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AN INVESTIGATION OF THE HYDRAULIC PERFORMANCE OF CULVERT GRATES

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16. Abstract

An experimental investigation of the hydraulic performance of culvert endsections is reported. Of particular concern is the effect on performance that the addition of safety gratings may have. The head-discharge characteristics for various model inlet treatments were measured to determine inlet performance. Hydraulic models of various end sections were tested in a recirculating flow facility. Experiments were conducted for both inlet control and outlet control, under both mild and steep slope conditions. The results of these experiments were analyzed and collected in graphical form, mapping the various regimes of culvert operation. Performance comparisons were made for culvert design, gratings and the presence of trash. The results of this investigation indicate that, in general, the addition of a grating has only a modest effect on performance. The associated problem of trash build up, however, can be very detrimental to performance. Particularly in outlet control situations, trash acts to produce additional losses. In the case of inlet control, moderate trash buildup does not act as a loss mechanism but reduces discharge and may change the point of control. For design purposes, the data have been correlated with empirical equations and tabulated. Suggestions and recommendations for design selections are made.

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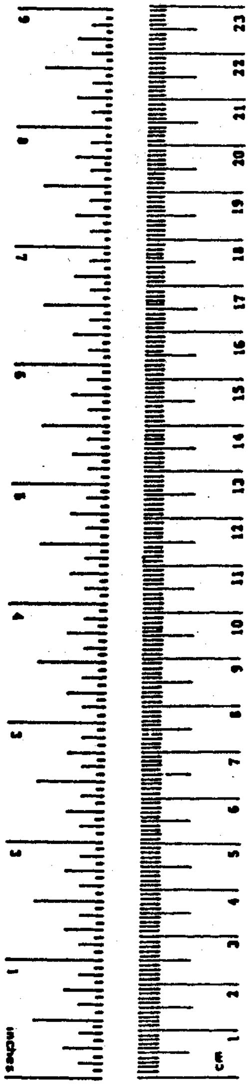
METRIC CONVERSION FACTORS

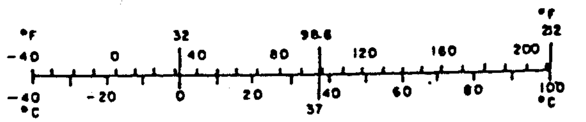
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10.286.

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SUMMARY

This investigation is concerned with the hydraulic performance of various culvert inlet endsections. Hydraulic performance is measured by determining the discharge of the culvert as a function of upstream headwater. Of particular concern is the effect that the addition of safety gratings has on performance. Often the freeboard available to accommodate the required headwater is restricted so that the addition of a grating along with the accumulation of debris may result in flooding of the area surrounding the inlet. The ultimate selection of a culvert design must also include considerations of safety, cost and material selection.

The goal of this research was to a) examine culvert performance for various entrance sections on a comparative basis, with and without safety grates, b) extend this work to include the effect of inlet blockage, and c) study influence of the outlet section on overall culvert performance. A review of the relevant literature was initiated. Experiments were conducted to determine inlet performance. Hydraulic models of the end sections were tested in a recirculating flow facility. Measurements were conducted for both inlet control and outlet control, under both mild and steep slope conditions. Performance comparisons were made for culvert design, gratings and inlet blockage. The same procedure was used to examine the effect of the outlet treatment structure.

The following items were accomplished during the research period:

1. Performance predictions for five different culvert inlet endsections were developed.

2. Data has been gathered to study the effect of added grates on endsection performance. These data have been compared to performance without grates.

3. Similarly, data has been gathered to study the effect of accumulated debris on the entrance and comparisons have been drawn with open end sections.

4. The outlet treatment including gratings and debris has been studied.

5. The effect of an added vortex suppression plate has been studied.

For design purposes, constants associated with empirical performance equations have been tabulated. In particular, the flared endsection appears to have substantial advantages over a broad range of applications. It is recommended that further effort be devoted to improving the overall performance of the mitered endsection. The results of this investigation indicate that, in general, the addition of a grating does not seriously affect performance. The associated problem of debris build up, however, can be very detrimental to performance. The results of this investigation can provide qualitative information about the magnitude of the problem. In outlet control situations, blockage by debris acts to produce additional losses. In the case of inlet control, moderate debris buildup does not act as a loss mechanism, but heavy buildup may change the control point and reduce performance.

INTRODUCTION

Culverts serve to convey water runoff under a roadway or other embankment. The performance of a culvert is simply the conveyance of the culvert as a function of upstream water depth. Depending on circumstances, many other factors such as downstream water depth, barrel characteristics and slope may influence performance. Thus the culvert can be viewed as a hydraulic control structure. The proper design of a culvert comprises hydrologic, hydraulic, structural, safety and economic considerations.

While complex, the flow regimes in a culvert have been widely studied and the operation of various culvert designs is well documented. The control, or hydraulic limitation to the flow, may occur at the inlet or result from conditions downstream from the inlet. Abrupt transitions between these two control states is a distinct possibility. Because a culvert often operates at relatively low hydraulic head and velocity, the flow in the barrel may be either closed conduit operating at a pressure differential with respect to the atmosphere or open channel with a free surface at constant pressure. It is not necessary that the flow remain steady; regimes of mixed flow, fluctuating in strength and entraining slugs of air may also occur. Under some conditions a substantial vortex may also form at the entrance.

The designer need not be concerned with all possibilities. In most cases, conditions are such that only a few regimes of operation are probable and depending on design philosophy, only one condition will be selected to represent performance. It is important to differentiate between the performance curve and the operational sequence, which refers to the different modes of operation that may occur as the culvert fills and empties. For instance, it is possible to begin with an inlet control situation at low water levels and to observe that this condition may persist as the head water rises, even though the performance curve would indicate that a switch to outlet control could take place.

In the present work, the discussion will be restricted to the hydraulic aspects of culvert performance. Primary concern is for culvert designs appropriate to the State of Florida, which is relatively flat and often has torrential storms. Typically, the slope of culverts is mild and the freeboard on the culvert is small. Outlets are often submerged. It is of particular interest to examine the hydraulic effects of the addition of safety gratings, designed to alleviate serious automotive accidents. There are several ways in which the presence of a grate may affect the hydraulics of the culvert but one of the principal concerns is the increase in the collection of debris. This is a double sided issue; on the one hand, barrel blockage is reduced and debris removal is facilitated by the addition of a grate. On the other hand, accumulated debris on the grate can easily contribute to substantial flow losses and decreased performance. Furthermore it is essential to examine the performance and operation of the total culvert. Often design calculations consider only the effect of the inlet structure and the culvert barrel whereas the installed culvert may include an outlet structure and, as discussed below, safety gratings at both the entrance and exit. The goal of the present study is to examine the overall performance of various culvert endsections and then to develop comparative assessments of performance when gratings are added. Although not investigated exhaustively, the effect of debris accumulation causing inlet blockage is also examined. All work reported here is based on laboratory experiments and no field tests were conducted.

To facilitate a discussion of culvert operation, the various operational regimes are shown in Figure 1. Here the dependent variable is the headwater above the entrance invert plotted against a flow parameter proportional to the square of the discharge. The performance of a culvert is the locus of all operating points on this graph. In contrast, the operational sequence is the locus of operating points joined sequentially as the headwater rises. Performance maps constructed in this fashion are generally useful for any geometrically similar culvert, as discussed below. It should be noted that the range of operation depicted in Figure 1 is necessarily limited. At higher headwaters it is possible that the outlet performance curve may cross the inlet performance curve.

Figures 2 and 3 show several operational modes of interest in this study. At the lowest headwaters, the control of the flow may be located at the inlet or the outlet. The inlet control mode has the characteristics of weir flow (Figure 2a) and develops if neither the barrel nor the tailwater force an outlet control state. Thus the inlet is not submerged, the flow is accelerated towards the entrance and critical depth is reached in the mouth or throat depending on the geometry of the inlet. The barrel is well ventilated from the entrance. A hydraulic jump could conceivably form downstream but neither the presence of a jump or barrel friction affect the flow rate so long as inlet control is maintained. Outlet control with an unsubmerged entrance is indicated in Figure 1 and shown pictorially in Figure 3a. In this case the culvert acts as an open channel carrying subcritical flow.

For both types of control, as the headwater rises the entrance is eventually submerged. The entrance may alternately seal and break to admit air in a periodic "gulping" action and an entrance vortex often develops. If the flow began in weir control, it is near this point that the culvert operational sequence may split into two paths, tending either to develop a true inlet control or shift to outlet control. The flow in this regime is transitional in nature and difficult to describe analytically. Furthermore, experimental measurements taken in this region are unreliable, since negative pressures may develop in the region just downstream of the inlet. For design purposes, projected lines can be used to join the various regions as shown in Figure 1.

Orifice inlet control (Figure 2b) can resemble a sluice gate in that the flow separates near the overt of the entrance and forms a vena contracta profile as a free surface. Downstream conditions do not affect the discharge. In some cases, the inlet mode may be stable and persistent as the headwater continues to rise. It is also possible that the entrance and throat geometry will support a "slugging" mode with alternating open areas and full barrel flow. This mode is further complicated by the presence of a vortex.

Often a switch to an outlet control mode occurs at some point in the operational sequence. As pointed out earlier, this may develop soon after the entrance is submerged, or may occur later after an inlet mode is fully developed. It should be noted that the operation of the culvert is truly bistable, and that the jumps from inlet to outlet control may be triggered by several factors. In other words, it may be possible that the operational sequence followed as the headwater is raised and lowered does not exhibit reproducible transition points. In fact, several investigators have suggested adding extra hydraulic controls to force a uniform operational sequence so that performance according to design can be assured.

Outlet control (Figure 3) is distinguished by the fact that the flow is limited either by the barrel losses or by conditions at the outlet. This type of flow can be substantially affected by the tailwater. The maximum flow rate will occur if the barrel is running full and critical depth is reached at the exit. Thus it is possible to generate a prediction for the performance of the culvert functioning in this mode, assuming no interference from the entrance vortex, and furthermore that suitable data is available to predict the entrance and exit losses as well as losses in the barrel.

Finally, at the headwater elevations greater than the freeboard of the culvert, the roadway is overtopped and the flow continues to increase with only a slight elevational increase. Various crest and weir models are commonly used to estimate performance under these conditions.

LITERATURE SURVEY

The literature survey presented here is not intended to be a comprehensive historical review of the research concerning culverts, but rather a brief summary of knowledge and design approaches considered from the standpoint of hydraulic performance. Since the earliest application of culverts as drainage structures, performance has been closely observed in order to produce acceptable designs . Much of current design practice relies on the observations and correlations of several early studies [1,2]. These studies were made to clarify the operation of culverts and to gather data for performance predictions.

It is often noted that the proper design of a culvert is not as simple a task as it first appears. Culverts have many operational modes and furthermore, complete design information is often not available. In the recent past, there have been several attempts to further clarify and document the more complex aspects of culvert operation [3,4]. These investigations focus on the inlet and the barrel as determining factors for the operational regime [5,7].

Recognizing that the inlet treatment has a substantial effect on overall culvert performance, several investigations have focused on design improvements for the inlet [8-13]. These include various hood modifications and also changes in the entrance tapers. The suppression of entrance vorticies by various auxiliary devices has been examined.

There are numerous design manuals and computer programs that summarize the information on culvert performance and explain design computations for culverts [14-18]. Much current design practice is based on Reference 16. This manual includes a complete discussion of culvert hydraulics, various empirical design formulas, nomographs and data to facilitate the design of typical culverts. Previous publications [10, 14 and 15] are incorporated.

The requirements, design and application of safety gratings are discussed in References 19-22. There have been several studies of the influence that various designs of gratings and trash screens exert on culvert hydraulics [23-29]. Modest alteration with gratings is indicated. Attendant problems with debris accumulation have been likewise considered [28].

Finally, it has often been noted that outlet treatments cannot be ignored [30-33]. When outlet control dominates, substantial opportunities exist for increasing culvert capacity by recapturing energy at the exit. Special outlet treatments may be utilized to achieve this effect. Despite the obvious advantages of increasing capacity, the application of this concept does not appear to be widespread, perhaps because of the difficulty of ensuring that outlet control can be maintained.

ANALYSIS OF CULVERT PERFORMANCE

Understanding the flow phenomena that occur in culvert structures requires careful analysis. Among the numerous effects which may have influence on the flow are the presence or absence of a free surface, the slope and roughness of the barrel and the possible presence of a hydraulic jump. In the discussion below, the fundamental hydraulic relationships governing culvert flow are reviewed briefly. Then various analytical models that can be used to represent culvert performance are summarized and finally, scaling parameters appropriate to the experimental study are discussed.

This study is restricted to culverts with circular cross section. Consider the definition sketch in Figure 4a, which shows the coordinates for flow in a partially full channel. The included angle may be related to the dimensionless depth, d as follows:

$$\theta = 2\cos^{-1}\left(1-\frac{2d}{D}\right) \tag{1}$$

Here θ is the included angle, D is the barrel diameter and d is the depth of flow.

Geometrical factors for the area, wetted perimeter, hydraulic radius, top width, and hydraulic depth can be expressed in terms of the included angle [34]. It is also possible to calculate conjugate depths for flow in a circular channel, and also to calculate hydraulic jumps. These relationships along with typical flow profiles for a circular channel are discussed in Reference 35.

Critical depth occurs when the specific energy H_0, is a minimum for a particular flow rate. In terms of a discharge factor q:

$$q = \frac{Q}{D^{2.5}} \tag{2}$$

the specific energy can be expressed as

$$\frac{H_0}{D} = .0252\frac{A^2}{A_f^2}q^2 + \frac{d}{D} \tag{3}$$

Where A_f is the flow area and A is the barrel area. The units of this equation are English. The discharge parameter given in Equation 2 arises naturally from similarity considerations. This parameter is utilized extensively in this study and will be discussed in more detail below. The minimum may be located and replotted as a function of the discharge factor. For purposes of design and analysis it is more useful to have the critical depth as a function of flow rate. In this investigation, a polynomial fit has been developed from the previous result to give the critical depth as a function of flow rate in terms of the discharge factor (Equation 2). With Q in cubic feet per second and with the diameter and the critical depth d_c both in feet

$$d_c = 0.165 + 0.2761q - 0.0313q^2 + 0.0012q^3 \tag{4}$$

Uniform flow occurs in an open channel when the slope of the channel, the energy grade line and the hydraulic grade line are equal and constant. Consider Manning's equation (English units):

$$Q = \frac{1.49}{n}R_h^{\frac{2}{3}}S_b^{\frac{1}{2}}A_f \tag{5}$$

Here R_h is the hydraulic radius and A_f is the area of the flow. For a particular flow Q, bed slope S_b, and Manning's n, there is only one value of depth that will satisfy this equation. Normal depth is the depth of flow under this circumstance. The dimensionless depth must be less than or equal to 1 or the flow will be a pressure flow rather than a free surface flow. Starting from Manning's equation and substituting for the hydraulic radius and the area

$$Q = \frac{1.49}{n} S_b^{\frac{1}{2}} [0.125(\theta - \sin\theta) D^2] \left[.25(1 - \frac{\sin\theta}{\theta}) D \right]^{\frac{2}{3}} \tag{6}$$

The slope is mild when the normal depth is greater than the critical depth and the slope is steep when the critical depth is greater than the normal depth. When the two depths are equal the slope is critical and the discharge is given in reduced form as:

$$Q_c = \frac{.044\sqrt{g}\,(\theta - \sin\theta)^{\frac{3}{2}} D^{\frac{5}{2}}}{[\sin(.5\theta)]^{\frac{1}{2}}} \tag{7}$$

For a given flow rate, Equations 6 and 7 can be solved for normal and critical depth.

In order to make the experimental data easily available to the designer, it is necessary to provide an analytical or empirical model equation. The parameters of the model can then be adjusted to give the best fit to the data. Figure 4b defines the notation used in the following discussion.

Figure 3 depicts outlet control as determined by tailwater depth. In cases a) and b) the tailwater is at or above the overt of the exit so that the barrel exit is totally submerged. In this case, Bernoulli's equation may be written as

$$H_w + LS_0 - T_w = \sum LOSSES \tag{8}$$

H_w and T_w are the head water and tailwater, respectively, and the product LS_0 is the barrel length times the barrel slope.

In many cases the head water and tailwater can be considered to be reservoir conditions with no substantial velocity. Thus the difference in elevation is the sum of all losses along the direction of flow. Although some interpretation is required, these basically consist of the hydraulic loss at the inlet which is determined by experiment, the barrel losses, and the loss at the outlet. In general, the exit loss factor may be taken equal to 1 if the ratio of the downstream channel area to the barrel area is large. Frictional losses may be computed from the D'arcy-Weisbach formula if the culvert barrel operates under pressure:

$$BARREL\ LOSSES = \frac{fL}{D}\frac{V^2}{2g} \tag{9}$$

where f is the D'arcy-Weisbach friction factor. This method was chosen for the model studies reported here in order to obtain accurate estimates for the smooth pipes used. For design purposes, it is common practice to use the Manning formula to compute the energy gradeline [16] . This method should give similar values for the frictional losses.

In Figure 3c), the hydraulic grade line pierces the barrel top and critical depth is reached at the exit. While this is the condition for maximum discharge under outlet control, the barrel does not run full and complex backwater computations must be completed to determine the hydraulic grade line. Often the tailwater is approximated instead by [16]

$$T_w = \frac{D + d_c}{2} \tag{10}$$

Thus the relationship defining the outlet control region becomes

$$H_w = T_w - LS_0 + (1 + K_e + \frac{fL}{D})\frac{V^2}{2g} \tag{11}$$

with the tailwater depth established by either actual value or Equation 10.

Inlet control requires a different approach since the flow is not governed by the outlet conditions and only slightly by the barrel slope. Inlet control (Figure 2) may be categorized as either a weir type condition or an orifice flow. Figure 2a shows weir flow with the inlet unsubmerged and ventilated. Two correlations based on weir models are suggested in Reference 16 (cf. p. 146). The first of these is

$$\frac{H_w}{D} = \frac{H_c}{D} + K\left[\frac{Q}{AD^{.5}}\right]^m + SLOPE\ CORRECTION \tag{12}$$

Where H_c refers to the specific energy at critical depth and A is the area of the barrel. K and m are empirical constants determined by experiment, with typical values given in Reference 16. This formula is difficult to implement because the difference between the headwater and the specific energy at the crest is relatively small. An alternative which eliminates this problem is

$$\frac{H_w}{D} = K\left[\frac{Q}{AD^{.5}}\right]^m \tag{13}$$

Again, K and m are empirical constants. These correlations are generally applicable as long as

$$\frac{Q}{AD^{.5}} < 3.5 \tag{14}$$

Figure 2b shows the submerged entrance and a type of inlet control which closely resembles an orifice flow or the flow beneath a sluice gate. For an orifice flowing under gravity or pressure, the velocity is computed by Bernoulli's equation. Usually the conversion to kinetic energy is efficient so that only minimal loss of kinetic energy occurs. The orifice configuration instead produces an area reduction which ultimately reduces the flow rate. Thus, the headwater is proportional to the square of the discharge.

To formulate a model, the discharge is related to the nondimensional headwater as measured from the invert of the culvert. Modification of this relation by the addition of a constant term is often suggested. This constant incorporates numerous corrections. For example, taking the headwater from the invert may overestimate the fall, since the inlet diameter may be a substantial fraction of the headwater. The barrel may be partially filled behind the inlet so that the flow is not truly free. This effect may also partially depend on the slope of the barrel so a term is also frequently added to incorporate this correction. Again, an empirical relation describing orifice control has been suggested in Reference [16]

$$\frac{H_w}{D} = C\left[\frac{Q}{AD^{.5}}\right]^2 + Y + SLOPE\ CORRECTION \tag{15}$$

applicable for

$$\frac{Q}{AD^{.5}} > 4 \tag{16}$$

Where C and Y are empirical constants and all other terms have been previously defined.

In the present study the final term is neglected since all measurements were conducted with modest slopes and the effect is minor. As discussed earlier, correlations for the weir and inlet regime do not quite overlap, and usually the two regimes are joined by a fair curve.

Finally, it should be noted that several types of transient operational modes are possible. Figure 2c shows a situation where air is aspirated periodically (either through vortex formation or a gulping action) to form slugs which move down the barrel. Other transient modes include rapid transitions between inlet and outlet control. Such movement may be accompanied by a short term reduction in the upstream head as the barrel primes and the flow rate increases. These phenomena are easily seen in model experiments and may be due in part to surface tension effects and the development of negative pressures in the barrel, but might also be observed in practice.

To complete the analysis of the models, it is necessary to discuss the scaling relationships which exist between the experimental model and actual prototypes. The geometrical scale of the models is nominal 1/3 to 1/4, to represent culvert diameters of 30 to 40 inches. Since typical culverts run from about 15 to 60 inches, the scale factor is not much different than the prototype. It is also noted that in general, reported values for the entrance loss coefficient do not indicate a dependence on the size of the culvert.

As in most hydraulic model studies, the appropriate nondimensional parameters are the Reynolds Number and the Froude Number. Usually, it is not possible to maintain these two parameters simultaneously. When the entrance and barrel are running full (outlet control), at a typical velocity of 6 feet per second, the Reynolds number alone may suffice and is at least $4X10^5$. In this case, dependence on the Reynolds number is minimal since the flow tends to be fully developed and Reynolds scaling does not need to be rigorously maintained. Under some circumstances, it may be necessary to provide a correction for the differences in barrel losses and barrel roughness. It has been noted [36] that both surface tension effects and approach conditions can influence tests on small models. It is not possible to state that problems such as these do not affect the current experiments and furthermore it is difficult to anticipate every condition which exists in practice. However, since the model is 1/3 to 1/4 scale, and efforts have been made to reduce approach velocities it will be assumed that these effects are minimal.

When inlet control is studied, free surface effects tend to dominate and the Froude Number is the appropriate scaling parameter [34]. The discharge parameter used in many studies is

$$DISCHARGE\ PARAMETER = \frac{Q}{D^{2.5}} \tag{17}$$

which is closely related to the Froude number and was utilized previously in Equation 3. Although commonly in use, this variable is unfortunately dimensional, since the gravitational acceleration has been omitted from the parameter. It should be noted that some authors use an area relationship instead (also dimensional)

$$DISCHARGE\ PARAMETER = \frac{Q}{AD^{.5}} \tag{18}$$

In fact the empirical equations describing orifice and weir flow are written in terms of this parameter. If a conversion is necessary

$$\frac{Q}{AD^{.5}} = \frac{4}{\pi}\frac{Q}{D^{2.5}} \tag{19}$$

In the analyses that follow, the square of the parameter given in Equation 17 will be used and referred to as a discharge parameter, with units of feet per second^2. In this way, correlations based on kinetic energy are anticipated and this term will work equally well for outlet control, providing Equation 11 is rewritten in the nondimensional form

$$\frac{H_w}{D} = \frac{T_w}{D} - \frac{LS_0}{D} + \frac{1}{2g}\left(1 + K_e + \frac{fL}{D}\right)\left[\frac{Q}{AD^{.5}}\right]^2 \qquad (20)$$

It is emphasized that the resulting locus is a function of the slope and the outfall conditions. In contrast, inlet control is not dependent on the barrel and is only very weakly dependent on slope, thus curves representing orifice and weir control depend only on the inlet configuration.

In order to construct a performance map such as Figure 1, the values of the empirical constants appearing in Equations 13, 15, and 20 must be determined experimentally. Both inlet and outlet control relationships may be represented on the same performance map and in the experimental work reported below, performance maps will be used to provide comparisons between data taken under various circumstances.

For design purposes, consideration should be given to the regime of the performance map with regard to potential design application and also with respect to the experiments which follow. In many situations, a design velocity in the barrel would not exceed 7 feet per second (and in most cases would be less). For a circular culvert the scaling parameter reduces to

$$\frac{Q^2}{D^5} = \frac{49}{16}\frac{\pi^2}{D} \qquad (21)$$

at a flow of 7 feet per second. This expression provides an estimate of the range for model tests as well as for prototype design. Because the model diameter is smaller than any culvert used in practice, a experimental range of discharge parameter from 0 to 35 feet/second^2 will span a practical design range.

EXPERIMENTAL FACILITY AND MEASUREMENTS

The experimental apparatus is shown schematically in Figure 5. Two large holding tanks served as reservoirs with three independent, parallel return lines and centrifugal pumps used to form a recirculating loop. The model culvert system was located between the tanks to complete the loop. The model end sections were placed inside the tanks on specially constructed platforms.

One 6 inch and two 4 inch PVC supply lines were used, with separate flow meters in each line to measure discharge. The pumps in each line were also independently controlled. The larger line included a manual gate valve and one smaller pump was driven by a variable speed drive. Maximum flow rate between the reservoir was found to be about 3.5 CFS which gave a maximum velocity of about 7 feet per second.

The holding tanks were fabricated on site using fiberglass-balsa core sandwich construction with nominal dimensions of 6 X 12 X 6 feet high. The large volume was used to permit high freeboard testing and also to provide sufficient stilling of the water flow. The receiving reservoir was fitted with an adjustable weir to assist in the control of the outflow water surface. Considerable effort was expended to ensure that the approach of water to the culvert entrance was uniform and as slow as possible to eliminate approach as a variable. The suction and discharge from the recirculation lines were located from under the support platforms through large perforated pipes to help disperse the flow. The platform also represented the ground floor adjacent to an entrance section.

The experimental study was restricted to circular culverts. The barrel of the culvert was fabricated from commercial lightweight PVC sewer pipe (9.875 inch I.D.). Provisions for static pressure measurement along the pipe were made. This pipe could be replaced by a clear plastic (10 inch I.D.) observation section. The barrel was supported at a low slope of 0.0028 between the two tanks. To obtain a steeper slope of 0.025, the head tank was elevated from the supporting slab. A slip penetration through the end walls of the tanks facilitated connections to the models end sections. Wherever a pipe joint was needed, a rubber coupling was used in order to minimize internal flow disturbances.

Models of the various end sections were constructed from sections of the same PVC sewer pipe and plywood. In some cases, various portions of the model were fabricated using balsa core fiberglass sections. Grate models were constructed from either wood strips or small diameter PVC pipe. The models were faired with polyester putty and resin coated for waterproofing. The dimensions for each model were taken directly from Florida Department of Transportation specifications [37]. Both the 272 and 273 models were held to 4:1 slopes and other slopes were not investigated. Figures 6a through 6d show the models used in these tests, along with grate designs tested.

The culvert consists of a 15 foot barrel and an entrance section. With the exception of a few experiments no outlet end treatment was used and the tailwater was held well below the overt at the exit so that the discharge was free. Thus if the culvert operates in an outlet control mode the flow will be critical at the exit and the extension method, Equation 10 can be used to calculate the hydraulic gradeline. Most of the data on inlet control was gathered at the higher slope so as to improve the operational range. Inlet control data is very insensitive to slope. In this case, the slope (0.025) is still low, so that no slope correction was needed.

Several experimental measurements were performed for each test. The headwater level in the supply tank was measured with a static piezometer tube fitted with a metal scale. Heights on this tube were referenced to the still tube setting at the beginning of the test. Once a steady state condition had been obtained, as indicated by a stationary water surface, flow velocities in each return pipe line were measured using paddle wheel type flow sensors. These measurements were combined with data on the internal pipe diameter to obtain the discharge through each line. In most of the tests reported here, the discharge was free so that tailwater measurements were necessary only for some experiments involving outlet control. In order to measure the tailwater as accurately as possible, and to avoid surface disturbances near the exit, a large diameter stilling tube was placed at one corner of the receiving tank. A sharp pointed indicator was set to just touch the water surface at the proper elevation.

EXPERIMENTAL OBSERVATIONS AND DISCUSSION

A series of experiments was conducted according to the protocols outlined previously. The purpose of these experiments was to:

a) develop performance information and correlations for each endsection tested

b) examine the effects of grating installations on performance

c) examine the effects of inlet blockage on performance

d) review and extend observations concerning outlet control

1. Performance of open endsections

Figure 7 shows data for the type 250 endwall treatment. Both inlet and outlet control are presented in the form of a performance map as discussed previously. In this case the data for inlet control may be compared to the correlations of others (Equations 12 and 5) as shown for both weir and orifice control. Also shown are the correlations developed in the current work using Equation 13. All correlations for inlet control in this investigation were performed using data taken with the culvert set on the steep slope. Tables 1 and 2 summarize the empirical coefficients. It was observed that the culvert would not perform under orifice control at the lower slope. As shown in Figure 7, outlet control data were taken at the higher slope with critical flow at exit (free discharge) for comparison. The effective tailwater elevation was taken equal to the diameter of the pipe if running full or computed from Equation 10. Entrance loss factors were taken from [16] and also developed independently in this investigation as discussed below. It is seen that overall agreement is good, lending confidence to correlations for other endsection designs for which little or no reference data exists.

Considerable effort was expended to document the type 272 mitered end section, using the same method as that described for the type 250 section. These results are shown in Figure 8 along with both correlations of others [16] and those developed here. Unfortunately the correlation quoted in Reference 16 is for a corrugated metal pipe of unknown face slope, and the empirical equation is not of the same form. Even with this limitation, agreement is reasonably good. In the case of the mitered end section, the culvert could be induced to perform in a orifice control mode under mild slope conditions. These data have been added to Figure 8 and show good agreement with the steep slope data as would be expected.

Results for type 270 flared endsection are shown in Figure 9. It is noted that under outlet control, the performance prediction agrees quite well. Inlet control data indicate that unlike most other types of endsection treatments, virtually no operation in the orifice control regime was observed for the steep slope condition. Instead, the results follow a path from weir control to outlet control which occurs at a head elevation just slightly greater than the overt of the inlet. Correlation for data taken in this region could be fitted to the same form as that for inlet control, but the results obtained indicate a more efficient discharge. The absence of an orifice controlled operational regime seems to be due to the tapered inlet design. Thus critical velocities may never be produced at the inlet or throat. This particular design may also act as a hood to the inlet, a feature which has been shown to substantially improve performance [8].

Figures 10 and 11 show data and correlations for type 260 and 261 box end sections without grates. The results for these endsections are almost identical and closely resemble the mitered endsection for inlet control conditions. Experiments with the type 261 box endsection indicated that operation in orifice control on a mild slope was possible.

2. Effect of added grates

In order to examine the influence of the addition of gratings to the end section design, data taken with these alterations have been compared to the correlations developed in the previous section. In Figure 12, data for the type 273 mitered end section with transverse cross bars and a type 272 mitered endsection with added T-bar grate show that the grate modifications result in only a modest performance alteration. Performance under outlet control is about the same. Correlation of the outlet control data indicates a slight improvement, which may not actually be significant. This is in agreement with the work reported in Reference 28. It appears that for inlet control the grate tends to force the transition to outlet control at a lower headwater elevation, and because the shift is towards higher flow parameter, performance is slightly improved over inlet control. Operation at mild slope for this endsection treatment was observed as shown in Figure 12.

Gratings are frequently employed on type 260 and 261 box end sections. Figures 13 and 14 show the consequences of adding gratings to the endsections. Comparisons with the correlations for open box endsections can be made. Again the presence of a grate does not appear to produce a large effect, although in the case of the type 260 a slight decrease in the performance for weir control can be noted. Operation under orifice control for the type 261 endsection with the grating in place could not be induced.

3. Debris accumulation

Debris accumulation presents an entirely different set of circumstances. If the culvert is flowing in outlet control the effect of inlet blockage can dramatically increase the entrance losses, as discussed in Reference 28. Inlet loss factors can be elevated by a factor of three or more with 50% occlusion, depending on the location of the blockage on the inlet face.

In order to assess the effect of debris on the entrance section when the culvert is flowing in inlet control, tests of discharge were conducted with partial occlusion of the entrance. Obviously, due to the highly variable nature of debris accumulation, these observations should be treated as qualitative information only. Again for comparison, these data were superposed on the correlations developed previously. In most cases, there was little effect as long as orifice control was maintained and as long as the control remained at the inlet throat section. For most designs, the grating and consequently the blockage stands off to some extent from the throat section. This is most obvious for the box end sections. Occlusion sufficient to shift the control section from the entrance or throat to the location of the blockage is a possibility and is likely to be accompanied by a reduction of flow.

Figures 15 to 18 show the effect of blockage for standard grate designs. As long as inlet control is maintained and discharge is not too high, the effect of blockage is modest. As with the presence of gratings, it appears that blockage may actually induce an earlier transition to outlet control, although this observation may be distorted by the development of regions of negative pressure in the barrel. In the case of the mitered endsection, the experimental T-bar grate was not tested but it is believed that similar results would be obtained. That inlet control can be shifted to the point of debris accumulation has been observed and may be seen in Figures 15 and 18. This effect occurs for substantial (75%) buildup at the bottom and is accompanied by a marked reduction in performance. Figure 16 shows the performance of type 270 flared end section with the top sloped face of the inlet obscured. Even with this severe condition, the performance is still very good.

4. Effect of an outlet endsection

Experiments were conducted to examine the performance of the culvert flowing under inlet control when an outlet endsection is included. No effect should be observed as long as the control point is not shifted to the outlet. This shift could be induced by the endsection treatment, the addition of a grate or by debris blockage, and will depend on the slope of the barrel. Figure 19 shows the results for a model culvert tested with a type 273 grated mitered endsection at both inlet and outlet. Comparisons can be made with the correlations developed for the type 272 entrance endsection as explained previously. Clearly there is little influence, even when the outlet is obscured by a 50% blockage (located at the bottom), until higher discharges are reached. At this point a gradual transition to outlet control is indicated.

5. Influence of vortex formation

Vortices are a commonly observed phenomenon of culvert hydraulics. Once the culvert entrance submerges and full flow is established a vortex often forms near the entrance, especially if the water level over the top of the entrance is small. This vortex can be quite substantial and air is often aspirated into the barrel. Frequently the vortex is cyclic or irregular in nature, alternately forming and disappearing. The actual influence of the vortex is yet to be determined. In the work of Reference 28 it was difficult to see any reduced performance due to the vortex, but this may be due in part to the scale of the facility. The circulation pattern may have an influence on bank erosion and on the accumulation of debris.

Several investigators have examined vortex suppressors. One method incorporates a vertical plate oriented along the axis of the barrel protruding from the entrance treatment. This method is very effective in reducing the vortex. Some types of debris may be captured more readily on the plate, although some devices act to align floating debris to pass more successfully along the barrel. Depending on design, vortex suppressors may act to accumulate debris or to align floating objects to pass through the culvert more successfully.

Experiments were conducted to determine the effect of the entrance vortex on the head discharge characteristic using the flat plate aligned with the flow as described previously. As seen in Figure 20, the data show that either inlet or outlet control can be maintained and that little difference in performance is observed when compared with the results when a vortex is allowed to form. Operation in transition zones between inlet and outlet control modes has been observed. It appears that one effect of the plate is to stabilize the mode of operation and may limit sudden jumps from inlet to outlet control.

6. Extended measurements of inlet loss factors for outlet control

Because the work reported here includes an extended regime of operation beyond that of previous work [28], it was found that better correlations were needed to predict operation under outlet control. Accordingly, more experiments were conducted to measure the entrance loss incurred as a result of outlet control. The facility was operated with both the entrance and exit submerged, the tailwater being held at the crown of the exit pipe. Additionally, data sets taken at outlet control with a free discharge were also utilized. These data were combined with the results of Reference 28.

When the flow is well into the turbulent regime, losses are generally taken to be directly proportional to the kinetic energy of the flow, independent of the elevations of the head and tailwater. In keeping with simple models for minor losses, correlations are made to the square of the barrel velocity, computed from the area and discharge. Thus the total head loss is measured, the barrel and exit losses are subtracted and the remaining loss is taken as the inlet loss. As explained previously, the exit loss factor is taken as one, signifying the loss of all exit kinetic energy in the receiving basin. Because the culvert was flowing full and under pressure the D'arcy-Weisbach formulation was used to estimate the barrel losses. For the higher discharge data a friction factor of .014 was taken. Measurement of the hydraulic gradeline in the barrel confirmed this approach, although a region of reduced pressure near the inlet was observed. This region extends for about 4 feet from the entrance and appears to result from the adjustment of the separated zone downstream of the entrance.

The entrance loss is correlated with the kinetic energy (both in feet of water) through the equation

$$H_e = K_e \frac{V^2}{2g} \tag{22}$$

which is fitted to the data to solve for K_e, the entrance loss factor (nondimensional). As explained previously, K_e is taken to be a constant independent of the Reynolds Number.

As seen in Figures 21 to 28, the current data do not form a good straight line with the previous data. The two data sets may not be exactly comparable. Especially for the box end sections with gratings the data from Reference 28 appeared to be more scattered in comparison to the current data. The strongest possibility however, is that some degree of nonlinearity may be present and that the empirical description given by Equation 22 is flawed. A linear correlation is most likely to be poor at lower velocities, since turbulence may not be fully developed, or when the water surface is close to the inlet. Rather than abnormally biasing the estimate of the entrance loss factor and because the designer is principally concerned with performance at higher flow rates and headwaters, a correlation using Equation 22 was performed for data taken above 5 feet per second.

Results for a linear least squares regression are summarized in Table 3 and are believed to be the most consistent and conservative design values. As would be expected from the previous discussion, all entrance loss factors were found to be higher than previously stated [28]. Qualitatively, the results agreed with the conclusions of Reference [28]. End section performance varied widely with design, the best performance exhibited by the flush end wall. The mitered treatment performed poorly. It was observed that the addition of grates had only a small deleterious effect on the performance of the inlet treatment. These results are reported in Table 3.

CONCLUSIONS AND RECOMMENDATIONS

In summary, the findings and recommendations of this investigation are as follows:

1. Correlations for the performance of open ended and grated culverts have been developed from experimental data. For design purposes, the correlations are collected in Tables 1, 2, and 3. In general it was found that the correlations developed in Reference 28 for outlet control are low compared to the extended data of this investigation. For conservative design it is recommended that the

higher values should be used. Some modest improvement may be gained from a continued study of entrance loss factors.

2. As a qualitative evaluation, the overall best performance was judged to be the 270 flared endsection because of the difficulty in producing inlet controlled operation. Although the loss factor for the type 250 endwall is more favorable, it is possible to operate the 250 endsection in inlet mode on a steep slope, giving poorer performance. It seems likely that the performance of the type 270 endsection is due to partial hooding of the inlet, which is known to have substantial benefits.

3. In general the effect of practical grates on the performance of inlet endsection treatments is small. In some cases, most notably the box endsections, capacity under weir control may be reduced. In other cases such as the mitered endsections with grates, the presence of the grate seems to accelerate the transition to outlet control. It is not recommended however, that designs rely on this effect. Previous studies [28] have indicated that the top bar may influence the flow for mitered end sections. These observations, combined with the results for the type 270 inlet indicate that it may be possible to retrofit or redesign the upper portion of the mitered end section to both improve the discharge and also to force an outlet control mode. Because of the wide application of mitered endsections, it is recommended that a study of possible modifications be conducted.

4. Based on the observations made in this investigation concerning the use of a vortex suppressor, it can be stated that the suppressor does in fact act to reduce or eliminate the entrance vortex. However, it does not appear that reduction of the vortex has a noticeable effect on performance, at least over the range on the data taken in the current work.

5. The effect of inlet blockage was found to be highly variable. In general modest accumulation can be tolerated, but substantial build up can lead to added losses under outlet control and reduced discharge coefficients for inlet control.

6. It does not appear that the outlet endsection treatment is particularly critical, assuming that blockage with debris does not occur. It is however noted that numerous investigations have pointed out the benefit of designs that promote partial head recovery when running a submerged discharge under outlet control.

REFERENCES

1. Yarnell, D.L., Nagler, F.L., and Woodward, S. M., "The Flow of Water Through Culverts", Bulletin 1, Univ. of Iowa Studies in Engrg., Iowa City, Iowa, 1926

2. Mavis, F. T., "The Hydraulics of Culverts", Bulletin 56, Engrg. Experiment Sta., Penn. State Coll. University Park, Pa., 1942

3. Bossy, H.G., "Hydraulics of Conventional Highway Culverts", Tenth National Conference, Hydraulics Division, ASCE, August, 1961

4. Blaisdell, F. W., "Flow in Culverts and Related Design Philosophies", J. Hydraulics Division, Proceedings ASCE, Vol. 92 No. HY2, March 1966, pp. 19-31

5. Straub, L.G., Anderson, A. G., and Bowers, C. E., "Importance of Inlet Design on Culvert Capacity, with Discussion and Closure", Highway Research Board Research Report 15-B, pp. 53-71 Washington, D. C., 1953

6. Schiller, R. E., "Tests on Circular-Pipe-Culvert Inlets", Highway Research Board, Bulletin 126, 1955 (see also discussion pp. 20-22)

7. French, J.L., "Hydraulic Characteristics of Commonly Used Pipe Entrances", National Bureau of Standards Report, No. 4444, Washington, D.C. 1956

8. Blaisdell F. W.,"Hood Inlet for Closed Conduit Spillways", J. Hydraulics Division, Proceedings ASCE, Volume 128 1963 Part I, p1-25 (see also discussion following)

9. French, J.L. "Tapered Inlets for Pipe Culverts", J. Hydraulics Division, Proceedings ASCE, Vol 90, No. Hy2 March 1964, pp.255
see also discussion HY6 p315

10. Harrison, L.J., et.al., "Hydraulic Design of Improved Inlets for Culverts", HEC No.13, Federal Highway Administration, August, 1972, 172 p.

11. Normann, J.M.,"Improved Design of Highway Culverts", Civil Engineering -ASCE, March 1975

12. Smith, C.D., "Culvert End Treatment to Improve Hydraulic Performance", Proceedings, 1982 Annual Conference - Canadian Society for Civil Engineering. (Volume 3: Hydrotechnical, Municipal Environment, Computer Applications.

13. Piehl, B.T., Pyles, M.R., and Beschta, R.L., "Flow Capacity of Culverts on Oregon Coast Range Forest Roads", Water Resources Bulletin, Vol. 24, No. 3, June 1988

14. Herr, L.A., and Bossy H.G., "Capacity Charts for the Hydraulic Design of Highway Culverts", HEC 10, U.S. Department of Commerce, Washington, D.C., March 1965

15. Herr, L.A., and Bossy, H.G., "Hydraulic Charts for the Selection of Highway Culverts", HEC No. 5, Federal Highway Administration, Dec 1965, 54p.

16. Normann, J.M, Houghtalen, R.J. and Johnston, W. J., "Hydraulic Design of Highway Culverts", Hydraulic Design Series No. 5, Report No. FHWA-IP-85-15, Sept. 1985

17. Young, G. K., and Krolak, J. S., HYDRAIN - INTEGRATED DRAINAGE DESIGN COMPUTER SYSTEM, VOLUME 1-5 FHWA-RD-88-120, NTIS, NOV 1987

18. CDS - CULVERT DESIGN SYSTEM, Wyoming State highway department Hydraulics section, January, 1980, 181p.

19. anon., "Safety Treatment of Roadside Drainage Structures", Transportation Research Record N868, 1982 12p.

20. anon.,"Traffic-Safe and Hydraulically Efficient Drainage Practice", Highway Research Board NCRP Synthesis of Highway Practice, No. 3, 1969, 38p.

21. Ross, H.E., and Post E.R., "Tentative Criteria for Design of Safe Sloping Culvert Grates Highway Research Record, Highway Research Board N386, 1972, pp. 101-10 (also "Criteria for the Design of Safe Sloping Culvert Grates", Research Report 140-3, Texas Transportation Institute, Texas A&M University, College station, TX, Aug 1971)

22. Kohutek, T.L., and Ross H.E, "Safety Treatment of Roadside Culverts on Low Volume Roads", Research Report No 225-1, FHWATX77-225-1, Texas Transportation Institute, Texas A&M University, College Station, TX. March 1978

23. Davis, C. V., Handbook of Applied Hydraulics, McGraw-Hill Book Co., New York, N.Y., 1952

24. Reihsen, G. and Harrison, L.J., Debris Control Structures, HEC 9, Federal Highway Administration, March, 1971, 38 p.

25. Mays, L.W., Walker, M.E., Bennett, M.S., and Arbuckel, R.P., "Hydraulic Performance of Culverts with Safety Grates" Research Report No. 301-1F, FHWA/TX-82/55+301F, Center for Transportation Research, Bureau of Engineering Research, University of Texas, Austin, March 1983, 342 p.

26. Magenis, S.E., "Trash Screens on Culverts in Urban Areas", Journal of the Institution of Water and Environment Management, Vol. 2, No. 5. Oct 1988 pp 476-484

27. Weisman, R.N., "Model Study of Safety Grating for Culvert Inlet", Journal of Transportation Engineering, Vol. 115, No. 2, March, 1989, pp 130-138

28. Kranc, S.C., Anderson, M.W., and Villalon A.A., "An Investigation of the Hydraulic Performance of Culvert Grates", Florida Department of Transportation Report, Project No. 99700-7452-010, June 1989

29. Pagan, A. R., Screening Devices for Hydraulic Structures, Better Roads (undated)

30. Cottman, N. H., "Experiences in the Use of Minimum and Constant Energy Bridges and Culverts", Conference on Hydraulics in Civil Engineering, Sydney, Australia, Oct. 1981

31. Kells, J.A. and Smith, C. D., "Head Losses at Abrupt Pipe Outlets",Proceedings - Canadian Society for Civil Engineering, Fifth Canadian Hydrotechnical Conference, 1981, pp. 741-759

32. Apelt, C.J., "Hydraulics of Minimum Energy Culverts and Bridge Waterways", Civil Engineering Transactions, 1983, pp. 89-95

33. Laliberte, G.E., Shearer, M.N., and English, M.J., "Design of Energy-Efficient Pipe-Size Expansion", Journal of Irrigation and Drainage Engineering, Vol 109, No. 1, March, 1983, pp 13-28

34. Simon A. A., Practical Hydraulics, 2nd ed. Wiley, 1981

35. Olsen, R. M., Essentials of Engineering Fluid Mechanics, 4th ed., Harper Row, 1980

36.Metzler, D.E., Rouse, H., "Hydraulics of Box Culverts", Bulletin 38, State University of Iowa Studies in Engineering, Iowa City, Iowa, 1959

37. Roadway and Traffic Design Standards, Florida Department of Transportation, 1990

Table 1: Correlations for weir control

ENDSECTION	DATA CORRELATION			
	CURRENT (Eqn.13)		Ref.16 (Eqn.12)	
	m	K	m	K
250 ENDWALL	0.61	0.50	2.50	0.0018
272 MITERED	0.62	0.52	1.33	0.0210
270 FLARED	0.61	0.51	--	--
260 BOX	0.59	0.54	--	--
261 BOX	0.56	0.56	--	--

Table 2: Correlations for orifice control

ENDSECTION	DATA CORRELATION			
	CURRENT (Eqn.15)		Ref. 16 (Eqn.15)	
	C	Y	C	Y
250 ENDWALL	0.030	0.733	0.0300	0.74
272 MITERED	0.046	0.598	0.0463	0.75
270 FLARED	0.010	1.062	--	--
260 BOX	0.048	0.487	--	--
261 BOX	0.048	0.487	--	--

Table 3: Entrance endsection loss factors - K_e

ENDSECTION	DATA CORRELATION		
	CURRENT	Ref. 28	Ref. 16
250 ENDWALL	0.22	0.18	0.2
272 MITERED	0.75	0.57	0.7
273 MITERED GRATE	0.73	0.55	--
270 FLARED	0.41	0.27	--
260 BOX	0.66	0.33	--
260 BOX GRATE	0.62	0.34	--
261 BOX	0.64	0.47	--
261 BOX GRATE	0.67	0.51	--

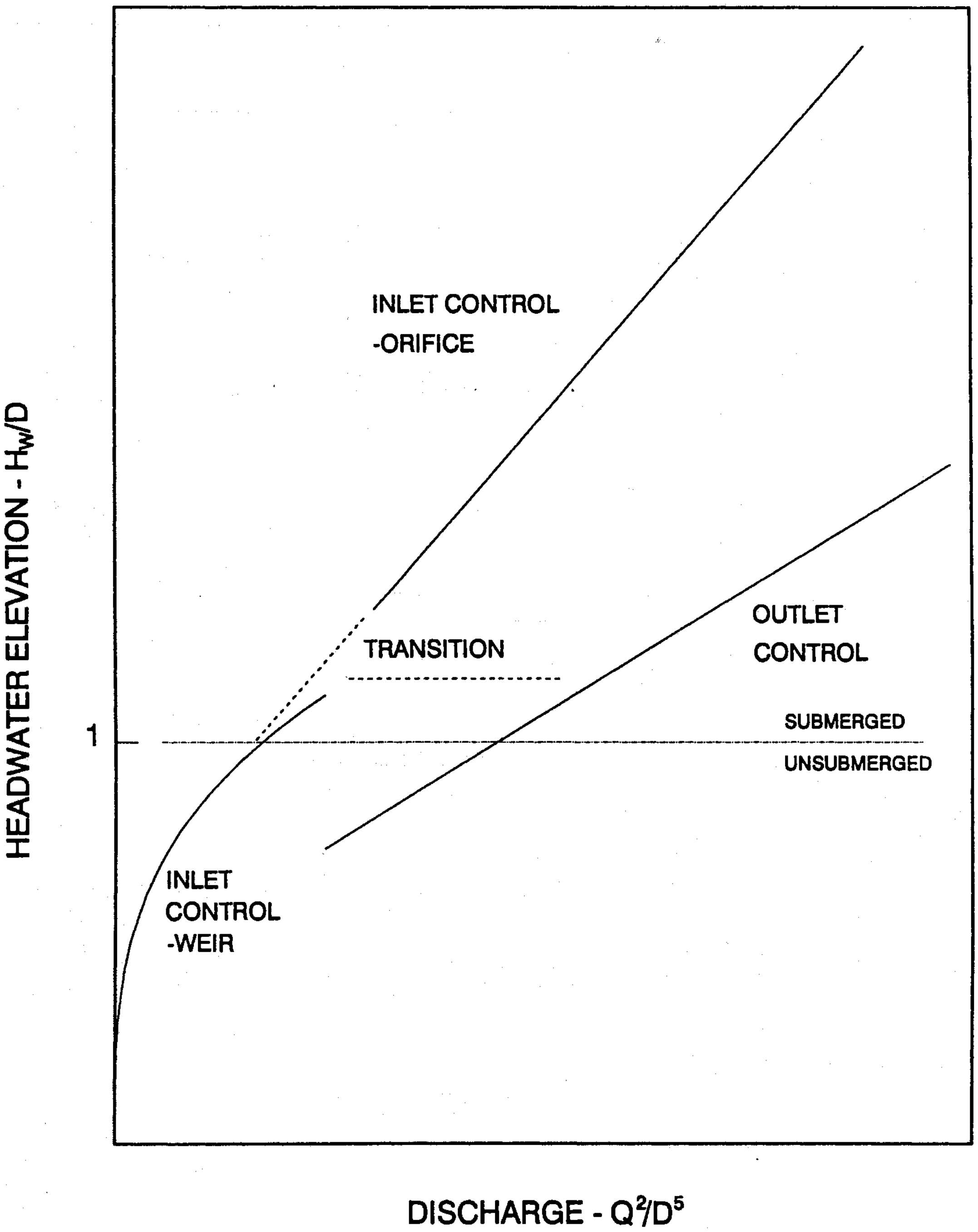
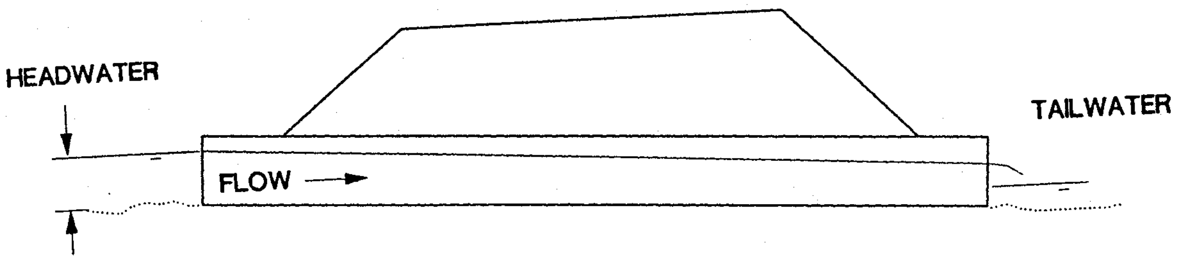
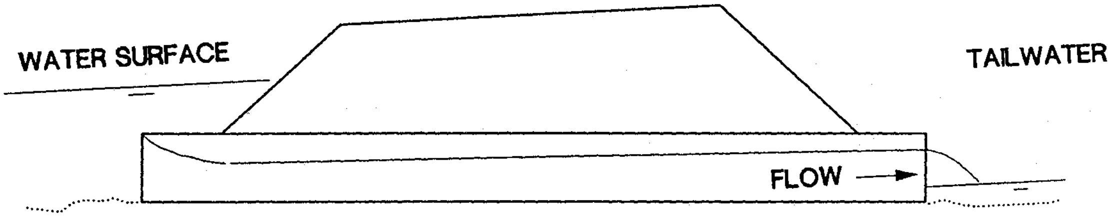


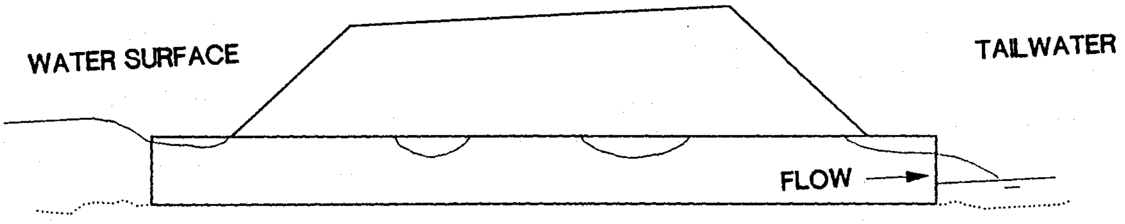
Figure 1: Regimes of culvert operation appropriate to this study. Nondimensional headwater elevation is displayed as a function of the discharge parameter given by Equation 17.



a) WEIR FLOW

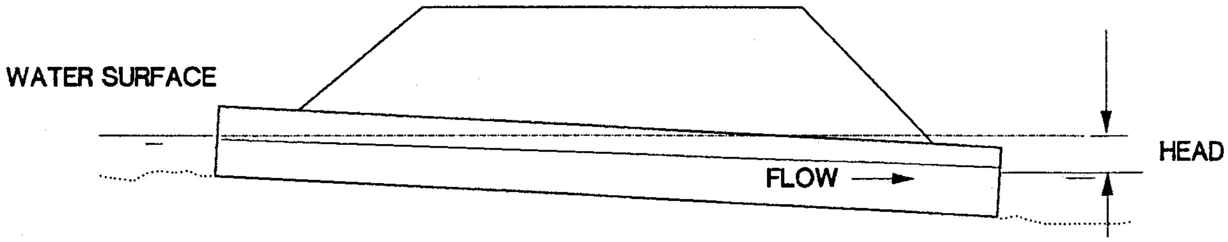


b) ORIFICE FLOW

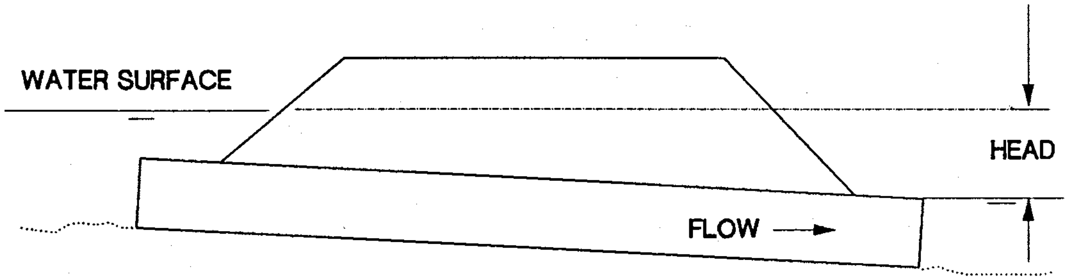


c) SLUG FLOW

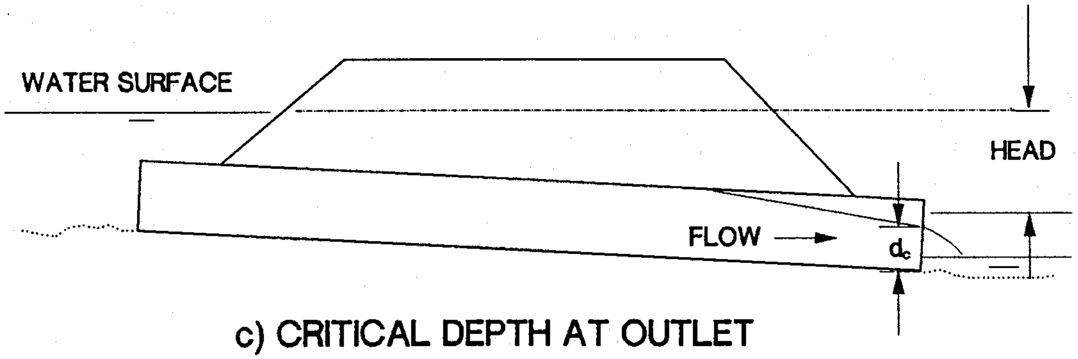
Figure 2: Illustration of three modes of inlet control relevant to the experiments reported here. Downstream water level in all cases is less than critical depth at the exit.



a) OUTLET UNSUBMERGED

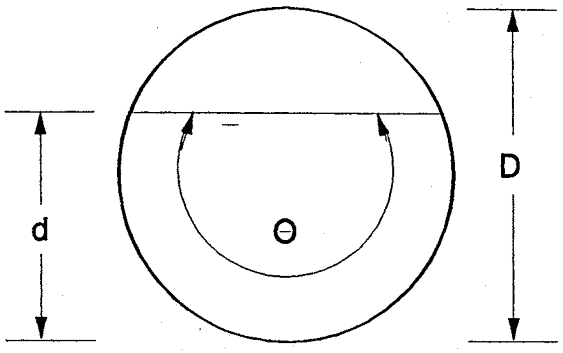


b) OUTLET SUBMERGED

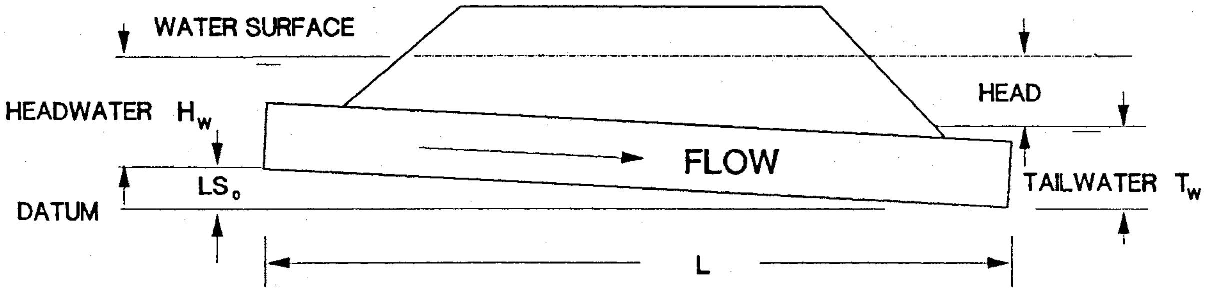


c) CRITICAL DEPTH AT OUTLET

Figure 3: Illustration of three modes of outlet control relevant to the experiments reported here. Subcritical free surface flow is shown in a). In b) the tailwater is held at the outlet overt and in c) the discharge is critical and the downstream water level is less than the critical depth at the exit. In this case the effective tailwater is computed according to Equation 10.



a) CULVERT BARREL



b) CULVERT ELEVATION

Figure 4: Notation and definitions for analytical formulation. In a) an end view of the culvert barrel is shown flowing partially full. Figure b) shows the relationship between the elevation of the culvert, the slope and the water level. The outlet invert is taken as the datum.

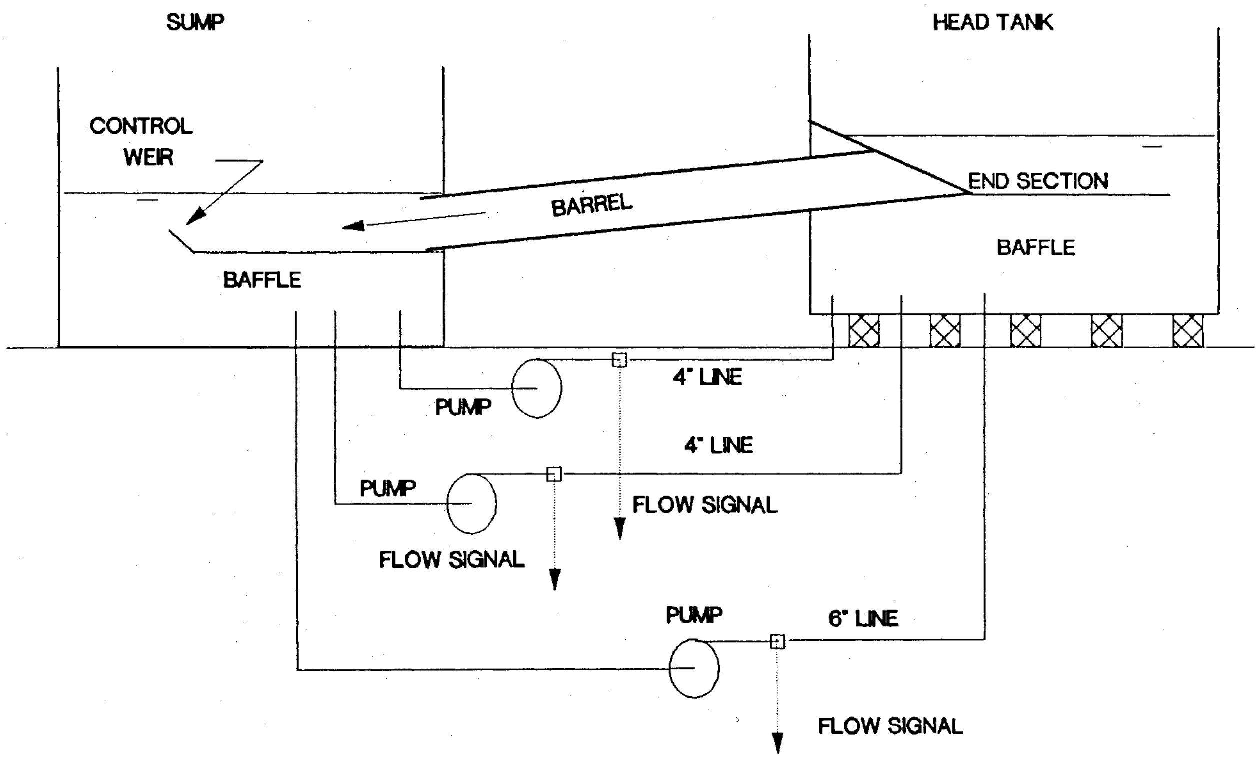


Figure 5: Schematic diagram of the experimental facility.

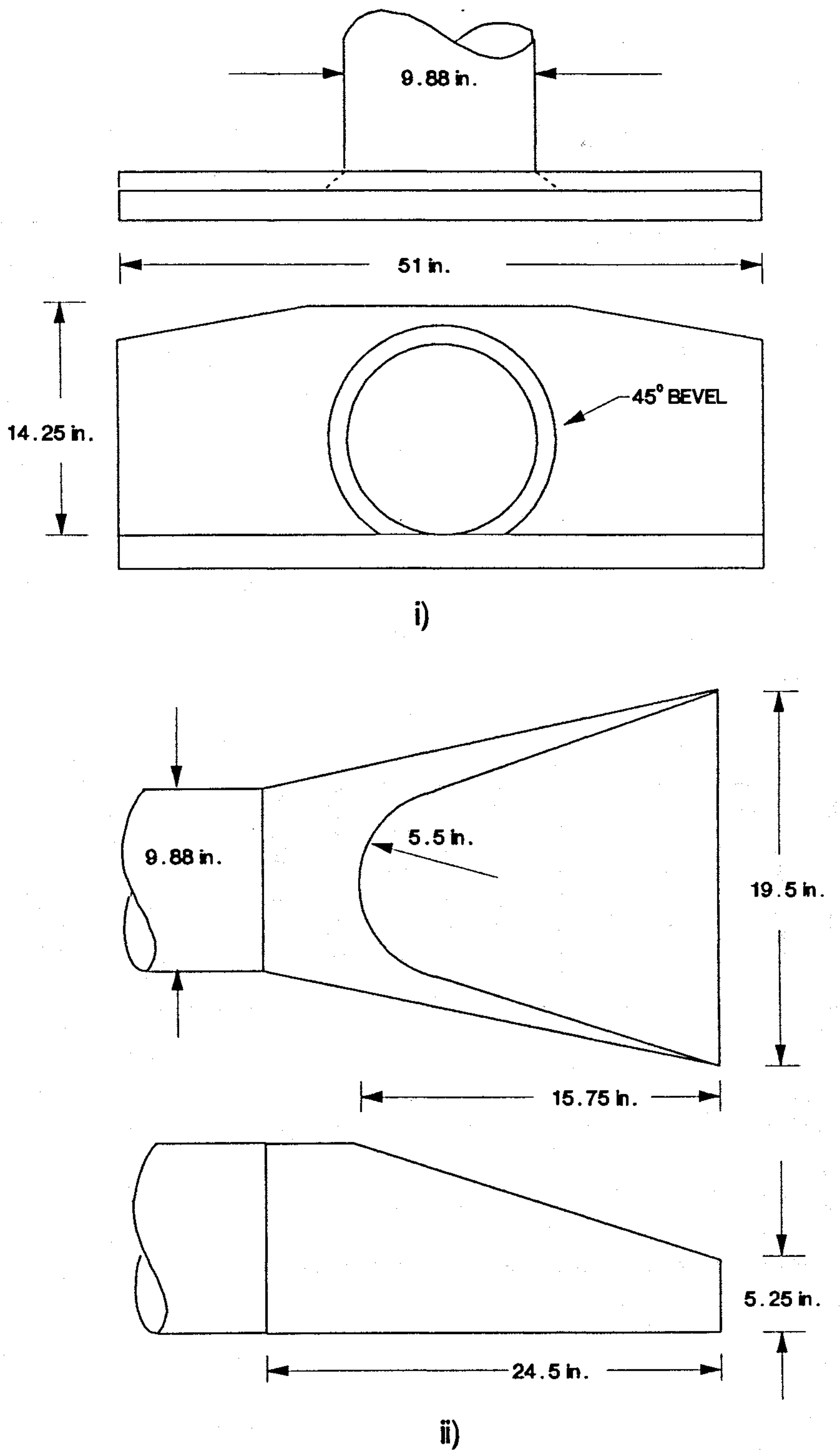


Figure 6a: Model endsections: i) type 250 straight endwall, ii) type 270 flared endsection. Model geometric ratio 1:4, not drawn to scale (cf. Ref. 37 for detail).

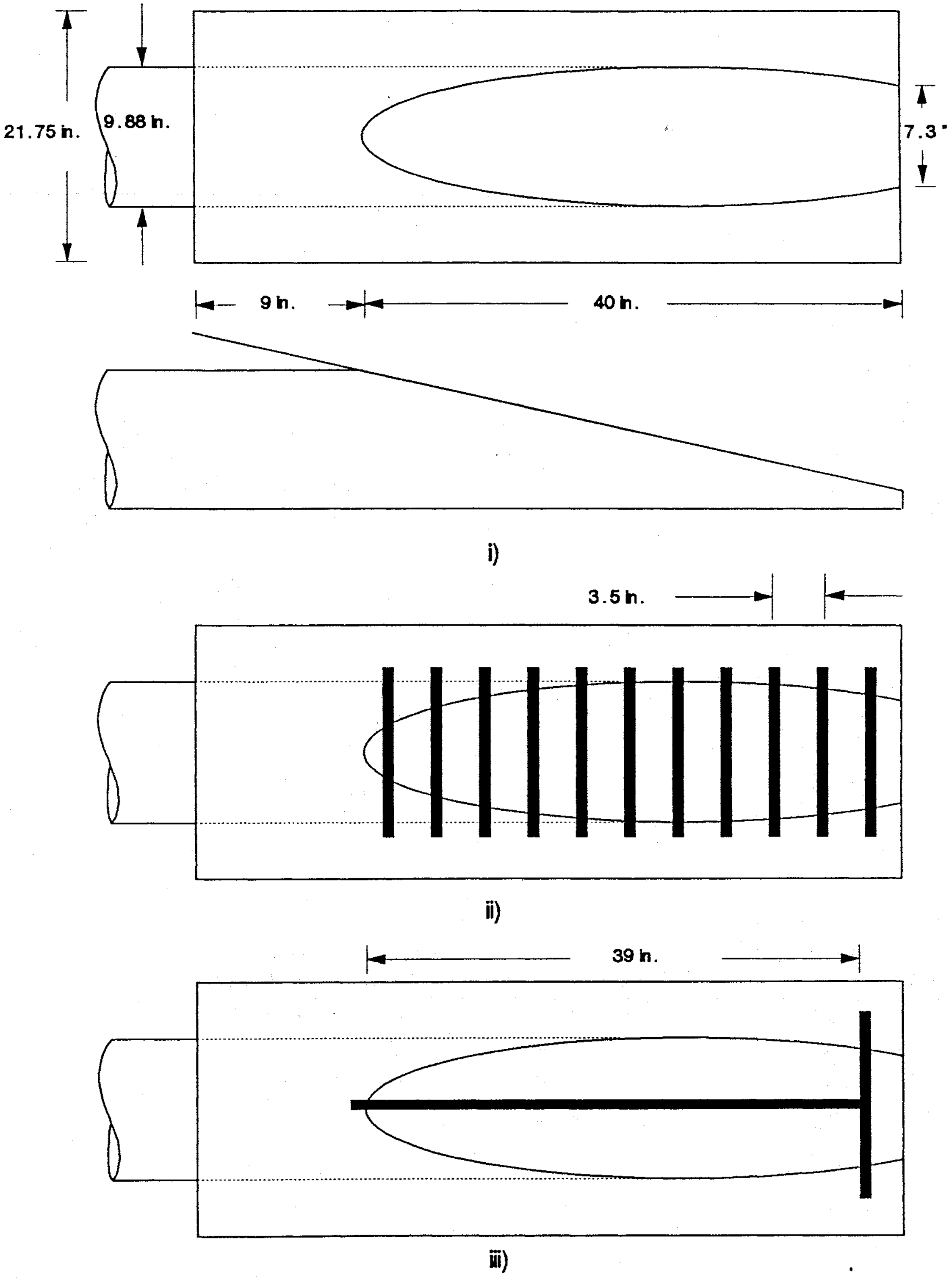
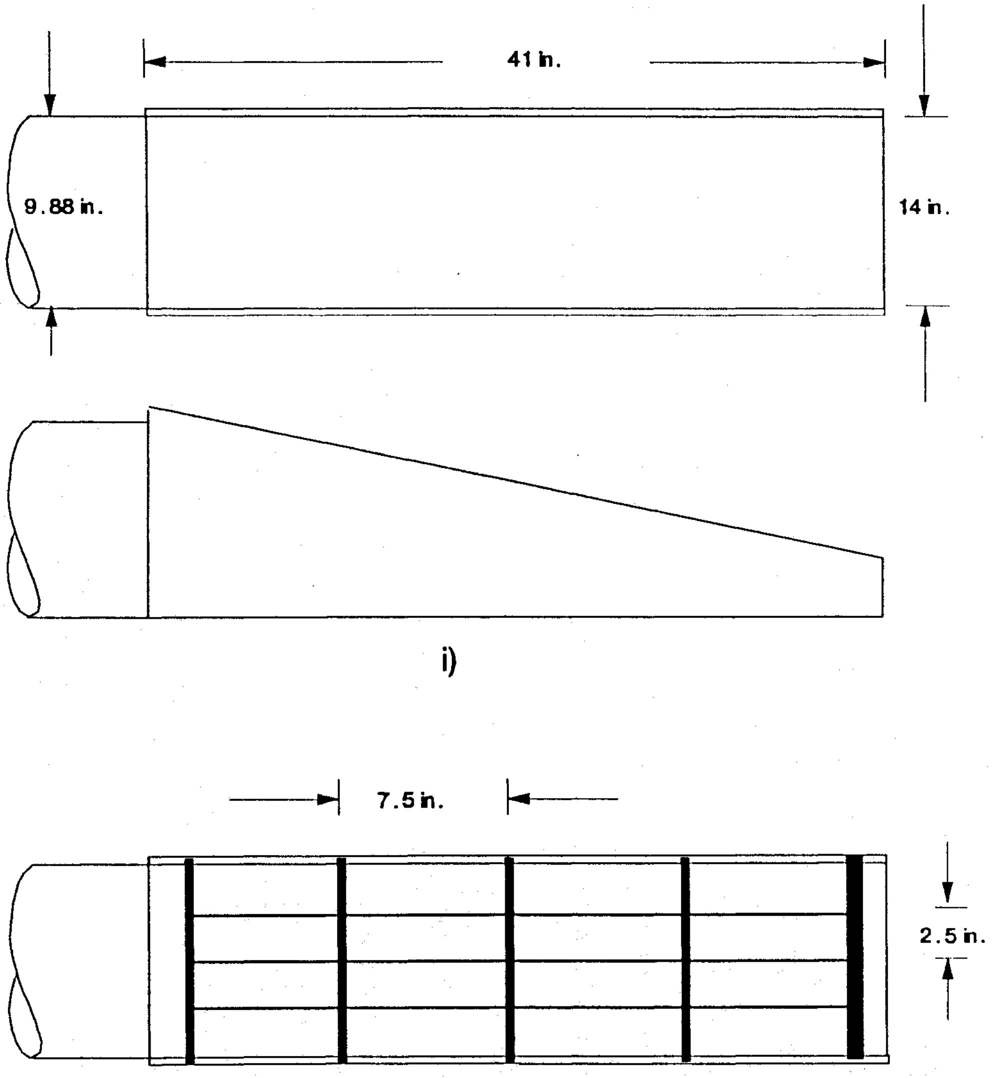


Figure 6b: Model endsection: i) type 272 mitered endsection, ii) type 273 mitered endsection with transverse grate, iii) type 272 fitted with T-bar grate. Model geometric ratio 1:4, not drawn to scale (cf. Ref. 37 for detail).



i)

ii)

Figure 6c: Model endsection i) type 260 box end section, ii) type 260 with grate. Model geometric ratio 1:3, not drawn to scale (cf. Ref. 37 for detail).

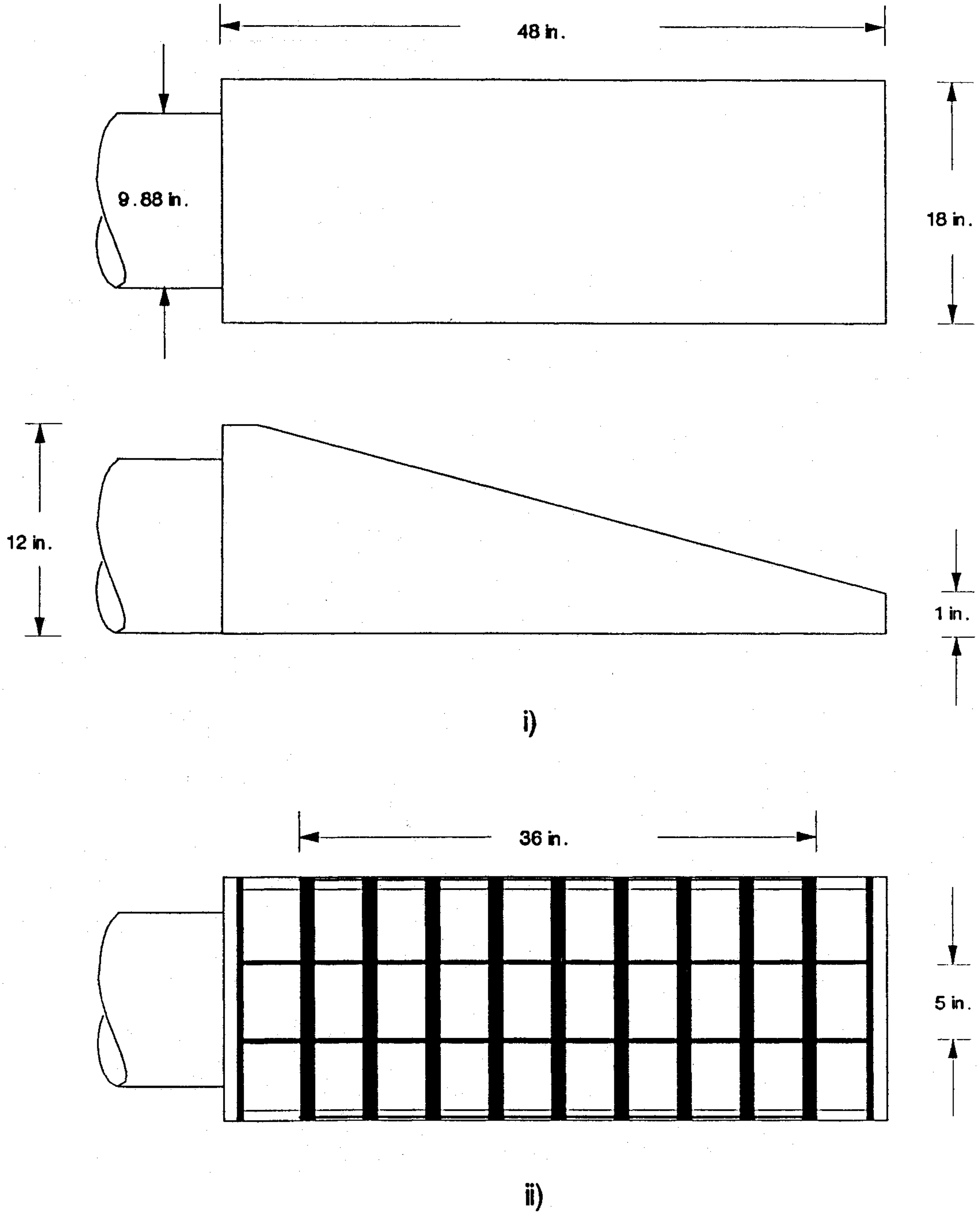


Figure 6d: Model endsection i) type 261 box end section, ii) type 261 with grate. Model geometric ratio 1:3, not drawn to scale (cf. Ref. 37 for detail).

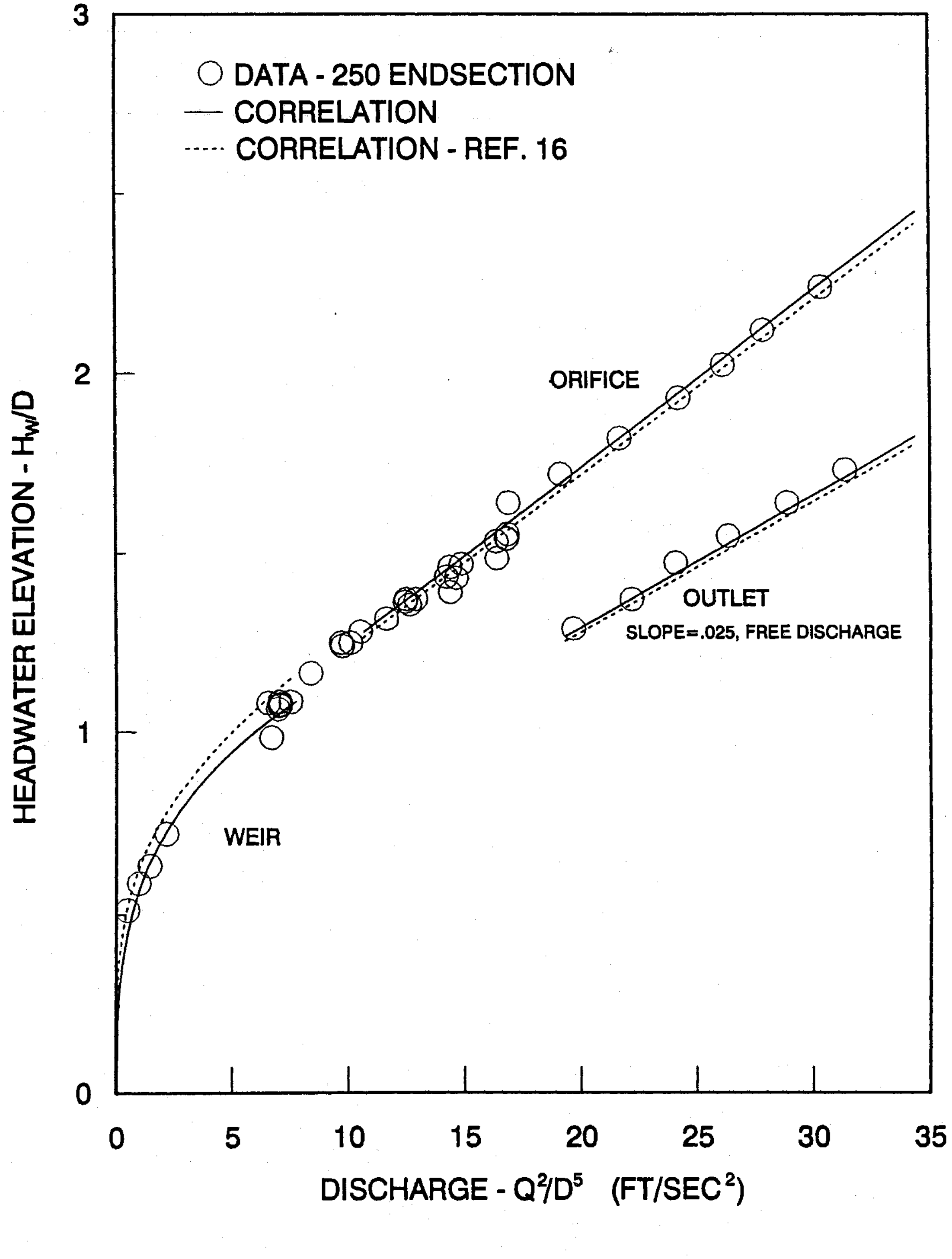


Figure 7: Nondimensional headwater elevation as a function of discharge parameter for the type 250 endwall endsection with beveled entrance. All data taken at .025 slope. Correlations based on composite data of Ref. 16 shown as dotted lines.

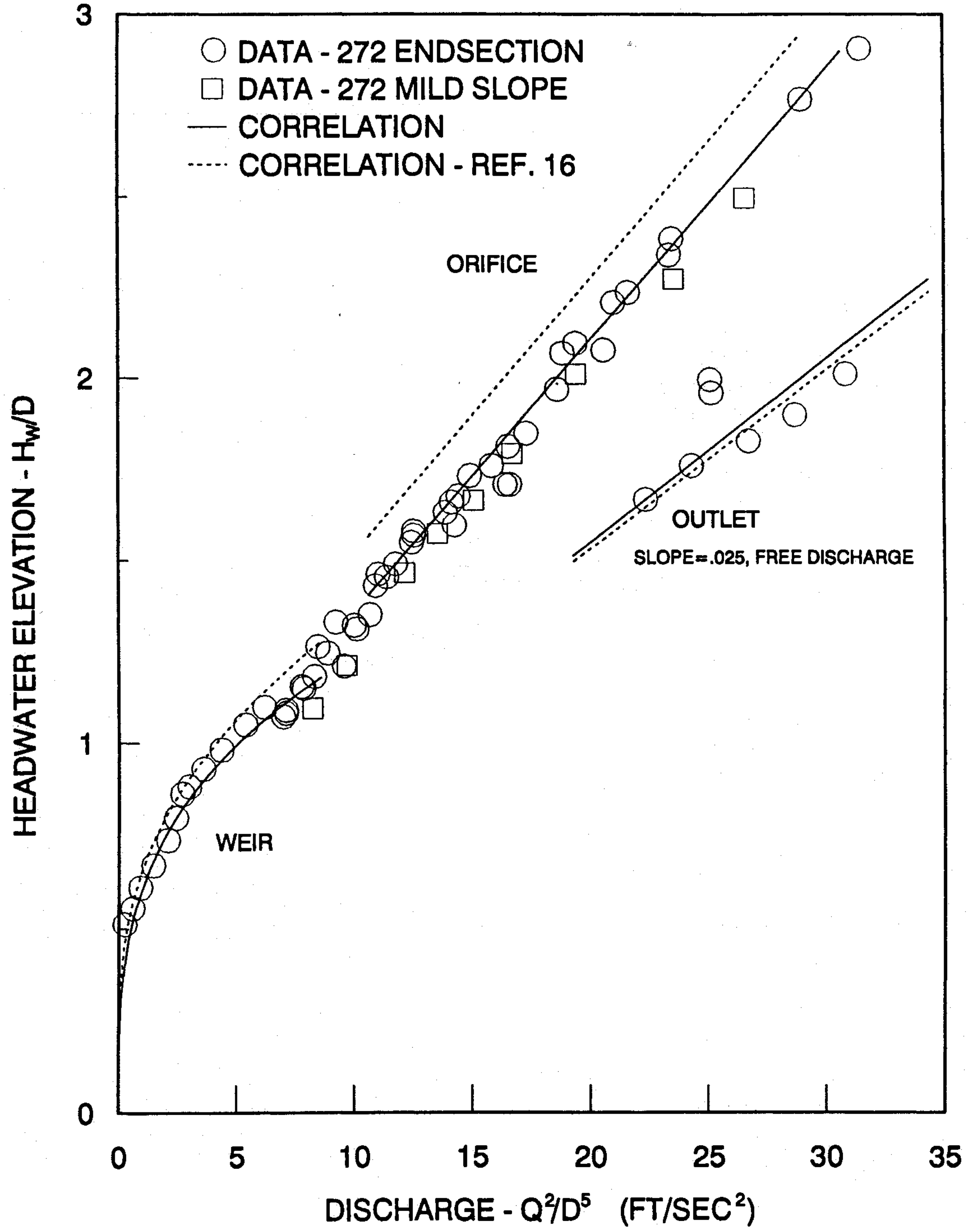


Figure 8: Nondimensional headwater elevation as a function of discharge parameter for the type 272 mitered endsection. Correlations shown as solid lines are for data taken at .025 slope. Data taken at .0028 slope are shown for comparison. Correlations based on composite data of Ref. 16 shown as dotted lines.

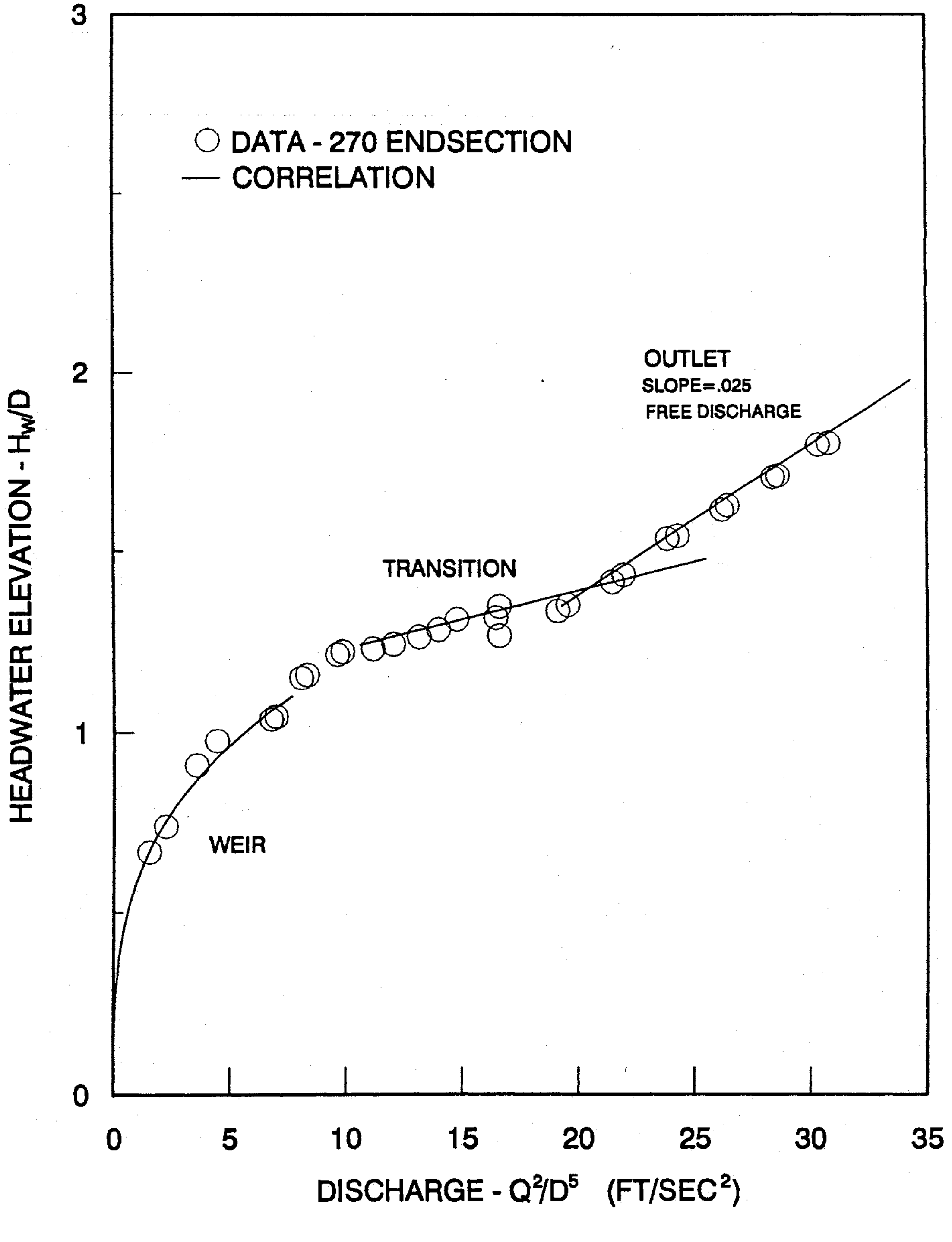


Figure 9: Nondimensional headwater elevation as a function of discharge parameter for the type 270 flared endsection. Data taken at .025 slope. Note the transitional zone between weir control and outlet control regimes.

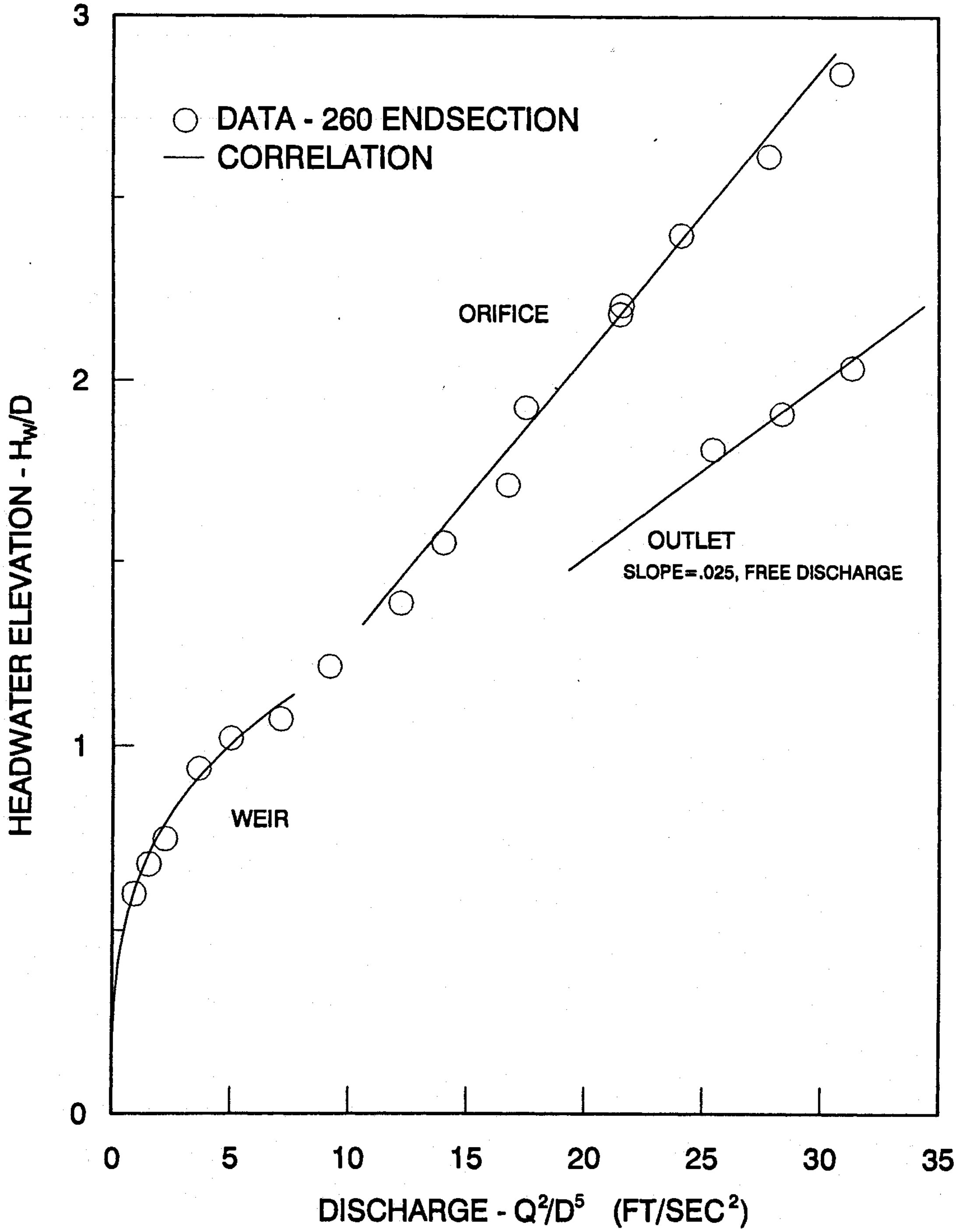


Figure 10: Nondimensional headwater elevation as a function of discharge parameter for the type 260 box endsection.

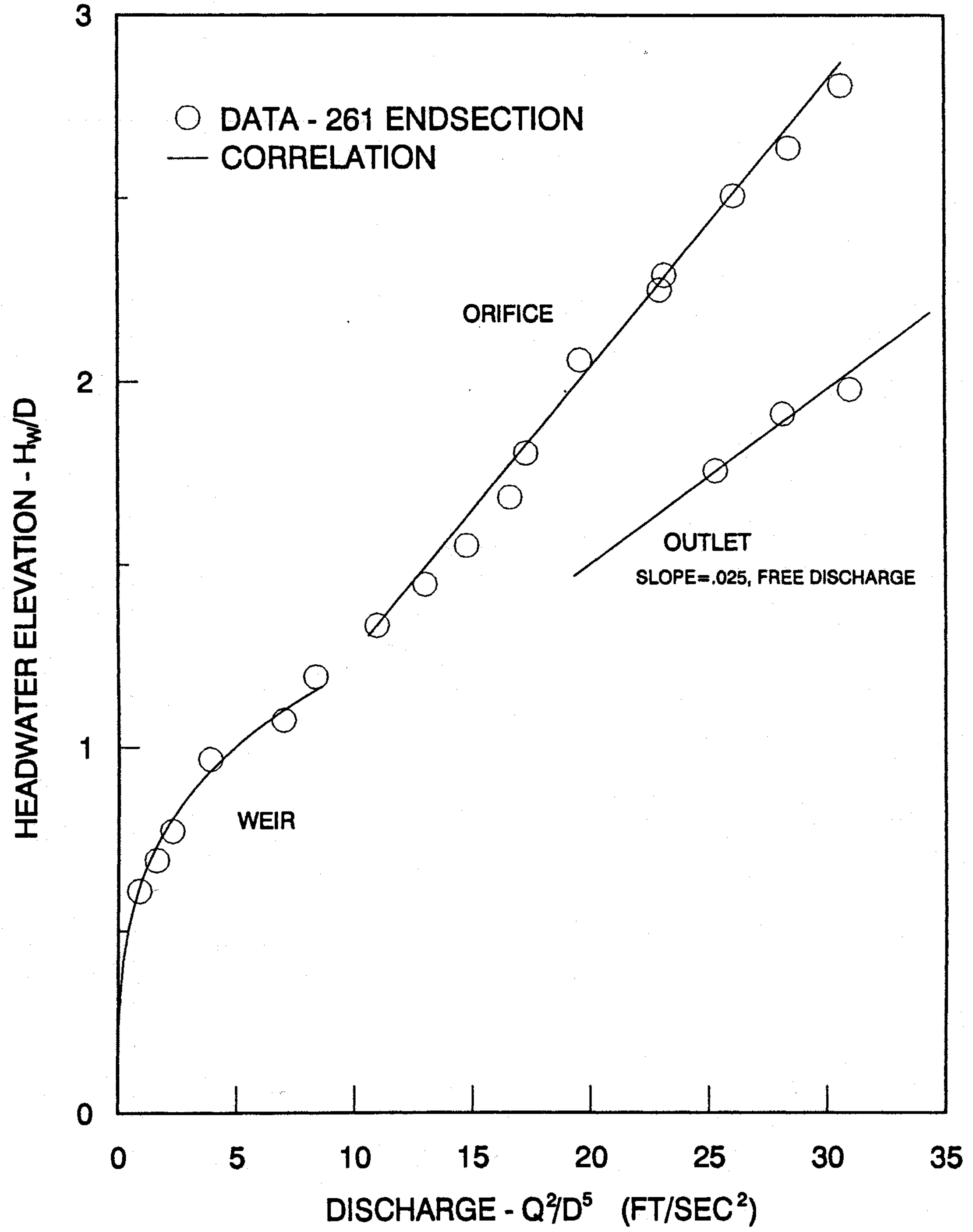


Figure 11: Nondimensional headwater elevation as a function of discharge parameter for the type 261 box endsection.

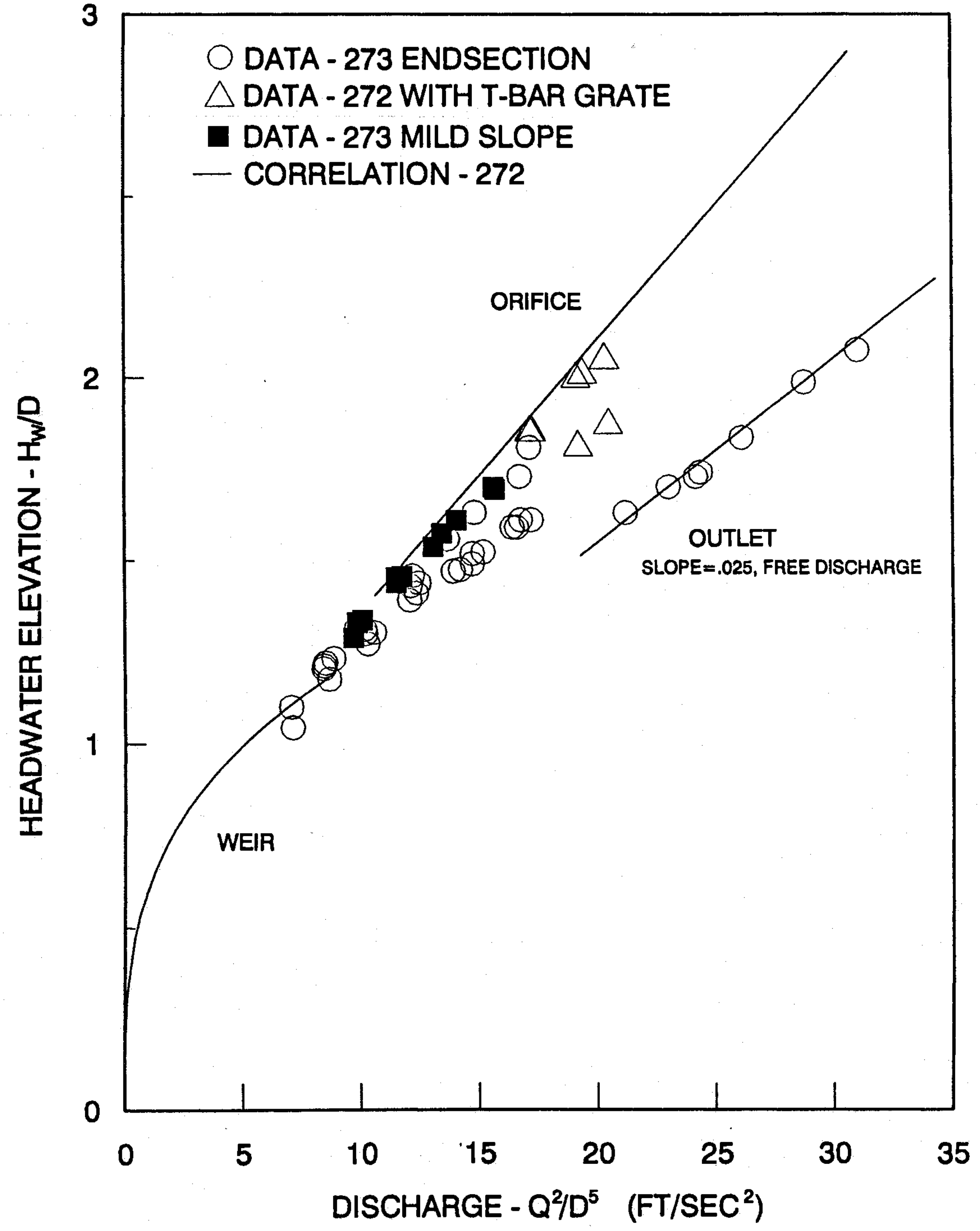


Figure 12: The effect of added grates on the performance of mitered endsections. Standard 273 mitered endsection on .025 slope and .0028 slope are shown along with a modified T-bar grate. Correlations for the 272 mitered endsection are shown for comparison.

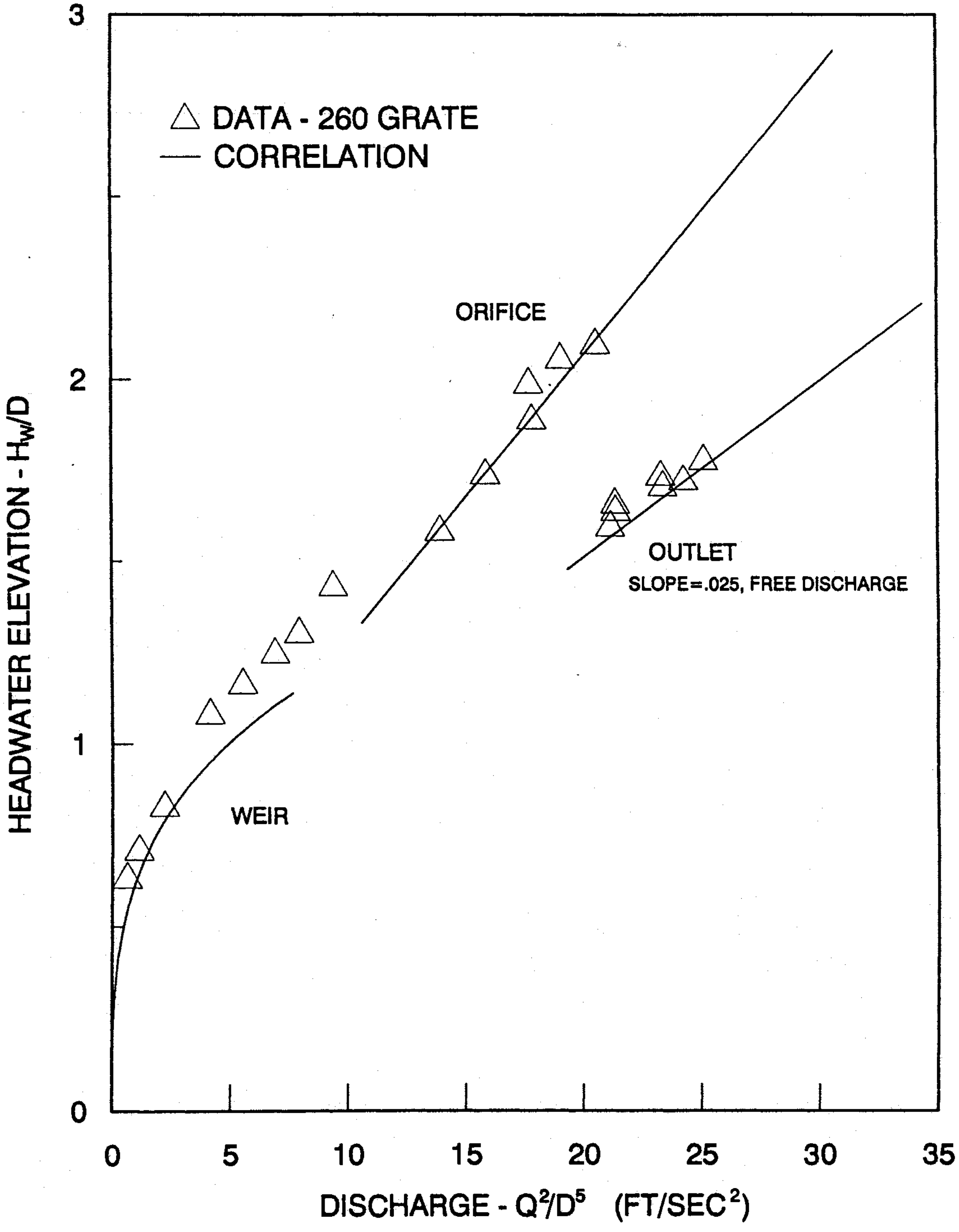


Figure 13: The effect of added grates on the performance of the type 260 box endsection operated at .025 slope. Grating is standard design, rectangular bar. Correlations for the type 260 endsection are shown for comparison.

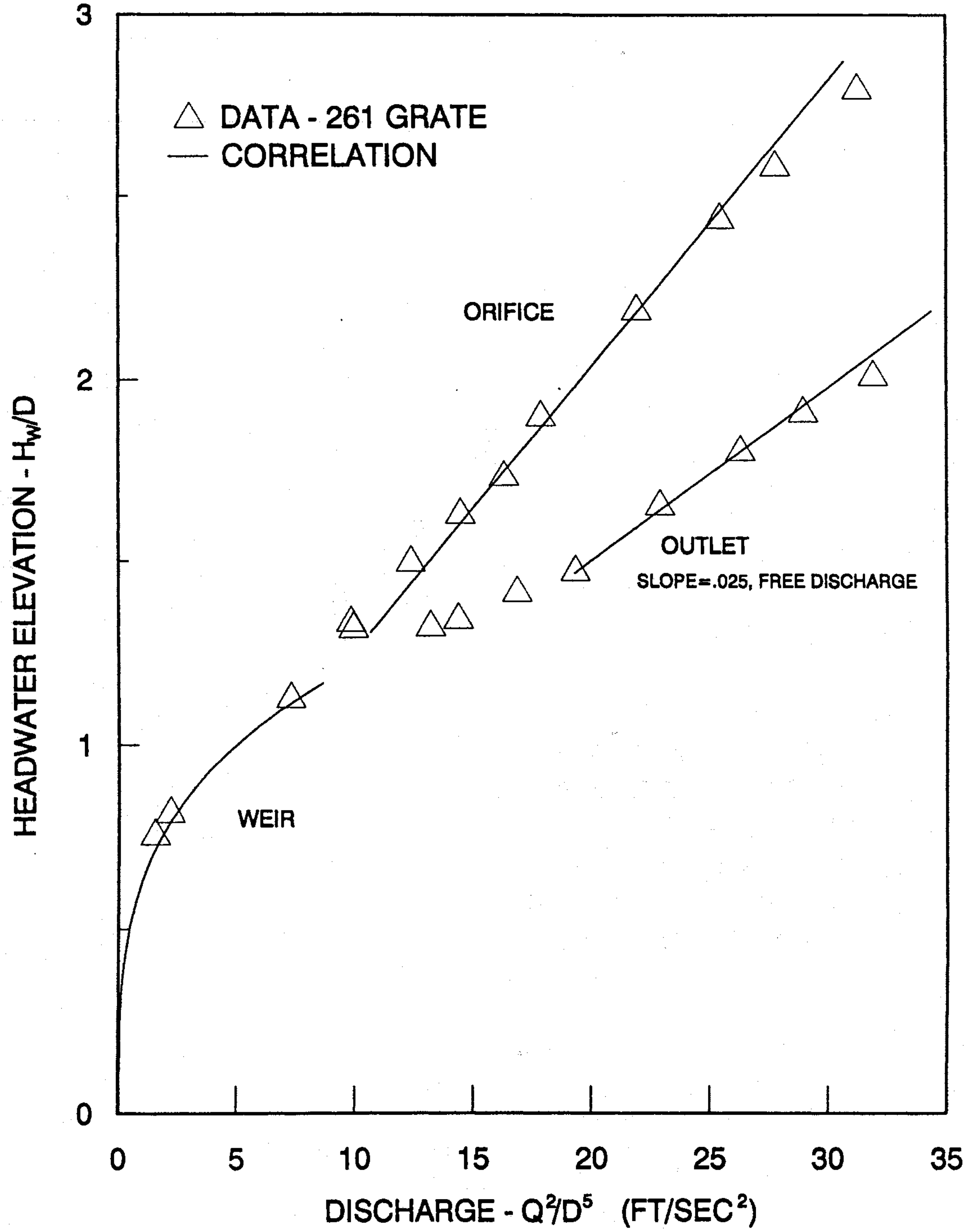


Figure 14: The effect of added grates on the performance of the type 261 box endsection operated at .025 slope. Grating is standard design, rectangular bar. Correlations for the type 261 endsection are shown for comparison.

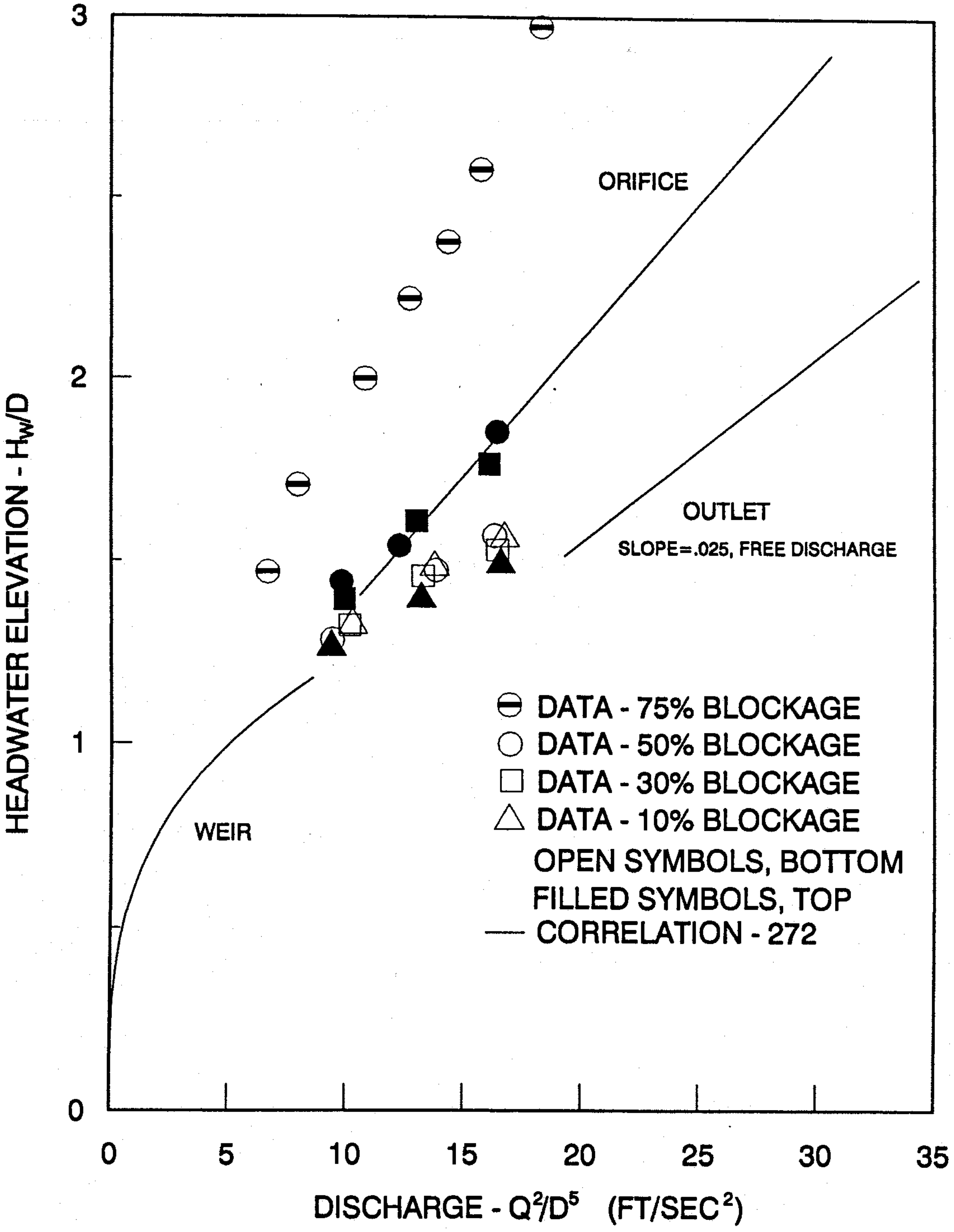


Figure 15: Effect of blockage on the performance of the type 273 mitered endsection. Open symbols denote blockage located at the bottom of the endsection, filled symbols denote top location. Correlations for the type 272 endsection are shown for comparison. Note the shift in control point with 75% blockage at bottom.

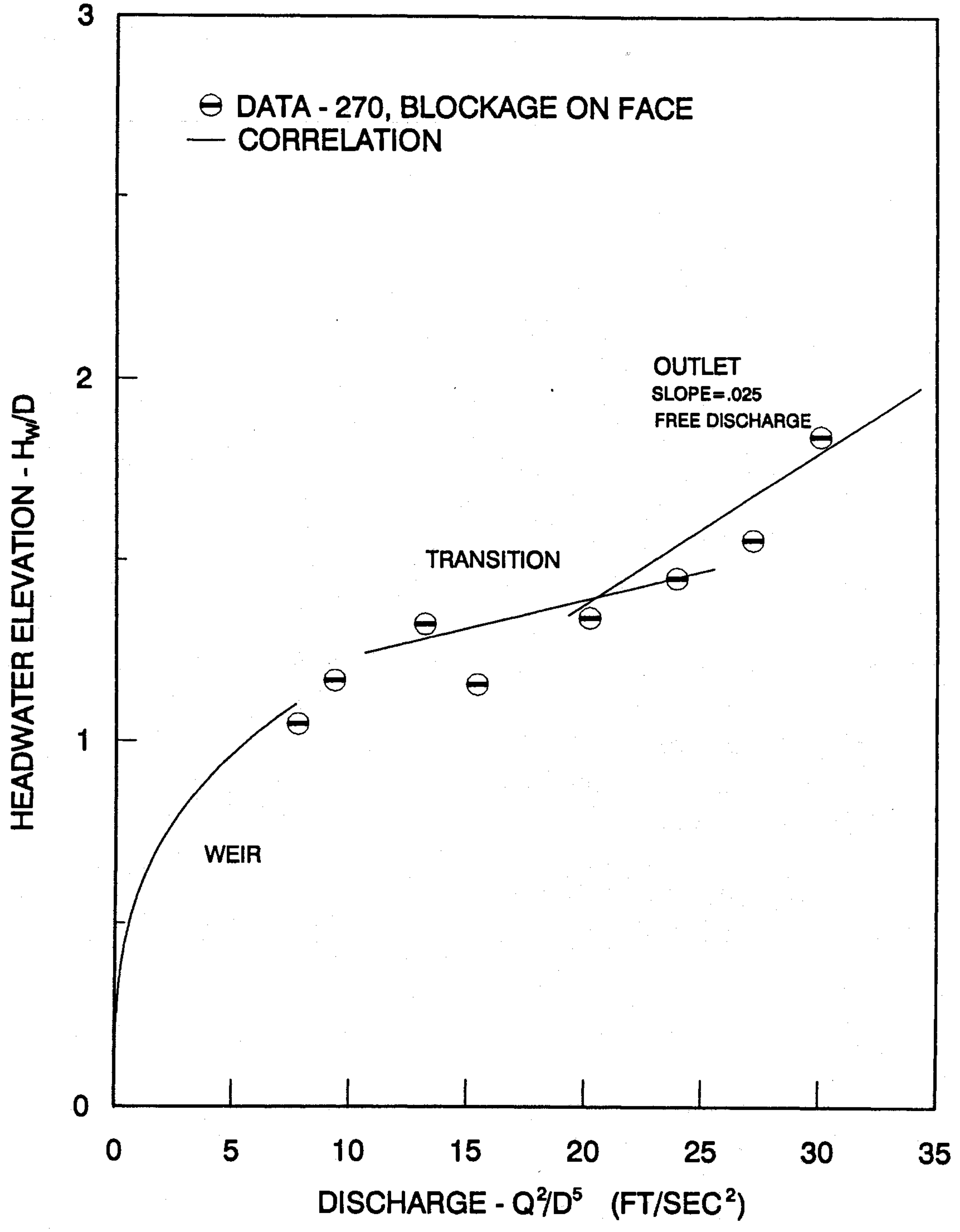


Figure 16: Effect of blockage on the performance of the type 270 flared endsection. Blockage covers sloped face of endsection. Correlations for the type 270 endsection shown for comparison.

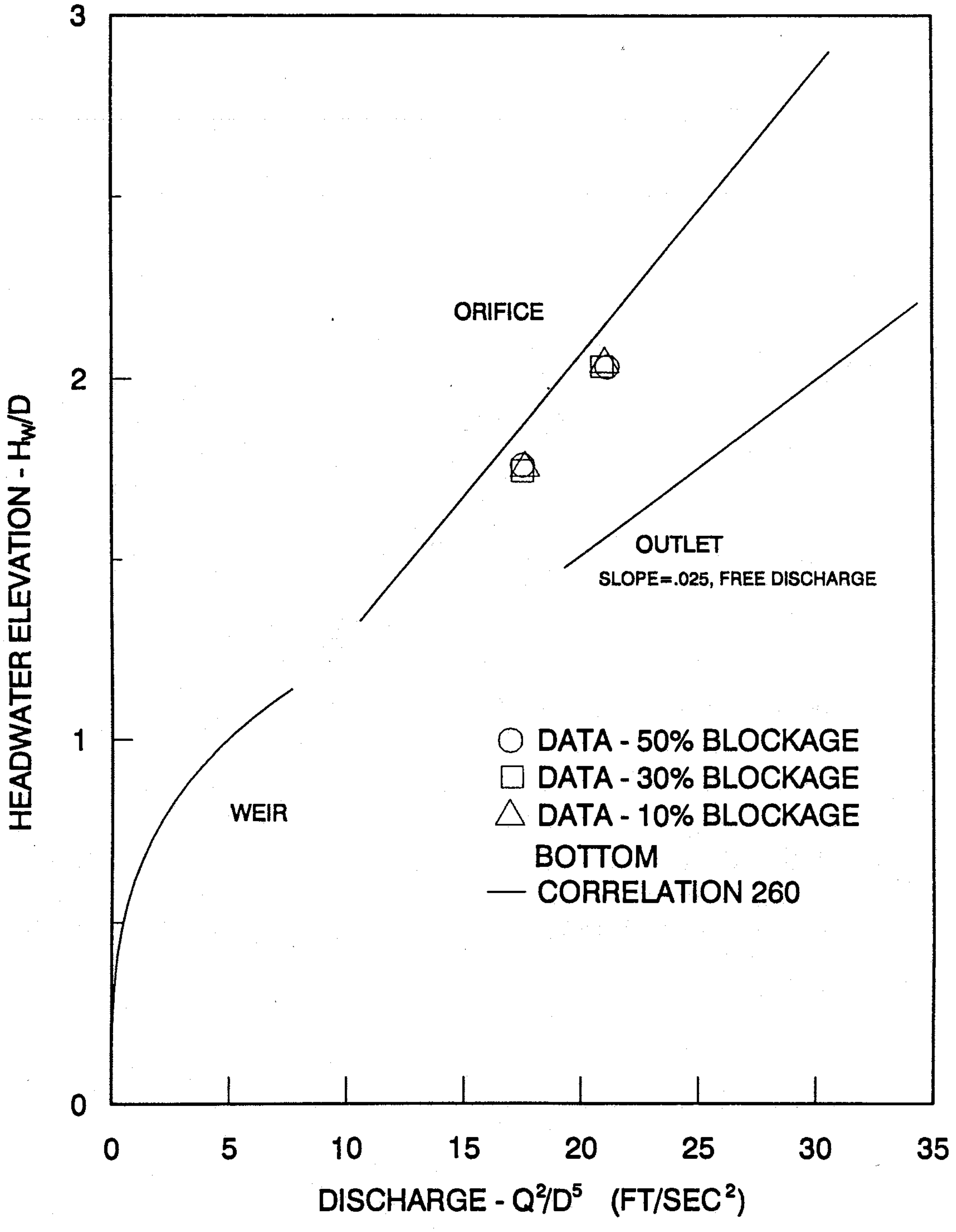


Figure 17: Effect of blockage for the type 260 box endsection with correlations for this endsection shown for comparison. Blockage located at bottom of endsection.

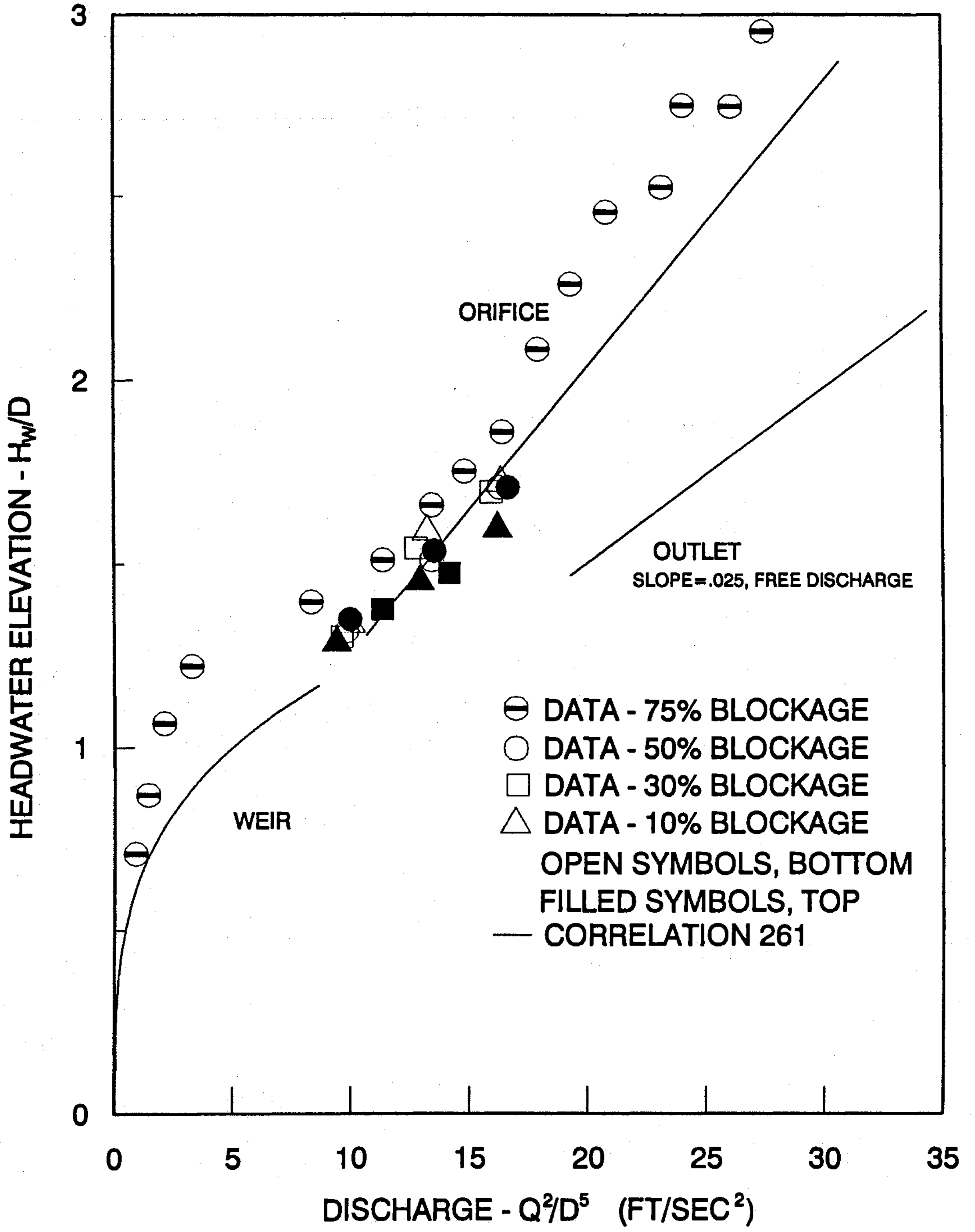


Figure 18: Effect of blockage for the type 261 box endsection with correlations for this endsection shown for comparison. Open symbols denote blockage located at the bottom of the endsection, filled symbols denote top location. Note shift in control point for 75% blockage at bottom.

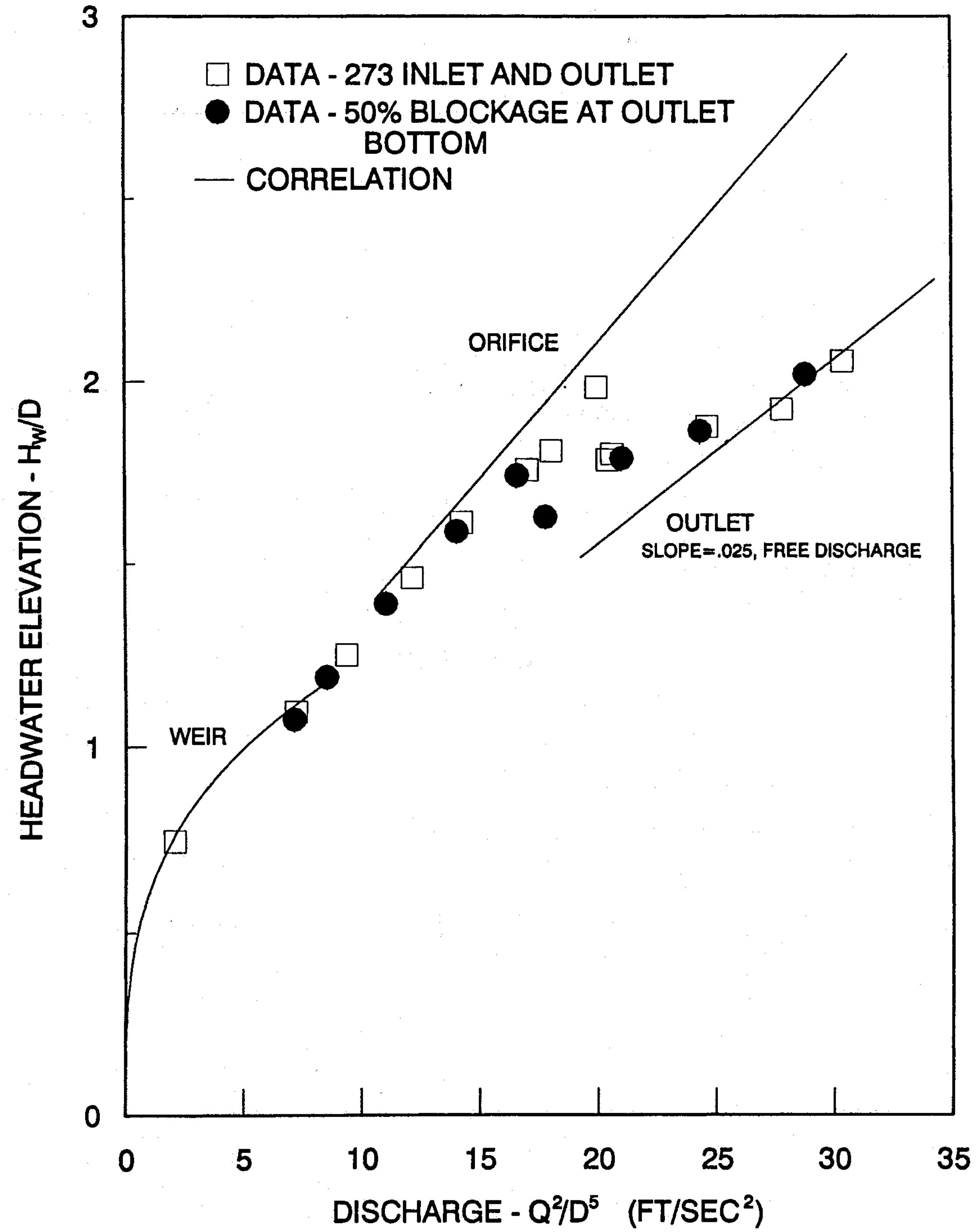


Figure 19: Performance of culvert with type 273 endsection at both inlet and outlet. Also shown is the effect of blockage at the outlet. For comparison the correlations for the type 272 endsection are shown.

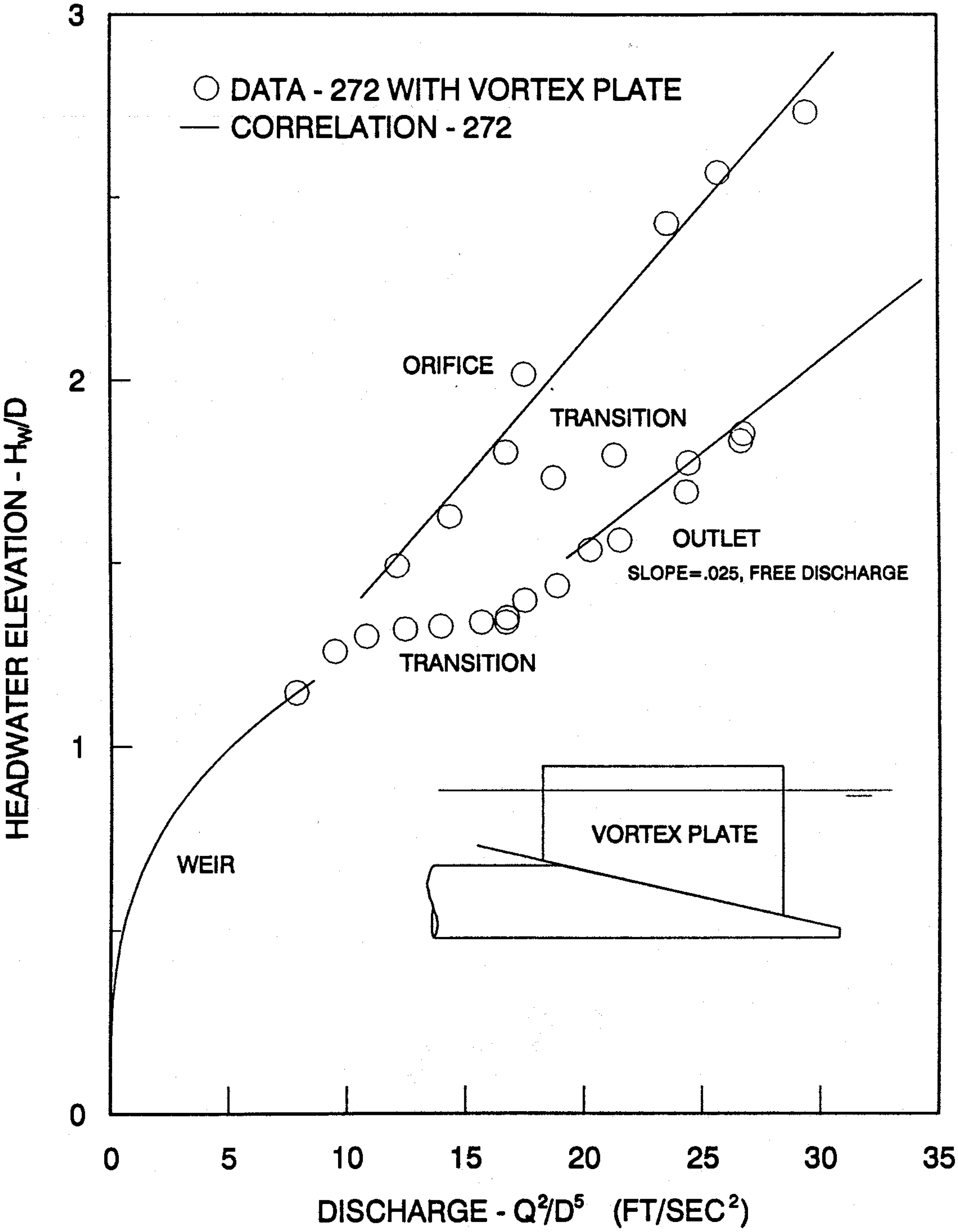


Figure 20: Influence of the addition of a vertical vortex suppressor plate on the performance of a type 272 mitered endsection. For comparison the correlations for the type 272 endsection are shown.

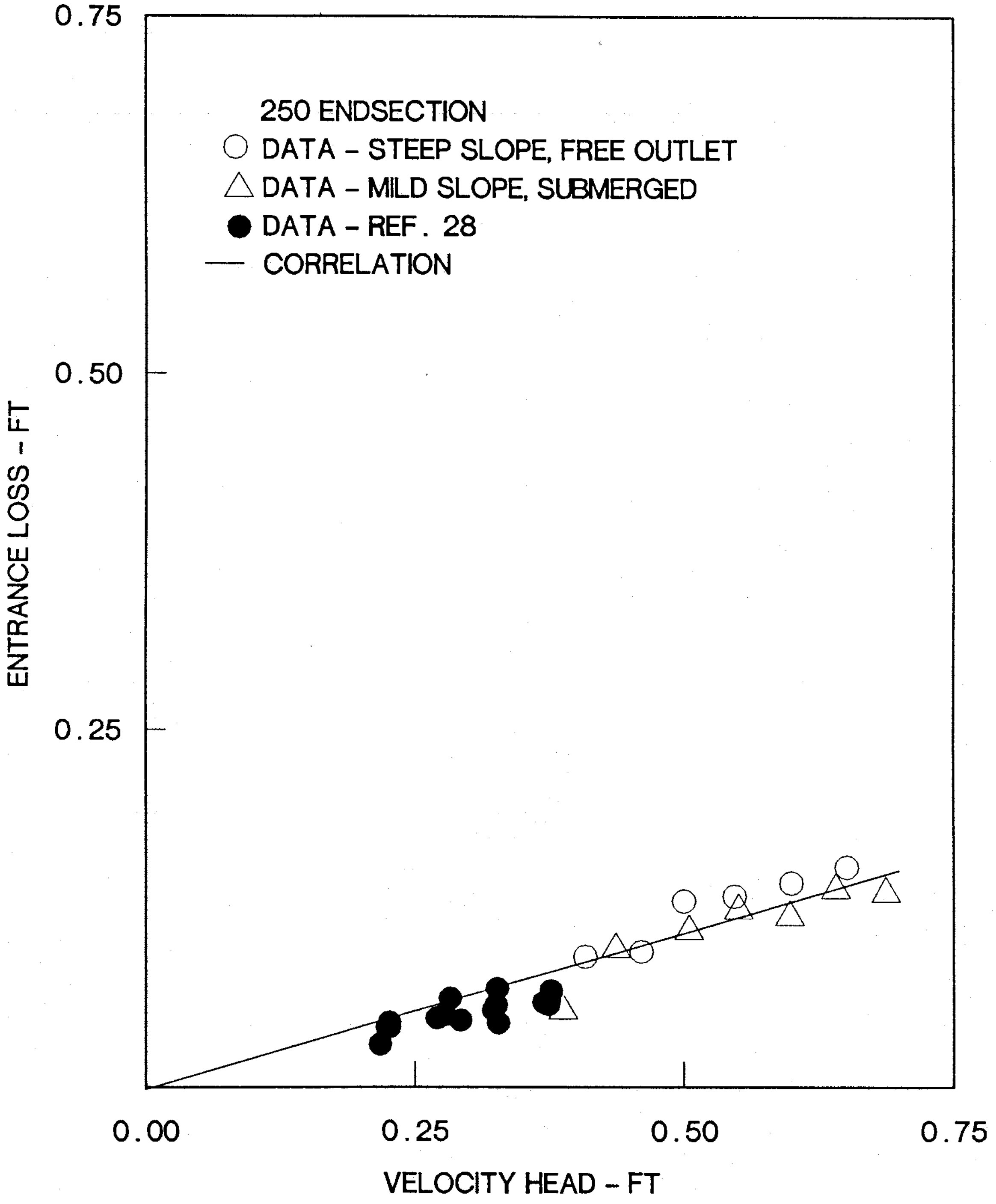


Figure 21: Correlation of head loss at inlet with kinetic energy in barrel for a type 250 endsection.

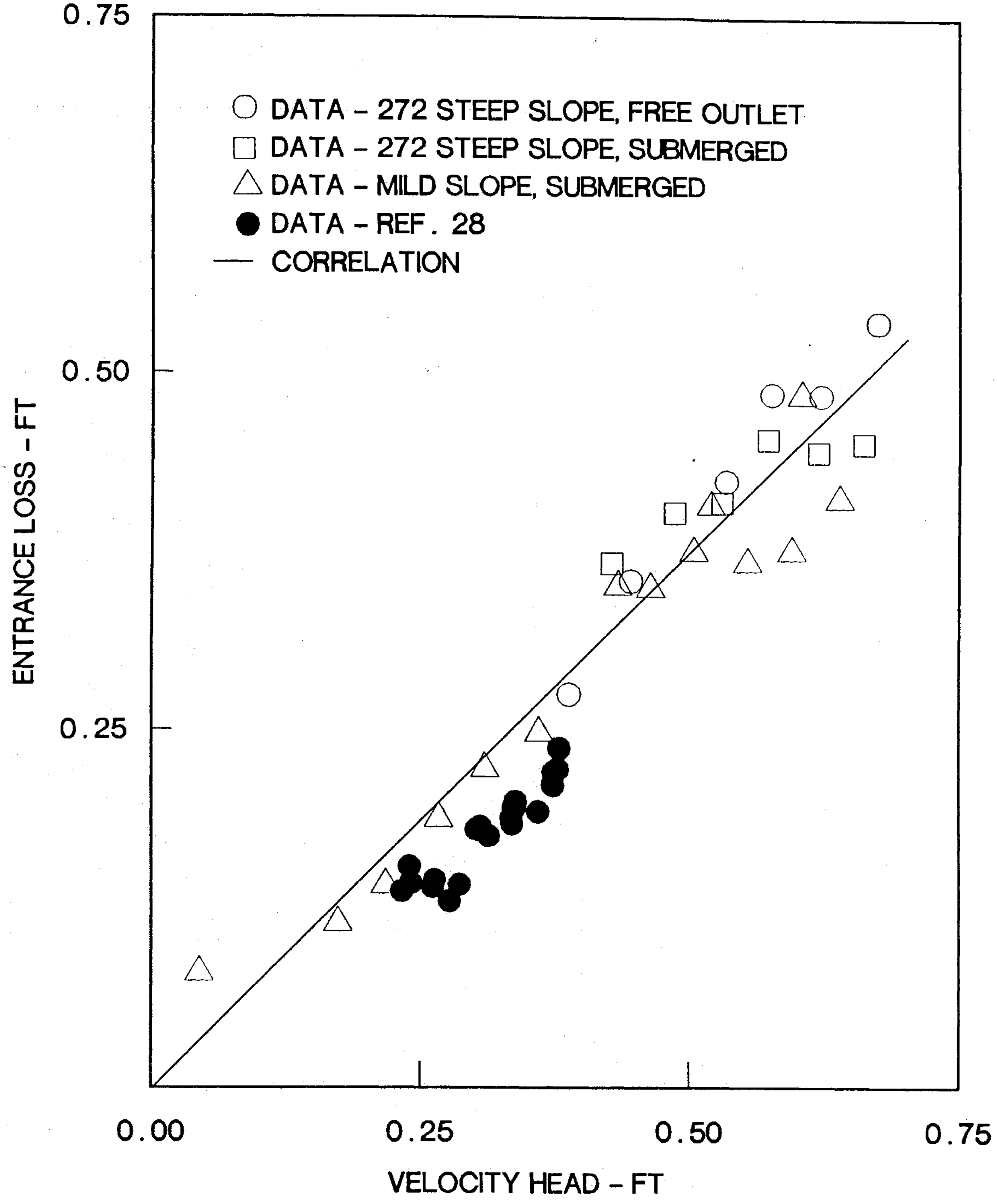


Figure 22: Correlation of head loss at inlet with kinetic energy in barrel for a type 272 endsection.

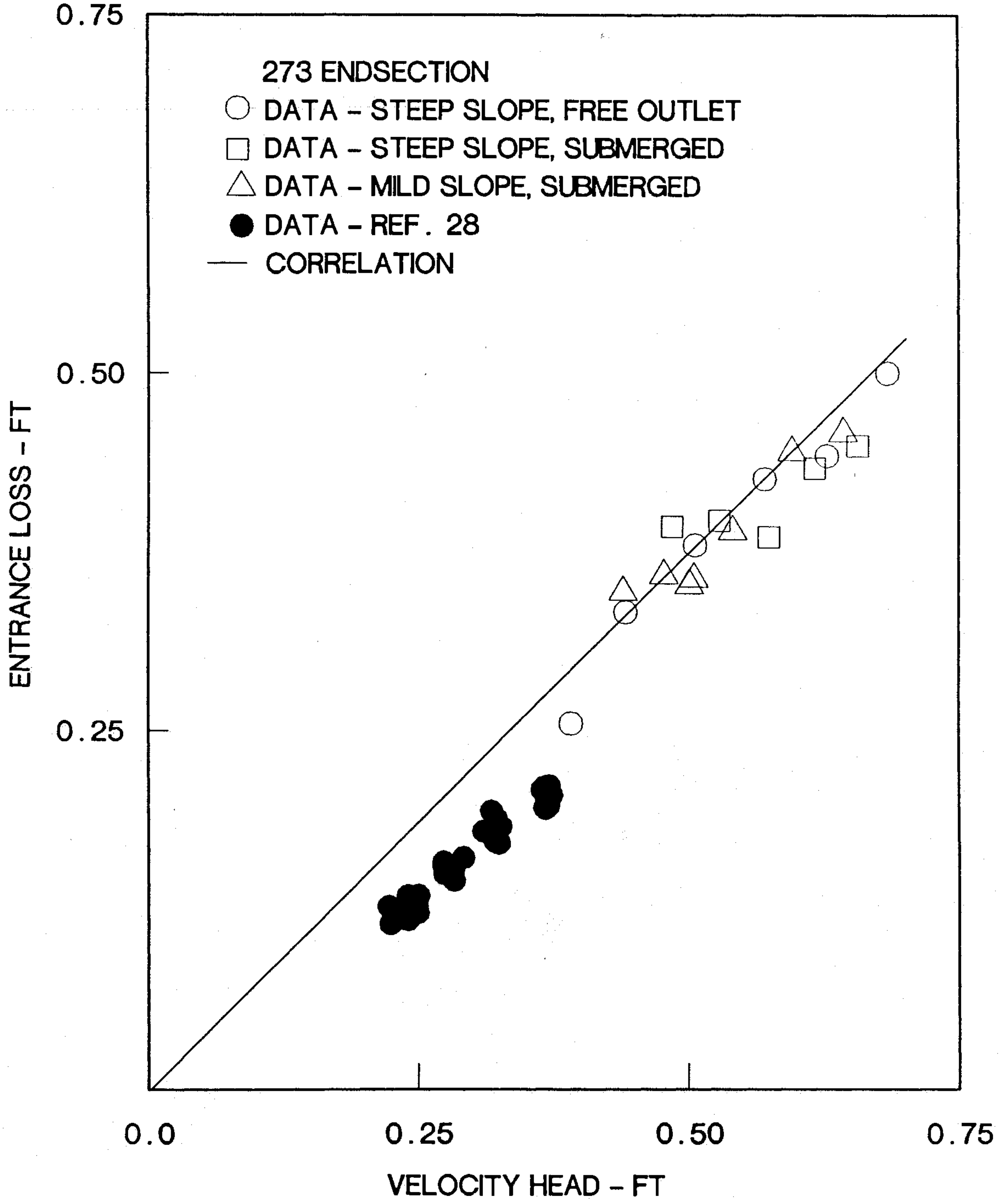


Figure 23: Correlation of head loss at inlet with kinetic energy in barrel for a type 273 endsection.

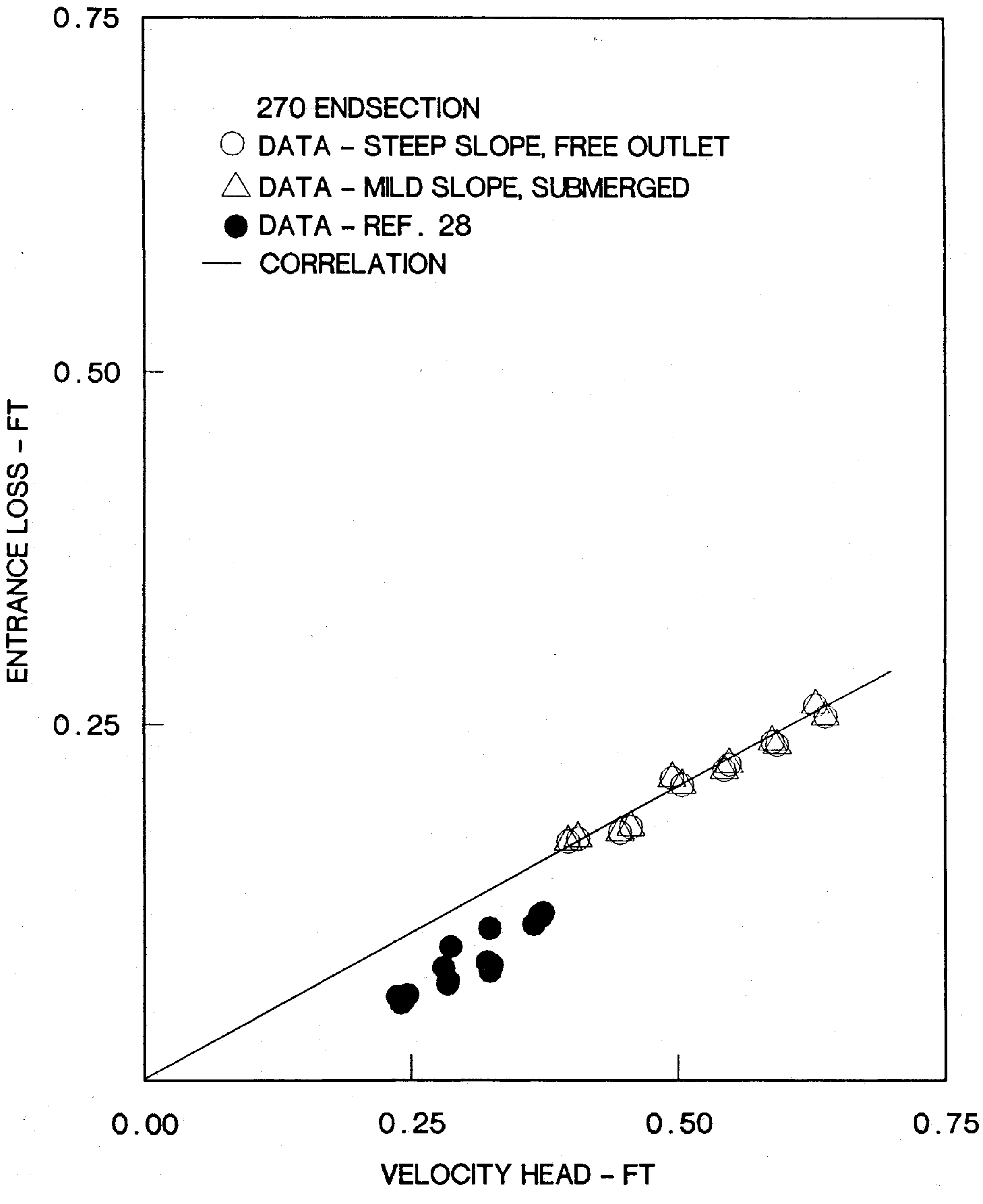


Figure 24: Correlation of head loss at inlet with kinetic energy in barrel for a type 270 endsection.

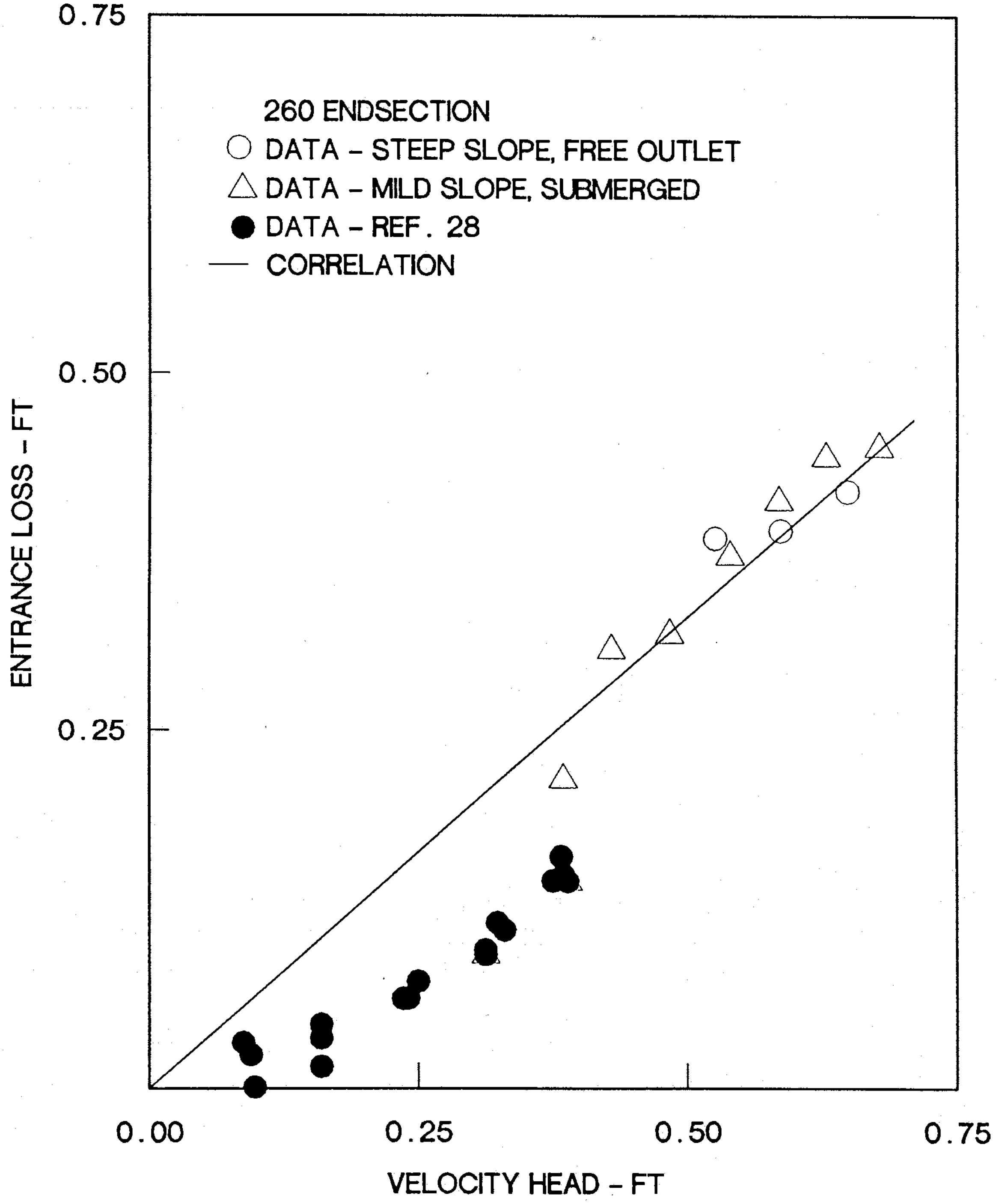


Figure 25: Correlation of head loss at inlet with kinetic energy in barrel for a type 260 endsection.

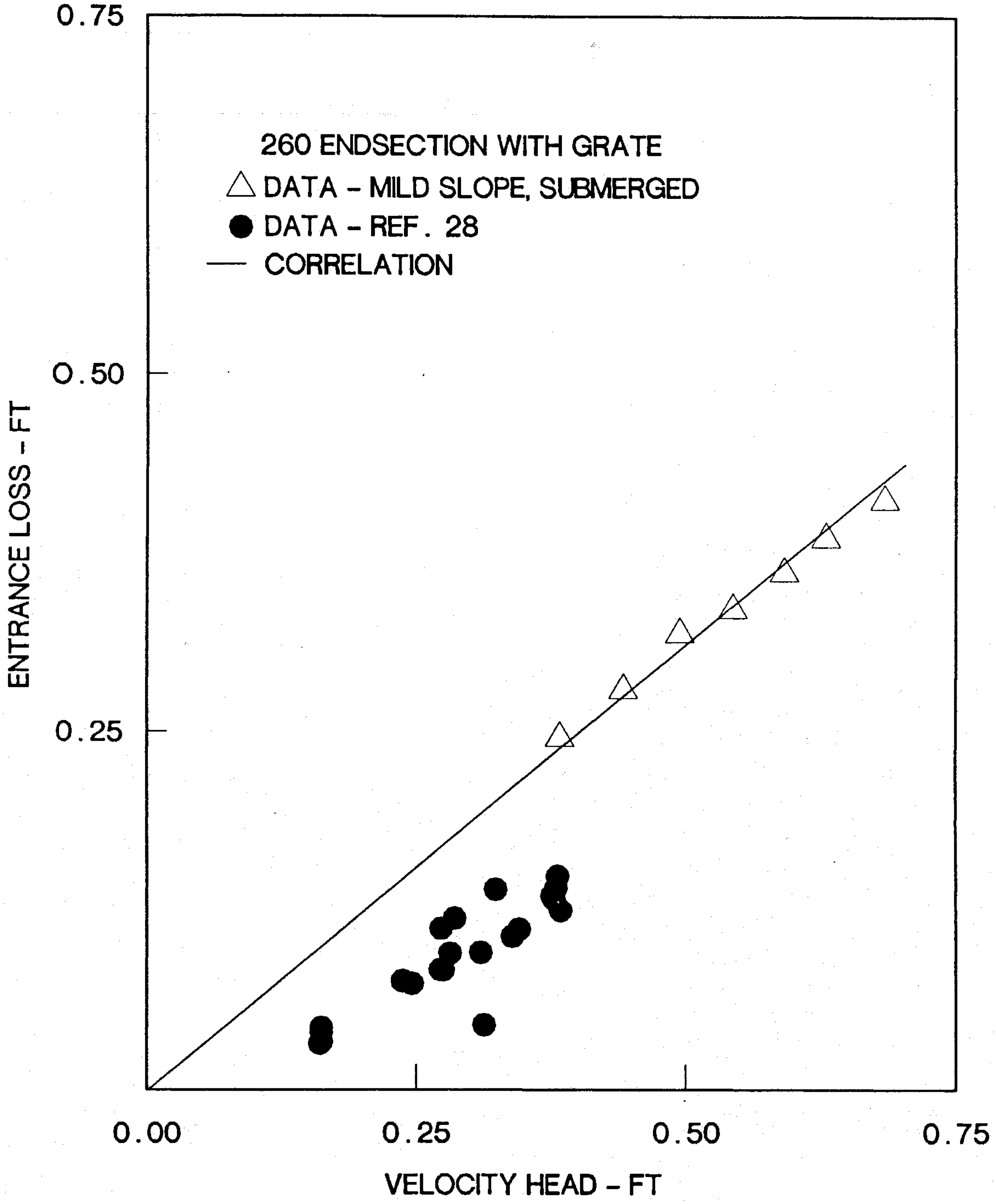


Figure 26: Correlation of head loss at inlet with kinetic energy in barrel for a type 260 endsection with grate.

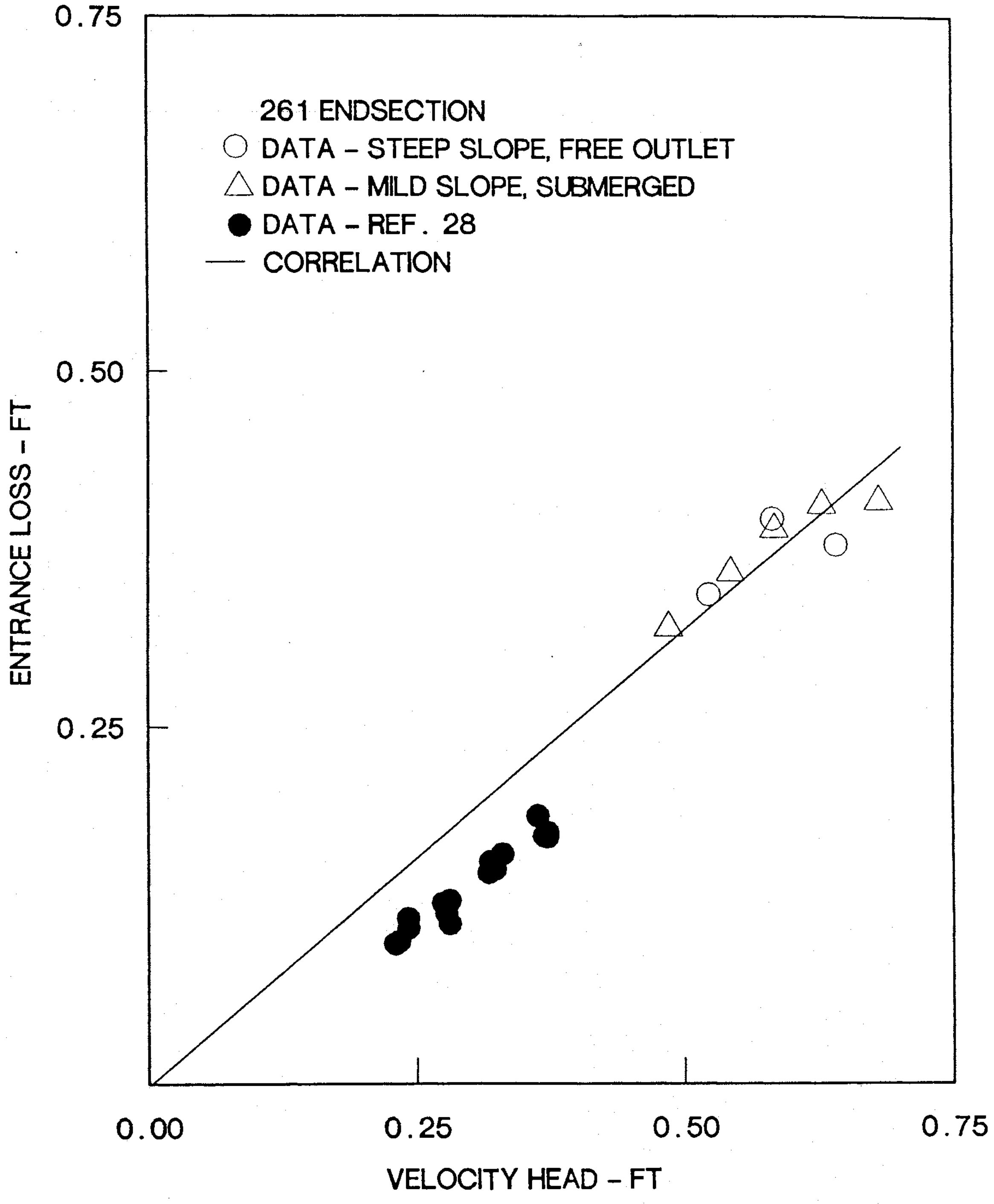


Figure 27: Correlation of head loss at inlet with kinetic energy in barrel for a type 261 endsection.

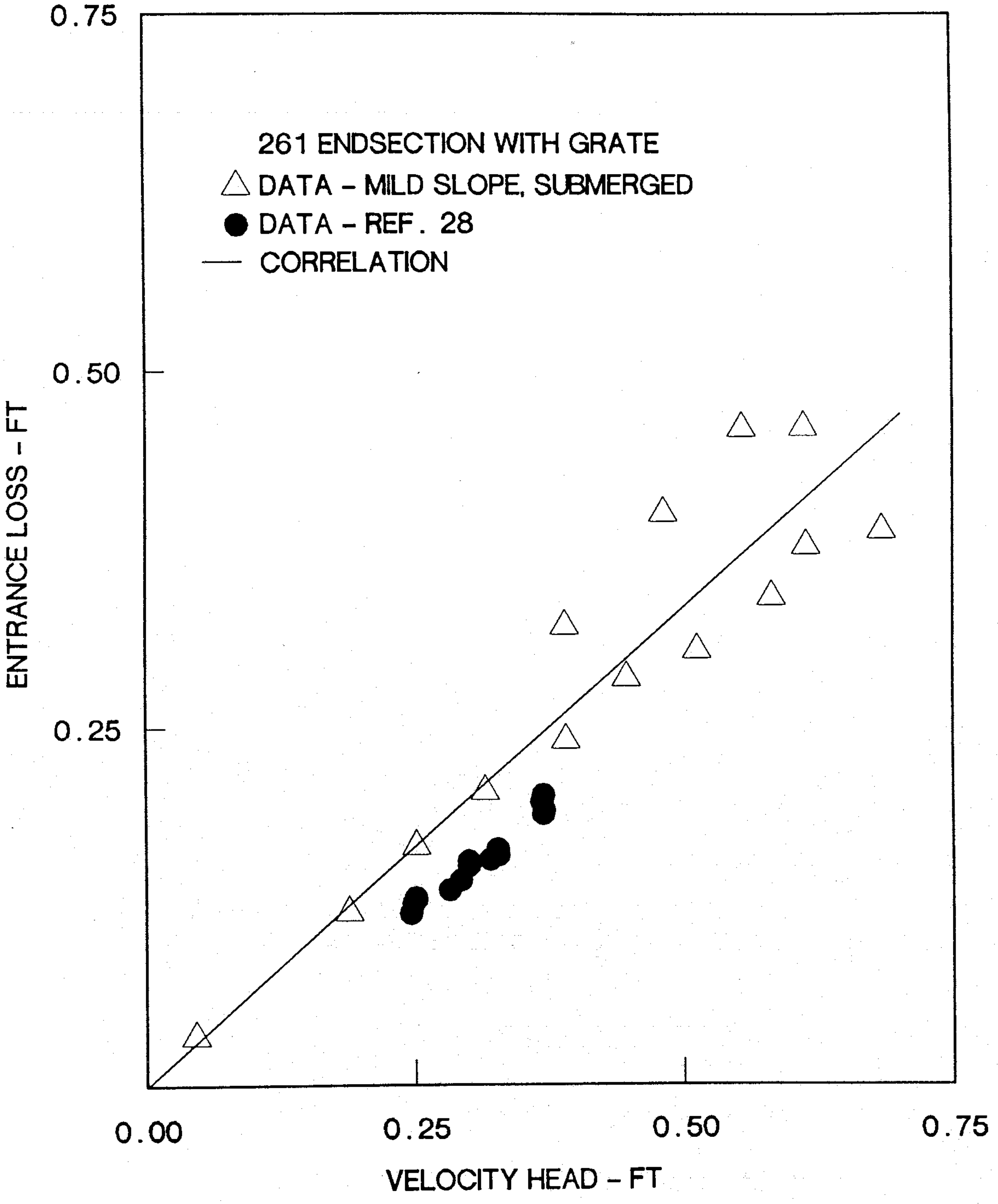


Figure 28: Correlation of head loss at inlet with kinetic energy in barrel for a type 261 endsection with grate.