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HYDRAULIC PERFORMANCE OF SEVERAL CURB AND GUTTER INLETS

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with
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FINAL REPORT

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16. Abstract

This report details a performance analysis of several curb inlets and one grated gutter inlet currently used by the Florida Department of Transportation for pavement drainage. For each inlet an experimental analysis of the hydraulic performance of a one-half scale model was made. These results were then used to predict full scale performance. Results were compared to those of a previous investigation.

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TABLE OF CONTENTS

CONVERSION FACTORS

British units are used in this report.

To convert	British	SI	multiply by
Acceleration	ft/s^2	m/s^2	3.048E-1
Area	ft^2	m^2	9.290E-2
Density	$slugs/ft^3$	kg/m^3	5.154E+2
Length	ft	m	3.048E-1
Pressure	lb/ft^2	N/m^2	4.788E+1
Velocity	ft/s	m/s	3.048E-1
Volume flowrate	ft^3/s	m^3/s	2.832E-2
Volume flowrate	gal/min	l/s	6.310E-2

CONSTANTS

Acceleration of gravity	32.19 ft/s^2	9.81m/s^2
Density of water	1.94 $slugs/ft^3$	1000 kg/m^3
Manning's constant	1.485	1.0

SUMMARY

This investigation of hydraulic performance of several curb and gutter inlets was divided into three distinct phases. The first phase of the investigation was concerned with extending the range of performance data (to lower longitudinal slopes) for three inlets tested previously under WPI 0510790. The second phase comprised a re-examination of Type 5 inlets as a comparison test related to previously obtained performance data. The last phase of the investigation was an examination of grated gutter inlets, specifically because questions have been raised about the nature of data obtained by another investigator.

Models were constructed at half scale and tested in a hydraulics facility that was used in several previous investigations. Measurements of inlet capacity were obtained for each inlet tested and related to the total flow in the gutter as well as indirectly to the depth in the gutter. Ultimately, this information can be used to design an effective drainage system as well as to estimate spread onto the pavement.

INTRODUCTION

Curb and gutter inlets are employed along roadways to capture and divert runoff from pavements. Planning for adequate capacity is important for vehicular safety, which can be adversely impacted by the spread of water into traffic lanes. Satisfactory design for pavement drainage requires an understanding of the hydraulic performance of the particular curb and gutter configuration to be installed. While some information is available, there remain numerous gaps and questions about hydraulic performance in general.

This investigation was concerned with the hydraulic performance of various inlets currently employed by the Florida Department of Transportation [1], as detailed in Table 1.

Table 1: Schedule of experimental investigation.

INDEX	DESCRIPTION	PREVIOUS	PRESENT INVESTIGATION
219	Barrier wall inlet	Ref. 2	Extend to low slope
213 Type 8	Curb inlet	Ref. 2	Extend to low slope
Prototype	Concrete flume	Ref. 2	Extend to low slope
211 Type 5	Curb inlet	Ref. 3	Performance study, comparison
220 Type S	Gutter inlet	Ref. 3	Performance study, comparison

Hydraulic performance is defined as the inlet capture, either as a function of total flow approaching or the depth in the gutter just upstream. It is a tacit assumption that the flow is at normal depth in the gutter. The flows must balance at the inlet. With subscripts t, i and b denoting total, inlet and bypass respectively,

$$Q_t = Q_i + Q_b \qquad (1)$$

An inlet efficiency is customarily defined as

$$e = \frac{Q_i}{Q_t} \qquad (2)$$

Several issues were of interest in this investigation. For the first three inlet types, previous testing was conducted at one-half scale by the present investigator [2]. It was determined that the range of longitudinal slope should be extended to include lower slope values. Repeating a study of the Type 5 inlet (previously tested by Anderson [3] in 1972) was determined to be an effective means of investigating the quality of all data. Finally, the Type S grated gutter inlet was tested. This inlet was also tested by Anderson in 1972 (at that time this inlet configuration was called Type Y). Because some anomalous data was suspected it was decided that a second investigation should be conducted. Since the configuration of the grated gutter inlet is somewhat different than conventional curb inlets, the organization of this report will include a separate section on this inlet type, following a general discussion of the results for all others listed in Table 1.

EXPERIMENTAL FACILITY AND OBSERVATIONAL METHODS

Experiments reported here were performed at the Hydraulics Research Lab at the University of South Florida in Tampa. This facility has been used in several past studies and consists of two large holding tanks and two centrifugal pumps that can be combined in parallel as needed. The facility (Figure 1) was reconfigured in the following manner for the purposes of the inlet tests described here. A tilting bed was constructed over the two reservoir tanks. Support was arranged so that both cross and longitudinal slope could be varied, using a long level to set the desired value. Water was supplied to the bed by the pumps through lines fitted with paddlewheel type flow meters for measurements. Calibration provided by the manufacturer was accepted. A large vertical riser was installed to supply water at the end of the bed about forty feet upstream of the inlet being tested. After passing over the bed and through the inlet, water was returned to the reservoir. The bed was constructed with a base of resined plywood, with an edge stop to contain water. For all inlets tested, except the grated gutter inlet, this bed (Figure 2) was representative of the curb and gutter configuration.

The experimental arrangement is shown in Figure 1. Water flow into the central riser is measured by paddle wheel sensors located in the supply pipes. Water flowing towards the grate (Q_t) is either captured by the inlet (Q_i) or bypassed (Q_b). When total capture occurs $Q_t=Q_i$. As far as can be determined, the velocity measurements for paddle wheel sensors have been reasonably reliable and will be accepted. There are some variations in performance due to various combinations of pipe and pumps as indicated by total capture testing. Water surface and water depth were measured by using a direct station gauge at several points across the spread (Figure 2). Although not a particularly accurate measurement, the spread onto the model pavement was measured directly from the curb edge. In a few cases, for large flows and shallow slopes, the entire bed was filled and the water surface extended to the opposite wall. In such cases, the total flow was adjusted by the ratio of the total flow area for full width to actual flow area.

FLOW ANALYSIS FOR SIMPLIFIED CURB AND GUTTER

To analyze the information obtained during inlet capacity experiments, the analysis of flow in simple gutters presented here follows closely that given in Reference 2 (the analysis made in conjunction with the study of grated gutter inlets is more complex and deferred to a later section).

The pavement slope can be described by cross slope S_c and longitudinal slope S_0. For simplicity, it was assumed that the curb forms a 90° angle with the pavement so that a triangular section is formed with depth h, as shown in Figure 2. Because the cross slope is a small angle, the spread is approximately the same as the length across the pavement and the depth h, is very close to the measurement y, against the curb, as seen in the figure. Thus, the spread is approximately

$$T \approx \frac{y}{S_c} \tag{3}$$

The area is given approximately as

$$A \approx \frac{y^2}{2S_c} \tag{4}$$

The hydraulic radius becomes

$$R_h \approx \frac{y}{2} \tag{5}$$

The flow velocity may be obtained from continuity and the total flow, Q_t

$$V \approx \frac{2Q_t S_c}{y^2} \tag{6}$$

From this point, a straightforward analysis of the frictional flow in the channel can be made, however it is often suggested [4] that because the surface width of the flow is very large in comparison to depth, the standard formulation for a channel of triangular cross section is not completely satisfactory for predicting flow conditions. Experimental evidence appears to confirm this discrepancy. An alternative formulation has been developed by integrating Manning's equation for infinitesimal rectangular elements of variable depth across the channel width, giving

$$Q_t \approx \frac{3kS_c^{5/3}S_0^{1/2}T^{8/3}}{8n} \tag{7}$$

This formula yields results about 20% higher for the flow rate than that predicted by assuming a channel of triangular cross section. The normal depth associated with Equation 7 is

$$y_n \approx [\frac{8Q_tS_cn}{3kS_0^{1/2}}]^{3/8} \tag{8}$$

DIMENSIONAL RELATIONSHIPS

Due to the size of the available test facility, it was necessary to resort to a one half size model instead of a full size inlet. The method and discussion presented here are the same as [2]. A generally accepted modeling technique for inlet flows requires that the Froude number of model and prototype be identical. The relationship between the velocities and discharge derive from this assumption and the length ratio $L_r = l_p/l_m$. Thus

$$\frac{V_m^2}{gy_m} = \frac{V_p^2}{gy_p} \tag{9}$$

Since the ratio of the depths is equal to the length ratio

$$\frac{V_p}{V_m} = L_r^{1/2} \tag{10}$$

applying continuity yields

$$\frac{Q_p}{Q_m} = L_r^{5/2} \tag{11}$$

and application to the Manning equation results in

$$\frac{Q_p}{Q_m} = L_r^{8/3} \frac{n_m}{n_p} \tag{12}$$

combining the last two equations

$$\frac{n_m}{n_p} = L_r^{-1/6} \tag{13}$$

Substituting for the flow ratio yields a transfer relationship for the roughness. No effort was made to separately account for roughness in this study. The surfaces of the bed and models were relatively smooth, although a stipple resulting from the resin treatment could be felt. All transfer relationships for a scale factor of one-half are summarized in the table below.

Table 2: Scaling relations for a half scale model

LINEAR DIMENSION	L_r	2.00
FLOW RATIO	Q_r	5.65
VELOCITY RATIO	V_r	1.41
ROUGHNESS RATIO	n_r	0.89

REVIEW OF DATA FOR INLETS INDEX 219, INDEX 213 AND PROTOTYPE FROM PREVIOUS STUDY

As part of the investigation of inlets Index 213, Index 219 and a prototype inlet reported here, a review of data obtained under WPI 0510790 (Hydraulic Performance of Drainage Structures, Phase I and II, Report # 790) was conducted. For comparative purposes in this report, data from the previous investigation have been converted to English units. These data were fit to simple quadratic relationships (in English units) as summarized in Table 3 (following).

The following errors and changes are noted, including suggestions for implementation.

1. Figure 7a, p19 is erroneously captioned and should refer to a longitudinal slope of 8%. Likewise, Figure 7b, p20 is erroneously captioned and should refer to a longitudinal slope of 4%. It is noted that these data are virtually identical and no problems should arise from this mistake.

2. As reported here, data obtained with observed spread exceeding the width of the bed require modification to correctly report apparent total flow approaching the inlet. Corrections were retroactively made in the same manner as described in this investigation, affecting the following data sets (no corrections were made for less that 5% error):

> Index 219 - 4% longitudinal, 2% cross slope, correct last point
> Prototype - 4% longitudinal, 2% cross slope, correct last four points

3. Data set for Index 219 at 8% longitudinal, 2% cross slope had indicated discrepancies based on comparisons of actual to indicated spread, however nothing else appeared abnormal in the data set .

4. Index 213 at 4% longitudinal, 6% cross slope suffers from possible spread problems (compared to predictions from depth). No other problems could be identified.

5. The prototype inlet at 4% longitudinal, 2% cross slope suffers from possible spread problems. This data set also lies below the bulk of other data and it may be realistic to consider dropping this set. As presented the results are conservative.

6. The prototype inlet at 4% longitudinal, 3.65% cross slope appears low in comparison to the remainder of the data.

7. In some cases relatively poor fits to quadratic relationships were produced (as noted in Table 3). Because of extremely poor fit in the case of Index 213 at 8% longitudinal slope, 6% cross slope, the actual data have been substituted for clarity. It is noted that this

observation does not imply that the data are flawed, merely that the simple quadratic fit used here did not represent the data well.

INVESTIGATION OF INLETS INDEX 219, INDEX 213 AND PROTOTYPE AT REDUCED SLOPE

Inlet capacity was measured using the same models as tested previously (constructed from resined wood and plastic [2], reconditioned for these tests) and using essentially the same procedure as described above. Data obtained with observed spread exceeding the width of the bed (a few points only) required modification to correctly report apparent total flow approaching the inlet. Corrections were made in the same manner as described in the preceding section, no correction amounting to less than 5% was attempted.

The results of this part of the investigation are shown in Figures 3-11. Note that the information is plotted so that each individual graph corresponds to a particular cross slope, and shows a family of curves for longitudinal slopes. Data shown in these figures were scaled to full size using the scaling factor 5.65, then fit to empirical relations (Table 3), also plotted. For completeness and comparison, empirical fits for steeper slopes from Reference 3 have been added to these figures (these data were refitted in English units). Because of extremely poor fit in the case of Index 213 at 8% longitudinal slope, 6% cross slope, the actual data have been substituted for clarity. It is noted that this change does not imply that the data are flawed, merely that the simple quadratic fit used here did not represent the data well. In the case of the earlier Prototype data, the 4% longitudinal slope, 4% cross slope data was actually taken at 3.67% cross slope, and the 4% longitudinal slope, 6% cross slope data was approximated by merging two data sets, one at 6.8% cross slope and one at 5% cross slope. This result was substituted in the graphical presentation but should not affect overall conclusions.

An interpretation of hydraulic performance curves may be made in the following manner. Initially, the total flow is captured by the inlet so that the data lies along a 100% efficiency line (45°). An important observation is the maximum capture at 100% efficiency, which occurs just before the first indications of bypass are seen. The efficiency of the inlet at any flow can be evaluated as the performance is reduced from total capture. Lines of constant efficiency less than 100% are straight, emanating from the origin.

Results show the general trend that performance improves with increasing cross slope, and grows worse with increasing longitudinal slope. As expected for curb inlets, most bypass occurs at low cross slope and high longitudinal slope. Overall the best performing inlet was Index 219, and the results appeared to be more consistent for this inlet when compared to Index 213 and the prototype. It is difficult to separate problems with experimental observations from unusual performance characteristics. Based on several reproducibility checks, variations of 10% in the data are to be expected. It must also be noted that results shown in these graphs represent two different sets of observations taken at different times with different experimental arrangements.

Table 3 presents the coefficients for empirical curve fits to a simple quadratic equation. Also noted is the R^2 or coefficient of determination parameter and notations when poor correlations were encountered. For the case of the prototype data the 6% cross slope at 4% longitudinal data, the merged data set have been inserted as discussed previously. In a few cases, fits to data slightly exceeded the 100% efficiency line. When such discrepancies occur, the 100% value should be used.

Table 3: Empirical parameters for inlets. $Q_i = A+BQ_t+CQ_t^2$ (CFS)

INDEX	**219**		**INDEX**	**213**		**PROTO**	**TYPE**	
SLOPE L/C			SLOPE L/C			SLOPE L/C		
8/2	A	0.1630	8/2	A	0.2642	8/2	A	0.0563
	B	1.1428		B	0.9097		B	1.0796
	C	-0.0713		C	-0.0806		C	-0.1179
	R^2	0.9909		R^2	0.9791		R^2	0.9743
8/4	A	-1.3985	8/4	A	0.9246	8/4	A	1.1046
	B	1.7348		B	0.5508	POOR	B	0.4887
	C	-0.0957		C	-0.0187		C	-0.0383
	R^2	0.9962		R^2	0.9230		R^2	0.6299
8/6	A	0.1535	8/6	A	2.0758	8/6	A	0.7720
	B	1.1576	POOR	B	0.0011	POOR	B	0.7964
	C	-0.0603		C	0.0276		C	-0.0791
	R^2	0.9886		R^2	0.7502		R^2	0.6674
4/2	A	-0.2887	4/2	A	0.0403	4/2	A	0.1073
	B	1.3493		B	1.1503		B	1.1031
	C	-0.0881		C	-0.1084		C	-0.0776
	R^2	0.9945		R^2	0.9866		R^2	0.9823
4/4	A	0.4328	4/4	A	1.1948	4/4	A	0.3986
	B	0.9979		B	0.5928		B	0.8452
	C	-0.0398		C	-0.0289		C	-0.0684
	R^2	0.9848		R^2	0.9615		R^2	0.9250
4/6	A	-2.1429	4/6	A	-1.1665	4/6	A	0.599998
	B	2.1335		B	1.9639	MERGED	B	1.019916
	C	-0.1464		C	-0.1822	POOR	C	-0.076415
	R^2	0.9875		R^2	0.9487		R^2	0.813013
2/2	A	0.1999	2/2	A	0.1455	2/2	A	0.0880
	B	0.8635		B	0.7211		B	0.7013
	C	-0.0172		C	-0.0266		C	-0.0332
	R^2	0.9983		R^2	0.9997		R^2	0.9997

Table 3 (continued)

2/4	A	0.2414	2/4	A	0.3288	2/4	A	0.0842
	B	0.9781		B	0.7856		B	0.8845
	C	-0.0219		C	-0.0288		C	-0.0433
	R^2	0.9999		R^2	0.9995		R^2	0.9998
2/6	A	-2.9972	2/6	A	0.1738	2/6	A	-0.0408
	B	2.2534		B	1.0549		B	1.1345
	C	-0.1304		C	-0.0564		C	-0.0792
	R^2	0.9905		R^2	0.9961		R^2	0.9844
0.8/2	A	0.1841	0.8/2	A	0.2833	0.8/2	A	0.3849
	B	0.9044		B	0.6701		B	0.5512
	C	-0.0114		C	-0.0052		C	0.0040
	R^2	0.9995		R^2	0.9974		R^2	0.9998
0.8/4	A	-0.4492	0.8/4	A	0.6486	0.8/4	A	0.3997
	B	1.3168		B	0.6733		B	0.8457
	C	-0.0504		C	-0.0111		C	-0.0369
	R^2	0.9961		R^2	0.9996		R^2	0.9988
0.8/6	A	-2.7757	0.8/6	A	0.0339	0.8/6	A	-0.3138
	B	2.0789		B	1.1542		B	1.3178
	C	-0.1025		C	-0.0536		C	-0.0778
	R^2	0.9978		R^2	0.9983		R^2	0.9999

TYPE 5 PERFORMANCE MEASUREMENTS

A model inlet was constructed at half scale from resined wood and plastic according to Index 211 and mounted on the test bed under experimental conditions. The inlet cover was omitted and the grate employed in conjunction with this inlet was machined to scale from aluminum. Testing was conducted as previously described for the other curb inlets. Figures 12, 13 and 14 are plots of performance curves fit to data scaled to full size as discussed in the previous section. Note that these curves are plotted for constant longitudinal slope with cross slope as the parameter. Table 4 contains empirical correlations for the data obtained in this investigation.

Figures 15, 16 and 17 show the same empirical curves obtained during this investigation but superimposed are the original predictions for full size performance due to Anderson [3]. As indicated previously, the principal motivation for these experiments as to compare two completely independent measures of performance. Inspection of these results indicates that Anderson's data predict generally better performance than that observed here. It is noted that Anderson was working at one-third scale rather than half scale as in this investigation. Comparison issues are discussed further in the next section.

Table 4: Empirical parameters for Type 5 inlet (Index 211). $Q_i = A+BQ_t+CQ_t^2$ (CFS)

SLOPE L/C			SLOPE L/C			SLOPE L/C		
1/2	A	0.6565	4/2	A	0.1966	6/2	A	0.1961
	B	0.5776		B	0.6176		B	0.7155
	C	-0.0300		C	-0.0471		C	-0.0590
	R^2	0.9890		R_2	0.9955		R_2	0.9978
1/4	A	1.4948	4/4	A	1.0925	6/4	A	0.8024
	B	0.4603		B	0.3567		B	0.5308
	C	-0.0125		C	-0.0001		C	-0.0168
	R^2	0.9848		R_2	0.9874		R_2	0.9999
1/6	A	0.9839	4/6	A	0.9273	6/6	A	1.6838
	B	0.8160		B	0.5866		B	0.2263
	C	-0.0377		C	-0.0118		C	0.0199
	R^2	0.9827		R_2	0.9812		R_2	0.9822

In a supplemental investigation, performance of the grate was judged in the following manner. Three experiments were conducted at 1% longitudinal slope, 6% cross slope, using no grate, replacing the grate with a solid surface and finally the grate itself. As seen in Figure 18, there is little apparent difference, especially between the solid surface and the grate. Opening the grate area completely results in a small change, indicating that most of the capture occurs directly. A similar conclusion was reached by Anderson [3] and this conclusion indicates that grating differences would not likely explain the differences in performance between his results and those of the present investigation.

GUTTER CAPACITY, DEPTH AND SPREAD

For good drainage design, inlet selection and placement specification is based on ensuring adequate capacity to carry away runoff and simultaneously preventing excessive spread onto the pavement. Because runoff contributes continuously to the flow in the gutter, inlets must be spaced at the correct interval to reduce spread. The designer makes the tacit assumption that flow is at normal depth for the particular gutter/curb configuration. Velocity, depth, slope and configuration may all affect inlet capture, but the spread is related directly to the flow in the gutter. Thus it is not realistic to relate spread to inlet performance but rather both spread and inlet performance should be independently related to total flow approaching the inlet. Here the curb and gutter configuration has been treated in a simplified fashion as presented in Reference 2 and results from several parts of this investigation have been combined to give a more complete interpretation to the results.

Spread onto the pavement is a relatively difficult and sensitive parameter to measure (and to scale up) because of the difficulty in identifying the actual boundary due to fluctuations and other uncertainty. It is also likely that the true pavement - gutter profile will not be as simple as that presented here. In view of this problem, it is recommended that spread be estimated as indicated in Equation 3 or similar relationship. It is of interest to examine the relationship between flow and depth obtained from observations. For the simple gutter configuration the depth measurement (surface elevation above the vertex formed by the sidewall and bottom) can be correlated with flow in the gutter by use of Equation 8, but it is necessary to assume Manning's n. As stated previously the surface is smooth but a stipple in the resin finish can be observed so that a minimal value of $n=0.01$ to 0.011 is probably reasonable. A combination of data from the Type 5 observations as well as those from Index 219 and 213, and the Prototype have been analyzed in this fashion and the results are shown in Figure 19. Good agreement is indicated if the data lies along a 45° line. The data appear reasonable (although there is a slight upward trend), indicating that spread could be estimated from Equation 3. Efforts to produce a correlation between observed spread and that predicted produced reasonable results, as similarly reported in Reference 2.

A similar approach was taken with Anderson's data for the Type 5 inlet and the results are shown in Figure 20. It is apparent that there may be a systematic error in some measurement that could account for the offset data. This observation could be the source of some of the discrepancy discussed previously between measurements for the Type 5 inlet reported here and that of Anderson.

PERFORMANCE OF GRATED GUTTER INLETS

The grated gutter inlet refers to a specific design used frequently in Florida along embankments and overpasses (Florida Department of Transportation, Index 220, Type S) [1]. This inlet style is installed in a gutter without substantial curb and covered by a shallow V-shaped grate conforming to the gutter profile, for safety and trash control. The gutter inlet shape actually deviates slightly from the gutter, dropping below the gutter line for improved capture. Unlike curb inlets, spread onto the pavement is arbitrarily limited by the requirement that spread onto the shoulder should not pass the barrier posts. The motivation of this phase of the investigation was to measure hydraulic performance and compare the results to those of Anderson, due to questions raised concerning some of the trends of his data. Although relatively simple in configuration, performance of the gutter inlet is still complicated by the transition from the gutter and the presence of the grate. Thus performance cannot be easily predicted by analytical methods and must be measured instead. The work reported here follows Reference 5 closely.

The goal of this portion of the study is twofold: to measure the hydraulic performance of the grated inlet system, and secondly to better understand the influence of the grating installed over the inlet. Experiments reported in the present study were limited to supercritical flow conditions in the gutter approaching the inlet. No investigation of grated inlets operating under sump conditions was attempted here, but this topic has been considered elsewhere [6]. Ultimately, the usefulness of this part of the study is to improve the methods of design and selection of grated gutter inlets.

A model gutter inlet was constructed at one-half scale according to Index 220, from a combination of resined wood and sheet plastic with taped seams. For this inlet the gutter has no curb and is configured differently than the simple shape adopted for the previous studies (Figure 21). Accordingly, the gutter was constructed of sheet PVC plastic (with seams taped to minimize leaking) mounted on the bed used in the previous investigations. The bed was tilted to 12° so that upstream of the inlet the gutter profile was correct except for the final transition to pavement which continued to rise at 12°. Approaching the inlet a transition was installed so that the model configuration reproduced actual conditions around the inlet except for the shoulder which terminated prematurely at the edge stop.

Two types of grating configurations (Figure 22) were tested in this investigation, the crossbar and reticuline. Model gratings were constructed from plastic, with the crossbar reproducing the prototype closely. It was extremely difficult to reproduce the design of the reticuline grating; instead a simple crosshatched design having the same open area and spacing was substituted. It is believed that none of the deviations discussed here affected the overall conclusions of the investigation. All other details of the experimental measurements followed closely the methods discussed above for other grating types.

Tests were conducted for two grate configurations using a one-half scale model on longitudinal slopes ranging from 0.8% to 8%. Total flow approaching the inlet was varied from the point of total capture until the spread limitation was reached or the capacity of the system was exceeded. Figure 23 depicts model gutter inlet performance, inlet flow (Q_i) vs total flow (Q_t), for both grating types (data taken at a slope of 0.8% has been omitted since capture was very nearly complete for all flows tested). Note that these curves are plotted with longitudinal slope as the parameter, cross slope being constant. As currently specified the inlet is not set on a cross slope but the pavement slopes at 6% approaching the inlet. Data have been scaled to full size using the relationships given in Table 2. The general shape for the resulting performance curves follows that for typical curb inlets. Performance can be evaluated by examining several factors. Efficiency, maximum capacity and the maximum 100% capture point all decrease with increasing longitudinal slope as would be expected. Only slight differences in capture between the two grate types was observed, with the crossbar grate performing slightly better at small slope and the reticuline at the highest slope. For design purposes correlations for full size performance are presented in Table 5 (shown in Figure 24):

Table 5: Empirical parameters for grated inlet (Index 220). $Q_i = A + BQ_t + CQ_t^2$ (CFS)

SLOPE	RETICULINE		CROSSBAR	
0.02	A	-0.014	A	-0.388
	B	1.120	B	1.397
	C	-0.041	C	-0.061
	R^2	0.999	R^2	0.998
0.04	A	0.052	A	-0.040
	B	1.059	B	1.140
	C	-0.045	C	-0.049
	R^2	1.000	R^2	0.997
0.06	A	0.113	A	0.352
	B	0.899	B	0.784
	C	-0.039	C	-0.028
	R^2	0.997	R^2	0.997
0.08	A	0.221	A	0.089
	B	0.644	B	0.874
	C	0.006	C	-0.051
	R^2	0.998	R^2	0.999

In 1972 Anderson [3] reported on a study for the Florida Department of Transportation during which a similar inlet configuration (designated Type Y, it should be noted however, that little is known about the grating type tested) was tested at one third scale and transformed to full size predictions. It is of considerable interest to examine the data obtained by Anderson in light of the results of the present study. Figure 25 presents the full size, empirical design predictions (for the crossbar grating) as above, with the comparable data from Anderson's study. A regular progression of declining efficiency with increasing longitudinal slope, as might be expected, was found in this investigation (cf. also Figure 23). In some cases Anderson's data appear inverted, making steeper slopes appear to perform better than would be expected (this observation was noted in his report). Plotting the data as hydraulic performance, Q_i vs Q_t, tends to de-emphasize this effect, and the data from Anderson's investigation tend to bunch together with little variation. Close inspection shows agreement with the 4% longitudinal slope results obtained here while data for other longitudinal slopes are not comparable. Anderson's data for 1% longitudinal slope produced less than 100% efficiency while here it was found that a comparable slope (0.8%, not shown) produced nearly complete capture. A specific cause for these discrepancies was not found, although it was noted that Anderson's cross slope setting may possibly have been applied to the inlet. The effect of grating was also examined (as discussed below) but did not appear to be a cause of the discrepancy.

During this investigation an effort was made to better understand the specific causes of bypass flow, which are directly related to the decline in performance efficiency. At low flow rates approaching the inlet, all the flow is captured and the efficiency is 100%. As the total flow increases, at some point a small fraction of the flow moves around the inlet and is not completely captured. Due to the design of the inlet, with a small depressed area on the downstream side, water may pond, allowing some back flow into the inlet. Even with this partial recovery, some of the flow renters the gutter and continues downstream. At higher approaching flows, water begins to travel directly across the grating by skipping or jumping across the grating bars with some portion of the flow being sheared off and dropping into the inlet. At high flow rates, solid flow is observed over the grate. Figure 26 contrasts the difference in appearance of the flow across the grating for both types tested, with much larger jumps occurring on the crossbar grating. To some extent, it appears that these two modes of bypass are related since the development of flow on the grate tends to promote some of the flow around the sides of the inlet.

It is possible to employ a simple model for the flow in the structure of the grating assembly, to better understand this phenomena. As shown in Figure 27, water approaches the upstream lip of the grating as a sill flow. The water stream drops over the lip with a ballistic trajectory, but is intercepted and deflected by the first bar of the grating. Depending on the horizontal spacing of this cross bar from the lip, part of the flow is deflected upwards and part downward to conserve momentum in the vertical direction. The portion of the flow deflected in the upward direction also has a horizontal component of momentum and is carried forward, interacting with other crossbars downstream in a similar manner. Under some conditions, a fraction of the water can be carried completely across the grating. This portion of the flow is not captured and contributes to inefficient behavior of the grating. This simple analysis also indicates that flow across the grating should obey the same scaling relationships as the gutter flow.

What is apparent from this discussion is that broader spacing of the first bar can cause a much larger initial jump, perhaps over the grate entirely. Photographs of the flow over the reticuline grate and the crossbar grate illustrate this effect (Figure 26). Flow across the reticuline grate involves many small interactions while very large vertical jumps are apparent for the crossbar style grate. These observations may also help explain why the crossbar configuration captures more of the low slope flow (due to wider spacing), while at higher flow rates performance is poorer (more bypass due to larger jumps). It should also be noted that a simple scaling analysis indicates that the same similarity relations should apply to the flow on the grate as apply to the overall configuration.

It is also of interest to examine ways of improving inlet performance. Obviously, one way to increase capture is to make the longitudinal dimension of the grate opening larger to decrease bypass over the grate surface and perhaps increase capture from the flow moving around the side. Several qualitative experiments were conducted to test alternative approaches. Tilting the grate slightly in the inlet frame appeared to make little difference. A second possibility explored concerned blocking the flow at the back side of the grate entrance (sometimes introduced on terminal inlets). In a simple experiment, ponding was developed by placing a small sand bag at the downstream edge of the grate. A dramatic improvement in capture, about 35% at highest flows, was observed and complete capture capacity was extended considerably. While these results are encouraging, to be practical any means of improving ponding could not pose a traffic hazard. Furthermore it should be noted that if trash accumulates on the upstream edge of the grate, bypass around the inlet may increase, reducing efficiency.

DEPTH OF FLOW, GUTTER CAPACITY AND SPREAD FOR THE GRATED GUTTER INLET

As with the previous inlets, a part of this study comprised an examination of the relationship between gutter capacity and depth. Analysis of the relationship between gutter capacity and depth is complicated by the cross sectional profile of the gutter. To assist in analyzing the information obtained during inlet capacity experiments a brief treatment of the gutter flow is presented. The pavement slope can be described by cross slope S_c and longitudinal slope S_0. The gutter channel has a shallow cross section, trapezoidal at first then with breaks in the side slope to match the pavement. The normal depth in the gutter is defined at gutter line and the spread is also taken from this point (cf Figure1). The average flow velocity may be obtained from continuity and the total flow, Q_t.

Both the spread and the area of the flow can be calculated from the geometrical configuration. The wetted perimeter and hydraulic radius may also be obtained, so that an analysis of the frictional flow in the channel can be made using Manning's equation. As noted for the simple curb and gutter model treated earlier, because the surface width of the flow is very large in comparison to depth, the standard formulation for a gutter channel shape is not completely satisfactory for predicting flow conditions and experimental evidence appears to confirm a higher flow rate than expected.

A spreadsheet calculation of area, wetted perimeter, depth, surface profile (including spread) and flow capacity was constructed for the model (Figure 28). According to FDOT design guidelines, shoulder spread would normally be restricted to the edge of the safety barrier support posts (Figure 23). This limitation may be related directly to the spread on the pavement or the normal depth in the gutter. The spread onto the pavement from the gutter line is only slightly larger than the spread back onto the shoulder (also measured from the gutter line). It is estimated that flow capacity at this point would be about 3 CFS for a 1% longitudinal slope.

Figure 29 depicts inlet capture for both grating types as a function of normal depth in the gutter upstream of the inlet, measured as described previously (cf. Figure 2). A reasonable correlation was obtained, although some scatter is apparent. This result indicates that at least over the range of values tested, performance of the inlet is governed primarily by upstream depth and there is little dependence on other factors such as bed slope or velocity. This result is consistent with the previous observation that tilting the grate slightly produced no significant improvement. It should be noted that Figure 29 was generated for the model bed upstream of the transition and is therefore not to be used for design purposes.

CONCLUSIONS

1. Data and empirical correlations were extended for three inlets examined in a previous investigation.

2. A model Type 5 inlet was constructed and tested. Empirical correlations for this data were produced. Information obtained in this investigation was compared with data obtained by Anderson in 1972. Data obtained here predicts less capacity than that predicted by Anderson. No cause was found for this discrepancy but it appears that his capacity data may suffer from a systematic error. The results of this investigation would be conservative if used for design.

3. The performance characteristics of a grated gutter inlet have been documented for

several longitudinal slope conditions and for two grate configurations. Performance generally follows that for other gutter/curb inlets. Design information was developed. It was observed that bypass can occur either by flow around the entrance or flow traveling directly across the top of the grating and a simple model to explain transport directly across the grating has been developed. Inlet capture appears to be primarily a function of normal depth in the gutter upstream, at least for the range of parameters examined here. An attempt was made to resolve discrepancies with results previously obtained by Anderson. The unusual inversion in performance data observed by Anderson was not supported by the findings here. It is recommended that his results be replaced by those of this investigation.

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5. Cromwell, C., Rabens, C, and Kranc, S.C., Hydraulic Performance of a Grated Gutter Inlet, to be presented at the World Water and Environmental Resources Congress, Orlando, FL, May 20-24, 2001

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FIGURES

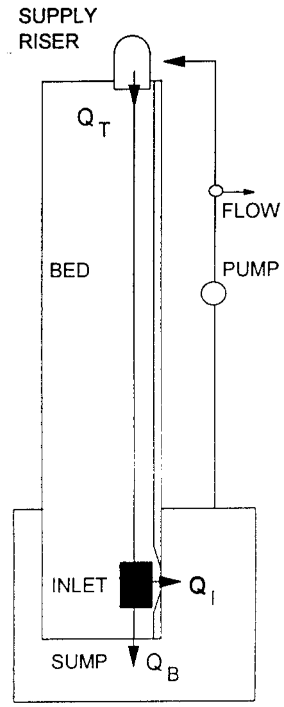
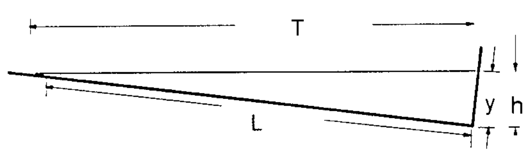


Figure 1: Experimental apparatus, plan view. Grated gutter inlet is represented.



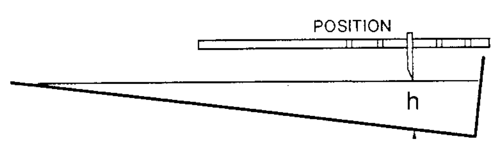


Figure 2: Simplified Curb and Gutter cross sectional profile

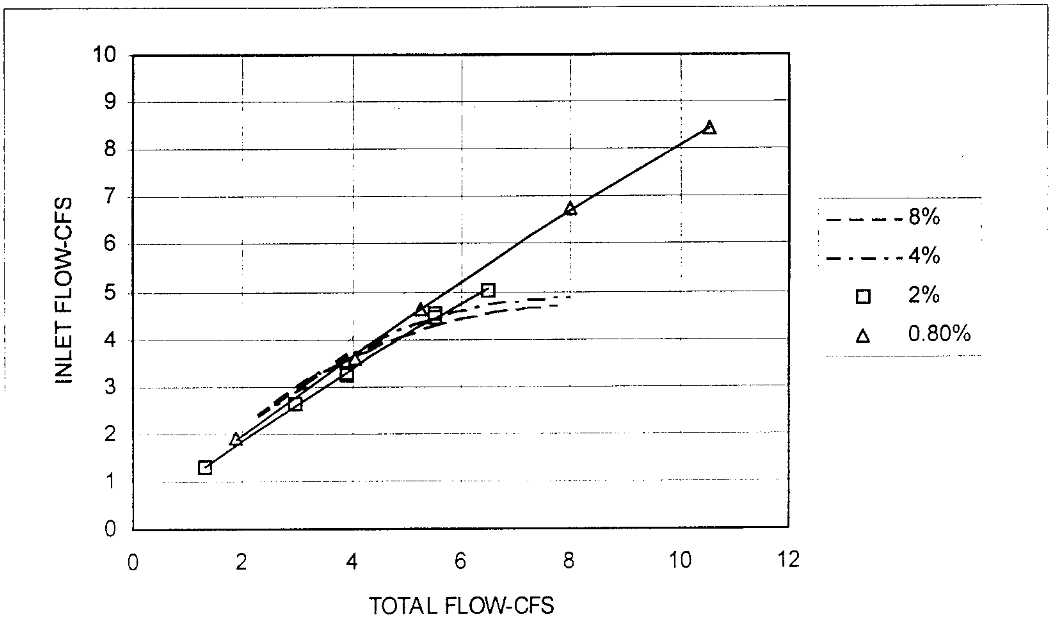


Figure 3: Full size performance curves for inlet Index 219 at 2% cross slope. Parameter is longitudinal slope.

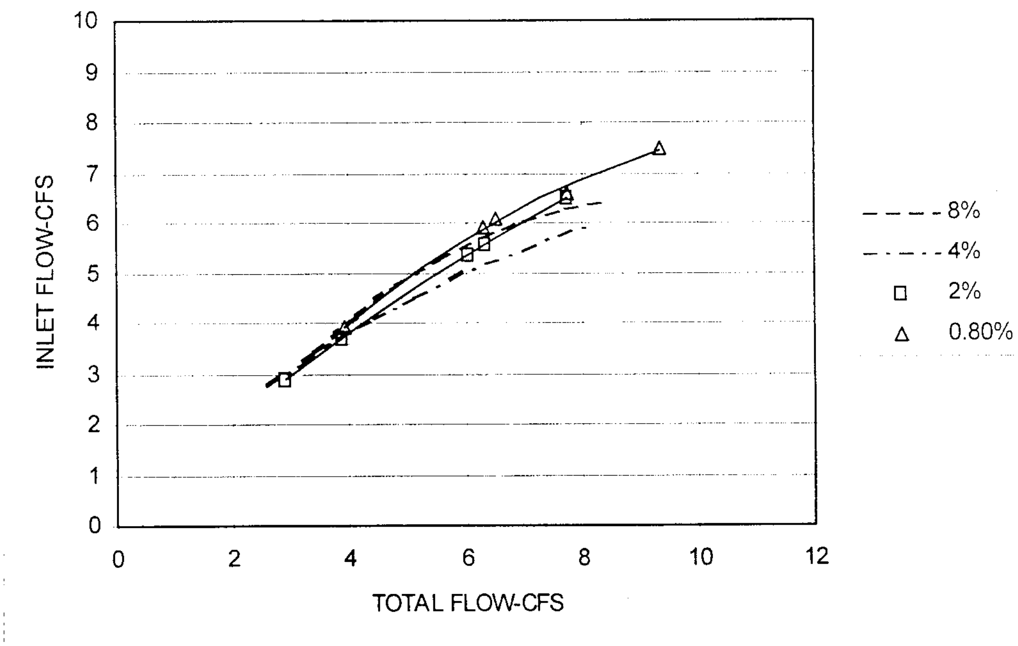


Figure 4: Full size performance curves for inlet Index 219 at 4% cross slope. Parameter is longitudinal slope.

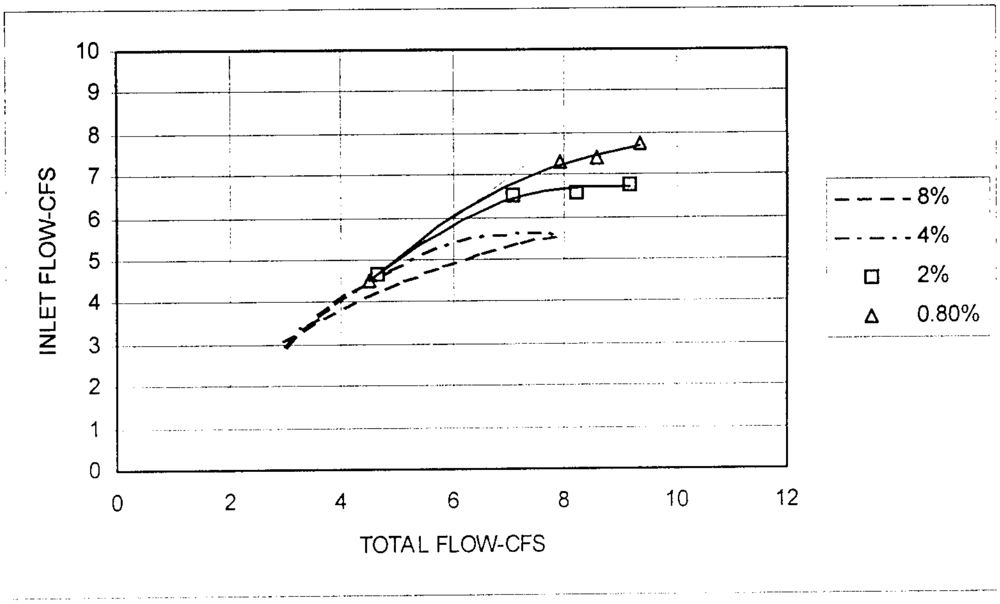


Figure 5: Full size performance curves for inlet Index 219 at 6% cross slope. Parameter is longitudinal slope.

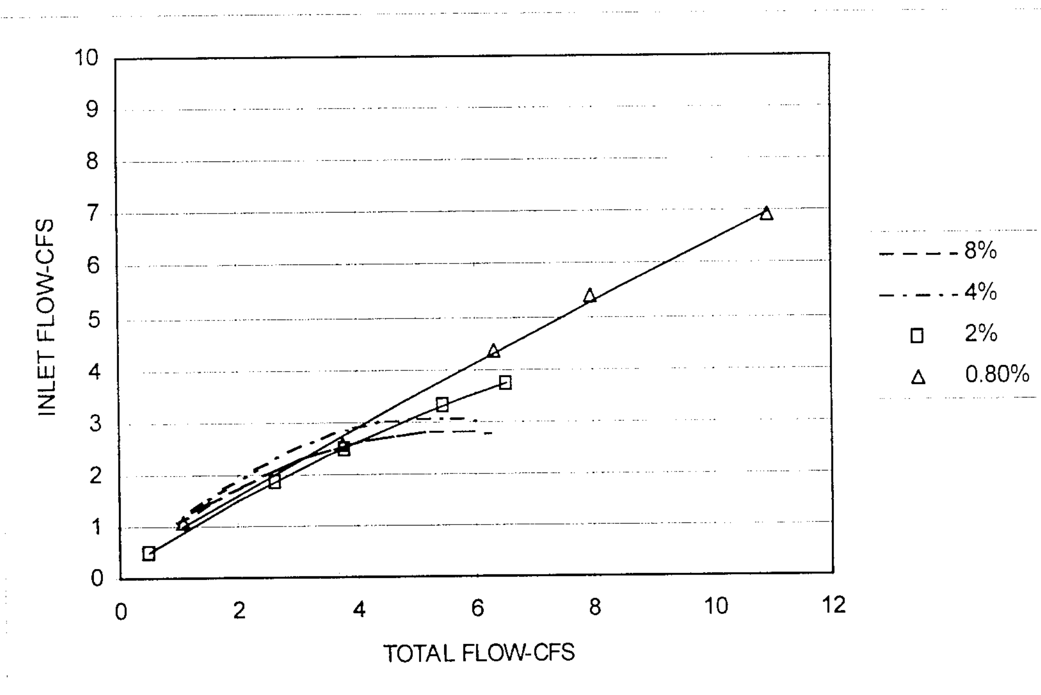


Figure 6: Full size performance curves for inlet Index 213 at 2% cross slope. Parameter is longitudinal slope.

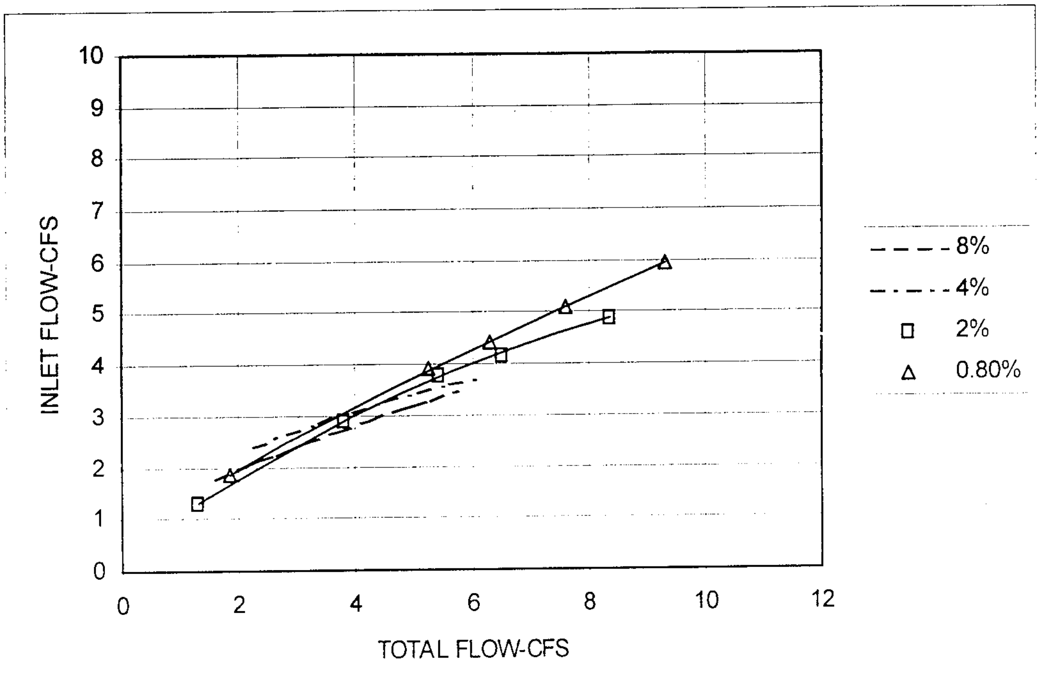


Figure 7: Full size performance curves for inlet Index 213 at 4% cross slope. Parameter is longitudinal slope.

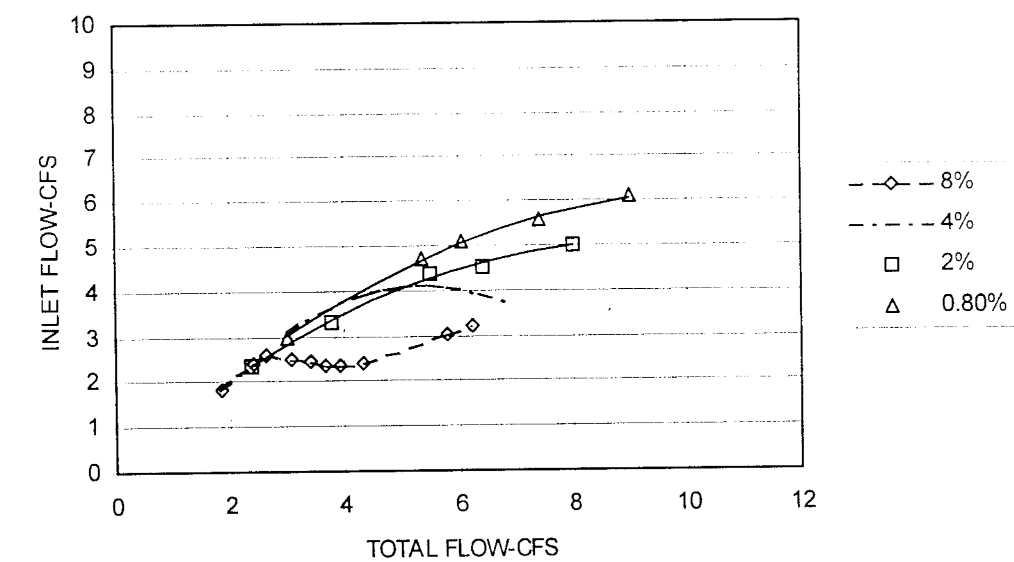


Figure 8: Full size performance curves for inlet Index 213 at 6% cross slope. Parameter is longitudinal slope.

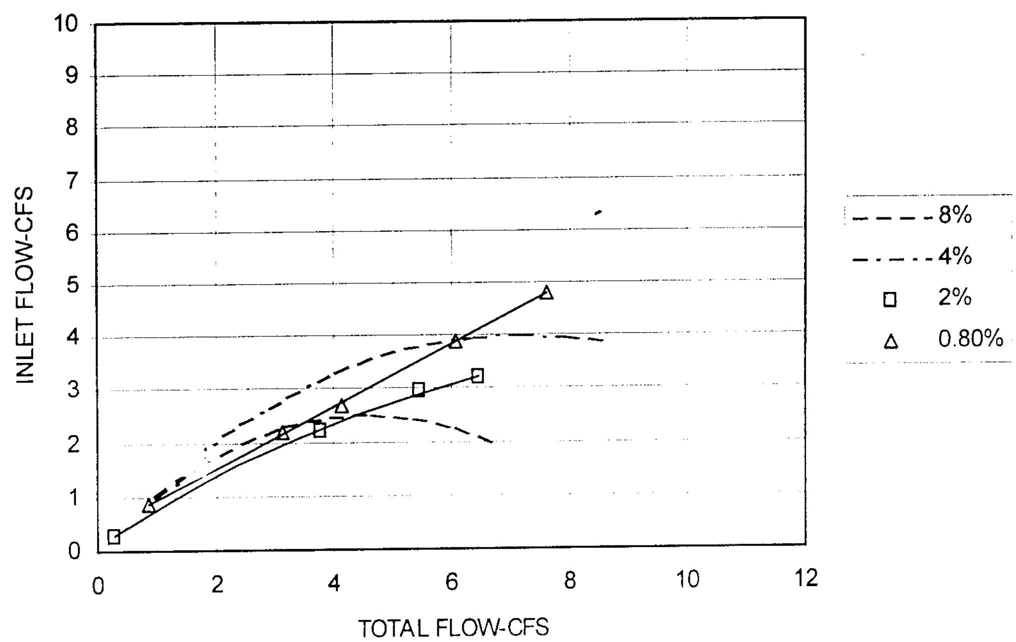


Figure 9: Full size performance curves for inlet Prototype inlet at 2% cross slope. Parameter is longitudinal slope.

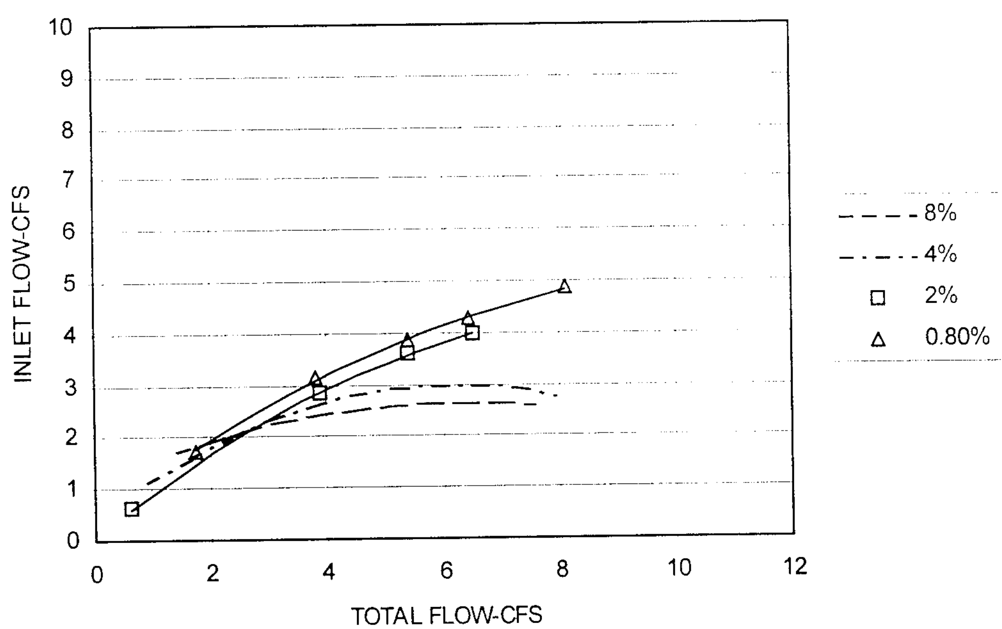


Figure 10: Full size performance curves for inlet Prototype inlet at 4% cross slope. Parameter is longitudinal slope.

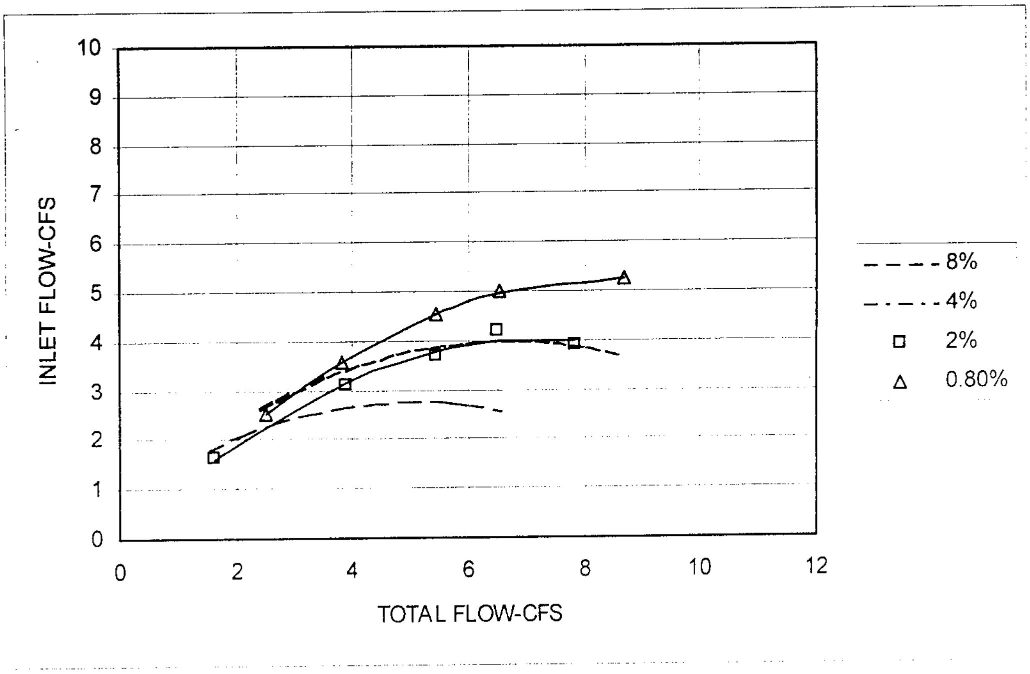


Figure 11: Full size performance curves for inlet Prototype inlet at 6% cross slope. Parameter is longitudinal slope.

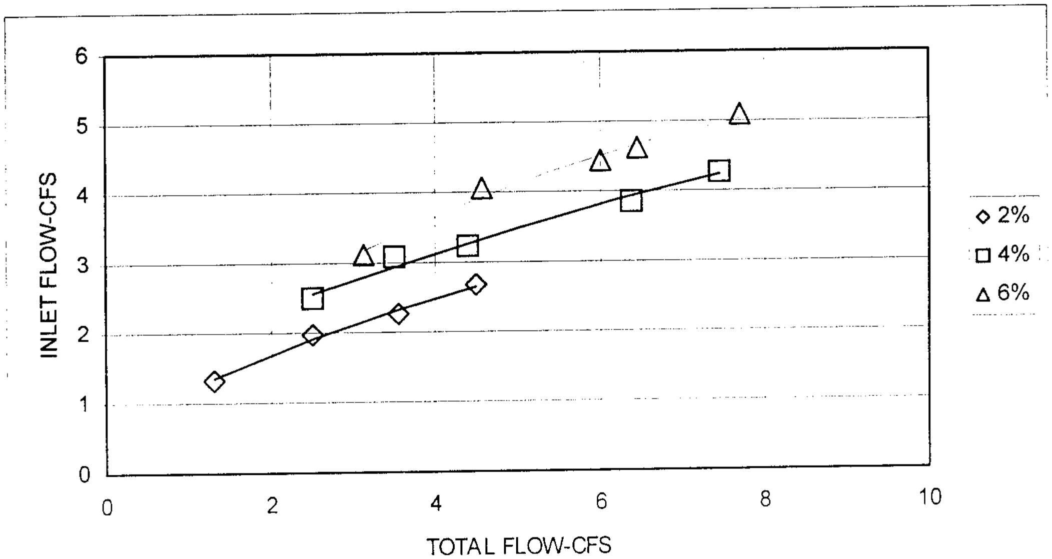


Figure 12 : Results of investigation for Type 5 inlet at 1% longitudinal slope, solid symbols represent data, solid lines represent empirical fits. Parameter is cross slope.

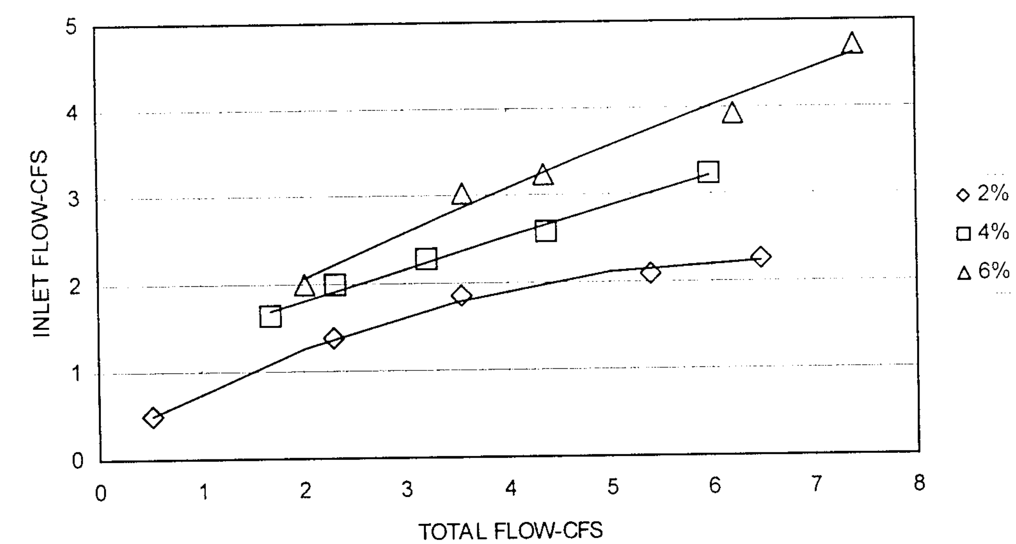


Figure 13: Results of investigation for Type 5 inlet at 4% longitudinal slope, solid symbols represent data, solid lines represent empirical fits. Parameter is cross slope.

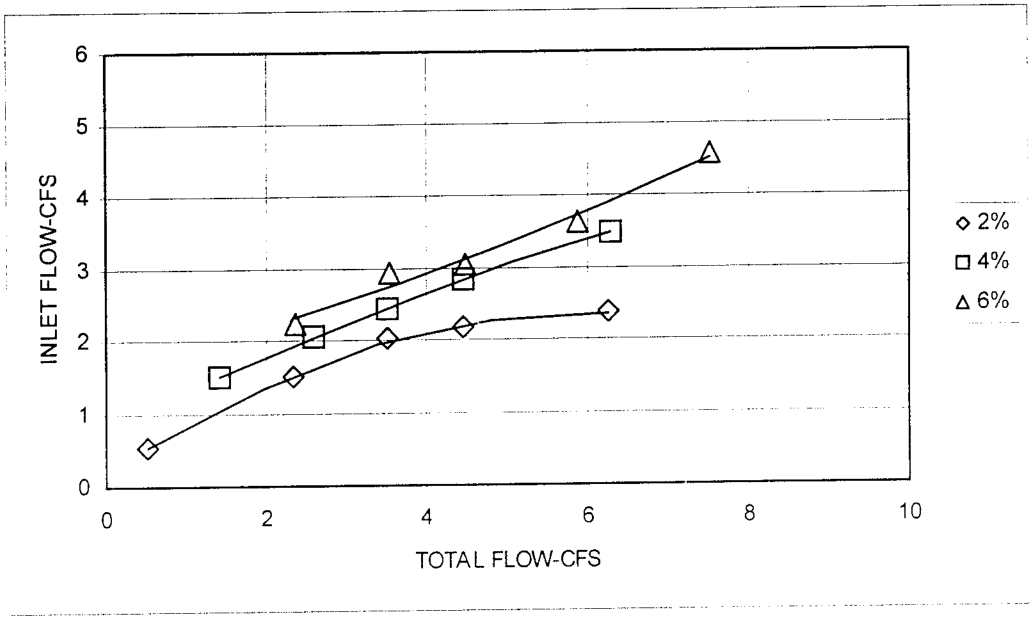


Figure 14: Results of investigation for Type 5 inlet at 6% longitudinal slope, solid symbols represent data, solid lines represent empirical fits. Parameter is cross slope.

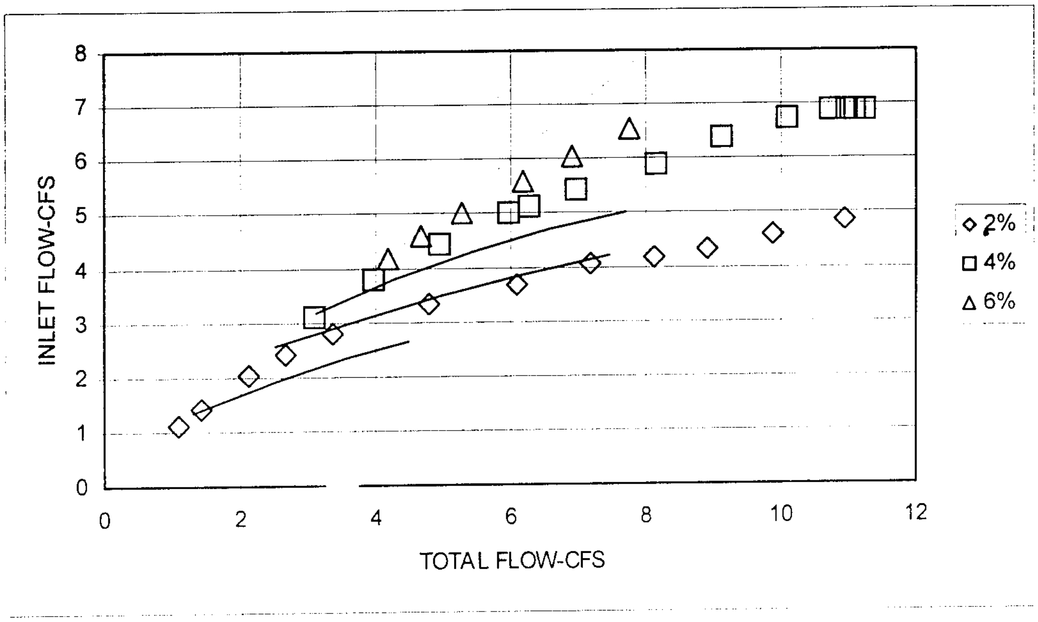


Figure 15: Comparison of data (Reference 3, symbols), with results of this investigation (solid lines), taken at 1% longitudinal slope; as a function of cross slope. Type 5 inlet.

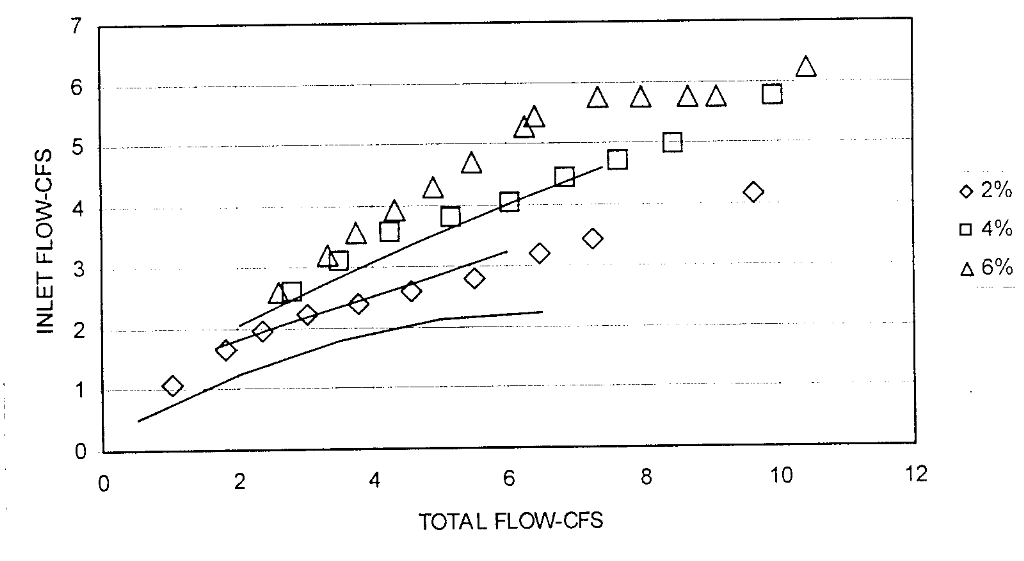


Figure 16: Comparison of data (Reference 3, symbols), with results of this investigation (solid lines), taken at 4% longitudinal slope; as a function of cross slope. Type 5 inlet.

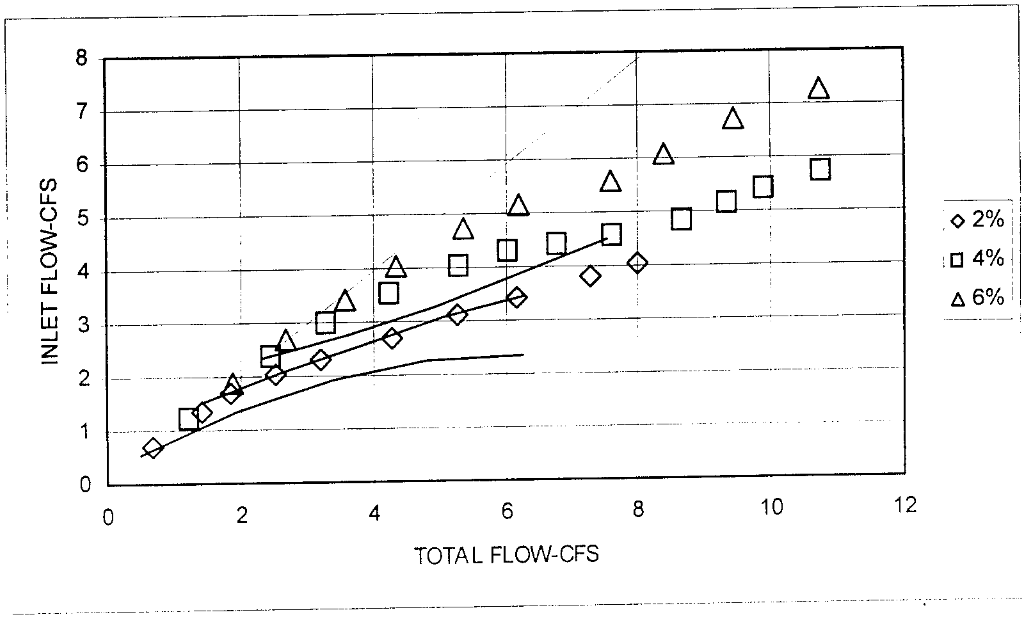


Figure 17: Comparison of data (Reference 3, symbols), with results of this investigation (solid lines), taken at 6% longitudinal slope; as a function of cross slope. Type 5 inlet.

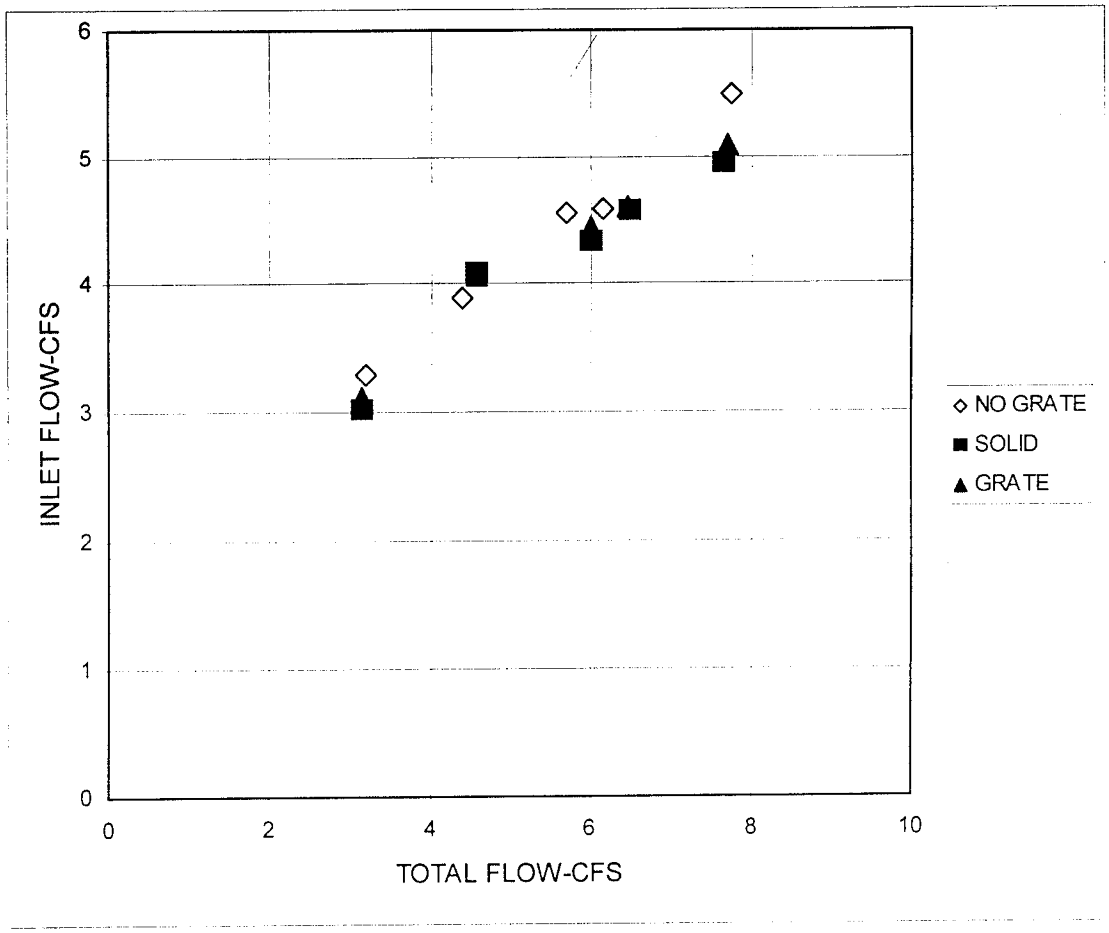


Figure 18: Grate performance for Type 5 inlet at 1% longitudinal slope, 6% cross slope.

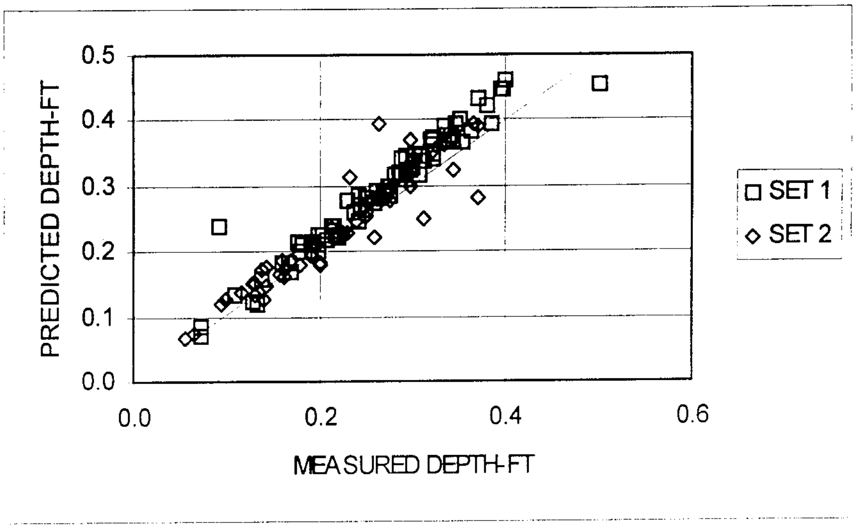
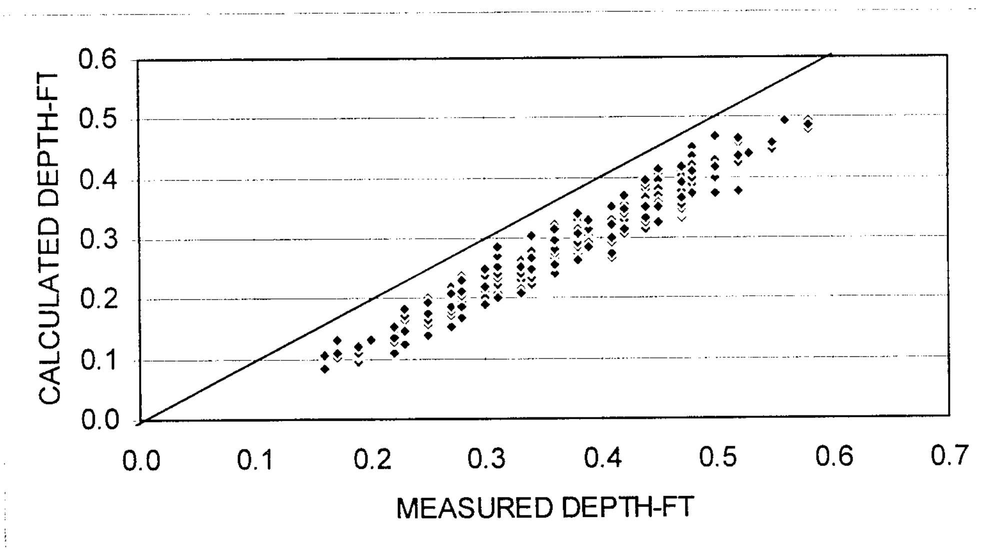


Figure 19: Correlation of measured depth vs predicted normal depth, this investigation. Set 1 refers to data taken with Index 213, Index 219 and the Prototype inlets; Set 2 refers to data taken with the Type 5 inlet.



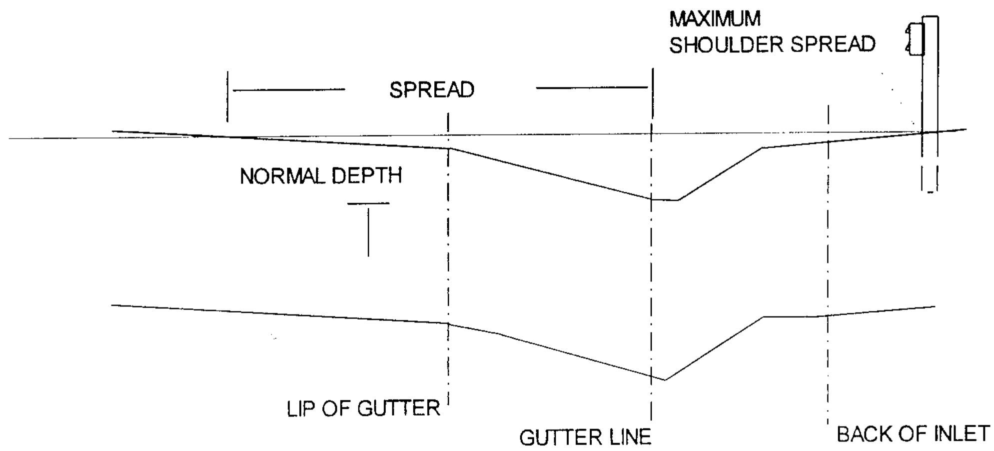


Figure 21: Cross sectional profile of gutter and grate. Note definition of spread from gutter line, and position of normal depth. Limiting shoulder spread is arbitrarily set at the traffic barrier.

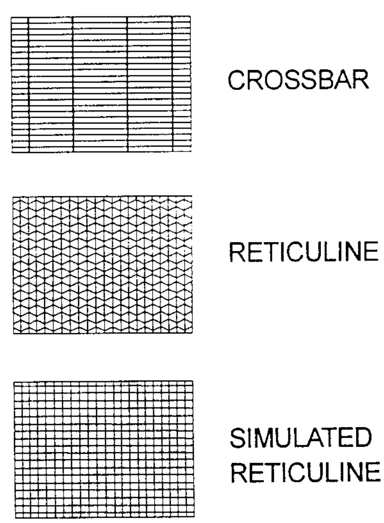


Figure 22: Grating styles. In this study the simulated reticuline grate was used instead of a true reticuline grate employed in field installations.

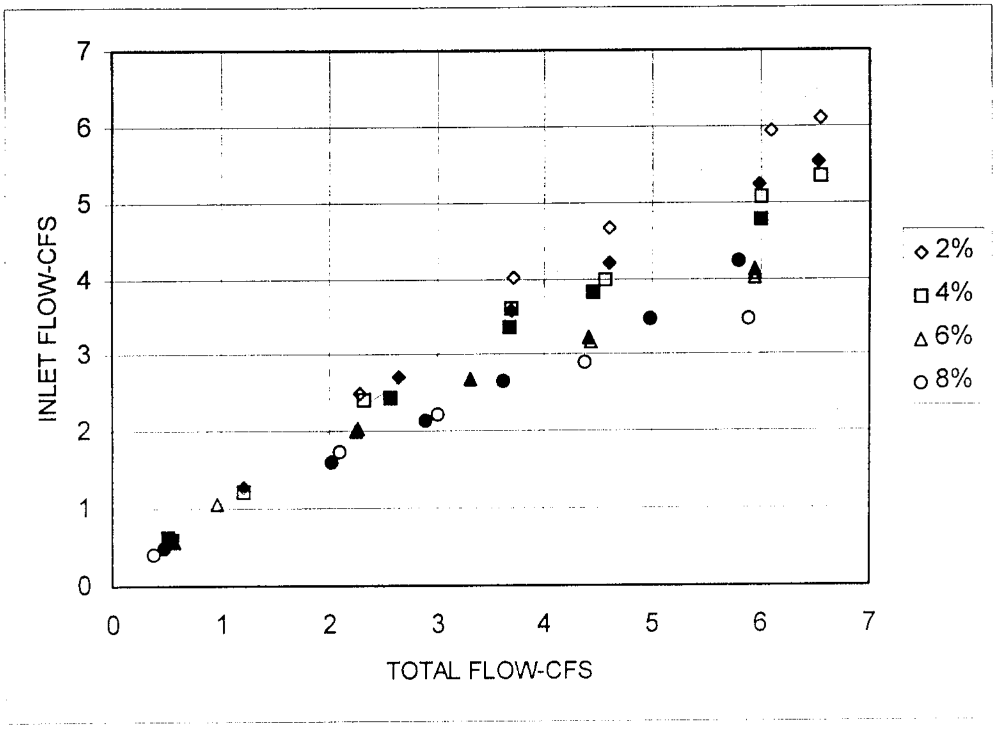
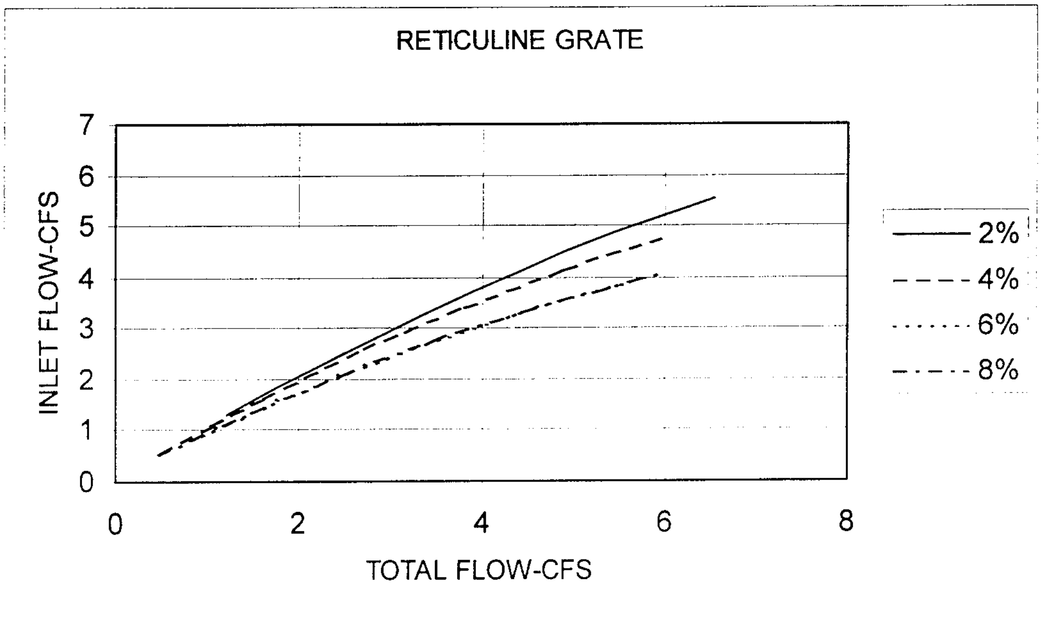


Figure 23: Collected data for model grated gutter inlet (Type S, Index 220). Longitudinal slope indicated at side bar, solid symbols denote data for reticuline grates, open symbols denote crossbar grates. Not to be used for design purposes.



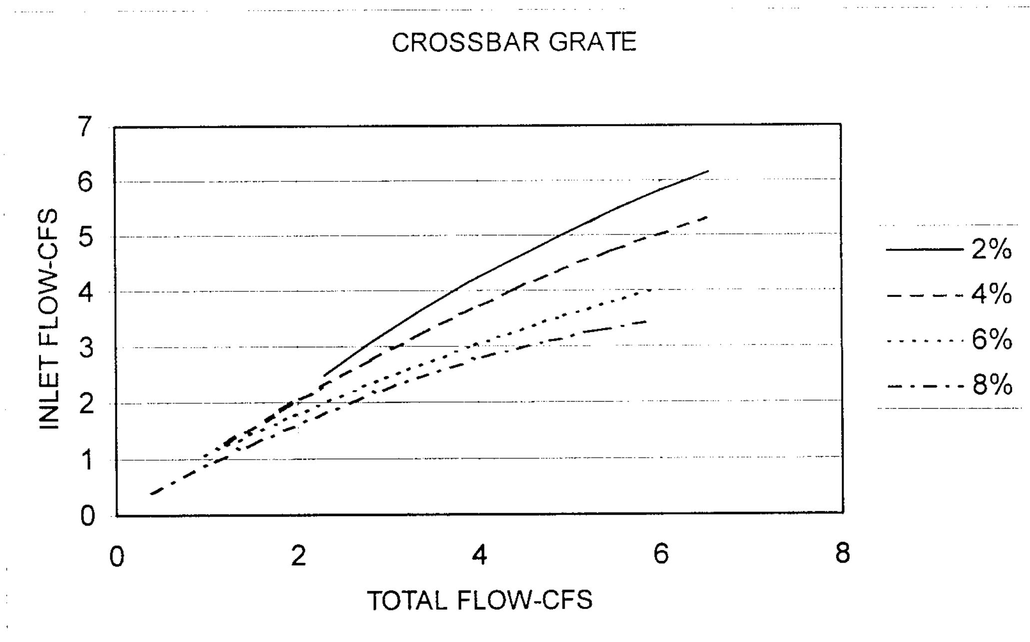


Figure 24: Design graphs for Type S gutter inlet (Index 220). Curves taken from empirical fits in Table 5 , scaled to full size from data. Longitudinal slopes indicated in sidebar (for the reticuline grate, curves for 6% and 8% are nearly identical). Note fit to actual data overlaps 100% efficiency line slightly. Use 100% efficiency.

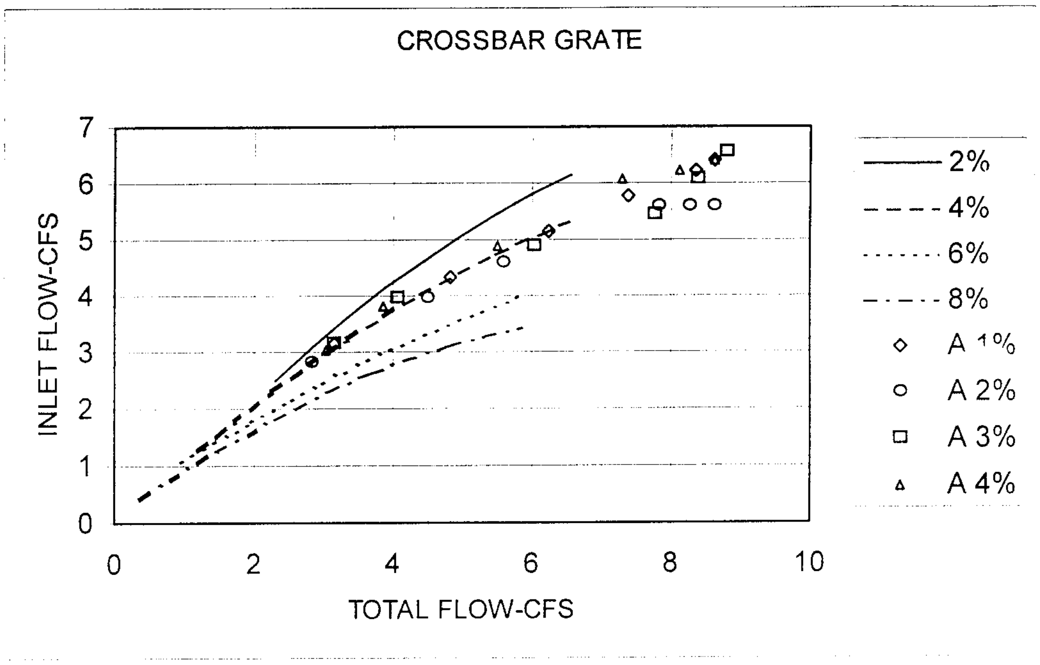


Figure 25: Anderson's data compared to data from this investigation, crossbar grate.

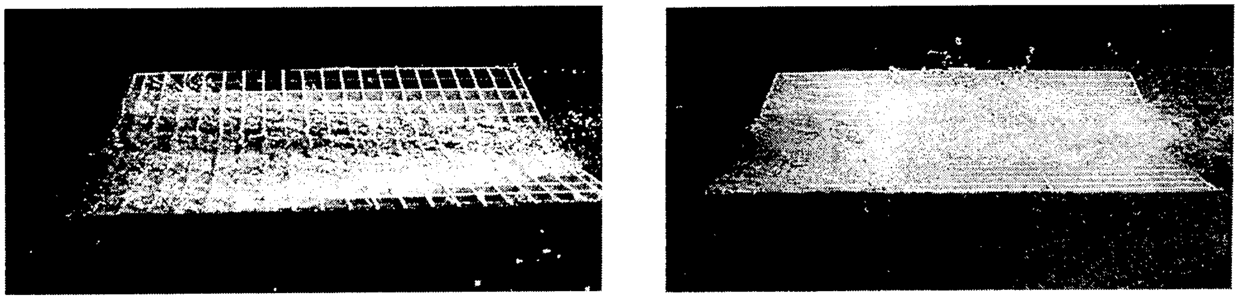


Figure 26: Flow across grating, reticuline grate (left), crossbar grate (right) at longitudinal slope 4% and a total flow of 1 CFS. Note water splash is much higher in the case of the crossbar grate.

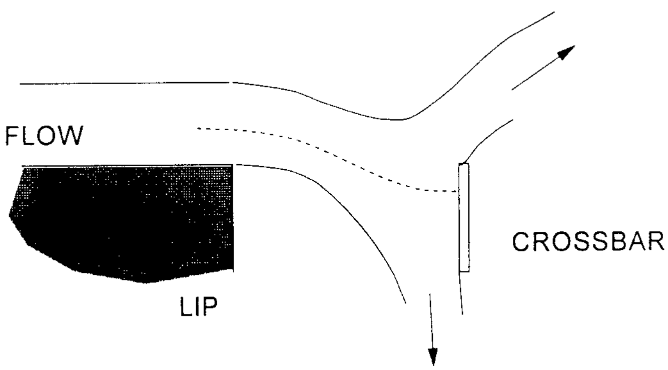


Figure 27: Illustrating flow at upstream lip of inlet and interaction with first crossbar to produce jumping and skipping across grate.

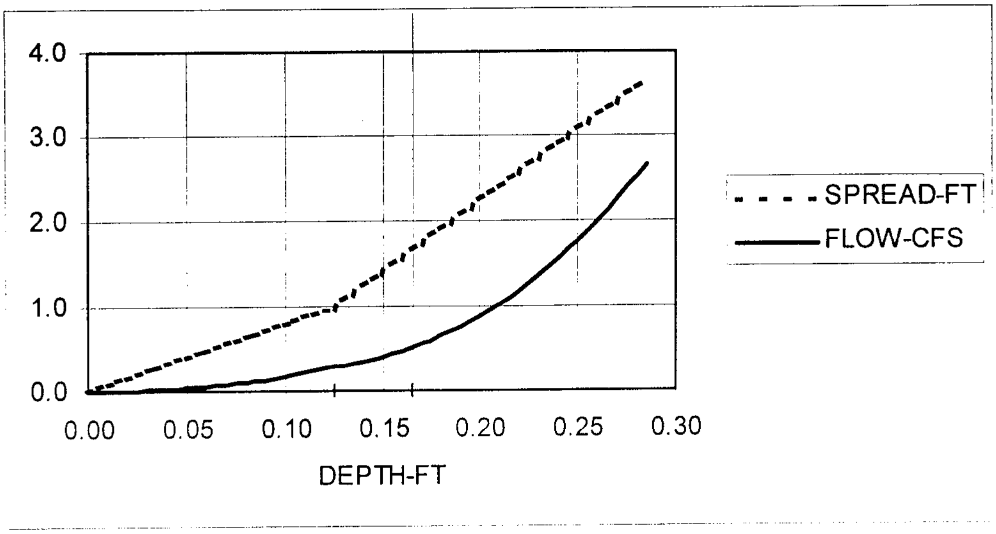


Figure 28: Spread and capacity as a function of depth for the model grated gutter inlet at 1% longitudinal slope. Vertical line shows maximum allowable shoulder spread.

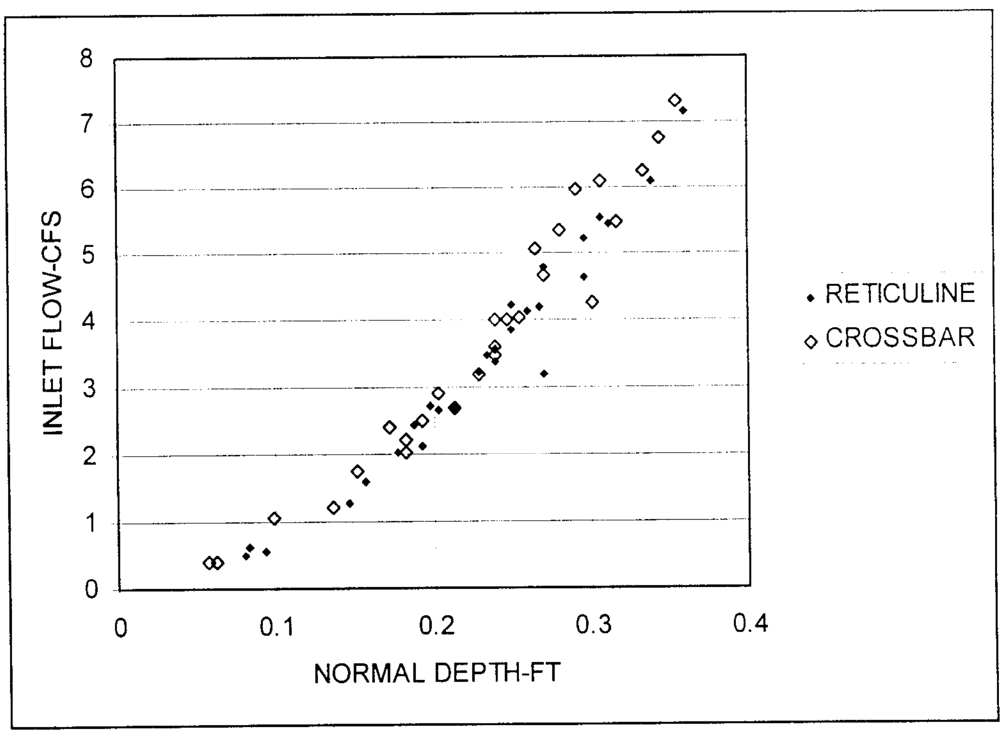


Figure 29: Correlation between normal depth upstream and inlet flow for both grating types. Measurement point upstream of bed transition.