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# DESIGN OF GRATE INLETS WITH DECAY-BASED CLOGGING FACTOR

James C.Y. Guo, *PhD, P.E.*
*Professor, Department of Civil Engineering, University of Colorado at Denver,*
*Denver, CO 80217-3364, E-mail: james.guo@cudenver.edu*

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*Abstract: The design procedure for sizing a single-grate inlet has been expanded to the design of multiple-grate inlets. The decay function derived in this study converts a single-grate clogging factor to a multiple-grate clogging factor. The design procedure has been revised to apply the clogging factor to the length of the inlet. The revised equation provides consistent predictions of the required length of a grate inlet on a sloping street.*

## INTRODUCTION

The hydraulic characteristics of a street inlet are complicated. An inlet may operate like a weir when the water depth is shallow or like an orifice when it is submerged. Among various types of street inlet, grates are considered to be efficient in both hydraulic performance and trash control. Design of a grate inlet under no-clogging is well documented by many urban drainage criteria and design manuals (*Denver Urban Drainage and Flood Control District in 1969, Clark County Regional Flood Control District for Las Vegas Area in 1990*). However, with the consideration of a clogging factor, the current practice becomes inconsistent in the predictions of inlet capacity among various sizes, and even has a discrepancy between single- and multiple-grate inlets. In this paper, the recommended clogging factors developed for single-grate inlets have been systematically expanded to the design of multiple-grate inlets. And the current design procedure for grate inlets on a sloping street has been revised to apply a clogging factor to the length of the inlet. The revised equation produces consistent predictions among various sizes and clogging conditions.

## STREET HYDRAULICS

The street hydraulic conveyance capacity (SHCC) is determined from the gutter geometry and street hydraulic characteristics, and then subject to safety considerations (Guo 2000). Street curbs and gutters are designed to intercept storm water safely until the water spread becomes too wide and the flow velocity becomes too high. Figure 1 illustrates a composite street gutter cross section. Storm water flowing through such a gutter section can be described by the revised Manning's equation as (Izzard 1946):

$$Q = \frac{K}{n} S_x^{1.67} T^{2.67} \sqrt{S_o} \quad (1)$$

in which Q = street hydraulic conveyance capacity (SHCC), K=0.56 for the English system or 0.376 for the SI system, n = Manning's roughness of street surface, $S_x$ = street transverse slope, $S_o$= street longitudinal slope, and T= water spread width on the street. In general, a value of 0.016 is recommended for Manning's roughness and 1% or 2% for street transverse slope. As shown in Figure 1, the storm water collected by a street gutter is divided into a gutter flow which is the amount of flow carried within the gutter width, and a side flow which is the amount of flow carried by traffic lanes. Assuming that the friction on an internal water surface is negligible, Eq. 1 can be separately applied to both the gutter flow and the side flow. The total discharge is then equal to

$$Q = Q_x + Q_w \quad (2)$$

in which $Q_x$= side flow, and $Q_w$= gutter flow which is calculated with the side slope across the gutter, $S_w$, as:

$$S_w = S_x + \frac{D_s}{W} \quad (3)$$

Referring to Figure 1, the following equations are used in the calculation of street storm water flow:

$$A = 0.5YT + 0.5WD_s \quad (4)$$

$$T = W + T_x \tag{5}$$

$$V = \frac{Q}{A} \tag{6}$$

in which Y = gutter flow depth, W= gutter width, $D_s$= gutter depression, $T_x$= water spread width for side flow, A = flow area, and V = cross sectional average flow velocity.

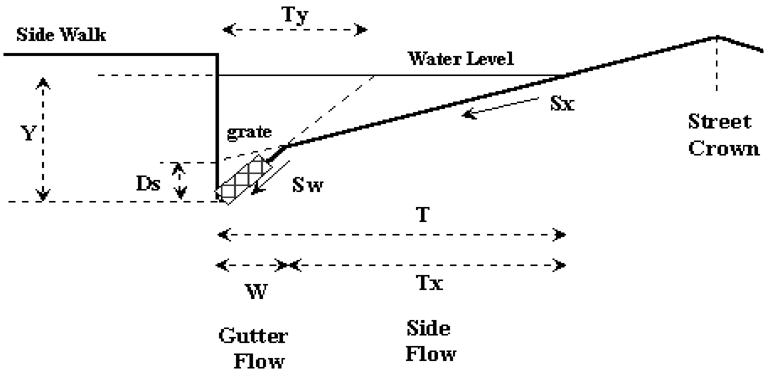

**Figure 1. Illustration of Street Cross Section**

The ratio of a gutter flow to the total runoff flow on a street is defined as (Guo, 1997):

$$E_w = \frac{Q_w}{Q} = \left(\frac{S_w}{S_x}\right)^{1.67}\left(\frac{T_y}{T_x}\right)^{2.67}\left[1 - \left(\frac{T_y - W}{T_x}\right)^{2.67}\right] \tag{7}$$

in which $E_w$= ratio of gutter flow to total runoff flow, $Q_w$ = gutter flow carried by gutter, Q = total runoff flow on street, $S_w$ = gutter transverse slope, $S_x$ = street transverse slope, W = gutter width, $T_x$ and $T_y$ = water top widths defined in Figure 1. Eq 1 was developed for a composite street section with a gutter depression. For a straight street cross section, we have $D_s$ =0, $S_w = S_x$ and $T=T_y=T_x$. As a result, the above equation is reduced to

$$E_w = 1 - \left(1 - \frac{W}{T}\right)^{2.67} \tag{8}$$

Eq 8 agrees with Design of Urban Highway Drainage (1979), and Drainage of Highway Pavements-HEC 12 (1984). The ratio of the side flow, $Q_x$, to the street flow, Q, is

$$E_x = \frac{Q_x}{Q} = 1 - E_w \tag{9}$$

in which $E_x$ = ratio of side flow to total runoff flow on the street. The interception of gutter flow by a grate is determined by the average cross sectional water velocity, water splash velocity due to the interference of the grate, and length of the grate. In this study, a regression analysis is performed on the laboratory data reported by HEC-12 published in 1984, and resulted in the following empirical formula for determining the splash-over velocity, $V_o$, as a function of the grate length and type.

$$V_o = \alpha + \beta L - \gamma L^2 + \eta L^3 \tag{10}$$

in which $V_o$ = water splash velocity on grate, L = unit length of grate inlet, $\alpha, \beta, \gamma,$ *and* $\eta$ = constants, depending on the type of grate as shown in Table 1.

| Type of Grate | $\alpha$ | $\beta$ | $\gamma$ | $\eta$ |
|---|---|---|---|---|
| Bar P-1-7/8 | 2.22 | 4.03 | 0.65 | 0.06 |
| Bar P-1-1/8 | 1.76 | 3.12 | 0.45 | 0.03 |
| Vane Grate | 0.30 | 4.85 | 1.31 | 0.15 |
| 45-Degree Bar | 0.99 | 2.64 | 0.36 | 0.03 |
| Bar P-1-7/8-4 | 0.74 | 2.44 | 0.27 | 0.02 |
| 30-Degree Bar | 0.51 | 2.34 | 0.20 | 0.01 |
| Reticuline | 0.28 | 2.28 | 0.18 | 0.01 |

**Table 1 Splash Velocities for Various Types of Inlet Grates**

The interception capacity of a grate is separately determined for the frontal and side flows (NTIS 1984). The interception percentage of a frontal flow, $Q_w$, is estimated as:

$$R_w = 1 - 0.09(V - V_o) \quad if \quad V \geq V_o, \quad otherwise \quad R_w = 1 \tag{11}$$

in which $R_w$ = capture ratio of gutter flow. For most cases, the condition, $V<V_o$, prevails, or $R_w$ =1.0. The interception percentage of the side flow, $Q_x$, is expressed by

$$R_x = \frac{1}{(1+\frac{0.15V^{1.8}}{S_x . L^{2.3}})} \tag{12}$$

in which $R_x$ = capture ratio of side flow. As a result, the interception capacity of a grate inlet is equal to

$$Q_i = R_w Q_w + R_x Q_x = [R_w E_w + R_x(1 - E_w)]Q \tag{13}$$

in which $Q_i$ = interception with no clogging.

## CLOGGING EFFECTS

With the consideration of a clogging effect, the inlet interception capacity determined by Eq 13 is subject to a reduction. The current design procedure suggests as:

$$Q_a = (1 - C_o)Q_i \tag{14}$$

in which $Q_a$ = actual interception, and $C_o$ = single-grate clogging factor. Eq 14 has been recommended by *Colorado Department of Transportation since 1990, Storm Water Drainage Design Criteria Manual for Denver Area since 1969, Hydrologic Criteria and Drainage Design Manual for Las Vegas Area since 1992*. Eq 10 may function acceptably for a grate inlet designed to collect less than 60% of runoff flow on the street, but fails to predict the required inlet length when a 80 to 90% of runoff collection is targeted. It is simply because Eq 10 treats a clogging factor like a discharge reduction factor. For instance, with a clogging factor of 0.5, Eq 10 will always leave 50% of the runoff flow on the street. In addition, Eq 10 may work for a single-grate inlet, but fails for a multiple-grate inlet because the value of $C_o$ developed for a single grate tends to overestimate the amount of debris for the design of a multiple-grate inlet. In an urban area, the amount of debris is largely associated with the first flush volume which can be the first 0.5 inch of a storm event (Guo and Urbonas, 1996). In current practice, empirical clogging factors have been developed or measured for a single-grate inlet. Shall a single-grate clogging factor be directly applied to a multiple-grate inlet? If so, the inlet whose size is hydraulically determined to be six grates will be enlarged to 12 grates when a clogging factor of 0.5 is applied. It is obvious that the clogging effect by debris should decrease with respect to the number of grates. To directly apply a single-grate clogging factor to a multiple-grate inlet tends to overestimate the debris amount and results in inlets with an excessive length. For instance, the inlet at South Federal Avenue and Belleview Avenue in the City of Denver, Colorado becomes 45 feet long. In this study, it is suggested that the clogging effect on a multiple-grate inlet decays with respect to the length of the inlet as:

$$C_{i+1} = eC_i \tag{15}$$

in which C = clogging factor, e = decay factor, i = i-th grate. For a number of grates in series, the multiple-grate clogging factor is:

$$C = \frac{C_o}{N}(1 + e + e^2 + e^3 + ..... + e^{N-1}) = \frac{C_o}{N}\sum_{i=1}^{i=N} e^{i-1} \qquad (16)$$

in which C = multiple-grate clogging factor, $C_o$ = single-grate clogging factor, e = decay factor, and N = number of grate. Eq 16 agrees with the single-grate clogging factor when N=1. When N becomes large enough, Eq 16 is reduced to

$$C = \frac{C_o}{1-e} \qquad (17)$$

In this study, Eq 16 is further evaluated by the field experience about inlet clogging recommended by Adams County in the state of Colorado. Table 2 indicates that Eq 16 agrees with field experience when e=0.50.

| Number of Grate | Clogging Factor Field Experience For Single Grae | Clogging Factor with e=0.5 Eq 16 | Clogging Factor with e=0.25 Eq 16 |
|---|---|---|---|
| 1 | 0.50 | 0.500 | 0.500 |
| 2 | 0.35 | 0.375 | 0.313 |
| 3 | 0.24 | 0.250 | 0.208 |
| 4 | 0.15 | 0.188 | 0.156 |

**Table 2 Comparisons between Predicted and Experienced Clogging Factors**

It is also noticed that Eq 14 produces inconsistent predictions among various grate sizes. For instance, the capacity of two grates with a clogging factor of 50% is not the same as one grate with no clogging. Such a discrepancy is caused by applying clogging factor to inlet capacity. In this study, the current design procedure is revised to apply the clogging factor to the length of a grate inlet as:

$$L_e = (1 - C)NL \qquad (18)$$

in which L = unit length of a grate. With the aid of Eq 18, Eq's 10 and 12 are revised as

$$V_o = \alpha + \beta L_e - \gamma L_e^2 + \eta L_e^3 \qquad (19)$$

$$R_x = \frac{1}{(1 + \frac{0.15V^{1.8}}{S_x . L_e^{2.3}})} \qquad (20)$$

To design a multiple-grate inlet, Eq 16 converts the single-grate clogging factor to a multiple-grate clogging factor, depending on the number of grates. Eq's 18, 19, and 20 will evaluate the impact of clogging effects on the inlet length. With these revisions, the design procedure for grate inlets becomes consistent and predicts the required length for a grate inlet within reasonable limits.

## DESIGN EXAMPLE

A discharge of 10.66 cfs is carried by a street cross section illustrated in Figure 1 with a longitudinal slope, $S_o$ = 0.01 and Manning's roughness, n=0.016. Considering a series of vane grates to intercept the runoff flow on the street. The average cross sectional water velocity is found to be 3.65 fps by Eq 6 which is much less than the splash velocity by Eq 10. As a result, $R_w$ = 1.0 for this case. Table 3 presents a comparison between the revised and current design procedures for sizing a multiple-grate inlet. Considering that $C_o$= 0.50, L= 3.0 feet, and e = 0.50, the revised method indicates that it takes four grates under a multiple-grate clogging factor of 0.23 to collect a discharge of 8.70 cfs, or six grates under the single-grate clogging factor of 0.50 to collect a discharge of 8.64 cfs. The multiple-grate clogging factor of 0.23 implies approximately one grate out of four grates will be clogged, and a single-unit clogging factor of 0.5 implies that a total of 3 grates out of the 6 grates are assumed to be clogged. It is obvious that the approach of single-grate clogging factor overestimates the amount of debris when dealing with a multiple-grate inlet.

On the other hand, to apply the current practice to this example, the inlet can be designed to have a capacity exceeding the design flow of 10.66 cfs on the street, but will never be able to reach an interception of more than 5.24 cfs because of the reduction by $C_o$ = 0.50 on the inlet capacity. Consequently, the design procedure leaves a residual flow of 5.42 cfs on the street, regardless of the length of the grate inlet. This dilemma often leads to a longer inlet which may not be necessary.

| | Method 1 | | | | Method 2 | | | | Method 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of Grate | Adjusted Clogging Factor | Effective Length ft | Rx | Inlet Capacity Qi cfs | Constant Clogging Factor | Effective Length ft | Rx | Inlet Capacity cfs | Constant Clogging Factor | Effective Length ft | Rx | Inlet Capacity |
| | Eq 16 | Eq 18 | Eq 20 | Eq 13 | | Eq 18 | Eq 20 | Eq 13 | | | Eq 12 | Eq 14 |
| 1.00 | 0.50 | 1.50 | 0.03 | 4.67 | 0.50 | 1.50 | 0.03 | 4.67 | 0.50 | 3.00 | 0.14 | 2.67 |
| 2.00 | 0.38 | 3.75 | 0.22 | 5.81 | 0.50 | 3.00 | 0.14 | 5.35 | 0.50 | 6.00 | 0.45 | 3.62 |
| 3.00 | 0.29 | 6.38 | 0.48 | 7.46 | 0.50 | 4.50 | 0.30 | 6.30 | 0.50 | 9.00 | 0.67 | 4.32 |
| 4.00 | 0.23 | 9.19 | 0.68 | 8.70 | 0.50 | 6.00 | 0.45 | 7.24 | 0.50 | 12.00 | 0.80 | 4.71 |
| 5.00 | 0.19 | 12.09 | 0.80 | 9.44 | 0.50 | 7.50 | 0.58 | 8.03 | 0.50 | 15.00 | 0.87 | 4.93 |
| 6.00 | 0.16 | 15.09 | 0.87 | 9.86 | 0.50 | 9.00 | 0.67 | 8.64 | 0.50 | 18.00 | 0.91 | 5.05 |
| 7.00 | 0.14 | 18.09 | 0.91 | 10.11 | 0.50 | 10.50 | 0.75 | 9.09 | 0.50 | 21.00 | 0.94 | 5.13 |
| 8.00 | 0.12 | 21.09 | 0.94 | 10.26 | 0.50 | 12.00 | 0.80 | 9.42 | 0.50 | 24.00 | 0.95 | 5.18 |
| 9.00 | 0.11 | 24.09 | 0.95 | 10.36 | 0.50 | 13.50 | 0.84 | 9.67 | 0.50 | 27.00 | 0.96 | 5.21 |
| 10.00 | 0.10 | 27.09 | 0.96 | 10.43 | 0.50 | 15.00 | 0.87 | 9.85 | 0.50 | 30.00 | 0.97 | 5.24 |

Notes: Method 1 adjusted clogging fctor applied to inlet length
Method 2 constant clogging factor applied to inlet length
Method 3 constant clogging factor applied to inlet capacity

**Table 3 Comparisons among Three Inlet Design Methods**

## CONCLUSIONS

(1) The current design procedure for sizing a grate inlet was developed for single-grate inlets under the condition of no clogging. In practice, a multiple-grate inlet is often needed to cope with a large amount of storm runoff on the street. In this study, the single-grate inlet design method has been systematically expanded to the designs of multiple-grate inlets.

(2) The decay function derived in this study converts a single-grate clogging factor to a multiple-grate clogging factor. The decay coefficient can be selected based on the incremental inlet capacity when adding an additional unit.

(3) The current practice applies a clogging factor to the inlet capacity and results in inlets with an excessive length. This discrepancy has been resolved in this study by applying the clogging factor to the length of the inlet. Using the effective length of a grate inlet, inlet capacities can be consistently predicted among various combinations between grate sizes and clogging factors.

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