Improvements in Curb-Opening and Grate Inlet Efficiency

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Draining storm water quickly and efficiently from highways is an essential part of any highway program. Laboratory experiments were conducted to develop curb-opening and grate inlet efficiency curves for the Nebraska standard inlet (single and in series), the city of Lincoln canted inlet, a new grate inlet (single and in series), and an inlet affected by resurfacing. Experiments were performed for the on-grade inlets on a full-scale roadway surface that was treated with sand-imbedded paint to produce an average Manning's n-value of 0.016. The constant longitudinal and cross slopes were 3 and 2 percent, respectively. Supercritical flow prevailed over the flow range of 0.5 to 5 ft^3/sec. Results show that the Nebraska standard inlet provides about 20 percent greater efficiency than the equivalent AASHTO-type inlet. Canted inlet performance was only marginally better than that of the Nebraska standard inlet. The new grate inlet performance was very similar to that of curb-opening inlets. Inlets in series increased efficiencies by almost 20 percent over the efficiencies of single inlets. Finally, roadway resurfacing that covers inlet transitions reduces efficiency by about one-half.

Curb-opening inlets and grated inlets are important components of highway storm water removal systems. Whether located on grade or in a sag, inlets improve driving safety by reducing water spread and depth on the highway. Several laboratory studies have established the efficiencies of very basic inlet shapes (*1–7*). Results for these basic configurations are consistent and predictable from basic principles (*7*). However, the efficiencies of several new and increasingly common curb-opening inlet configurations have not been reported.

PURPOSE AND ORGANIZATION

In 1991 the University of Nebraska at Lincoln tested several curb inlet configurations for the Nebraska Department of Roads (NDOR). The purpose of this paper is to highlight the results of the testing program. These results will be of interest to other state highway departments. The paper is organized as follows: a description of the experimental facility is followed by a brief description of the testing program. Results and discussion follow, and the paper concludes with recommendations for curb inlet use and roadway resurfacing.

EXPERIMENTAL FACILITY

A 44-ft-long by 12-ft-wide roadway deck of ¾-in. plywood was constructed in the University of Nebraska–Lincoln Hydraulic Modeling Basin (Figure 1). The fixed longitudinal and transverse roadway slopes were 3 and 2 percent, respectively, sufficient to maintain supercritical flow at all flow rates tested. The paint used for the roadway surface was mixed with no. 10 sieved sand to simulate a concrete finish.

Two curbing systems were used for the tests. A standard 6.-in.-high curved curb was used for the curb inlets, whereas a triangular curb rising 4 in. in a span of 1 ft was used for the grate inlets.

Water was supplied from a storage reservoir and variable-speed pump, with flow rates varying from 0.5 to 5 ft^3/sec (cfs). A head box at the upstream end of the roadway was constructed with the lip even with the transverse-sloping roadway surface to provide a smooth flow to the roadway system. Flow entering and bypassing the inlet was measured with separate, calibrated weirs.

TESTING PROGRAM

Only a small part of the testing program is reported here. For complete details the reader is referred to the work by Hotchkiss and Bohac (*8*). Two major types of inlets were tested: curb-opening inlets and grate inlets. Curb-opening inlets included a standard NDOR inlet with a parabolic apron and the same inlet in series and the Lincoln, Nebraska, canted inlet. A relatively new grate inlet for use with triangular mountable curbs (referred to as a Saddle Creek grate) was tested singly and in series. A final test simulated a resurfaced roadway with all transitions and depressions paved over, providing only a simple inlet for water collection.

The standard NDOR inlet is 6 ft long and has a parabolically shaped apron that begins 3.3 ft from the curb face (Figures 2 and 3). This parabolic apron drops a total of 5 in. to the inlet and is easily constructed in the field with a prefabricated form. This NDOR inlet is installed with upstream and downstream gutter transitions 5 ft long that depress the curb invert 5 in. from the main roadway surface to match the parabolic apron. The inlets in series were separated by 10 ft. Although the separation distance is somewhat arbitrary, the 10-ft distance is standard on Nebraska highways.

Canted inlets (Figure 4) are popular in Lincoln and have been used on some Nebraska highways by NDOR. Inlet efficiencies, however, have been unknown, and it has been questioned whether the additional construction expense is justified by the expected increased interception efficiencies. The canted configuration is achieved by setting the upstream end of the curb opening back 1 ft from the original gutter line. This is accomplished with an 8-ft transition section sloped back from the original curb at the rate of 1:8. Other aspects are similar to the NDOR parabolic apron design.

The Saddle Creek grate tested (Figure 5) is 4.04 ft long and 2.4 ft wide. Longitudinal bars and transverse bars are spaced 2.75 and 8 in. apart, respectively. The grate has a folded shape so that the invert matches the gutter invert and a portion of the grate extends both up the curb and into the street. The grated inlet has an insignificant depressed section and is considered to be bicycle safe.

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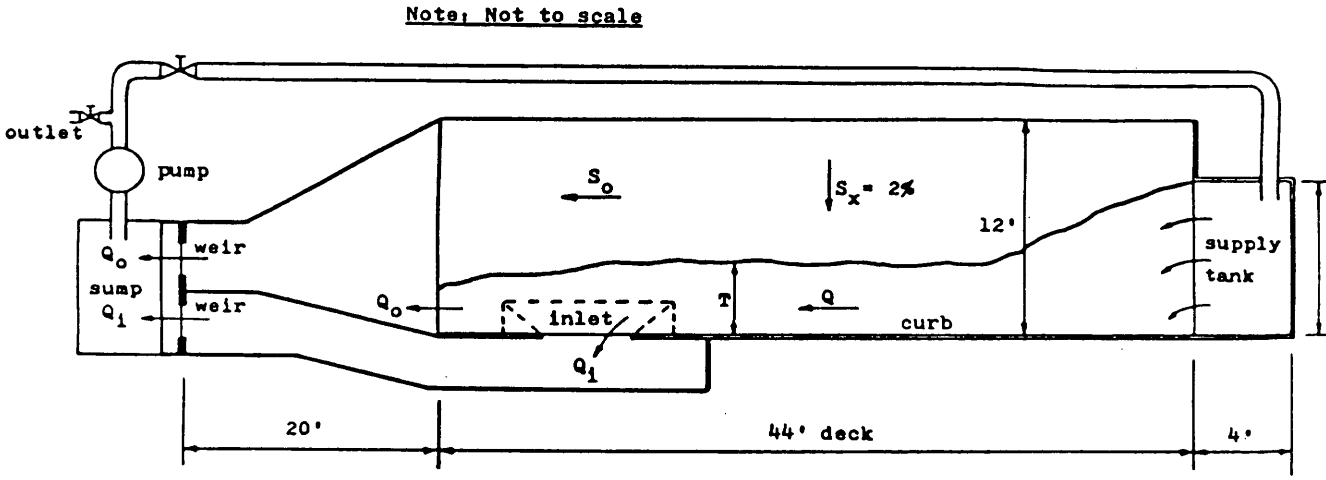
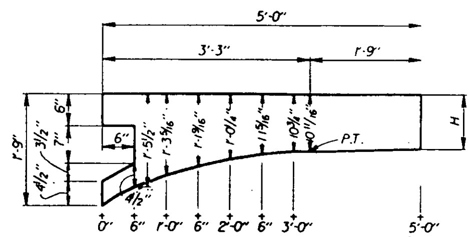


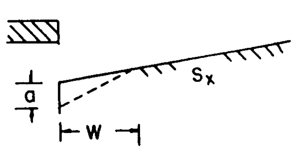
FIGURE 1 Plan view of roadway used in testing program.



PAVING CROSS SLOPE (FT/FT)	0.01	0.02	0.03	0.04	0.05	0.06
H	10 7/16"	10 1/4"	10 1/16"	9 7/8"	9 5/8"	9 7/16"

DETAILS OF GUTTER DEPRESSION TEMPLATE

(a)



(b)

FIGURE 2 (*a*) Elevation view of parabolic template and (*b*) equivalent AASHTO definition sketch.

RESULTS

Results for the testing program are listed in Figures 6 to 11. Efficiency (E) is defined as

$$E = \frac{Q_i}{Q_t} \tag{1}$$

where Q_i is equal to the amount of water intercepted by the inlet (in ft^3/sec), and Q_t is the total amount of water approaching the inlet (in ft^3/sec). Efficiency decreases with increasing approach discharge for all inlets tested. The measured Manning's n-value ranged from 0.014 to 0.018 and averaged 0.016.

DISCUSSION OF RESULTS

Standard NDOR Inlet

In Figure 6 the observed and predicted interception rates for the standard NDOR inlet without the parabolic apron are plotted with

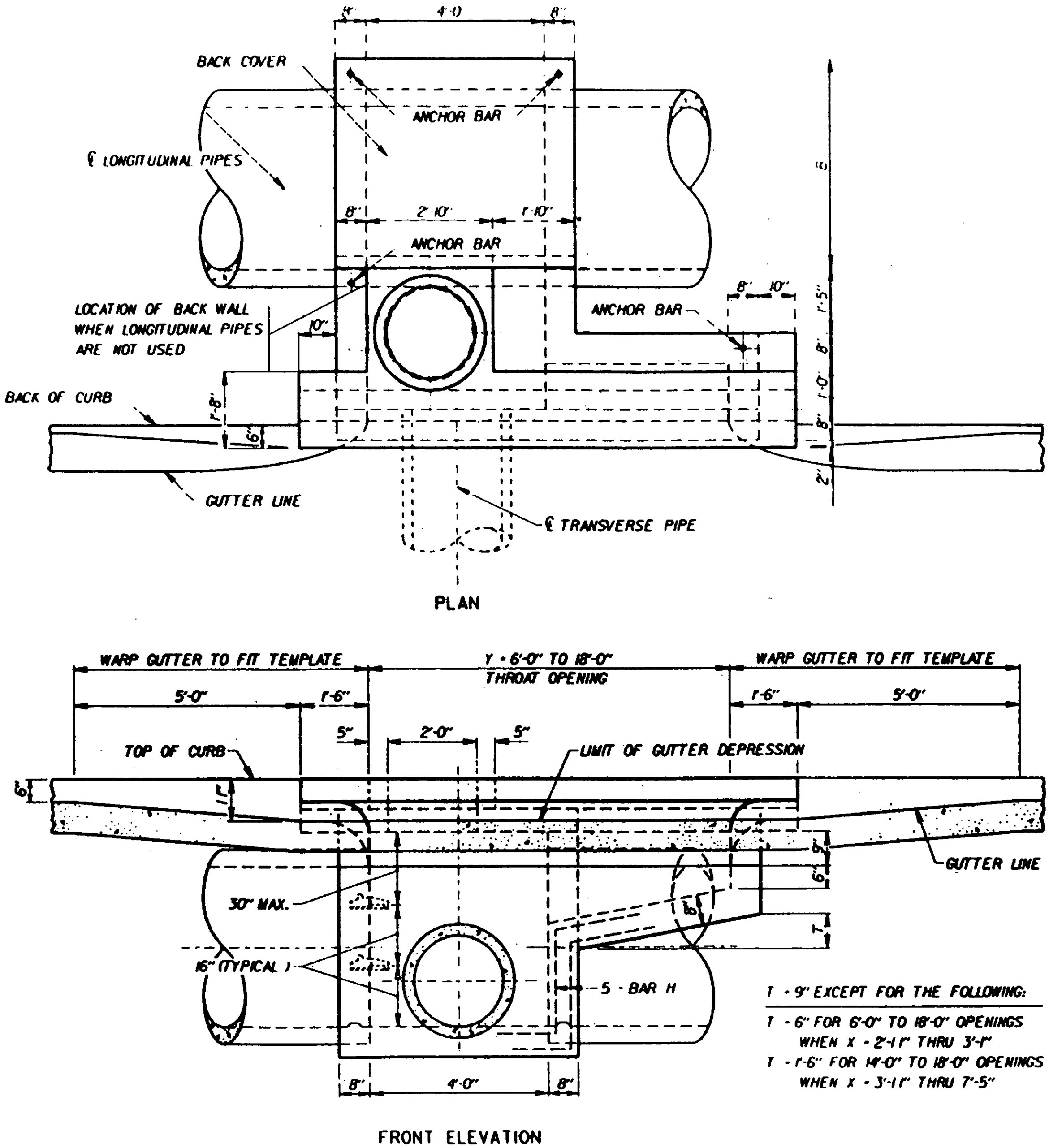


FIGURE 3 Plan and front elevation views of NDOR standard inlet with parabolic apron.

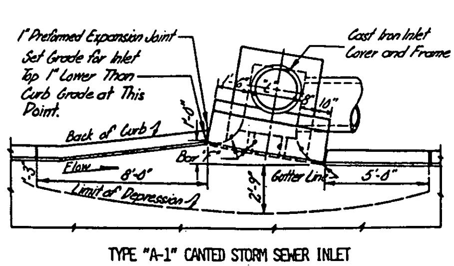


FIGURE 4 Plan view of city of Lincoln canted curb-opening inlet (flow from left to right).

the predicted length required for total interception. Roadway characteristics are included in Figure 6. The predicted efficiency, from Equation 14 in the work by Johnson and Chang (7), (referred to as HEC-12) is

$$E = 1 - (1 - L/L_T)^{1.8} \tag{2}$$

where L is the actual length of the curb opening (6 ft in this case), and L_T is the length required to intercept all of the flow predicted from HEC-12 Equation 13

$$L_T = 0.6\, Q^{0.42}\, S^{0.3} \left(\frac{1}{nS_x}\right)^{1.6} \tag{3}$$

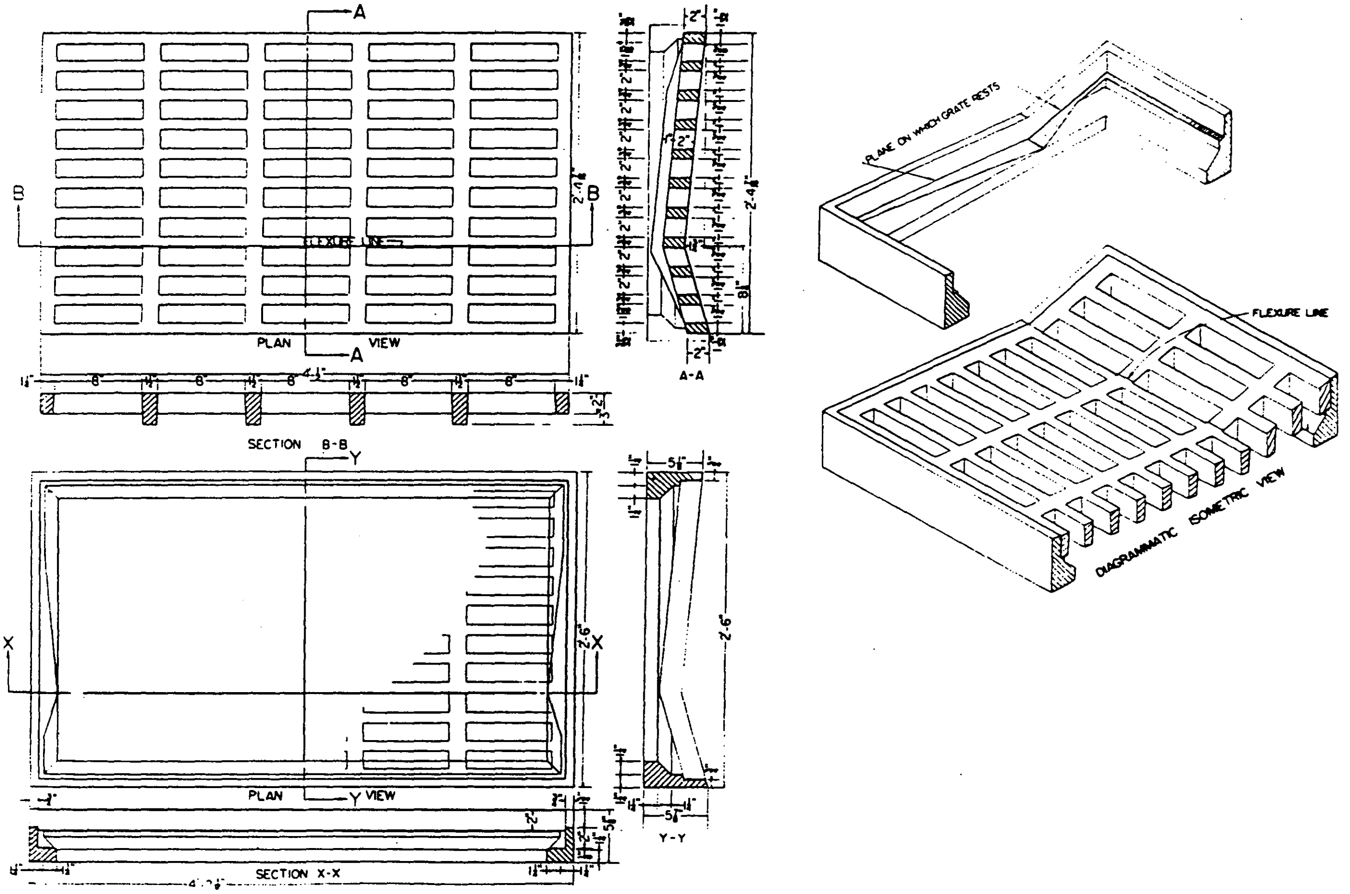


FIGURE 5 Standard plans for single grate inlet (*9*).

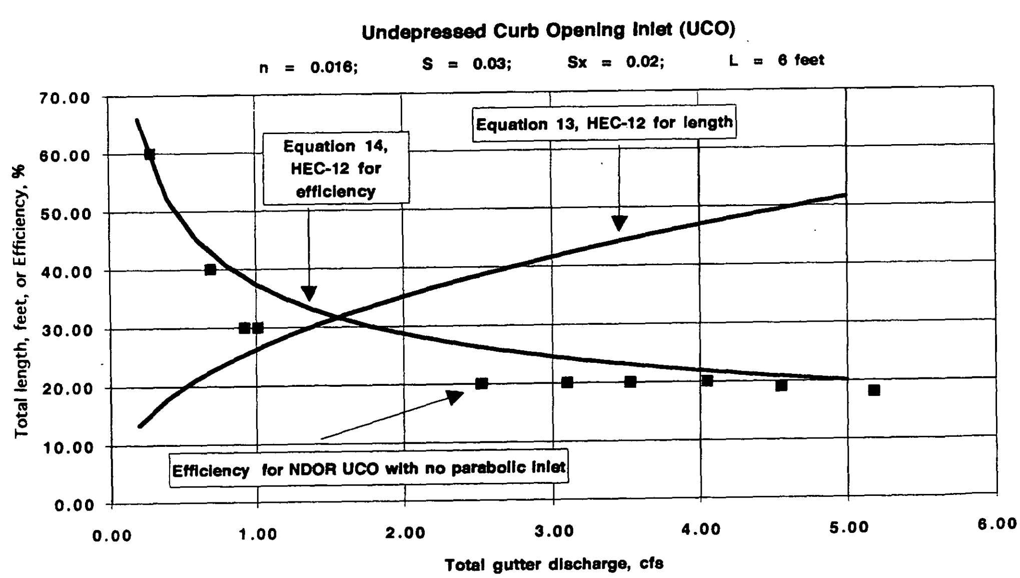


FIGURE 6 Predicted and observed efficiencies of NDOR inlet without parabolic apron.

where S is the longitudinal slope, and S_x is the roadway cross slope. Equation 2 predicts the efficiency quite well for the range of experimental data.

The observed and predicted efficiencies for the same inlet with the parabolic apron in place are compared in Figure 7. The addition of the parabolic inlet dramatically improves efficiency over the entire range of tested discharges. For example, for 4 ft^3/sec, efficiency increases from about 20 percent to about 58 percent with the addition of the parabolic apron. The HEC-12-predicted efficiency is for an equivalent depressed curb-opening inlet with a width of 3.3 ft and a depression of 5 in. [see Figure 2(*b*) for a definition sketch]. The NDOR inlet with the parabolic apron has much greater efficiency than that predicted for the equivalent depressed curb-opening inlet. The predicted efficiency that matches the experimental data has been reported elsewhere (*10*) as

$$E = 1 - (1 - L/L_T)^{2.5} \quad (4)$$

where the exponent is taken from the work of Izzard (*5*). A depressed curb-opening inlet with a straight-plane apron would need either a much steeper drop or a greater drop than the parabola to achieve the same efficiency. Such a steep depression may be hazardous to drivers.

Standard Inlet in Series

The effect of adding a second standard NDOR inlet 10 ft downstream from the first one is shown in Figure 8. The double inlets are especially effective at higher flow rates, exhibiting up to a 22 percent improvement in interception over a single inlet. Approximately 82 percent of the flow is intercepted at an oncoming flow rate of 4 ft^3/sec.

Canted Inlet

In Figure 9 the canted inlet used by Lincoln is compared with the standard NDOR inlet. As expected interception rates for the canted inlet are higher, but not as high as those from adding an additional standard inlet downstream. There is no gain in efficiency for approach discharges of less than 2 ft^3/sec. Gains in efficiency subsequently increase with discharge, reaching 7 percent greater efficiency than the efficiency of the standard inlet at a flow rate of 5 ft^3/sec. The overall increase in performance, however, is somewhat disappointing. For example, with an oncoming flow rate of 4 ft^3/sec, the canted inlet intercepts 64 percent of the water, compared with 58 percent for the standard inlet.

Grate Inlets

The results for grate inlets, both single and in series, are shown in Figure 10. For the tested roadway (3 percent longitudinal slope and 2 percent cross slope) the single grate performed approximately the same as the standard NDOR single curb-opening inlet. A double grate intercepts between 5 and 10 percent less than two standard inlets in series. Two standard grates in series are capable of intercepting 72 percent of the flow at a discharge rate of 4 ft^3/sec. Overall, the performance of the grate series tested was excellent, providing high rates of water removal. Debris clogging was not considered in the study.

It was not possible to compare the efficiency of the grate inlet with those of the others tested (e.g. those found in HEC-12) because of the differences in grate geometries. The so-called splash-over velocity was not defined for the grate tested, and there is no apparent break in the efficiency curves that indicate when the splash-over velocity was reached.

Effect of Resurfacing

The importance of considering storm water inlets when resurfacing highways is demonstrated in Figure 11. Plotted in Figure 11 are the efficiency curves for the standard NDOR inlet and an inlet in which the upstream and downstream transitions and parabolic apron have been covered, rendering it little more than a curb opening. The effi-

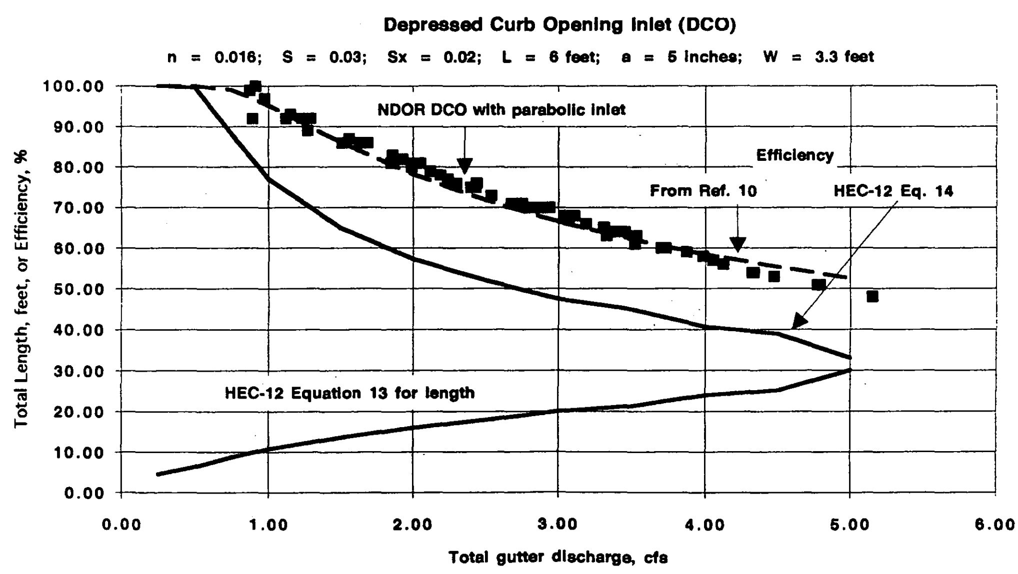


FIGURE 7 Predicted and observed efficiencies of NDOR inlet with parabolic apron.

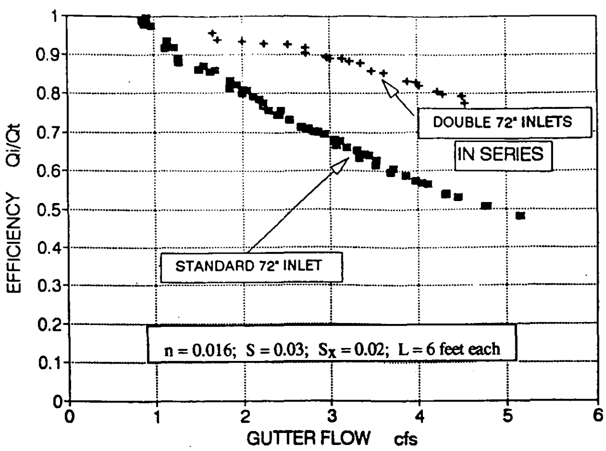


FIGURE 8 Efficiencies of two Nebraska standard inlets in series.

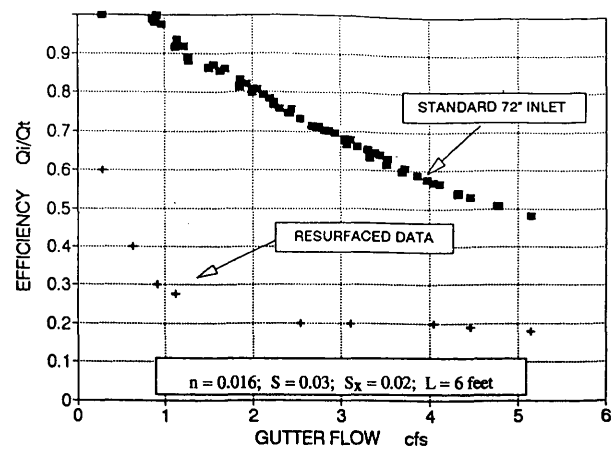


FIGURE 11 Effect of resurfacing on inlet efficiency.

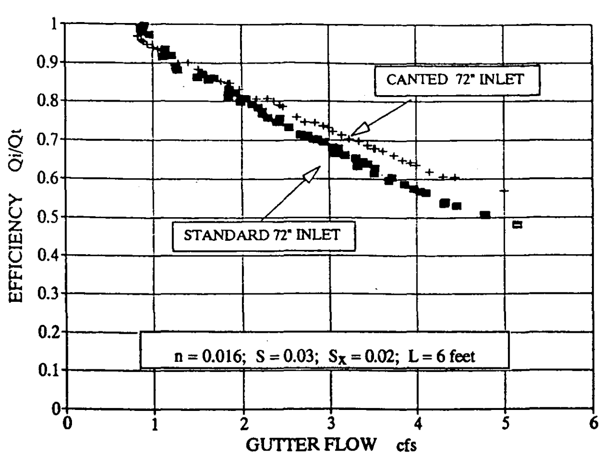


FIGURE 9 Efficiency of city of Lincoln canted inlet.

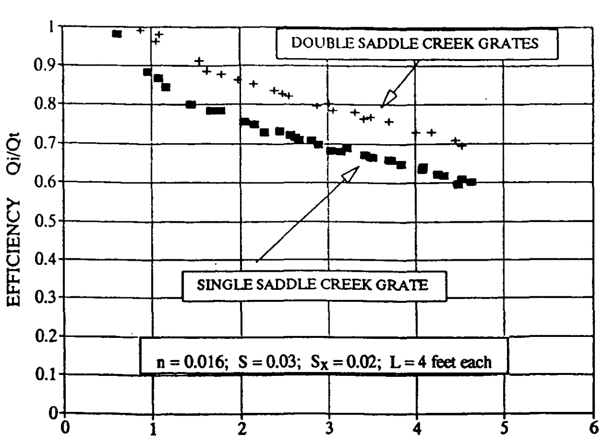


FIGURE 10 Efficiencies of single grate inlet and two grate inlets in series.

ciency of this inlet was previously shown and predicted by using HEC-12 methodology (Figure 6). Inlet efficiencies drop dramatically. For example, for an approach discharge of 4 ft^3/sec, efficiency drops from 58 percent to only 20 percent. Care should be taken when resurfacing streets to conserve, where possible, the geometry of the original inlet.

DISCUSSION OF RESULTS

The results from the present study are from a rather limited experimental program (one longitudinal slope and one cross slope). However, for the curb-opening inlets a statement similar to that found in HEC-12 (*7*) is true: "It is accurate to conclude that curb-opening inlet interception capacity and efficiency would increase with steeper cross slopes. It is also accurate to conclude that interception capacity would increase and efficiency would decrease with increasing discharge." The hydraulic behavior of the parabolic inlet is similar to those of other tested curb-opening inlets, and the increase in efficiency should be similar for different cross slopes and longitudinal slopes from considering Equations 3 and 4 presented earlier.

An example of extrapolation for different curb-opening lengths (but with the same slopes used in the present study) is shown in Figure 12. The methodology used in the present study refers to Equation 4, which was found to apply to the inlet with a parabolic apron. A gutter depression equivalent to 20 percent was used so that the AASHTO efficiency matches those of the parabolic apron inlets.

Results from the grate inlet should not be extrapolated to other circumstances because of the complex nature of the flow across the inlet. The approaching flow can be divided into three zones: a zone that crosses the inlet itself, a zone on the street side of the inlet, and a zone on the curb side of the inlet. It is not clear that the efficiency curves for other street slopes will be similar to those found in the present study.

RECOMMENDATIONS

It is recommended that (a) the Nebraska standard inlet with parabolic apron or the Lincoln canted inlet be considered by other states as a significant improvement over their nonparabolic standard

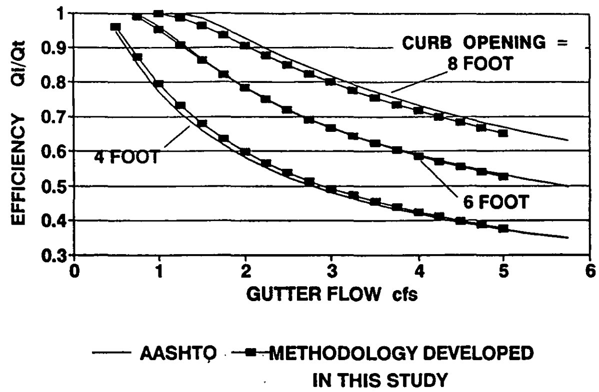


FIGURE 12 Efficiencies for inlets with parabolic aprons and hydraulically equivalent depressions.

inlets; (b) grates be considered in areas where debris is not anticipated as a problem; (c) the use of double inlets be investigated with local cost factors, because the increase in efficiency may well be worth the increased installation cost; and (d) city, county, and state engineers be reminded of the importance of maintaining transitions and aprons on inlets when resurfacing roadways. Figure 11 may be a helpful reminder.

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