness coefficient is 0.016. The composite street cross section includes a gutter depression of 2 inches. The design discharge on the street is 20 cubic feet per second that produces water spread width of 16.25 feet. Substituting the design parameters into Eq's 3 through 9 yields E_o = 0.584, S_w = 1.03, and S_e=0.08.

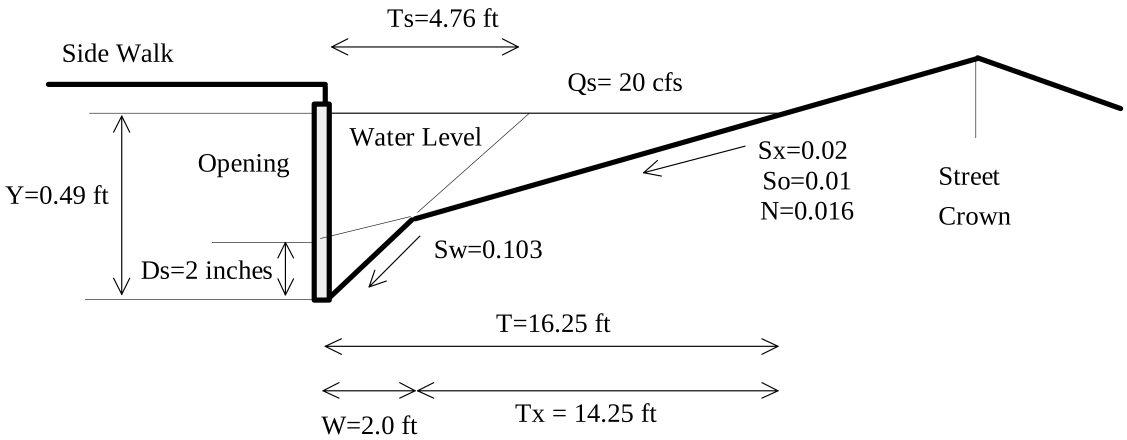

Figure 5 Street Geometry and Flow Condition for Design Example

For the purpose of comparison, Eq 10 was set to have a 100% collection. The required curb opening length is found to be 29.0 feet, or L_t = 29.0 feet and Q_o=Q_s= 20 cfs for this case. Consider that C_o= 0.50, L_i= 5.0 feet, and e = 0.50. Table 1 shows that the interception rates increase with respect to the number of units. It takes 6 units or a 30-ft curb opening to achieve the target collection using the modified method presented in this study. Referring to Figure 2, the corresponding multiple-unit clogging factor is 0.16 for N=6 or 84% of the 30-ft opening length remains clear from clogging. On the contrary, the current method indicates that it takes 5 units to achieve the target collection without considering clogging. With a clogging factor of 0.5, these 5 units can only collect 9.74 cfs because 2.5 units were assumed to be clogged. Consequently, the current design procedure leaves a carry-over flow of 10.26 cfs on the street. Mathematically the interception rate using the current method can never be greater than (1-C_o), regardless of the curb opening length. This dilemma often leads to doubling the length of curb opening, or 10 units for this case. Of course, this practice results in inlets with an excessive length.

Number of Units	Revised Method		Current Method		
	Multiple-unit Clogging Factor Eq 1	Interception with Clogging Eq 14	Single-unit Clogging Factor	Interception without Clogging Eq 10	Interception with Clogging Eq 12
		cfs		cfs	cfs
1.00	0.50	3.01	0.50	5.81	2.90
2.00	0.38	7.12	0.50	10.71	5.36
3.00	0.29	11.26	0.50	14.67	7.34
4.00	0.23	14.89	0.50	17.62	8.81
5.00*	0.19	17.70	0.50	19.47	9.74*
6.00	0.16	19.51	----	---	---
10.00	---	---	0.50	---	20.00*

Notes: --- not applicable

* 5 inlets to collect 19.47 cfs or 10 inlets to collect 20 cfs under C=0.5

Table 1 Inlet Capacities under Revised and Current Methods for Design Example.

CONCLUSIONS

This paper presents pivotal revisions to the current Federal Highways Administration's design guidelines for street inlets. The modified method conforms to the design parameters recommended for a single-unit inlet, and then expands such parameters into the applications to multiple-unit inlets. The debris decay function derived in this study can consistently convert a single-unit clogging factor to a series of multiple-unit clogging factors. The debris decay ratio must be numerically less than unity. The selection of decay ratio reflects the amount of debris in the urban environment and can be referred to the diminishing inlet capacity when adding an additional unit. Based on the field observations, the debris decay ratio of 0.25 is recommended for curb-opening inlets and 0.5 is recommended for grate inlets. Both values have been adopted for Denver metropolitan area for inlet designs.

To resolve the mathematical discrepancy in current practice, this paper also suggests that a clogging factor of 50% should not be interpreted as that 50% of inlet units are to be clogged. A clogging factor must be applied to the length of an on-grade inlet or to the opening area of a sump inlet. Using the effective length of an inlet, a consistent basis can be established to compare various alternatives for inlet selections. Although this paper uses the curb-opening inlet as an example, the similar approach can be extended to the designs of grate (Guo 2000 c) and slotted inlets.

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APPENDIX II: Notations

C = multiple-unit clogging factor for an inlet with multiple units
C_o = single-unit clogging factor
C_d = discharge coefficient such as 0.60
D_S= gutter depression of 2 inches
e = debris decay ratio less than unity
E_o = flow rate ratio
g = gravitational acceleration
H = height of curb opening
K_L = unit conversion factor
K_n= dimensional conversion factor
n = Manning's roughness of 0.016
N = number of inlet unit
L_i = unit length
L= total length without clogging
L_e= unclogged (effective) length
L_t = required curb-opening length
Q_o = flow intercepted by inlet without clogging
Q_i = flow intercepted by inlet with clogging
Q_x = side flow rate,
Q_w = gutter flow rate,
Q_s = design flow on street,
S_e = equivalent transverse street slope
S_w= gutter crossing slope
S_x = street transverse slope,
S_o = street longitudinal slope,
T_s and T_x = water spread widths in Figure 3,
W = gutter width
Y= water depth
Y_s= water depth in sump.