Generalized Hydraulic Characteristics of Grate Inlets

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Five basic types of grate inlets were investigated. A rational qualitative analysis of the variables governing the efficiency of a grate inlet was verified through experimental measurement. The experimental results are presented in a generalized graphical fashion valid for any size grate. These plots can be used for design purposes, and a method is presented for determination of the length of grate required for operation at optimum efficiency.

The five basic types of grates are classified according to their decreasing hydraulic efficiencies. Grates constructed with curved-vane type bars were found to be the most efficient over the largest range of gutter velocities.

•SURFACE drainage of streets and urban highways is frequently accomplished through the use of curb inlets, grate inlets, or a combination of both. If drainage is to be accomplished in the most economical manner, the relative merits of each drainage device must be known. Curb inlets have the disadvantage of being inefficient flow interceptors unless used in conjunction with some form of gutter depression (1, 2). Use of depressed gutters is not a desirable practice on today's modern, high-speed roadways. Consequently, considerable attention has been focused on the hydraulic characteristics of grate inlets. Li, Goodell, and Geyer (2) have generalized hydraulic characteristics to the extent that they were able to investigate models at less than full scale. Through their generalized analysis, they were able to formulate approximate relationships for hydraulic design.

Larson and Straub (3) have made an attempt to generalize the results of experimental studies in terms of a "velocity index" $\sqrt{S_0}/n$ where S_0 is the longitudinal gutter slope and n is the Manning coefficient. However, their graphical results apply only to the size of grate investigated. They also conducted self-cleaning tests on their grates.

The investigation reported herein was conducted with the thought in mind that generalized hydraulic characteristics, independent of scale, provide the only firm means of comparing the operating efficiencies of two grates.

PHYSICAL CONSIDERATION OF THE FLOW

Flow over, through, and around any particular grate inlet is very complex at best. However, if consideration is given to the fluid, geometric, and flow variable involved, it is possible to clarify the picture to a large degree.

The variables which play a role in determining the efficiency of any grate are the following:

Q_0 = flow rate approaching the grate;
Q_i = flow rate intercepted by the grate;
ρ = density of the water;

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γ = specific weight of the water;
W = width of the grate (normal to the flow);
L = length of the grate (parallel to the flow);
D = depth of flow upstream from the grate (in this case measured at the curb);
β = a dimensionless characteristic which will be assumed to completely describe the geometric configuration of the grate;
S = cross slope of the gutter; and
S_o = longitudinal slope of the gutter.

Functionally the variables are related by the expression

$$Q_i = f(Q_o, \rho, \gamma, W, L, D, \beta, S, S_o) \tag{1}$$

If the technique of dimensional analysis is applied to Eq. 1, the functional relationship can be changed to

$$\frac{Q_i}{Q_o} = \phi\left(\frac{Q_o}{\sqrt{\frac{\gamma}{\rho}D}}, \frac{L}{D}, \frac{D}{W}, \beta, S, S_o\right) \tag{2}$$

In Eq. 2, the leftmost term inside the parentheses is in actuality the Froude number of the approaching flow and can be written without reduction in generality as $V_o/\sqrt{gD}$ (4). The term Q_i/O_o is the efficiency of the grate. Evidently the efficiency of the grate will be influenced by the Froude number of the approaching flow, the relative length of the grate L/D, the relative depth of flow D/W, the cross slope S, the longitudinal slope S_o, and the geometric configuration of the grate β. All the parameters in Eq. 2 are dimensionless and are therefore applicable regardless of the absolute size of the grate or the dimensional units used.

The role of the Froude number is qualitatively clear. For any given depth, the faster the flow, the greater the tendency for water to bypass or jump over the grate. Hence, efficiency can be expected to decrease with increasing $V_o/\sqrt{gD}$.

Relative length of the grate is known to be important. For a given length of grate, a wide grate will intercept more flow than a narrow grate. Hence, efficiency will increase with a decrease in L/W (certain limits can be expected to occur).

For a given Froude number, efficiency of a grate will be decreased with an increase in relative depth D/W because more flow can then be expected to go around and over the grate.

The role of the geometry is somewhat more complicated. The shape of the grate as well as the shape, spacing, number, thickness, and orientation of the bars is all assumed to be included in the parameter. Obviously more than one parameter would be needed to completely describe the configuration of the grate.

Eq. 2 indicates a qualitative relationship between the variables influencing the hydraulic efficiency of any grate. Although understanding of fluid flow made it possible to predict certain behavior, an experimental study must ultimately be carried out to obtain the quantitative relationships necessary for design purposes.

EXPERIMENTAL APPARATUS AND PROCEDURES

Incorporation of the alternate form of the Froude number transforms Eq. 2 to

$$\frac{Q_i}{Q_o} = \phi\left(\frac{V_o}{\sqrt{gD}}, \frac{L}{D}, \frac{D}{W}, \beta, S, S_o\right) \tag{3}$$

To investigate experimentally the functional relationship indicated by Eq. 3, it is necessary to have independent control over all variables except the dependent variable

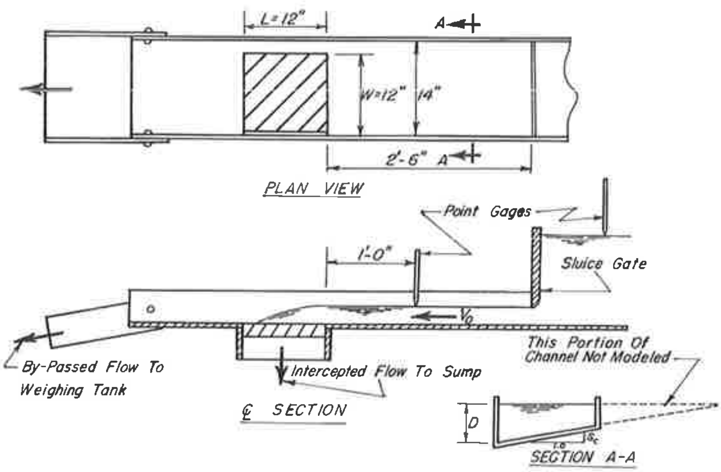

Figure 1. Experimental apparatus.

Q_i/Q_o. Other experimenters have set a particular slope S_o and then varied the discharge Q_o. Such a procedure does not provide absolute control over the depth of flow, because it is dependent on the cross slope, the longitudinal slope, the boundary roughness, and the discharge rate. To investigate the effect of S_o alone, it was obviously necessary to provide independent control of both $V_o/\sqrt{gD}$ and D/W. Such control was established by discharging water under a sluice gate into the gutter. The bottom of the sluice gate was cut in such a fashion that flow under the sluice gate occurred with a level free-surface and without contraction. Depth of flow was controlled by adjusting the sluice gate opening, and the velocity of flow was controlled by the head maintained. Discharge rate upstream from the gate was measured with a calibrated venturi meter. The discharge not intercepted by the grate (Q_o - Q_i) was directed into a weighing tank.

Cross slope of the gutter was set by tilting the entire flume about its longitudinal axis, while the longitudinal slope was set by rotating the flume about a transverse axis. Sluice gates with the proper bottom slope were utilized for each different cross slope. Depth of flow was measured with a point gage at a point 1.0 ft upstream from the grate. Arrangement of the experimental apparatus is shown in Figure 1.

Six different grate geometries were studied experimentally. The proportions of these grates are shown in Figure 2. Procedure was identical for each grate:

1. The sluice-gate opening was set to produce a particular depth of flow.

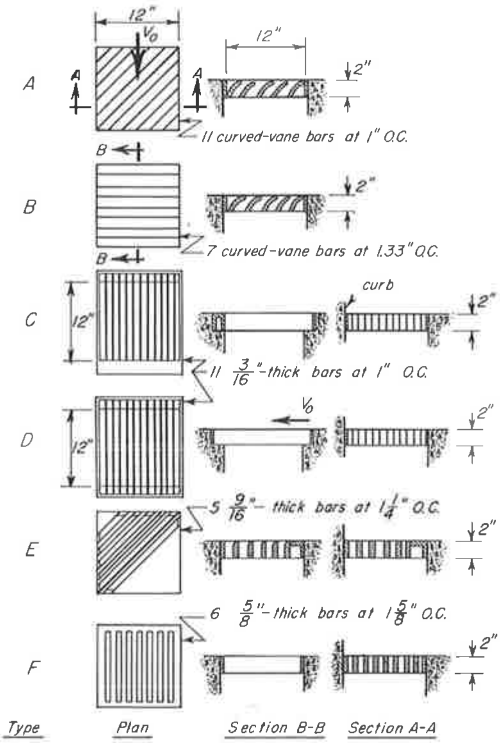

Figure 2. Grate configuration.

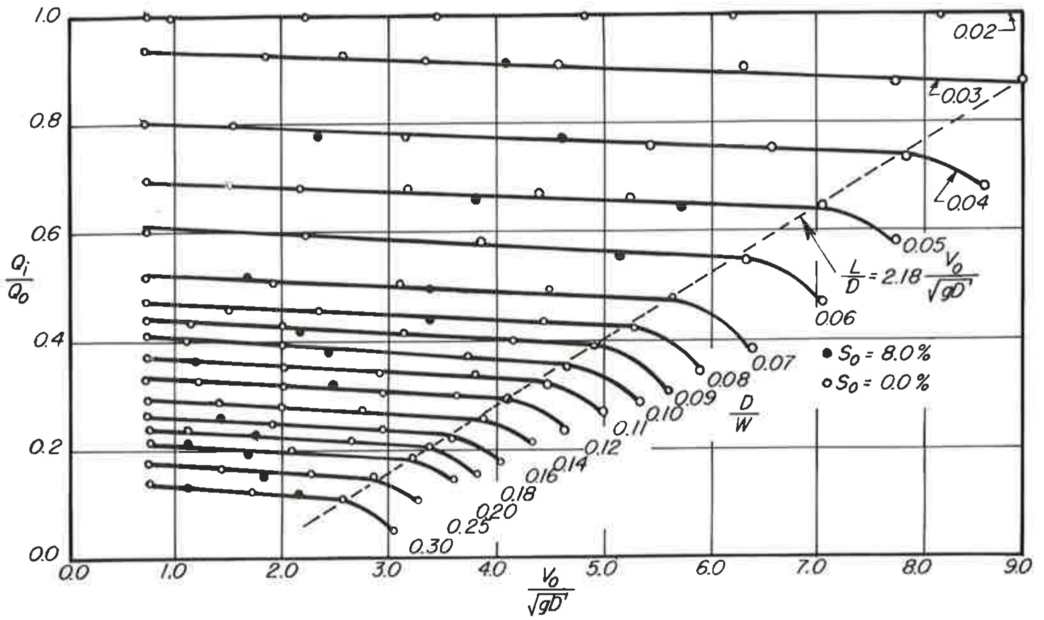

Figure 3. Type A grate, 50.0 to 1.0 cross slope.

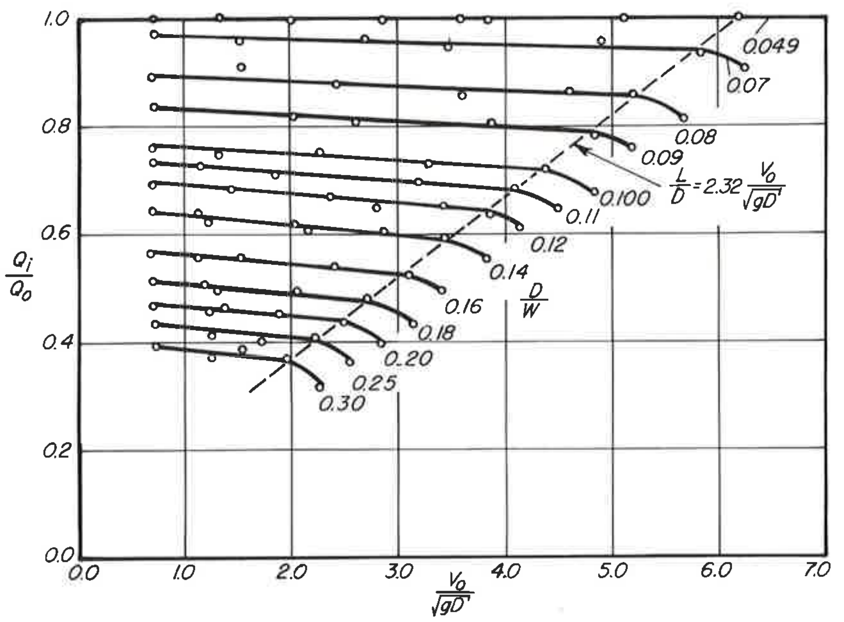

Figure 4. Type A grate, 20.6 to 1.0 cross slope.

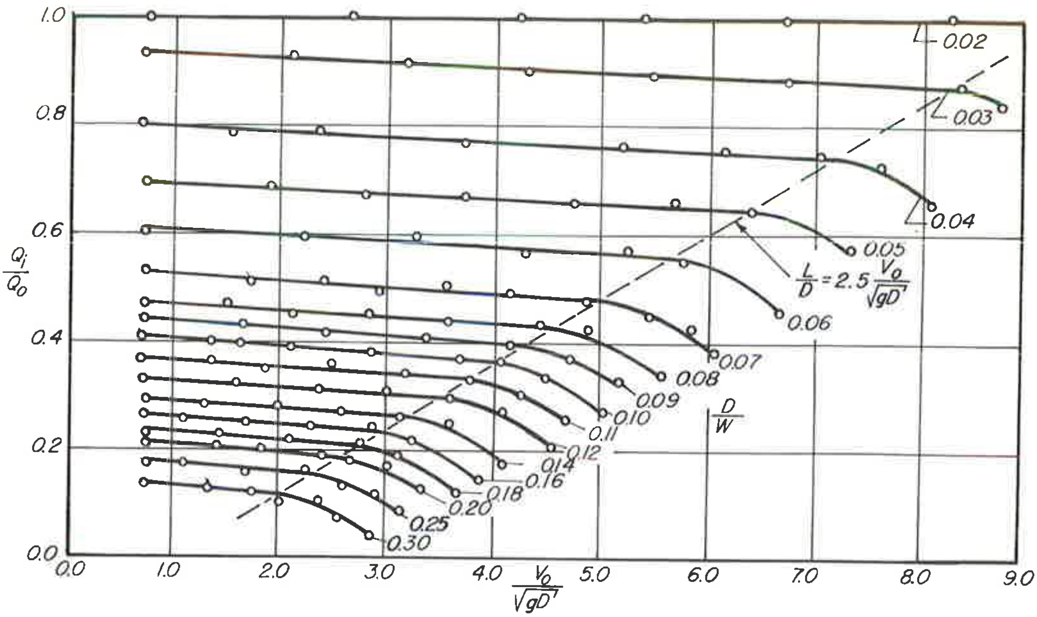

Figure 5. Type B grate, 50.0 to 1.0 cross slope.

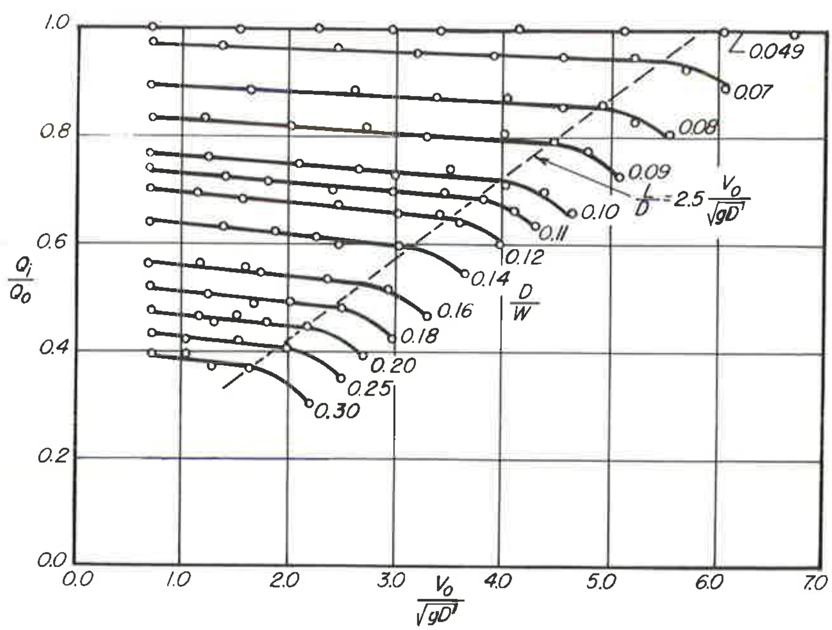

Figure 6. Type B grate, 20.6 to 1.0 cross slope.

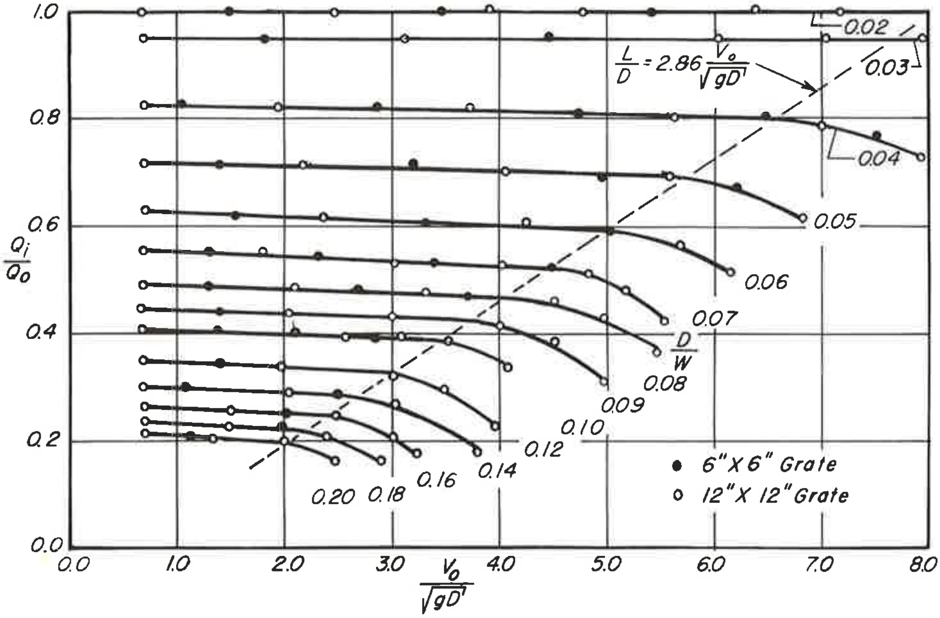

Figure 7. Type D grate, 50.0 to 1.0 cross slope.

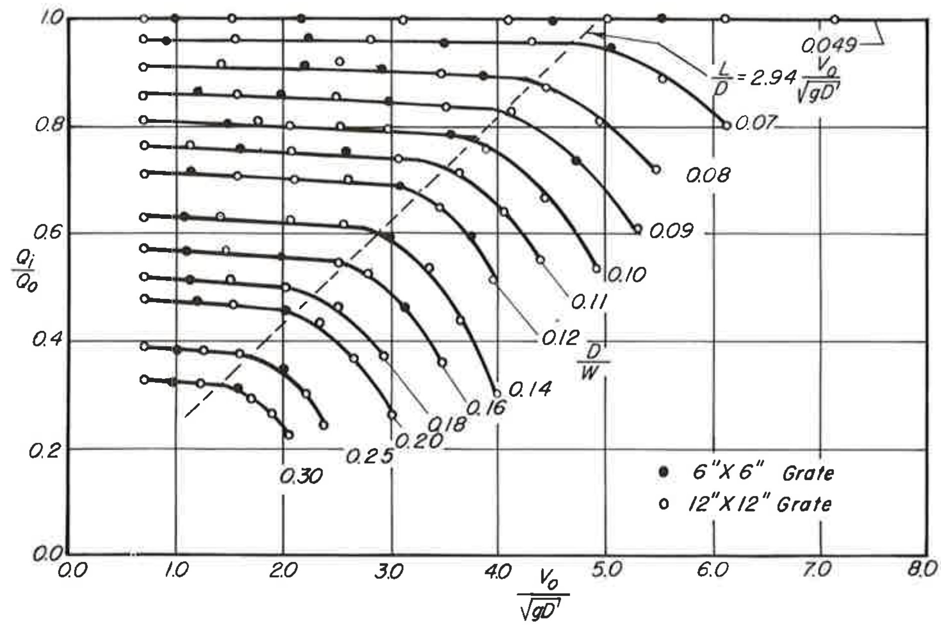

Figure 8. Type D grate, 20.6 to 1.0 cross slope.

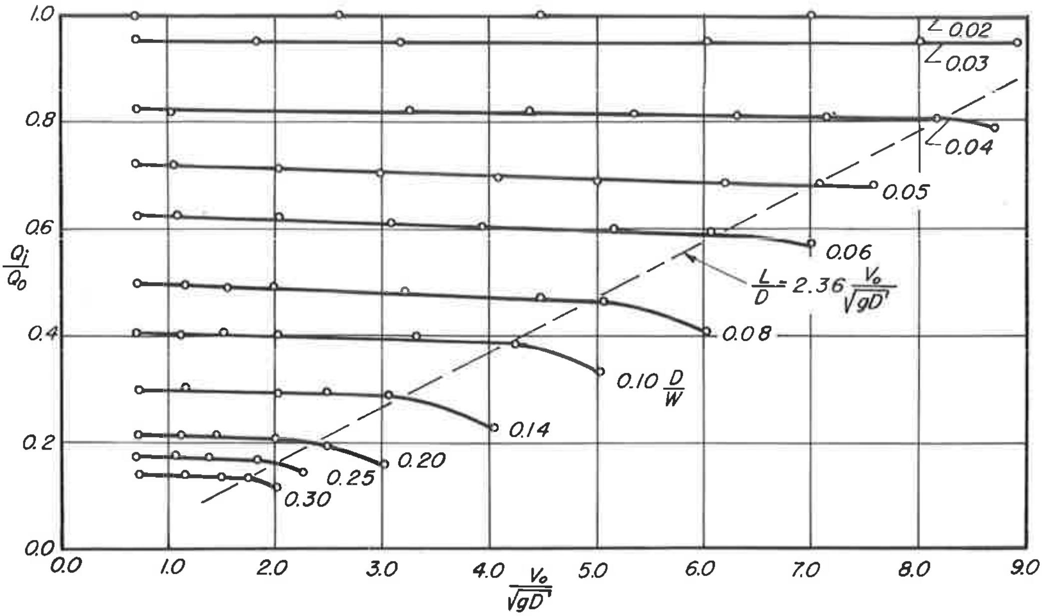

Figure 9. Type C grate, 50.0 to 1.0 cross slope.

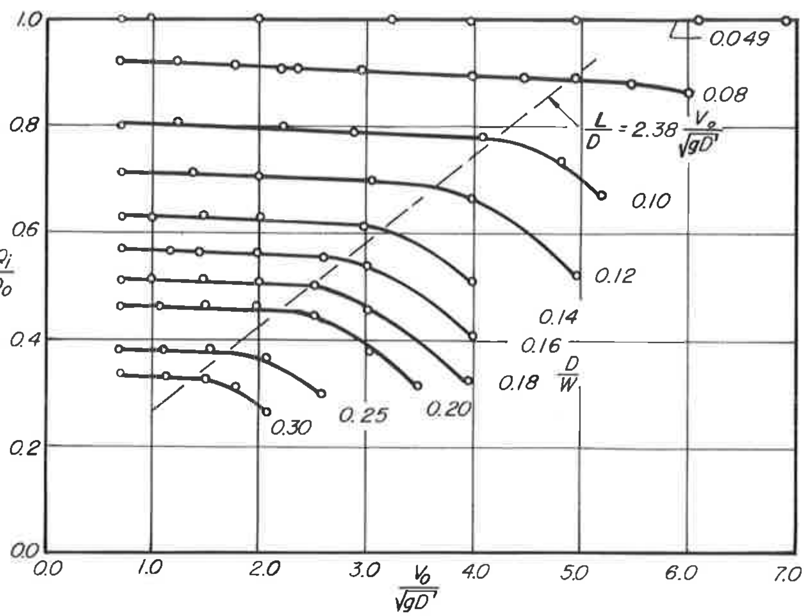

Figure 10. Type C grate, 20.6 to 1.0 cross slope.

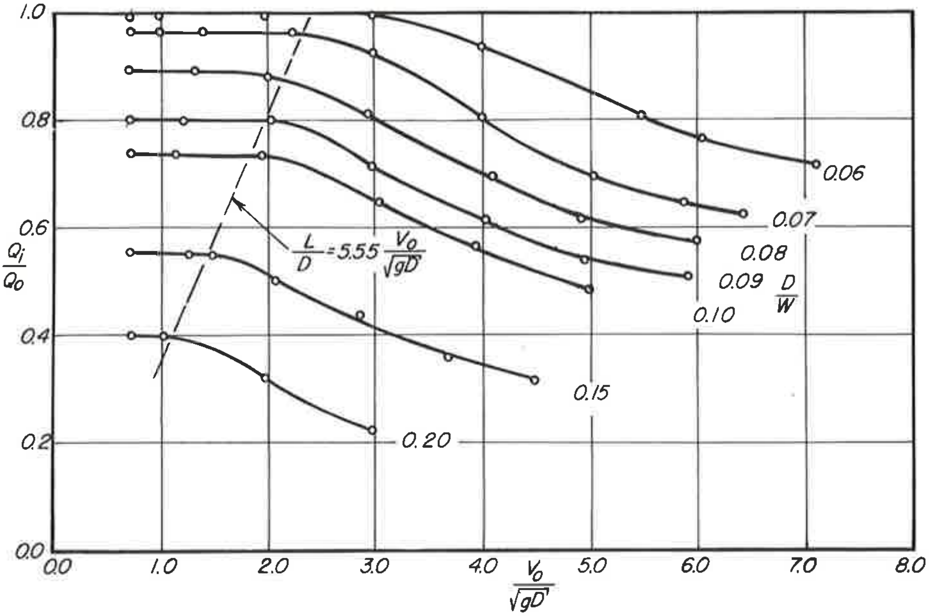

Figure 11. Type E grate, 20.6 to 1.0 cross slope.

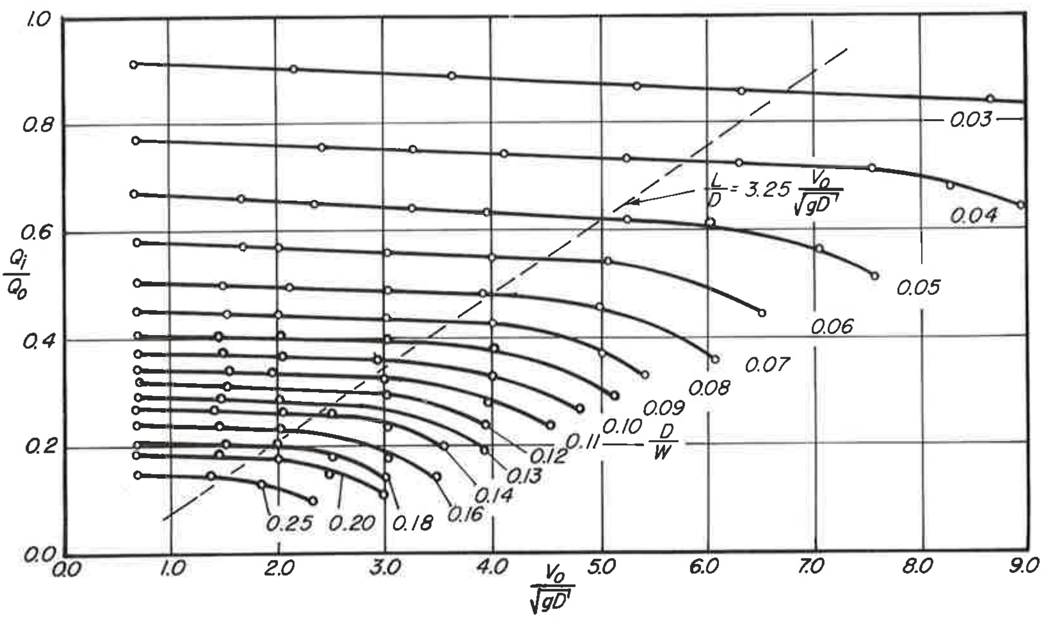

Figure 12. Type F grate, 50.0 to 1.0 cross slope.

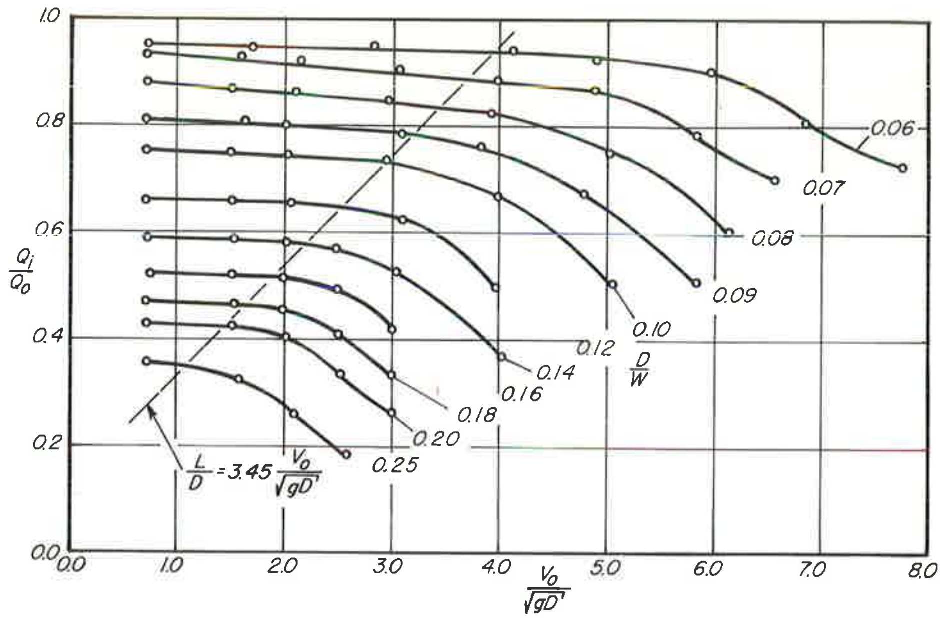

Figure 13. Type F grate, 20.6 to 1.0 cross slope.

2. Flow rate was adjusted to produce a particular Froude number.
3. The flow not intercepted was weighed.
4. The three foregoing steps were repeated for each of two cross slopes for each grate.

Experimental results for the six grates are shown in Figures 3 through 13. Because each grate was 1.0-ft square, the ratio L/W = 1.0 in every case. Cross slopes of 20.6 to 1 and 50 to 1 were used for each grate.

RESULTS

Hydraulic Characteristics

It was possible to eliminate the longitudinal gutter-slope from the parameters involved in Eq. 3. Actually the longitudinal slope plays an important role in determining the average velocity of flow in the gutter. Unless the gutter is on an extremely steep slope (for instance, 45 degrees), it might well be expected that the longitudinal slope would play a minor role in determining the grate efficiency. This hypothesis was checked experimentally at the outset of the program. Grate A was studied on a zero slope and again on an 8 percent slope. No noticeable change in characteristics was observed (Fig. 3). Therefore, in all of the remaining experiments, a horizontal gutter was used.

A flume with a 14-in. width was used to represent the gutter. Because the grates used were only 12 in. wide, a triangular flow section was obtained only for small depths. To compute the grate efficiency, it was assumed that flow would take place at average velocity in the imaginary portion of the triangular cross-section (Fig. 1). This is obviously an approximation because both viscous and surface tension effects will be important in the actual triangular section. However, the average velocity in the triangular portion of an actual highway gutter would, without question, be somewhat lower than was assumed herein because of increasing importance of viscous forces with decreasing depth. From the design standpoint, the assumption made here was assumed to be conservative. The validity of this assumption was investigated experimentally. A grate, geometrically similar to Grate C but only half the size (6 in. by 6 in.), was constructed and tested in the 14-in. wide flume. Hence, a triangular flow cross-section was obtained for a value of D/W twice as large as that for the 12-in. square grate. The experimental results (Figs. 7 and 8) indicate that the magnitude of the error in efficiency produced by assuming that flow would occur at average velocity in the triangular section is negligible. This reduced scale model also verified that the efficiency was truly a function of the variables indicated in Eq. 3.

Two distinctly different flow patterns were observed for each grate (Figs. 3 through 13). At relatively low values of the relative depth D/W or the Froude number $V_o/\sqrt{gD}$, no flow crossed over the grate and the flow pattern was smooth. Eventually, as either the relative depth or the Froude number is increased, the flow strikes the downstream side of the grate creating a violent disturbance—not unlike a hydraulic jump—on the grate itself. Once the disturbance is formed, flow begins to pass directly over the grate and the efficiency Q_i/Q_o is accordingly reduced rather abruptly. The onset of the disturbance is indicated (Figs. 3 through 13) by the point at which the efficiency curves bend abruptly downward.

As long as flow does not pass directly over the grate, the length of the grate has only a minor effect on efficiency. For a long grate, as opposed to a short one, more flow enters the grate from the roadway. However, Li et al. (2) have shown that this contribution to the intercepted flow is quite small unless the grate is depressed.

The dotted line (Figs. 3 through 13) indicates the limiting condition at which a hydraulic jump will form and water will begin to flow directly over the grate. An approximate equation was formed for each of these lines and is shown on the graphs. Each of the equations has the form

$$\frac{L}{D} = m \frac{V_o}{\sqrt{gD}} \tag{4}$$

The magnitude of m is an indication of the grate's efficiency. Large values of m indicate that a hydraulic jump forms readily, while a small value indicates the opposite trend. Grates with a small value of m are obviously the most desirable because the value of m is directly proportional to the length of grate required to insure maximum efficiency of operation at high flow rates.

Eq. 4 is of further use to the designer. Rewritten as $L = Dm (V_o/\sqrt{gD})$, Eq. 4 yields the length of grate required to eliminate flow passing directly over the grate for gutter flow at given values of depth and Froude number.

Although the experiments conducted in this study were performed on square grates, Figures 3 through 13 are applicable for any grate with similar bar design, regardless of size, as long as the length of the grate is not less than that given by Eq. 4.

Observation of the dimensionless plots shows that grates utilizing curved vane-type bars[1] are of the most efficient type (Grates A and B). At low values of $V_o/\sqrt{gD}$, the efficiency of a grate with narrow, widely-spaced longitudinal bars (Grate C) is essentially the same as ones formed with curved vanes, but curved vane bars are more effective in preventing the formation of a hydraulic jump. Hence, the range of maximum efficiency is extended through use of the vane-type bars. Further evidence of the benefits of properly shaping the vanes is obtained by a comparison of efficiency curves for Grates A and E.

Grates with closely-spaced, relatively wide, flat bars (Grate F) are inefficient in the entire range (Figs. 12 and 13). Considerable flow follows the bars and passes directly over the grate prior to the formation of a hydraulic jump. In fact, the hydraulic jump is drowned out virtually as soon as it forms and the grate operates as an orifice.

A comparison of Figures 3 and 4 (Grate A) with Figures 5 and 6 (Grate B) shows that sloping of vanes has only a small effect on the efficiency of the grate, with the maximum efficiency being obtained for vanes placed at 45 degrees to the direction of flow.

In general, the hydraulic jump is formed when flow strikes the downstream side of the grate and rebounds upward. The range of efficient operation of Grate D was extend-

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[1]The use of such bars in a highway grate has been patented.

ed greatly by the slight revision required to produce Grate C. Clear opening is the same in each case but the hydraulic jump forms much more readily on Grate C. The revision is a minor one, but highly desirable.

Application to Design

All of the experimental results (Figs. 3 through 13) could have been set forth in dimensional plots on which the intercepted flow rate Q_i was plotted against average gutter velocity V_o; individual curves would have been obtained for each separate value of D. A separate graph would then have been required for each size of grate tested as well as for each separate cross slope used. However, by plotting the curves in dimensionless form a graph is obtained which is valid for any size of grate because no absolute quantities appear in any of the plotted parameters. Both forms of plotting are equally useful in design, but the dimensionless form is the most compact.

To use the dimensionless graphs, the designer simply combines his calculated or known independent variable, V_o, W, D, to form the equivalent dimensionless parameters, $V_o/\sqrt{gD}$, D/W, used on the graphs. An example problem is presented in the Appendix to illustrate the use of the dimensionless plots for design purposes.

CONCLUSION

From the results of this investigation, the following conclusions can be made with regard to the operating characteristics of grate inlets:

1. The absolute hydraulic characteristics of any two grate inlets can be compared if the results of experimental tests are generalized according to the expression

$$\frac{Q_i}{Q_o} = \phi \quad \frac{V_o}{\sqrt{gD}}, \frac{D}{W}, \frac{L}{D}, S \quad .$$

2. For all practicual purposes the efficiency of any grate inlet is not a function of the longitudinal gutter slope if the slope is less than 8 percent. However, the slope plays an important role in determining the average flow velocity.

3. The curves of efficiency vs Froude number and relative depth presented herein may be used for proportioning or spacing grate inlets.

ACKNOWLEDGMENTS

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Appendix

EXAMPLE DESIGN PROBLEM

During the peak period of a design storm, runoff enters a gutter at the rate Q_e = 0.004 cfs per ft. The roughness of the gutter corresponds to a Manning's n equal to 0.02. Determine the required length and spacing of Type A gratings in order that gutter flow will not spread more than 8.0 ft toward the centerline. Longitudinal slope of the gutter is 4.0 percent and cross slope is 2.0 percent.

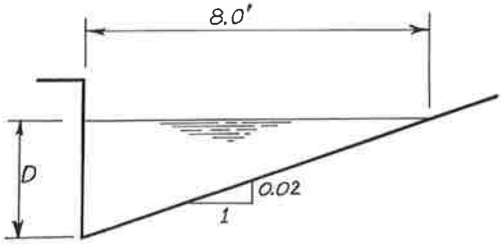

Figure 14. Gutter section at maximum depth.

Assume W = 2.0 ft

D (maximum depth) = 8(.02) = 0.16 ft

A (Flow area) = $0.16 \dfrac{8.0}{2} = 0.64 \text{ ft}^2$

To determine the discharge Q_o at depth D, use the relationship proposed by Hicks (5):

$$Q_o = 0.56 \left(\frac{Z}{n}\right) S^{1/2} D^{8/3}$$

where Z = 1/S.

Thus,

$$Q_o = 0.56 \left(\frac{50}{0.02}\right) (0.04)^{1/2} (0.16)^{8/3} = 2.11 \text{ cfs}$$

$$V_o = \frac{Q_o}{A} = \frac{2.11}{0.64} = 3.30 \text{ fps}$$

$$\frac{V_o}{\sqrt{gD}} = \frac{3.30}{\sqrt{32.2(0.16)}} = 1.45$$

$$\frac{D}{W} = \frac{0.16}{2.0} = 0.08$$

From Figure 3

$$\frac{Q_i}{Q_o} = 0.46$$

$$Q_i = 0.46(2.11) = 0.973 \text{ cfs}$$

$$\text{Spacing} = \frac{Q_i}{Q_e} = \frac{0.973}{0.004} = \underline{\underline{243 \text{ ft}}}$$

$$L = D(2.18)\frac{V_o}{\sqrt{gD}} = 0.16(2.18)(1.45) = \underline{\underline{0.50 \text{ ft}}}$$

If the grates are constructed with a length of 0.50 ft and a width of 2.0 ft, their hydraulic characteristics will be as shown to the left of the diagonal line in Figure 3 regardless of the fact that the corresponding ratio L/D = 0.25 instead of 1.0.