

# Model Studies of Tapered Inlets for Box Culverts

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Model studies of box culverts on steep grades were conducted in cooperation with and sponsored by the Oregon State Highway Commission and the Bureau of Public Roads. Objectives of the experiments were: (1) clarification of the theory of operation of box culverts and (2) modification of the design of the Oregon State Highway standard inlet in order to increase the over-all effectiveness of the culvert as a drainage structure.

Test data were taken from a 1:12 scale model of a 4- by 4-ft. box culvert 82 ft. long. This model was provided with a trapezoidal approach channel and a section of embankment slope with means for installing different types of inlets without major changes in the model.

The program consisted of testing three basic types of inlets: the Oregon State Highway Commission standard inlet with no flare or taper, an inlet with a taper in the sides and top of 1 to 10, and an inlet designed primarily for operation under entrance control. All three of these inlets were provided with wing walls at an 8 to 12 angle with the axis of the culvert. Essentially, the initial testing consisted of three general types of comparisons: (1) analysis of the operation of all three inlets in nonsubmerged states, (2) operation of the standard inlet as a sluice gate, and (3) full-flow operation of the standard and tapered inlets.

The nonsubmerged operation of the inlets followed the theory of entrance control with critical depth, and it was indicated that designs for entrance control could be based upon critical depth theory with little or no modification. In the submerged state the standard inlet operated normally as a sluice gate, while the 1:10 tapered inlet showed no sluice contraction and flowed full automatically as it became submerged, with a resultant increase in flow as compared to the standard inlet. It was discovered that the increase in capacity was the result of: (1) the shift in the lower energy reference from inlet to outlet of the culvert and (2) the increase in the effective area of flow due to elimination of the contraction at entrance which occurred with the standard inlet. Test results indicate that the standard inlet flowing as a sluice can be treated with existing orifice theory and that existing theory regarding pipe flow can be used for the full-flow conditions of the tapered inlet.

It was discovered that the culvert with standard inlet could be made to flow full artificially by temporary elimination of the sluice contraction and would remain full so long as air was prevented from entering the inlet section. Under ordinary full operation, however, air admitted through the action of vortices in the upstream pool caused the culvert to revert to sluice operation.

A practical approach to assurance that the culvert barrel would flow full and remain full upon submergence of its inlet was to modify the inlet to eliminate the contraction at that location. The procedure followed was to form a taper in the entrance by extension of the top slab of the culvert upstream from the parapet wall over the wing walls and the extension of a portion of the wing walls to meet the

top slab; thus the tapered section was formed by the wing walls and the top slab. The shortest practical length of extension was determined experimentally to be that required to produce an area ratio of entrance to culvert barrel of 2 to 1. The resulting inlet design showed a substantial increase in capacity, upon inlet submergence, over any other inlet tested. Effectively, this inlet allowed no change in headwater level from the discharge required to just submerge the inlet to that required by the culvert flowing full. With the culvert on a 4-percent grade and operating at the head of submergence, the modified inlet allowed an increase of approximately 100 percent over that obtainable from the culvert equipped with the standard inlet. Experiments with flat, 4-, and 8-percent grades confirmed a hypothesis that, within limits, the ratio of areas required for the foregoing type of operation is the same, regardless of the slope or angle of wing walls.

Conclusions derived from the experiments were: (1) a significant saving of materials could result from designing culverts on steep grades to flow full, (2) the formation of a tapered inlet by the extension of the top slab and wing walls would be a practical solution to the problem of assuring full flow, and (3) by proper application existing theory is adequate for the design of culverts on steep grades.

● COSTS of drainage structures are known to be high percentages of highway construction costs, and of these structures box culverts comprise a significant portion. For the biennium from July 1950 to June 1952, the State of Oregon alone spent \$676,000 on box culverts as compared to \$8,500,000 for all highway structures and a total of \$38,000,000 for actual highway construction. Thus, any improvement in the design of box culverts which would allow reductions in size for given installations could result in major savings in construction costs.

With these savings in mind, engineers of the Bureau of Public Roads in Division 8 employed an improved inlet design for box culverts installed in forest highway projects as early as 1948. The improvement, which was in the form of an enlargement of the entrance in the form of a taper, was prompted by field observations that many box culverts on steep grades flowed less than half full, even when operating at maximum discharge with deeply submerged entrances. Subsequently, several culverts with enlarged entrances installed along the Pacific Highway near Canyonville, Oregon, were subjected to severe floods, and the operation of one of these was much better than had been expected on the basis of theoretical analysis.

In the meantime, the Oregon State Highway Commission became interested in using this type of inlet design on some of their

box culverts. The unexpectedly good operation of the tapered inlet culverts on the Canyonville project (constructed by the Bureau of Public Roads) clearly emphasized the need for a thorough understanding of the hydraulics of this type of structure. As a result, the Oregon State Highway Commission and the Bureau of Public Roads agreed to jointly sponsor laboratory tests to investigate the problem by means of scale models. An agreement was entered into with Oregon State College to conduct the investigation, and work was started in June 1951 as an engineering experiment station project. The laboratory experiments were completed in November 1952.

The model studies reported here were made on the basis of two general objectives. The first of these was to investigate the theory of operation of the Oregon State Highway Commission standard box culvert on steep grades with a free overfall at the discharge end. This investigation was intended to include studies of both non-submerged and submerged inlet operation. The second objective was to determine means for improving the effectiveness of operation of this culvert barrel by means of tapered inlets. In the progress of the experiment, this objective was modified to apply to determination of an economical means of causing the culvert barrel to flow full upon submergence of the inlet. A corollary objective was to investigate some-

what the effect of the geometry of the inlet section (with wing walls) upon the operation of the culvert.

The model studies reported here were conducted with box culverts on steep and flat grades and having free overfalls, and the results of these experiments are necessarily applicable only to structures in this category.

**THEORETICAL CONSIDERATIONS**

The operation of a culvert through its overall range of discharge can be subdivided into two phases, each of which is dependent upon a different head-discharge relationship. The first of these applies through the range of discharges during which the inlet is not submerged. If the

a culvert by knowledge of the width at which critical depth should theoretically occur. The following equation, based upon the relation of critical depth with discharge for a rectangular cross section, makes it possible to compute the upstream pond level, above the flow line at the control section, for a given discharge per foot of width of barrel (1):

$$H = 1.5(q^2/g)^{1/3} \dots\dots\dots (1)$$

If the entrance of a culvert is square edged, its submerged operation may be considered analogous to that of a sharp-edged orifice, discharging horizontally, on the premise that the momentum of the fluid approaching the entrance nonaxially will cause a contraction in the area of flow

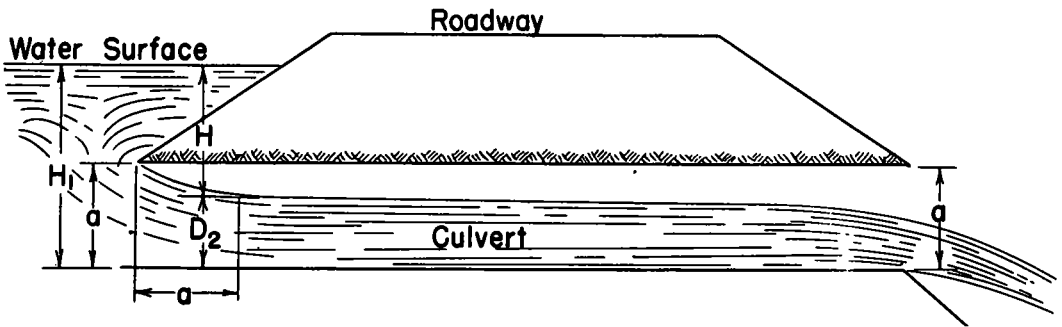


Figure 1. Definitive sketch for sluice-type operation of a culvert.

culvert is on a steep grade and the flow in the upstream pool is subcritical (the ordinary case), critical depth will occur in the region of the entrance (1) with an accompanying acceleration of the flow. The location of this depth will be near the entrance to the uniform barrel in the case of a continuous flow line and near the break in slope in case there is a drop in the flow line.

Since the flow in the culvert barrel must be supercritical, the effects of roughness and slope of the culvert barrel cannot be reflected upstream to the entrance; consequently, the geometry of the entrance alone (specifically the width at which critical depth occurs) determines the quantity of flow carried by the culvert for a given upstream pool elevation. Thus, when the inlet of a culvert on a steep grade is not submerged, the structure can be said to operate under critical depth control at the entrance. In most cases it should be possible to compute the discharge through such

downstream from the opening. It has been shown that, in the case of an orifice, the contracted area (or "vena contracta") is the controlling area with respect to discharge computations (2). The energy available for producing flow is, in this instance, a function of the head measured between the center line of the orifice (the location of the pressure line in the case of a nonsupported jet) and the upstream energy grade line,

$$Q = A_j C_v \sqrt{2gH} \dots\dots\dots (2)$$

where  $A_j$  represents the area of the jet at the vena contracta,  $C_v$  the coefficient of velocity of the orifice.

For a culvert with a square-edged entrance, if the flow downstream of the entrance is unobstructed, it is reasonable to assume that approximately the same relationship will hold. In the ordinary case, the flow line is more or less a continuation of the upstream channel flow line, and

wing walls are provided at the sides of the entrance so that only a top contraction should occur, as in a sluice gate. The flow producing energy (see Fig. 1) would then be measured between the upstream energy grade line and the water surface at the contracted area, with the realization that the hydraulic grade line (or pressure line) is in the water surface in the case of a supported jet; thus

$$Q = W D_2 C \sqrt{2g H_2} \dots\dots\dots (3)$$

in which  $W$  is the width at the vena contracta,  $D_2$  the depth at the vena contracta,  $C$  the coefficient of velocity, and  $H_2$  the available

head. In all cases, however, there is some loss of head in the jet, so in terms of Equation 3, the coefficient of discharge would be:

$$C_d = \frac{D_2}{a} C_v \dots\dots\dots (4)$$

where  $D_2$  is the depth at the vena contracta and  $a$  is the height of the opening.

In contrast to the sluice operation of the submerged inlet, operation of a full culvert barrel utilizes not only the energy available with respect to its entrance elevation, but any additional head provided by the fall in the length of the barrel. Furthermore, the area of flow is the total area of

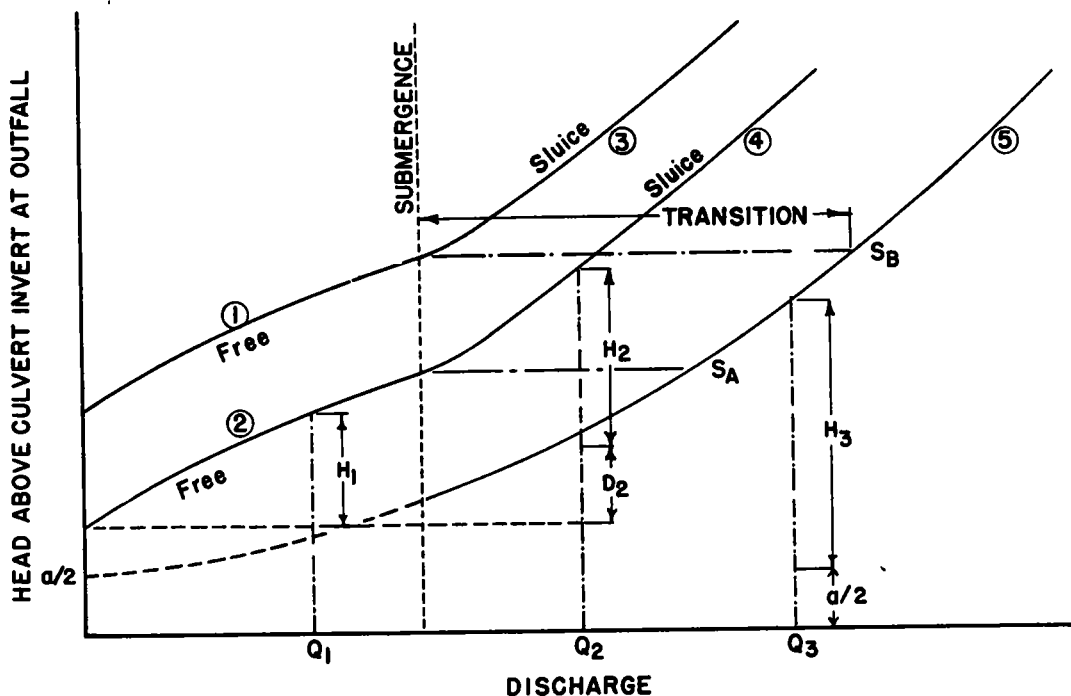


Figure 2. Rating curves for typical culvert installations.

head. Both Equations 2 and 3 can be derived upon the basis of the energy equation and the continuity equation, taking into consideration all velocity and pressure heads. A more rational concept of Equation 3 is that the head  $H_2$  is the energy available for conversion into velocity head, measured from a datum through the water surface at the vena contracta, and that if there were no losses in the jet, the coefficient of discharge of the sluice would be the decimal fraction of the area of the opening that was available at the contrac-

tion. In all cases, however, there is some loss of head in the jet, so in terms of Equation 3, the coefficient of discharge would be: the culvert, which gives an opening considerably greater than the contracted area of the sluice. As with a short tube, however, if the entrance of the culvert is square edged, the top contraction will occur even with the barrel full, with a consequent low pressure area in the vicinity of this contraction (3). Continuing the analogy with a short tube, if air is admitted to the contraction, the opening will revert to sluice operation, providing there is no obstruction to the flow downstream from the entrance.

The energy available to produce flow when the culvert barrel is flowing full should be measured from the upstream energy grade line to the pressure line at the discharge end of the culvert, which line will be located near the center of the jet in the case of free overfall, provided that the velocity head is not less than 0.8 times the height of the culvert (6), or in the water surface in the case of a supported jet. The discharge, then, will be a function not only of the entrance loss and barrel friction loss, but of the slope and length of the culvert barrel.

With this information it is possible to make an analysis of the operation of a culvert with its inlet submerged, on the basis of (1) operation analogous to a sluice gate and (2) operation analogous to a pipe flowing full. Rating curves for typical culvert installations are given in Figure 2, showing the discharge characteristics for two culverts of the same length on grades  $S_A$  and  $S_B$ .

Three types of curves are shown in this figure; one covering the range of discharges during which the inlet is not submerged, another showing the operation as a sluice gate, and the third a single curve covering the possible total range of full flow. Curves 1 and 2 originate at the invert elevation of the culvert entrance and assume that critical depth control occurs at that point. Curve 5 is not influenced by the grade of the culvert because the full flow discharge is determined by the difference in elevation of the water surface at the inlet and the position of the pressure grade line at the outlet, which is taken as a height of  $a/2$  above the outfall invert. The effective head for producing discharge is shown for each case, and the formulas for discharge are as follows:

Curve 2 (critical depth control):

$$Q_1 = W (g) \left[ \frac{H_1}{1.5} \right]^{3/2} \dots \dots \dots (5)$$

Curve 4 (sluice):

$$Q_2 = C_d A (2g H_2)^{1/2} \dots \dots \dots (6)$$

Curve 5 (full):

$$Q_3 = A [2g (H_3 - \text{losses})]^{1/2} \dots \dots (7)$$

Equation 4 and Figure 2 ignore the drop in the flow line between the entrance of the

culvert and the vena contracta due to the grade of the culvert. In very steep grades this would have to be considered.

The ordinary box culvert with the Oregon standard inlet and with free outfall should follow Curves 1 and 3 or 2 and 4, depending upon the grade of the barrel. If the culvert can be made to flow full upon submergence of its inlet, the discharge under a given head should be increased considerably, as shown on the chart; the amount of increase being dependent upon the grade of the culvert and the length of the culvert barrel.

In the transition range between entrance control and full flow, the quantity of flow required by a full culvert barrel would, in the cases shown, be in excess of that supplied by the approach channel, and the result would be an intermittent free-full condition, during which the headwater level would be restricted to a height equal to or less than the height of the culvert entrance. Thus the portion of the full-flow curve available for use at a given grade would be that part above a horizontal line drawn from the head of submergence of the culvert.

Discharge calculations for culverts operating in any of the three manners previously discussed can be made from Equations 5, 6, and 7, provided that proper choice is made of coefficients and that allowance is made for the grade and length of the culvert.

The model-to-prototype scale ratio chosen for these experiments was 1 to 12, which is quite conservative for this type of study. In most cases the water changed elevation rapidly, indicating that the forces of gravity and inertia are the predominant forces acting. Since the relationship between these forces is defined by the Froude number, scale ratios for amplifying various quantities such as depth, velocity, and discharge to prototype scale can be derived by reference to the equality of Froude numbers. There may be some question as to the validity of the discharge scale ratio in the case of the barrel flowing full; because of the increased importance of viscous forces due to fluid friction. However, a sufficiently practical evaluation of full-flow discharge through a full-scale culvert can be made on the basis of existing data on pipe friction factors and entrance loss coefficients, and there is no particular need for consideration of scale errors in model roughness which would affect simi-

larity relationships with respect to full-flow conditions.

There can be little doubt as to the similarity of operation of the model inlets to the operation of geometrically similar full-scale culvert inlets. Therefore, the results from entrance control conditions in the model experiments should be representative of the operation of full-scale culverts of similar construction, and these results should be of value in future design.

### THE CULVERT MODEL

The hydraulic model upon which these experiments were made comprised an in-

the end section containing the embankment slope. Channel slope adjustments were made possible by means of blocks and four leveling screws.

The inlet sections, which will be described later, were connected by flanges to a 4- by 4-in. Plexiglas culvert barrel 6 ft. long. The barrel was supported by a steel I beam, which was provided with leveling screws at the ends for slope adjustments. Free overfall from the culvert barrel was directed into a box equipped with a triangular weir which discharged into a sump. The sump used was a tank calibrated for volumetric measurements and was employed at the start of the ex-

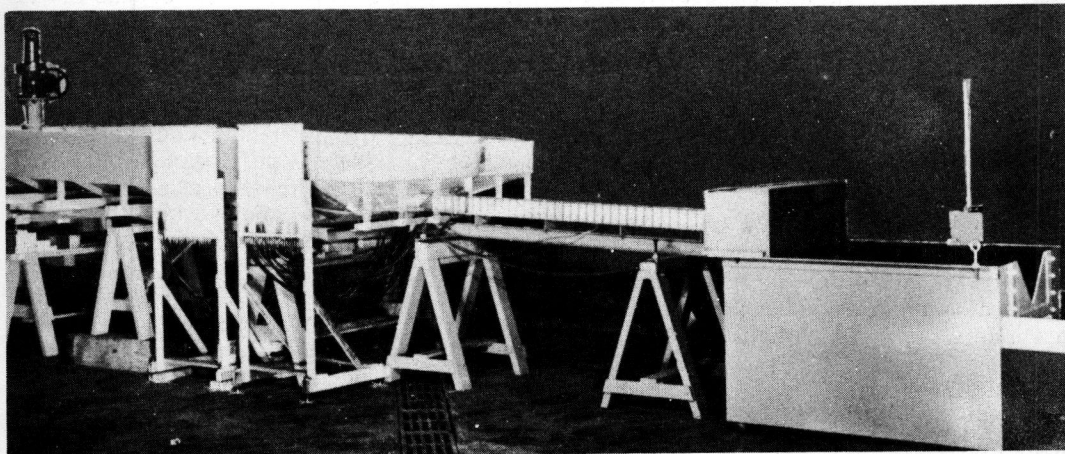


Figure 3. General view of model.

take box, approach channel, culvert inlet and barrel, and a triangular weir, as shown in Figure 3.

The intake box was supplied through a 4-in. line from the laboratory pumping system, and was 4 by 5 by 3 ft. deep, the 5-ft. side being connected to the approach channel, the bottom of which was approximately  $1\frac{1}{2}$  ft. above the bottom of the box.

The approach channel was 10 ft. long and 26 in. wide at the bottom, having sides 16 in. high with slopes of 2 to 1 at the bottom and the remaining 8 in. vertical. The channel terminated in a simulated section of highway embankment with a 2 to 1 slope for the first 8 in. of height and a vertical end wall. The embankment slope was cut to receive flanged sections, forming flush joints at the wall and floor. In the construction of the channel, use was made of  $\frac{1}{2}$ -in. exterior plywood (painted) on wood and steel framing, and Plexiglas for

periments for calibration of the weir.

Inlet sections tested in these experiments can be compared by reference to Table 1. The only major deviation from the Oregon State Highway Commission plans was that for all inlets the wing walls were extended to meet the toe of the embankment, which is not the usual case in practice.

Adjustments in slope were made with an engineer's level and a sharp-pointed rod divided into tenths of an inch. All readings were taken to an estimated accuracy of 0.01 in.

### Hydraulic Measurements

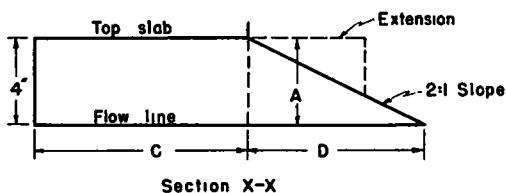
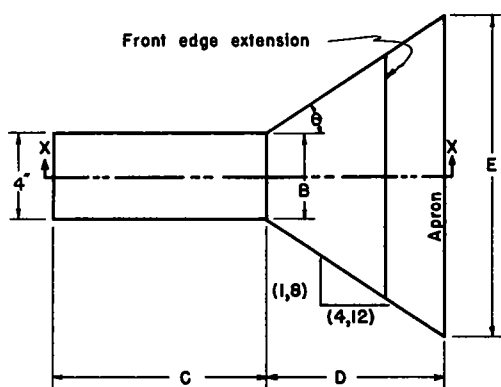
Discharge. A 90-deg. triangular, sharp-crested weir with a capacity of approximately 0.9 cu. ft. per sec. was used for the measurement of discharge, in conjunction with a hook gage readable

TABLE 1  
Inlet Models

All dimensions in inches

No.	Entrance			C	$\theta$	Apron		Remarks
	A	B	Area			D	E	
1	4	4	16	10	8:12	8.25	15	Oregon State Highway Comm. standard (Dwng 9656). Control inlet for experiments
2	5	6	30	10	8:12	10.25	20	Standard tapered inlet (Dwng 9656). 1:10 side and top tapers
3	4.63	4.63	21.4 See Note 6	5.27	8:12	9.21	17.3	Developed by Hydraulics Branch, Bur. of Pub. Roads (Hydraulic Information Circ. No. 2)
4	4	8.63	34.6	13.5	8:12	4.75	15	Modification of No. 1. 3.5-in. top slab extension. See Note 5
5	4	4	16	10	1:4	8.25	8.12	Modification of No. 1
6	4	6	24	14	1:4	4.25	8.12	Modification of No. 5. 4-in. top slab extension.
7	4	6.75	27	15.5	1:4	2.75	8.12	Modification of No. 5. 5½ in. top slab extension

1. Actual dimensions taken from inlet models.
2. All models constructed of  $\frac{1}{8}$ -in. Flexiglas.
3. Flanges provided for joining inlets to 4- by 4-in. culvert barrel.
4. Parapet wall the same height for all inlet models.
5. Top slab extended parallel to flow line between wing walls, and wing walls built up to meet extension.
6. Drop of 1.76 in. in flow line within inlet section (dimension C, below).



to 0.001 ft. installed in a stilling well. The weir was calibrated in place by use of a volumetric tank in which a rise of 1 ft. represented an increase of 170.7 cu. ft. of water. The rate of rise of the water in the tank was measured by an electrical-contact point gage and a stop watch, with readings taken to provide an accuracy of three significant figures. A sufficient

number of weir-hook gage readings were taken for each run in the model tests to provide a reliable average observation, and the discharge values were read from a rating curve prepared from the calibration.

**Pressure and Water Level.** Pressure and water level indications were taken

from piezometer tubes connected to the bottom of the channel and culvert. The piezometer holes were made by a No. 40 drill, the connecting tubing was  $\frac{1}{4}$ -in. I. D. transparent "Tygon" and the piezometer tubes were  $\frac{1}{2}$ -in. I. D. glass. Special precautions were taken to remove burrs from the edges of the holes, and where possible, the holes were drilled from the inside out with a drill press before assembly of the model. Air was eliminated from the tubing before each test by agitating the water in each tube with a syringe until visual inspection revealed the absence of bubbles.

proach channel at that location. The remaining connections were made to the apron, inlet, and culvert barrel; their locations for the various test runs are given in the appendix.

The piezometer readings were taken photographically with a tripod-mounted Kodak "Tourist 800" camera provided with an f/4.5 Anastar lens, using Plus-X 620 roll film. It was found that roll film was most satisfactory for the purpose (for most cases), because of the speed usually required to ready the camera for the next picture. In location of the camera, par-

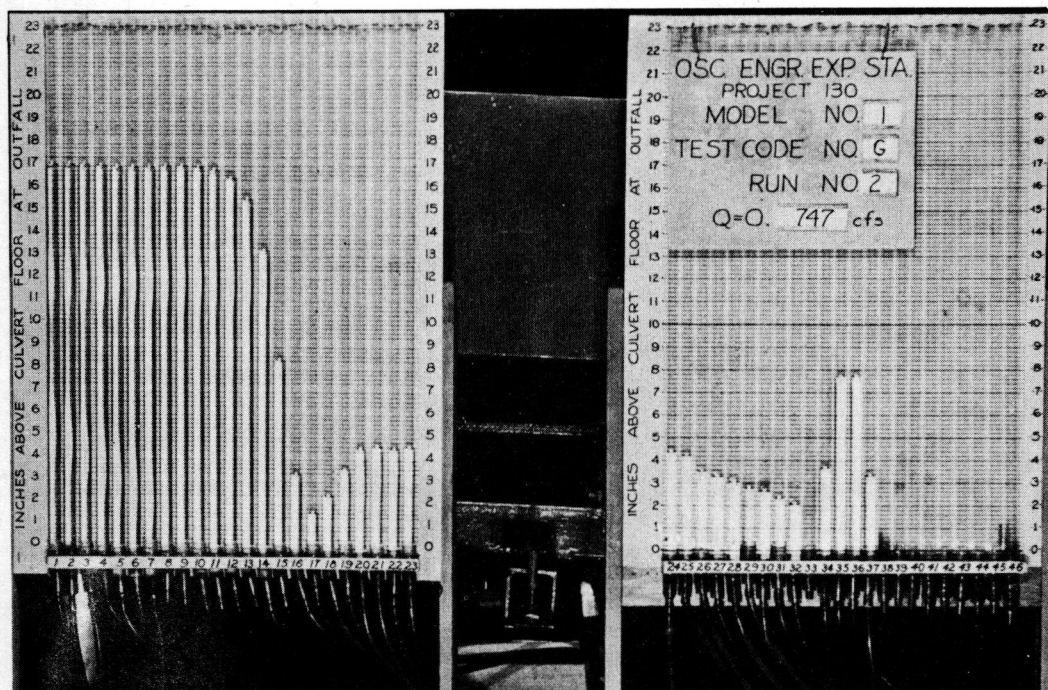


Figure 4. Typical data picture for Inlet 1 flowing full, showing piezometer boards and test run designations. Tubes 2 and 10 to 32 inclusive are along centerline of channel and culvert.

The glass tubes were mounted in two banks on boards provided with 0.2-in. divisions which were ruled with india ink on white acetate. To provide protection against water damage, the boards were painted with clear synthetic enamel. The piezometer boards were mounted on standards provided with leveling screws.

Three piezometer connections located in the approach channel were used for indications of the upstream water level. These connections were 18 in. upstream of the toe of the embankment slope and were at the center and sides of the invert of the ap-

proach channel at that location. The remaining connections were made to the apron, inlet, and culvert barrel; their locations for the various test runs are given in the appendix.

Because of the requirements for enlargement (in many cases a single reading of the two boards was made on one quarter of a  $2\frac{1}{4}$ -by  $3\frac{1}{4}$ -in. negative and then enlarged to 5 by 7 in.), correct exposure and uniform lighting were necessary for elimination of graininess in the negatives; consequently,



the exposures were measured by a meter and a neutral-gray test card. No coloring of the water in the tubes was required, because the lighting delineated the meniscus at the top of each water column. Satisfactory readings were subsequently taken from 5- by 7-in. glossy prints made on average contrast paper. Figure 4 shows a sample photograph to demonstrate the method of identification of runs.

Approximate water level readings in the culvert barrel were provided by  $\frac{1}{2}$ -in. divisions in blackpaint parallel to the axis of the culvert and 2-in. divisions perpendicular to the axis. When backed by white paper, the lines were quite useful for interpretation of photographs taken to record the general flow patterns.

### Accuracy of Measurements

Before discussing the accuracy of the measurements it may be well to describe the flow conditions in the approach channel for the three culvert grades studied.

For all grades, a pool of some variety was formed at the entrance of the culvert. With the culvert on a flat grade, a pool formed for the length of the channel, so that no great turbulence occurred. Although the velocity distributions were notably nonuniform in the channel, the kinetic energy in the pool was negligible.

When the model was on a 4-percent grade, the flow conditions were much more widely varied. For the small discharges, a hydraulic jump occurred in the approach channel, its distance from the culvert inlet varying with the discharge. However, for all except the smallest flows, the water surface a short distance downstream of the jump was reasonably calm, and the velocities were small enough to be neglected in energy calculations. Conditions were such that the hydraulic jump disappeared shortly after the inlet submerged, since the top of the inlet was approximately at the same level as the upstream end of the channel.

Flow conditions in the approach channel for the 8-percent grade were much less satisfactory than those for the flatter grades. In this case, the location of the hydraulic jump was, for all but a few cases, in the approach channel, with the result that the surface of the water was quite turbulent. The velocities encountered when the culvert was flowing full

were so great that there was considerable turbulence in the channel at the culvert inlet even at the highest heads. Due to the nature of the flow, it was impossible to obtain satisfactory measurements in most cases.

In the calm pools that existed at the various grades, formation of free vortices was common. These vortices had a considerable effect upon the flow conditions in some of the inlet models by the tendency to admit air to low-pressure areas.

It is believed that the discharge measurements were the most accurate of the quantities measured by reason of the calibration of the weir in place, for the experiments. This accuracy was set at three significant figures.

The piezometric readings were, in themselves, accurate to 0.05 in. but, depending upon the flow conditions at the culvert connections, were accurate to different degrees as indications of depth or pressure. For depth measurements, it is assumed that the damping provided by small holes and connecting tubing allowed representative readings in locations where the flow was stable or, at least, parallel to the channel or culvert invert. These locations were (1) in the approach channel when the depth was great enough to provide a reasonably calm pool and (2) in the culvert where the depth was either constant or changing very gradually. Regions of curvilinear flow occurred at the entrance of the culvert due to the acceleration of the water and in the vicinity of the outlet; at such locations piezometer indications are not reliable as depth measurements. In pressure measurement for the full culvert, the readings were assumed accurate only in locations where the velocities could be deduced to have normal distribution. There was considerable evidence of impact on the connections in certain regions, especially those on the apron at the entrance of the culvert, where the water velocities had definite downward components.

There was no practical means for estimating error caused by the foregoing effects, and as a general rule, all piezometric readings should be regarded with reservation due to this circumstance. However, since only qualitative information was required in many cases, the piezometers were considered satisfactory for procurement of the data. Furthermore, it should be mentioned that, for similar flow con-

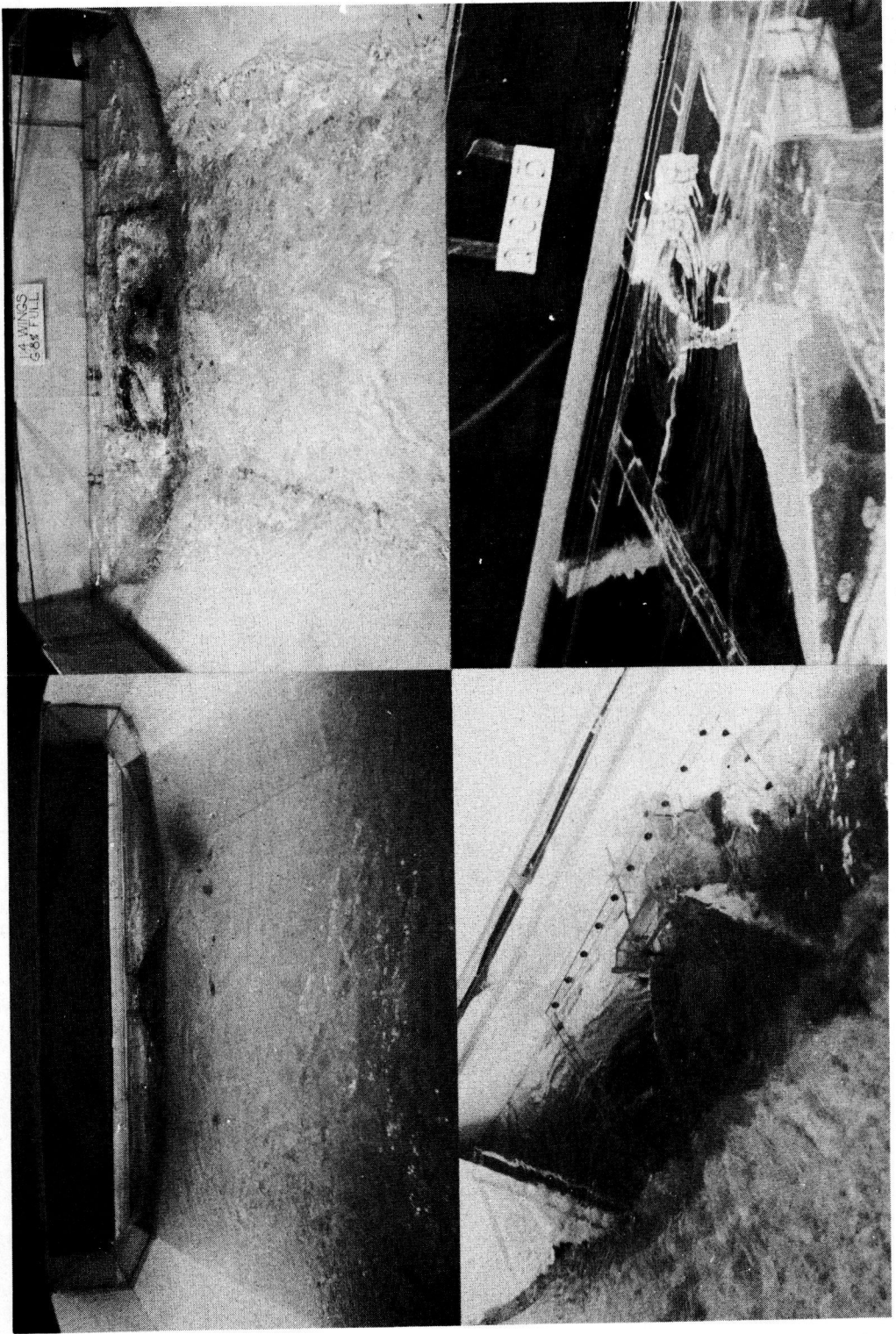


Figure 5. Flow conditions in approach channel: Upper-left, 4-percent grade, Inlet 1 installed; upper-right, 8-percent grade, Inlet 5 installed; lower-left, 4-percent grade, flow into Inlet 1; and lower-right, 4-percent grade, typical vortex in pool.

ditions in two arrangements, the piezometer readings should also be similar, so that they should be satisfactory for use in obtaining comparison data. There was remarkable consistency in the piezometric data throughout the experiments, especially in the measurements taken for the purpose of rating the culvert. Results were even uniform for the conditions when the model was set on an 8-percent grade and the water in the approach channel was extremely turbulent.

### Experimental Procedure

As a general rule, for discharge rating experiments, the inlet to be tested was run through its total range of discharge with an experimental plot carried for the purpose of obtaining the required intervals between observations. For a given run, the discharge was set at approximately the value to produce the desired upstream pool elevation, after which visual pool elevation readings were taken until equilibrium was reached by the model. Successive hook-gage readings at the weir were then taken until the average of three readings was constant, after which a series of three to five readings were averaged. The discharge reading determined from the weir-rating curve was then inserted into the placard on the piezometer boards, together with data for identification of the run, and a picture was taken of the boards. If there was much variation of the column heights, several photographs were taken.

As a means of providing a constant check on the data during the experiments, a discharge-rating curve was plotted concurrently from visual observations of headwater level, and if the run followed the proper trend, the discharge was adjusted to a new value.

The specific order of testing the various inlets, along with the identification of the test runs, is given in the appendix. Generally, the tests were run in the following order: First, Inlets 1, 2, and 3 were tested on a 4 percent grade, after which Inlet 1 was reinstalled to obtain data not taken in the first tests. Subsequently, modifications were made to Inlet 1 to improve its operation, and at the completion of these tests the grade was reduced to zero. After testing Inlets 1 and 4 on the flat grade, Inlets 5 and 6 were developed.

The grade was then adjusted to 4 percent for tests of Inlets 5, 6, and 7 and then was increased to 8 percent for comparison of Inlet 1 and its final modifications, Inlets 4, 5, and 7.

## RESULTS

The presentation of the results of these experiments will be separated into two sections, one dealing with the operation of Inlets 1, 2, and 3, and the other dealing with modifications of Inlet 1.

### Inlets 1, 2, and 3, General (4 Percent Grade)

The operation of Inlets 1, 2, and 3 can be best described by reference to Figure 6, which contains rating curves for the inlets. These curves, which were obtained from the model with the barrel set to a 4-percent grade, describe the discharge characteristics of the inlets for their total range of operation on the given grade. Hydraulic grade lines (or pressure lines) obtained from piezometer readings are included in the appendix as a means of presentation of the original data from the experiments.

Inlet 1 normally followed the free-flow discharge curve with critical depth control at entrance occurring for the nonsubmerged condition and with operation closely resembling that of a sluice gate for the submerged condition, as shown in Figure 10. For all but the highest discharges, the culvert grade was sufficient to produce accelerating flow in the culvert barrel, and for all discharges the flow was controlled at the entrance. As shown in Figure 10, the major part of the sluice contraction occurred within the first 4 in. of the culvert barrel, after which the depth either decreased gradually or remained reasonably constant.

Full-flow conditions for this inlet could be attained only by placing a temporary obstruction to flow at the outfall or by inducing turbulence in the stream at the culvert entrance. Under full-flow condition, the discharge for a given headwater elevation was increased considerably, substantiating the general theory of the inlet operation.

When the culvert was flowing full, the contraction of streamlines at the inlet section persisted and was accompanied by a local drop in pressure a short distance beyond the entrance. The minimum pres-

sure occurred approximately 4 in. downstream of the entrance. Whenever sufficient air was admitted to the inlet section, the water broke away from the top of the culvert barrel at the entrance and the typical sluice contraction formed. Subsequently, the culvert reverted to free-flow operation with a consequent rise of the headwater pool. If the quantity of air

fore, decided that with the culvert on a 4-percent grade the full-flow operation of the culvert equipped with Inlet I was unstable and, therefore, unreliable as a possibility for field application.

The operation of Inlet I was also studied with the culvert on a flat grade in order to determine whether or not the sluice contraction would cause the culvert to flow

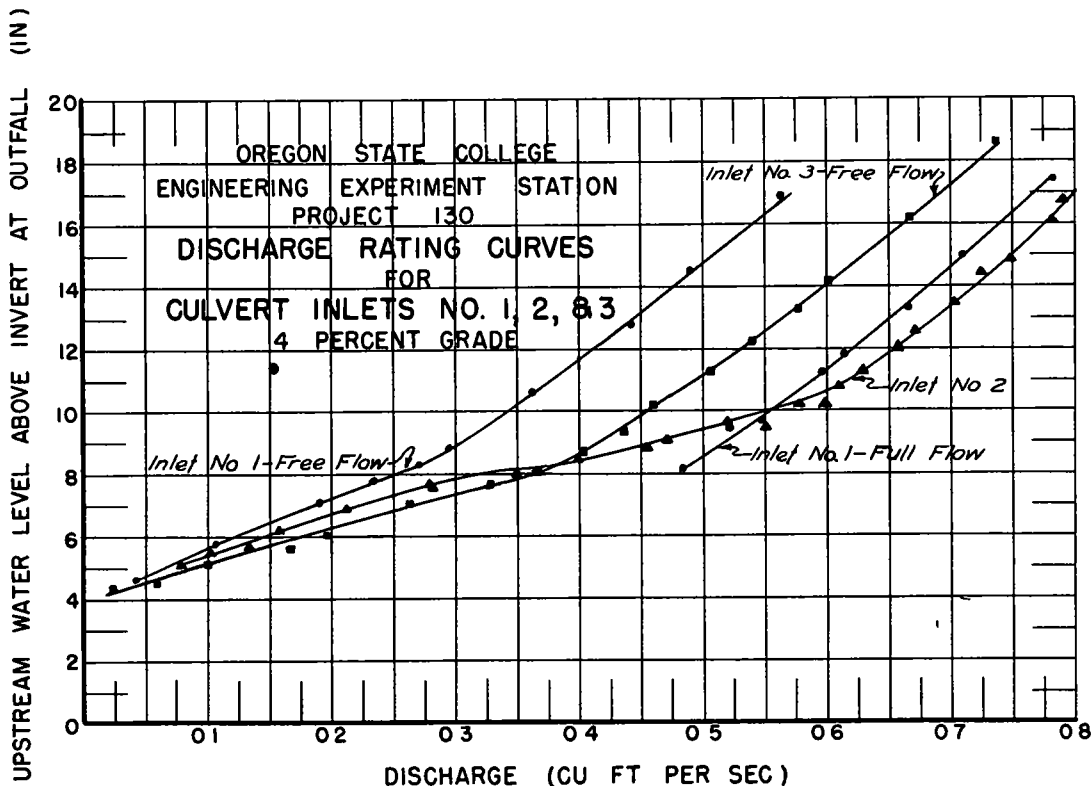


Figure 6. Discharge rating curves for culvert inlets 1, 2, and 3.

was limited, the contraction would occur at the entrance, but a hydraulic jump would form downstream in the culvert barrel, with the result that only part of the barrel would flow free. As the quantity of air supply was increased, the jump would move downstream until eventually the water surface in the culvert would be completely free.

After the culvert barrel had been artificially filled, it would remain full, so long as no air was admitted to the entrance. In the ordinary case, however, a free vortex would form in the pool above the entrance and admit air to the inlet in sufficient quantity to allow the culvert to revert to sluice operation. It was, there-

free upon inlet submergence. On this grade, as the discharge was increased, the control was critical depth near the outlet until the water surface in the upstream portion of the culvert barrel met the top of the barrel. This occurred at the upper end of the barrel, because there was always a drawdown of the water surface along the length of the culvert barrel to critical depth near the outlet. Subsequently, the culvert barrel flowed full until vortices forming at the corners of the parapet wall vented the sluice contraction. The length of the vented portion increased with discharge until the water surface was completely free for the length of the barrel. The head at which the foregoing vortices

formed was very low, and the range of discharges during which the culvert barrel flowed full was insignificant with respect to the total capacity of the culvert. When the culvert barrel was flowing free with its inlet submerged, the depth of the water increased downstream of the contraction because of the lack of slope of the barrel. Since the velocity of water leaving the contraction was greater at higher heads, the increased momentum of the jet allowed less downstream rise as the head was increased. By reference to the foregoing description, it can be seen that the length of a culvert on a flat grade, as well as

rating curve followed very closely the trend of the full-flow curve of Inlet 1 after the culvert barrel was completely full.

When the culvert barrel was flowing full, there was no local pressure drop at the entrance to the culvert, implying that the contraction experienced when Inlet 1 was flowing full was not present in this case. The absence of this contraction allowed the culvert barrel to remain full, even upon the admission of air to the entrance; thus, vortex action in the pool above the entrance had no appreciable effect upon the full-flow capacity of the

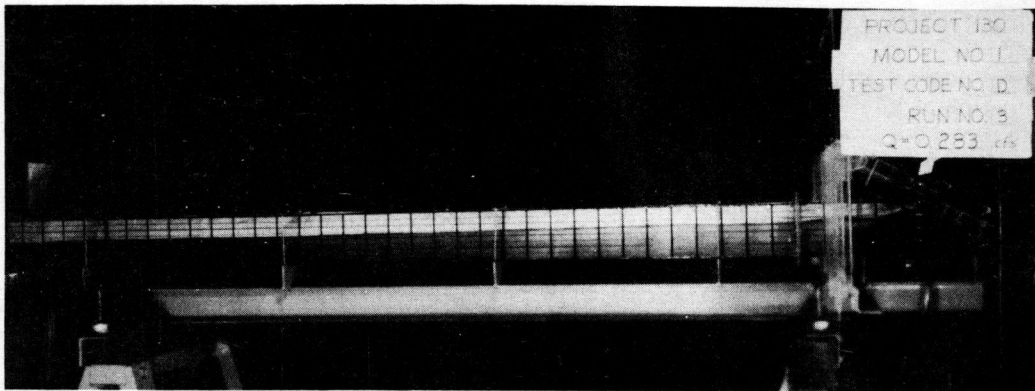


Figure 7. Model on 4 percent grade with Inlet 1 installed. The inlet is not submerged. Note depth at outfall.

the headwater level, are major factors in establishing the type of flow within the culvert barrel. It is conceivable that some long culverts on flat grades may never be capable of flowing free for their entire lengths, because of the resistance losses in the barrel.

The discharge characteristics of Inlet 2 differed radically from those of Inlet 1. As the discharge through the culvert was gradually increased, the culvert flowed under entrance control until the headwater pool intersected the top of the tapered section, after which the tapered section and then the culvert barrel flowed full. The rating curve for Inlet 2 (see Fig. 6) shows a large increase in flow for a small increase in head after the inlet was submerged. This range of operation on the model was characterized by an intermittent free-full discharge in the culvert barrel, a condition caused by the lack of sufficient flow in the approach channel to supply a full culvert barrel at the head of submergence. The

culvert. It was therefore concluded that full flow was the normal submerged condition of the culvert with Inlet 2 installed and that the principle of operation of the inlet was worthy of further consideration.

Inlet 3 was designed primarily for operation in a nonsubmerged condition with critical depth control at the entrance. In the design, a drop in the flow line was provided within a tapered entrance section in order to accelerate the water to the velocity required for uniform flow in the culvert barrel. The design provided for an overall grade, including the inlet section, of 4 percent, in which case the slope of the culvert barrel was 1.85 percent.

With Inlet 3 installed the model operated as designed in the nonsubmerged range of discharges and proved to be more satisfactory in this range than the others tested (see Fig. 6). However, the combination of the drop in the flow line and abrupt angle between the tops of the taper and culvert barrel caused a contraction of the water surface at the entrance to the

culvert barrel, so that the normal submerged operation of the model under these circumstances was free flow.

Since the over-all operation of this inlet was less satisfactory than that of Inlet 2, further analysis of this design was abandoned in favor of full-flow studies of other inlet types. Had the angle between the tops of the taper and culvert barrel been made less abrupt by streamlining the boundary, it is probable that the culvert barrel could have been made to flow full automatically, but limitations of time did not permit investigation of this possibility.

### Critical Depth Control (4 Percent Grade)

The degree with which the nonsubmerged operation of Inlets 1, 2, and 3 conformed with the theory can best be described by use of the equation

$$H = 1.5 \left[ \frac{q^2}{g} \right]^{1/3}$$

where  $H$  is the total head above the culvert inlet at the location of critical depth (the control point) and represents the upstream pool elevation above that point when velocity head in the pool is neglected. Figure 8 is based upon the foregoing equation, with the dotted lines plotted for the widths shown. The locations of critical depths computed from given discharges were determined by reference to hydraulic grade lines plotted from the piezometer tube readings. These locations are shown in Figure 9 with sketches describing the configurations of the inlets in the vicinity of the control points. For Inlet 3, the location of critical depth was upstream of the break in slope and between the wing walls; since this location varied with discharge, the average width of 5.15 in. was used for the plot in Figure 8 simply as a reference for the plotted points.

The points plotted in Figure 8 are the actual upstream pool elevations above the control points as determined from piezometer readings. For the 4-in. width, the experimental data match the theoretical heads (dotted lines) very closely, and for the 5.15-in. width there is exceptional correspondence, considering that the width used for the dotted-line plot was an average and open to question.

Figures 8 and 9 demonstrate the extent to which critical depth theory can be used

to compute discharge through a culvert. If it is possible to estimate the location of the control section, the discharge can be accurately determined from the elevation and width at that section. With Inlets 1 and 2, in cases where the grade of the culvert is relatively flat (but still supercritical for the given discharge), a reasonably accurate computation could be made upon the assumption that critical depth occurred at the entrance to the uniform culvert barrel, but on steeper grades the error caused by the difference between the

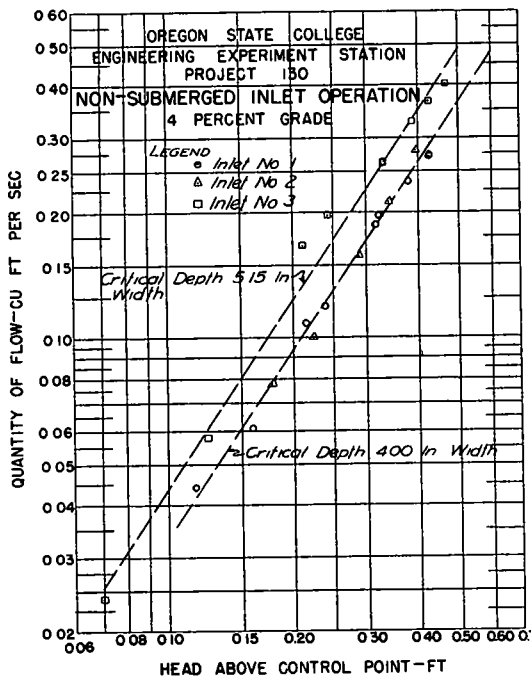


Figure 8. Nonsubmerged operation of culvert Inlets 1, 2, and 3. Dashed lines are plotted from theoretical calculations.

elevation of the control section and that of the upstream end of the culvert could be significant. From the results of these experiments, the maximum discharge error resulting from the foregoing assumption was found to be 7 percent for Inlet 1 and 6 percent for Inlet 2, with the model on a 4-percent grade. For Inlet 3 the variation of width at which the control is located makes necessary a more-precise determination of the location of the control for discharge computations.

The conformance of the experimental data with the theoretical curves in Figure

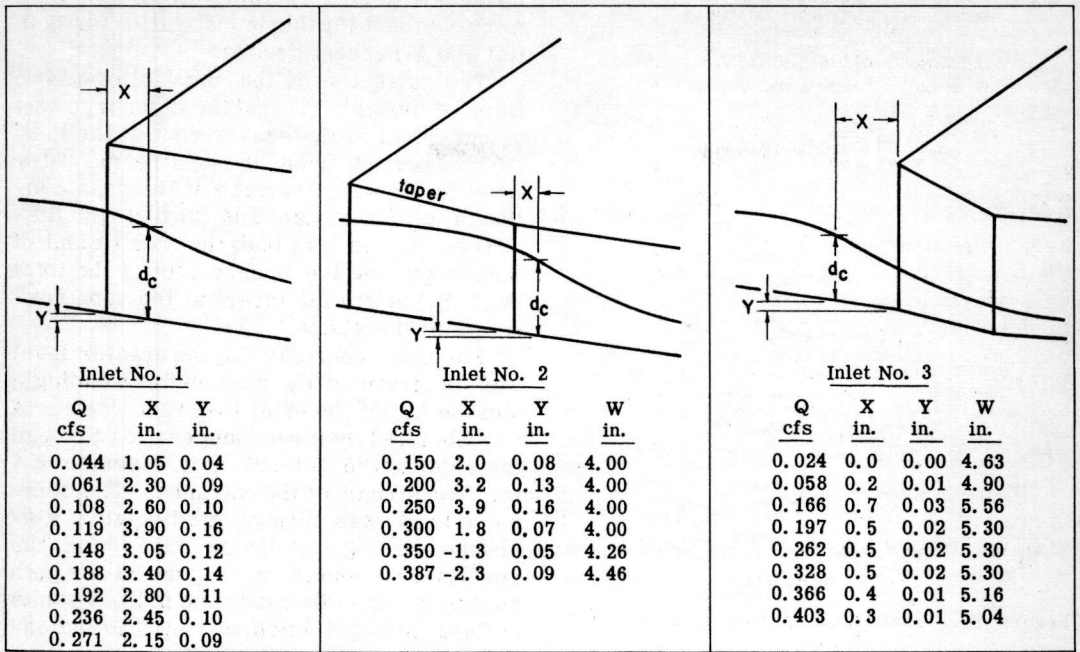


Figure 9. Measured location of critical depth.

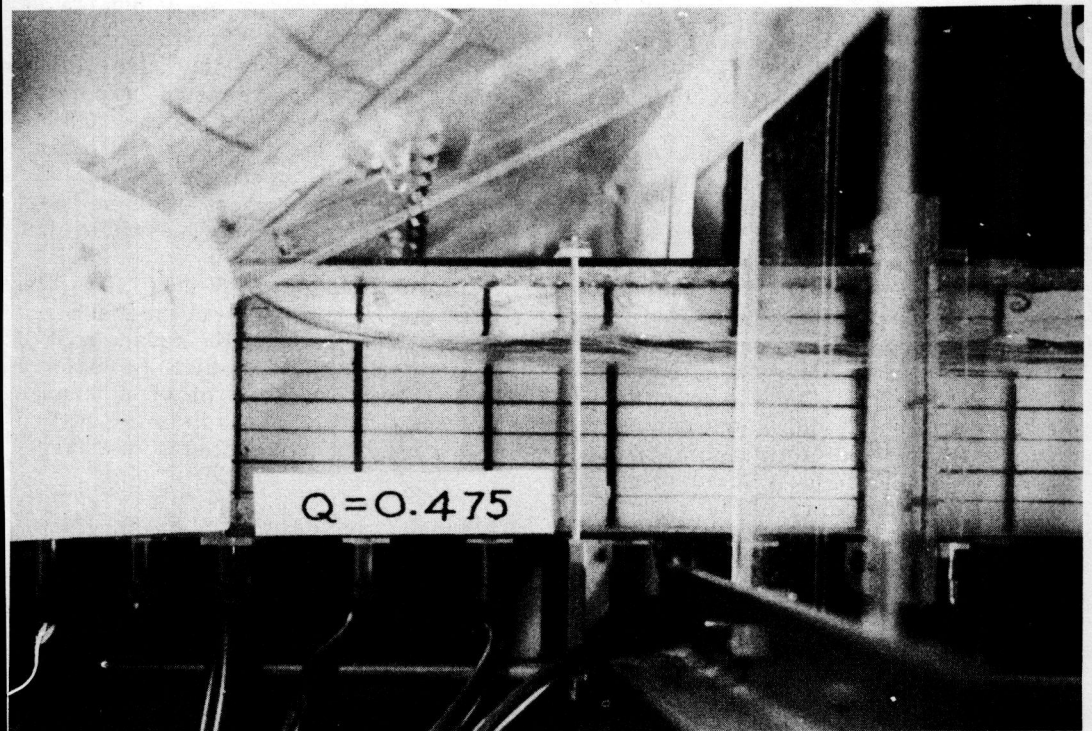


Figure 10. Sluice contraction in culvert on a 4-percent grade with Inlet 1 installed.

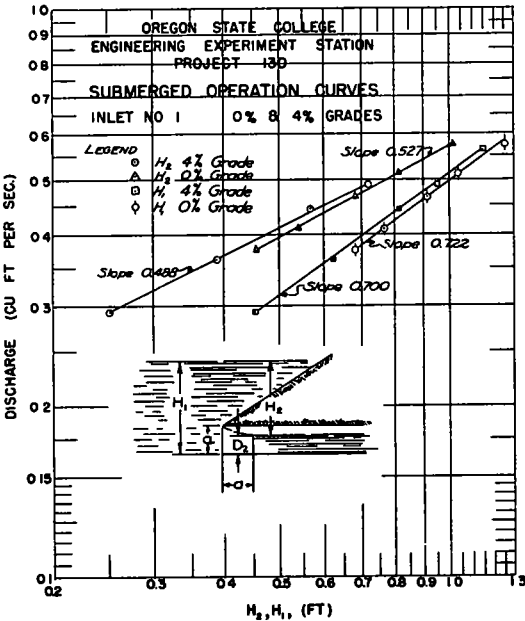


Figure 11. Submerged operation curves for Inlet 1.

8, indicates that the location of the control sections in these experiments was sufficiently accurate. However, since the scope of these experiments with respect to location of critical depth was limited, no attempt will be made here to generalize the results to apply to the experimental inlets on different grades or to other types of inlets.

There may be some question as to the accuracy of the use of piezometric measurements for the determination of the location of critical depth in these experiments, since the measurements were taken in a region of curvilinear flow. It is known that, in the case of downward curvature of the water surface, the centrifugal action of the water can cause a piezometric depth indication to be less than the actual depth; conversely, upward curvature can cause piezometric depths to be greater than actual depths. At the location of critical depth, however, the curvature of the water surface is zero, in which case the surface effects should cause little error in piezometric indications.

### Sluice-Gate Operation

Because the submerged operation of Inlet 1 appeared to be similar to that of a sharp-edged sluice gate with only a top contraction, an investigation of the data

was made to confirm this similarity. Data were obtained for this investigation for both flat and 4-percent grades.

The analysis of the data followed two lines of thought: (1) that the discharge was proportional to the square root of the head ( $H_2$ ) measured from the upstream water level to the water surface at the vena contracta of the sluice and (2) that the discharge varied with both the coefficient of discharge and the square root of the total head ( $H_1$ ) above the invert at the vena contracta of the sluice.

For both analyses the headwater level was determined by piezometer readings, and the water level at the vena contracta was obtained by direct observation through the side of the culvert at a distance of 4 in. downstream of the entrance. The computed head was then plotted against discharge on log-log graph paper and the results are shown in Figure 11 for both analyses. In both cases the plotted points defined straight lines, giving the indication that, within the range of these experiments, the discharge was proportional to some constant power of the head for either type of analysis. Using the sluice head,  $H_2$ , the slopes of the lines for the two grades were close to 0.5, which shows that the theoretical assumptions were nearly correct in this case. Since the head in these experiments was small with respect to the height of the opening, some variation from the proportionality of discharge to the square root of the head might be expected, much on the same basis as with orifices discharging under low heads.

With reference to Figure 11, it will be noted that in no case was the discharge directly proportional to the square root of the head, a condition which requires a variation of the coefficient of discharge with some function of the head if Equation 6 is to be used for computation of discharge.

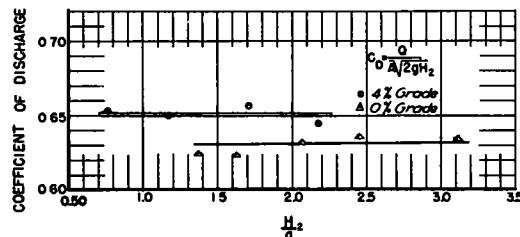


Figure 12. Submerged operation of Inlet 1, variation of sluice coefficient.



Plots of  $C_d$  against  $H/a$  are shown in Figures 12 and 13, demonstrating the manner of variation of  $C_d$  for the two analyses. In view of the fact that in no case could the coefficient of discharge be assumed constant, it is apparent that the analysis based on  $H_1$  would be the most useful in the application of the results, since only one variable need be chosen in order to make a discharge calculation from a given  $H_1$ . In contrast, in order to utilize the results of the analysis involving  $H_2$ , the depth at the vena contracta in addition to the coefficient of discharge must be determined for a given head. This depth was constant when the culvert was on the flat grade but increased slightly with discharge when the grade was 4 percent.

A point of interest arising from the results of both investigations was the variation of the discharge coefficients with culvert slope. The increase of the coefficients with slope is expected for two reasons: (1) for a given upstream pool elevation the effective head above the entrance area is greater for the horizontal culvert than it is for the inclined culvert and (2) the vertical angle with which the water approaches the top of the opening is less when the culvert is inclined, with the result that the contraction should be less. Insufficient data were obtained from these experiments to make possible an analysis of the foregoing variation, and the necessity of further experiments for this purpose is indicated.

### Full-Flow Operation

With reference to the full-flow rating curves in Figure 6, it will be noted that with the same barrel slope and length the discharge capacity of Inlet 2 was slightly greater than that of Inlet 1. The reason for the increased capacity of Inlet 2 can be explained on the basis of the pipe-flow theory. The total head causing flow in the culvert at a given slope is the sum of the loss of head caused by the conditions at entrance, the loss caused by the fluid friction in the culvert barrel, and the velocity head in the culvert. The head loss caused by the entrance conditions is a function of the shape of the entrance and is usually expressed in terms of the velocity head in the culvert. Since the downstream turbulence caused by a tapered-inlet section will be less than that for a uniform-inlet section with a square top edge due to the

lack of an entrance contraction, the head loss at a given discharge will also be less, with the result that the capacity of the culvert is increased by use of a tapered inlet.

The analysis of the friction and entrance losses in the full culvert barrels requires a culvert long enough so that the turbulence caused by the entrance conditions is not present in the lower reaches of the barrel, since a definite trend in friction loss must be established. Although the pressure lines (see appendix) appear to establish reasonable trends, it is not believed that the barrel length (approximately 20 diameters in most cases) was sufficient for exact determinations of entrance and friction loss coefficients in these studies.

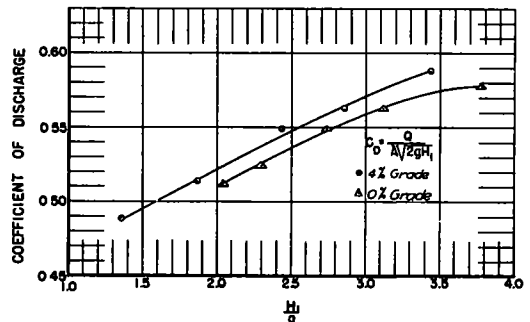


Figure 13. Submerged operation of Inlet 1, variation of sluice coefficient.

### Modification Experiments

Tests on Inlets 1 and 2 indicated that a desirable objective of these experiments was the development of a culvert inlet which would allow the culvert barrel to flow full upon inlet submergence. This objective was based upon the increased discharge capacity of the culvert model when equipped with Inlet 2 over that of the model with Inlet 1 operating as a sluice. Since it appeared possible, as a result of preliminary experiments, to make simple modifications to Inlet 1 to accomplish the foregoing objective, it was decided to explore the possibilities of modifications in lieu of attempting major changes of inlet design.

The submerged operation of Inlets 1 and 2 indicated that the elimination of the entrance contraction was necessary for stable full-flow operation of a culvert barrel. Since the approach conditions to Inlet 2 were almost identical with those of Inlet 1, there was some reason to believe that

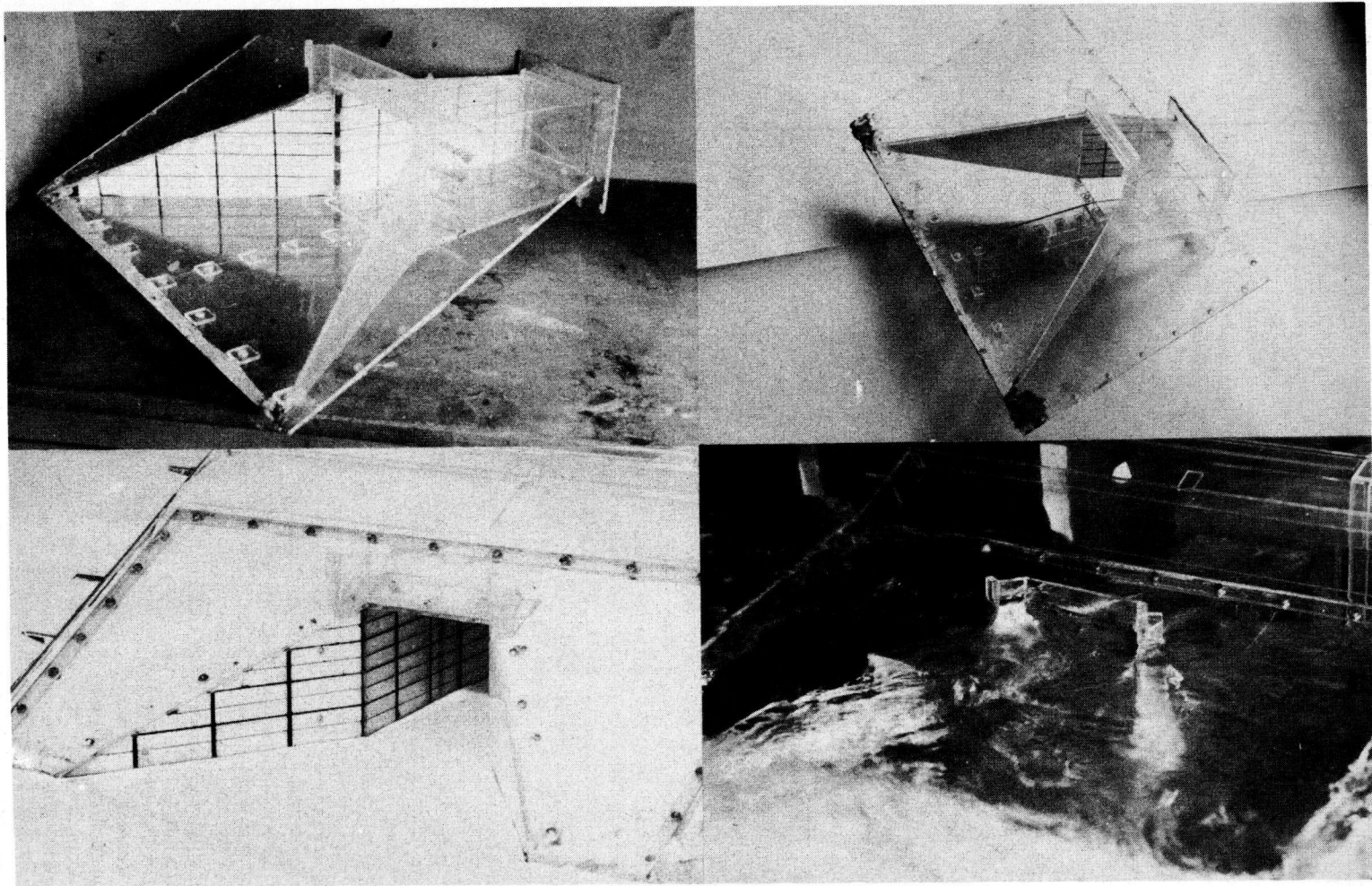


Figure 14. Inlet models: Upper-left, Inlet 2, top and side taper on 1:10 slopes to 4- by 4-in. flanged end; upper-right, Inlet 3; lower-left, Inlet 1 installed in model; and lower-right, flow into Inlet 1 with 4-in. top slab extension (the culvert barrel is flowing full in this case).

if a contraction occurred at the entrance of Inlet 2 it would bear the same relationship to entrance area as did the contraction of Inlet 1. The sluice experiments with Inlet 1 indicated a contraction of approximately two thirds of the entrance area was to be expected at the entrance of Inlet 2, and since the area of the entrance of the latter inlet was nearly twice that of the culvert barrel, it was possible that the

entrance area, the first trial in entrance enlargement was extension of the top slab to provide an entrance area of 1.5 times the area of the culvert barrel. Trial runs with this modification showed elimination of the top contraction, with the result that the culvert barrel would flow full upon submergence of its inlet. It was discovered, however, that side contractions occurred, whenever air was admitted to the

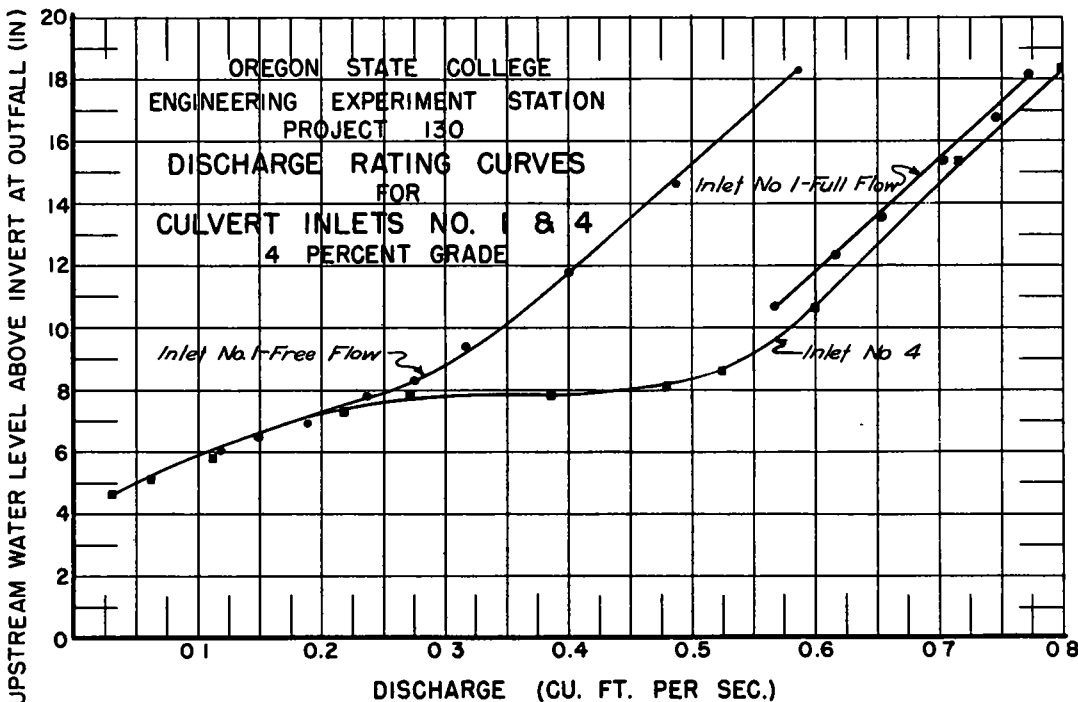


Figure 15. Discharge rating curves for culvert Inlets 1 and 4, 4-percent grade.

contraction which should have been present in the inlet was suppressed by the enlargement of the entrance.

In addition, the tendency for the formation of a contraction at the entrance of Inlet 2 should have been less because of the reduction of the approach velocities in the vicinity of the entrance.

On the basis of the foregoing analysis, one practical possibility for modification of Inlet 1 was to enlarge the entrance by extending a portion of the wing walls to meet an extension of the top slab upstream of the parapet wall (see Fig. 14). The taper thus formed was only in the sides of the inlet, with no change in culvert height within the inlet.

Since the contraction experienced with Inlet 1 was approximately two thirds of the

entrance of the culvert, indicating that either the sidetaper was too abrupt or that the tapered section was too short. The principal difference between the operation of this inlet and that of Inlet 1 was that, if the supply of air was discontinued, the culvert barrel would automatically fill.

Considering the possibility that a greater enlargement of area than 1.5 to 1 would be necessary, a sheet aluminum extension of 4 in., giving an area ratio of 2.33 to 1, was installed in the model. Trial runs indicated that the extension provided was adequate for the elimination of all contractions and that the culvert barrel would flow full for all values of  $H_1/a$  greater than 1.13. Subsequently, the extension was shortened progressively by  $\frac{1}{4}$ -in. steps until the side contractions occurred. At a

top slab extension of  $2\frac{1}{2}$  in. (area ratio of 1.83 to 1) it was decided that the full-flow operation of the culvert was unstable, and the shortening tests were discontinued. Complete tests were then run on the inlet equipped with a more precise extension of Plexiglas, 1 in. longer than the minimum length previously determined. This inlet, hereafter designated as Inlet 4, thus had a top slab extension of 3.5 in., providing an area enlargement of 2.16 to 1 (see Fig. 14).

section during the total range of full-flow discharges.

While the model was on the flat grade for investigation of the sluice-gate operation of Inlet 1, a series of tests was run on Inlet 4 to determine the advantage of full flow on this grade. The resulting rating curve in Figure 16 shows that there is an increase in the full capacity of the culvert equipped with Inlet 4 over that of the culvert operating as a sluice. This advantage

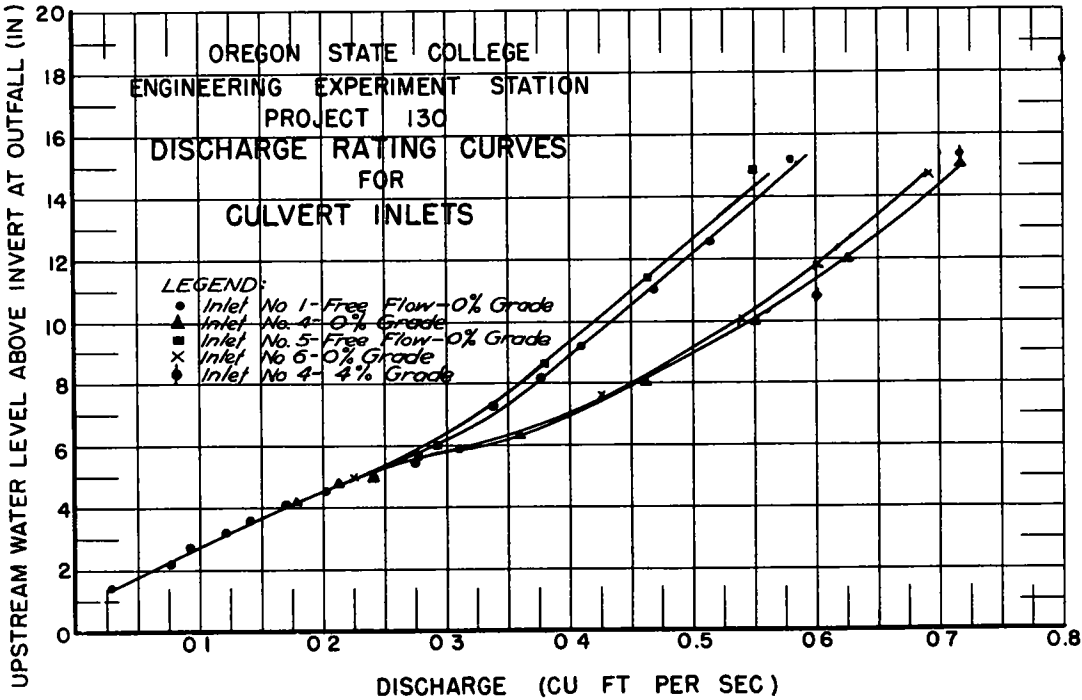


Figure 16. Discharge rating curves for culvert inlets.

The operation of Inlet 4 is compared with that of Inlet 1 in rating curves in Figure 15 for the 4-percent grade. In this figure it is seen that upon submergence of Inlet 4 the discharge increased to a value nearly double that required for submergence before the upstream water level increased perceptibly. During this increase of discharge the culvert barrel flowed intermittently free and full, with very little change in upstream water level. Figure 14 shows the flow conditions at the entrance of Inlet 1 with a 4-in. top-slab extension and operating in this range of discharges. The hydraulic grade lines obtained from these tests (see appendix) show that there was no contraction within the entrance

is presumed to be due to an increase in the flow area by the elimination of the entrance contraction, in addition to the fact that the culvert barrel was sufficiently short that friction losses in the barrel were not excessive. It is conceivable that the advantage due to the increase in area of flow could be lessened by friction losses in a longer culvert barrel.

In order to add to the general value of the experiments, it was decided to determine to some extent the effect of variation of wing-wall angle upon the necessary length of the top-slab extension. Inlet 1 was modified by reduction of the wing-wall angle to 1 to 4, an angle chosen as the minimum for which any significant savings could

be made in materials required for construction of the apron between the wings. The resulting inlet was designated as Inlet 5.

It was determined that, when the culvert was on the flat grade, a top slab extension providing an entrance enlargement of 1.5 to 1 (Inlet 6) was sufficient for elimination of the entrance contractions, and the results are shown in Figure 16. On the 4-percent grade, however, it was found that the operation of Inlet 6 was unstable, because of strong vortex action at low heads. This operation was considered undesirable, since there was such variation of piezometer readings that it was impossible to obtain satisfactory measurements. Furthermore, the presence of strong vortex action in a culvert installation should be undesirable, because of the tendency of the vortices to suckfloating drift into the inlet at times when the capacity of the culvert would be the most critical.

On the 4-percent grade the same procedure used for the development of Inlet 4 was then applied to Inlet 5, and it was determined that a minimum entrance enlargement of 2 to 1 was required for stable operation of the inlet. As the top slab extension was shortened from an original length of 8 in. , it was noted that the tendency for the formation of vortices above the entrance appeared to be a function of the length of the tapered section, with apparently greater tendencies with shorter sections. Since the velocity at the entrance is a function of the area of the entrance, it was concluded that the tendency for the formation of vortices above the entrance was a definite function of the entrance velocity. This indication was also observed during the development of Inlet 4; however, to a lesser degree. The enlargement of the entrance area in a culvert, then, should not only eliminate the undesirable effects of vortices but also should discourage their formation.

Observation of the hydraulic grade lines for the flat and 4-percent grades when Inlet 4 was installed raised some question as to the possible operation of the inlet with the culvert on steeper grades. The principal reason for this uncertainty was the probability that the pressure gradients for full discharges at low heads would have sufficiently flat slopes to fall below the invert of the culvert at the entrance. Under these conditions subatmospheric pressures would exist at the

entrance with the possibility for unstable full-flow operation, as was the case when Inlet 1 was flowing full on a 4-percent grade. Furthermore, the unsatisfactory operation of Inlet 6 on the 4-percent grade indicated that the necessary inlet enlargement could be a function of the culvert grade.

Accordingly, the grade of the model was increased to 8 percent, and the operation of Inlets 1, 4, 5, and 7 (the minimum top slab extension of Inlet 5 on the 4-percent grade) were compared for identical discharges under similar flow conditions. On this grade the operation of Inlets 4 and 7 was entirely satisfactory with stable conditions occurring in the full culvert for all discharges. The full operation of Inlets 1 and 5 was unstable, as was the case on the flatter grades.

Pressure measurements (see appendix) showed that subatmospheric pressures occurred at the entrance when Inlet 4 flowed full under a low head, but no undesirable effects resulted from this condition. It was interesting to note that the increased slope of the pressure gradients resulting from greater losses caused the pressure at the entrance to rise as the discharge was increased.

## CONCLUSIONS AND RECOMMENDATIONS

### Nonsubmerged Inlet Operation

For box culverts on steep grades where critical depth control must be at the entrance, these experiments indicated that the application of existing theory can produce satisfactory results in discharge calculations, if variation of the location of the control section can be ignored. It was determined that error resulting from the assumption of a fixed control would be small in cases where only the variation of the elevation of the control section is involved but would be great when the width of the section is also variable.

### Submerged Inlet Operation

The normal submerged operation of a culvert provided with an inlet similar to Inlet 1 should follow the sluice theory as presented in this paper, and the experimental results provide a satisfactory

means for calculation of the discharge through such a culvert. Since in these tests the maximum headwater depth above the culvert invert at the entrance was limited to four times the height of the culvert, the experimental results are necessarily applicable only to cases within that limit. However, it is believed that the experimental range of operation is typical of the majority of culvert installations, so that the limits of the experiments do not seriously affect the usefulness of the results.

The general operation of a full-scale culvert provided with Inlet 4 should be similar to that of the model, and the range of operation between critical depth control and complete full flow can be analyzed by application of the laws of similitude to the results of these experiments. However, for reasons previously discussed, the results from the full-flow experiments cannot be accurately applied to full-scale culverts for the purpose of discharge calculations, and resort must be made to the use of available data from full-scale culvert studies for this purpose.

The submerged operation of Inlets 2 and 4 leaves little doubt as to the possible economy that can be gained by the design of a culvert on a steep grade to flow full, since for a given discharge and upstream-pool elevation a smaller cross section of culvert barrel is required for a full culvert than for one discharging as a sluice gate. This advantage is not necessarily limited to cases where it is possible to operate culverts under considerable inlet submergence, because of the extreme increase in capacity of culverts equipped with Inlets 2 and 4 at the head of submergence. For example, with reference to the rating curves in Figure 15 for the models on a 4-percent grade, a culvert equipped with an inlet similar to Inlet 1 and with a height equal to that of Inlet 4 would require a width of approximately twice that of Inlet 4, in order to discharge an equal quantity of flow under the same low head. It should be noted that the example cited is applicable only to culverts on the 4-percent grade. The advantage of full flow would, of course, vary with the grade and length of the culvert, being less marked on a flatter grade.

The results have indicated that a culvert inlet similar to Inlet 4 is a practical and economical design for the purpose of caus-

ing a culvert barrel to flow full upon inlet submergence. The simplicity of construction of this inlet over that of Inlet 2 is the factor determining its choice, since the two inlets are nearly comparable in discharge capacity (within the range from 0.57 to 0.80 cu. ft. per sec., Inlet 2 has the slight advantage). In addition, the inlets of existing culverts having insufficient capacity by reason of an inability to flow full at inlet submergence can be modified to be similar to Inlet 4.

### Recommendations for Further Experiments

1. The study of the nonsubmerged operation of the culvert inlets suggested the necessity for investigations of the variation of the location of the critical depth control point with discharge and culvert grade.

2. Since it was determined that the sluice coefficient of a culvert varied with both grade and head, it is recommended that further investigations be made under widely varied conditions in order to obtain some generally applicable results.

3. The inlet design resulting from these experiments was undoubtedly but one of many possibilities for causing a box culvert to flow full, and further experimentation could possibly provide a more simple and economical design for the purpose. As an example, curved sections were not investigated in these experiments.

4. Tests of pipe culvert and arches on steep grades, made on the same basis as these experiments, could possibly produce more economical designs than those in use at the present time.

### ACKNOWLEDGMENTS

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## Appendix

### Identification of Experiments

The organization of the experimental data was made in the following manner: (1) a run was designated as a set of readings taken at a given discharge through the model and (2) a series of runs taken for a specific purpose were grouped into a set and coded with a letter.

The following tests were made on the inlet models. For all tests reported a complete series of piezometer readings were taken unless otherwise indicated.

<u>Inlet Number</u>	<u>Test Code</u>	<u>Grade Percent</u>	<u>Purpose</u>	<u>Data Sheet Number</u>
1	A	4	Preliminary experiments (not reported)	-
	B	4	Free flow, total range of heads	1
	C	4	Full flow, total range of heads	2
	D, E	4	Descriptive photographs	-
	F	4	Free flow, total range of heads (re-run)	3
	G	4	Full flow, total range of heads (re-run)	4
	J	0	Free flow, total range of heads	6, 7, 8
2	A, A-1	4	Total range of heads	9, 10, 11
3	A	4	Free flow, total range of heads	12
4	H	4	Modification development experiments	5
	I	4	Total range of heads	13, 14
	M	0	Total range of heads	15
5	K	0	Free flow, total range of heads	16
	O	4	Modification experiments	17
6	L	0	Full flow, total range of heads	18

Test code P included comparison experiments of Inlets 1, 4, 5, and 7 on the 8-percent grade as given below:

<u>Inlets</u>	<u>Condition</u>	<u>Data Sheet Number</u>
1, 5	Critical depth control, identical discharges	19
1, 5	Submerged free, identical discharges	20
1, 4, 5, 7	Submerged full, two sets of identical discharges	21, 22

O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

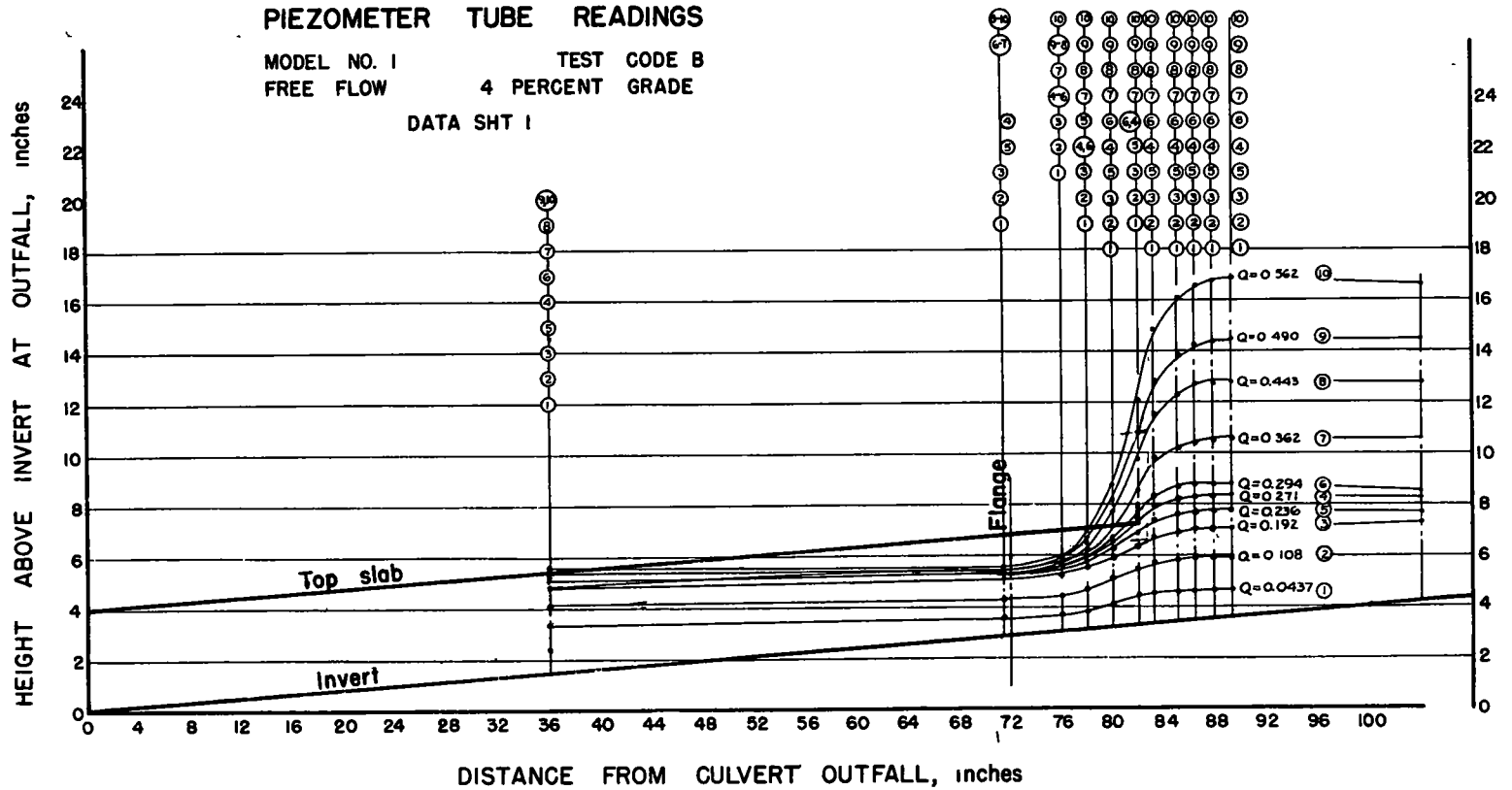
HYDRAULIC GRADE LINES

FROM

PIEZOMETER TUBE READINGS

MODEL NO. 1 TEST CODE B  
FREE FLOW 4 PERCENT GRADE

DATA SHT 1



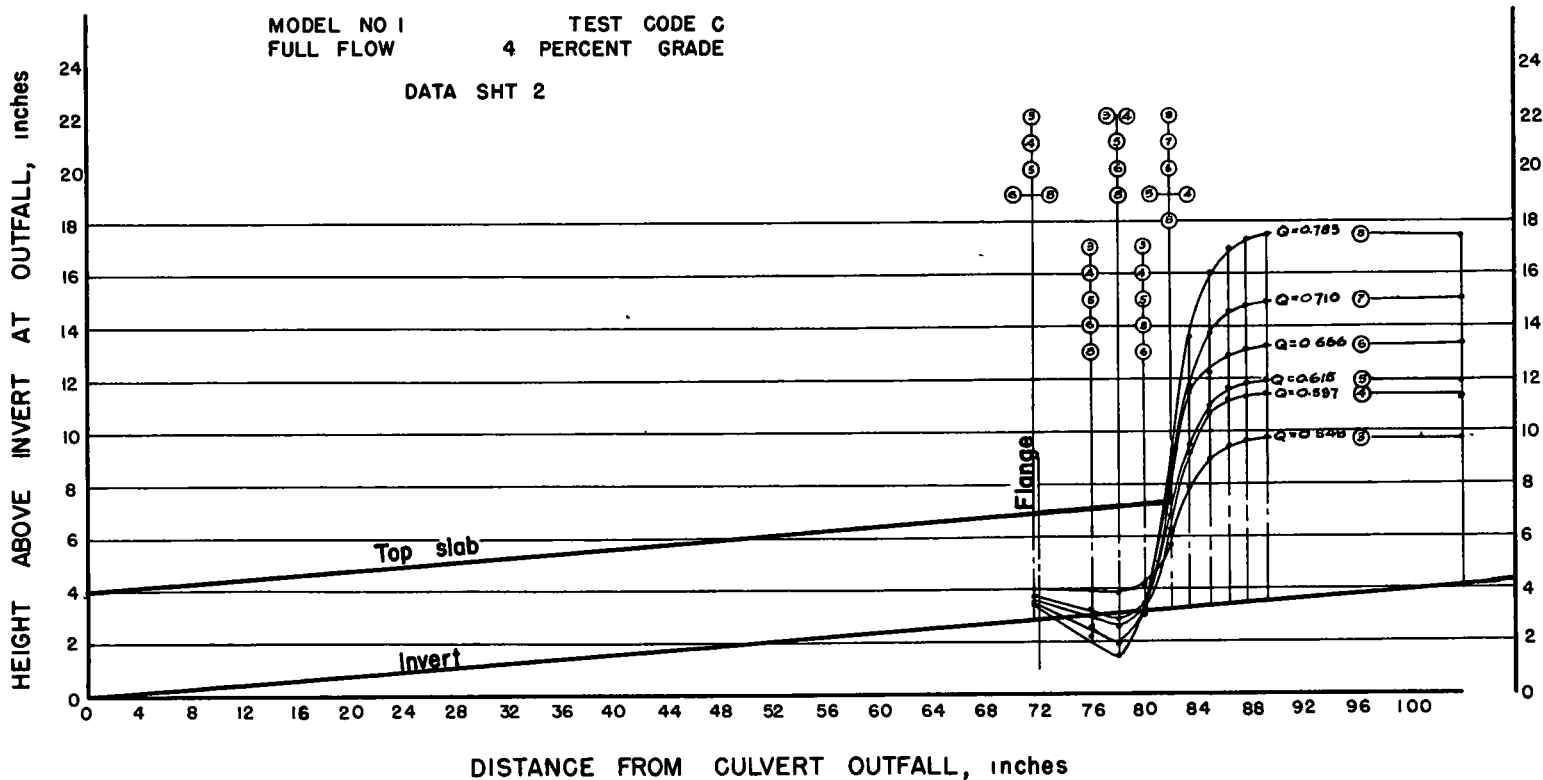


O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM  
PIEZOMETER TUBE READINGS

MODEL NO 1 TEST CODE C  
FULL FLOW 4 PERCENT GRADE

DATA SHT 2



O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

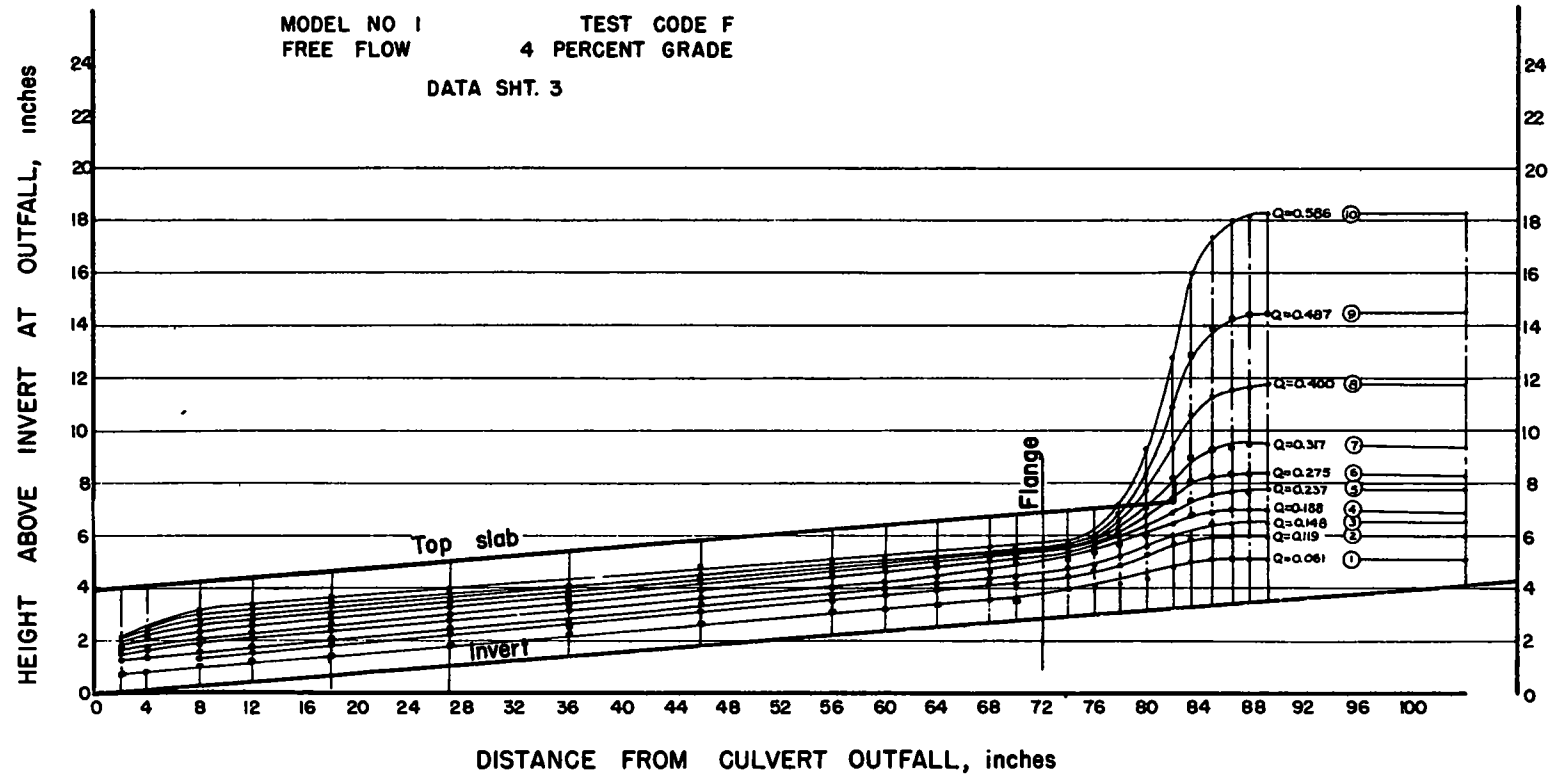
### HYDRAULIC GRADE LINES

FROM

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MODEL NO 1                      TEST CODE F  
FREE FLOW                      4 PERCENT GRADE

DATA SHT. 3

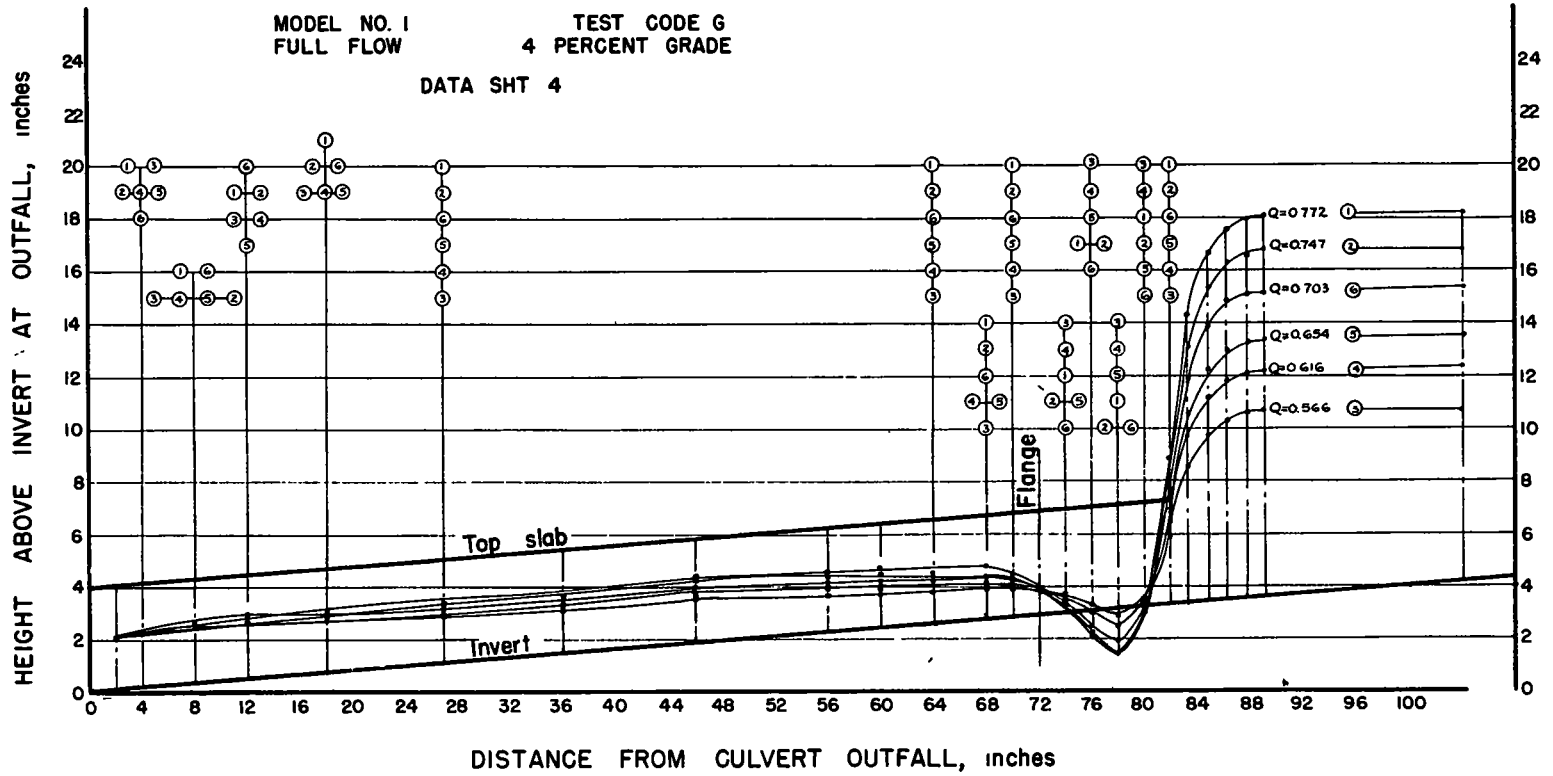


O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM  
PIEZOMETER TUBE READINGS

MODEL NO. 1 TEST CODE G  
FULL FLOW 4 PERCENT GRADE

DATA SHT 4



O S. C. ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES

FROM

PIEZOMETER TUBE READINGS

MODEL NO. 1

TEST CODE H

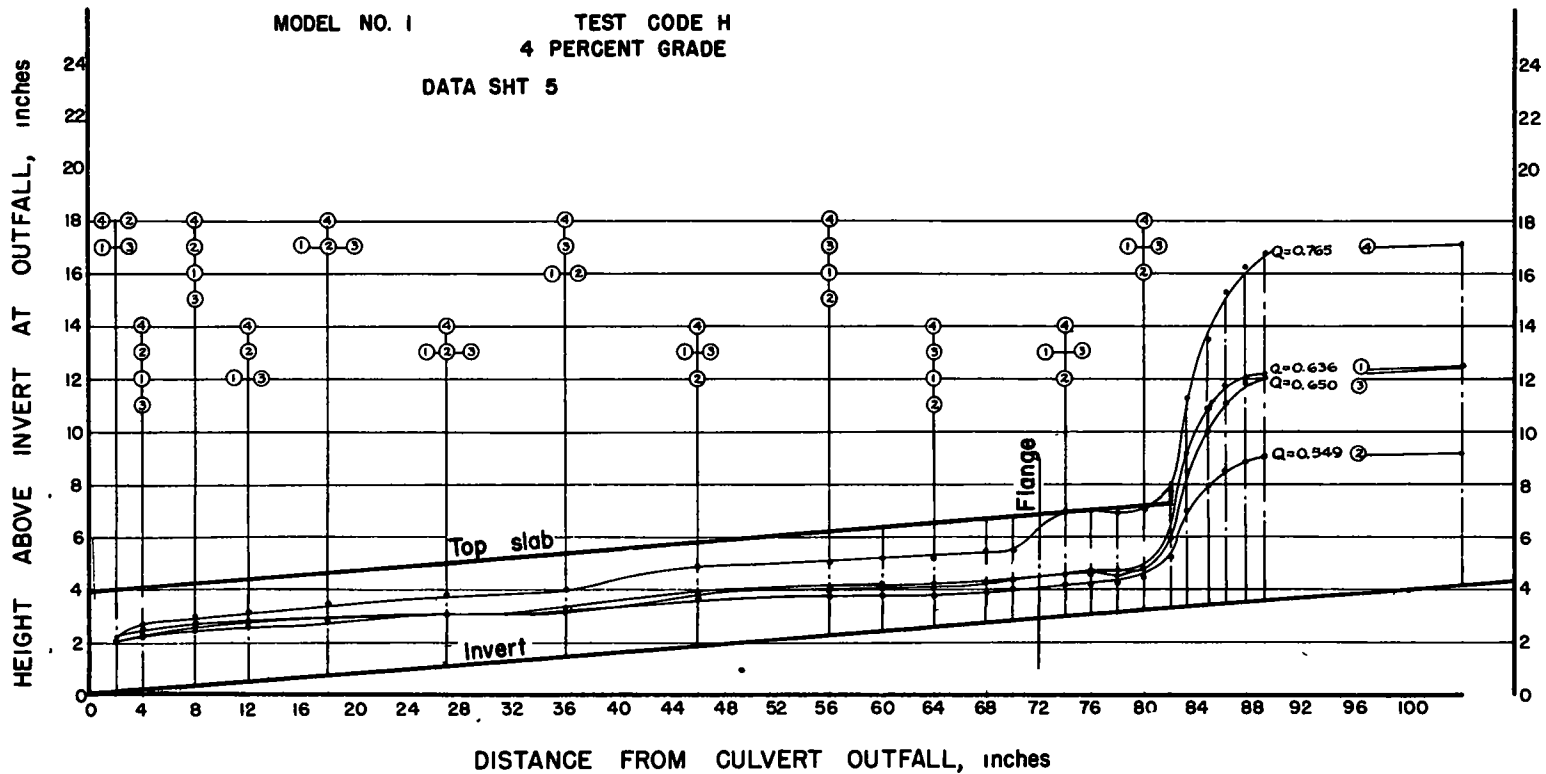
4 PERCENT GRADE

DATA SHT 5

NOTE RUN 1 — 1½" TOP SLAB EXT.

- 2 — " " " "
- 3 — 4" " " "
- 4 — 3¾" " " "

\*

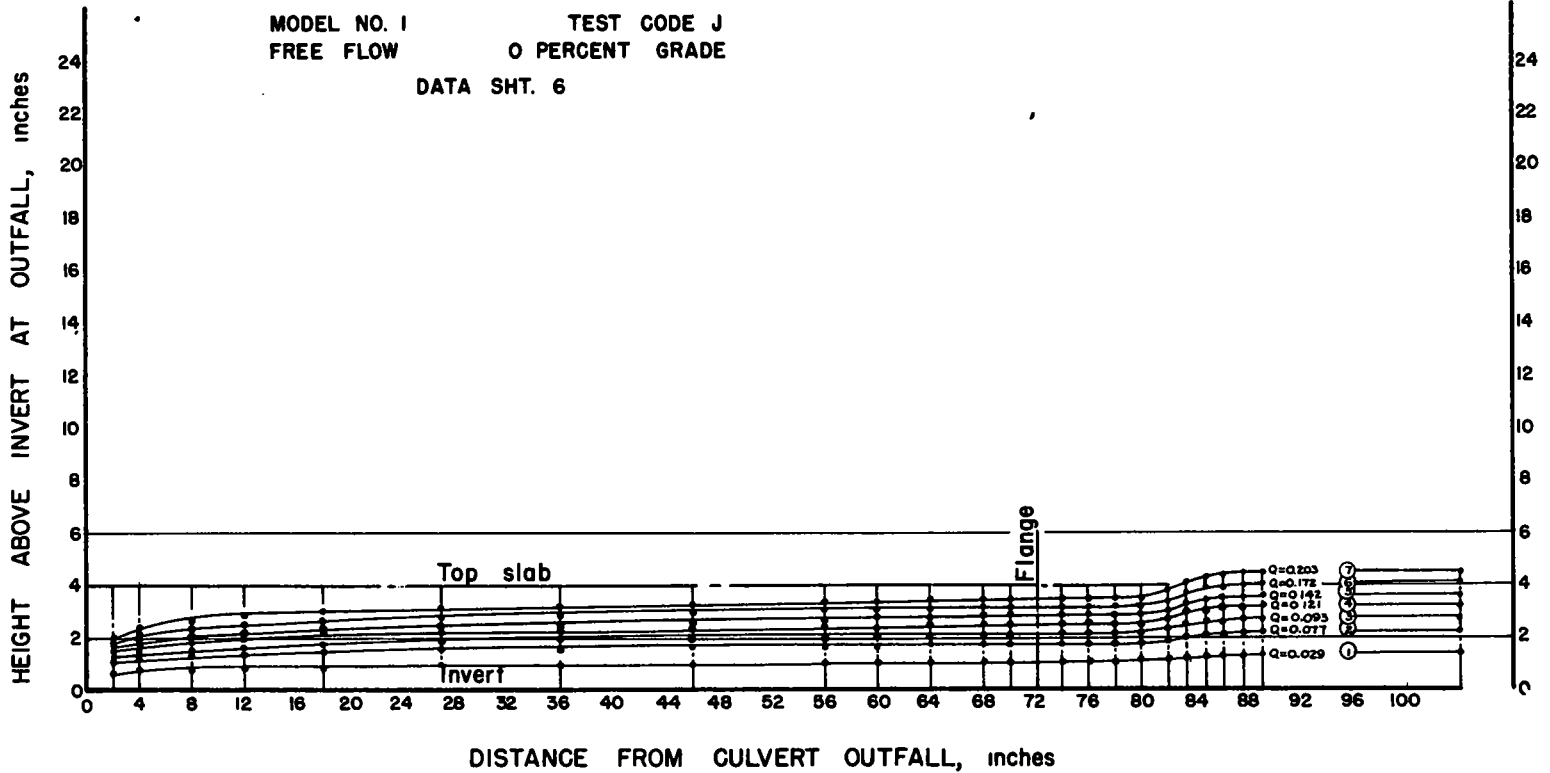


O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM  
PIEZOMETER TUBE READINGS

MODEL NO. 1 TEST CODE J  
FREE FLOW 0 PERCENT GRADE

DATA SHT. 6



O S C. ENGINEERING EXPERIMENT STATION  
PROJECT 130

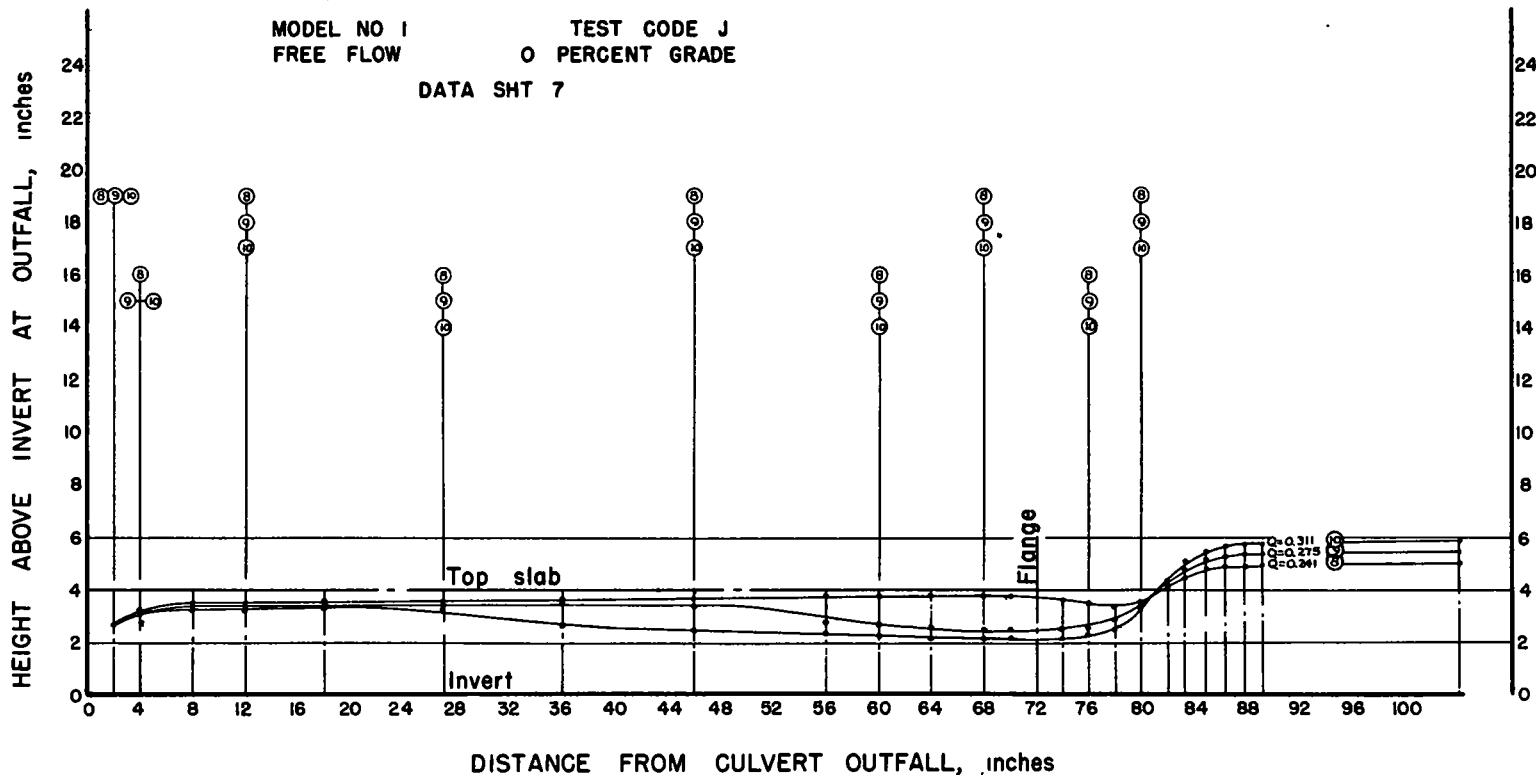
HYDRAULIC GRADE LINES

FROM

PIEZOMETER TUBE READINGS

MODEL NO 1 TEST CODE J  
FREE FLOW 0 PERCENT GRADE

DATA SHT 7



O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

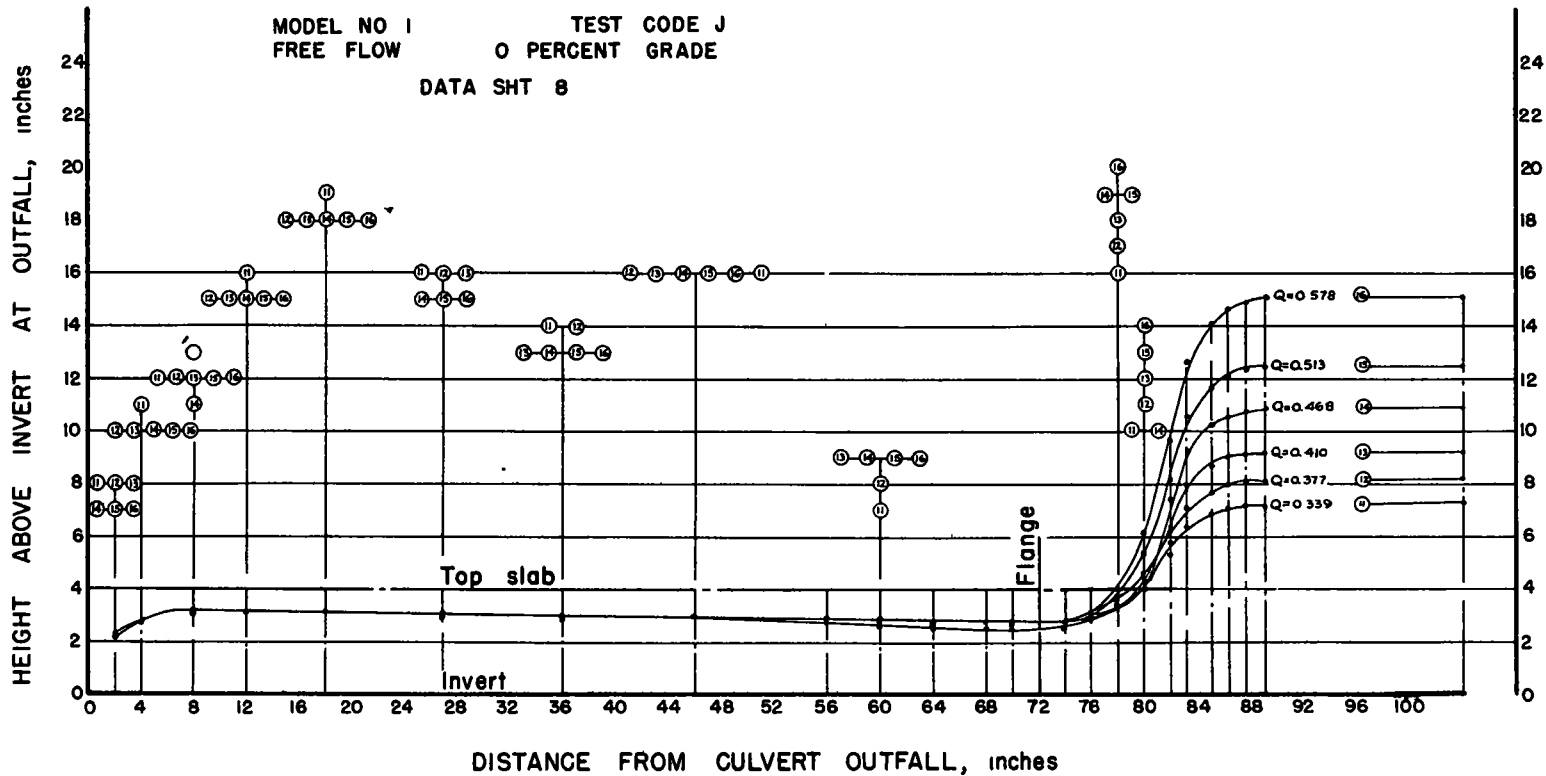
HYDRAULIC GRADE LINES

FROM

PIEZOMETER TUBE READINGS

MODEL NO 1 TEST CODE J  
FREE FLOW 0 PERCENT GRADE

DATA SHT 8

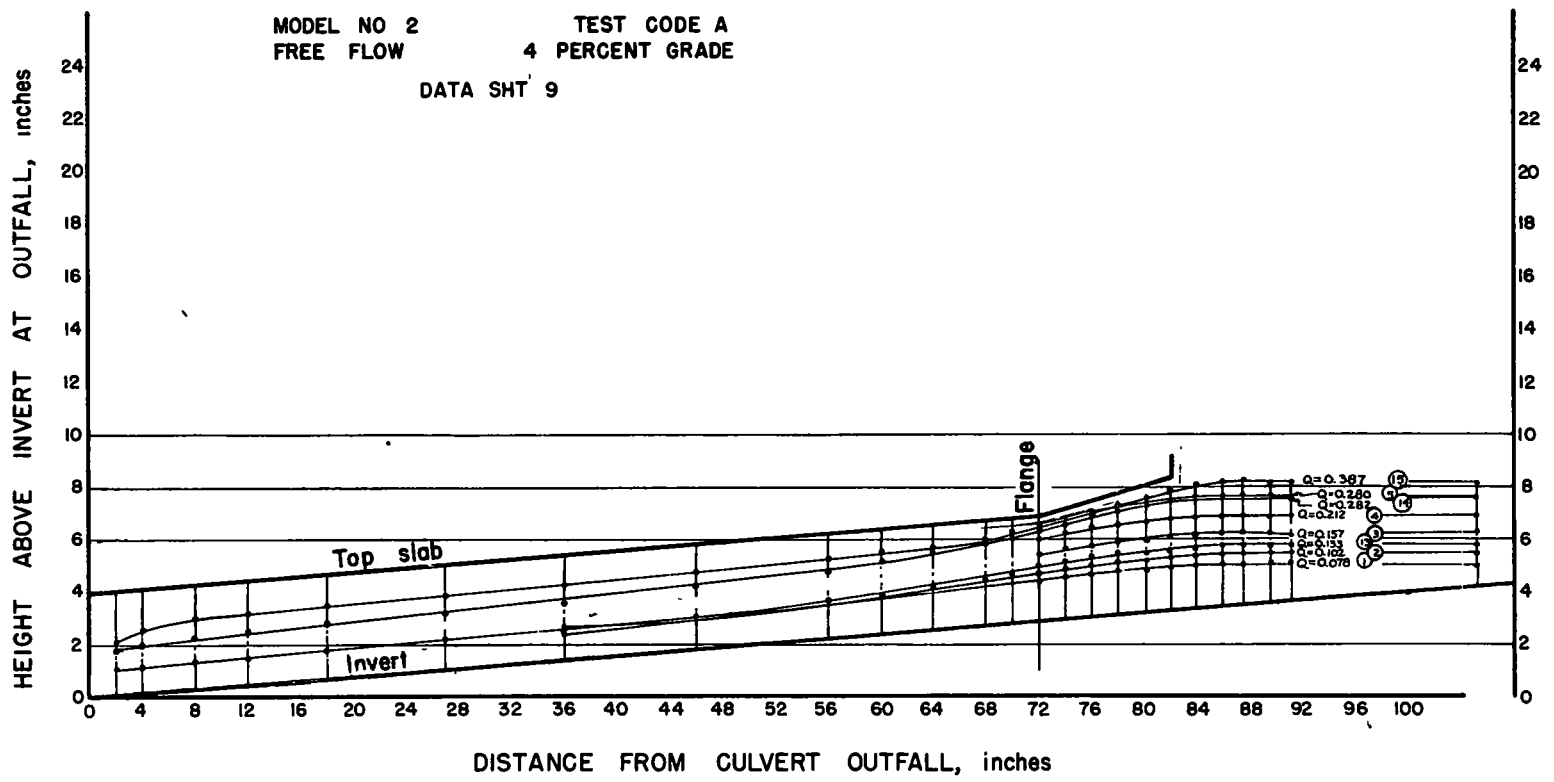


O. S. C. ENGINEERING EXPERIMENT STATION  
 PROJECT 130

HYDRAULIC GRADE LINES  
 FROM  
 PIEZOMETER TUBE READINGS

MODEL NO 2 TEST CODE A  
 FREE FLOW 4 PERCENT GRADE

DATA SHT 9



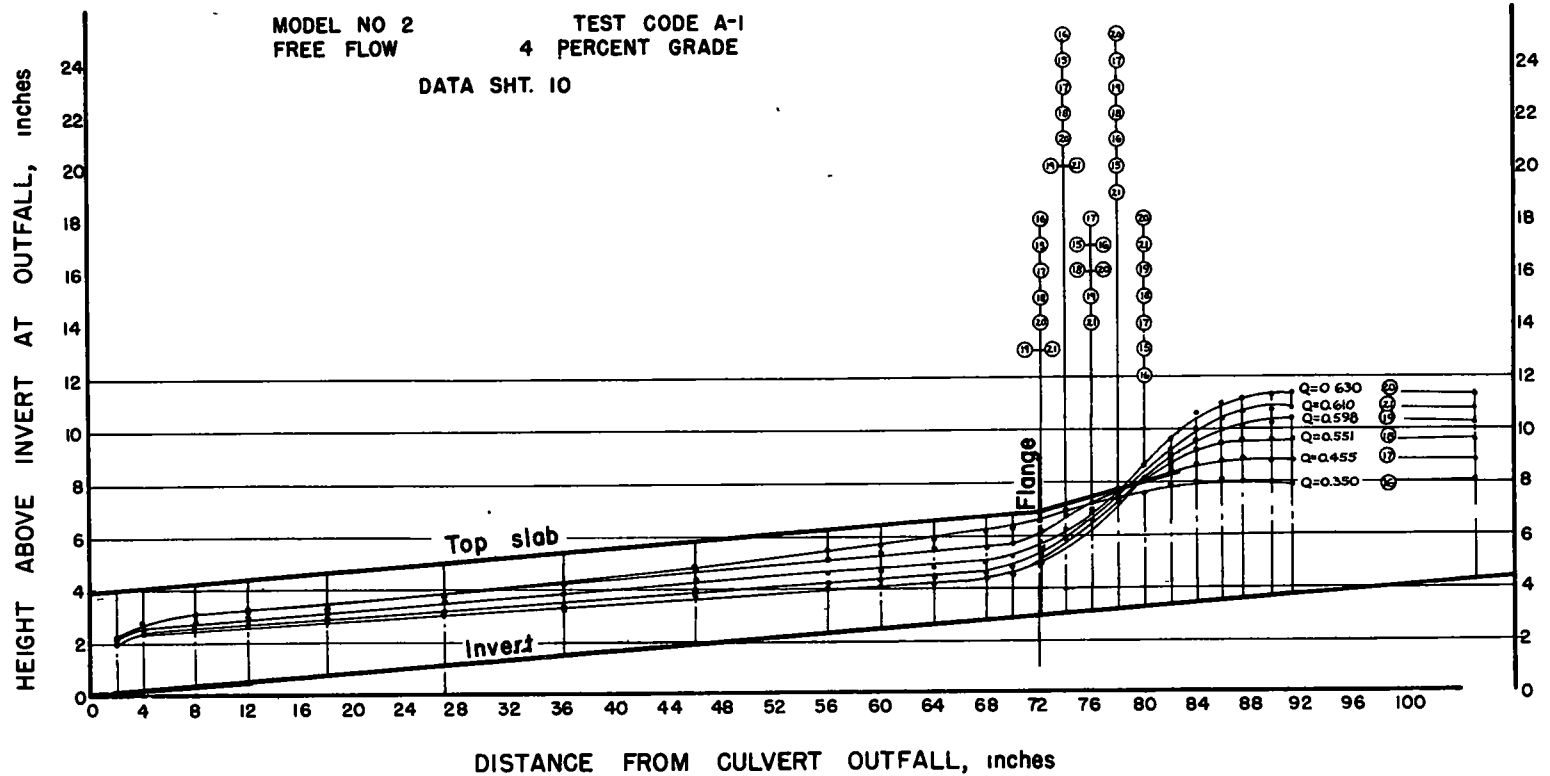


O S. C. ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM  
PIEZOMETER TUBE READINGS

MODEL NO 2 TEST CODE A-1  
FREE FLOW 4 PERCENT GRADE

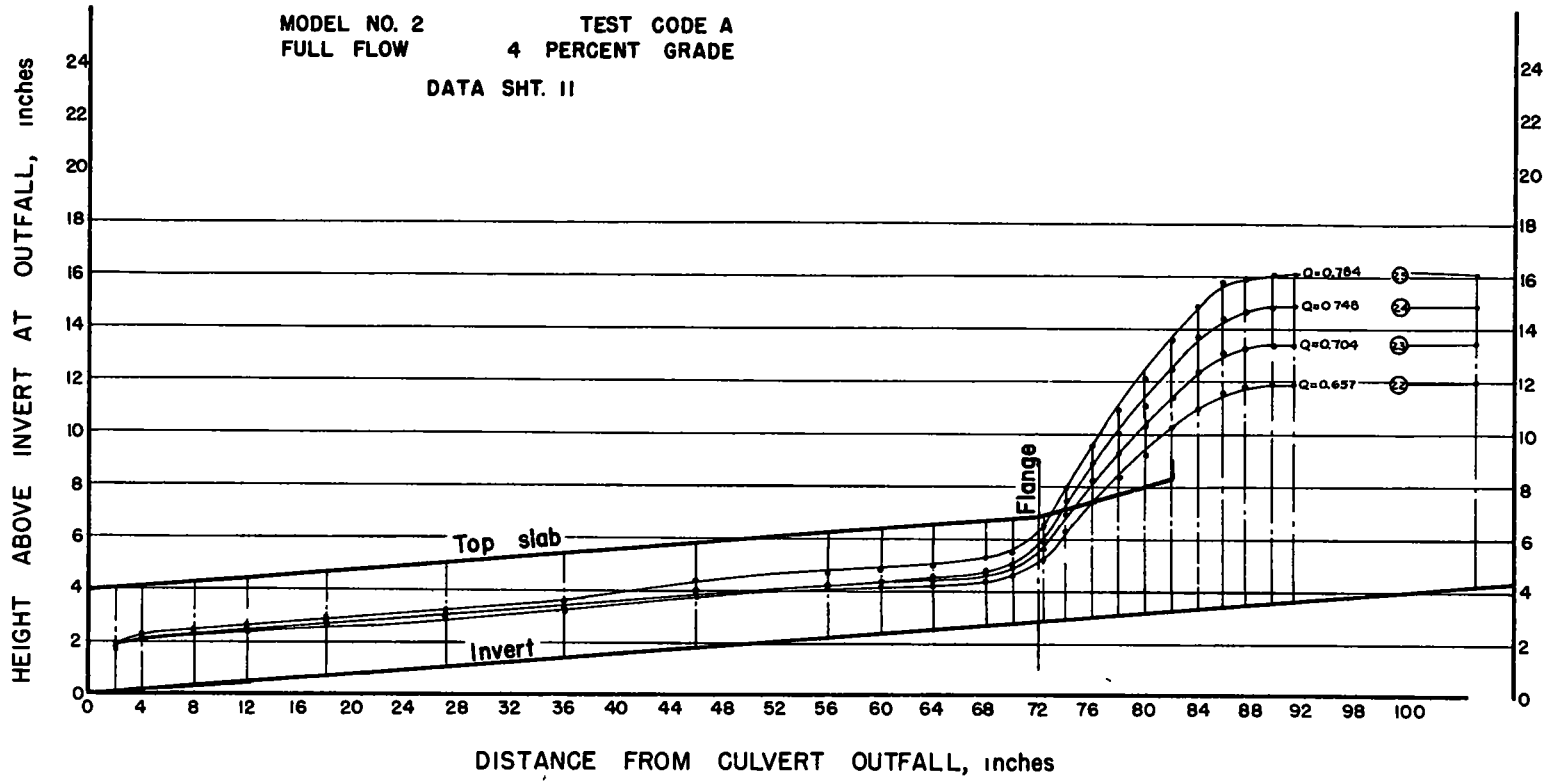
DATA SHT. 10



O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM  
PIEZOMETER TUBE READINGS

MODEL NO. 2                    TEST CODE A  
FULL FLOW                    4 PERCENT GRADE  
DATA SHT. II

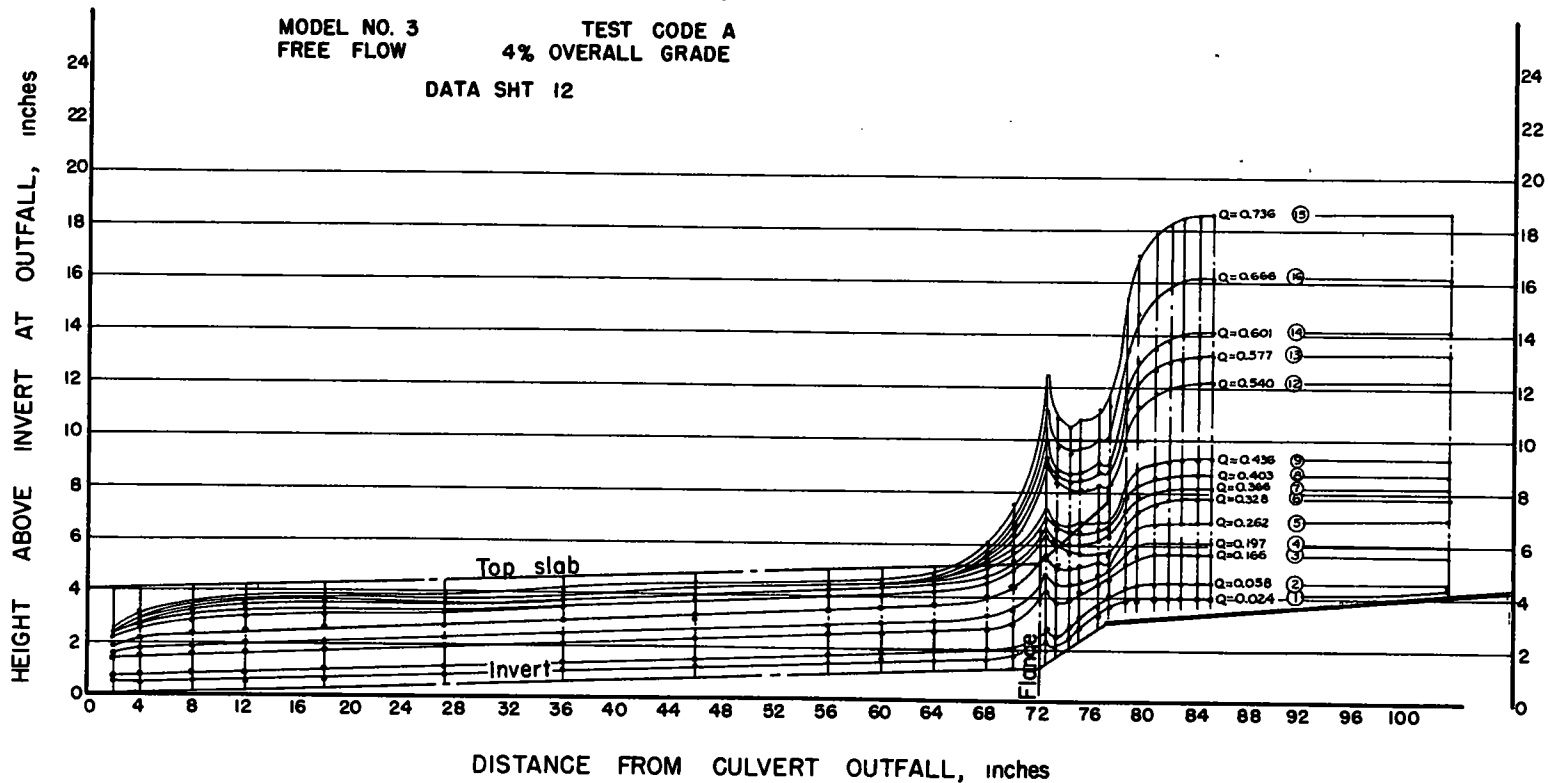


O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM  
PIEZOMETER TUBE READINGS

MODEL NO. 3 TEST CODE A  
FREE FLOW 4% OVERALL GRADE

DATA SHT 12



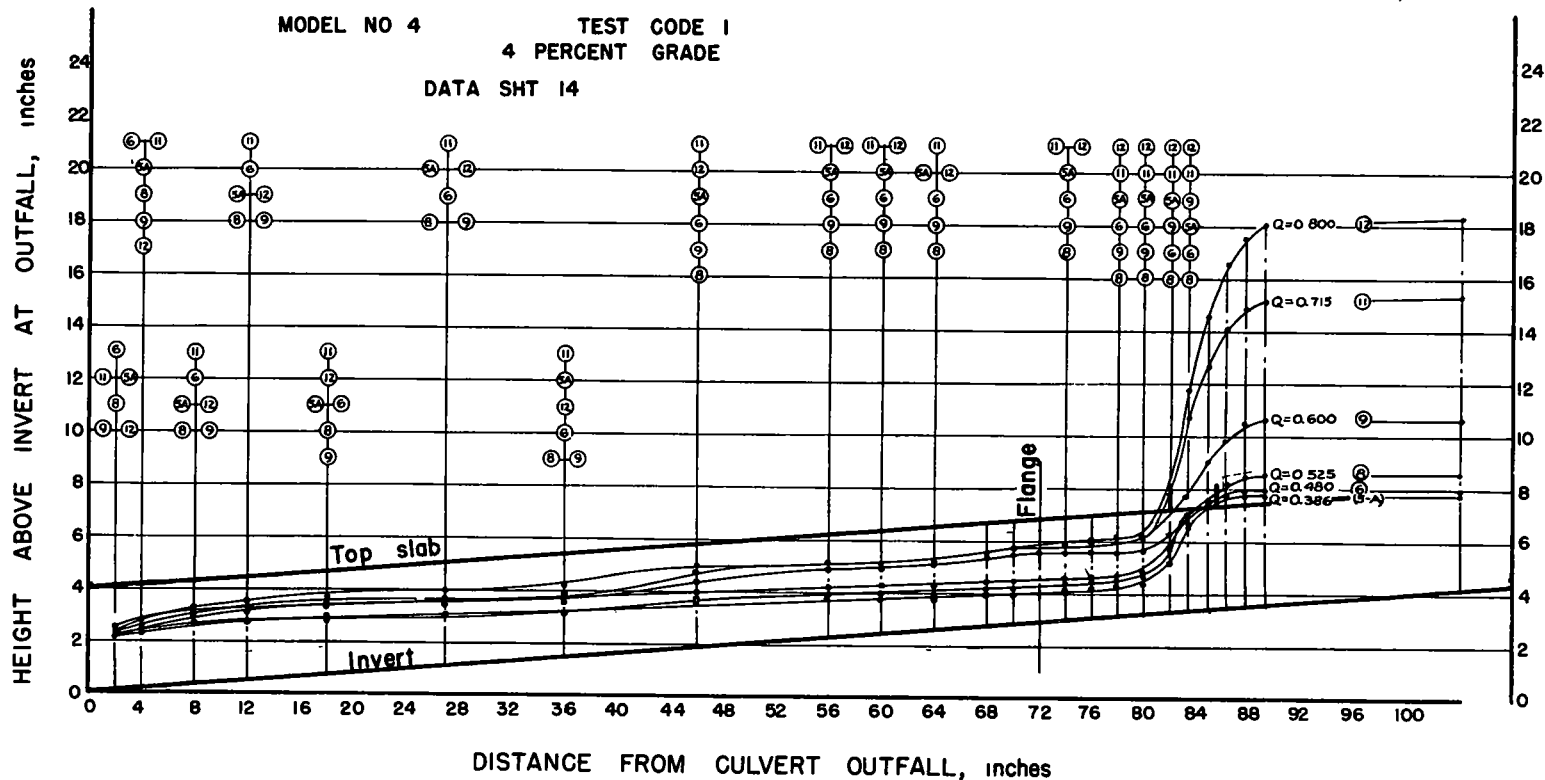


O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM

PIEZOMETER TUBE READINGS  
MODEL NO 4 TEST CODE I  
4 PERCENT GRADE

DATA SHT 14

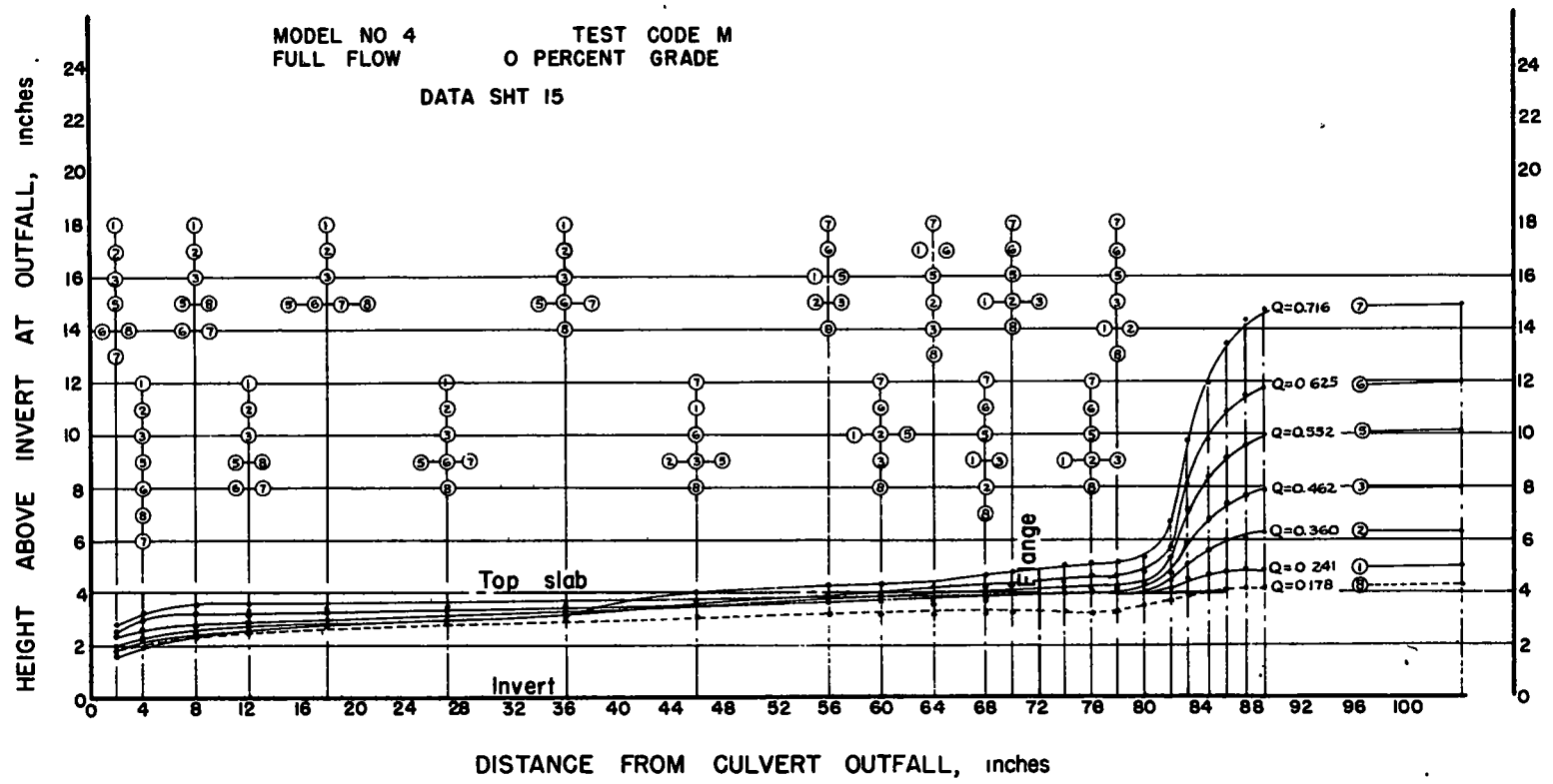


O. S. C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM

PIEZOMETER TUBE READINGS

MODEL NO 4 TEST CODE M  
FULL FLOW 0 PERCENT GRADE  
DATA SHT 15



O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES

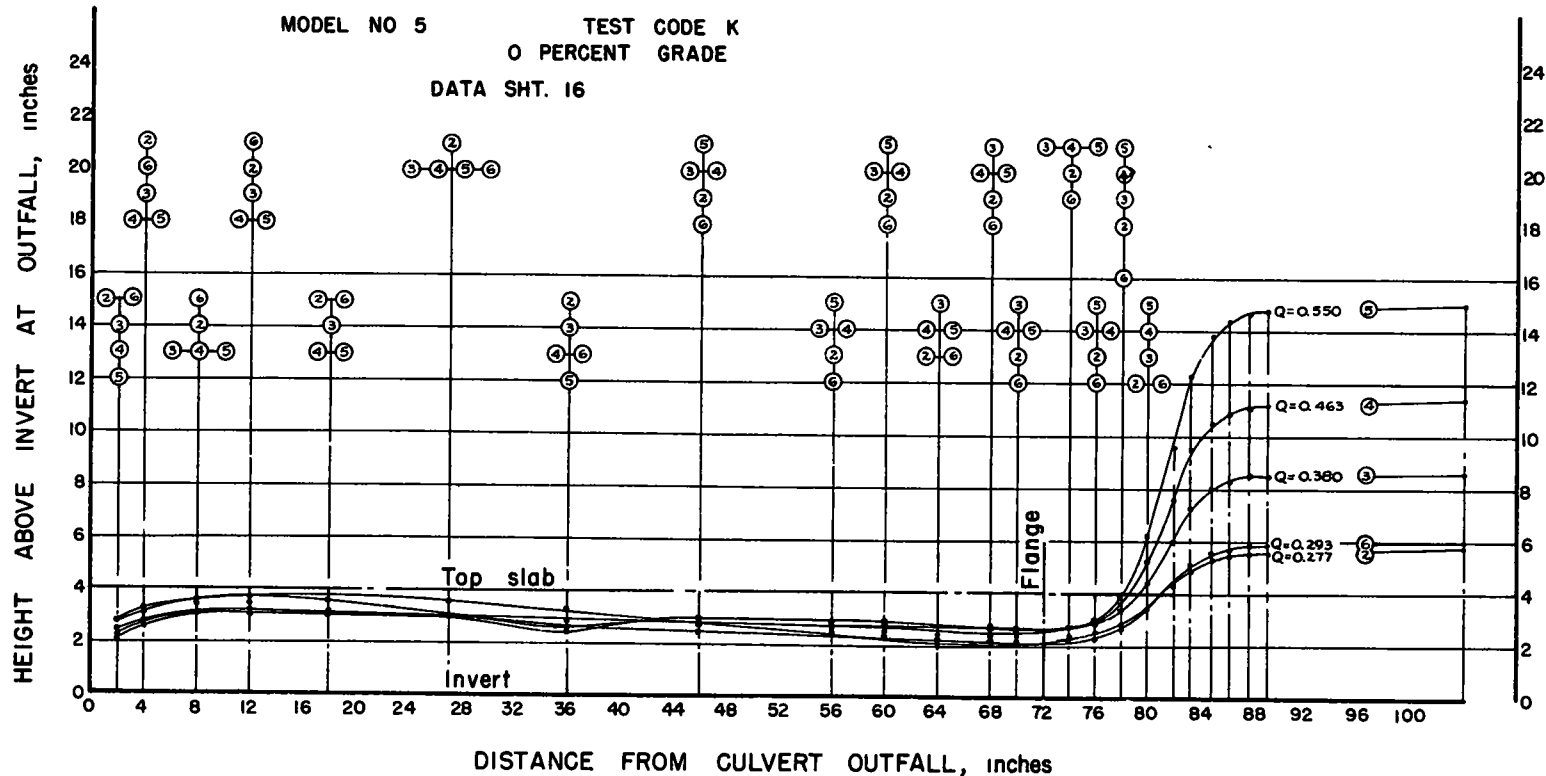
FROM

PIEZOMETER TUBE READINGS

MODEL NO 5 TEST CODE K

0 PERCENT GRADE

DATA SHT. 16



O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES

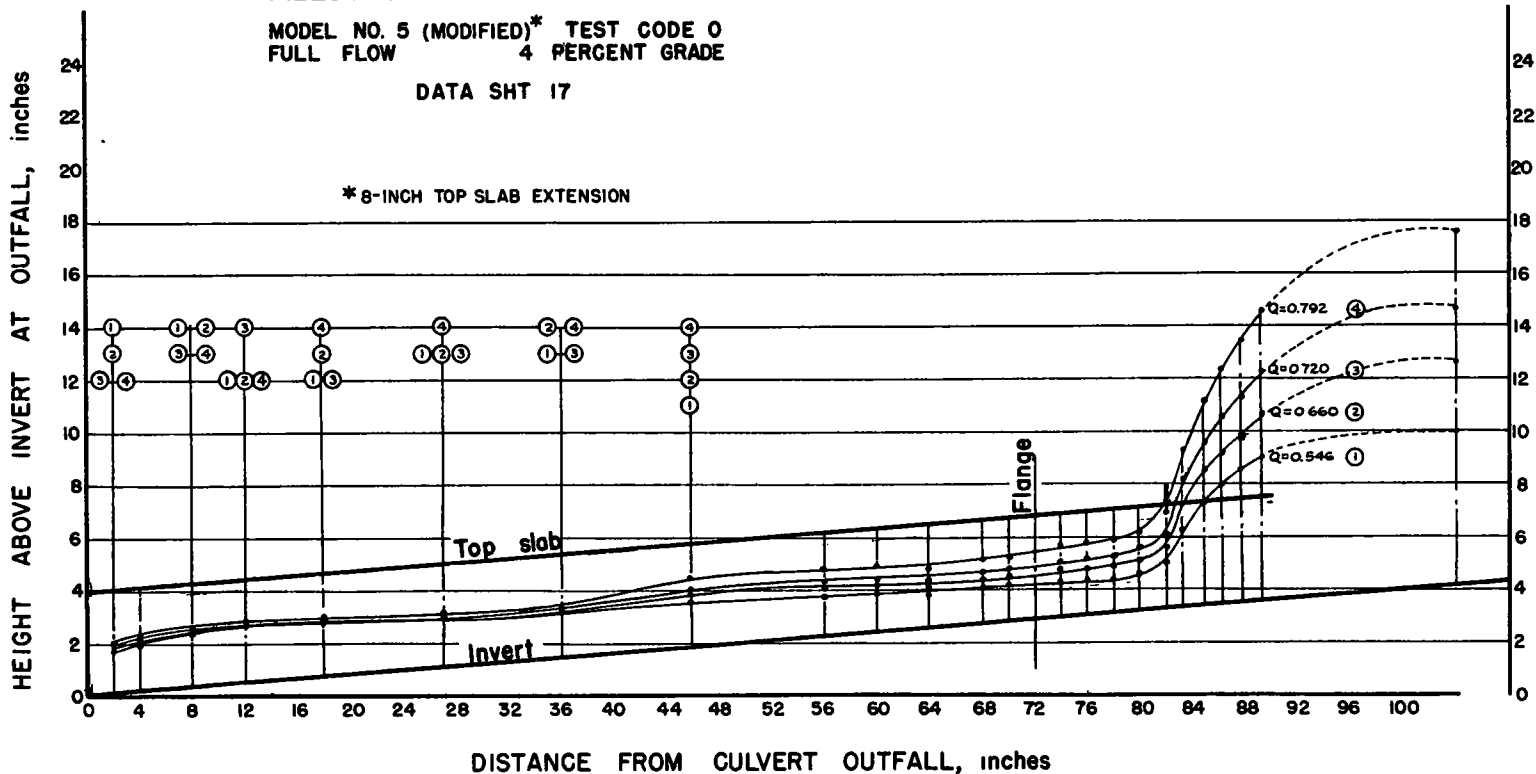
FROM

PIEZOMETER TUBE READINGS

MODEL NO. 5 (MODIFIED)\* TEST CODE 0  
FULL FLOW 4 PERCENT GRADE

DATA SHT 17

\* 8-INCH TOP SLAB EXTENSION





O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

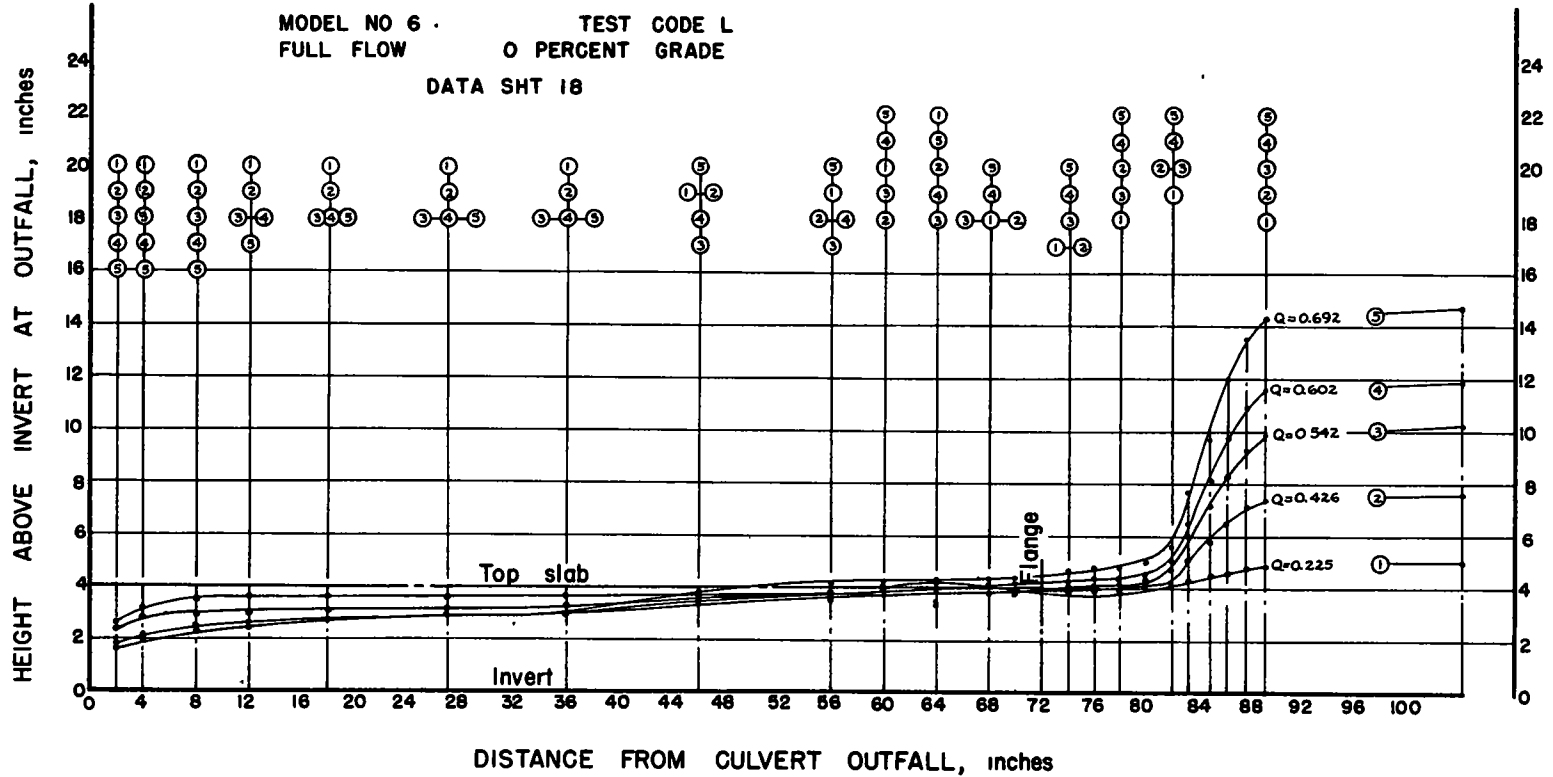
HYDRAULIC GRADE LINES

FROM

PIEZOMETER TUBE READINGS

MODEL NO 6 . TEST CODE L  
FULL FLOW 0 PERCENT GRADE

DATA SHT 18

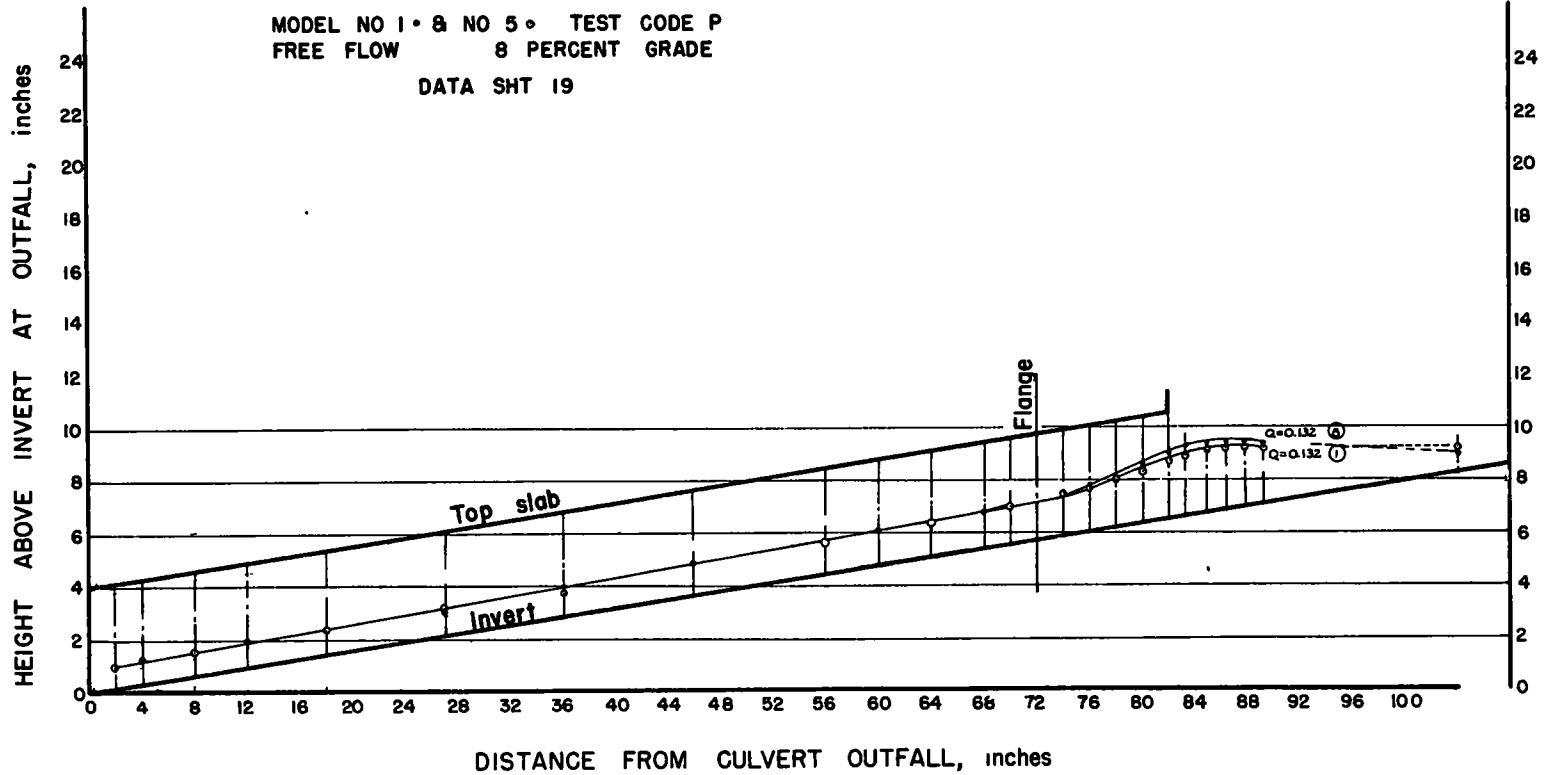


O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM  
PIEZOMETER TUBE READINGS

MODEL NO 1 • 8 NO 5 • TEST CODE P  
FREE FLOW 8 PERCENT GRADE

DATA SHT 19

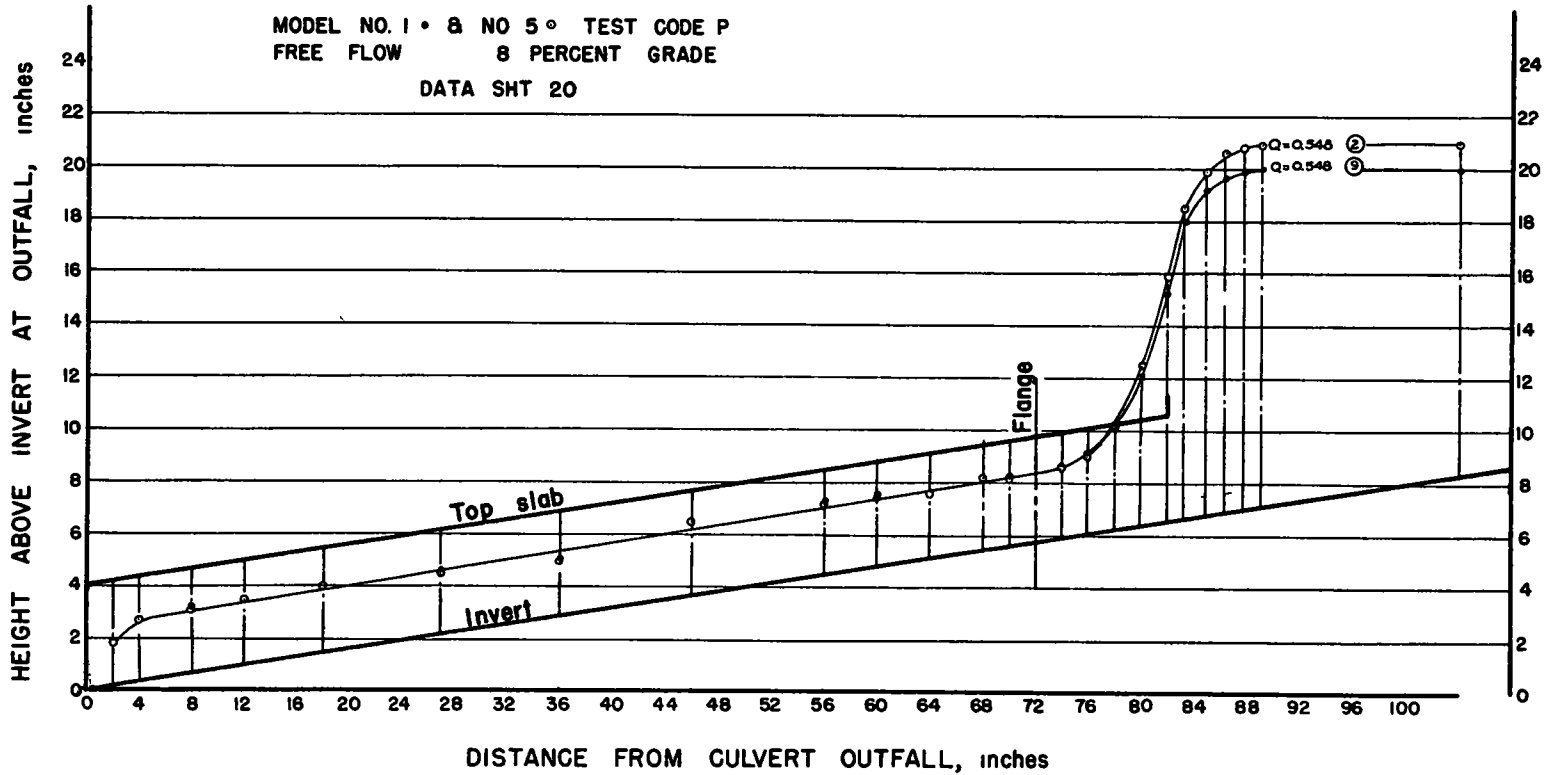


O. S. G. ENGINEERING EXPERIMENT STATION  
PROJECT 130

HYDRAULIC GRADE LINES  
FROM  
PIEZOMETER TUBE READINGS

MODEL NO. 1 • & NO 5 • TEST CODE P  
FREE FLOW 8 PERCENT GRADE

DATA SHT 20



O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

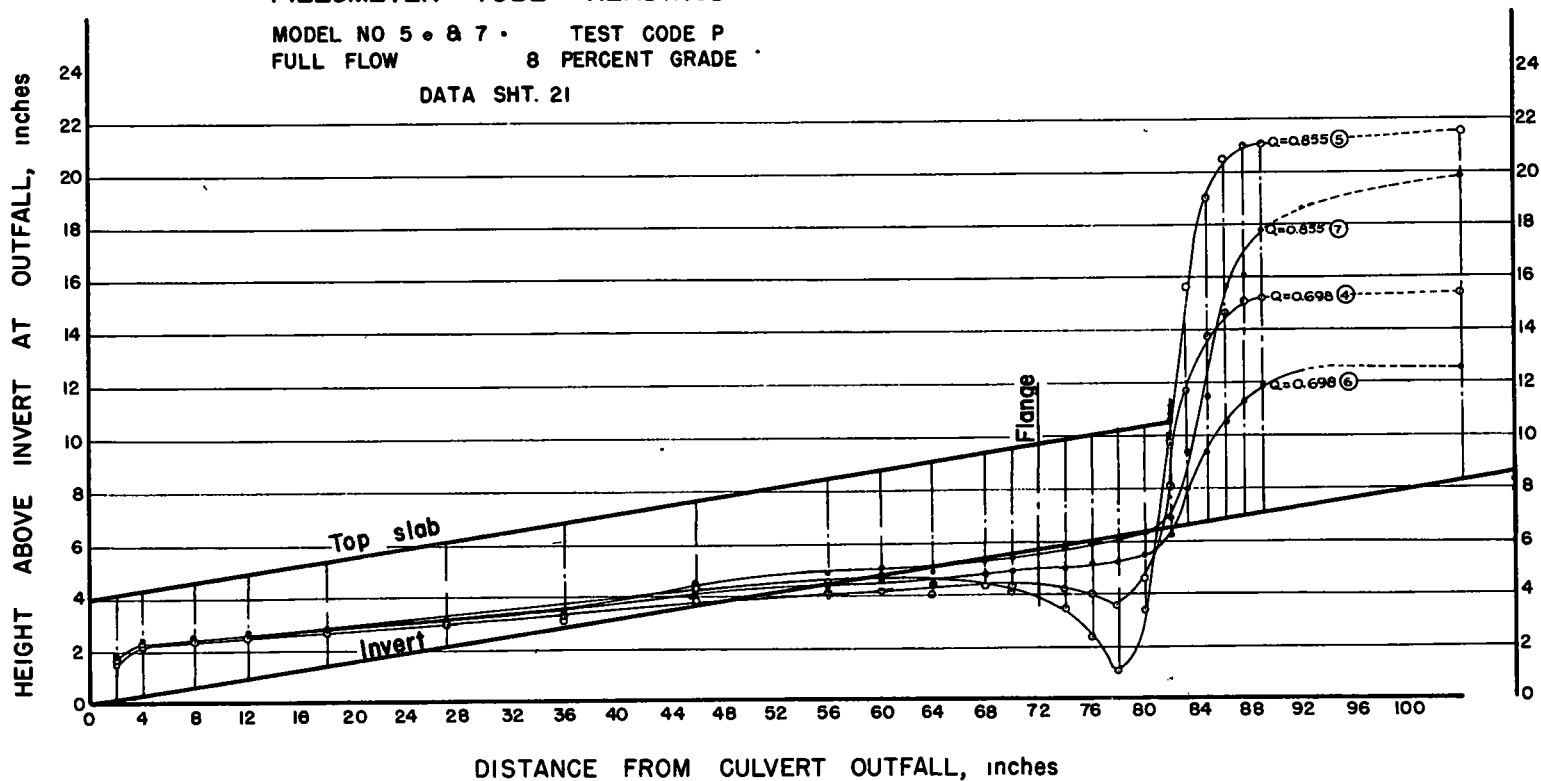
### HYDRAULIC GRADE LINES

FROM

### PIEZOMETER TUBE READINGS

MODEL NO 5 • & 7 • TEST CODE P  
FULL FLOW 8 PERCENT GRADE

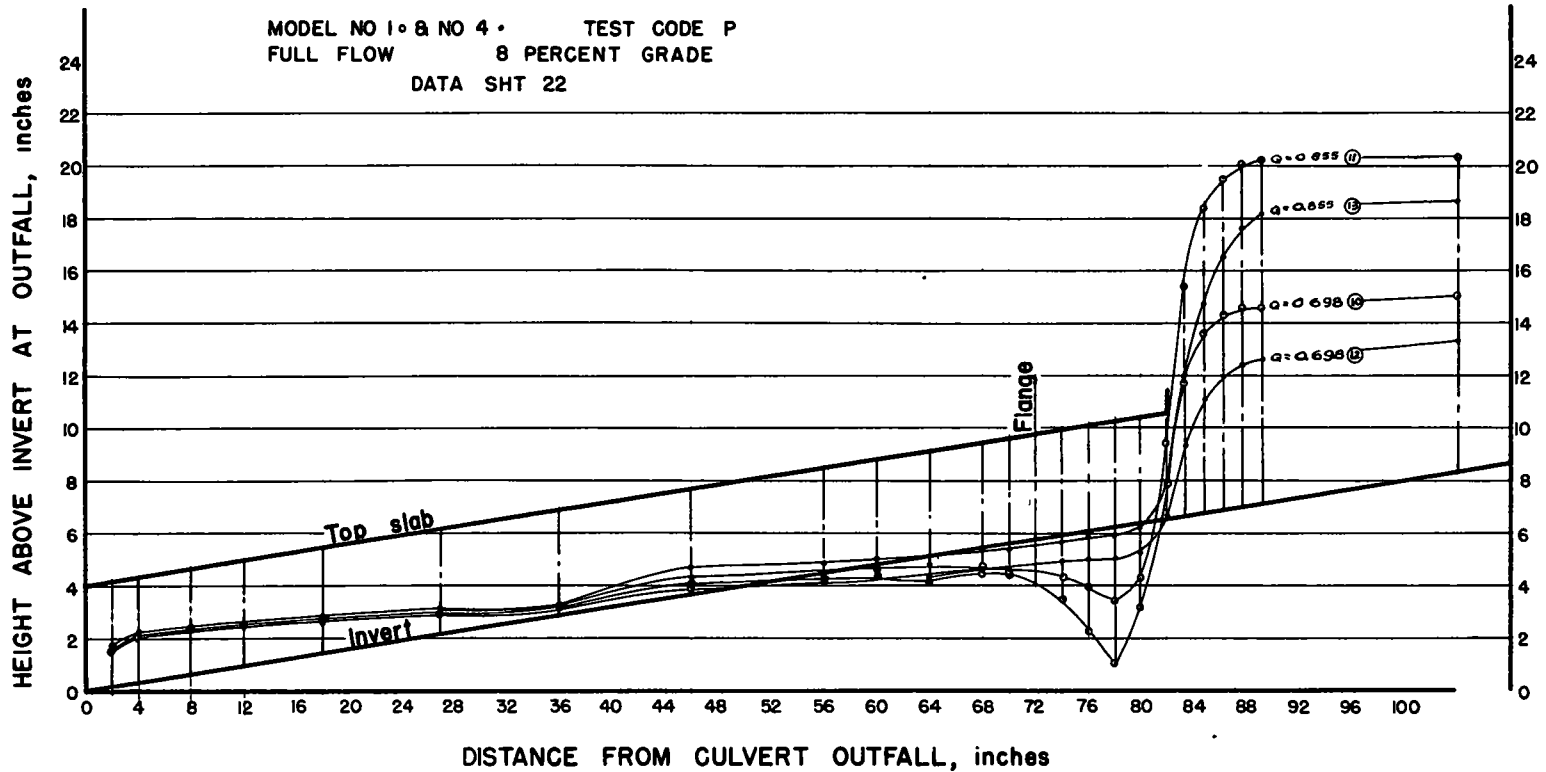
DATA SHT. 21



O S C ENGINEERING EXPERIMENT STATION  
PROJECT 130

**HYDRAULIC GRADE LINES**  
FROM  
**PIEZOMETER TUBE READINGS**

MODEL NO 10 & NO 4 • TEST CODE P  
FULL FLOW 8 PERCENT GRADE  
DATA SHT 22



## Discussion

W. O. REE, Project Supervisor, Soil Conservation Service Research, Stillwater Outdoor Hydraulic Laboratory, Stillwater, Oklahoma — The writer has recently completed model studies of some box culverts in order to determine their suitability as runoff measuring devices. In the course of these experiments the sluice-gate-type flow was observed. It was noted that nearly 50 percent of the culvert cross-section was not occupied by water at the time of peak flow. This seemed to be a waste of space and that something could be done. Therefore it was not exactly surprising to learn that at the very same time Shoemaker and Clayton were performing experiments with this in mind.

In the short time available it is impossible to give this fine paper the detailed study it deserves. However, a few comments which occur to the writer will be made. The writer agrees with the authors in their choice of formula to describe sluice gate flow. It is the most practical and further it agrees with the analytically derived expression:

$$Q = \frac{C_c}{\sqrt{1 + \frac{C_c a}{H_1}}} a \sqrt{2gH_1}$$

where

$$C_d = \frac{C_c}{\sqrt{1 + \frac{C_c a}{H_1}}}$$

These formulas are taken from "Elementary Mechanics of Fluids" by Hunter Rouse. The notation is the same as the authors. The additional term  $C_c$ , is the contraction coefficient and is the ratio of the depth of the jet to the height of the opening.

The writer found in his experiments that critical depth theory gave a satisfactory estimate of the head-discharge relationship for nonsubmerged flows through steep culverts. The expression derived from the experiments was:

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

This compares well with the theoretical relationship for flow at entrance at critical

depth, since the theoretical coefficient is 3.09 instead of 3.06. In the foregoing expression  $W$  is the culvert width, and  $h$  is head referred to culvert floor at entrance.

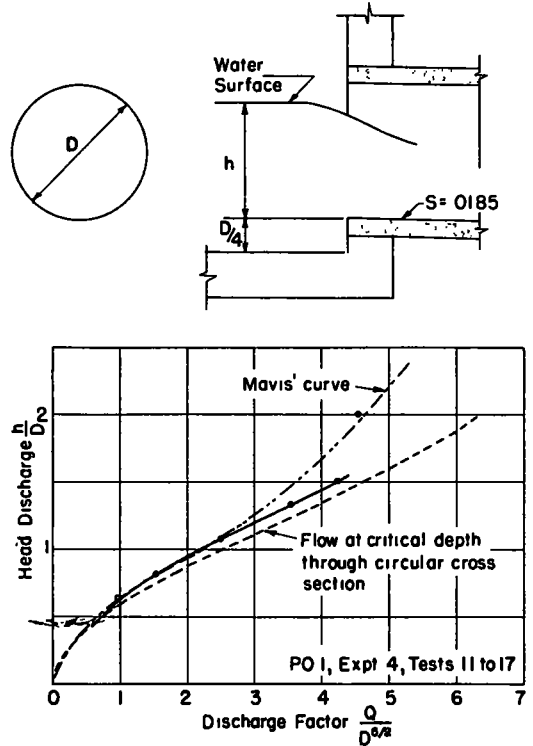


Figure A. Head-discharge relationship square-edged circular entrance for control at entrance, pipe outlet spillway.

Other recent experiments at the Stillwater Outdoor Hydraulic laboratory may be of interest here. Tests were made to determine the hydraulic characteristics of a pipe outlet spillway such as used on detention reservoirs in agricultural flood control works. In these tests the loss coefficients of the component parts of the spillway were evaluated. The first section of the spillway is a 24-in. reinforced-concrete culvert pipe 108 ft. long and laid on a 0.0185 slope. At the entrance to this pipe is a straight 4-ft.-wide wall with the wing walls perpendicular to it. The invert of the pipe is 6 in. above the apron of the inlet structure. Three entrance forms for

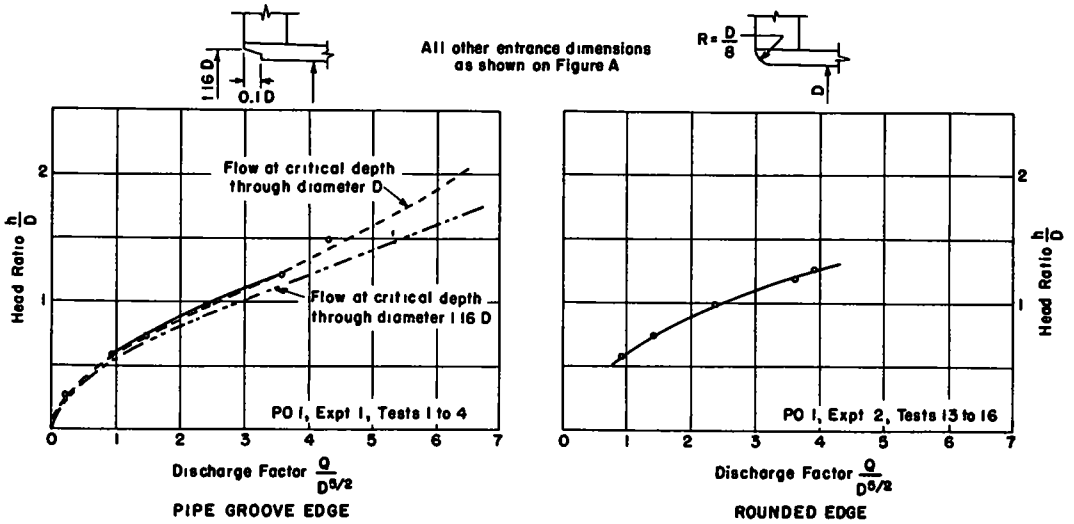


Figure B. Head-discharge relationships for circular entrances for control at entrance, pipe-outlet spillway.

the pipe were tested. For full pipe flow the entrance coefficients obtained were: Standard pipe groove entrance  $K_e = 0.33$   
 Rounded entrance, 3-in. radius  $K_e = .27$   
 Square-edged entrance  $K_e = .70$

The values of  $K_e$  are to be applied to the velocity head to determine the loss in feet.

Tests also were made on these same entrances for flows less than full. Since the pipe below was on a steep grade the entrance controlled the discharge. The results of these tests are shown Figures A and B. There are dimensionless rating curves with a discharge factor,  $\frac{Q}{D^{5/2}}$ ,

plotted against the corresponding head ratio,  $h/D$ . In these ratios  $h$  is the head above the invert at pipe entrance,  $D$  is the pipe diameter, and  $Q$  the volumetric discharge rate. Some additional curves are shown for comparison purposes. On the square-edged diagram are the curve from Mavis' experiments and a curve showing the head-discharge relationship for flow at critical depth through a circular cross-section. Critical depth curves for both the pipe diameter are shown on the pipe groove data plot to determine which diameter controlled the flow. Evidently the smaller diameter controls. Since these data are limited no further explanatory remarks will be made. However, the

data will be of some value in the form presented.

CARL F. IZZARD, Chief, Hydraulic Research Branch, Bureau of Public Roads—  
 The investigation described in this paper had its beginning in the conviction of engineers in the Portland Division Office of the Bureau of Public Roads that culvert barrels on steep grades were larger than necessary and that the main problem was to get the water through the entrance. They developed the design designated as Inlet 2 in this report. The tests by Shoemaker and Clayton amply confirm the value of this type of inlet and show why it works. By careful observation of the model in operation they developed even simpler modifications of a standard culvert, as in Inlet 4, which would accomplish the same purpose. The latter type has the advantage that it can easily be built onto an existing culvert with flared wingwalls by simply extending the top slab out from the headwall and building up the wingwalls to meet this extension.

The highway engineer should take note, however, that the degree of reduction in headwater depth obtainable by tapering the entrance depends on the difference between the headwater resulting from what the authors call "sluice" action and that for the same barrel flowing full. This difference can be readily determined by first computing the headwater depth for entrance control and comparing it with the headwater

depth which would occur if the barrel flowed full. The latter depends on the length, roughness, and slope of the barrel, as well as the entrance loss coefficient.

Fortunately, charts to facilitate these computations are already available to highway engineers. Public Roads Hydraulic Chart No. 1043 gives the headwater depth with entrance control and agrees closely with the curve for Inlet 1 in Figure 6. Chart No. 1041 gives the head loss in a culvert flowing full. The entrance loss coefficient for a tapered entrance can be assumed as 0.1 (based on velocity head in the uniform barrel). The length of the culvert should include the length of the tapered entrance. An example of the use of these charts is given at the conclusion of this discussion.

### Operation of Inlets 1, 2, and 3

Figure 8 indicates that nonsubmerged-inlet operation on a steep grade is controlled by critical depth, and Figure 9 shows variations in the location of critical depth. An analysis of the data made by plotting the drop in pressure against the distance from each piezometer to the plane of the entrance, both in terms of critical velocity head, shows that for a standard culvert, Inlet 1, critical depth occurs within the barrel a distance of about 1.4 times critical depth. The water surface, as sketched in Figure 9, will strike the top of the entrance when critical depth becomes about equal to 0.85 times the culvert height.

For Inlet 2, tapered entrance, critical depth occurs about the same (or somewhat shorter) relative distance within the uniform barrel, the position being less well defined than for Inlet 1. For both inlets, the barrel slope was 4 percent which was definitely supercritical. Obviously critical depth control near the entrance requires that the barrel slope be supercritical.

A study of data for Inlet 3 shows that critical depth occurs at or very close to the entrance, i. e., where the barrel steepens abruptly. Critical depth in a channel of uniform width would be expected to occur upstream from the break but in this case the converging walls force the critical section to occur about at the break. The total head is actually slightly less than the minimum total head for critical depth probably because of negative pressure due to lack of aeration of the underside of the nappe.

Inlet 3 is designed in accordance with the criteria set forth in Hydraulic Information Circular No. 2 (Public Roads), page 19. The model tests indicate that the culvert operates as expected provided the inlet is not submerged. Once the barrel flows full there is no advantage to the break in grade; in fact, as shown in Figure 6, the head-discharge curve is higher than for Inlet 2. The primary advantage of Inlet 3 over Inlet 2 would be in discharging water more rapidly on the rising hydrograph, thus leaving more storage area available to knock the peak off the hydrograph. Also, where either Inlet 2 or Inlet 3 is expected always to flow partly full, the headwater with Inlet 3 will always be less than that for Inlet 2, because the control section for the latter is based on the width of the uniform barrel whereas Inlet 3 has the control section at the widened entrance.

The head  $H_2$ , as plotted in Figure 11, was determined as the difference between the elevation of the water surface at a point 4 in. from entrance as observed through the side of the flume and the elevation of the pool as determined by piezometric readings. The difference in discharge coefficients shown in Figure 12 for the 0- and 4-percent slopes is not explained, but it is not surprising considering the fact that the actual mean depth at the vena contracta is difficult to measure. It may be noted, however, that a plot of observed head  $H_1$  against  $V^2/2g$  for the full barrel, both of which are quite accurately determined, yields an equation

$$H_1 + 3a S_0 = 0.267 + 2.33 \frac{V^2}{2g}$$

which fits the data for both slopes. The left side of this equation represents the head  $H_1$  plus the fall to a point  $3a$  or 12 in. from the entrance. A study of the piezometric profiles indicates that the latter point more nearly indicates the position of the vena contracta, which conceivably could be different on the center line from what it appears to be as viewed through the side wall. From the sketch in Figure 11, since  $H_2$  is the drop in water surface from  $H_1$  to  $D_2$  the equation can be written

$$H_1 + 3a S_0 = D_2 + H_2.$$

By comparison of the two equations above it follows that  $D_2 = 0.267$  ft. and  $H_2 = 2.33$



$\frac{V^2}{2g}$  by this indirect method. From Equa-

tion 6, solved for  $H_2$ , it follows that  $C_d = (1/2.33)^{1/2} = 0.655$  which agrees fairly well with the value of  $C_d$  shown in Figure 12 for the 4-percent slope. Substituting  $D_2 = 0.267$  and  $C_d = 0.655$  in Equation 4 gives

$$C_v = \frac{0.655 \times 0.333}{0.267} = 0.82 \text{ indicating a loss}$$

of energy between the two sections.

A comparison of curves for Inlet 1 on a zero slope in Figure 16 with curve for same inlet on 4-percent slope in Figure 15 indicates that adding the fall of  $(3a S_0) = 3 \times 4 \times 0.04 = 0.48$  in. to the latter curve will cause it to coincide very nearly with the curve for Inlet 1 on zero slope. [Note: Figure 15 based on re-run of Inlet 1, as shown in data Sheets 3 and 4, is more accurate than similar curve in Figure 6.]

### Modification Experiments

The authors are to be commended for the careful observation which led to the modifications of Inlet 1 and development of Inlet 4 which for practical purposes is the equivalent of Inlet 2. Further tests with wingwalls on a 1-to-4 angle demonstrated that the area of the entrance should be about twice the barrel area in order to eliminate excessive vortex action and to enable the barrel to flow full.

Unfortunately time did not permit testing modifications of Inlet 2 in which the rate of taper of the barrel (1 to 10 for Inlet 2) was varied. However, it is reasonable to assume that rates of 1 to 1.5 and 1 to 4 would be satisfactory provided the area of entrance was twice the barrel area, since these angles were satisfactory on Inlets 4 and 7, respectively. It also appears that the enlargement may be made on the sides only or on the sides and top. Keeping the wall height constant would have a construction advantage and would also be advantageous hydraulically because it would cause the barrel to begin flowing full at a lower upstream water level. Submergence of the entrance by about 20 percent of the entrance height, as shown in Figure 6 for Inlet 2, and in Figure 15 for Inlet 4, appears to be necessary before the barrel can begin to flow full.

### Comparison with Results on Model Pipe Culvert

There is very good agreement in the conclusions which can be drawn from the Oregon tests on square box culverts and the Minnesota tests on round pipe culverts, both with free outlets:

1. Both operate with critical depth control on supercritical slopes, this relation being affected in only a minor degree by the rounding on the pipe or the wingwalls on the box. Critical depth control will cease to exist when discharge in the pipe exceeds  $4D^{5/2}$  or discharge in the box exceeds  $4BD^{3/2}$ .

(D = diameter, or height;

B = width of box; all in feet).

2. Both operate with contracted flow when entrance is square-edged, the contraction becoming substantially constant for headwater greater than 1.5 times the entrance height.

3. Elimination of the contraction in either type causes the barrel to flow full for part of the length or for the full length as the discharge rate increases to the point where utilization of the entire fall available in the barrel is required.

4. The headwater depth for both pipe and box culverts can be reduced by improving the inlet and causing the barrel to flow full, provided the head losses in the full barrel when added to the elevation of the pressure line at the outlet give a headwater elevation lower than that for entrance control with contracted flow in the partly-full barrel. Since the losses in the full barrel depend on length, size, and roughness of the barrel as well as entrance loss coefficient, all these variables must be considered but the fall in the barrel generally determines when the improved entrance will be advantageous. A guide covering most, but not all, situations is that the fall in the barrel should be at least 0.4 of the culvert height and that the head loss (H) for the full barrel must be less than 2.5 times the velocity head in the barrel.

5. The minimum head above the crown of a culvert expected to flow full with improved inlet is about 0.2 of the entrance height. If the head loss for the full barrel when added to the elevation of the pressure line at the outlet plots below this minimum elevation, the barrel will flow full for only part of its length and the pool elevation will

not drop below this minimum elevation. (Discharge must, of course, be above the limitation for critical depth control cited in 1. above)

### Discussion of Culvert Head - Discharge Relations

The foregoing conclusions indicate the many variables involved in the head-discharge relation of culverts with free outlets. The best way of comparing alternate cul-

to be entirely in the width, the height being the same as the barrel height. For the pipe an adequate rounding to eliminate the contraction is assumed. The curves are plotted only for headwater greater than culvert height.

The curves were computed from Public Roads Hydraulic Charts 1041, 1042 and 1043, minor deviations of computed points from a straight line being ignored. The curve for entrance control is dotted above  $HW = 1.5D$ , and the curve for outlet control

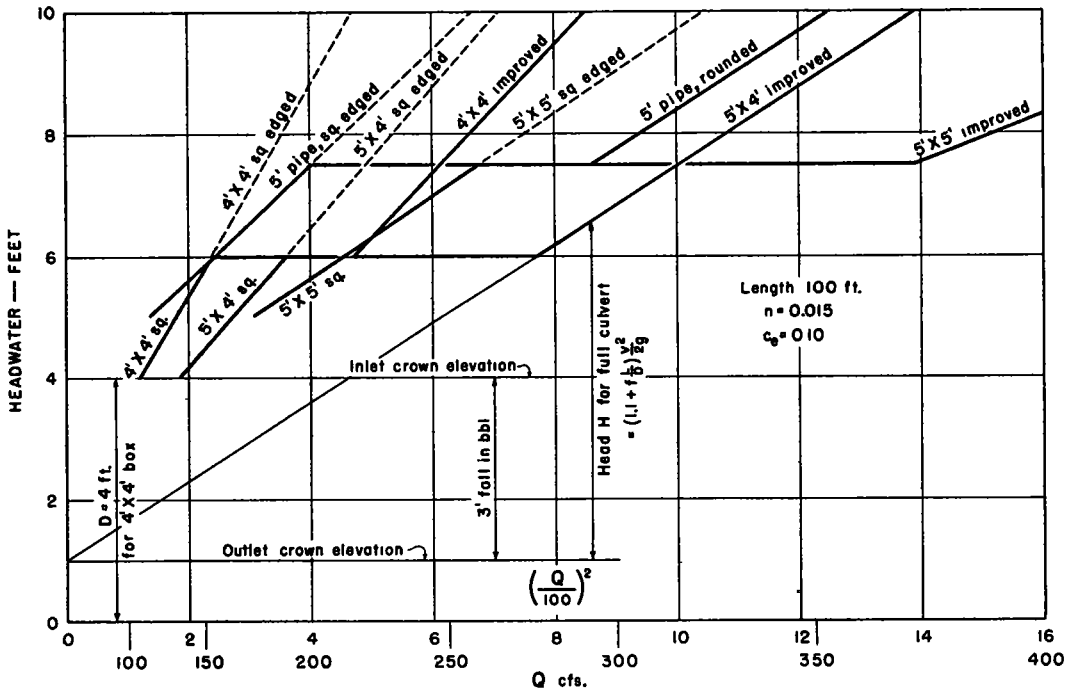


Figure A. Typical head-discharge curves for headwater greater than culvert height for culverts with and without improved entrances.

verts which might be used at a given site is to make a diagram similar to Figure A which shows the headwater depth as a function of  $(Q/100)^2$ . The abscissa could be in terms of  $Q$  to the first power, but since the head for either entrance control (above  $1.5D$ ) or full flow with outlet control varies as  $Q^2$ , the curves plot as straight lines in this form. A scale is added for  $Q$  for convenience.

Two curves are drawn for each barrel size, one for a square-edged inlet, and one for an improved inlet meeting the criteria set forth in the previous summary discussion. In the case of the boxes the enlargement of the entrance was assumed

is not drawn below  $HW = 1.5D$ , since the culvert cannot be depended on to flow full unless the inlet is submerged by at least  $0.4D$ , a slightly higher limit being set to be conservative. The horizontal line connecting the two curves indicates this minimum headwater for the full barrel.

The curves for entrance control are plotted directly from the values of headwater computed from Chart 1042 for pipe or 1043 for boxes. With full flow, however, the head  $H$  read from Chart 1041 (with  $C_e = 0.1$  and  $n = 0.015$ ) is plotted above the elevation of the outlet crown in relation to the inlet invert, which assumes the pressure line to be at the outlet crown. The culvert

length is uniformly 100 ft., disregarding slight changes which would normally occur due to difference in culvert height, as these differences would not change the head loss significantly. The fall is 3 ft., making the slope 3 percent.

In plotting curves for entrance control, points should be computed over the entire range above 1.5D. Only two points need be plotted for a full culvert; this line extended must pass through the outlet crown elevation at zero discharge.

The half hour which might be required to plot a diagram such as Figure A should be worthwhile as in similar cases (with appreciable fall in the barrel), it is usually possible with an improved entrance either to use a smaller barrel or to gain reserve discharge capacity with the same barrel size. In other cases it may be shown that the extra cost of an improved entrance, if any, may result in no appreciable saving in headwater beyond the difference in entrance loss represented by 0.4 of the velocity head. The latter does become appreciable for velocities in excess of 10 or 12 ft. per sec.

To illustrate, we may note in Figure A that if the limiting HW = 6 ft. and Q = 210 cfs., a 4 by 4 box with improved inlet is the equivalent of either a 5 by 5 box with square-edged inlet, or a 5 by 4 box with improved inlet. If the head is increased to 8 ft., the latter then has a capacity of about 330 cfs. as compared to 260 cfs. for the 4 by 4 improved inlet. This could mean that if 210 cfs. is the 10-yr. peak runoff the 25-yr. flood, being about 25 percent greater, could be handled by the 4 by 4 improved inlet with 2 ft. increased headwater. On the other hand, the 5 by 4 improved inlet could handle a 50 percent greater flood at the 8-ft. stage, which would be about a 50-yr. flood. The designer must then decide whether or not the increase in cost for the larger structure is justified by the increased protection afforded, taking into consideration the conditions at the site.

Attention is called to the fact that the 5-ft. pipe with improved inlet operates with about 1 ft. more headwater than that for the 5 by 4 improved inlet box for any discharge greater than 300 cfs. This difference is due primarily to the elevation of the outlet crown. The lower height of the 5 by 4 improved inlet also accounts for the fact that it operates at a lower head than the 5 by 5 improved inlet for

discharges from 210 to about 320 cfs. In this case, however, the lower head is due to the fact that more depth is needed to submerge the 5-ft. high entrance. Above 320 cfs. the increased area of the 5 by 5 becomes effective so that it will carry 18 percent more discharge with headwater at 7.5 ft. and an increasing percentage for higher heads.

The following table shows the relative increase in discharge for these particular culverts resulting from improving the inlet when headwater is 2D.

Increase in discharge resulting from improving entrance if HW = 2D

Size	Discharge		Percent increase
	Square edged	Improved	
4 by 4	187 cfs.	256 cfs.	37
5 by 4	232	328	41
5 by 5	325	450	39
5-ft. pipe	256	353	38

Another comparison is the amount of lowering of the headwater which is possible at the discharge where the barrel with improved inlet begins to flow full for entire length, as compared to the same culvert with square-edged inlet.

Decrease in headwater at discharge where improved culvert begins to flow full for entire length

Size	Dis-charge cfs.	Headwater, ft.		Decrease in head-water, ft.
		Square Edged	Improved	
4 by 4	217	10.2	6.0	4.2
5 by 4	277	10.7	6.0	4.7
5 by 5	373	12.2	7.5	4.7
5-ft. pipe	293	12.0	7.5	4.5

The form of diagram in Figure A lends itself especially well to studying the effect of fall in the barrel upon the comparative headwater elevations for a given barrel size with and without an improved inlet. The line for the full culvert is fixed in slope but the position depends on the elevation of the pressure line at the outlet. Consequently by drawing a parallel line through the outlet crown elevation

plotted at  $Q = 0$ , the operating curve for any fall in the culvert of the same length is immediately determined, bearing in mind that it is fully effective only for headwater greater than  $1.5D$ . In the case of the 4 by 4 box a line parallel to the 4 by 4 improved inlet line drawn through the headwater of 6 ft. where it intersects the line for the 4 by 4 square-edged inlet, indicates that a fall of 0.5 ft. is necessary to equalize capacities. Consequently on this slope there is no advantage to using an improved inlet at this headwater although there is a slowly increasing advantage for higher pool elevations. The following table gives equivalent values for the other culvert sizes.

Minimum fall for equivalent discharge with square-edged and improved inlets at  $H = 1.5D$

<u>Size</u>	<u>Fall</u>	<u>Headwater</u>	<u>Discharge</u>
4 by 4	0.5	6.0	152
5 by 4	0.4	6.0	190
5 by 5	0.2	7.5	260
5-ft. pipe	0.1	7.5	200

The general characteristics of the head-discharge curves plotted in the form of Figure A are as follows:

1. The entrance control curve depends only on the dimensions of the entrance and is fixed in position for a given culvert. Length, roughness and slope of culvert are immaterial, except as a rising water surface may force the barrel to flow full.

2. The curve for full flow has a slope which depends on the entrance loss coefficient, the roughness, length, hydraulic radius and area of the barrel. The position of the curve depends only on the elevation of the pressure line at the outlet.

3. The horizontal line for minimum submergence is drawn at  $1.5D$  which is probably conservative; culverts may actually begin to flow full at inlet for somewhat lower heads.

4. For headwater less than  $1.2D$  critical depth controls and the head-discharge curve would not plot as a straight line in Figure A because head is not directly proportional to the discharge squared. For such low heads the barrel will usually be flowing with a free water surface and the form of the inlet has a relatively small effect on headwater (except in the special case of an enlarged inlet with a steep drop in the tapered portion of the barrel, (Inlet 3 in Oregon report).

The Bureau of Public Roads is preparing a series of charts with head-discharge curves for any size and length of culvert with square-edged entrance operating under low head. This is possible because the variation in headwater with length is either zero as on supercritical slopes, or of small magnitude on mild slopes. These curves will enable direct comparison of headwater for various sizes with only a minor correction for longer culverts on relatively flat slopes and will obviate use of Charts 1042 and 1043 in this range.