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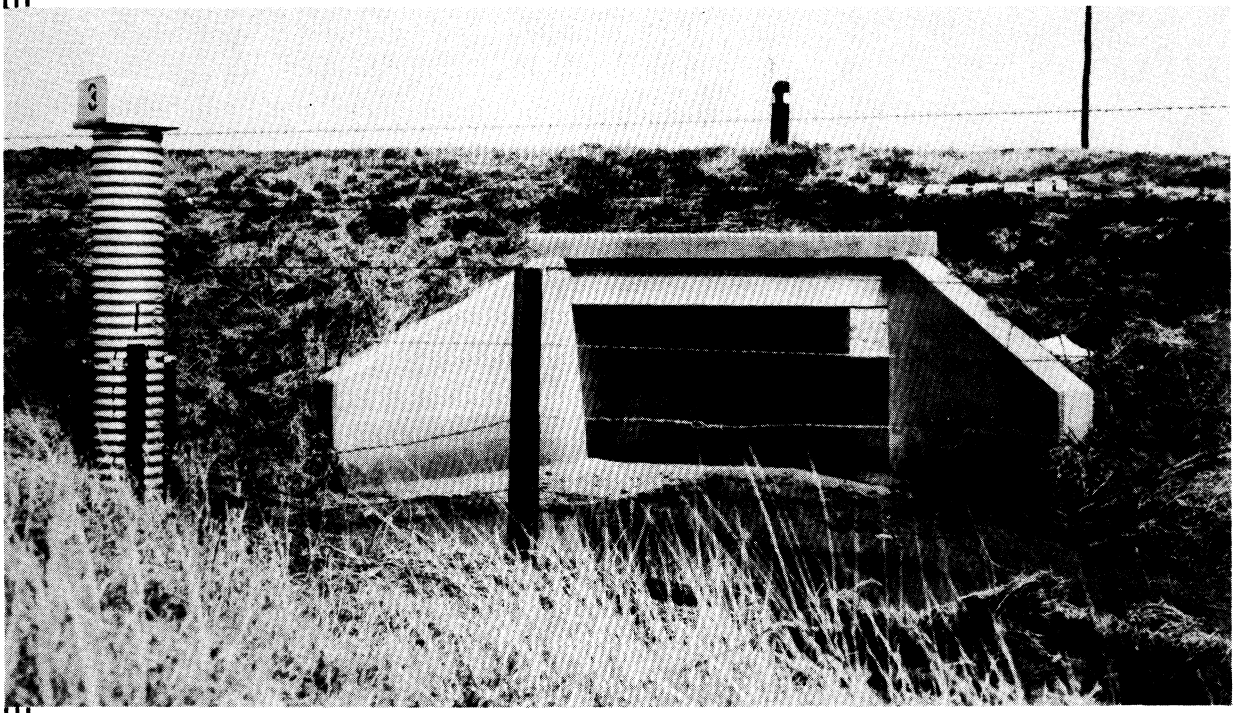
Measuring Runoff Rates With Rectangular Highway Culverts

By

W. O. REE and F. R. CROW



OKLAHOMA AGRICULTURAL EXPERIMENT STATION
Oklahoma A. & M. College, Stillwater
A. E. Darlow, Director
Louis E. Hawkins, Vice Director

in cooperation with

UNITED STATES DEPARTMENT OF AGRICULTURE
Soil and Water Conservation Branch
Watershed Hydrology Section

Technical Bulletin No. T-51
November, 1954

PREFACE

The agricultural and industrial development of any area increases the demand for water. This in turn requires that water resources be developed to achieve the maximum growth of farming or industry. In fact, water supply is the limiting factor in the economic development of many sections of this country.

In Oklahoma, one large source of water is surface runoff. Therefore an accurate estimate of the amount of runoff to be expected is highly important. Such estimates are especially needed in planning farm ponds for livestock, domestic supply, and irrigation; in designing large reservoirs, which store the flow of streams that originate as surface runoff; and in planning the handling of flood waters in channels and spillways. It would be folly to build a pond or reservoir so large it would never fill; and safety of any water channel or storage basin depends upon the structure being large enough to take care of flood flows.

Estimates of the amounts and rates of surface runoff are based on past observations of runoff from similar areas. Unfortunately, such observations are not plentiful enough, and at times the estimates are guesses at best. The lack of runoff data is one of the greatest obstacles to planning efficient use of water resources.

This bulletin describes a simple and relatively inexpensive gaging station for use by engineers desiring to obtain runoff data on specific areas. The station described makes use of existing highway culverts, thereby considerably reducing the cost.

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Measuring Runoff Rates With Rectangular Highway Culverts

By W. O. REE and F. R. CROW +

INTRODUCTION

This bulletin presents the results of studies on the use of rectangular highway culverts for measuring runoff rates. These studies were limited generally to short culverts with free outfall. Considerable emphasis was placed on studying the hydraulics of weir sills. Both hydraulic model tests and observations on actual field installations were employed in this research. Figures 1 and 2 show one of the highway culverts set up as a runoff measuring station.

Several reasons led to the investigation of the use of rectangular highway culverts for runoff measurement. First, when certain conditions are met, the culvert has stable and well defined flow characteristics and thus can be a good flow meter. Second, these culverts are quite universal, being used on most all modern highways. Usually such culverts drain areas of 3000 acres or less. Thus, they are well suited for measurement of runoff from small agricultural areas.

Rectangular culverts require a modification if they are to be used to measure very low flows. A weir sill which concentrates these small flows to measurable depths has been selected for this purpose. The primary object of this study was the determination of the relationship between depth of flow and the discharge rate through culverts equipped with such weir sills. However, the experience gained in constructing and installing weir sills seems worthy of recording. Accordingly, this material is also included in the report. The paper is divided into two parts. The first part is concerned with the hydraulics of the weir sills, and the second part with their construction and installation.

PART I: THE HYDRAULICS OF CULVERTS EQUIPPED WITH WEIR SILLS

Background

The hydraulics of highway culverts have been subjected to considerable study by hydraulic engineers. The work of F. T. Mavis (1)* clarified the basic laws governing flow through culverts. He shows that culverts operate under five different flow conditions. Of these five conditions, only two are applicable to this study. These are:

Part full with free outfall - Type I
Part full with outfall partially submerged - Type II

The designators, Type I and Type II, are Mavis'.

Culverts which operate part full with free outfall, condition Type I, can be used as runoff rate measuring devices. The relationship between depth of water above culvert entrance and the discharge rate is well defined and stable, provided the flow depth immediately down stream from the entrance is less than critical. Thus a single measurement of the depth of water upstream from the culvert entrance will determine the discharge rate. Once a culvert entrance is calibrated, a depth recording gage placed immediately upstream will obtain the necessary runoff data.

Culverts selected for flow rate measurement should have a free outfall. This requirement does not necessarily eliminate all others. Some of those that flow part full and partially submerged can also be used. However, the requirement that flow depth be less than critical depth immediately downstream of the culvert entrance must be met. This requires that floor slope be greater than critical slope or that the culvert be short with entrance flowing as a sluice gate.

Present knowledge of the hydraulic behavior of culverts makes their use in hydrologic investigations practicable. Selected culverts with stable flow condition and calibrated entrance,

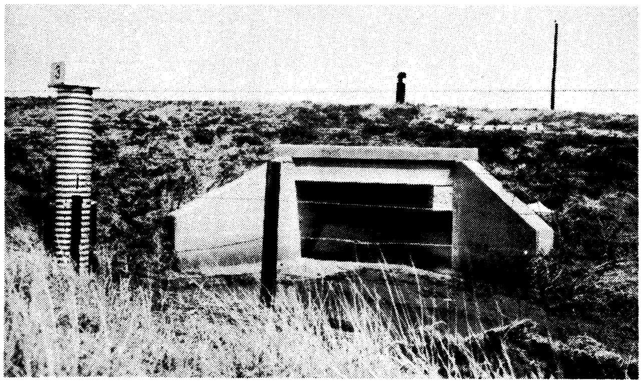


Fig. 1. --Entrance of a 4 foot deep, 8 foot wide rectangular highway culvert equipped with weir sills, depth recording gage and gage well.

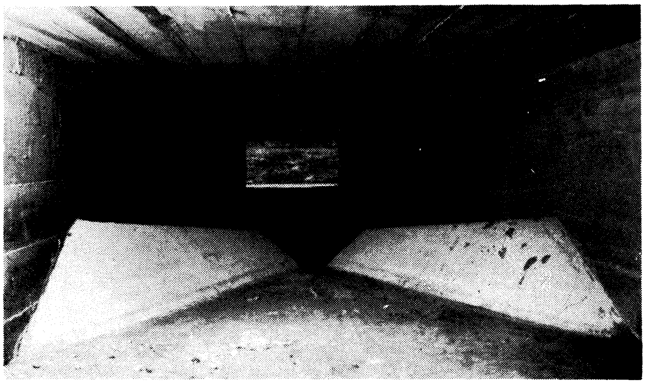


Fig. 2. --Precast weir sills installed in a 4 foot deep by 8 foot wide highway culvert.

+ Respectively: Project Supervisor, Stillwater Outdoor Hydraulic Laboratory, Agricultural Research Service, U. S. Department of Agriculture; and, Assistant Professor, Department of Agricultural Engineering, Oklahoma A. & M. College.

The use of culverts for runoff measurement was suggested by Mr. L. A. Jones when he was Chief of the Division of Drainage and Water Control, Soil Conservation Service Research. The development of the idea was made possible by the efforts of Professor E. W. Schroeder, Head, Department of Agricultural Engineering, Oklahoma A. & M. College, who initiated the cooperative project between the Oklahoma Agricultural Experiment Station and the Soil Conservation Service to undertake these studies. Acknowledgement is made of the help of Mr. T. L. Willrich, who made the initial field installations, and Mr. Jack Fryrear, draftsman, Agricultural Engineering Department, who prepared the charts and diagrams.

* Numbers in parentheses refer to items in "Literature Cited," page 18.

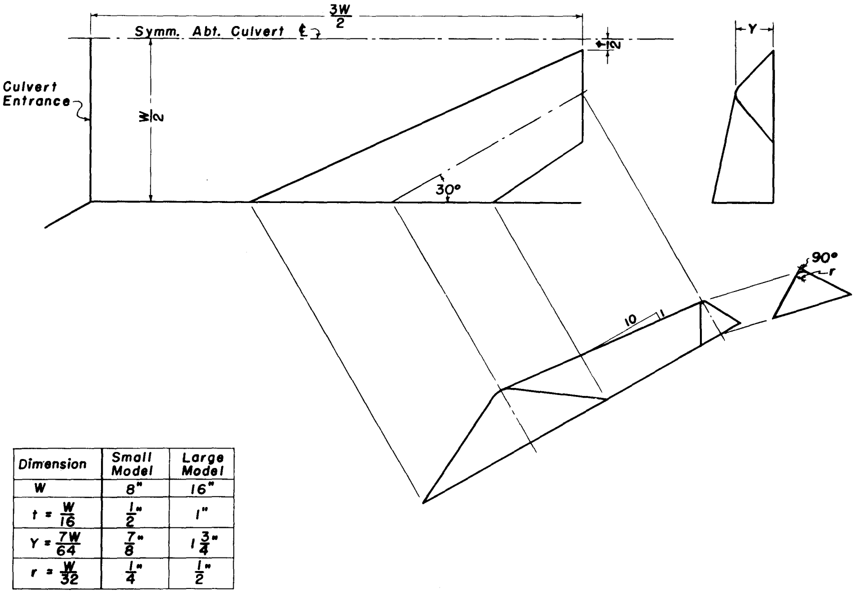
and equipped with flow depth recorders, can be used to determine runoff rates. However, if very small rates of flow are to be measured accurately, a modification of the standard culvert is needed. A practical answer to this problem is the weir sill developed by Villemonte (2). His method consists of placing a pair of weir sills on the culvert floor, leaving a space between. Very low flows pass through this narrow opening or throat and are of measurable depth. This throat controls the depth of small flows. As flow rate increases, the weir sills are submerged and the control gradually passes to the culvert entrance. Thus a culvert which flows part full with free outfall, and which is provided with a weir sill, is a good flow meter. Discharge rates from the very low to the maximum capacity of the culvert can be measured with satisfactory accuracy.

The Villemonte weir sill was chosen for several reasons. First, this sill had been developed and perfected in a general way. No exploratory work was necessary. The form of the weir sill was accepted on the basis of the previous studies. Second, the weir sill does not reduce the maximum capacity of the culvert in which it is placed. Finally, because of its shape, the sill will not become fouled easily with debris, nor will the throat become clogged with sediment.

The work of Villemonte provided the starting point for this study. It was carried forward by further research on the use of the weir sills in culverts of the kind found in local use. This was done by model studies.

The Model Experiments

The prototype for the models was a typical rectangular highway culvert such as found in Northern Oklahoma. This culvert is straight, of uniform rectangular cross-section, and is relatively short. It is provided with flared wingwalls (30 degree flare with respect to culvert center line) and has all corners sharp or square edged or slightly chamfered. The maximum depth of water at the culvert entrance is seldom more than twice the culvert depth, usually less. Model experiments were performed on this type of culvert equipped with weir sills. The objectives of these experiments were:



Dimension	Small Model	Large Model
W	8"	16"
$t = \frac{W}{16}$	$\frac{1}{2}$"	1"
$Y = \frac{7W}{64}$	$\frac{7}{8}$"	$1\frac{3}{4}$"
$r = \frac{W}{32}$	$\frac{1}{4}$"	$\frac{1}{2}$"

Fig. 3.--Dimensions of model weir sills.

Objectives

1. Find a location for the weir sills near the culvert entrance that would not adversely affect the hydraulic performance of the sills or the culvert.

2. Determine the head-discharge relationship of culverts equipped with weir sills.

3. Determine the effect of culvert slope on the head-discharge relationship.

4. Determine the effect of culvert shape (depth to width ratio) on the head-discharge relationship.

5. Determine the minimum measurable discharge rate for weir sills on various culvert slopes.

Description of the Weir Sill

The Villemonte weir sill consists of two triangular, tapered, converging sills placed on the culvert floor with an opening left between them. The sill used in these experiments is very similar. It differs in being about one and one-half times as large in height and in throat opening as the Villemonte sill for a culvert of same width. The sill described here has been standardized with all dimensions being proportional to the culvert width.

Figure 3 is a sketch of the weir sills used in those studies.

Description of the Apparatus

Two model setups were used in these studies, one indoors and the other outdoors. Better control of model dimensions and better working conditions were possible with the indoor model. However, space and flow capacity were limited, so some of the experiments were performed on the outdoor setup.

Indoor Laboratory Setup

A view of the indoor setup is shown on Figure 4. The model is one-half of a 16 inch wide culvert. Since a culvert is symmetrical about its longitudinal centerline, the half model could be used. Its advantages are: (1) The capacity of the testing system is doubled; and (2) The water surface profile can be viewed through the glass panel placed along the centerline of the culvert.

The half model was 8 inches wide, 8 inches deep and 36 inches long. The 36 inch length was sufficient to simulate the flow conditions downstream of the weir sill. The floor of the culvert model was hinged at the entrance to permit testing on various slopes up to 6 percent. The model was constructed of white pine, sanded smooth, and given two coats of spar varnish. Dimension changes during the testing were negible.

The flow through the model was supplied by a constant head tank. Rates were measured by a 0.4 HS rate measuring flume. A recorder on this flume served to indicate when steady flow was obtained in the system. The depths of flow were measured along the centerline with a point gage mounted on the profiler. Measurements to the nearest 0.01 inch were possible.

Outdoor Laboratory Setup

The outdoor setup is shown on Figure 5. The model in

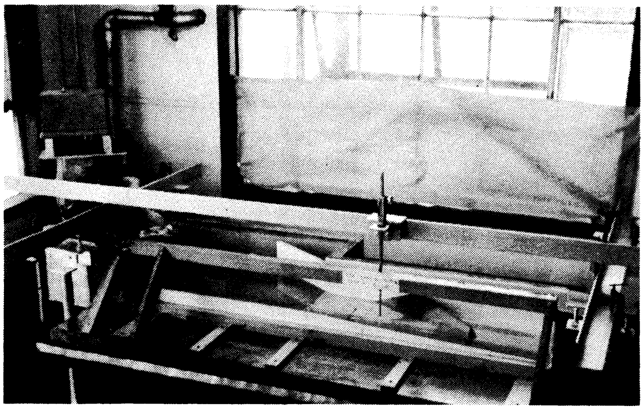


Fig. 4. --Indoor model setup. The test flow is confined to the weir sill throat. The point gage for depth measurement is upstream of the weir sill throat and downstream of the culvert entrance.

place for testing is a 1/12th scale model of one of the culverts being used in the field studies. The dimensions of the prototype are: width 8 feet, depth 4 feet, length 70 feet, floor slope 2 percent, and wing wall flare 34 degrees. This particular model was the first one tested and served as a pilot study for the subsequent experiments. The succeeding models placed in this setup for testing are listed in the section on experiments.

In each case the model was built of white pine, sanded smooth, and given two coats of spar varnish.

The water to this setup was supplied by gravity flow through a line directly connected to the water supply. Discharge rates were measured by a 1.0 foot H flume or a 0.4 foot HS flume. A weighing tank and scale were provided to check the flume ratings. A profiling apparatus with a point gage measuring to the nearest 0.01 inch was mounted over the model. This profiler permitted measurement of the floor elevation and depths of water at any point in the model. Depth recorders were placed on the measuring flume and the entrance forebay to the culvert. These served to indicate when steady flow existed.

The Experiments

Table I summarizes the experiments performed both on the indoor and outdoor models.

Sixty-two separate experiments were run. An experiment represents some physical change in the structure being tested, either a new model, or a change in slope, or a change in entrance. For each experiment the model was subjected to a number of different flows called tests. About 25 test flows were run for each experiment.

Test Procedure

The model to be tested was installed in the test setup. The entrance form was attached and the floor adjusted to the desired slope.

Before beginning the experiment, the profiler was checked. Point gage readings were taken on a level water surface. Differences in readings indicated irregularities in the profiler. These differences were applied to readings observed during a test to eliminate the profiler error. Also before each experiment, a profile of the entrance forebay and culvert floor along the centerline was measured.

A schedule of tests was selected so that a good spacing of points along a logarithmic head-discharge plotting resulted. Testing was usually started with the lowest flow on the schedule. The control valve was set to admit the approximate desired test flow into the model. When the water level recorders indicated steady flow throughout the system, the observations were made.

The head on the rate measuring flume was measured by a calibrated point gage. Observations were made at the beginning, middle and end of each test. The water surface profile within the culvert and for some distance upstream was measured by the profiler point gage. To make these observations possible the culvert top was left off. Where the test indicated that full flow might be possible a cover was placed on the culvert. In this case only the upstream head could be measured. This head was measured 1 1/2 W upstream from the culvert entrance.

The Results of Model Experiments

General Findings from Pilot Model Studies

The first experiments were made on a full 8 inch model, 4 inches deep, and without weir sills. The slope of the culvert was 2 percent and the outlet had free fall. These tests disclosed that the culvert barrel flowed part full even when the entrance was submerged. The entrance alone thus controlled the head-discharge relationship. A logarithmic plot showed that two laws governed the flow. Critical depth of the entrance cross-section controlled the flow until the culvert entrance was submerged. Flows submerging the entrance occurred as sluice gate or orifice flow. A sketch plot of this flow behavior is shown on Figure 6-A.

A profile of the water surface during a maximum capacity test indicated that a good location for the weir sills might be

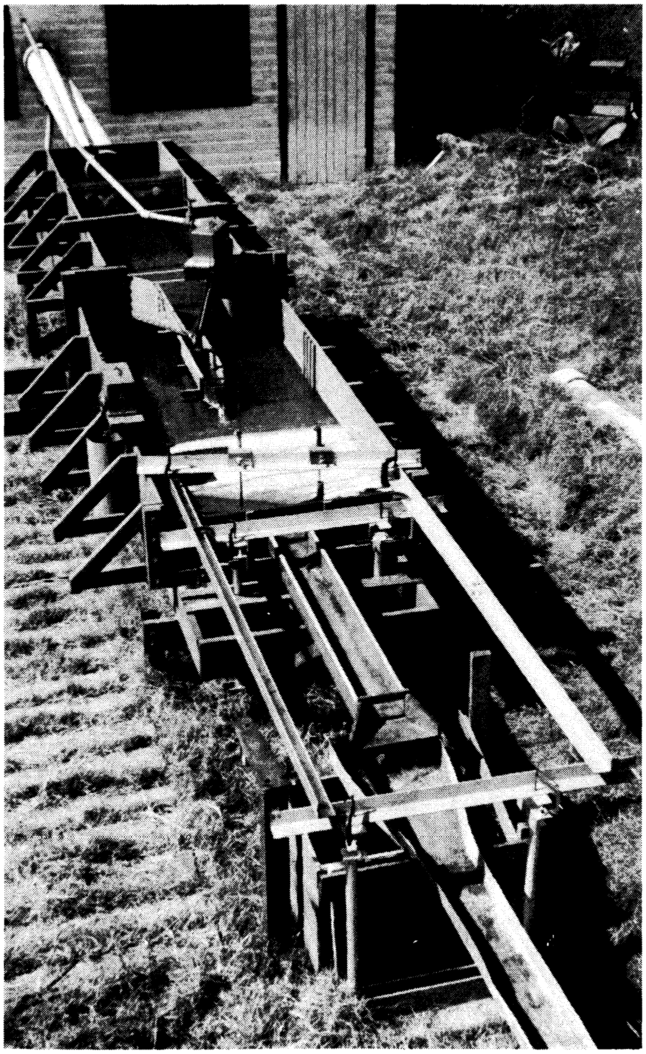


Fig. 5. --Outdoor model setup. The model in place is a full culvert 4 inches deep and eight inches wide.

with the throat a distance 1 1/2 W downstream from the culvert entrance. Here the sills were far enough downstream to prevent choking the culvert entrance, yet near enough to the entrance to enable head measurements to be made upstream. The sills were fixed in this location and another set of tests was run. The results of this second experiment are shown on Figure 6-B. This plotting illustrates the changing of the flow control as the discharge rate increases. Low flows are controlled by the weir sill throat, with control shifting gradually to the culvert entrance for the higher flows. Throughout these shifts of control the flow condition is stable and only one discharge rate is possible for a given head.

The advantage of the weir sill is the more accurate measurement of the low flows. However, a disadvantage is also evident from 6-B. The rating curve is very flat for part of the intermediate flow rates. In this range a culvert with weir sills is a less sensitive measuring device than one without.

The head discharge relationships for the culvert with and without weir sills are compared on Figure 7. Immediately evident is the coincidence of the two curves when the submerged flow condition is reached. Thus the presence of the weir sills does not reduce the maximum capacity of the culvert.

These first studies satisfied the initial objectives. They were: (1) That a satisfactory place for weir sills was with the throat 1 1/2 W downstream from the entrance, and (2) That the weir sills did not reduce the maximum capacity of the culvert. With these objectives met, the detailed tests to determine the head-discharge relationships of culverts equipped with weir sills and under different slopes and width-depth ratios were undertaken.

Table I. --List of Experiments.

Setup	Model Size	Slope Range	D/W Range	Remarks
Indoors	16" half	0 to 6	---	Low flows only
Outdoors	8" full	2%	0.5	Pilot model with and without weir sills.
	16" half	0 to 6	.375 to .75	
	8" half	0 to 6	1.0 to 1.5	

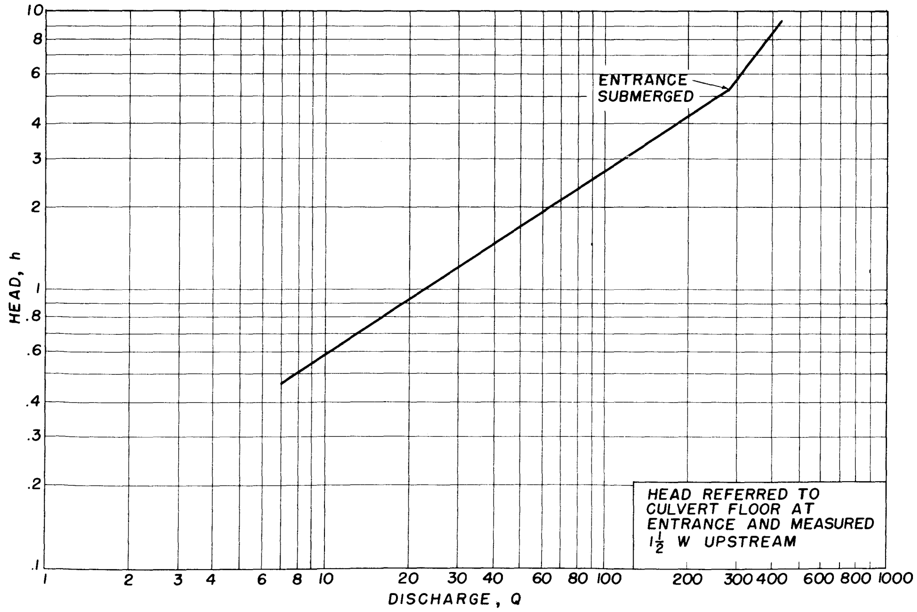


Fig. 6A. --Head-discharge relationship for a rectangular culvert without weir sills.

The Head-discharge Relationship

The results of the tests are plotted on Figures 8 to 13. A separate plotting is made for each slope. The points are actual observations. The dashed lines are the plots of the equations which are the best fit of the data. Where a simple functional relationship existed between head and discharge rate, the equation was derived by analytical means and the coefficients and exponents evaluated by statistical methods. In the transition zones no attempt was made to write the equation for the head-discharge relationship. Instead the observed points are connected with a solid line which represents the best visual fit.

The Head Measurement

The head on a culvert equipped with weir sills is defined as the difference in elevation between the floor of the culvert at the weir sill throat and the level water surface upstream from the culvert. The point of measurement of the water surface is 1 1/2 W upstream from the entrance. For the flows controlled by the weir sill this method of head determination is satisfactory. When the control shifts to the culvert entrance the proper reference point would be the culvert floor at entrance. Or if the orifice flow law governed, the proper head reference point would be the elevation of the center of the culvert opening. However, to change the point of zero head for each type of flow would be confusing. For this reason all heads are referred to the culvert floor at the weir sill throat.

Dimensionless Representation

The data are presented in dimensionless form. Culvert width has been chosen as the base dimension. Thus head is expressed as the ratio of head to culvert width, or h/W. Discharge in this system becomes the ratio of discharge rate to culvert width to the five-halves power, or $Q/W^{5/2}$. Slope is dimensionless since it is the ratio of fall to length. Finally, the culvert cross-section is described by the ratio D/W, where D is the depth of the culvert. Given in this form the data are of greatest usefulness, since they can be applied to culverts of any width and data from different sized models can be compared readily.

The Rating Curve of the Culvert with Weir Sills

The rating curve of a culvert with weir sills has already been presented in general terms. It will now be discussed in greater detail.

The Flow Through the Throat. --Flows less than h/W = 0.113 in depth are contained wholly within the straight sides of the throat of the weir sills. The relationship of head to discharge in this range plots as a straight line on logarithmic paper. The equation of this line, as determined graphically is:

$$\frac{Q}{W^{5/2}} = 2.404 \left(\frac{h}{W}\right)^{2.195}$$

Above a depth of h/W = .113 the flow is still contained within the throat for a short range. However, the throat sides now widen because of the crest radius, and the discharge is no longer a simple power function of the head. When a depth reaches h/W = 0.15, flow starts over the crest of the weir sills.

The question may arise as to why the flow is still within the throat for heads greater than the depth of the throat. The answer is found in the fact that the water surface drops as it approaches the throat, while the head is measured upstream out of the drawdown range.

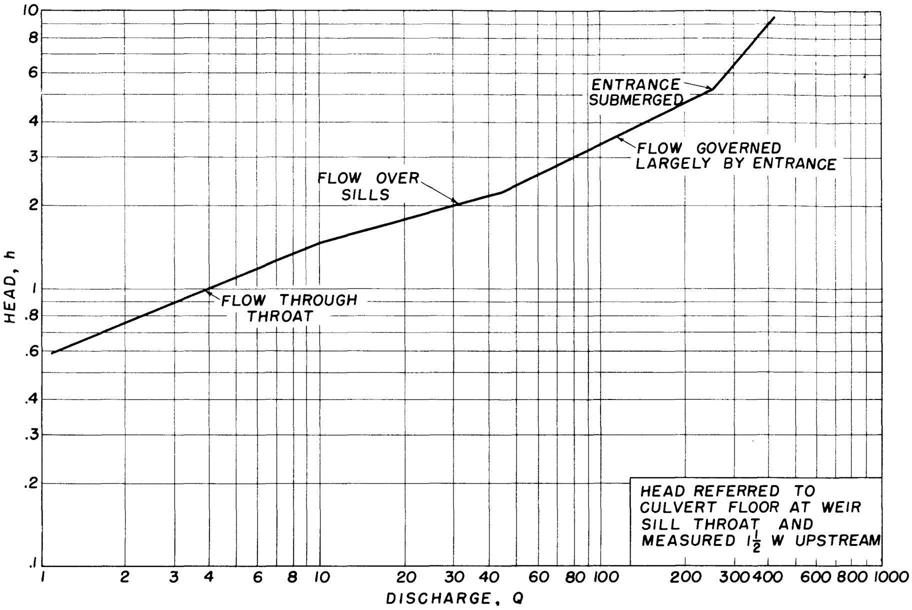


Fig. 6B. --Head-discharge relationship for a rectangular culvert equipped with weir sills.

Flow Over and Controlled by the Weir Sills. --For a small depth range, from h/W = .15 to h/W = .18, flow is occurring over the weir sills and is controlled by them. A photograph of this flow condition is shown on Figure 14. Since the flow is a combination of that through the throat and over the sill crest, the head-discharge curve is skewed. No attempt was made to write an equation for the curve in this range. As pointed out earlier, it is in this range where the curve is the flattest. A small error in head measurement can result in a relatively large error in the estimate of discharge rate.

Flow Control by Sills and Culvert Entrance. --When flow depths exceed h/W = .18, the entrance begins to exercise some control over the flow. However, the sills remain the primary control until h/W reaches some higher value, depending on the slope of the culvert; then the culvert entrance becomes the primary control. In the range where the sill is the primary control, the head-discharge relationship is difficult to analyze so no attempt is made to derive an equation for it.

Flow Control by Culvert Entrance --Critical Depth Flow. --As mentioned in the previous section, the head at which the culvert entrance exercises primary control of the flow depends on the slope of the culvert floor. These limitations for the slopes tested are given in Table II. Above the lower limits of h/W given in the table, the head-discharge relationship can be expressed by the following equation:

$$\frac{Q}{W^{5/2}} = 2.795\ S^{.03847}\left(\frac{h-\frac{3SW}{200}}{W}\right)^{1.545\ S^{-.02277}}$$

This formidable semi-empirical equation was derived by applying analytical curve fitting methods to the data. This is the equation of the dashed lines drawn on the data plots, Figures 8 to 13. In general the fit of this expression to the data is very good. The chief advantage of this equation is that it permits the determination of the head-discharge relationship for culverts on any slope. However, since it is partly an empirical expression it should be limited to the range of slopes used in the experiment.

Some discussion of this equation may be enlightening. The subtractive term 3SW/200 is the fall of the culvert floor from the entrance of the culvert to the weir sill throat. Including it has the effect of referring the head to the point of primary control for flow of this type. The slope terms are small and reflect the minor backwater effect of the weir sills on the flow depths at the culvert entrance. It is desirable to point out here that the term S indicates percent slope and not absolute slope. It will be noted that the exponent of the head term is approximately 1.5, which would be the exponent for critical depth flow for a rectangular cross-section. The equation holds until the flow submerges the entrance.

Flow Control by Culvert Entrance - Submerged Entrance. --When flow depths become great enough to submerge the culvert entrance, the head-discharge relationship changes. This is indicated by the steeper lines on Figures 8 to 13. With culvert entrance submerged and culvert barrel only part full, the flow most closely resembles sluice gate flow. The formula for sluice gate flow as given by Rouse (3) is

$$Q = C_d W D \sqrt{2 g h_e}$$

In this formula C_d is a discharge coefficient which varies with the head and the contraction coefficient. The head, h_e, is the difference in elevation between the upstream water and the culvert floor at entrance. Expressed in dimensionless form the formula becomes:

$$\frac{Q}{W^{5/2}} = C_d \frac{D}{W}\sqrt{2 g \frac{h_e}{W}}$$

To test the applicability of this formula, the experimental values of h_e/W were plotted against $Q/W^{5/2}$ on logarithmic paper. The resulting equation, which gave an approximate fit of all

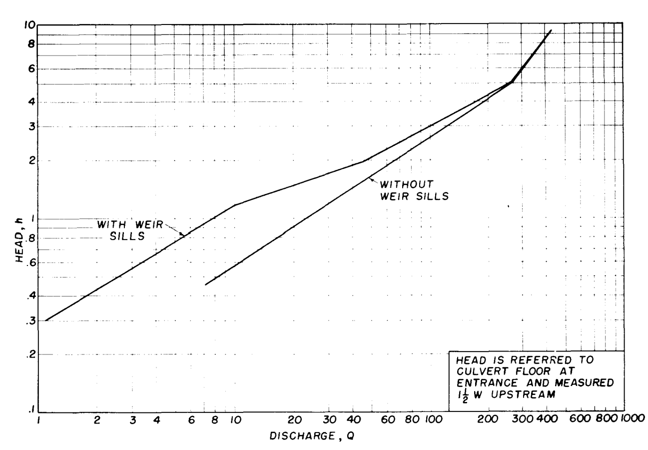


Fig. 7. --Comparison of the head-discharge relationships for a culvert with and without weir sills.

points, was

$$\frac{Q}{W^{5/2}} = 3.10\left(\frac{D}{W}\right)^{.61}\left(\frac{h_e}{W}\right)^{.93\left(\frac{D}{W}\right)^{.125}}$$

The exponents of D/W and h_e /W differed considerably from the theoretical. The reason for this difference is that the discharge coefficient is a variable depending on h_e and the depth of the opening, D. Since the equation does not provide a good fit for all points it is not of greatest usefulness.

A better fit for all points was obtained by analyzing the data by assuming that the orifice flow law governed the head-discharge relationship. This was done by plotting the values of $Q/W^{5/2}$ against corresponding values of h_o/W, where h_o is the head with respect to the center of the opening. This resulted in the equation:

$$\frac{Q}{W^{5/2}} = 4.416\left(\frac{D}{W}\right)^{-.0912} S^{.0158}\,\frac{D}{W}\left(\frac{h_o}{W}\right)^{.588}$$

If head is referred to the culvert floor at weir sill throat, the term h_o/W must be replaced by

$$\frac{h-\frac{D}{2}+\frac{3SW}{200}}{W}$$

The $(D/W)^{-.0912}$ term in the above equation probably reflects the contraction effect at the entrance. The slope term is small and probably represents backwater effects of the weir sill on the culvert entrance. It should be noted that the exponent of the head term, 0.588, compares favorably with the theoretical exponent of 0.5 for orifice flow. It should be mentioned again that the slope term S is percent slope.

The dashed lines in the orifice flow range on Figures 8 to 13 are graphical representations of the equation. In general, the fit of this formula to the data is very good. However, a few deviations should be noted. In a few cases the fit is poor at the point where orifice flow begins. Also the fit for the points for D/W ratios of .5 and 1.0 on the 6 percent slope culvert is not good. The reason is not known.

Table II. --Lower Limit of Applicability of Equation for Critical Depth Control.

Slope	Lower limit of h/W
1	.615
2	.630
4	.410
5	.400
6	.390

Even though the derived expression does not provide a perfect fit to all points, it is satisfactory. Also it has the advantage of providing a means of interpolating the head-discharge relationship for culverts of any slope and D/W ratio. However, the application of the formula should be confined to the range of values covered by the experiment. This is no severe restriction, since the experiments covered the range usually encountered in the field.

Effect of Culvert Slope on Minimum Measurable Discharge Rate

Since the datum for head measurement, the weir sill throat, is lower than the culvert entrance there is some minimum head at the gaging station representing the beginning of control by the weir sills. The culvert apron is, in effect, a low barrier between the gage well and the weir sill throat. Until the backwater curve from the weir sill submerges the culvert entrance and extends to the gage well, the sill does not control the upstream flow depth. Up to this point, control is exercised by the channel characteristics of the culvert entrance. The minimum measurable head will depend on the culvert slope, since the steeper the culvert the lower the weir sill throat will be below the entrance. The values of the minimum measurable discharge rates corresponding to these heads for the various slopes were determined by examining the rating curves, Figures 8 to 13. The point at which the rating curve breaks away and becomes nearly horizontal in the very low flow range is the point where flow control by the weir sill throat ceases. The values of $Q/W^{5/2}$ at this point have been plotted against corresponding

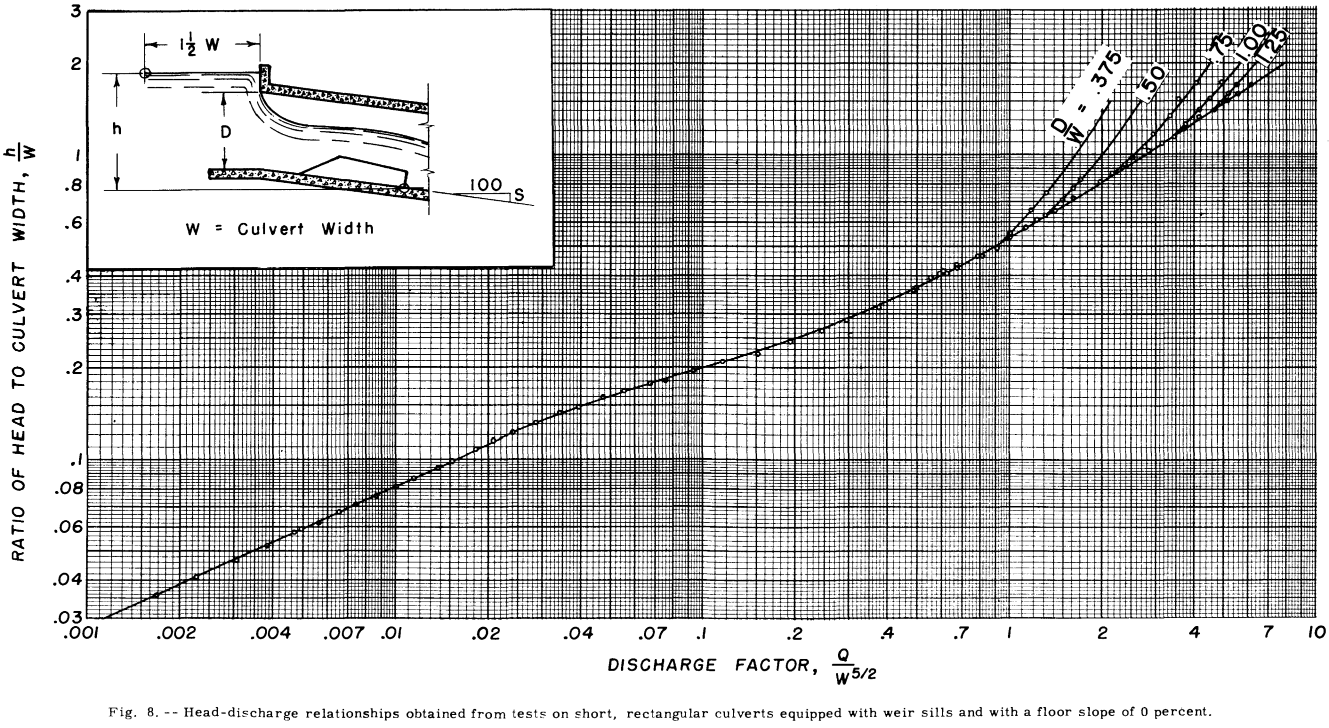


Fig. 8. -- Head-discharge relationships obtained from tests on short, rectangular culverts equipped with weir sills and with a floor slope of 0 percent.

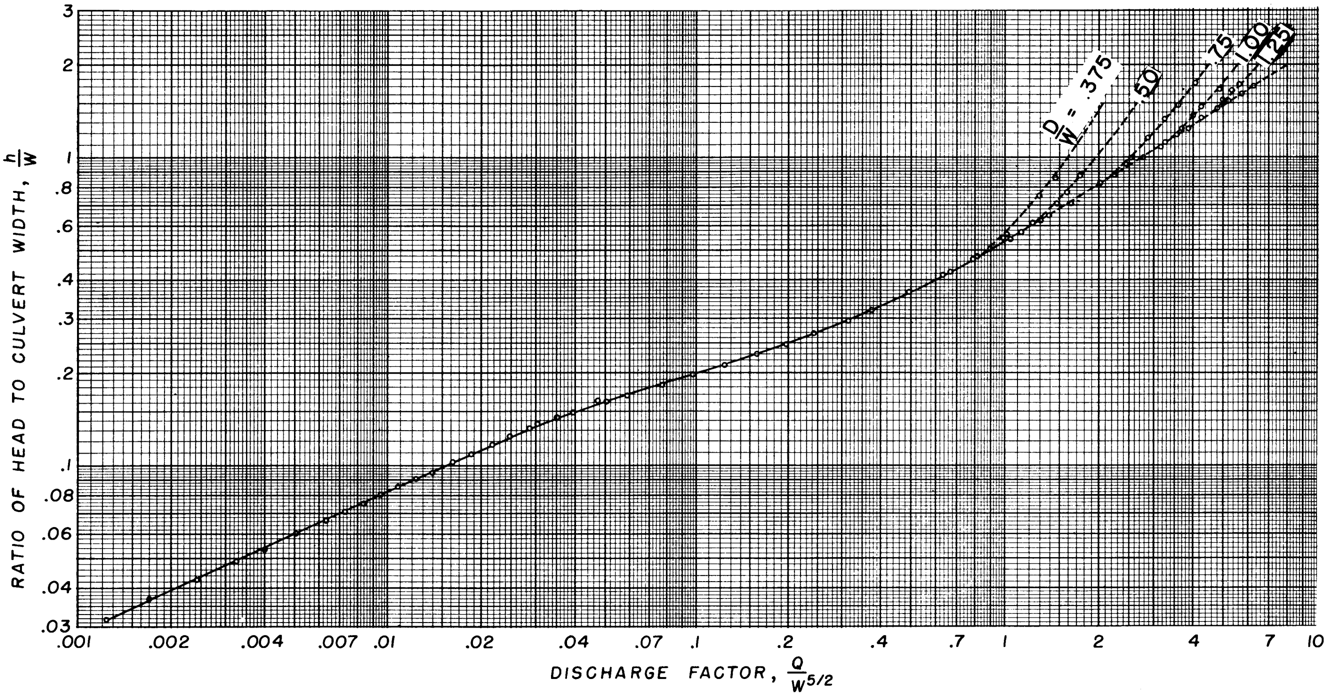


Fig. 9.--Head-discharge relationships obtained from tests on short, rectangular culverts equipped with weir sills and with a floor slope of 1 percent.

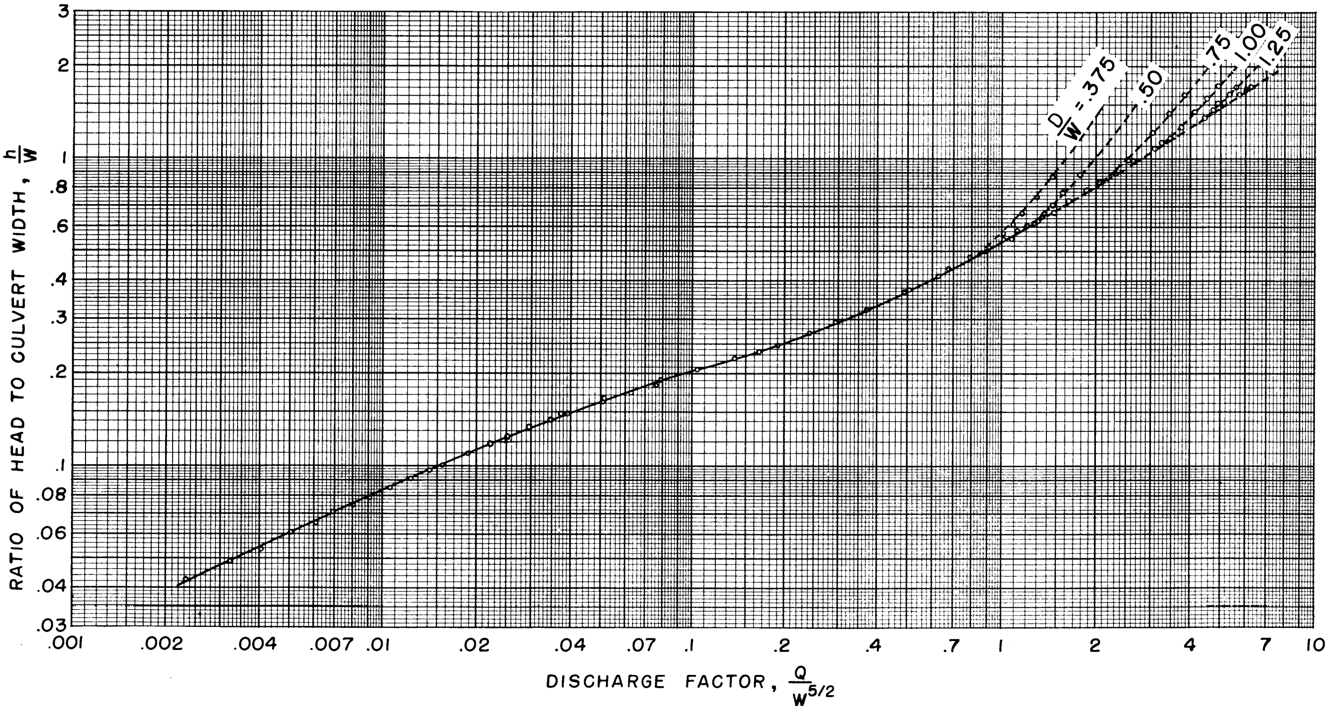


Fig. 10.--Head-discharge relationships obtained from tests on short, rectangular culverts equipped with weir sills and with a floor slope of 2 percent.

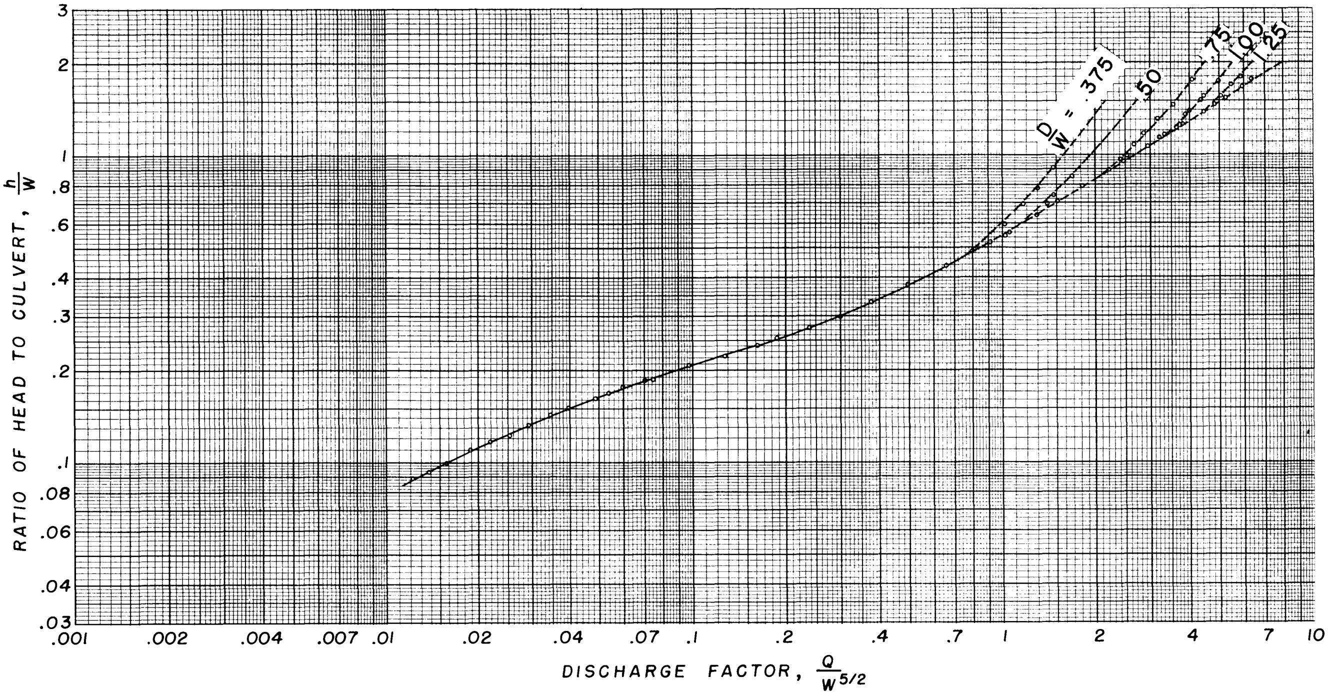


Fig. 11. --Head-discharge relationships obtained from tests on short, rectangular culverts equipped with weir sills and with a floor slope of 4 percent.

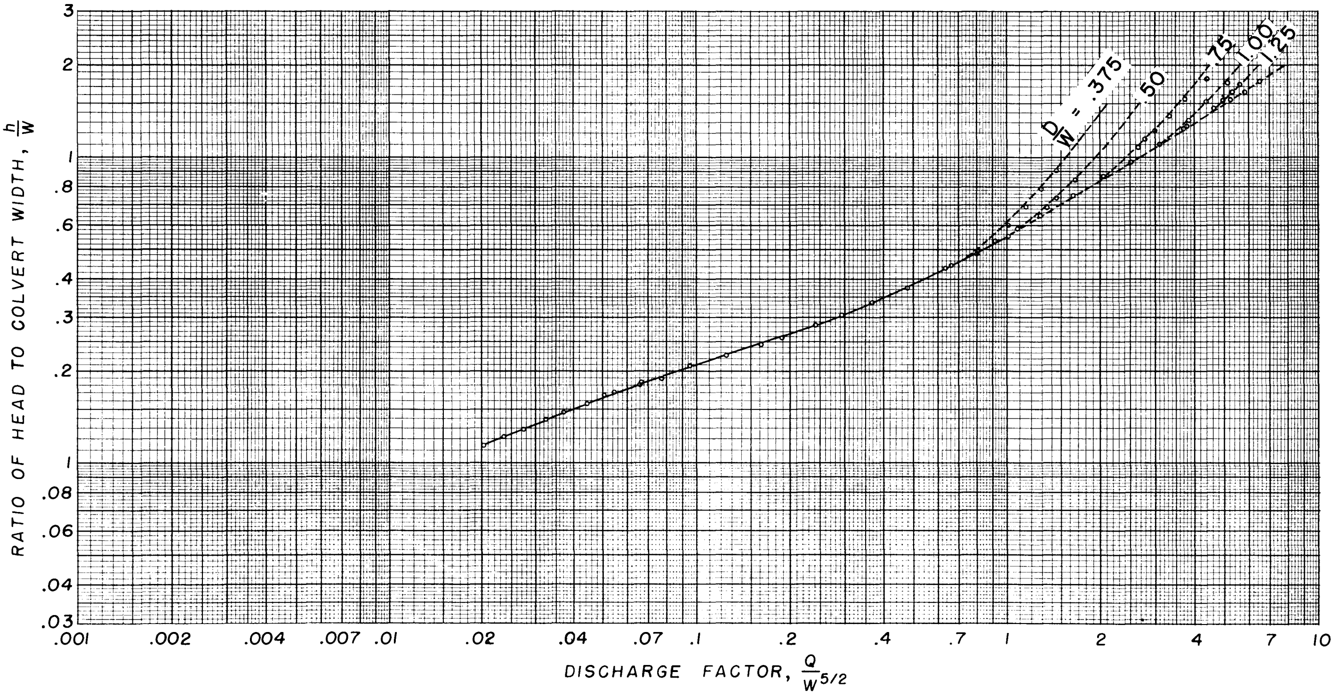


Fig. 12. --Head-discharge relationships obtained from tests on short, rectangular culverts equipped with weir sills and with a floor slope of 5 percent.

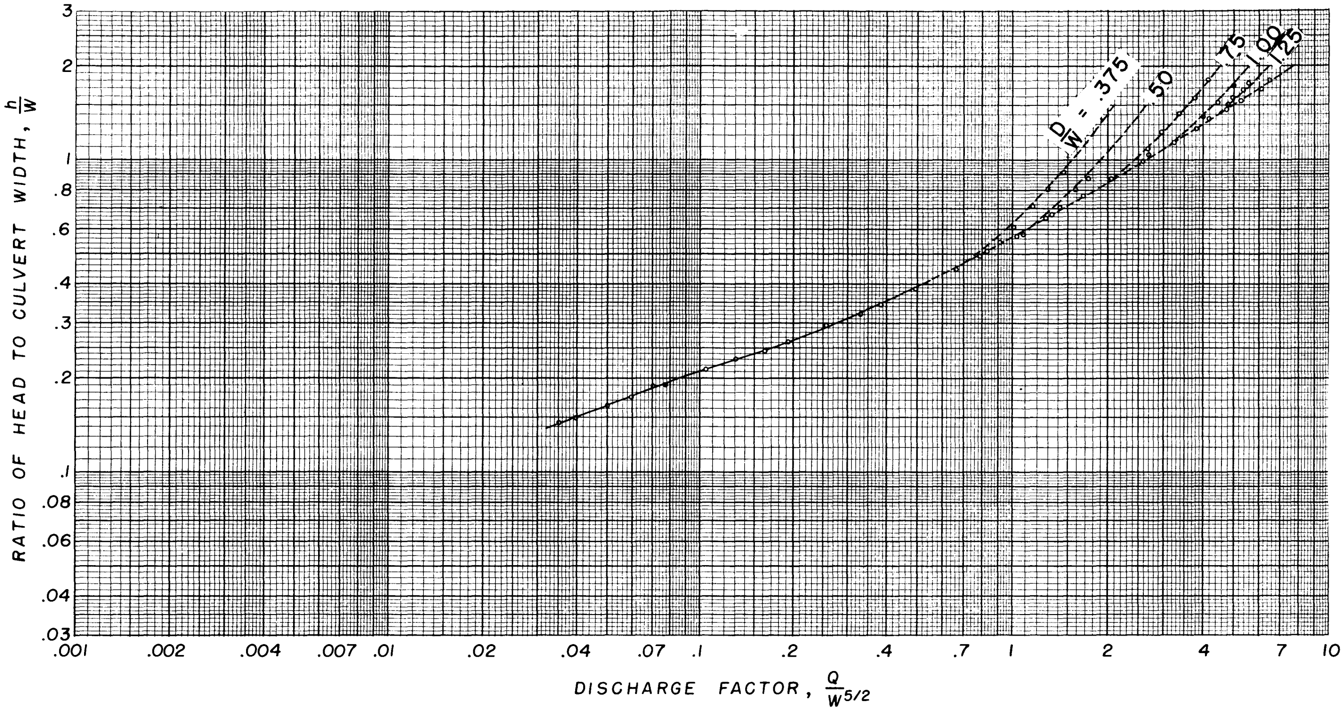


Fig. 13.--Head-discharge relationships obtained from tests on short, rectangular culverts equipped with weir sills and with a floor slope of 6 percent.

culvert slope on Figure 15. A straight line results on logarithmic paper with the equation $Q/W^{5/2} = .00038\ S^{2.4}$.

Head Measurement Within the Culvert

A study of the rating curves and the minimum measurable discharge as affected by slope indicates that head must be determined much nearer the weir sill throat if very low flows are to be measured. Villemonte solved this problem by placing a sump in the culvert floor and connecting it to the upstream gage well. This solution has not been seriously considered because of the difficulty of placing the connecting pipe without structural damage to the culvert. However, since there may be need to measure very low flows the data were examined to learn the best place to make the head measurement. The point finally selected after a study of flow profiles was located a distance W/2 upstream from the weir sill throat. The rating curve for the weir sill, with head measured at this point and still referred to the throat floor elevation, is given on Figure 16. The reason for the deviation of the rating for the 5 percent and 6 percent slope culverts probably is excess turbulence caused by a hydraulic jump below the culvert entrance and upstream of the point of head measurement. If this be true, the assumed hydraulic similitude may not exist and the model data for these two slopes may not correctly predict the behavior of the prototype.

The Head-Discharge Characteristics of Culverts Without Weir Sills

Although the original objectives of this study were concerned with the hydraulics of culverts equipped with weir sills, as the study progressed it became evident that there would be situations where weir sills would not be of much value or where they might not be needed. The latter condition would be true where peak flow rates alone were the object of the measurement. Since several such experiments were run during the course of this study, some data are available and will be presented here. However, the treatment was not as intensive as that for weir sills, so the data are limited. Only two ratios of depth to width were tested, these being .5 and 1.0. Two different slopes were used, since the ratings were for specific culverts. However, slope should not be a factor affecting the head-discharge relationship when slope exceeds critical. Thus the two ratings are plotted on diagram Figure 17. As pointed out in the general discussion of culvert hydraulics, two laws govern flow through culvert entrance: one is the critical depth law, and the other the sluice gate or orifice law. This is evidenced by the two lines on the plotting of head against discharge. However, below a value of h/W = .05 the relationship begins to deviate from the critical depth law. Apparently channel flow governs the relationship in this range.

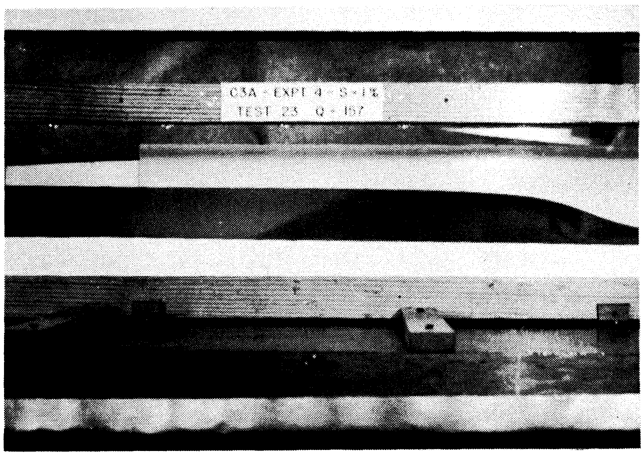


Fig. 14.--A profile view of a low flow passing over the weir sills and controlled by them.

The equation for flow with entrance not submerged is:

$$\frac{Q}{W^{5/2}} = 3.06 \left(\frac{h}{W}\right)^{3/2}$$

This compares well with the theoretical relationship for flow at entrance at critical depth, since the theoretical coefficient is 3.09.

When the entrance is submerged, the head-discharge relationship is given by the empirical equation:

$$\frac{Q}{W^{5/2}} = 4.65 \left(\frac{D}{W}\right)^{.917} \left(\frac{h-\frac{D}{2}}{W}\right)^{.6}$$

If the simple orifice flow law governed, the theoretical expression with a .6 contraction coefficient would be:

$$\frac{Q}{W^{5/2}} = 4.82 \frac{D}{W} \left(\frac{h-\frac{D}{2}}{W}\right)^{.5}$$

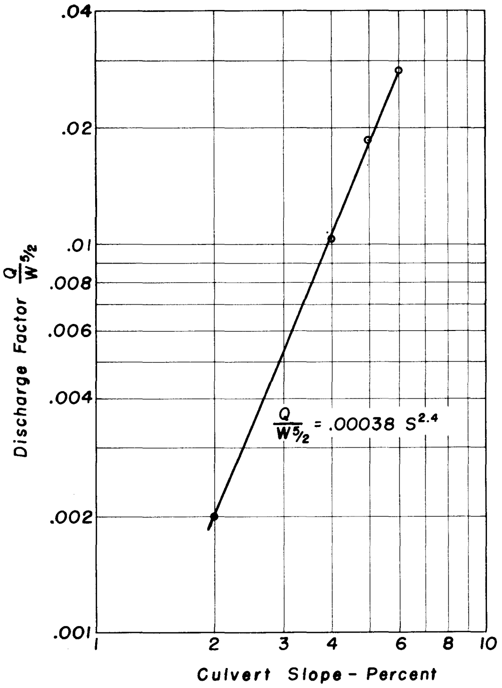


Fig. 15. --Minimum measurable discharge rates for culverts equipped with weir sills for various floor slopes.

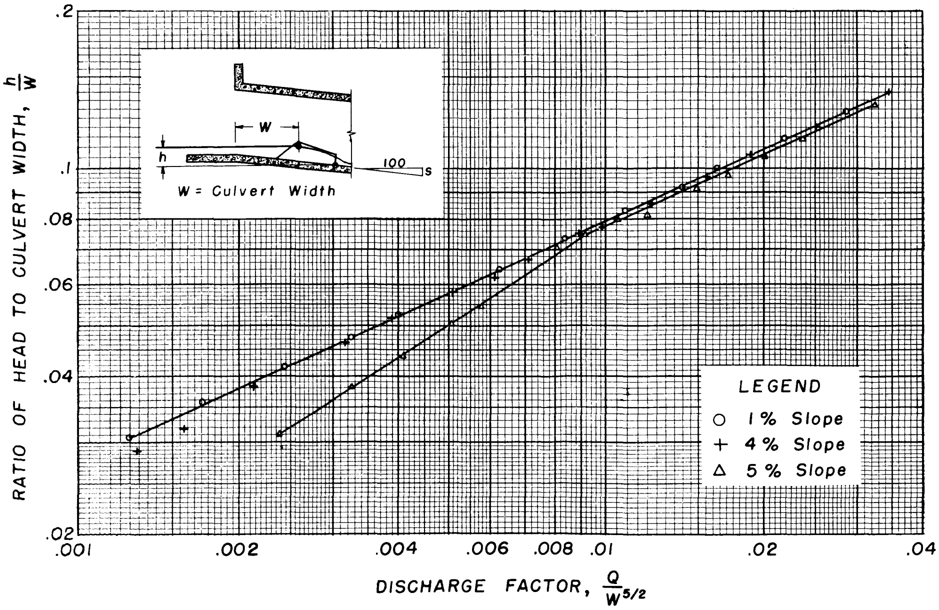


Fig. 16. --Head-discharge relationships for culverts equipped with weir sills with the point of head measurement a distance W downstream from the culvert entrance.

The agreement is approximate but very rough. One reason for the poor fit is that all the submerged flow tests were made over a very small range and very near the transition point. The equation, therefore, should not be used beyond the h/W range of the experiments. It should be satisfactory for interpolating the head-discharge relationships for intermediate values of the D/W ratio.

Application

The type of culvert suitable for a rate measuring device has been defined. Experiments have been run to determine the head-discharge relationship of culverts with and without weir sills. A discussion of the practical application of these findings will complete this section of the report.

Discussion of Critical Slope

It was stipulated at the outset that the culvert flow part full, have a free outfall, and that depth immediately downstream from the culvert entrance be less than critical. For culverts flowing part full and with relatively low entrance head, this requires a culvert floor slope greater than critical.

When normal flow depth is equal to critical depth for the given cross-section and discharge, the slope of the channel is then called critical slope. It can be determined as shown in the following example:

When flow depth is at critical depth in a rectangular cross-section, the velocity head of the flow is equal to one-half the depth. Then if d = depth of flow, $h_v = d/2$. Since

$$V = \sqrt{2 g h_v} \quad , \quad V = \sqrt{2 g \frac{d}{2}} = \sqrt{g d}$$

from Manning's formula

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

Let Slope, S = critical slope, S_c

$$\sqrt{g d} = \frac{1.486}{n} R^{2/3} S_c^{1/2}$$

$$S_c = \frac{g\, d\, n^2}{2.208\, R^{4/3}}$$

If g = 32.2 and n = .015, the equation becomes

$$S_c = \frac{32.2 \times (.015)^2 \times d}{2.208 \times R^{4/3}}$$

$$S_c = .00328 \frac{d}{R^{4/3}}$$

Values of Sc are given in Table III for flow at critical depth in culverts of various widths. This table will serve as a guide for a quick determination as to whether or not the culvert is steep enough. If the culvert is steeper than the tabular value for the given width and probable flow depth, it will be satisfactory. The expression "flow depth" is underscored to emphasize that the values of depth in the table are just that and not culvert depth. For a rough approximation, it can be assumed that flow depth is somewhat less than the depth of the culvert.

If the culvert is very rough, the critical slope will be greater than the tabular values. In that case another value for n can be assumed and the equation used to calculate the new values of critical slope.

Construction of Rating Tables

Culverts with Weir Sills. --After a culvert has been chosen to measure flow rates, a rating table is needed which gives discharge rates for the range of heads expected. A table arranged in the following form will be found convenient:

Rating Table for Culvert
Equipped with Weir Sills

Head	0	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0										
			(Discharge rates in body of table)							
0.1										
0.2										
			(Etc. to maximum value of h.)							

The values for the table can be calculated by direct use of the data plottings, by the equations provided, or by the use of dimensionless rating tables.* The equations can be used for any culvert within their range. However, they provide only part of the rating. The data plottings are limited to geometrically similar culverts; and, similarly, dimensionless rating tables are directly applicable only to culverts of similar slope and shape. Intermediate ratings will have to be determined by interpolation.

Table III. --Values of Critical Slope for Flow Depth Equal To Critical Depth in Culverts of Various Widths and Mannings' n = .015

	Culvert Width (feet)					
Depth	3	4	5	6	8	10
2	.0081	.0066	.0057	.0052	.0045	.0041
3	.0098	.0077	.0065	.0057	.0048	.0043
4	.0117	.0089	.0074	.0064	.0052	.0045
5	.0135	.0102	.0083	.0071	.0057	.0048
6	.0154	.0115	.0092	.0078	.0061	.0052

Culverts Without Weir Sills. --For culverts without weir sills, the preparation of a rating table is much simpler. If the culvert falls within the range of the experiments, the rating can be calculated directly from the equations given.

Pondage Corrections

The head on the culvert will measure the rate of flow through the culvert. This usually is not equal to the runoff rate from the watershed. The difference between the two is the rate of change of storage in the pond at the culvert. Therefore if the true runoff rate is desired it is necessary to make a pondage correction. Methods for doing this are given in a paper by Krimgold and Weber (4) and will not be repeated here. Suffice it to say that pondage corrections are often large, 50 percent not being unusual, so they cannot be ignored.

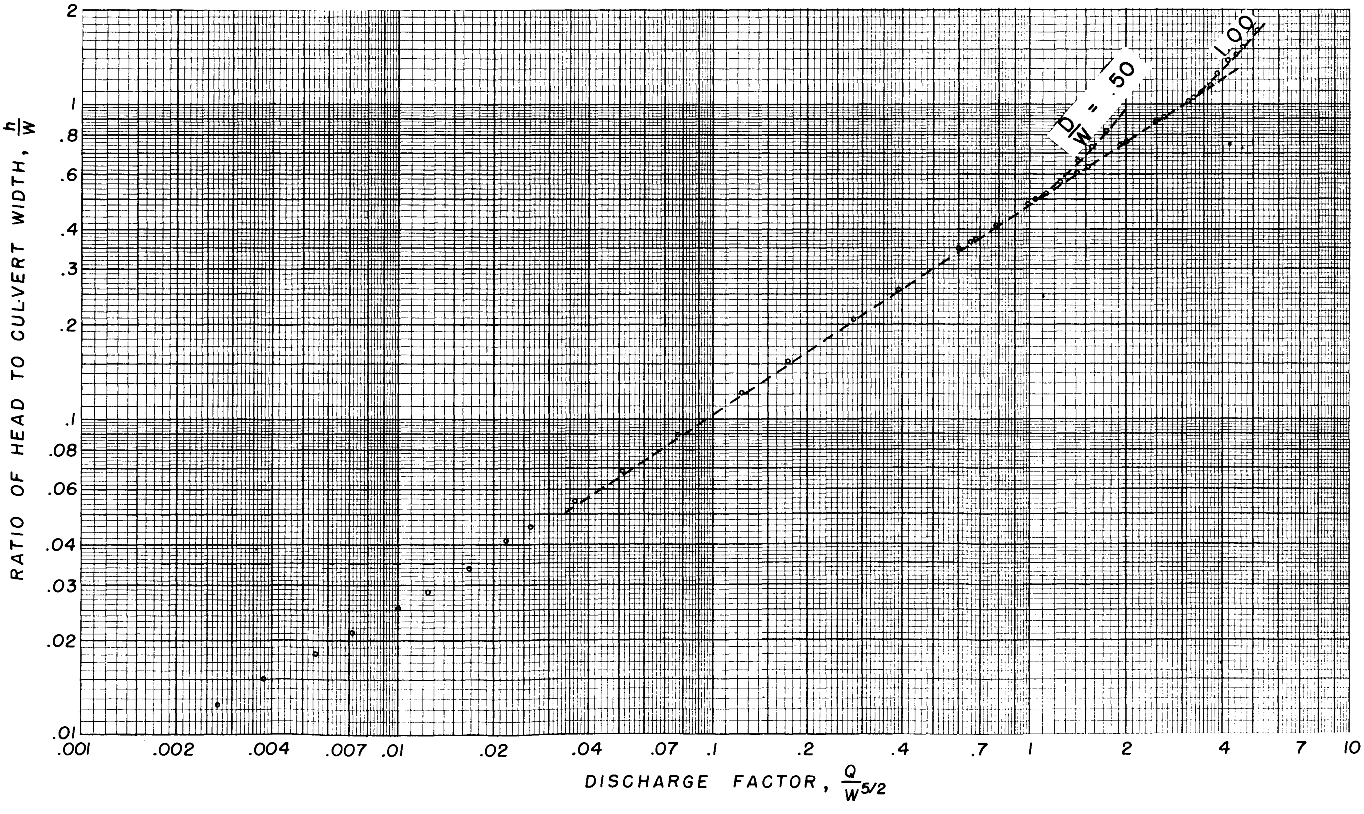


Fig. 17. --Head-discharge relationships obtained from tests on short, rectangular culverts with a floor slope of 2 percent. These culverts are not equipped with weir sills.

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* Dimensionless rating tables have been prepared and can be obtained by writing to the senior author.

Summary - Part I

The principal findings of this section of the report can be summarized in the following brief statements:

1. The rectangular highway culvert can be used for a flow rate measuring device if it flows part full and with free outfall.

2. The use of a Villemonte type weir sill can improve the accuracy of the measurement in the low flow range.

3. A standardized weir sill has been developed with all dimensions proportional to the width of the culvert in which it is placed.

4. A satisfactory location for the weir sill has been found to be with the throat a distance from the culvert entrance equal to 1 1/2 times the width.

5. The head-discharge relationship for various culverts equipped with weir sills has been determined by hydraulic model experiment.

6. Methods of determining the head-discharge rating for any culvert from the experimental data are given.

PART II: THE CONSTRUCTION AND INSTALLATION OF WEIR SILLS

The weir sill described in the first section is well suited to prefabrication of light weight aggregate concrete. This was the method used in the construction and installation of weir sills on the experimental watersheds. The experience gained in this operation may be of interest to those contemplating similar installations. The procedure therefore will be given in some detail.

Construction

The Form

The sills were cast in a simple right angle trough form. A sketch of the type used is shown in Figure 18. Placing two bulkheads, two chamfer strips, and a piece to shape the crest completes the form. The layout dimensions for various culvert widths are given in the next section.

Layout

The reference line for all layout dimensions for the weir sill is the theoretical crest. This crest is the apex of a sill without a rounded crest. This corresponds to the bottom corner of the trough form. The first step is to measure off the crest length of the weir sill in the bottom of the trough form. The four bottom corners of the sill are then laid off on the sides of the trough form. The procedure is illustrated in Figure 18. The values of the layout dimensions are given in Table IV.

The dimensions given in Table IV are theoretical. If the culvert width were exactly equal to the nominal dimensions and the floor perfectly flat, the sill would fit. This would allow no place for mortar to anchor the sill to the culvert floor. To allow for a mortar layer the sill should be made 1/2 inch less high than theoretical. This can be accomplished by dropping the four corner points 1/2 inch. If the culvert should be narrow at the sill location, it will be necessary to shorten the sill by cutting off at the large end. This is done by moving the large bulkhead inward the required distance. It is suggested that the culvert be carefully measured at the weir sill location before sill construction is started. These measurements will disclose deviation from the nominal dimensions. Tolerances on dimension on highway culverts seem to be around ± 1 inch.

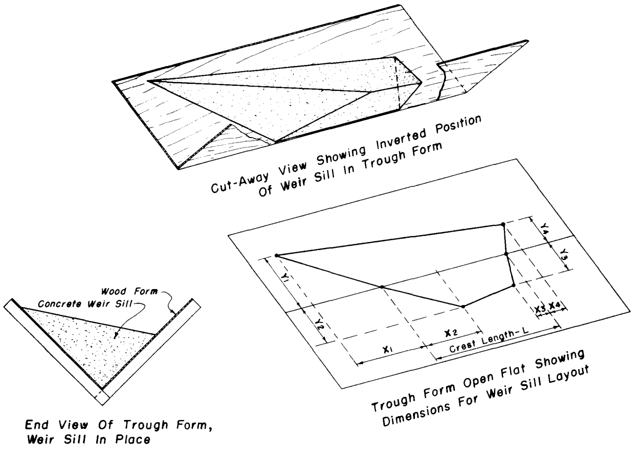

Fig. 18. --Details of right angle trough form for casting concrete sills. The values of the layout dimensions for culverts of various widths are given in Table IV.

When the four corner points and the two apex points have been located, the three sides of the triangle forming the bulkhead can be measured. This will determine the pattern for the construction of the bulkhead. The wall will have thickness so the edges will have to be cut on a slant in order that it will fit the trough form. A little trial and error will quickly indicate how it should be cut.

After the two end bulkheads have been installed, the rounded crest can be formed. For the larger weir sills this can be accomplished by curving a piece of sheet metal to the proper radius and nailing it to the sides of the trough form. For the smaller weir sills the crest can be a piece of pipe with anchors to fasten it to the concrete. A pipe size can be selected which will have an outside radius approximating that required for the crest. Chamfer strips are then placed to serve as screed for striking off the bottom of the weir sill.

Forming is now practically complete. However, if the weir sill is large it may have to be cast in two sections. The size section that can be cast will depend on its weight and on the equipment to handle it. In the case of the experimental watersheds the sills for the 8-foot-wide culverts were cast in two pieces. A plywood separator cut to fit and placed in the form will be all that is necessary. This need not be done with great care, but if a number of sills of the same size are being cast it will be necessary to identify matching halves. The two halves should be fastened together with a tie rod. The hole through the sill pieces for this tie rod can be formed by a well greased 1/2-inch pipe running through the end bulkheads and center separator.

Two more items are needed in the form before the sill is cast. One is a reinforcing rod to strengthen the slender upstream corner. The other is a U hook imbedded into the concrete to provide something to fasten the hoist to when the hardened sill is pulled from the form. A good oiling of all parts of the form in contact with the concrete completes the forming.

Materials

The sills were cast of a concrete having a light weight aggregate. The one used in this case was an expanded shale known commercially as "Featherlite." This yielded a concrete having a density of about 75#/cubic foot. There are lighter weight aggregates, but these would not provide the required strength or resistance to weathering.

Installation

The sill pieces were lowered onto the apron of the culvert and rolled into place on pipe rollers. The two pieces of a

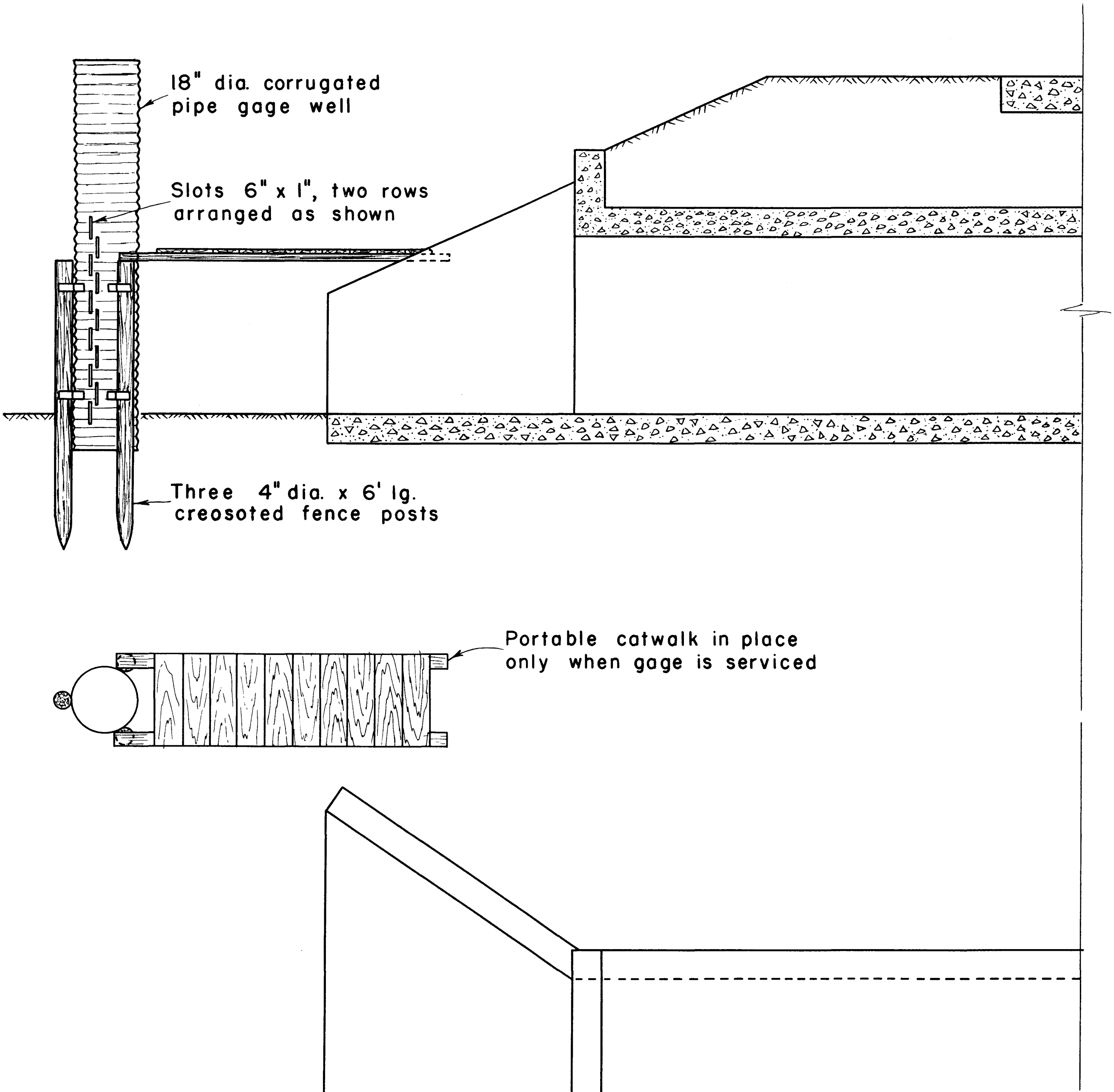

Fig. 19. --Details of gage well for depth recorder float. This is the type of well used on the experimental watersheds.

Table IV. --Layout Dimensions for Weir Sills. (All dimensions in inches except culvert width.)

Culvert Width (feet) W	Crest Length L	X_1	Y_1	X_2	Y_2	X_3	Y_3	X_4	Y_4	Crest Radius
3	24.30	13.45	11.60	10.66	8.19	2.23	6.58	2.82	5.86	1.12
4	32.40	17.94	15.46	14.21	10.92	2.97	8.77	3.76	7.81	1.50
5	40.50	22.42	19.33	17.76	13.65	3.72	10.96	4.70	9.77	1.88
6	48.60	26.90	23.20	21.31	16.38	4.46	13.16	5.64	11.72	2.25
7	56.72	31.40	27.06	24.87	19.11	5.20	15.35	6.58	13.68	2.62
8	64.80	35.88	30.93	28.42	21.84	5.95	17.54	7.52	15.63	3.00
9	72.88	40.36	34.80	31.96	24.57	6.69	19.74	8.46	17.59	3.38
10	81.02	44.84	38.67	35.51	27.30	7.42	21.92	9.40	19.44	3.75
11	89.10	49.32	42.53	39.06	30.02	8.18	24.11	10.34	21.50	4.12
12	97.20	53.80	46.39	42.61	32.77	8.92	26.30	11.28	23.45	4.50
14	113.42	62.75	54.12	49.71	38.21	10.41	30.70	13.16	27.36	5.25
16	129.60	71.76	61.86	56.84	43.68	11.90	35.08	15.04	31.27	6.00

(See Figure 18 for definition of dimensions.)

sill were bolted together with a tie rod with small separators between the pieces the thickness of the separator used in casting. The sills were blocked up with wedges and moved about until they were correctly placed in the culvert. A wet mortar was then forced under the sills, into the space between the two halves, and into the space between the culvert wall and the end of the weir sill. The wedges and separators were removed after the mortar had set. Some pointing up and hand rubbing of the sills completed the installation.

A steel plate is placed across the throat end of the weir sill. This plate protects the edge of the concrete weir sill at the throat and preserves the true dimension at this point.

Performance

The experimental weir sills have been in place about a year and have proved quite satisfactory. They have not been displaced nor have they cracked. The sills have caused some additional deposition to take place on the culvert apron because of lower approach velocity. However, the weir sill throat has stayed clean.

The Recording Gage Well

The depth of water flowing through the culvert should be continuously recorded. This requires a recording instrument and a well for its float. Only the gage well will be discussed.

The original calibration was made with the head measurement 1 1/2 W upstream. This was a sufficient distance upstream to get out of the draw-down range near the culvert entrance. The practical place for the gage well installation in the field is some place near the end of a wing wall. Generally this provides a distance upstream of more than 1 1/2 W, which is on the safe side.

A very simple type gage well was used on the experimental watersheds. The details are shown in Figure 19. The walkway from road shoulder to the well is portable and is in place only during the servicing of the gage. This type of well would not be satisfactory if considerable sediment were carried by the flow. Deposition would occur in the well, which would hold up the float and give an erroneous record. Since the experimental watersheds were in grassland, sedimentation has been a minor problem.

SYMBOLS

C_d	A coefficient of discharge
D	Depth of culvert cross-sections
d	Depth of flow in culvert
g	Acceleration of gravity
h	Head above weir sill throat, the difference in elevation between culvert floor at weir sill throat and the level water surface upstream of culvert entrance
h_e	Head above culvert entrance, head referred to culvert floor at entrance
h_o	Head above center of culvert opening
h_v	Velocity head = $V^2/2g$
n	Coefficient of roughness in the Manning channel flow equation
Q	Rate of flow in units of volume per unit time
R	Hydraulic radius of channel flow in culvert
S	Slope of culvert floor, percent
S_c	Critical slope for culvert
V	Velocity of flow
W	Width of culvert cross-section

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