HYDRAULIC INTERCEPTION CAPACITY OF INCLINED GRATE

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Abstract
An inclined grate is often installed on the top of an inlet box because the inclined angle can be adjusted to regulate the flow interception through the submerged portion of the grate. The inclined angle on the grate may vary between zero (flat) to function as a horizontal grate and 90° (vertical) to operate like a side grate. In general, the selection of inclined angle should be related to the hydraulic efficiency and the amount of floating debris in storm water. In current practice, there isn’t any quantifiable guidance as to how to choose the inclined angle for a grate. Under a joint research effort, a 1/3 scaled model was constructed in the hydraulic laboratory to test the theoretical capacity derived for inclined grate. The method of least-square error was then used to identify the best fitted values for discharge coefficients as a function of inclined angle with or without an inlet depression. The set of new equations derived and calibrated in this study can significantly improve the current design procedures for Type C and Type D highway median inlets.

Key words: Inclined gate, stormwater, highway drainage

Inclined grates are often used to collect storm runoff in highway medians. A Type C grate has a standardized square surface area of 1 by 1 m and a Type D gate is a doubled Type C grate. Both Type C and D grates are used for inlet designs that are aimed at a high hydraulic efficiency to intercept storm runoff through the highway medians. In practice, the performance of a horizontal grate is sensitive to debris clogging. As a result, it was speculated that a grate should be installed with an inclined angle because the inclined grate surface might accumulate floating debris on the water surface and then to leave the submerged grate area for flow entry. Secondly, a depression of 30 cm is preferred to increase the head water depth on top of the grate. According to the Hydraulic Design Manual issued by the Colorado Department of Transportation (CDOT 2004), this concept has been recommended for field tests, knowing that a further verification is underway.

As a joint research effort between CDOT and Urban Drainage and Flood Control District (UDFCD), a laboratory study was conducted to investigate the hydraulic performance of a 1/3-scaled model Type C grate with an inclined angle varied from zero to 30°. This
report presents the comparison between the theoretical formulas derived for flow interception and observed data collected in the laboratory. A set of discharge coefficients was derived using the method of least square errors. The design charts provide a quantifiable design procedure to assist engineers in selection of inclined angle for an inlet grate.

HYDRAULIC CAPACITY AND FLOW INTERCEPTION

The hydraulic performance of a grate depends on the water depth on top of the grate. When the water depth is too shallow to submerge the entire grate surface, the grate operates like a weir. When the grate area is completely submerged, the grate operates like an orifice. The transition from weir to orifice flow is a mixing flow (Guo et al. 2008). As shown in Figure 1, a grate is formed with I-beam bars. The net opening ratio for a grate is defined as the clear opening area for water to flow through the grate surface as:

\[ n = (1 - C \log) \frac{LB - L_bB}{LB} = (1 - C \log) \frac{L - L_b}{L} \]  

Where \( n \) = net area opening ratio, \( C \log \) = clogging factor \( 0 \leq C \log \leq 1.0 \) due to debris, \( L \) = grate length, \( B \) = grate width, and \( L_b \) = cumulative width of I-beam bars on grate. Eq 1 indicates that the grate’s area opening ratio for an orifice flow is equal to the length opening ratio for a weir flow. The selection of clogging factor depends on the highway condition, and a decayed clogging factor is recommended for multiple grates. Details can be found elsewhere (Guo 2000C, Guo 2006).

![Figure 1 Dimension of Inlet Grate](image)

The hydraulic capacity of a Type C grate is quantified according to its flow interception. The integral of flow interception is described as:

\[ Q = nC_d \int \sqrt{2gh} \, dA \]  

Where \( Q \) = flow rate, \( C_d \) = discharge coefficient, \( g \) = gravitational acceleration, \( dA \) = flow area, and \( h \) = headwater depth on \( dA \). For a given water depth, the grate may operate like a weir or an orifice, whichever is less in flow interception. In this study, two sets of...
equations were derived to predict both the weir and the orifice flows. The discharge coefficients are respectively derived and then calibrated with the observed measurements.

**WEIR FLOW CAPACITY**

As illustrated in Figure 2, the inclined angle is formed by the gate length, \( L \), and its height, \( H_b \). The coordination system \((h,x)\) is set to describe the flow condition in which \( h \)=water depth measured downward from the water surface, and \( x \)=wetted distance measured along the grate. Under a shallow water depth, the grate’s wetted perimeter may operate like a weir. Water overtops the three submerged sides into the inlet box, including two inclined sides and the lower base width.

\[ dA = (H - h) \cot \theta \, dh \]  
\[ y = H - h \]

Where \( \theta \) = inclined angle, \( H \)=water depth, \( y \)=location of \( dA \) above the ground, and \( dh \)=infinitesimal thickness for flow area. The weir flow overtopping the wetted length along the grate’s side is integrated from \( h=0 \) to \( h=H \). Aided by Eq 3, Eq 2 yields:

\[ Q_{ws} = \frac{4}{15} n C_d \sqrt{2g} \cot \theta H^\frac{5}{2} \]  
for \( H<H_b \)
Where $Q_{ws}$ = side weir flow. Under a high water depth as illustrated in Figure 2, the integration limit is divided into two zones for mathematical convenience as:

$$H = H_b + H_a$$  \hspace{1cm} (6)

Where $H_a$ = surcharge depth above the top base of the grate. The infinitesimal areas for the weir flow in these two flow zones are respectively formulated as:

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

$$dA_2 = L \cos \theta \, dh \hspace{1cm} H_a < h < H \text{ for Zone 2}$$  \hspace{1cm} (8)

The subscripts 1 and 2 represent the variables in Zones 1 and 2. The weir flow overtopping the wetted length is integrated as:

$$Q_{ws} = nC_d \int_{h=0}^{h=H_a} \sqrt{2gh}L \cos \theta \, dh + nC_d \int_{h=H_a}^{h=H} \sqrt{2gh} (H-h) \cot \theta \, dh$$  \hspace{1cm} (9)

Integrating Eq 9 yields:

$$Q_{ws} = \frac{4}{15} nC_d \sqrt{2g} \cot \theta (H^{5/2} - H_a^{5/2})$$  \hspace{1cm} (10)

Re-arranging Eq 10 yields:

$$Q_{ws} = \frac{4}{15} nC_d \sqrt{2g} L \cos \theta \frac{H^\frac{5}{2}}{H^\frac{2}{3}H_b} \left[ \frac{(H - H_b)^\frac{5}{2}}{H^\frac{2}{3}H_b} \right]$$  \hspace{1cm} \text{for } H > H_b \hspace{1cm} (11)

At $H = H_b$, Eq 11 agrees with Eq 5. The total flow collected into the inlet box is the sum of the weir flows overtopping the two wetted sides along the grate and the lower base width of the grate. The weir flow over the lower base is computed as:

$$Q_{wb} = \frac{2}{3} nC_d \sqrt{2g} B H^\frac{5}{2}$$  \hspace{1cm} (12)

In which $Q_{wb}$ = flow overtopping the low base width. The total weir flow is the sum as:

$$Q_w = 2Q_{ws} + Q_{wb}$$  \hspace{1cm} (13)

In which $Q_w$ = total interception for weir flow.
ORIFICE FLOW CAPACITY

When the grate surface area operates like an orifice as illustrated in Figure 3. As aforementioned, the integration of the orifice flow into the inlet box is separately conducted for the low and high water depth conditions.

For $H < H_b$, the infinitesimal flow area for orifice flow in Fig 3 is defined as:

\[
dA = n B \cos \theta \, dx
\]  
(14)

The head water depth, $h$, can be related to the wetted length, $x$, along grate’s side as:

\[
h = (1 - x/X)H
\]  
(15)

where $X$= wetted length that varies between $0 \leq X \leq L$, $x$= wetted distance along the grade between $0 \leq x \leq X$. Under a low flow condition, $H \leq H_b$, the orifice flow through the submerged surface area on the grate is integrated from $x=0$ to $x=X$ as:

\[
Q_o = \frac{2}{3} nC_d B H \cot \theta \sqrt{2gH} 
\]  
(16)

In which $Q_o$= orifice flow. When $\theta = 0$, Eq 16 is reduced to a horizontal orifice as:

\[
Q_o = \frac{2}{3} nC_d B L \sqrt{2gH} 
\]  
for $H = 0$ and $\theta = 0$  
(17)
Under a high flow condition, the entire grate surface area is submerged. The headwater is related to the wetted length along the grate as:

\[ h = H - \frac{x}{L}(H - H_s) = H - \frac{x}{L}H_b \]  

(18)

For mathematical convenience, 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 orifice flow under a high water depth is integrated from \( x=0 \) to \( x=L \) as:

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

(19)

At \( H = H_b \), Eq 19 agrees with Eq 16. Comparing with the conventional approach, the orifice and weir coefficients can be related to the discharge coefficient as:

\[ C_o = \frac{2}{3} C_d \]  

(20)

\[ C_w = \frac{4}{15} C_d \sqrt{2g} \]  

(21)

in which \( C_o \) = orifice coefficient and \( C_w \) = weir coefficient. Using the orifice and weir coefficients, the governing equations for various flow conditions are summarized as:

For \( H \leq H_b \), the orifice and weir flows are respectively estimated as:

\[ Q_o = nC_o BHCot\theta \sqrt{2gH} \]  

for low orifice flow  

(22)

\[ Q_w = 2n C_w Cot\theta H^\frac{5}{2} + nC_w B H^\frac{3}{2} \]  

for low weir flow  

(23)

For \( H \geq H_b \), the orifice and weir flows are respectively estimated as:

\[ Q_o = nC_o BLCos\theta \sqrt{2gH}\left[\frac{H^2}{H_b \sqrt{H}} - \frac{(H - H_b)^3}{H_b \sqrt{H}}\right] \]  

for high orifice flow  

(24)

\[ Q_w = 2nC_w LCos\theta H^\frac{3}{2}\left[\frac{H^5}{H_b^3} - \frac{(H - H_b)^5}{H_b^3}\right] + nC_w B H^\frac{3}{2} \]  

for high weir flow  

(25)

For a given water depth, the interception capacity through an inclined grate is dictated by weir or orifice flows, whichever is less as (Mays 2001):
\[ Q_c = \min (Q_w, Q_o) \text{ for a given water depth} \]  

(26)

In which \( Q_c \) = flow interception through grate. On the contrary, for a given design flow, the required headwater depth, \( H \), acting on an inclined grate is determined as (HEC-22):

\[ H = \max (H_w, H_o) \text{ for a given design flow} \]  

(27)

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

**LABORATORY TEST AND DATA ANALYSIS**

Laboratory tests were conducted using 1/3-scaled Type C grate models. According to the Froude number similarity, 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 grates were studied in the laboratory tests. As shown in Figure 4, a Type D grate is formed using two Type C grates in parallel. A rotated Type D grate is formed using two Type C grates in series. The inclined angle used in this study is varied from 0°, 10°, 20°, to 30°. The model grate was placed under a condition with or without a depression depth of 30 cm. Both Type C and D grates have an opening ratio of 0.7 for both the surface area and the side lengths.
There were 96 data sets measured at the Hydraulic Laboratory at the Colorado State University (Comport 2010). Each set of data includes flow rate intercepted and flow depth applied to the front of the model grate. In general, the range of water depths varies from 0.5 to 3 feet (15 to 100 cm) that covers the general applications to highway median drainage. The values of discharge coefficient are derived using the method of least square errors between the predicted and observed flow rates under the selected flow depths. In general, the laboratory data well agrees with the theoretical equations (Figures 5).

![Figure 5 Performance of Type C Grate with Angle 20°](image)

There are 6 design curves as presented in Figure 6 generated for cases including leveled C and D grates, 30-cm depressed C and D grate, and rotated D grate with or without 30-cm depression.
As revealed in Figure 6, a leveled grate has the highest hydraulic efficiency. As the inclined angle increases from 0 to 15°, the grate’s flow coefficient decreases. The grate
gradually recovers its hydraulic efficiency as the inclined angle increases from 15 to 30°. The difference caused by inlet depression and inclined angle become diminished when a horizontal grate is gradually raised toward a vertical. Figure 7 shows the improvements to the current design chart for a horizontal Type C grate. As observed in field and laboratory, any floating, sizable debris tends to land onto the grate surface and then becomes hardly moved due to the hydrostatic suction forces. The inclined angle does not elevate sizable debris bodies to the water surface.

CONCLUSION
In this study, the hydraulic efficiency for an inclined grate was investigated for its capability of flow interception. The hydraulic performance for a grate is dominated by weir or orifice flow, whichever is less. Two sets of weir and orifice formulas were derived for inclined grates. The flow interception quantified for an inclined grate varies between the horizontal and vertical grates, depending on its angle. The discharge coefficients for various inclined angles were calibrated with 96 sets of laboratory data, and then converted into the conventional orifice and weir coefficients for engineering applications. Care needs to be taken because weir coefficients are unit dependent. Secondly, all discharge coefficients were derived without any clogging effect. A decayed clogging coefficient is recommended for highway median drainage designs.

In comparison, the leveled, flat grate has the highest hydraulic efficiency. As revealed in the observed data, an inclined angle decreases the grate’s efficiency to its lowest at 15°. From 15 to 30°, the inclined grate gradually recovers its efficiency toward the vertical grate. An inclined angle creates a noticeable difference in hydraulic efficiency from 0 to 30°, and the difference becomes diminishing when the angle is greater than 30°. Although an inlet depression decreases the grate’s efficiency, the increased headwater depth would still enhance the flow interception through the grate.

The stipulation of the influence of an inclined angle on floating debris was not supported from the observations in field and in laboratory. An inclined angle does not elevate the floating debris to the water surface, but it decreases the grate’s performance. It is suggested that straw or sand bags be used around the grate as a debris control.

APPENDIX I


**APPENDIX II**

B=grate width  
$C_d$= discharge coefficient  
$C_o$ = orifice coefficient  
$C_w$= weir coefficient  
Clog = clogging factor $0 \leq \text{Clog} \leq 1.0$ due to debris,  
dA= flow area, and $h$ = headwater depth on dA  
$dh$ = infinitesimal thickness for flow area  
g=gravitational acceleration  
h=water depth variable measured downward from the water surface,  
$H_w$ = headwater for weir flow  
$H_o$= headwater for orifice flow  
$H$= design headwater or water depth  
n=net area opening ratio  
L=grate length  
$L_b$ = cumulative width of I-beam bars on grate  
$Q$= flow rate  
$Q_{ws}$= side weir flow  
$Q_{WB}$= flow overtopping the low base width  
$Q_w$ = total interception for weir flow  
$Q_o$= orifice flow  
$Q_c$ = flow interception through grate  
x= wetted distance measured along grate between $0 \leq x \leq X$  
$X$= wetted length that varies between $0 \leq X \leq L$,  
y=location of dA above the ground  
$\theta$ = inclined angle,  
The subscripts 1 and 2 represent the variables in Zones 1 and 2.