Capacity Charts for the Hydraulic Design of Highway Culverts

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U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

CAPACITY CHARTS FOR THE HYDRAULIC DESIGN OF HIGHWAY CULVERTS

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I. INTRODUCTION

Since hydraulic capacity is one of the most important factors in the design of a highway culvert, simple methods for making this determination are needed. This circular contains a series of hydraulic capacity charts which permit the direct selection of a culvert size for a particular site without making detailed computations.

The charts in this circular do not replace the nomographs of Hydraulic Engineering Circular No. 5 (HEC No. 5). The procedures given in the two circulars supplement each other by providing a solution for most designs likely to be encountered. Both circulars give identical answers in certain ranges of hydraulic operation, but the nomographs of HEC No. 5 must be used for the higher headwater depths and in cases of submerged outlets. This circular discusses the requirements and limitations for the use of the capacity charts and the instructions tell when HEC No. 5 must be used.

The designer, after becoming familiar with the capacity charts, will discover that these direct-reading charts have advantages over the trial and error procedure used in HEC No. 5. For instance, the capacity of the various types and sizes of culverts in common use can be compared rapidly and the charts provide a more accurate solution for low headwater depths which is the main limitation in the use of HEC No. 5. Sometimes the chart answer must be modified if a special culvert is used or an unusual site condition is encountered, but for the majority of culvert problems the capacity charts are adequate for the selection of a culvert size.

A list of the culvert capacity charts is given on the last page of this circular for eacy reference. All symbols, notations and descriptive terms used are the same as in HEC No. 5 and the appendix contains a discussion of the hydraulic computation methods used in compiling the culvert capacity charts.

In addition to the capacity charts and instructions for their use, this circular includes a brief discussion of other design considerations to emphasize that culvert capacity is only one of the many problems confronting the engineer in the design of a culvert.

II. DESCRIPTION OF CAPACITY CHARTS

A. Scope of Charts

Charts for nearly all culverts commonly used for highway construction are contained in this circular. The principal shape classifications are square, rectangular, circular, oval, and pipe-arch sections. A barrel shape is represented by separate charts if the barrel materials have significantly different roughness characteristics. Separate charts are not included for vitrified clay or timber culverts. Culverts of these latter materials may be designed by using the charts for concrete culverts. A list of charts is given on the last page of the circular.

The two basic types of culvert inlets included in the charts are: (1) headwalls with wingwalls and (2) projecting barrels to toe of embankment. The capacity charts can be used for several other entrance treatments without appreciable error. These entrances are discussed on the page preceding each group of charts.

Headwalls are commonly used in combination with wingwalls placed at various angles of flare, ranging from 0° to 90° with the longitudinal axis of the culvert. In box culverts flared wingwalls placed at 30° to 75° with the longitudinal axis are superior to wingwalls at other angles of flare. Two sets of charts for box culverts are included to show the hydraulic performance with these different angles of flare.

Tests have shown that wingwalls have little effect on the capacity of circular pipe or pipe-arch culverts. For these sections, the form of the edge at the entrance is the prime factor affecting capacity. A corrugated metal pipe projecting beyond the fill slope provides a thin-edged inlet and gives less capacity than the same pipe incorporated in a headwall. Consequently, all metal culverts are classified as a projecting or a headwall entrance on the charts.

Concrete pipes and other pipes made of material having a relatively thick wall perform nearly the same with or without headwalls. The standard tongue-and-groove pipe joint, if used as an entrance, provides sufficient enlargement to form the most efficient inlet of those commonly used. Charts for concrete pipe are provided for a square-edge entrance and for a groove-edged entrance with the limitation of various types of wingwalls given on page 10-35.

In the "chart listing" on the last page of this circular, mitered inlets or standard end-sections are not given. Separate charts are not required for these inlets, since the performance of these inlets is similar to other types that are included. The mitered inlet on metal pipe gives approximately the same performance as a projecting metal pipe (see chart 5 of HEC No. 5). Standard concrete and metal end-sections have the same headwater discharge relationship as a square-edged concrete pipe or a metal pipe in a headwall. Charts for these respective end treatments may be used for these standard end-sections, pgs. 10-35 and 49.

All the charts are designed for a range of headwater, discharge, length, slope and size adequate for the design of most highway culverts. The make-up of the charts is discussed in "Composition of Charts" below and in the appendix.

The use of the charts for the hydraulic design of special culverts, such as broken grade lines or paved inverts, is discussed in sec. IV, "Special Uses of Capacity Charts."

B. Composition of Charts

Each culvert capacity chart contains a series of curves which show the discharge capacity of each of several sizes of similar type culverts for various depths of headwater. Headwater depth is given in feet above the invert of the culvert at the inlet, referenced to the first complete cross-section of the barrel. The discharge rate per barrel is given in cubic feet per second (cfs). The invert of the culvert is defined as the low point of its cross section (sometimes referred to as the flow line). The solid-line curves represent inlet control and the dashed-line curves represent outlet control. (See HEC No. 5 or appendix A of this circular for a discussion of these controls). The $L/100S_o$ ratio marked on the curves is used to measure the degree to which headwater is influenced by length (L in feet) and invert slope (S_o in ft./ft.).

The solid-line inlet-control curves are plotted from model test data. A description of inlet control flow and diagrams of various stages of this condition are shown in HEC No. 5. In inlet control the inlet edge contour and the barrel size control the depth of headwater. The length and roughness of the barrel and the flow in the outlet channel have no effect upon the headwater required to discharge a given rate of flow in inlet control.

The dashed-line outlet-control curves were computed for culverts of various lengths with relatively flat slopes. Further details regarding the methods for computing the curves are given in appendices A and B. Free outfall at the culvert outlet was assumed. For this free outfall condition, tailwater or flow in the outlet channel has no effect on culvert performance. Diagrams of outlet control flow where the outlet is not submerged by tailwater are shown in figures 2B, C and D of HEC No. 5.

For all culvert types flowing in outlet control, loss of head at the entrance was computed by use of the entrance loss coefficients of table 1, appendix B, HEC No. 5. The hydraulic roughness of the various materials used in culvert construction was taken into account in computing resistance loss in full or part-full flow with outlet control of headwater. The Manning n values used for each culvert type are given in appendix A-4.

Headwater depths shown in the charts extend to 3 times the culvert height except for the large pipe sizes. Pipe-arches and oval pipe show headwater up to about 2.5 times their height, since they are normally used in low fills. The dotted line, stepped across the chart curves, shows headwater depths of about twice the barrel height. This line indicates the upper headwater limit for the unrestricted use of the charts. (See sec. III, "Requirements and Limitations for Use of Charts".)

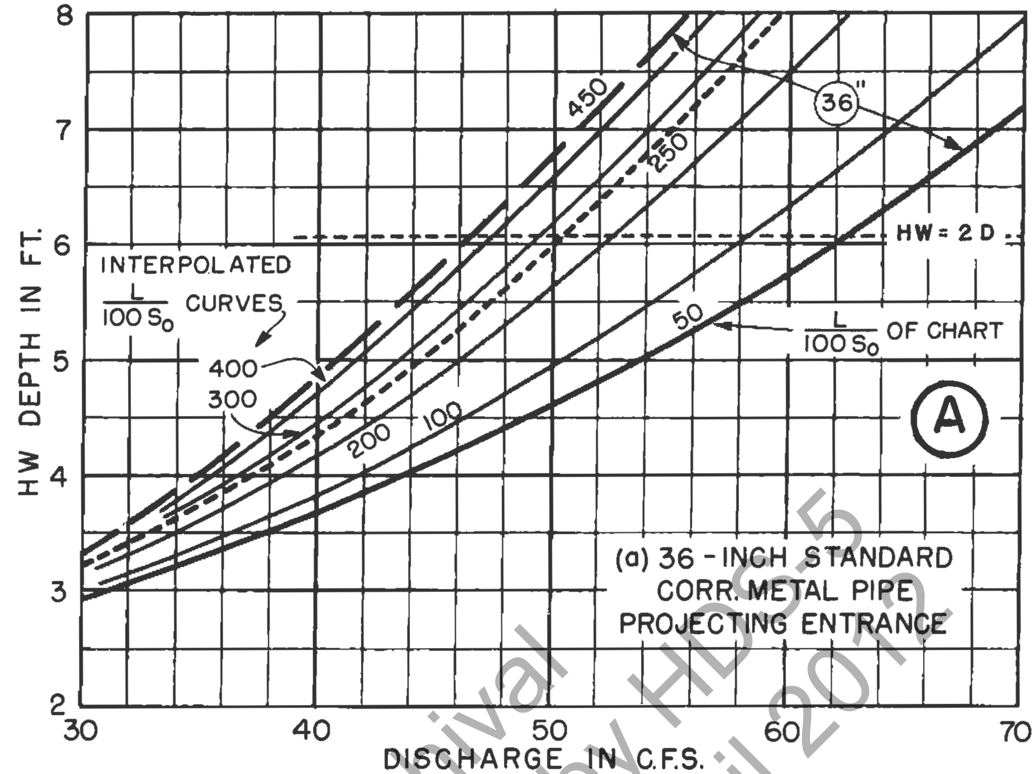
The headwater depth given by the charts is actually the difference in elevation between the culvert invert at the entrance and the total head; that is, depth plus velocity head for flow in the approach channel. In most cases the water surface upstream from the inlet is so close to this same level that the chart determination may be used as headwater depth for practical design purposes.

C. Reading of Charts

The capacity charts may be used for determining headwater or discharge of a given culvert installation or for selecting a size which will operate under a given set of conditions.

For purposes of illustrating how the charts are read, sections of charts are shown in fig. 1. Fig. 1A contains curves for a 36-inch pipe taken from chart No. 19, and combines in one graph the two separate sets of curves for a 36-inch projecting entrance standard corrugated metal pipe. Included are the inlet control curve with $L/100S_o$ of 50, and two outlet control curves with $L/100S_o$ of 250 and 450. Additional curves for $L/100S_o$ of 100, 200, 300 and 400 have been added to the chart 19 curves by linear interpolation. These additional curves are located by measurement along several discharge lines to divide the headwater depth range between curves into intervals proportionate to $L/100S_o$. The curves are shown to aid in illustrating the interpolation procedure which is to be used in reading headwater from a culvert capacity chart when the given $L/100S_o$ ratio is different from the chart curve.

Headwater depth is read from a capacity chart by entering at the design Q and following up the chart to intersect a curve with an $L/100S_o$ value computed from the length and slope of the particular culvert to be investigated. Headwater is read on the ordinate scale. Fig. 1A is prepared to show how this is done. If $L/100S_o$ is 50 or less, the culvert operates in inlet control, and headwater depth is read on the solid line inlet control curve. No lesser depth of headwater is



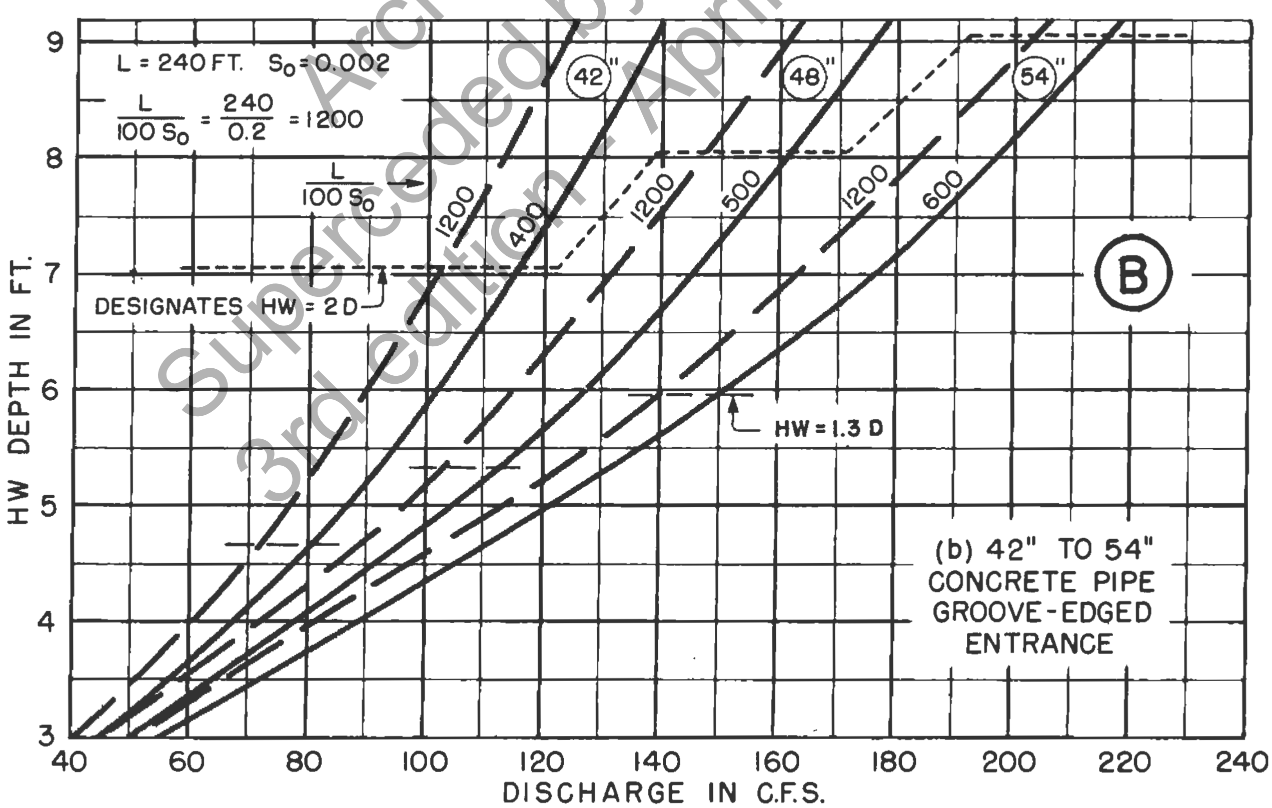


Figure 1 - TYPICAL CULVERT CAPACITY CHARTS

possible even for smaller $L/100S_o$ values. If the $L/100S_o$ happens to be that of one of the curves shown, headwater depth would be read from that curve. For any $L/100S_o$ value other than shown on the curves and within the chart limit, i.e., greater than 50 and less than 450, headwater depth must be read by interpolation between the curves.

For example, consider a peak discharge rate of 50 cfs. For a 36-inch culvert 78 ft. long on a 0.0056 slope ($L/100S_o = 140$), headwater depth will be 5.2 ft. Another culvert 166 ft. long at 0.5% slope ($L/100S_o = 330$), will require a headwater depth of 6.3 ft. at the same discharge rate.

It should be noted that the latter problem begins to get into the range of headwater depths (above 2D) where less reliable determinations of headwater can be made as discussed in "Composition of Charts", sec. II B. If the accuracy of the 6.3 ft. headwater depth is important to the solution of the problem, this depth should be checked by procedures given in HEC No. 5.

The factors governing culvert size selection include the design discharge rate, a limiting headwater depth, the culvert length and invert slope. The type of culvert must be preselected in order to locate the capacity chart to be used. Figure 1B, which is a part of chart No. 13 with an expanded scale, is used to demonstrate culvert size selection. The type selected is a concrete pipe with a groove-edged entrance.

For a culvert length of 240 ft. and slope of 0.002 as shown in fig. 1B, a range of headwater and discharges can be studied for the three sizes of groove-edged concrete pipe shown. The $L/100S_o$ ratio is 1200, therefore headwater-discharge values may be determined accurately along the "1200 curve" up to the HW = 2D line. If the problem under consideration stated that the discharge was 100 cfs for a limiting headwater of 6.0 ft., a 48-inch pipe must be selected, since the smaller 42-inch size gives a headwater of 6.8 ft. A 48-inch gives a headwater of 5.2 ft.

(The "HW = 1.3D lines" shown on fig. 1B are limits below which the maximum $L/100S_o$ ratios on the capacity chart may be extrapolated to 1.5 the value shown. In this case the curves may be extrapolated to $L/100S_o$ of 1800 below HW = 1.3D as discussed in sec. IV, case 9. The 1.3D lines are not shown on the capacity charts.)

A discharge rate of 120 cfs and an allowable headwater depth (AHW) of 6.0 ft. will be used to illustrate further the culvert selection procedure. Inspection of fig. 1B or chart No. 13 reveals that a 42-inch diameter culvert of this type would not be adequate for any length-slope ratio, because the minimum headwater depth is 7.4 ft. for the 120 cfs, not the 6.0 ft. desired. A 48-inch size would be a proper selection for all $L/100S_o$ ratios less than approximately 900. Some extreme length and small slope conditions giving higher $L/100S_o$ ratios would require a 54-inch culvert.

Some specific $L/100S_o$ ratios will be considered for the above allowable headwater of 6.0 ft. and discharge of 120 cfs. If $L/100S_o$ is approximately 900 or less, a 48-inch size would satisfy the limiting headwater of 6.0 ft. according to fig. 1B. A check computation may be made by use of the proper full-flow nomograph found in HEC No. 5. Assuming a culvert length of 210 ft. and a slope of 0.0023, $L/100S_o = 910$. Solving the problem by use of the full-flow nomograph and procedures of HEC No. 5, it is found that $H = 3.0$ ft. and $h_o = 1/2\ (3.3 + 4.0) = 3.6$ ft. For the conditions stated $LS_o = 0.5$ ft. Therefore, $HW = H + h_o - LS_o = 6.1$ ft. Considering the minor inaccuracies that are inevitable in reading the graphs, the two methods check.

Another problem for the same Q and AHW could involve a long culvert on a small slope, say L = 360 ft. and $S_o = 0.0024$, so that $L/100S_o = 1{,}500$. Obviously, from reading the chart the headwater exceeds 6.0 ft. for the 48-inch culvert, therefore, a larger culvert must be selected. By extrapolation of the 54-inch pipe curves for an $L/100S_o$ of 1,500, instructed by sec. IV, case 9, the headwater is read as 5.3 ft. (This headwater is less than 1.3D. Therefore, extrapolation is permitted by case 9a.) A more exact method, based on a backwater profile computation, (not shown) gives HW = 5.25 ft. An outlet control computation as given in HEC No. 5 gives HW = 2.2 + 3.8 - 0.9 = 5.1 ft., but this value of headwater as stated in the nomograph method, is slightly below the range for accurate answers. It should be clear, however, that either extrapolation of the capacity charts or the use of the nomographs of HEC No. 5 is adequate for the proper selection of a culvert size to pass the 120 cfs within a headwater limit of 6.0 ft.

III. REQUIREMENTS AND LIMITATIONS FOR USE OF CHARTS

Because culvert flow problems vary in complexity it is difficult to express headwater-discharge relationships in simple curves or charts without some limitations. The culvert capacity charts are designed to provide an easy method for the direct selection of culvert size for the majority of highway culvert installations, but the following requirements and limitations for the direct use of the charts must be observed for correct solutions.

A. Requirements and Limitations

1. The culvert type under consideration must be represented by the chart as noted in the title. (Other inlet types can be used -- see B-1 next page.)

2. The culvert size must be included on the chart.

3. The culvert invert must be on a continuous straight-line slope from inlet to outlet, and slope downward in the direction of flow (not level).

4. The $L/100S_o$ ratio must not exceed the largest value shown on the chart for the size involved.

5. The headwater depth must be less than 2D for the size considered.

6. The elevation of the tailwater in the outlet channel must not submerge critical depth at the outlet. (Critical depth for various culvert sections may be found from charts in HEC No. 5.)

B. Problems Not Meeting Above Requirements

Problems will be encountered which will not meet the above requirements for the direct solution by the charts. In many cases these problems can be solved by finding a chart for a culvert of similar characteristics (and, therefore, the same hydraulic performance) or by modification of the problem so that one of the charts is applicable. Therefore, the above requirements and limitations are discussed in the following paragraphs to broaden the use of the charts.

1. The charts may be used for some entrance types other than shown in the titles. The instructions preceding each set of charts list equivalent entrance types. Some charts may be used for solving problems involving other materials with similar roughness characteristics, i.e., vitrified clay can be assumed to have the same roughness as concrete. Also instructions are given in sec. IV, cases 1 and 2, for modification of problems when a corrugated metal pipe is paved.

2. Instructions for the use of the charts when sizes are not included on the charts are given in sec. IV, cases 3 through 6.

3. Procedures for the selection of culverts on zero slopes and broken grade lines (broken-back) are given in sec. IV, cases 7 and 8, respectively.

4. When a $L/100S_o$ ratio exceeds the chart's value for the size involved, refer to sec. IV, case 9 for instructions.

5. When the headwater depth exceeds 2D as indicated by the step-dotted line of the charts, values read from the curves become less reliable. If accurate headwater depths are important in this range, they should be checked by procedures in HEC No. 5.

6. The charts are prepared for free flow conditions at the outlet, i.e., tailwater is sufficiently low that it does not modify flow in the culvert. Therefore, a chart solution for culvert size should not be accepted until the depth of flow in the outlet channel has been compared to the indicated culvert barrel height and to critical depth at its outlet. Charts giving critical depth at the outlet are included in HEC No. 5.

The following procedures must be followed to determine headwater for the tailwater conditions stated:

a. Tailwater depth is less than barrel height and less than critical depth at the culvert outlet. In this case the culvert capacity chart solution for headwater depth is dependable, as in A-6 above.

b. Tailwater depth submerges the crown of the culvert outlet. In this case do not use the capacity charts, but follow procedures of HEC No. 5.

c. Tailwater elevation lies between critical depth and the crown of the culvert at the outlet. Find HW from the capacity charts as directed by steps (1) or (2) and check answer by (3) below:

   (1) If $L/100S_o$ is equal to or greater than 1/2 of the value on the solid line curve of the capacity chart, find HW by adding $\frac{1}{2}$ (TW - d_c) to the chart determination of HW, then check (3).

   (2) If $L/100S_o$ is less than 1/2 the value on the solid line curve, determine HW by using chart value of HW, then check (3).

   (3) In some cases, especially in problems involving large culverts and low flow, the tailwater elevation could be higher than the HW elevation given in steps (1) and (2). If the tailwater elevation is higher than above HW determination, refer to procedures in HEC No. 5.

IV. SPECIAL USES OF CAPACITY CHARTS

Some culverts cannot be selected directly from a culvert capacity chart because one or more of the requirements of sec. III are not met. In order that the charts can be more generally applicable, several special uses are described below:

Case 1. Paved invert corrugated metal pipe or pipe-arch culverts.

If the barrel roughness is changed by pavement of some type, use the chart for an unpaved culvert of the same entrance type. Reduce the culvert length by means of the following instructions and compute $L/100S_o$ using reduced length. Then use the chart in the normal manner.

0.75 L for standard or structural plate circular C.M. pipe with 25% of circumference paved.

0.60 L for standard (1/2") C.M. pipe-arch with 40% of circumference paved.

0.67 L for structural plate (2") C.M. pipe-arch with 33% of circumference paved (average value).

Case 2. Fully paved corrugated metal pipe with headwall entrance.

Use the square-edged entrance concrete pipe culvert charts, with $L/100S_o$ computed for the total length. The charts cannot be used for projecting entrance C.M. pipe nor for C.M. pipe-arch. For the latter cases, use the C.M. pipe of pipe-arch nomographs of HEC No. 5, adjusting the culvert length on the basis of n = 0.012 for outlet control.

Case 3. Rectangular concrete box culverts of 5 ft. height or more.

a. Select a trial size square box of the height desired.

b. Determine from chart the discharge Q for the allowable headwater and the square box selected. If Q is not equal to the design Q, find the required span B as follows: Determine discharge per foot of span (q) for the square box using the Q determined from the chart. The required span $B = \frac{Q\ Design}{q}$. If the span-to-height ratio is not satisfactory, try another trial square culvert.

c. All other conditions required for the direct use of the charts must be met, including the adjustment of HW for TW depth.

Case 4. Circular pipe sizes not included in the charts for concrete or corrugated metal pipe.

If all other conditions required for the direct selection procedure are met, pipe sizes of diameter half-way between those shown in the chart (such as half-foot diameters above 72-inch, or quarter-foot diameters below 36-inch) may be selected by interpolation horizontally as follows:

a. The Q-AHW point of the problem must be between chart curves, and sufficiently above the lower curve (larger size) to indicate that an intermediate size may be acceptable.

b. Note whether the culvert $L/100S_o$, as applied to the two adjacent sizes included in the chart, indicates that HW would be read on the solid line curve, a dashed line curve, or an intermediate position.

c. Working on the first HW grid line of the chart below AHW, note the point on the line at which the proper curve of $L/100S_o$ for each of the adjacent chart sizes, from step b above, will cross the selected HW grid line.

d. Then measure horizontally on this grid line to find a point midway between the two points found in step c. The headwater curve for the intermediate culvert size, as defined by $L/100S_o$, will pass through the midway point and be parallel with the chart curves of the same $L/100S_o$.

e. Examination of the approximate path of this interpolated curve for the intermediate size will show whether it will be below the Q - AHW point defined by the design conditions. If so, the size is acceptable. If not, use the next larger size, which in these cases is included in the chart.

f. Make adjustment for TW if necessary.

Case 5. Oval concrete pipe sizes not on the charts.

Three of the available pipe sizes within the range covered by charts 15 to 18, i.e., numbers 3, 5 and 7, are not included in the charts because of the small difference in headwater depths between the sizes shown. The headwater curves for each will pass through points on horizontal lines (headwater depth lines) midway between the curves for the adjacent chart sizes. The procedures of Case 4 are used to obtain an interpolated curve for the intermediate size based on the culvert $L/100S_o$. A table of oval pipe sizes is given in the instruction sheet preceding chart 15.

Case 6. Corrugated structural plate (2" x 6") pipe-arch sizes not on the charts.

The culvert capacity charts include headwater curves for only 8 of the 34 standard sizes generally available. A complete table of sizes of pipe-arches with corner plates of 18-inch inside radius, with dimensions and area of each, is included in the instruction sheet preceding the pipe-arch charts, p. 10-70. The number of sizes available between those represented by curves on the charts varies as shown by the listing of sizes. Horizontal interpolation can be used to determine curves for intermediate sizes as explained below:

a. The Q-AHW point of the design problem must be between the chart curves. In addition, a significant difference in resulting headwater depth should be indicated in order to justify selection of an intermediate size.

b. Find the points at which headwater curves for the two adjacent sizes of the chart, at the culvert $L/100S_o$, will cross the first headwater depth grid line below the AHW point.

c. Divide the horizontal distance along this headwater grid line, as found in step b, into a number of equal spaces corresponding to the number of intervals between available sizes in the range from one chart size to the next. For example, the horizontal distance between curves for sizes 12 and 17 of the chart would be divided into 5 equal spaces along any headwater depth line, and the curve for size 14 will be found at 2/5 this distance from number 12.

d. The interpolated curve for the intermediate size will pass through the division point on the headwater depth line, as obtained in step c, and will be nearly parallel with the chart curves of the same $L/100S_o$.

e. Examination of the approximate path of this interpolated curve will show if HW at design Q is below the AHW point, and therefore the size is acceptable. If not, use the next larger size.

f. All other conditions required for the direct selection must be met, including the adjustment of HW for TW depth.

Case 7. Culvert slope zero (level invert).

The ratio $L/100S_o$ cannot be computed for a zero slope, but a size meeting the design requirements can be selected by the following instructions:

a. In order to compute $L/100S_o$ for use of the charts, assign a fictitious slope S_o, and determine a fictitious fall of the invert $L \times S_o$. Use the following slopes:

0.002 for all concrete culverts.

0.004 for standard C.M. pipe and pipe-arch, unpaved or paved.

0.010 for structural plate C.M. pipe or pipe-arch, unpaved or paved.

For paved invert C.M. culverts use the reduced lengths of Case 1 to compute $L/100S_o$ and the fall $L \times S_o$.

b. To select a culvert size from the capacity charts, first reduce the AHW depth by the amount of the fictitious fall introduced in a above. Then use the standard procedure for the use of the capacity charts and the above computed $L/100S_o$ to select an acceptable culvert size. The culvert selected should meet the modified AHW requirement.

c. If the actual HW for the selected culvert is desired for recording purposes in the design procedure, it is found by adding the fictitious fall to the HW read from the chart.

d. All other conditions required for the direct selection must be met, including the adjustment of HW for TW depth. The increase for submergence of d_c by TW is in addition to the amount $L \times S_o$ added to the chart reading to compensate for the level invert.

e. If a culvert with level invert is also classified as one of the above 6 special cases for culverts not meeting the requirements for the direct use of charts, the above procedure is also used.

Case 8. Culverts with broken slopes.

The capacity charts may be used with the culvert invert on two different slopes if all other requirements for use of the direct size selection are met. Tailwater depth seldom affects HW for broken slope culverts. In most cases the steep slope of either the inlet or outlet sections will establish an outlet velocity sufficient to repel a depth established by the downstream channel.

With two slopes, the control section may be at the inlet, at the break in grade if the first slope is relatively flat and the second slope is steep, or at the outlet. Outlet control is possible under some conditions regardless of the two slopes of the barrel. Therefore, a check headwater computation must be made for outlet control using the total length and procedures in HEC No. 5.

In all cases a trial culvert size is selected from the appropriate culvert capacity chart on the basis of the ratio $L_1/100S_o$ for the first section of pipe, where L_1 and S_o equals the length and slope of this section. The following procedure is used regardless of whether the slope of the inlet section is the steeper or the flatter of the two slopes:

a. Using $L_1/100S_o$ for the first section, determine the size of pipe required, neglecting the second or outlet section of pipe.

b. Using the entire length of culvert find HW by procedures of HEC No. 5 for outlet control, where

$$HW = H + h_o - \text{fall of invert (from inlet to outlet)}$$

c. The correct headwater depth will be the highest HW given by steps a or b. If the headwater found in b is above the limiting AHW, the culvert size determined in a is not acceptable and a larger trial size must be selected until the HW in step b is satisfactory.

Case 9. The culvert $L/100S_o$ exceeds the chart value.

In such cases, the chart may still be used for culvert selection by estimating the effect of the greater $L/100S_o$, but the actual headwater depth for a possible size should be determined before considering that size to be acceptable. The check of HW depth may be made by one of two methods, depending upon relative depth of headwater.

a. If $L/100S_o$ is no greater than 1.5 times the largest value shown on the chart curves for the size under consideration, extrapolate above the chart curves on the basis of $L/100S_o$ to find HW for the design Q. If the resulting HW is equal to or less than 1.3D, the answer read from the charts is valid. (Refer to example in sec. II C, p. 10-7 and explanation, appendix B-2, part a, p. 10-84). If HW is greater than 1.3D refer to b below.

b. If HW is greater than 1.3D or if $L/100S_o$ exceeds 1.5 times the chart value for HW less than 1.3D, do not extrapolate above the chart curves. Use the size indicated by the capacity chart as a trial size, and determine HW by use of HEC No. 5. If headwater is low, methods of HEC No. 5 may not apply and backwater computations are required if accurate headwater depths are desired.

V. DESIGN CONSIDERATIONS

The objective in the design of an economical culvert is to provide a waterway opening adequate for the passage of floods. A primary consideration in selecting a culvert to meet this objective is the determination of its hydraulic capacity. The hydraulic capacity charts in this circular and the procedures of HEC No. 5 solve this problem. There are, however, other important design considerations which must be evaluated by the designer in order that the structure selected will operate satisfactorily. Some of these considerations are discussed briefly in the following paragraphs.

A. Magnitude and Frequency of Floods

In the last half century many formulas have been used to estimate flood discharges or to determine the size of a culvert. These formulas, developed from very limited streamflow data, are adjusted and modified by the designer to meet local conditions as determined by flood experience. Most highway engineers realize the shortcomings of these formulas and in recent years programs for gaging streamflow from small drainage areas have been initiated by many States to improve our methods for estimating floods.

As flood data become available, more reliable procedures for determining the magnitude and frequency of floods are being developed. Such procedures enable an engineer to estimate a design flood at a particular site and to determine a culvert size based on hydraulic principles rather than selecting a culvert on outdated methods used in the past.

The occurrence of floods is discussed in Hydraulic Engineering Circular No. 3, "Hydrology of a Highway Stream Crossing," and procedures for estimating floods on culvert-sized streams are available in many areas. Each local agency responsible for hydraulic design should develop estimating procedures for their area of responsibility. If streamflow data are not available, steps should be taken to accumulate the needed records.

The designer of a culvert should remember that once a culvert is installed, its flood capacity is fixed. This fact alone should emphasize the importance of estimating flood discharges and their frequency of occurrence.

B. Design Floods

Proper design can only be accomplished by first determining the magnitude of the design flood and then selecting a culvert to pass this flood on the basis of hydraulic principles and site conditions. The determination of the design flood is the most difficult part of the culvert design problem and involves both selecting the appropriate frequency flood and determining its magnitude.

Two aspects that should be considered are the accuracy of the estimating procedure and the probability of the flood selected being exceeded a short time after construction. The selection of a flood based on average frequency of occurrence alone is not entirely satisfactory since the risks due to a poor estimating procedure, costly construction and damage to adjacent property can be different - even within the limits of one construction project. Standards of risk for various culvert locations and types of highways are not well established. The common practice is to design minor roads for low average recurrence intervals, say 10 to 25 years and major highways for average recurrence intervals of 50 years or more. Specifying a high recurrence interval means the use of a larger design flood and a reduction in the risk from flooding or washouts but an increase in the cost of the structure.

The average recurrence interval does not measure the degree of safety or risk of damage for short periods of time. A flood peak of say a 50-year average frequency or recurrence interval has a 0.02 probability that at least one flood of this magnitude or greater may occur in any one year. Probability methods may be used to show that it also has an 0.18 probability, or about a 1 out of 5 chance of being equalled or exceeded at least once in any period of 10 consecutive years. For longer periods, the risk of at least one flood exceeding the 50-year frequency increases as follows: 0.38 for 25 years, 0.64 for 50 years and 0.86 for 100 years.

The greatest need in hydraulic research is to develop more accurate flood estimating procedures for small drainage areas so that highway culverts can be designed upon the more adequate basis of an evaluation of the risk arising from the occurrence of flood peaks greater than the design flood and the economics of the installation related thereto.

C. Allowable Headwater

Channel properties and discharge determine the depth of flow in a stream channel. A culvert which constricts the flow even a small amount will cause some increase in the depth of flow in the natural channel and upstream from the culvert entrance. The depth of water at the culvert inlet, measured vertically from the culvert invert, is called headwater.

The rate of discharge through a culvert increases with depth of headwater. It follows that the most economical culvert will be one which makes use of the maximum rise of the upstream pool (headwater) without endangering the roadway or causing significant damage from this ponding.

A culvert can be sized to produce a given headwater depth for a particular discharge. (As headwater increases, discharge increases and herein lies the significance of the allowable headwater as a design consideration.) For a given design flood the allowable headwater can be different for two crossings of the same stream, because of conditions at each site which determine ponding that can be tolerated and the damage which would occur in the event of a greater flood. Different culvert sizes might be justified for these crossings because of two different allowable headwaters.

D. Other Factors

Velocity of Flow - The flow in culverts is usually at velocities greater than those in the natural stream. These increased velocities make erosion at the culvert outlet a potential problem. This aspect of design is discussed briefly in HEC No. 5.

Sediment and Debris - The charts of this circular are based on hydraulic computations assuming clear water flow. It is well known that flood flow in particular carries various kinds of debris which could change the capacity from that given by the charts. In most instances, however, the effect of most moving debris on capacity is minor. Engineering judgment must be used to evaluate problems related to abrasion of the culvert walls and deposition of material in the barrel and at the entrance. Slope, alinement and oftentimes the size and type of culvert barrel are important factors in transporting sediment and debris. HEC No. 9, "Debris-Control Structures", describes various methods for the control of debris at the inlet to a culvert.

Structural Requirements - Although the structural design of highway culverts is not within the scope of this circular, it must be pointed out that structural failures have occurred because of hydraulic forces. Such failures are associated with uplift[1/], bending at the inlet and erosion at the outlet. Some failures are caused by water flowing along the outside of the culvert barrel and washing away supporting material.

Selection of Culvert Types - The selection of the culvert type is often based on the initial in-place construction cost. Although the initial cost is of prime importance, durability, replacement costs and maintenance should be considered in the selection. Ideally, the total annual cost of a culvert installation for the expected life of the highway should be kept to a minimum, but many factors important to such an analysis are not well defined, making it difficult to justify an individual analysis except for expensive installations.

Alinement and Grade - Ordinarily a culvert barrel is placed on an alinement and grade that generally conforms to the natural stream channel. Culverts skewed with the channel or located near bends can create a problem of sediment deposition particularly if the culvert is composed

1/ "Drainage Structures", Highway Research Board, Bulletin 286, page 13, 1960.

of several barrels. If straight alinement is not possible, mild curves can be used within the culvert barrel without creating a trap for debris.

Because of irregular stream profiles, culvert barrels are sometimes constructed with broken grade lines to avoid costly excavation. Methods for determining the hydraulic capacity of "broken-back" culverts are given in sec. IV, case 8 of this circular.

VI. DESIGN DATA

A. Hydrologic Data

The design of highway culverts by use of hydraulic methods such as the culvert capacity charts, requires that the design flood peak be selected by a reliable method, and that the average recurrence interval of the design flood be selected on the basis of a realistic evaluation of the damage which would occur during a greater flood. (See sec. V.)

The scope of the problems involved in determining flood magnitudes on an average frequency basis and in selecting the acceptable degree of risk of damage, make it clear that the estimation of floods is a duty of the highway design engineer, and may not be assigned to the location or field engineer.

However, the field engineer should obtain and report complete data regarding flood evidence. Highwater marks are very helpful in plotting water profiles and estimating past floods. Downstream controls of water stages should be noted. The size, invert elevations and complete descriptions of existing culverts or bridges can be helpful to the designer, particularly if a history of their performance during major floods can be obtained. If overflow of the existing road has occurred, a profile of the roadway will also be necessary. Flood estimates from a frequency analyses should be checked against the calculated rates of flow based upon field data. If serious discrepancies are found, both the field data and the method of flood estimation should be carefully reviewed. The site conditions indicating the degree of damage which may result from unusually high floods should be carefully considered before selecting the average frequency for design. In many cases it will be necessary to tabulate two or more flood magnitudes for use in design decisions, identifying each by its average frequency.

B. Topographic and Other Site Data

Adequate data describing the culvert site must be supplied by the locating engineer. More adequate data can be obtained if survey parties are given full instructions as to what is required and why each item is needed. One of the first requirements for design is a drainage area map defining each watershed area and showing the highway station number at which each stream channel crosses the route. For small culverts a minimum of data is required, but more extensive data, sometimes including a large scale contour map, are required where the size of the stream indicates the need for a large culvert. The minimum site survey data needed for culvert design are a dimensioned sketch of the channel alinement, with station and angle of crossing, stream cross-sections and a stream bed profile based on the highway survey datum and referenced to the stream location sketch.

Adequate stream channel data will include a profile extending a sufficient distance each side of the proposed location to determine the stream slope and appropriate culvert invert elevations at inlet and outlet. Sufficient cross sections of the channel should be taken to permit channel flow calculations for estimating tailwater depth. Data regarding the flow resistance characteristics (Manning n) of the channel should also be obtained. In addition, the downstream channel should be examined over a considerable distance for any evidence of degradation. Abrupt drops in the channel which may progress upstream to the outlet of a culvert are important design factors and should be fully described.

The survey party should give special attention to locating all structures of land improvement on the upstream side of the highway that could be damaged if flooded by the headwater pool. The exact elevation at which damage begins should be reported together with a statement describing the kind of damage and the probable costs caused by flooding.

The foundation soils at the culvert site should be investigated. Load carrying properties of foundations for small culverts may be judged by observation or probing, but test borings are usually required for large structures. The field report should also include estimates of the type, size, and probable amount of drift. This information is obtained from evidence along the stream and from the present and the potential use of the upstream land.

For large, long, or multiple barrel culverts sufficient topographic data should be obtained to permit preparation of large scale layouts. The culvert layout should be superimposed on a contour map prepared from these surveys. The layout is used to select the proper location and skew angle for the culvert and to provide data for calculating excavation quantities.

C. Stream Channel Calculations

The depth of flow in the natural stream channel must be calculated for the design flood. The channel sections, slope, and roughness data furnished by the field survey are used for this purpose. These calculations are usually made by assuming uniform flow unless there is an indication that controls downstream regulate the water stage. A plot of discharge against depth will be helpful in determining the stage for a specific rate of flow. The difference between channel stage at design discharge and the elevation of the culvert invert at the outlet is the tailwater depth, TW, in feet. Record this tailwater as Item D-9 following.

D. Design Data Tabulation

(see Tabulation Sheet in Circular No. 5)

1. Record the highway station number at the stream crossing, the watershed area, and the estimated peak rate of the design flood (more than one if required), designating the average recurrence interval, as for example:

Q_{10} = 460 cfs. (10-year average frequency)

Q_{50} = 750 cfs. (50-year average frequency)

2. Plot a roadway cross section along the center line of the culvert, using the skew angle indicated by the survey data.

3. From the cross section and the stream profile data, establish the culvert invert elevations at the inlet and the outlet.

4. Where a straight grade is used throughout the culvert length, compute the culvert barrel slope, S_o, in feet per foot, and in percent, 100 S_o. Where a broken invert grade is required, determine S_o for each section of straight grade.

5. Determine the approximate culvert length, L, in feet. The plan length, which may require the culvert height, is not necessary at this stage of design.

6. Compute the culvert length-slope ratio $L/100S_o$ from the above data. Where broken barrel slopes are used, compute $L_1/100S_o$ for the section at the inlet and also record the total L and the total fall, in feet, from inlet to outlet invert elevations.

7. Record the elevations of all headwater limits governing the design, such as:

   a. Low point of pavement within reach of the headwater pool, or if preferred, the shoulder elevation.

   b. Roadway channel bottoms at which overflow could occur.

   c. Points at which flood damage to structures on upstream property would begin.

8. From the data of No. 7 above and the <u>inlet</u> invert elevation of No. 3, determine the allowable headwater depth AHW, in feet, above the culvert invert at the inlet. If different flood frequencies apply to different elevations, record the design Q and AHW for each, for later determination of the governing condition.

9. From the stream channel calculations and the outlet invert elevation of No. 3, record the tailwater depth TW, in feet above the culvert invert at the outlet.

10. Determine Q per barrel, if a multiple culvert is a possible design. (See E below).

E. Multiple Barrel Culverts

In many cases the designer must decide whether a multiple barrel culvert is to be considered as one of the selections used in economic comparisons. The culvert capacity charts show the discharge rate per barrel. If a multiple culvert, consisting of the same type and size of barrel, is placed so that all the elements are equal, the total discharge is assumed to be divided equally to each of the barrels. Dissimilar barrels or unequal invert elevations require a trial procedure to find individual barrel discharge rates so that their sum equals the total Q at a common headwater elevation (but not necessarily equal HW depths).

Often the choice of culvert barrel height is restricted by the elevation of the roadway, and in some cases, it may be necessary to use arch or rectangular sections rather than raise the proposed roadway grade to provide cover for a circular section.

The general magnitude of culvert opening area required by the design flood is one factor involved in the decision as to types of culverts to be considered. Small flood peak rates may indicate that a small pipe culvert will be the economical choice. As the flood rates become larger, it is not at once obvious whether a single opening or multiple openings may be most advantageous. Selecting span and height dimensions most suitable for the site complicate the problem.

The following equation is suggested as a means of estimating a trial size:

$$\text{Total area of culvert opening} = \frac{Q}{10}$$

The total culvert area in square feet, an approximation only, may indicate use of a single barrel or a multiple culvert. Division of the total flood peak by the number of barrels of a trial selection will obtain a design Q per barrel to be used in selecting a culvert size from the charts.

VII. CULVERT CAPACITY CHARTS

The culvert capacity charts in this section provide a means for selecting a culvert of adequate size to convey the design discharge rate per barrel without exceeding an allowable depth of headwater determined by the site conditions. The allowable headwater depth AHW, and the actual headwater depth HW that results from the culvert size selected, are measured in feet above the culvert invert at the inlet. The 36 culvert capacity charts are divided into 8 groups according to eight basic types of culverts as determined by barrel shape and material. The charts appear in the order of the list shown on the last page of this circular.

Each group of charts is preceded by an explanation of the factors determining the two main inlet types represented by the charts. Information regarding other inlets types classified as equivalent to one of the two types shown in the titles and other design data necessary to the use of each group of charts are also included. Tables of dimensions and cross-sectional areas of the available sizes of each type of culvert are given in some instances.

The procedures for accumulating design data and for selecting a culvert size as previously discussed are summarized in the following steps: (This information should be tabulated on a prepared design data sheet to be used as a work sheet and a record. See tabulation sheet in HEC No. 5).

1. Select the average frequency of the design flood.

2. Determine the estimated peak discharge of the design flood.

3. Obtain all site data. Plot a roadway cross section at the culvert site and a stream channel profile. Make a contoured site plan where necessary.

4. Establish the culvert invert elevations at inlet and outlet and the culvert length. Then determine the invert slope S_o and compute $L/100S_o$.

5. Determine the allowable headwater depth (or depths) AHW, considering the factors discussed in sec. V.

6. Compute the depth of flow in the stream channel (including flood plain) for the design flood, and determine TW depth.

7. Select one or more appropriate culvert types. Compute an approximate barrel area $A_b = Q/10$ to guide selection of type and possible numbers and sizes of multiple barrels. Compute the discharge rate Q per barrel if multiple barrels are used.

8. Determine if the culvert types selected together with the governing headwater, length and slope, meet requirements for the direct use of charts, sec. III.

   a. Select the culvert capacity chart for the culvert and entrance type to be considered.

   b. On the chart, locate the point of intersection of Q and AHW.

   c. Use the culvert $L/100S_o$ and the $L/100S_o$ of the chart curves to determine the smallest culvert size which will result in an actual headwater depth HW equal to or less than AHW (sec. II C).

   d. Check tailwater as instructed in sec. III.

9. Culvert size may also be selected from the charts for some conditions where the requirements for direct selection of size from charts are not met and therefore step 8 above cannot be followed. These conditions include the following cases as described in sec. IV.

   Case 1 - Paved Invert C.M. Pipe or Pipe-Arch.

   Case 2 - Fully Paved C.M. Pipe.

   Case 3 - Rectangular Concrete Box sizes not in charts.

   Case 4 - Concrete or C.M. Circular Pipe sizes between those of chart curves.

   Case 5 - Oval Concrete Pipe sizes not in chart.

   Case 6 - Corrugated Structural Plate Pipe-Arch sizes not in chart.

   Case 7 - Culvert slope zero (level invert).

   Case 8 - Broken slope culverts.

   Case 9 - $L/100S_o$ exceeds chart value.

VII A. Concrete Box Culverts

Two groups of charts are included. The first group, Charts 1 to 5, are for box culverts with headwalls at 90 degrees to the culvert axis and sufficiently long to retain the fill slopes clear of the waterway opening. These headwall charts may also be used for culverts with wingwalls flared from 10 degrees to 20 degrees with the culvert axis. The headwater-discharge relation is based upon small chamfers at all exposed edges at the entrance.

The second group of charts, Nos. 6 to 10, are for box culverts with wingwalls flared from 30° to 75° with the culvert axis and chamfered edge at the top of the entrance. Culverts with wingwalls flared 30 degrees or more require less headwater depth for a given size and discharge rate than do those with just a headwall or 15° wingwalls.

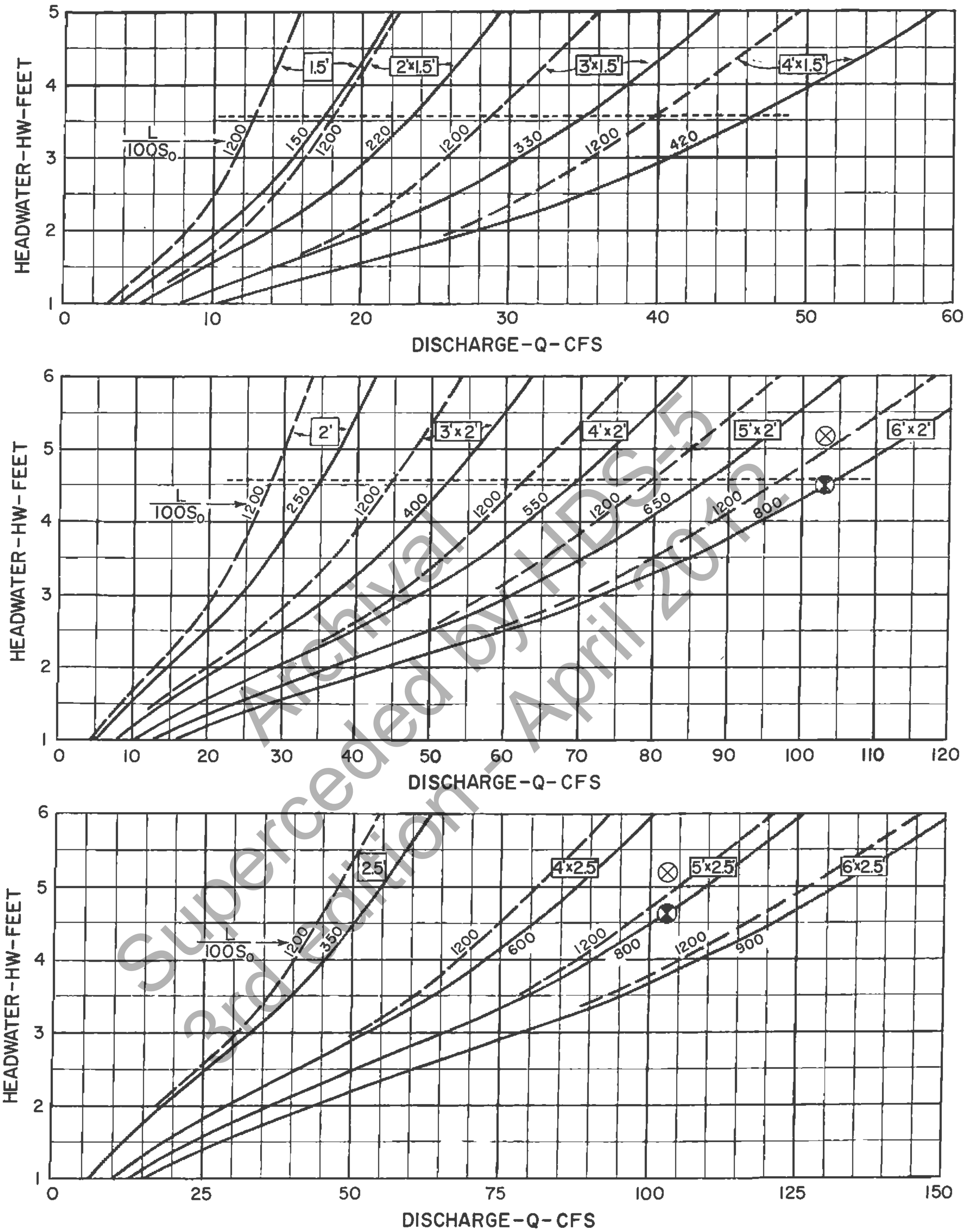
Culverts with parallel wingwalls formed by extension of the box side walls have a capacity less than the designs covered by these charts. It was not considered necessary to include charts for this inefficient type.

All charts are based upon an entrance face at right angles to the barrel axis. Model tests indicate that skew of the entrance reduces capacity of headwall types and increases capacity of flared wingwall types. However, for skews up to 45 degrees the head-discharge relation shown by the charts is not modified to a significant degree.

A square box culvert of half-foot dimension increments, if required for a special purpose, may be selected from the square box charts, which include only the sizes at foot intervals. Use the same method given in sec. IV, case 4, for selection of intermediate sizes of concrete pipe. The same procedure may also be used for rectangular boxes of half-foot increments in span if the height is equal to that of one of the charts for rectangular boxes. Note the example on Chart 7.

Chart curves are not included for all possible rectangular box sizes, particularly the wide-span boxes with height of 5 ft. or more. In this size range resistance losses are a small part of headwater depth with outlet control. Therefore, the capacity of a culvert of given height is nearly proportional to the span. Culvert sizes may be selected from the charts for square box culverts as explained in sec. IV, case 3.

CHART 1



EXAMPLE

⊗ GIVEN:
103 CFS; AHW = 5.2 FT.
L = 150 FT.; S_0 = 0.015

● SELECT 6' x 2'; HW = 4.5 FT.
OR 5' x 2.5'; HW = 4.6 FT.

CULVERT CAPACITY
RECTANGULAR CONCRETE BOX
90° AND 15° WINGWALL FLARE
1.5', 2.0' AND 2.5' HEIGHTS

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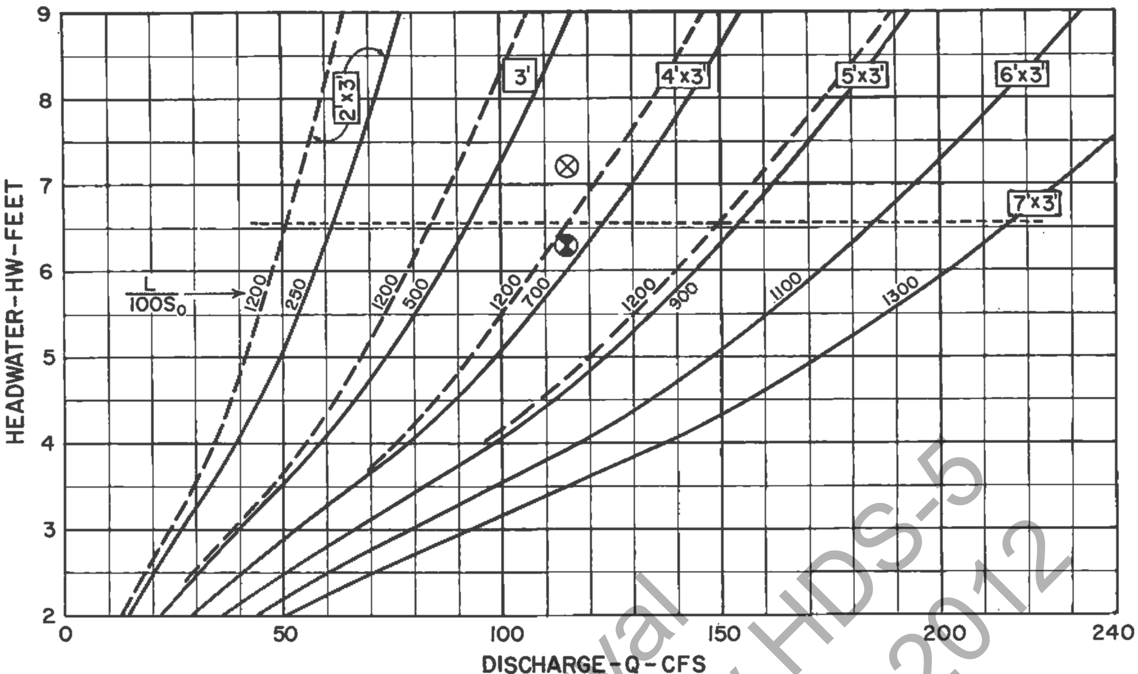
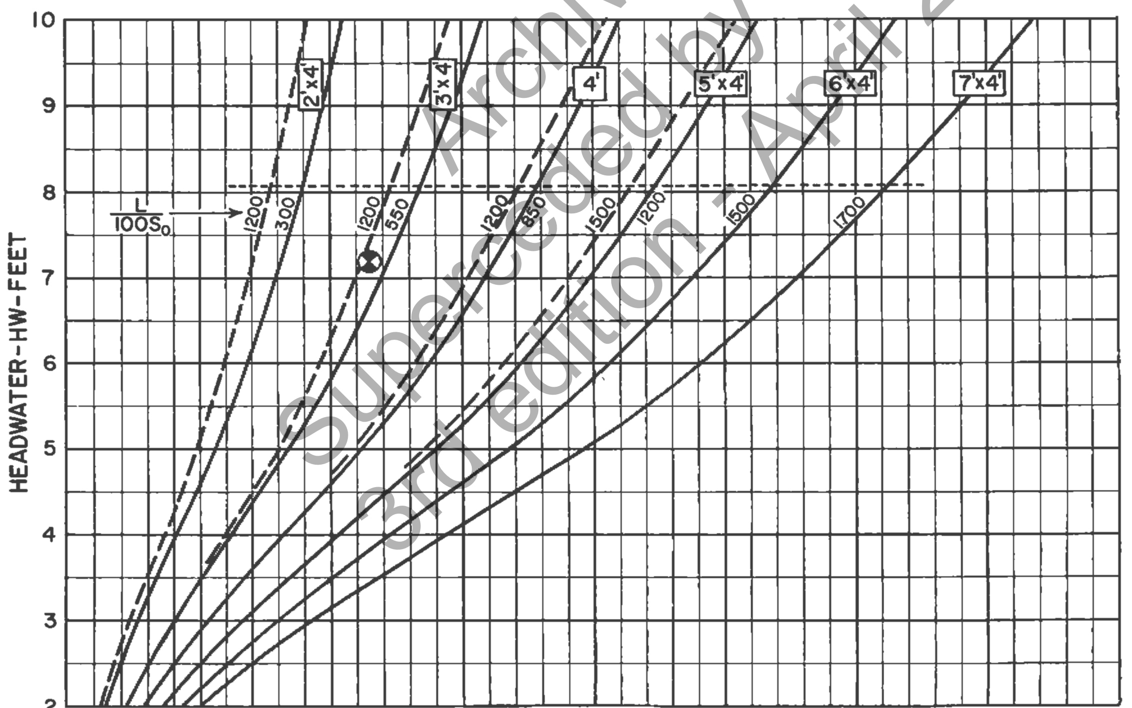
CHART 2





EXAMPLE

⊗ GIVEN;
115 CFS; AHW = 7.2 FT.
L = 300 FT.; S_0 = 0.003

⊗ SELECT 4' x 3'; HW = 6.3 FT.
OR 3' x 4'; HW = 7.2 FT.

CULVERT CAPACITY
RECTANGULAR CONCRETE BOX
90° AND 15° WINGWALL FLARE
3' AND 4' HEIGHTS ▯ & ▭

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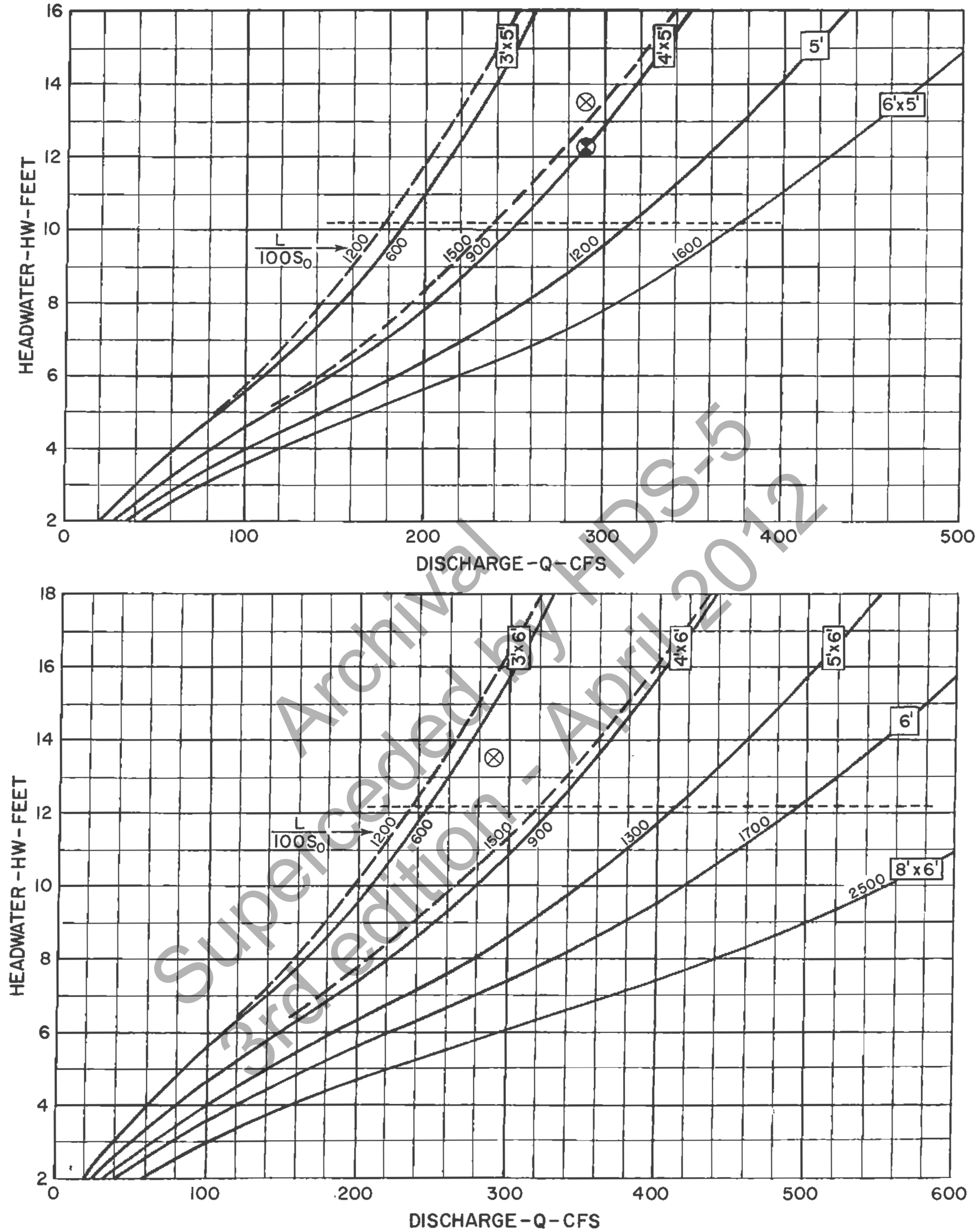
CHART 3



EXAMPLE

⊗ GIVEN:
290 CFS; AHW = 13.5 FT.
L = 250 FT.; S_0 = 0.010

⊗ SELECT 4' x 5'
HW = 12.3 FT.

CULVERT CAPACITY
RECTANGULAR CONCRETE BOX
90° AND 15° WINGWALL FLARE
5' AND 6' HEIGHTS

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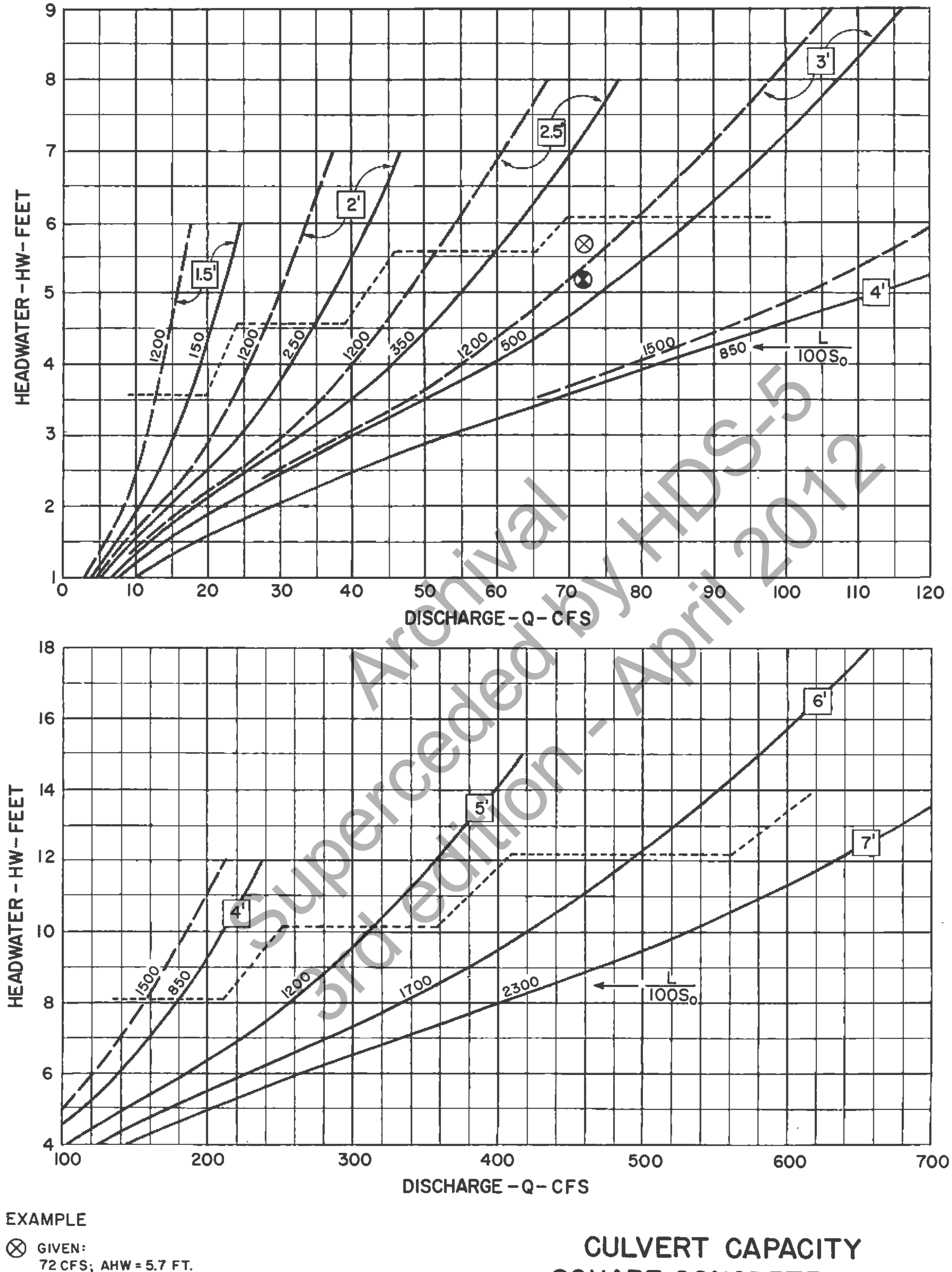
CHART 4



EXAMPLE

⊗ GIVEN:
72 CFS; AHW = 5.7 FT.
L = 200 FT.; S_0 = 0.002

SELECT 3' x 3'
HW = 5.2 FT.

CULVERT CAPACITY
SQUARE CONCRETE BOX
90° AND 15° WINGWALL FLARE
1.5' X 1.5' TO 7' X 7'

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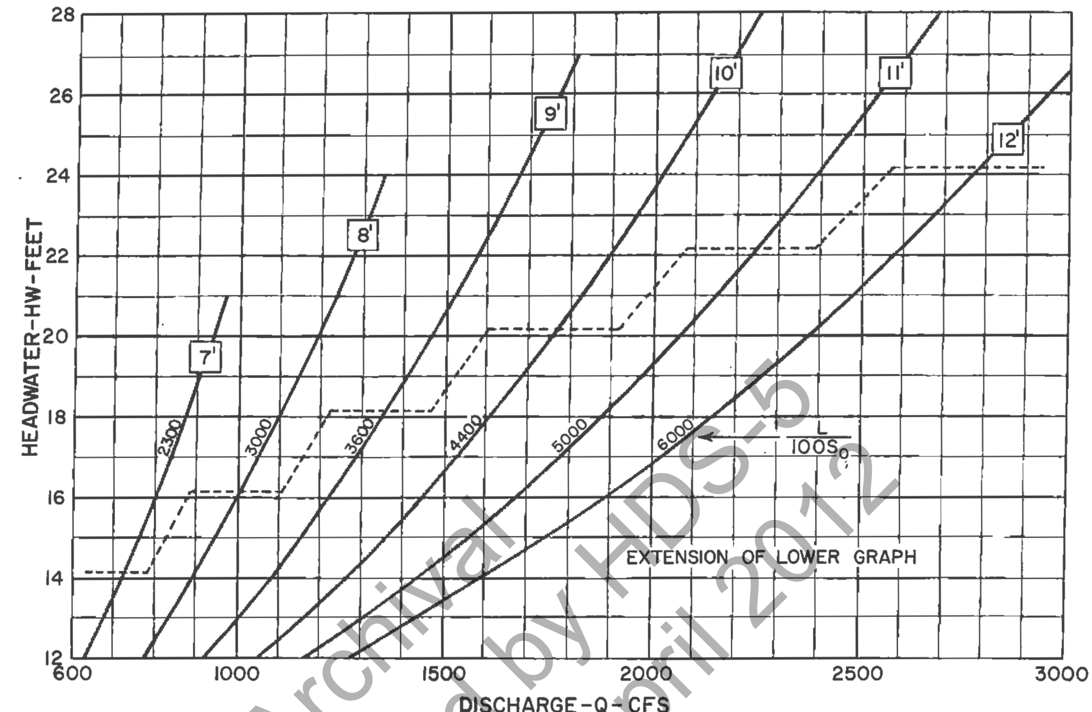
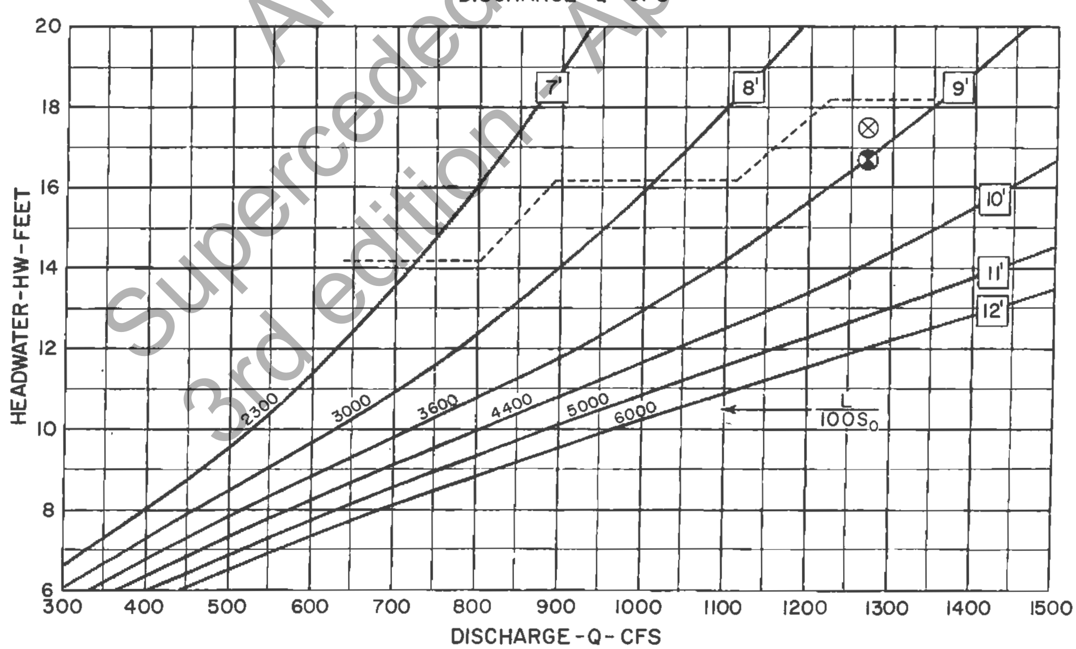
CHART 5





EXAMPLE

⊗ GIVEN:
1270 CFS; AHW = 17.5 FT.
L = 250 FT.; S_0 = 0.010

SELECT 9'x9'
HW = 16.7 FT.

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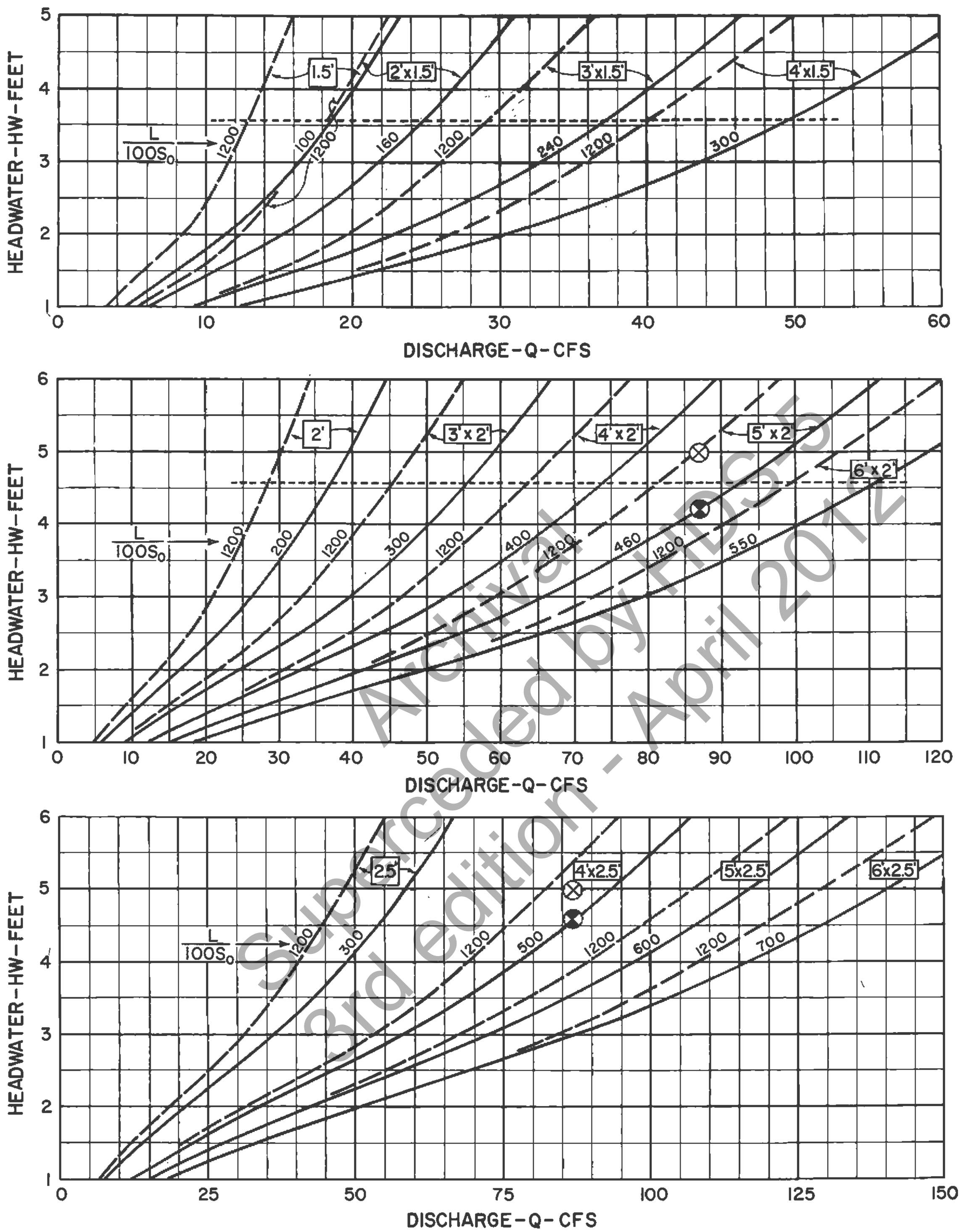
CULVERT CAPACITY
SQUARE CONCRETE BOX
90° AND 15° WINGWALL FLARE
7'X7' TO 12'X12'

CHART 6

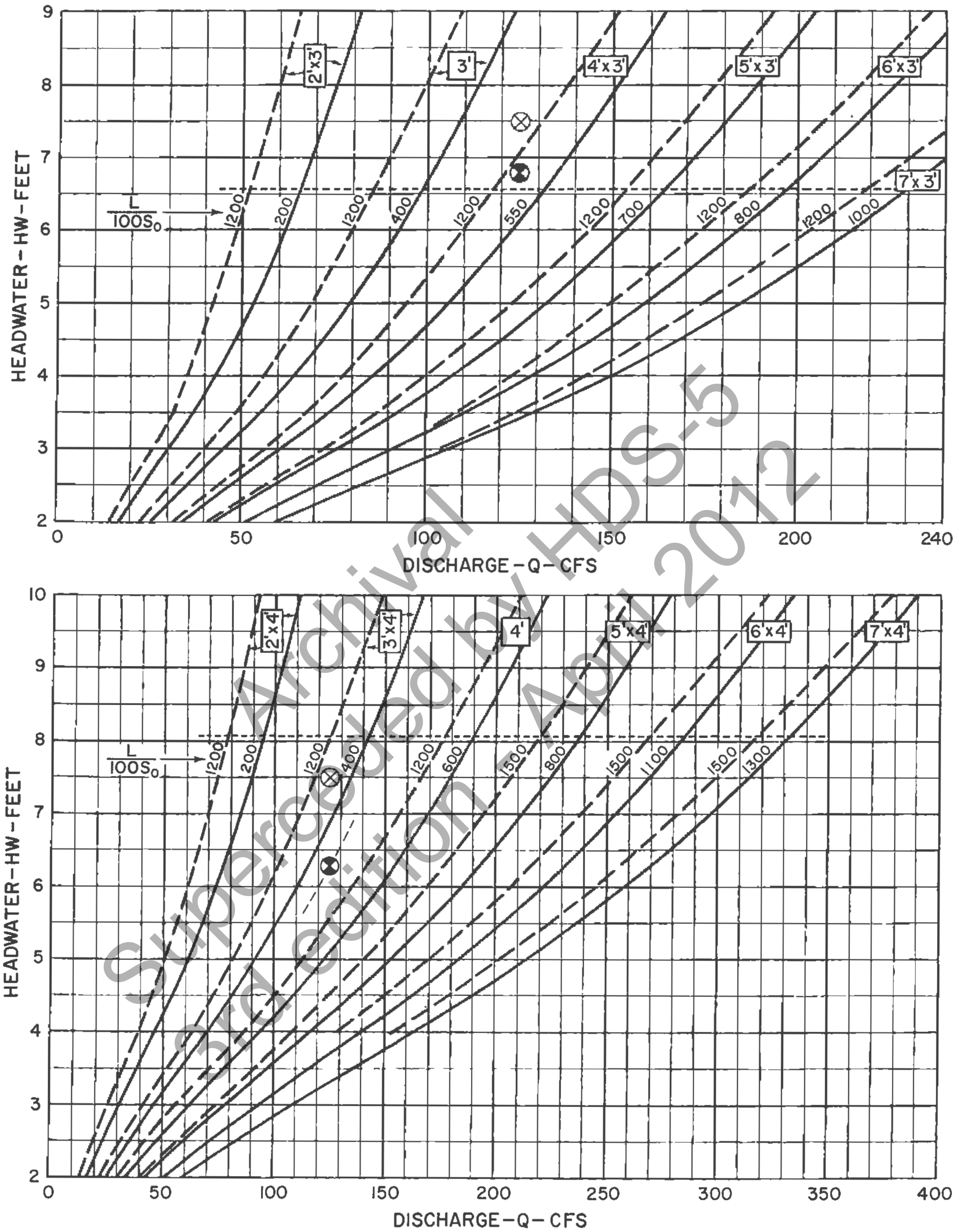


EXAMPLE

⊗ GIVEN:
87 CFS; AHW = 5.0 FT.
L = 120 FT.; S_0 = 0.003

● SELECT 5' x 2'; HW = 4.2 FT.
OR 4' x 2.5'; HW = 4.6 FT.

CULVERT CAPACITY
RECTANGULAR CONCRETE BOX
30° TO 75° WINGWALL FLARE
1.5', 2.0' AND 2.5' HEIGHTS



EXAMPLE

⊗ GIVEN:
125 CFS; AHW = 7.5 FT.
L = 400 FT.; S_0 = 0.004

● SELECT 4'x 3'; HW = 6.8 FT.
OR 3.5'x4'; HW = 6.3 FT.

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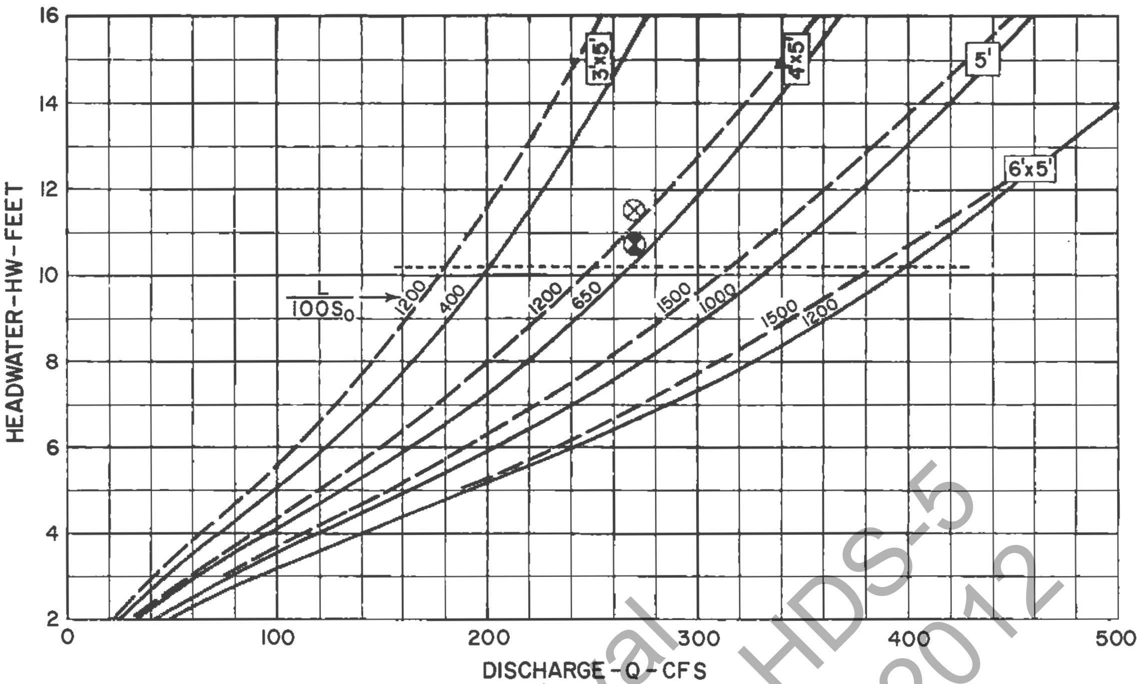
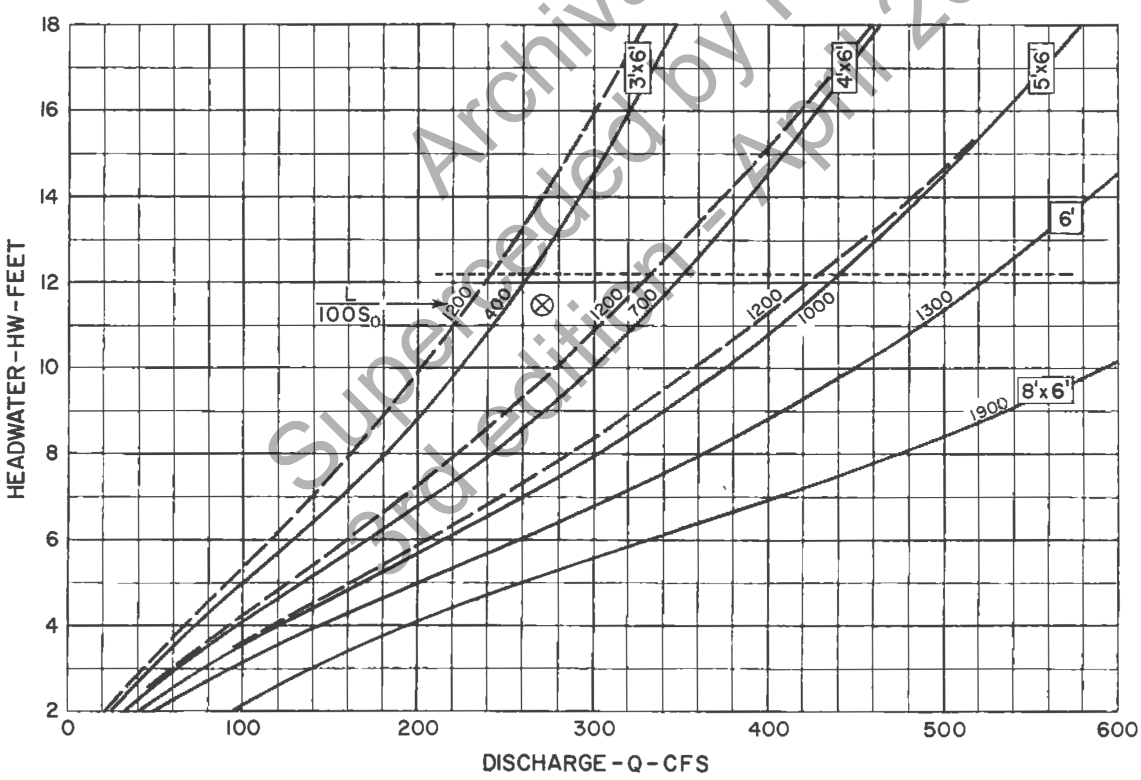
CULVERT CAPACITY
RECTANGULAR CONCRETE BOX
30° TO 75° WINGWALL FLARE
3' AND 4' HEIGHTS

CHART 8





EXAMPLE

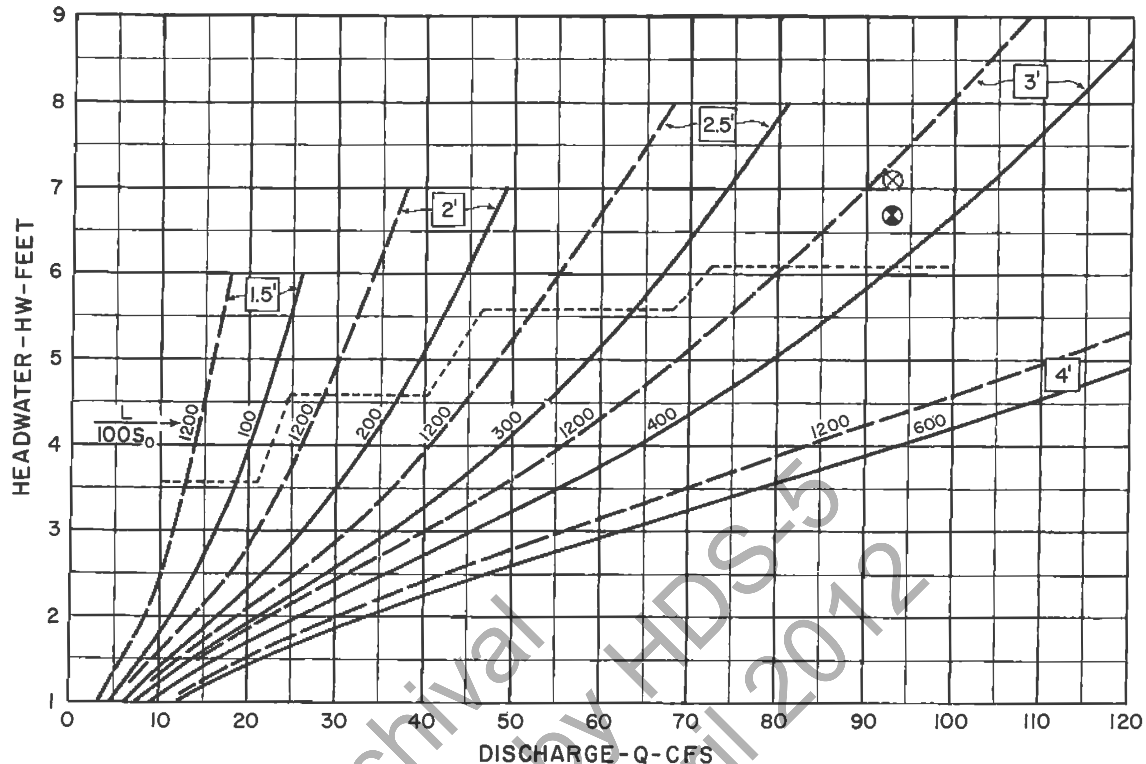
⊗ GIVEN:
270 CFS; AHW = 11.5 FT.
L = 450 FT.; $S_0 = 0.005$

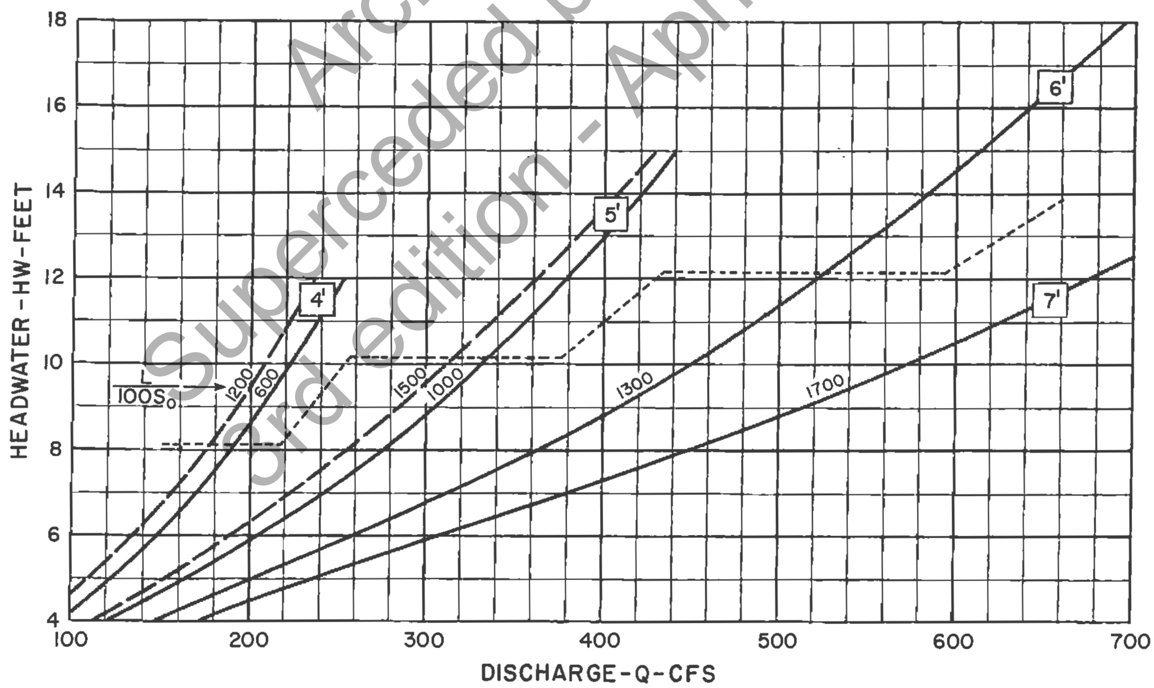
SELECT 4'x5'
HW = 10.7 FT.

CULVERT CAPACITY
RECTANGULAR CONCRETE BOX
30° TO 75° WINGWALL FLARE
5' AND 6' HEIGHTS

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 9





EXAMPLE

⊗ GIVEN;
93 CFS; AHW = 7.1 FT.
L = 280 FT.; S_0 = 0.0035

● SELECT 3' X 3'
HW = 6.7 FT.

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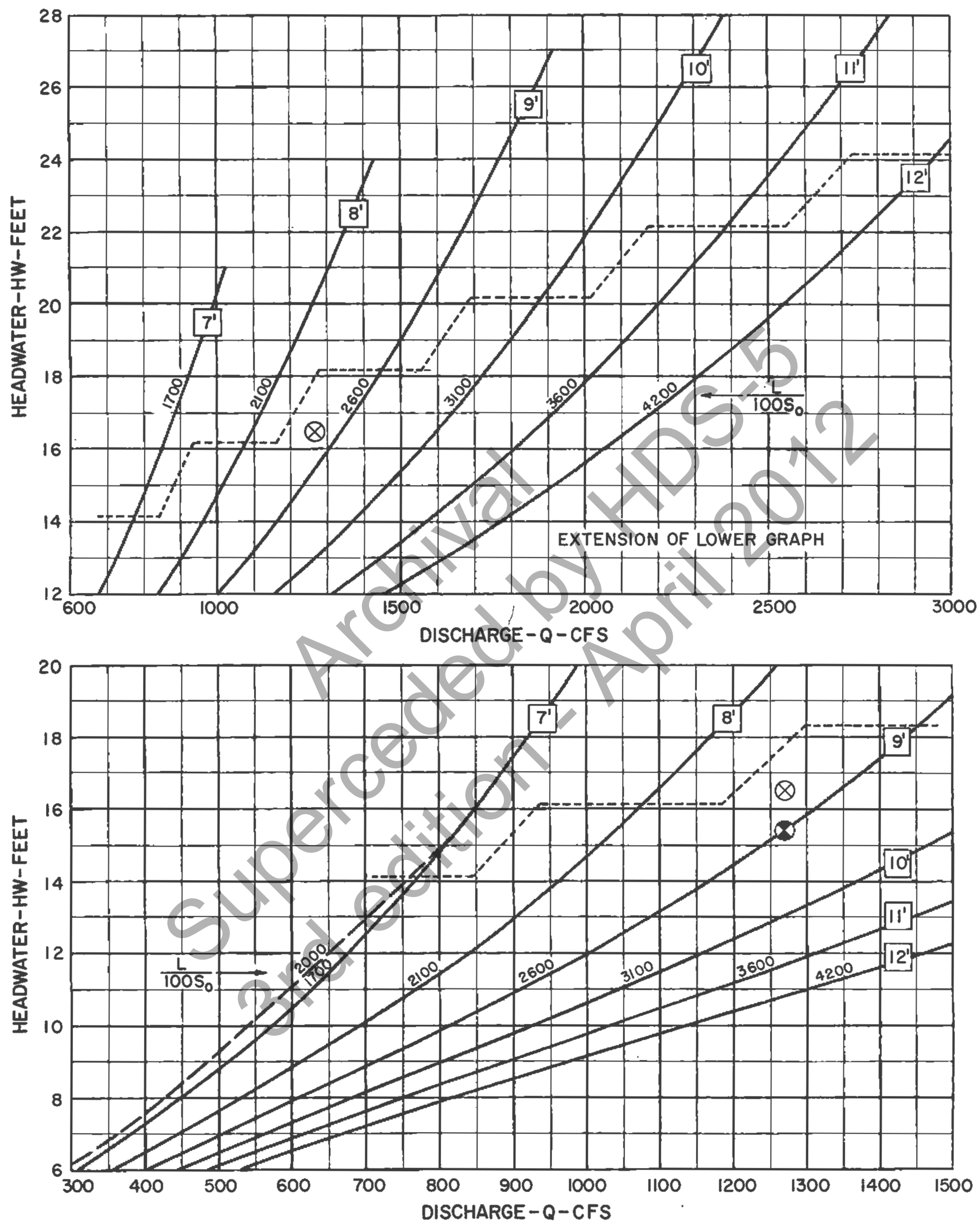
CULVERT CAPACITY
SQUARE CONCRETE BOX
30° TO 75° WINGWALL FLARE
1.5' X 1.5' TO 7' X 7' ▣

CHART 10



EXAMPLE

⊗ GIVEN:
1270 CFS; AHW = 16.5 FT.
L = 320 FT.; S_0 = 0.016

⊗ SELECT 9' x 9'
HW = 15.4 FT.

BUREAU OF PUBLIC ROADS JAN. 1963

CULVERT CAPACITY
SQUARE CONCRETE BOX
30° TO 75° WINGWALL FLARE
7'X7' TO 12'X12'

VII B. Circular Concrete Pipe Culverts

Charts 11 and 12 are for concrete pipe culverts with a square-edged entrance, and apply equally to culverts installed in a headwall, headwall and wingwalls, or projecting to or beyond the toe of the embankment slope.

A square-edged entrance is the result of cutting of concrete pipe sections to obtain a particular length. Culverts with such entrances have lesser capacity than those with a groove-edged entrance.

Inlet details for which the square-edged entrance charts may also be used:

a. Skewed inlets. (Inlet face skewed with longitudinal axis of culvert barrel.)

b. Flared wingwalls, with headwall over the crown. The flare angle may be as small as 20°. Headwater depth is reduced by such flared wingwalls, but the reduction is not enough to be significant in design.

c. Parallel wingwalls increase headwater depth. If the distance between walls is 1.25D or more the charts may be used for design. Do not use the charts for parallel wing walls only 1.0D apart.

d. Concrete culvert end-sections, with a short section of uniform barrel diameter. Headwater depth when these sections are used is slightly less than shown by the charts, but the charts will serve for size selection.

e. Concrete pipe cut to form a mitered inlet in the plane of the fill slope.

Charts 13 and 14 are for concrete pipe culverts installed with the socket end of a tongue-and-groove pipe joint forming a groove-edged entrance. The head-discharge relation of the chart curves is based on a projecting pipe. Although capacity of this pipe in a headwall is slightly greater, the difference is not significant. The semi-bell socket of a cast and vibrated pipe presents a larger groove which improves culvert capacity, but the difference is too small to justify separate charts for design. These charts may also be used for vitrified clay pipe culverts installed with the spigot end forming the entrance.

Inlet details for which the groove-edged entrance charts may also be used:

a. Flared wingwalls, as described for square-edged inlet variations, have little effect upon headwater when used with a groove-edged entrance.

b. Parallel wingwalls are acceptable if 1.25D or more apart.

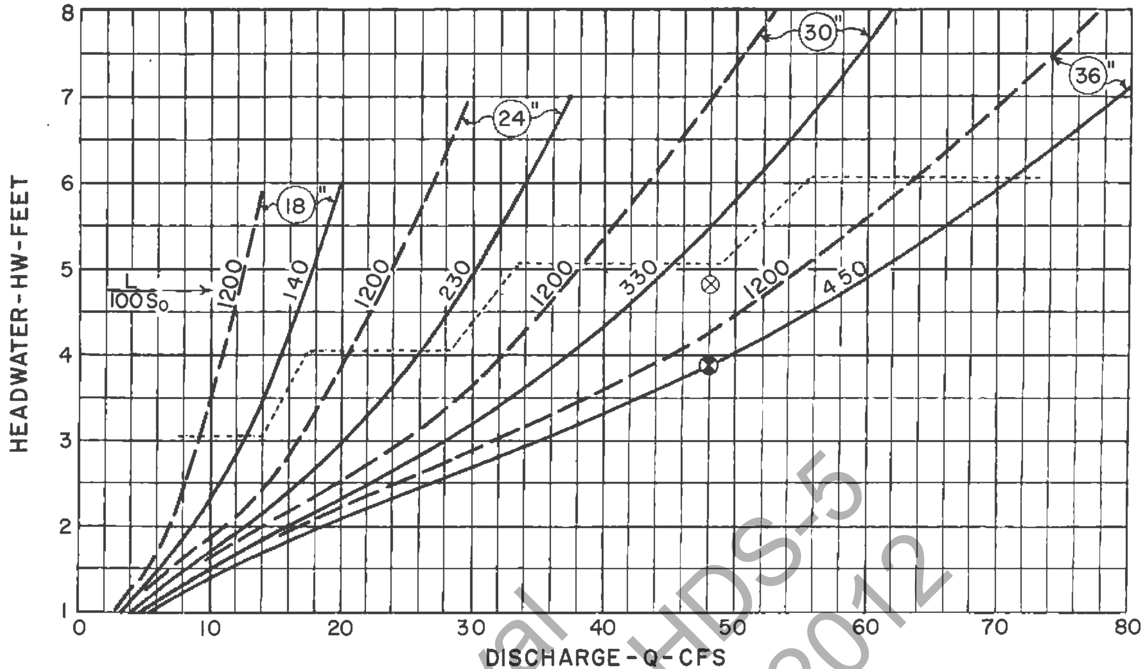
c. Filling the entrance groove with mortar to form a bevel has no effect on headwater. The charts may be used.

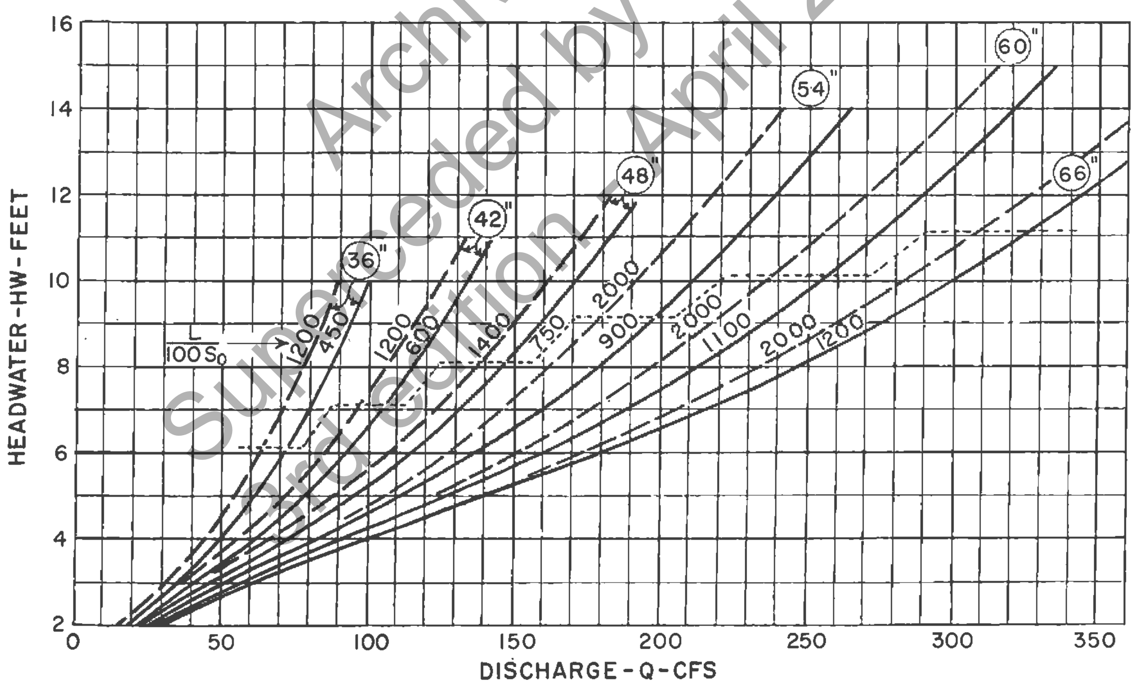
STANDARD SIZES OF CIRCULAR CONCRETE PIPE

Diameter in.	Diameter ft.	Area sq. ft.	Diameter in.	Diameter ft.	Area sq. ft.	Diameter in.	Diameter ft.	Area sq. ft.
12	1.00	0.79	54	4.5	15.90	120	10.0	78.5
15	1.25	1.23	60	5.0	19.64	126	10.5	86.6
18	1.50	1.77	66	5.5	23.76	132	11.0	95.0
21	1.75	2.41	72	6.0	28.3	138	11.5	103.9
24	2.00	3.14	78	6.5	33.2	144	12.0	113.1
27	2.25	3.98	84	7.0	38.5	150	12.5	122.7
30	2.50	4.91	90	7.5	44.2	156	13.0	132.7
33	2.75	5.94	96	8.0	50.3	162	13.5	143.1
36	3.00	7.07	102	8.5	56.7	168	14.0	154.
42	3.50	9.62	108	9.0	63.6	174	14.5	165.
48	4.00	12.57	114	9.5	70.9	180	15.0	177.

Sizes larger than 108-in. may not be available; consult local manufacturers.

CHART 11





EXAMPLE

⊗ GIVEN:
48 CFS; AHW = 4.8 FT.
L = 60 FT.; S_0 = 0.003

SELECT 36"
HW = 3.9 FT.

CULVERT CAPACITY
CIRCULAR CONCRETE PIPE
SQUARE-EDGED ENTRANCE
18" TO 66"

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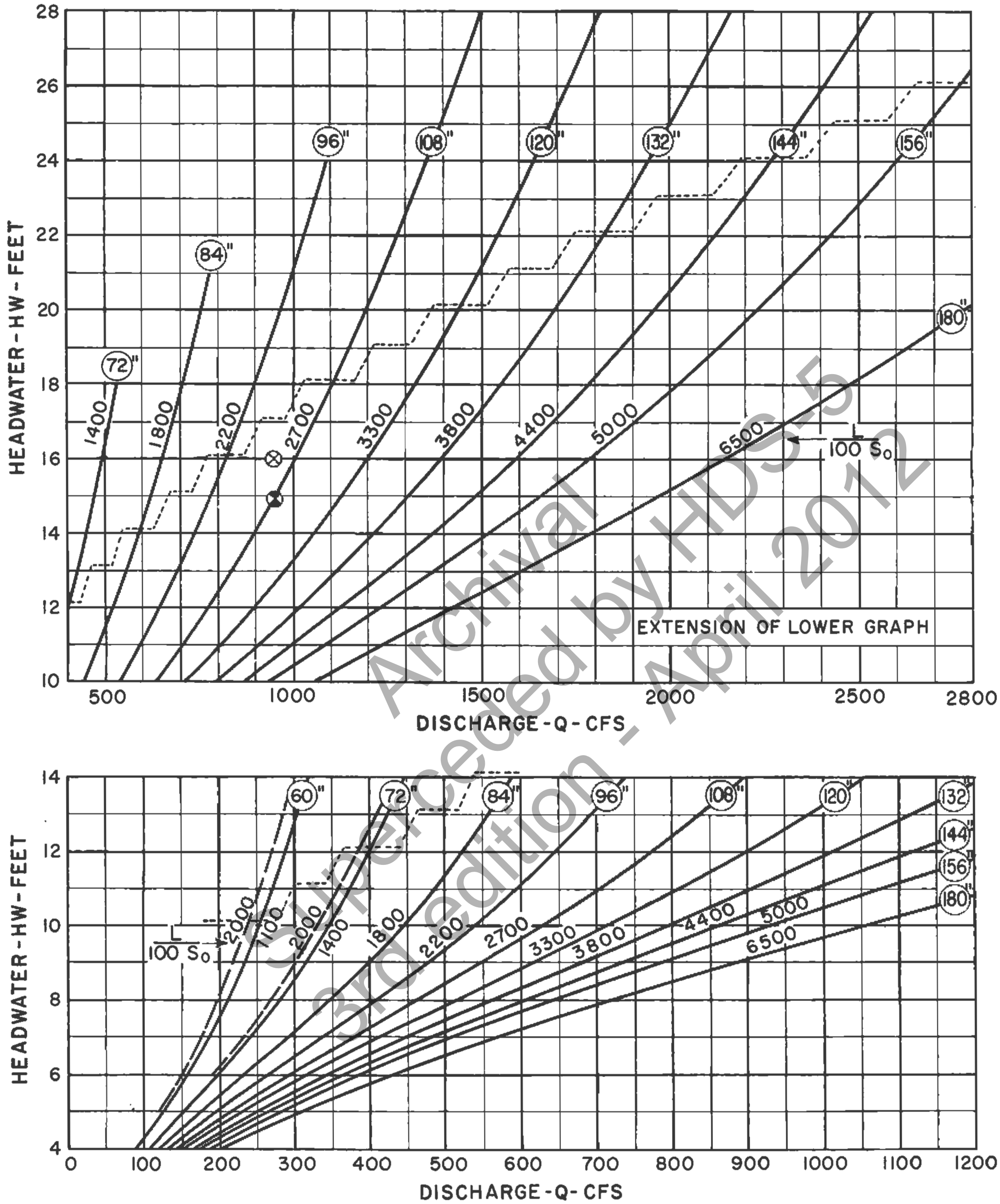
CHART 12



EXAMPLE

⊗ GIVEN:
950 CFS; AHW = 16 FT.
L = 480 FT.; S_0 = 0.040

⊗ SELECT 108"
HW = 15.0 FT.

CULVERT CAPACITY
CIRCULAR CONCRETE PIPE
SQUARE-EDGED ENTRANCE
60" TO 180" ◎

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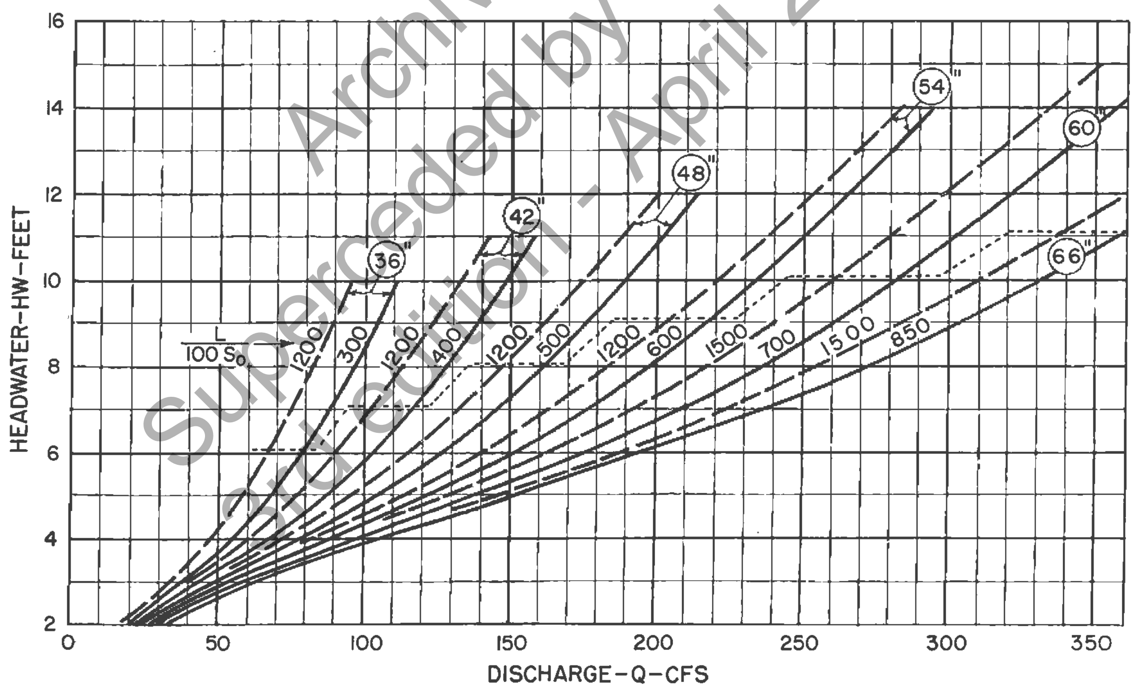
CHART 13



EXAMPLE

⊗ GIVEN :
43 CFS ; AHW = 5.4 FT.
L = 120 FT. ; S_0 = 0.002

⊗ SELECT 30"
HW = 4.7 FT.

CULVERT CAPACITY
CIRCULAR CONCRETE PIPE
GROOVE - EDGED ENTRANCE
18" TO 66" ◎

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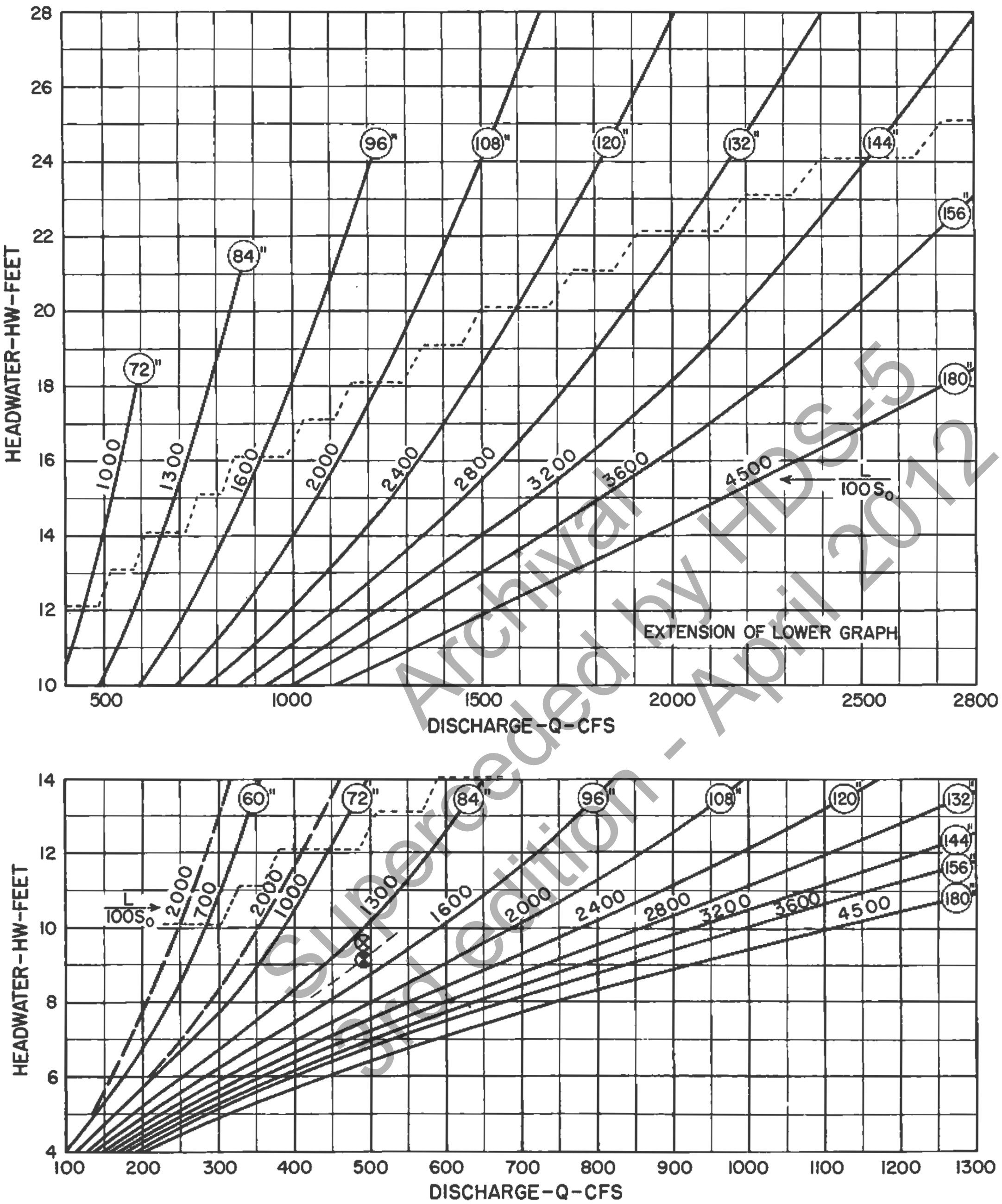
CHART 14



EXAMPLE

⊗ GIVEN:
490 CFS ; AHW = 9.6 FT.
L = 60 FT. ; S_0 = 0.000

SELECT 90" ($\frac{L}{D}$ = 8)
HW = 9.2 FT.

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CULVERT CAPACITY
CIRCULAR CONCRETE PIPE
GROOVE-EDGED ENTRANCE
60" TO 180" ◎

VII C. Oval Concrete Pipe Culverts

Long Axis Horizontal

The charts of this sub-section apply only to pipe installed with the long axis horizontal, suitable for low embankments.

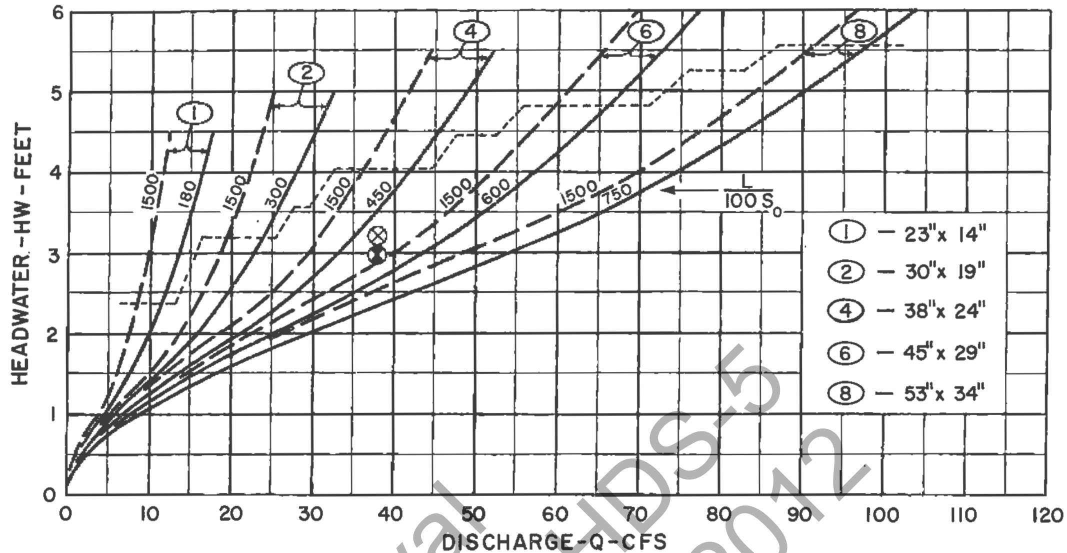
Chart 15 is for oval concrete pipe culverts with a square-edged entrance, as described for circular concrete pipe culverts. The chart also applies to all inlet variations given under circular concrete pipe with square-edged entrance.

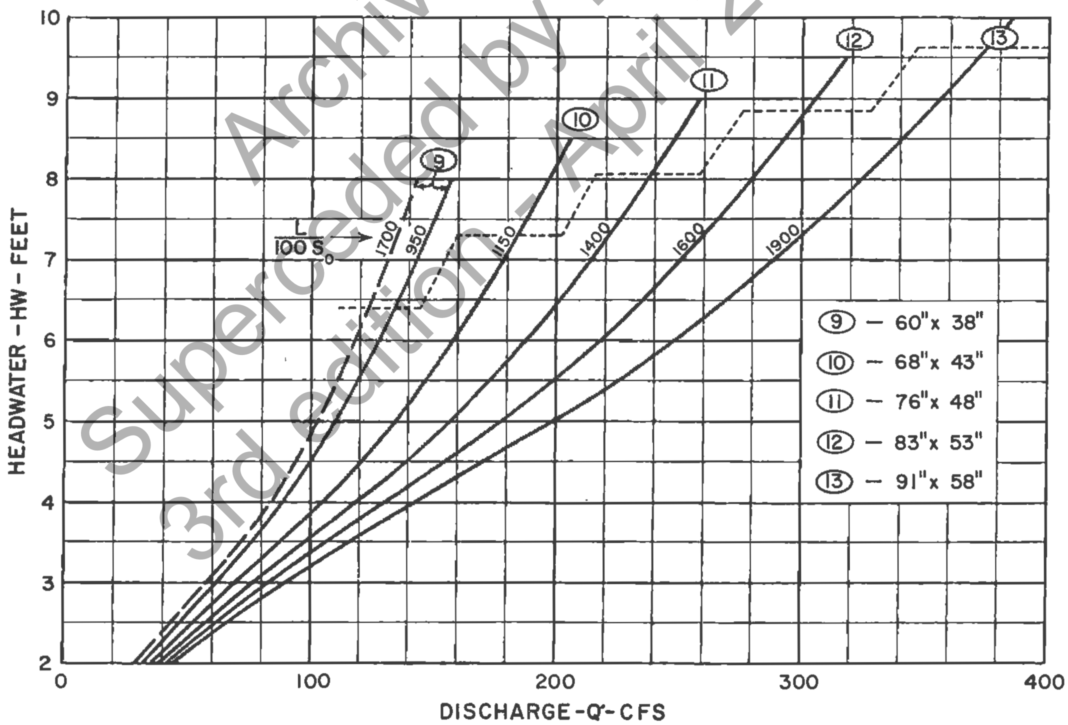
Chart 16 applies to oval concrete pipe culverts installed with the socket-end of a tongue-and-groove pipe joint forming a groove-edged entrance, as described for circular concrete pipe culverts. The chart also applies to all inlet variations given for circular concrete pipe with groove-edged entrance.

An oval concrete pipe resembles an ellipse and is made up of two pairs of circular arcs. The arcs on the inside of the section are of the following approximate radii in terms of the short dimension D of the pipe: long radius 1.35 D; short radius 0.43 D. The sizes generally available are given in the following table, with actual opening area.

Size No.	Nominal Size, In. Span	Nominal Size, In. Height	Actual Size, In. Span	Actual Size, In. Height	Area s.f.
1	23	14	22.83	14.31	1.84
2	30	19	30.30	19.20	3.28
3	34	22	34.11	21.57	4.14
4	38	24	37.86	23.99	5.12
5	42	27	41.93	26.71	6.31
6	45	29	45.44	28.79	7.37
7	49	32	49.49	31.57	8.80
8	53	34	53.28	34.02	10.21
9	60	38	59.92	38.28	12.92
10	68	43	67.88	43.42	16.60
11	76	48	75.50	48.17	20.5
12	83	53	83.02	53.01	24.8
13	91	58	90.54	57.86	29.5

Charts are not provided for all sizes listed in some manufacturers catalogs. Three intermediate sizes (Nos. 3, 5 and 7) are not included in the charts, but may be selected from the charts if desired by using the methods of sec. IV, case 5.





EXAMPLE

⊗ GIVEN:
38 CFS; AHW = 3.2 FT.
L = 66 FT.; S_0 = 0.0015

⊗ SELECT NO. 5, 42" X 27"
HW = 3.0 FT.

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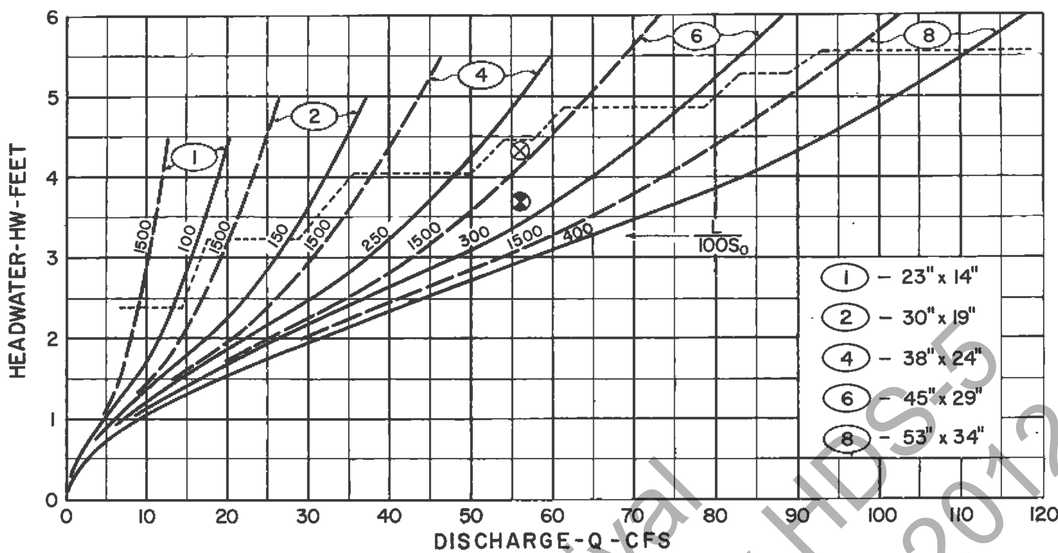
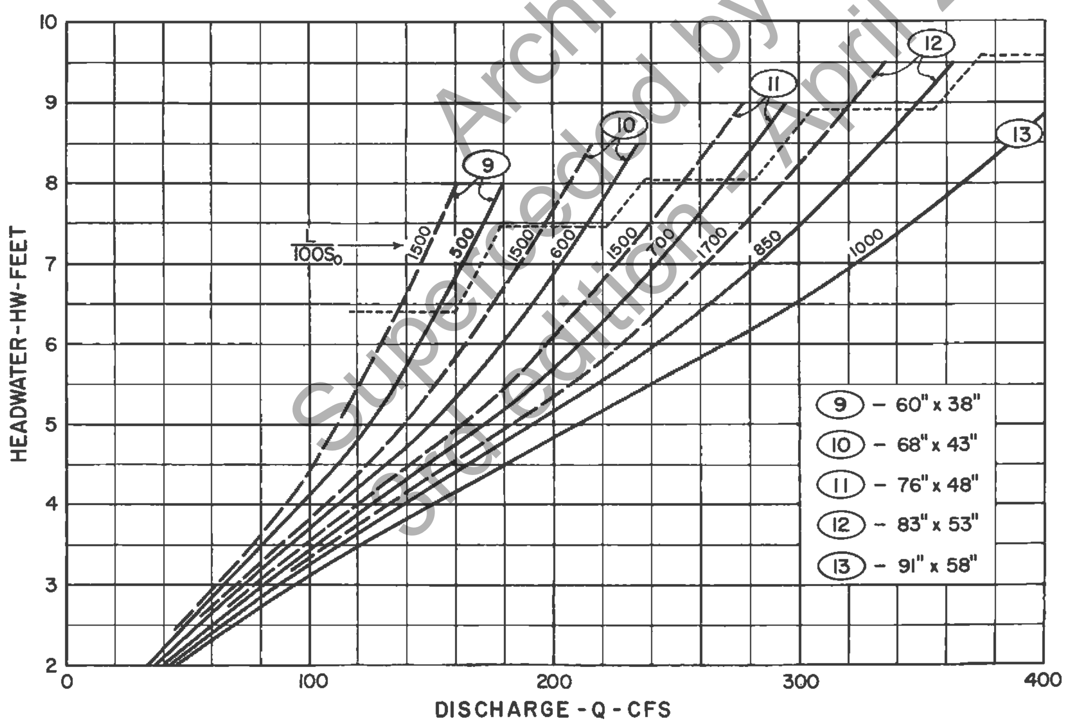
CULVERT CAPACITY
OVAL CONCRETE PIPE-HORIZONTAL
SQUARE-EDGED ENTRANCE
23" X 14" TO 91" X 58"

CHART 16





EXAMPLE

⊗ GIVEN:
56 CFS; AHW = 4.3 FT.
L = 109 FT.; S_0 = 0.0016

⊗ SELECT NO. 6, 45" x 29"
HW = 3.7 FT.

CULVERT CAPACITY
OVAL CONCRETE PIPE-HORIZONTAL
GROOVE-EDGED ENTRANCE
23" x 14" TO 91" x 58"

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VII D. Oval Concrete Pipe Culverts

Long Axis Vertical

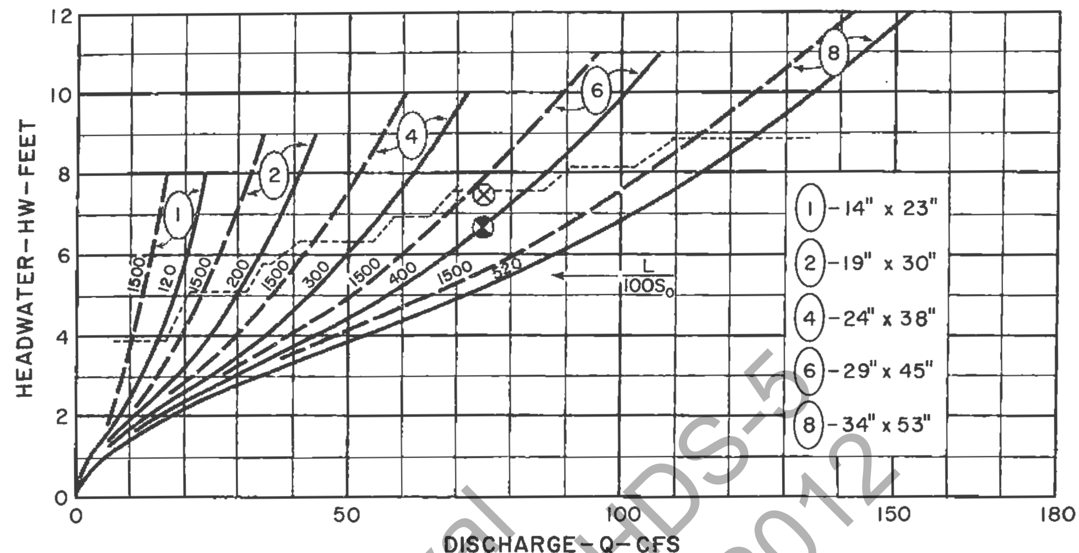
The charts of this sub-section apply only to pipe installed with the long axis vertical, as might be required by the load imposed by a high fill. The geometry of these pipes is the same as listed for oval pipe with long axis horizontal.

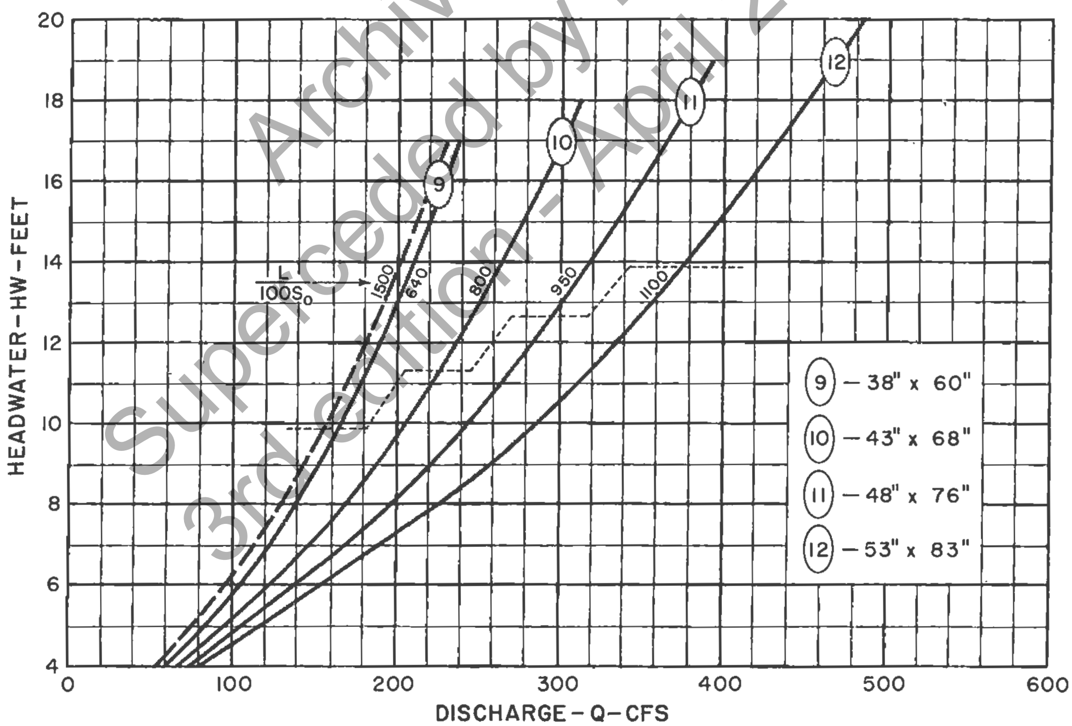
Charts are not provided for all sizes listed in some manufacturers catalogs. Three intermediate sizes (Nos. 3, 5 and 7) are not included in the charts, but may be selected from the charts if desired. Use the methods of sec. IV, case 5.

Chart 17 is for oval concrete pipe culverts with a square-edged entrance, as described for circular concrete pipe culverts. The chart also applies to all inlet variations given for circular concrete pipe with square-edged entrance.

Chart 18 is for oval concrete pipe culverts installed with the socket end of a tongue-and-groove pipe joint forming a groove-edged entrance, as described for circular concrete pipe culverts. The chart also applies to all inlet variations given for circular concrete pipe with groove-edged entrance.

CHART 17





EXAMPLE

⊗ GIVEN:
75 CFS; AHW = 7.5 FT.
L = 60 FT.; S_0 = 0.015

SELECT NO.6, 29" x 45"
HW = 6.7 FT.

CULVERT CAPACITY
OVAL CONCRETE PIPE-VERTICAL
SQUARE-EDGED ENTRANCE
14" x 23" TO 53" x 83"

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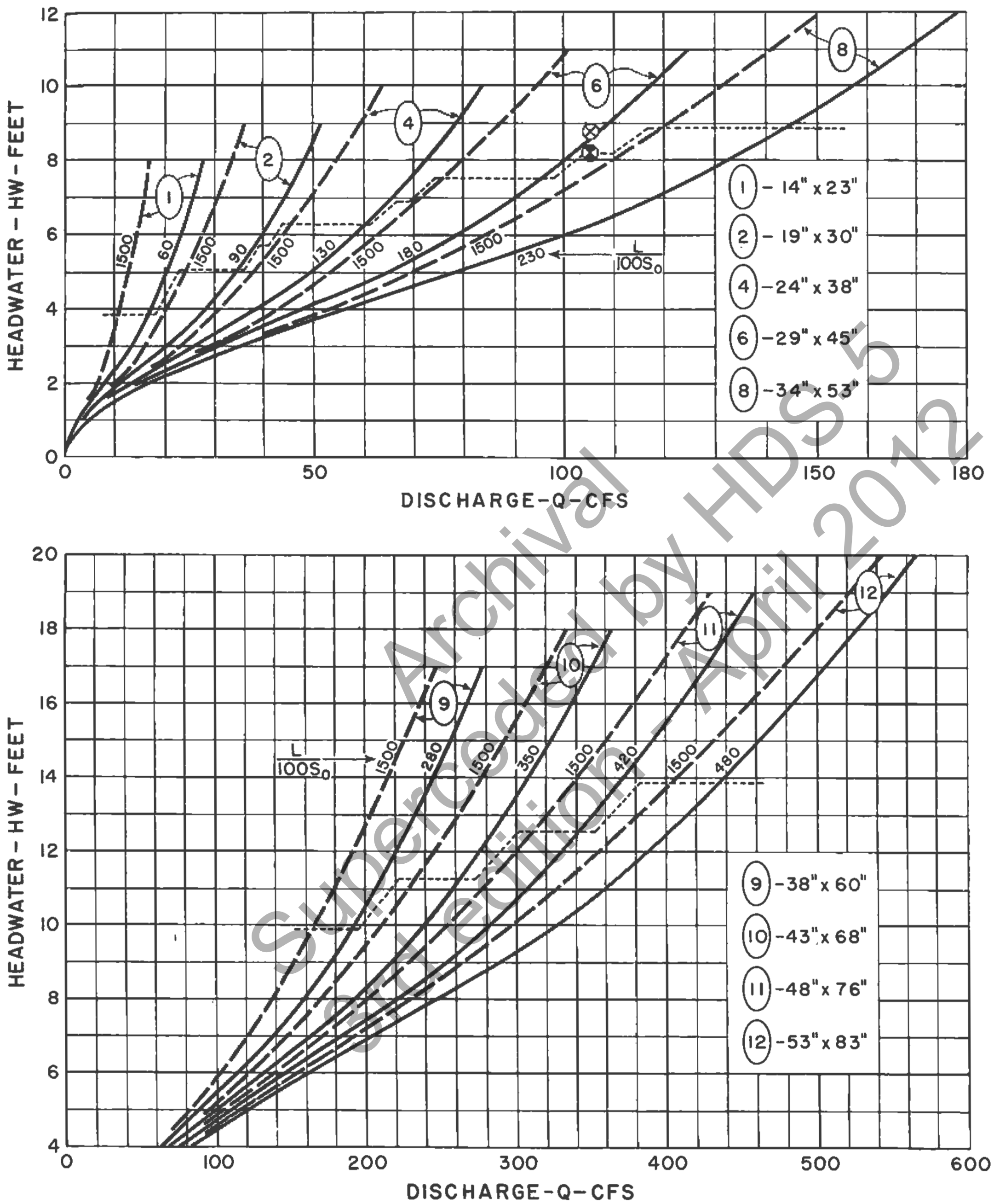
CHART 18



EXAMPLE

⊗ GIVEN:
105 CFS; AHW = 8.8 FT.
L = 115 FT.; S_0 = 0.0015

⊗ SELECT NO. 7, 32" x 49"
HW = 8.2 FT.

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CULVERT CAPACITY
OVAL CONCRETE PIPE - VERTICAL
GROOVE-EDGED ENTRANCE
14" x 23" TO 53" x 83"

VII E. Standard Circular Corrugated Metal Pipe Culverts

1/2-in. by 2-2/3 in. corrugation

Charts 19 to 21 are for circular corrugated metal pipe with inlet face normal to the axis and projecting to or beyond the toe of fill.

Other inlet details for which the projecting entrance charts (Charts 19 to 21) may be used are as follows:

a. Skewed inlets, with full pipe section cut on a skew to form a face parallel to the roadway.

b. Mitered inlets; normal or skewed, formed by a miter cut through the pipe on a plane inclined to the horizontal and conforming to the side slope of the fill.

c. Stepped mitered inlets, where the miter cut begins above the invert and ends below the crown.

d. Low height headwalls, extending less than 1/2 the barrel height, leaving the full-section pipe projecting from the fill above the partial headwall.

Charts 22 to 24 are for a full-height headwall at 90° to the culvert axis, extending at least 1/12 D above the pipe crown and of sufficient length to retain the fill slopes clear of the waterway opening.

Other inlet details for which the headwall entrance charts (Charts 22 to 24) may be used are as follows:

a. Flared wingwalls, with curb over the crown and at 90° to the barrel. The flare angle may be as small as about 20° with axis of culvert. Such wingwalls reduce the headwater depth, but not enough to be significant in design.

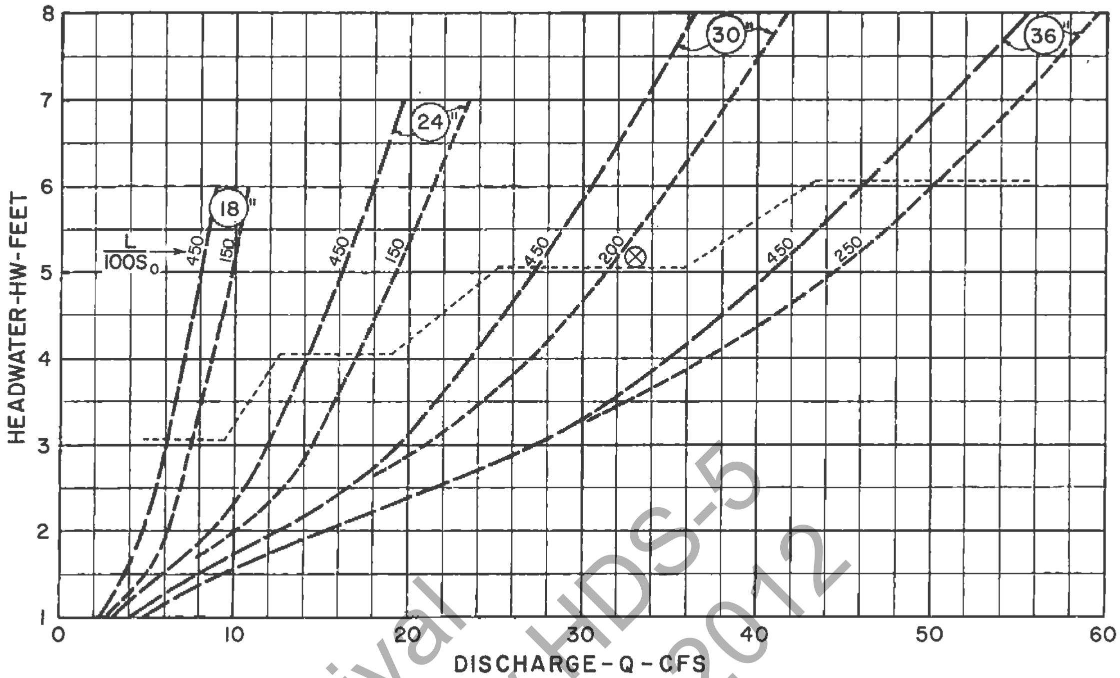
b. Parallel wingwalls increase headwater depth. If the distance between walls is 1.25 D or more, the charts may be used for design. Do not use the charts for parallel wingwalls only 1.0D apart.

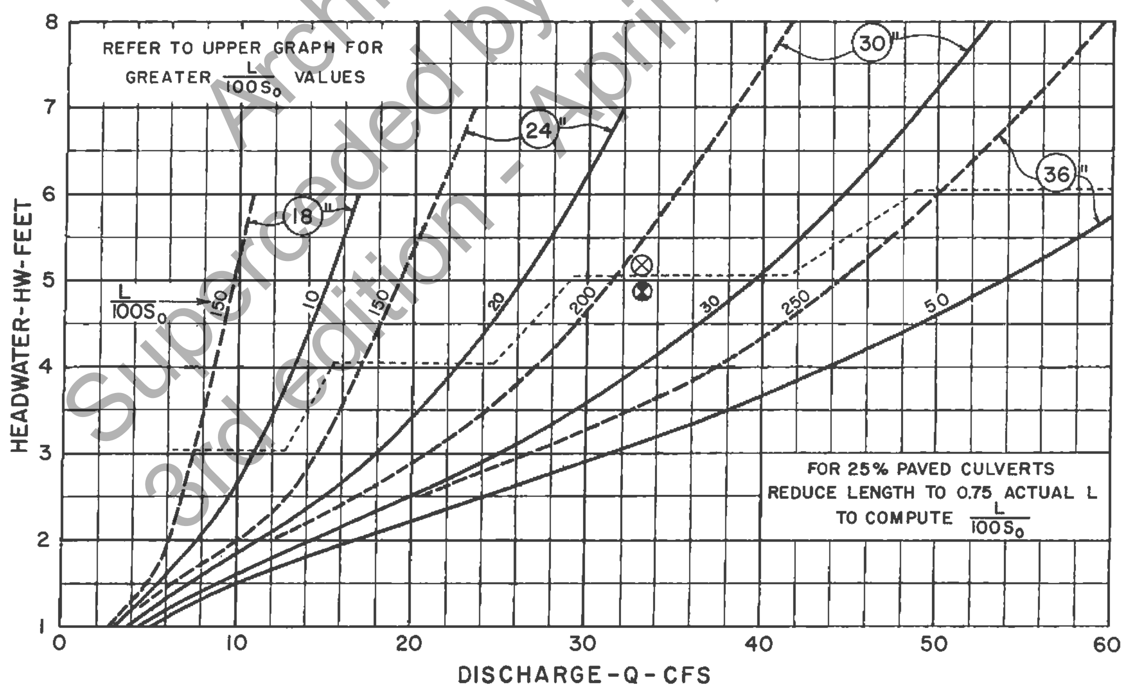
c. Skewed inlets, with the angle between the inlet face and a plane at 90° to the barrel axis (the skew angle) not exceeding 45°.

d. Standard metal culvert end-section, with apron and side wings.

Standard corrugated metal pipe diameters usually conform closely to the nominal diameter. Pipe diameters and areas are listed under sec. VII B.

For paved invert culverts, of all inlet types, use the charts in the normal manner, but reduce the culvert length to compute $L/100S_o$ as instructed in sec. IV, case 1.





EXAMPLE

⊗ GIVEN:
33 CFS; AHW = 5.2 FT.
L = 70 FT.; S_0 = 0.005

⊗ SELECT 30" UNPAVED
HW = 4.9 FT.

CULVERT CAPACITY STANDARD CIRCULAR CORR. METAL PIPE PROJECTING ENTRANCE 18" TO 36" ○

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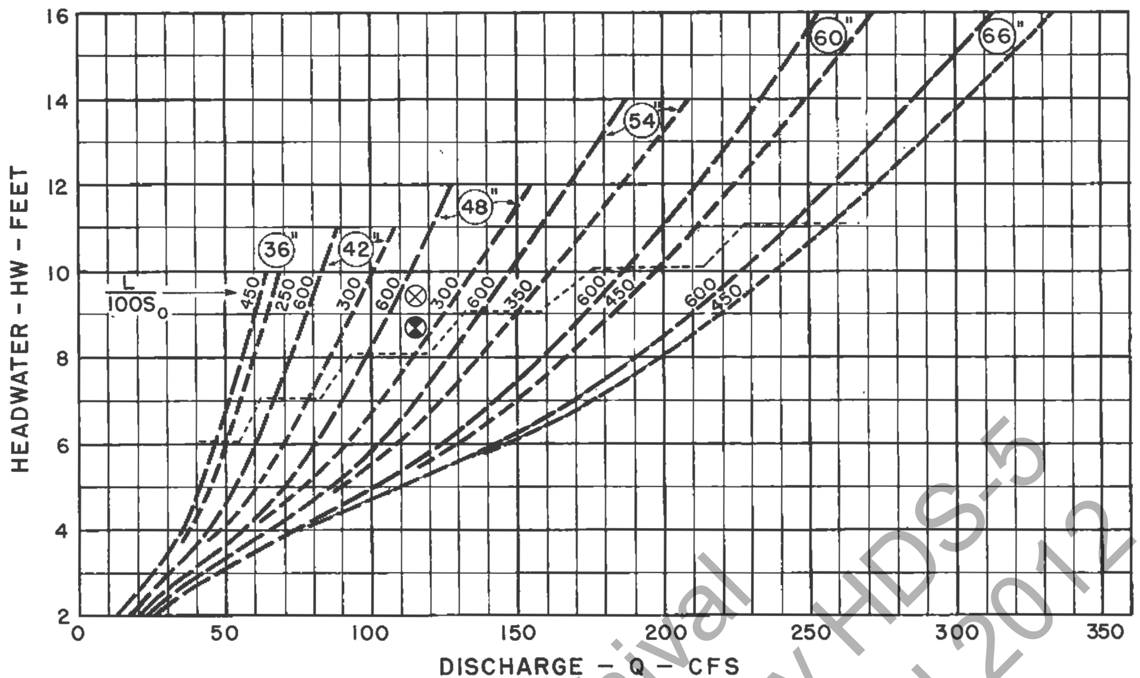
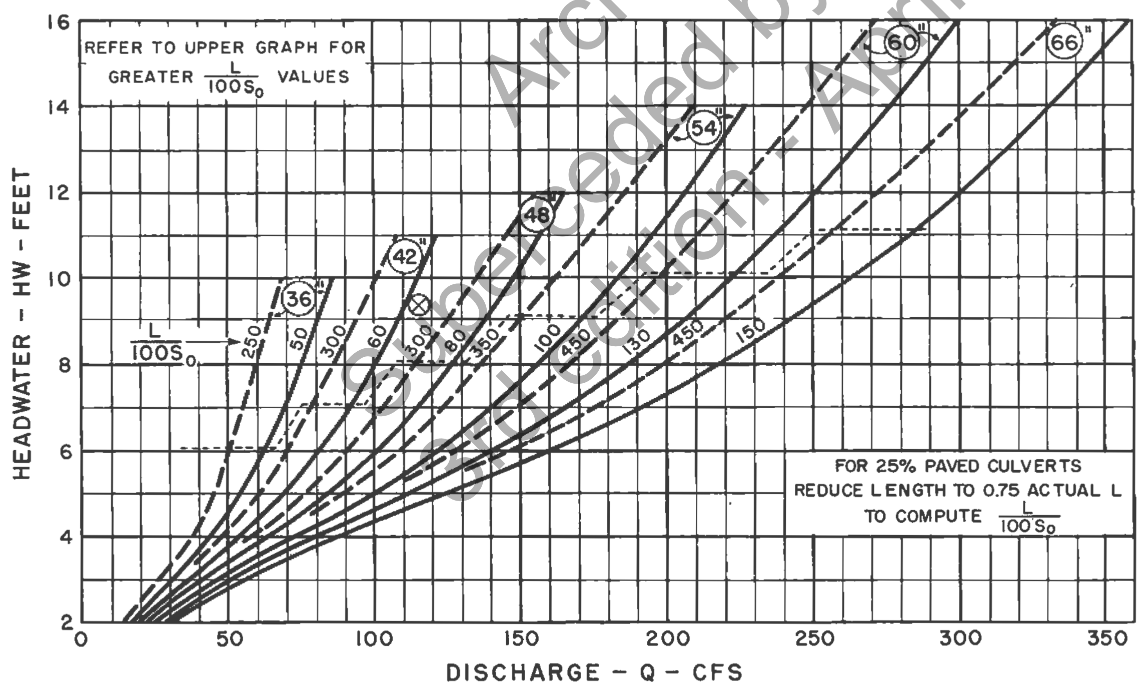
CHART 20





EXAMPLE

⊗ GIVEN:
115 CFS; AHW = 9.4 FT.
L = 135 FT.; S_0 = 0.0034

⊗ SELECT 48" UNPAVED
HW = 8.6 FT.

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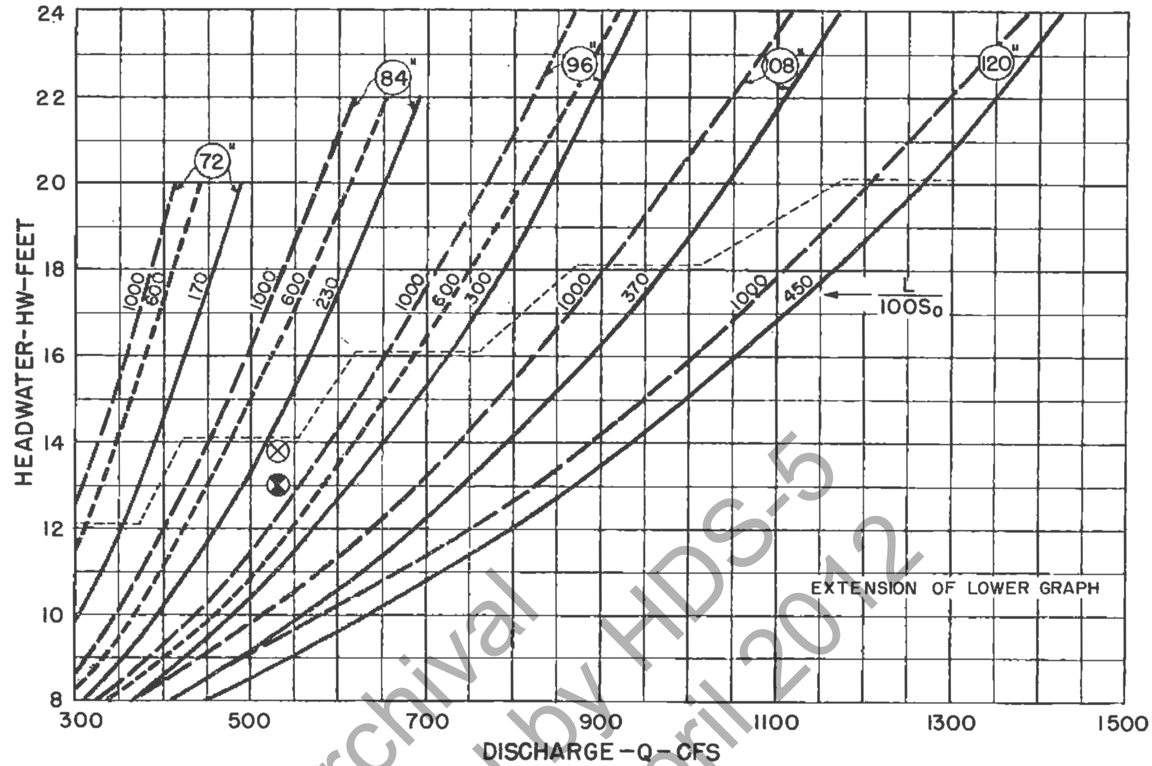
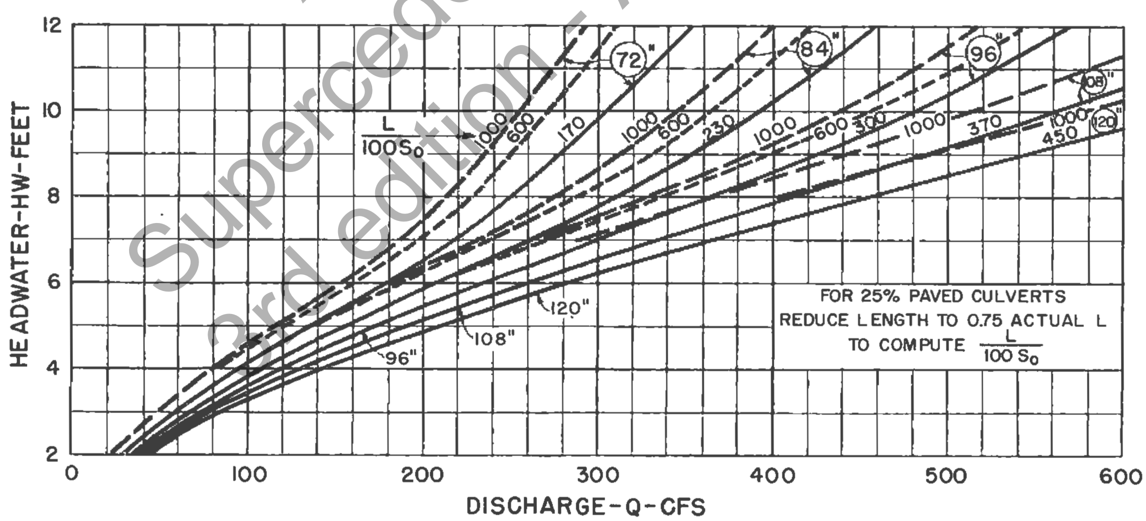
CULVERT CAPACITY
STANDARD
CIRCULAR CORR. METAL PIPE
PROJECTING ENTRANCE
36" TO 66" ○

CHART 21





EXAMPLE

⊗ GIVEN:
530 CFS; AHW 13.8 FT.
L= 270 FT; S_0= 0.0060

SELECT 90" UNPAVED
HW= 13.0 FT.

CULVERT CAPACITY
STANDARD
CIRCULAR CORR. METAL PIPE
PROJECTING ENTRANCE
72" TO 120" ○

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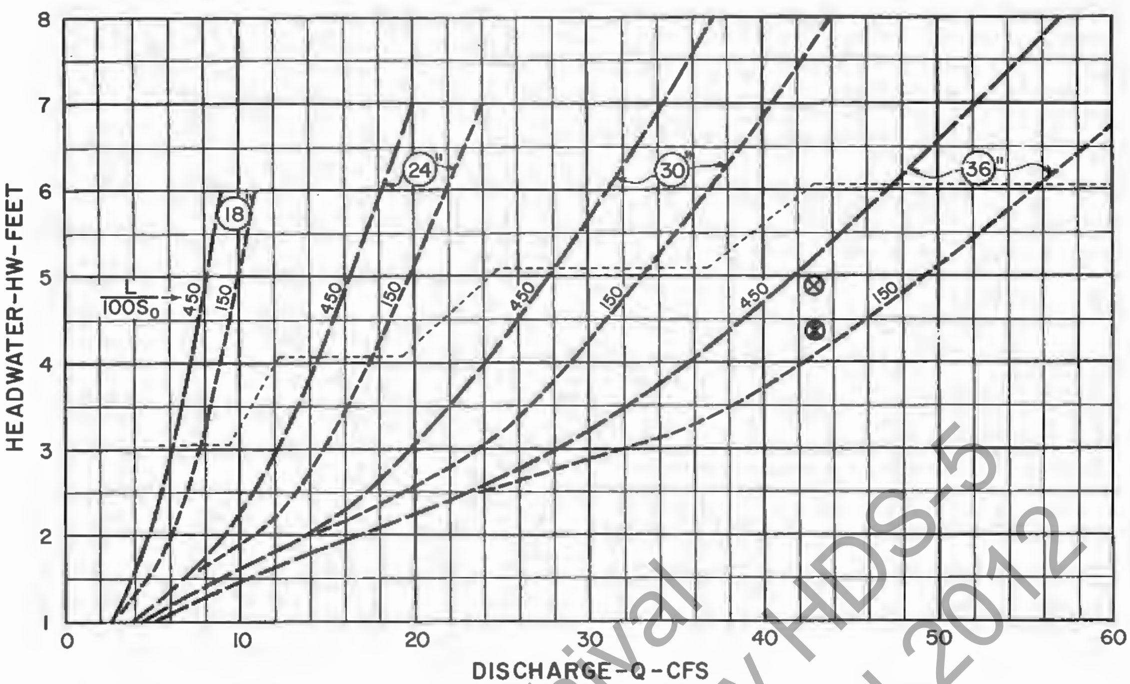
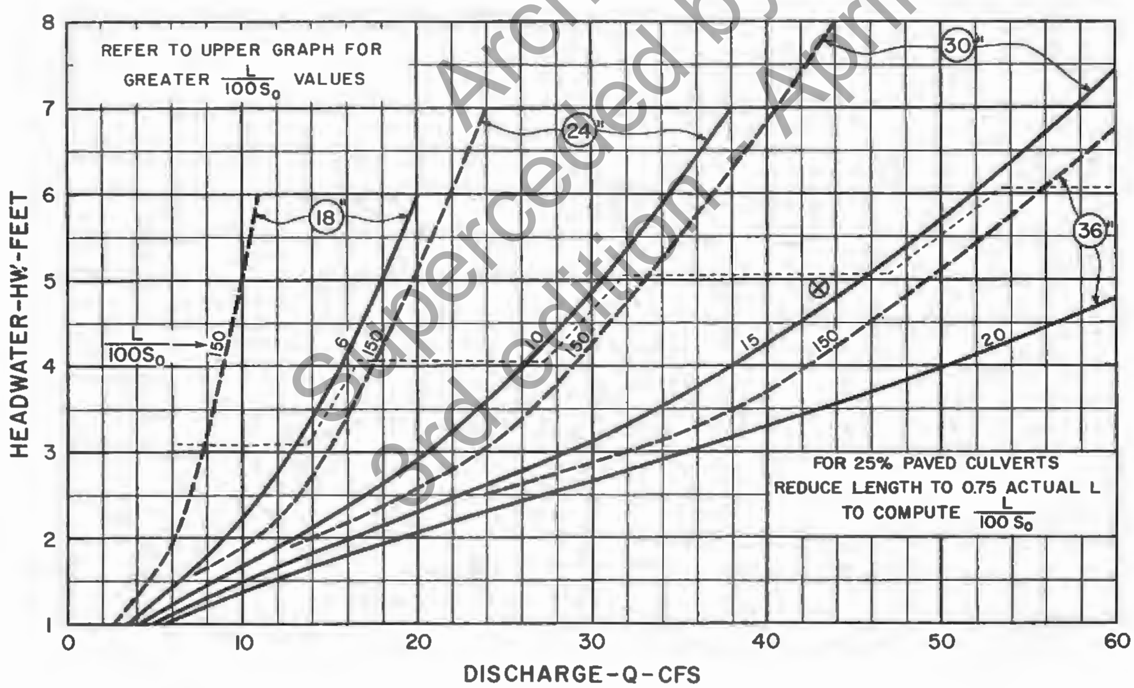
CHART 22





EXAMPLE

⊗ GIVEN:
43 CFS; AHW = 4.9 FT.
L = 72 FT.; S_0 = 0.003

⊗ SELECT 36" UNPAVED
HW = 4.4 FT.

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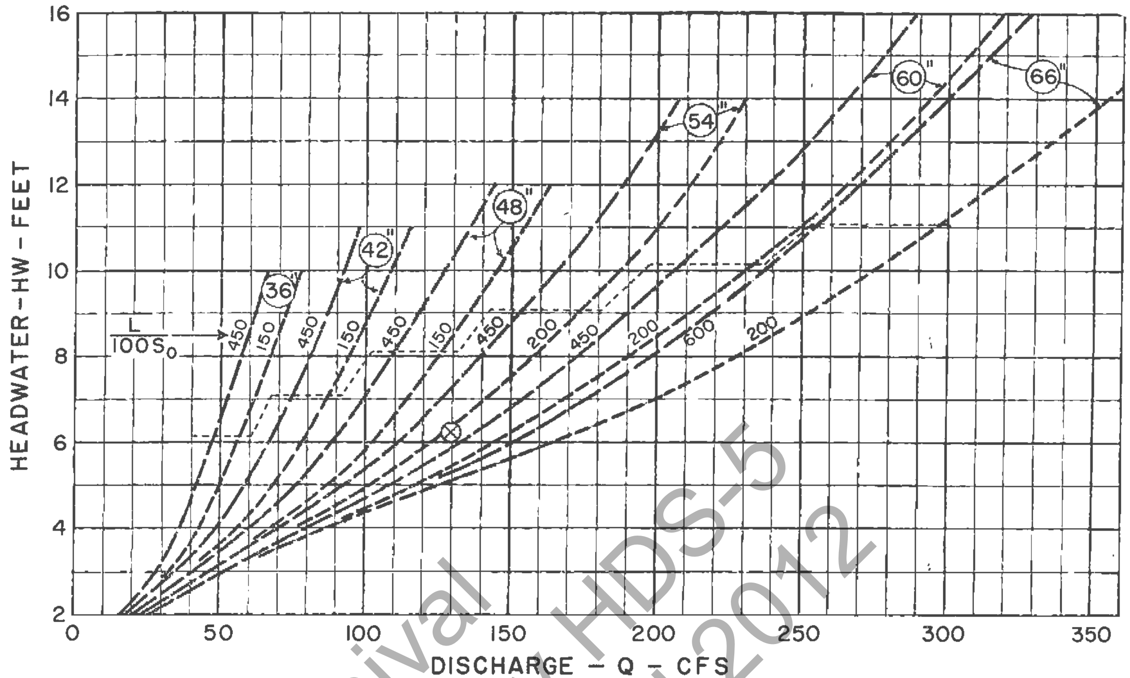
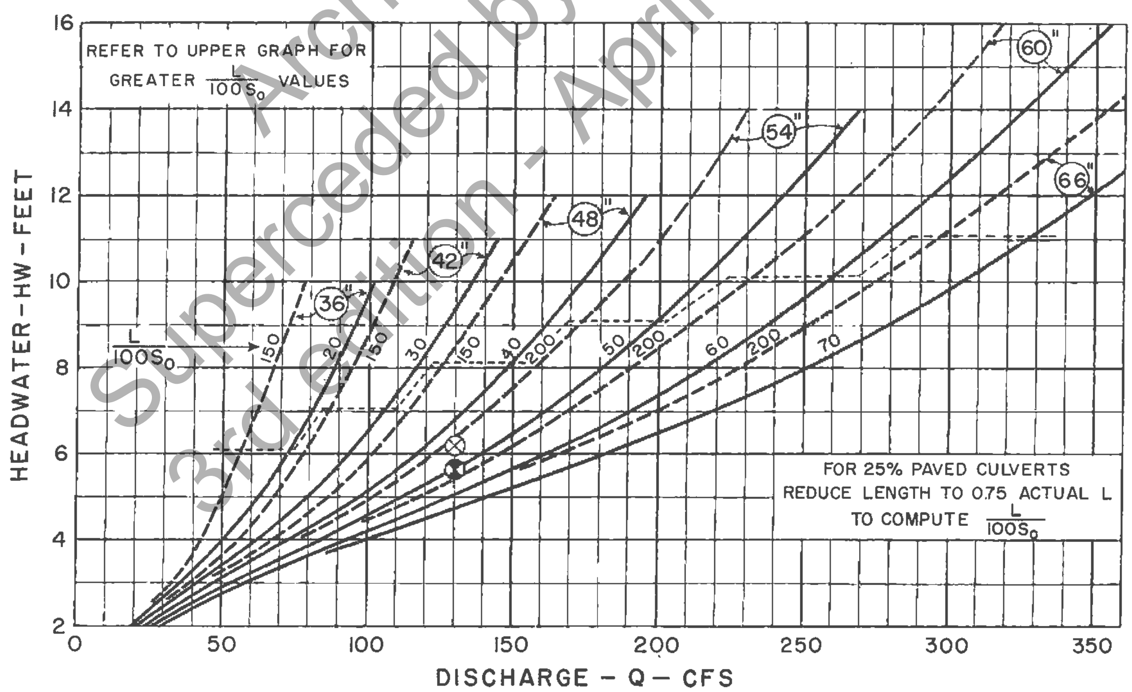
CULVERT CAPACITY
STANDARD
CIRCULAR CORR. METAL PIPE
HEADWALL ENTRANCE
18" TO 36" ○

CHART 23





EXAMPLE

⊗ GIVEN:
130 CFS; AHW = 6.2 FT.
L = 120 FT.; S_0 = 0.025

SELECT 54" UNPAVED
HW = 5.6 FT.

CULVERT CAPACITY
STANDARD
CIRCULAR CORR. METAL PIPE
HEADWALL ENTRANCE
36" TO 66" ○

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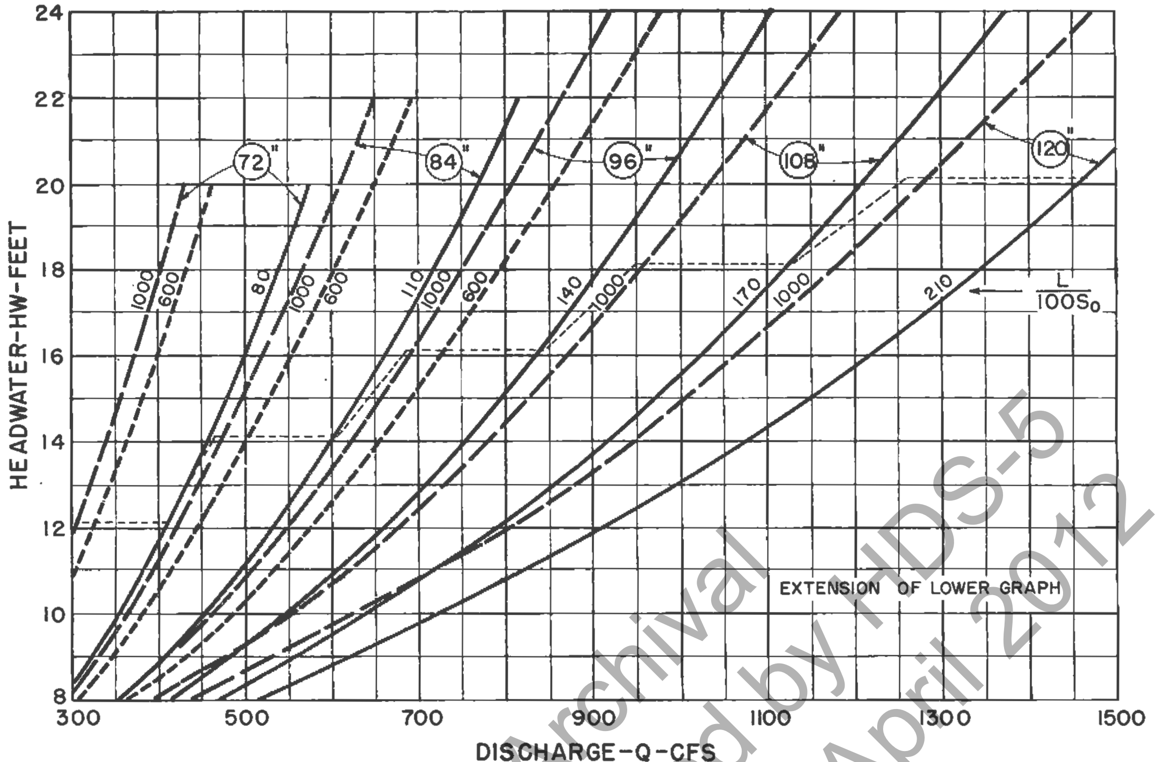
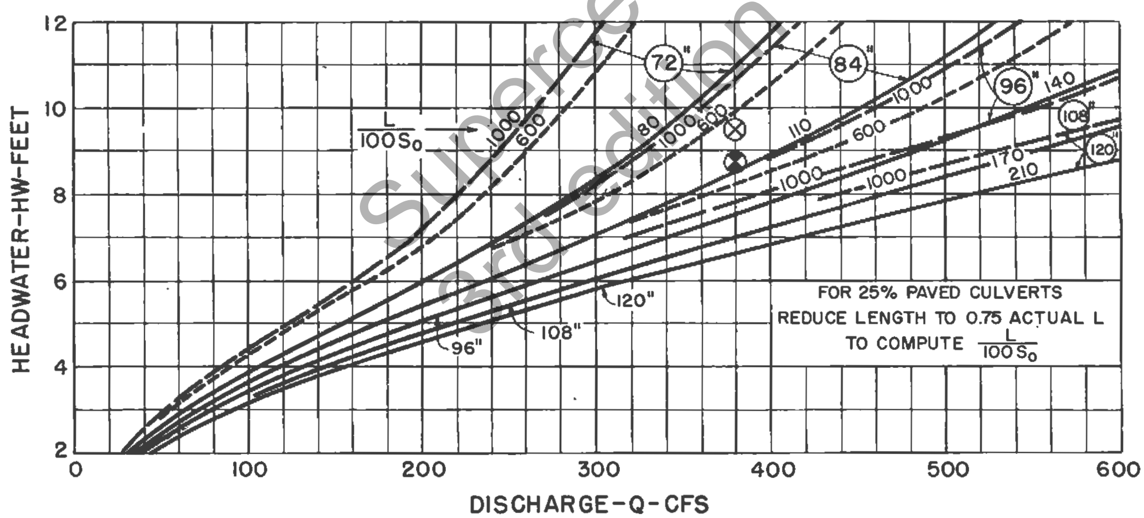
CHART 24





EXAMPLE

⊗ GIVEN:
380 CFS; AHW = 9.5 FT.
L = 120 FT.; S_0 = 0.0083

⊗ SELECT 84" UNPAVED
HW = 8.8 FT.

CULVERT CAPACITY
STANDARD
CIRCULAR CORR. METAL PIPE
HEADWALL ENTRANCE
72" TO 120" ○

BUREAU OF PUBLIC ROADS JAN. 1963

VII F. Standard Corrugated Metal Pipe Arch Culverts

1/2-in. by 2-2/3-in. corrugation

Curves for all commercially available pipe-arch culvert sizes are shown on the charts. The sizes shown on each graph are arranged in an alternate manner to avoid overlapping of the curves.

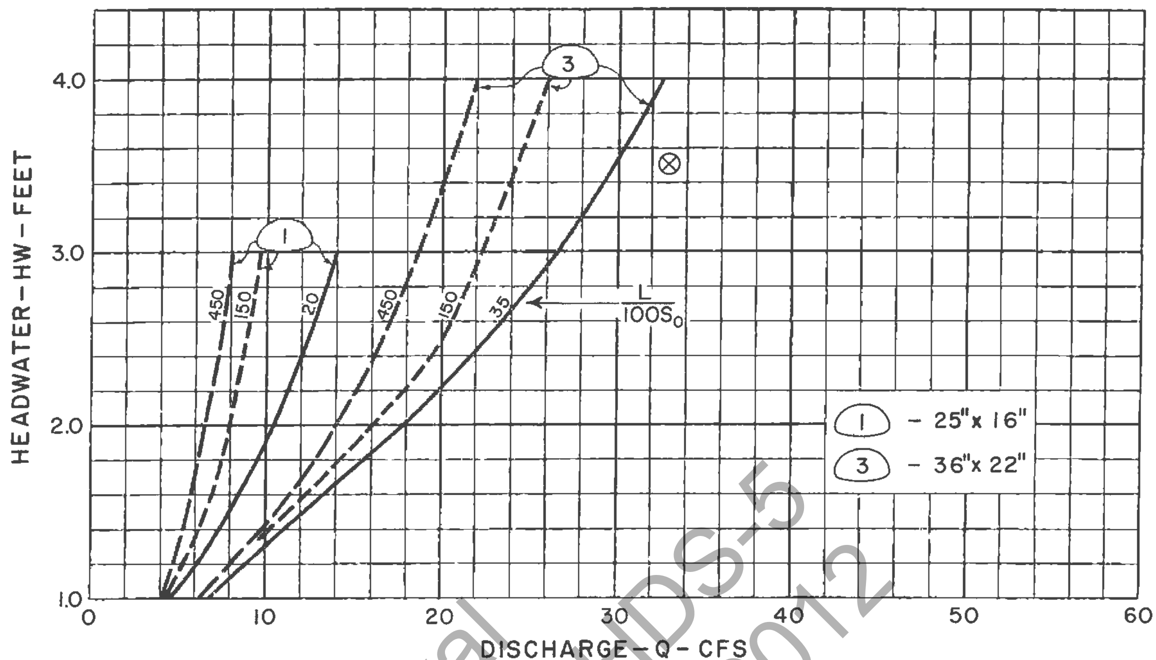
Charts 25 and 26 are for pipe-arch culverts with inlet face normal to the axis and projecting to or beyond the toe of fill. The charts may also be used for mitered inlets, and the other inlet variations listed under sec. VII E for circular corrugated metal pipe with projecting entrance.

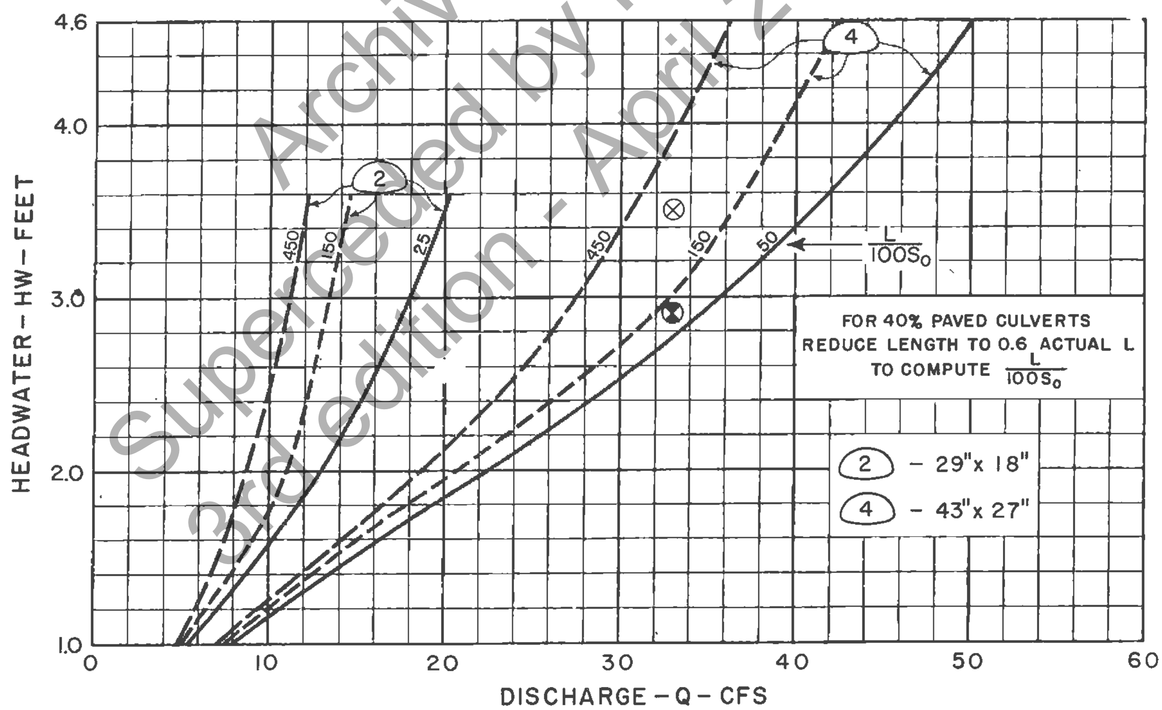
Charts 27 and 28 are for a full-height headwall at 90° to the culvert axis, extending at least 1/12 D above the pipe crown and of sufficient length to retain fill slopes clear of the waterway opening. The charts may also be used with all inlet variations listed under sec. VII E for circular corrugated metal pipe with headwall entrance.

Pipe-arches are made by pressing standard circular C.M. pipe to form sections with a span about 1.63 and a rise about 0.74 times the pipe diameter. The cross-sectional area is about 0.90 that of the circular pipe from which the pipe-arch is made. The charts are computed for a standardized section of the above dimensions. The inside dimensions (crest to crest) and area of each size are given in the table below.

Dimensions of
Standard C.M. Pipe-Arch Sections Included in Charts

Nominal Size inches	Span ft.	Height ft.	Area s.f.	Round Pipe diam., in.
25 x 16	2.11	1.29	2.16	21
29 x 18	2.41	1.48	2.83	24
36 x 22	3.01	1.85	4.42	30
43 x 27	3.61	2.22	6.36	36
50 x 31	4.22	2.59	8.65	42
58 x 36	4.82	2.96	11.30	48
65 x 40	5.42	3.33	14.34	54
72 x 44	6.02	3.70	17.7	60





EXAMPLE

⊗ GIVEN:
33 CFS; AHW = 3.5 FT.
L = 60 FT.; S_0 = 0.005

SELECT NO. 4, 43" x 27"
HW = 2.9 FT.
UNPAVED INVERT

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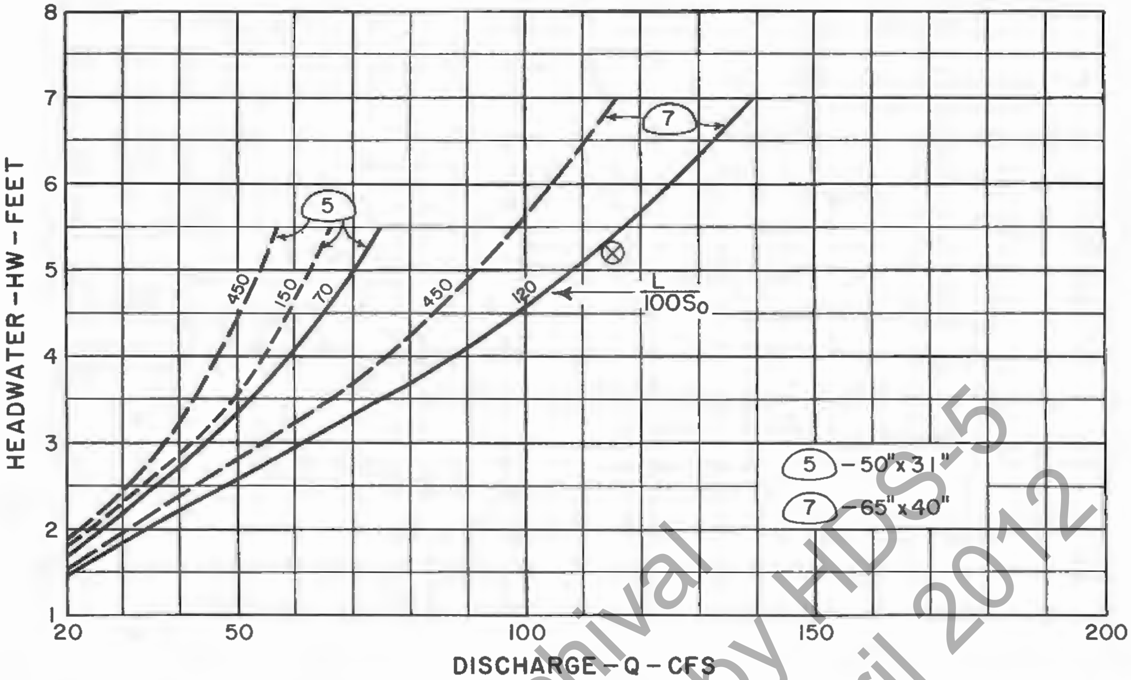
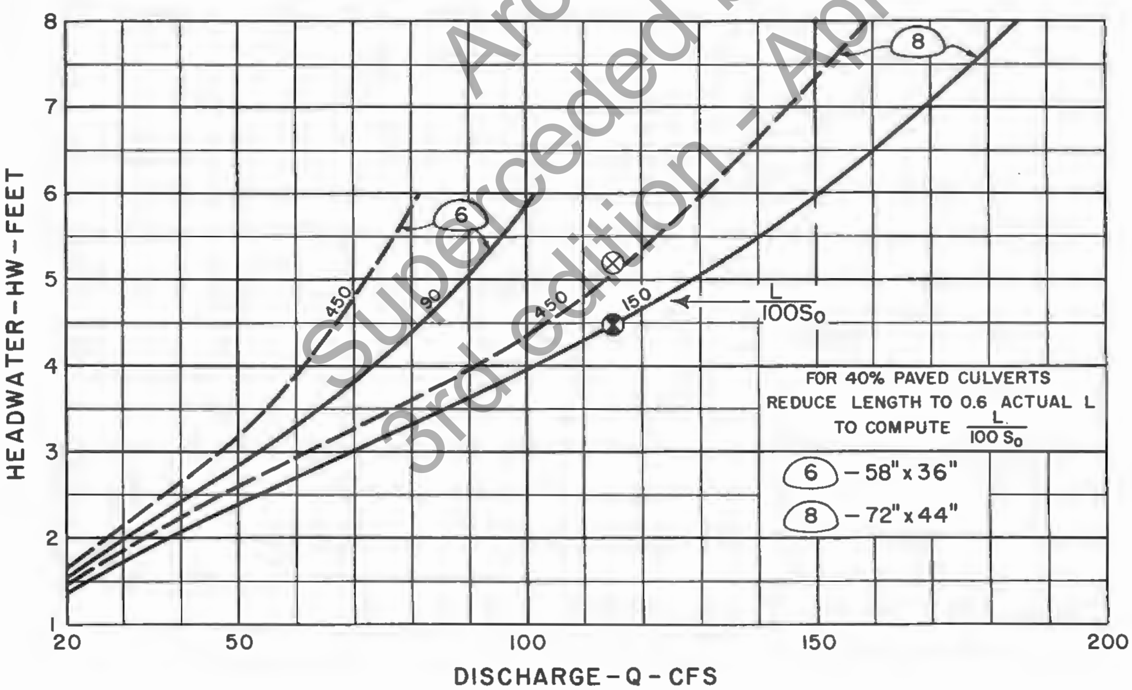
CULVERT CAPACITY
STANDARD CORR. METAL PIPE-ARCH
PROJECTING ENTRANCE
25"x16" TO 43"x27"

CHART 26





EXAMPLE

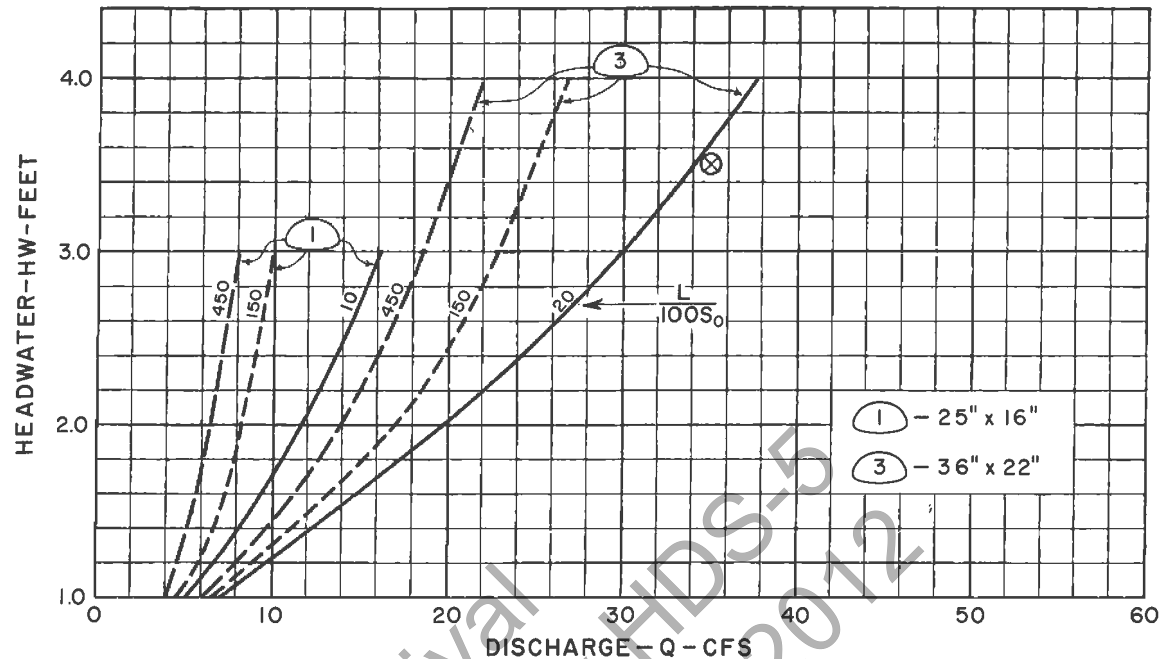
⊗ GIVEN:
115 CFS; AHW = 5.2 FT.
L = 110 FT.; S_0 = 0.0055

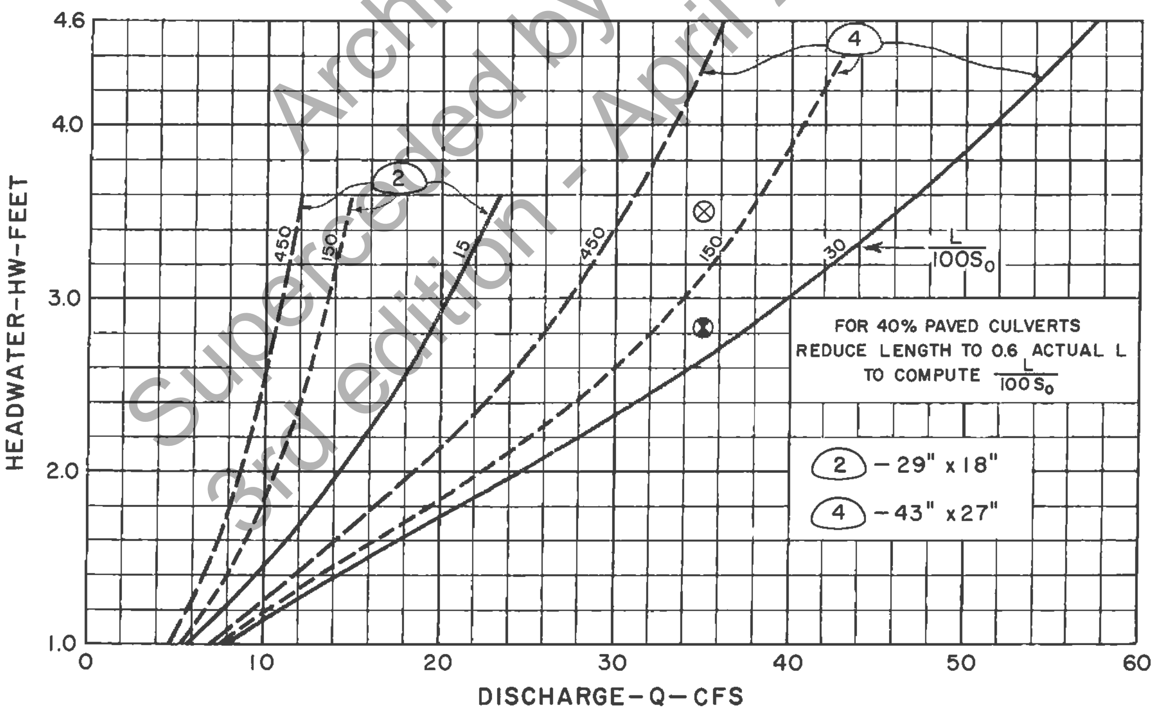
⊗ SELECT NO.8, 72" x 44"
HW = 4.5 FT.
PAVED INVERT

BUREAU OF PUBLIC ROADS JAN. 1963

CULVERT CAPACITY
STANDARD CORR. METAL PIPE-ARCH
PROJECTING ENTRANCE
50" x 31" TO 72" x 44"

CHART 27





EXAMPLE

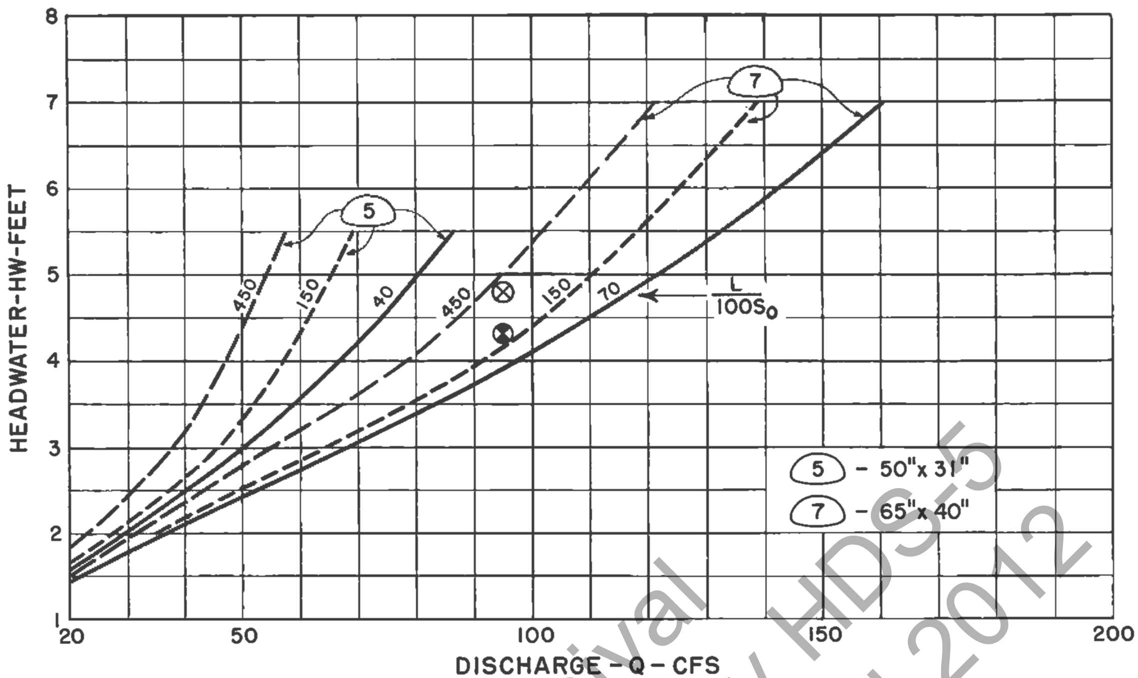
⊗ GIVEN:
35 CFS; AHW = 3.5 FT.
L = 145 FT.; S_0 = 0.020

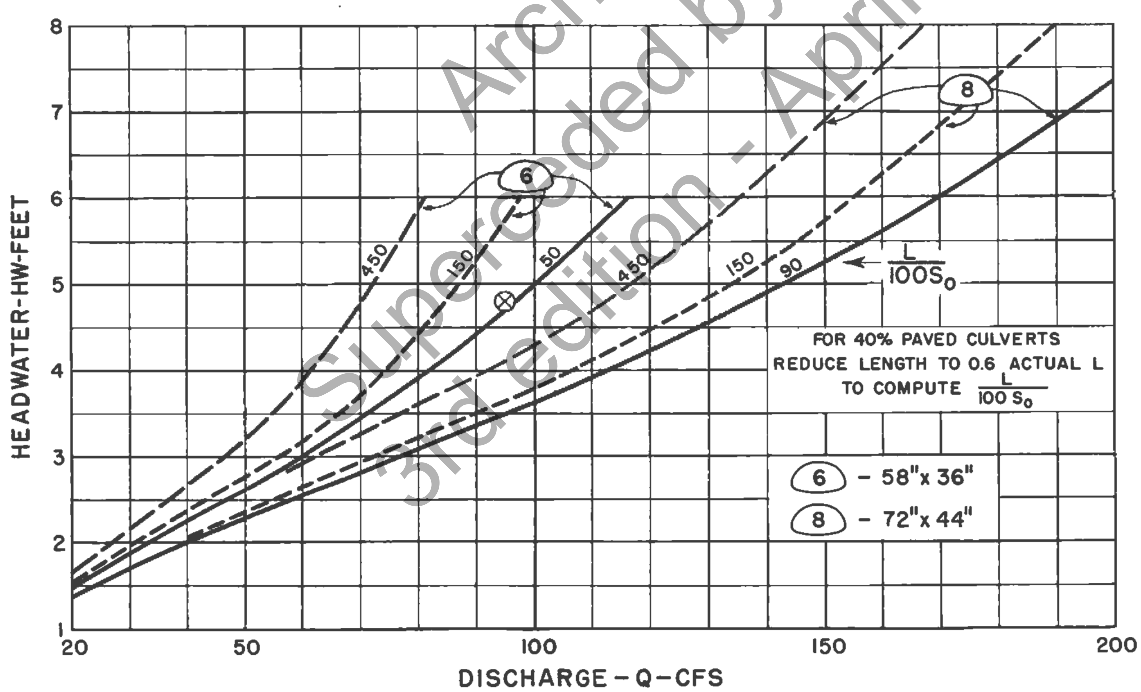
⊗ SELECT NO.4, 43" x 27"
HW = 2.8 FT.
UNPAVED INVERT

BUREAU OF PUBLIC ROADS JAN. 1963

CULVERT CAPACITY STANDARD CORR. METAL PIPE-ARCH HEADWALL ENTRANCE 25" x 16" TO 43" x 27"

CHART 28





EXAMPLE

⊗ GIVEN:
95 CFS; AHW = 4.8 FT.
L = 240 FT.; S_0 = 0.012

SELECT NO. 7, 65"x 40"
HW = 4.3 FT.
UNPAVED INVERT

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CULVERT CAPACITY
STANDARD CORR. METAL PIPE - ARCH
HEADWALL ENTRANCE
50"x 31" TO 72"x 44"

VII G. Structural Plate Circular Corrugated Metal Pipe Culverts

2-in. by 6-in. corrugation

Charts 29 and 30, are used for culverts with inlet face normal to the axis and projecting to or beyond the toe of fill. The charts may also be used for mitered inlets, and all inlet variations given in sec. VII E for standard (1/2" x 2-2/3") circular corrugated metal pipe with projecting entrance.

Charts 31 and 32, are used for a full-height headwall at 90° to the culvert axis, extending at least 1/12 D above the pipe crown and of sufficient length to retain the fill slopes clear of the waterway opening. The charts also apply to all inlet variations given in sec. VII E for standard circular corrugated metal pipe with headwall entrance, except that prefabricated metal end-sections are not available for structural plate pipe.

The high resistance loss for flow in unpaved structural-plate pipe indicates that the culvert invert slopes should be at least 0.01, if possible. Very flat slopes may require a size increase of 1 foot or more for culverts over 200 feet long. The outlet control curves (dashed lines) of the charts are computed for culverts on 0.01 slopes. Therefore the length, in feet, used for each size is equal to the $L/100S_o$ number. The coinciding curves for 300 ft. and 120 ft. culverts, or 400 and 240 ft., at low headwater depths mean that normal depth is reached on the backwater profile before it reaches the crown. In such cases, greater culvert length does not increase headwater depth.

Where it may be necessary to install structural plate culverts at slopes less than one percent, the normal method for determining headwater depth on the basis of the culvert $L/100S_o$ from a chart curve or by interpolation requires modification for more accurate results. Inlet control operation can occur on small slopes only for short culverts, that is, length less than 10 times the diameter, and then only after HW becomes greater than 1.3 D. For greater lengths or lower headwater with short lengths, outlet control will always govern. For slopes significantly less than 0.01, find HW by the following method, for both paved and unpaved culverts:

1. Compute $L/100S_o$ for the culvert L at a slope 0.01, that is, $L/100S_o$ is equal to L. Use reduced L for paved inverts (p. 10-9).

2. Use the $L/100S_o$ of step 1 to read HW from the chart curves for the size under consideration, on the solid line curve or by interpolation.

3. Compute the additional hypothetical fall of the culvert invert introduced by using the one percent slope, i.e., $L\ (0.010 - S_o)$, in feet.

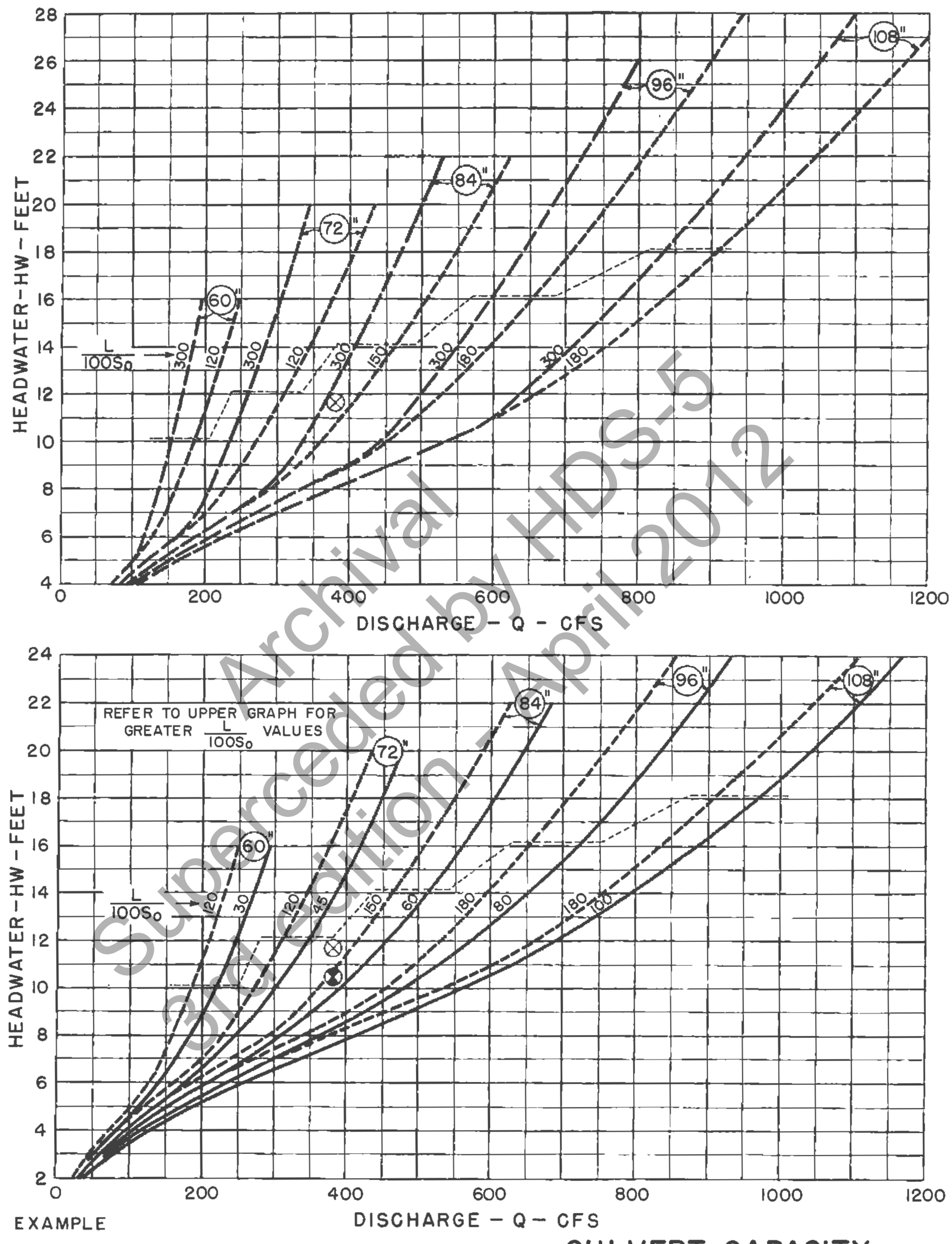
4. Add the amount from step 3 to HW read from the chart in step 2 to obtain a close approximation of the headwater depth required.

The pipe sizes given in the charts are the nominal inside diameter (crest-to-crest of corrugations). The charts are computed for the manufacturers standard inside diameters as given in the table below.

Table of Actual Inside Diameters
of Structural Plate C.M. Pipe

Nominal Diam., in.	Actual Diam. in.	Actual Diam. ft.	Area s.f.	Nominal Diam., in.	Actual Diam. in.	Actual Diam. ft.	Area s.f.
60	59.1	4.93	19.05	120	120.2	10.02	78.8
66	65.2	5.43	23.19	126	126.3	10.53	87.0
72	71.3	5.94	27.73	132	132.4	11.04	95.7
78	77.4	6.45	32.67	138	138.6	11.55	104.8
84	83.6	6.97	38.12	144	144.7	12.06	114.2
90	89.7	7.48	43.88	150	150.8	12.57	124.0
96	95.8	7.98	50.06	156	156.9	13.08	134.3
102	101.9	8.49	56.63	162	163.0	13.58	144.9
108	108.0	9.00	63.62	168	169.1	14.09	156.0
114	114.1	9.51	71.01	174	175.2	14.60	167.4
				180	181.3	15.11	179.3

CHART 29



EXAMPLE

⊗ GIVEN:
380 CFS., AHW = 11.7 FT.
L = 152 FT., S_0 = 0.0080

SELECT 84"
HW = 10.5 FT.

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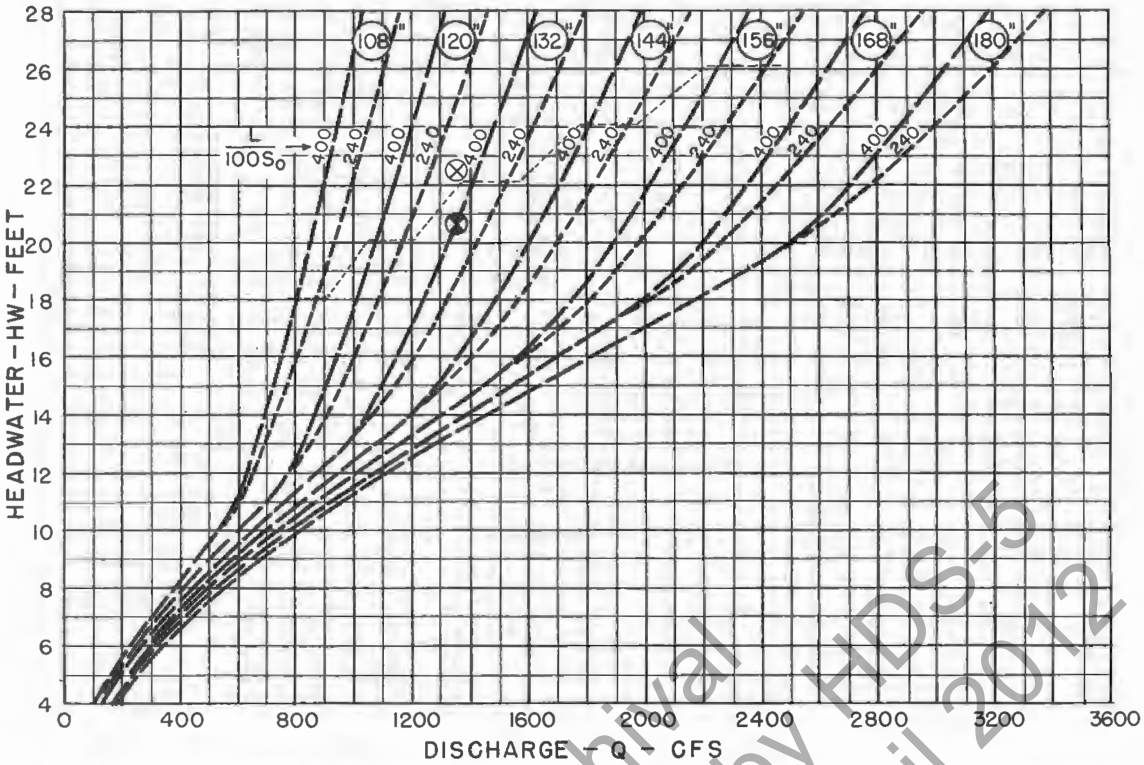
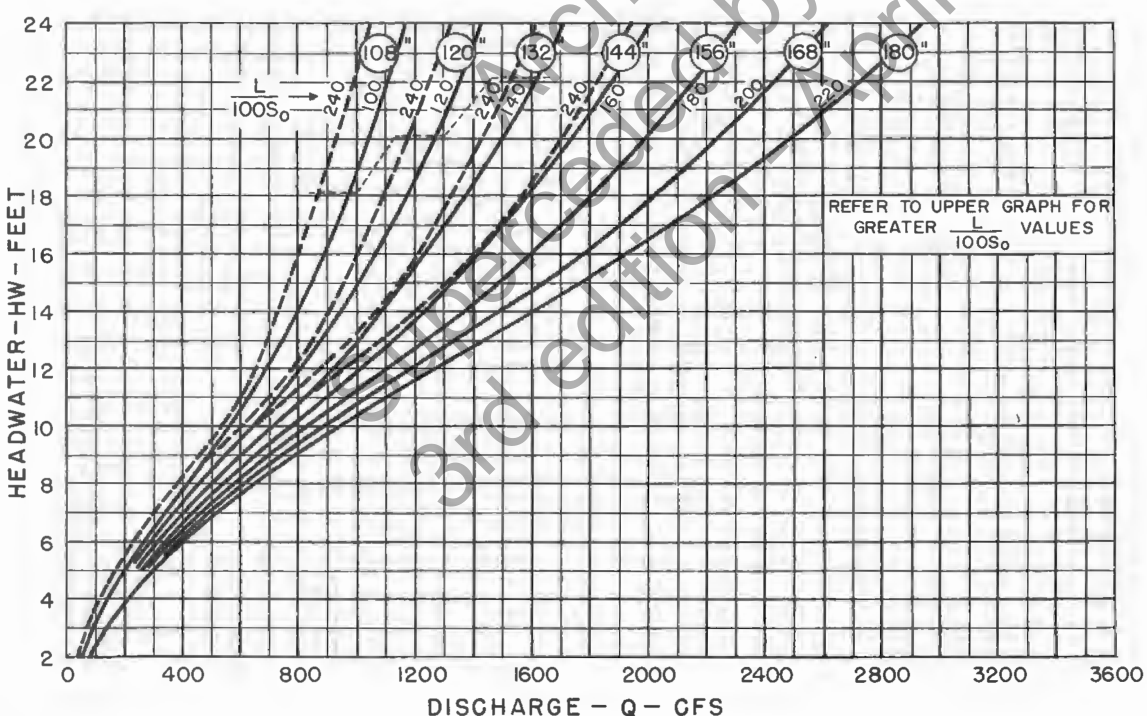
CULVERT CAPACITY
STRUCTURAL PLATE
CIRCULAR CORR. METAL PIPE
PROJECTING ENTRANCE
60" TO 108" ○

CHART 30





EXAMPLE

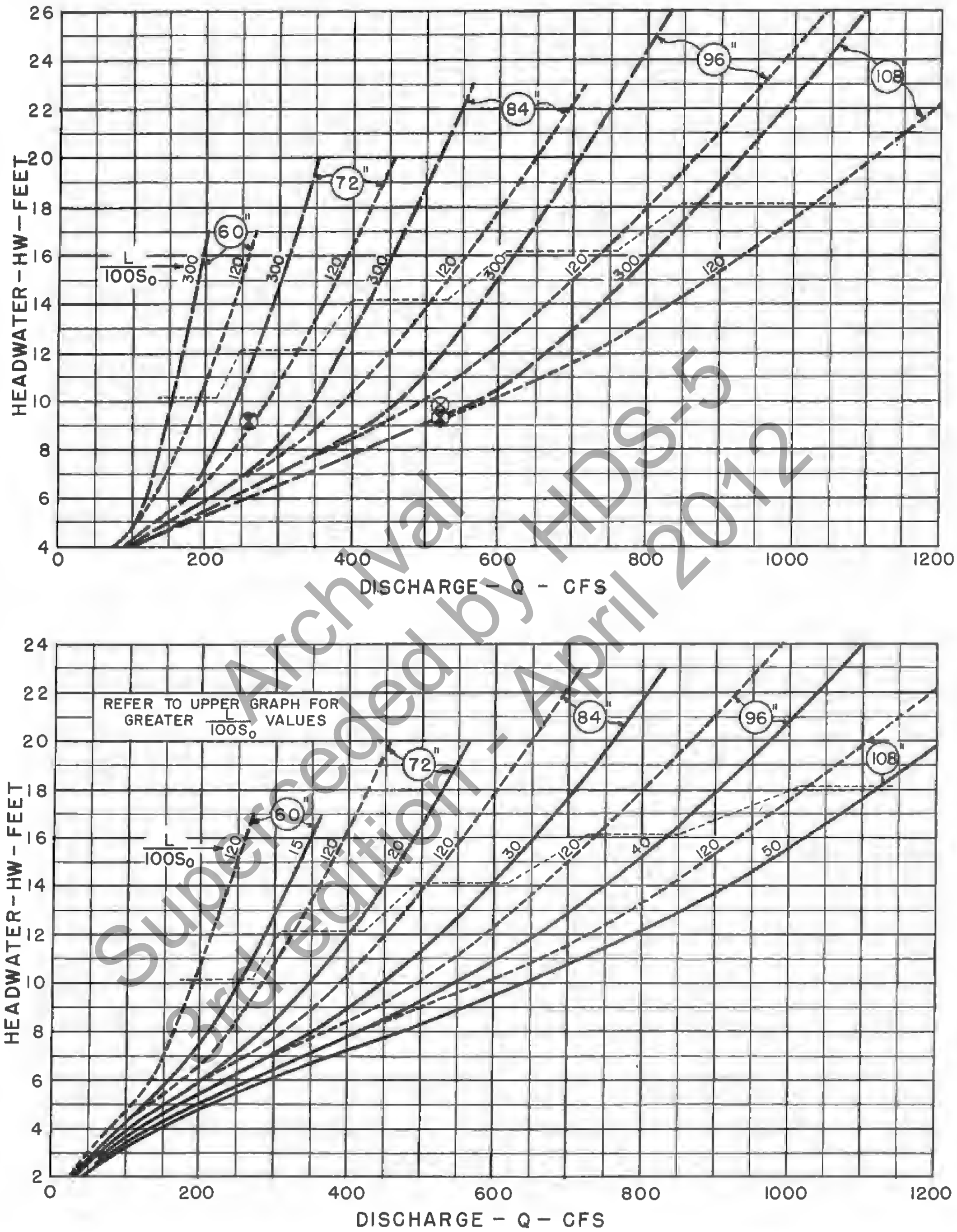
⊗ GIVEN:
1350 CFS., A HW = 22.5 FT.
L = 560 FT., S_0 = 0.014

⊗ SELECT 132"
HW = 20.6 FT.

INLET CONTROL $L/100S_0$ REVISED SEP. 1964

BUREAU OF PUBLIC ROADS JAN. 1963

CULVERT CAPACITY
STRUCTURAL PLATE
CIRCULAR CORR. METAL PIPE
PROJECTING ENTRANCE
108" TO 180" ○



EXAMPLE

⊗ GIVEN:
520 CFS., AHW=9.8 FT.
L = 114 FT., S_0=0.0085

SELECT
DUAL 72" HW=9.2 FT. OR
SINGLE 108" HW=9.3 FT.

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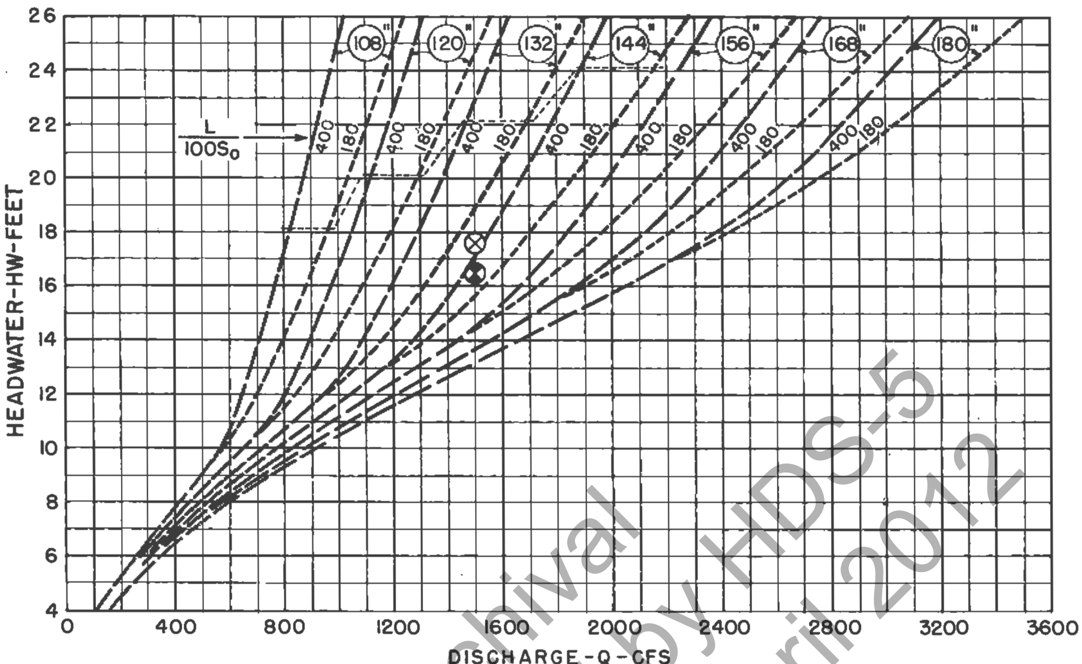
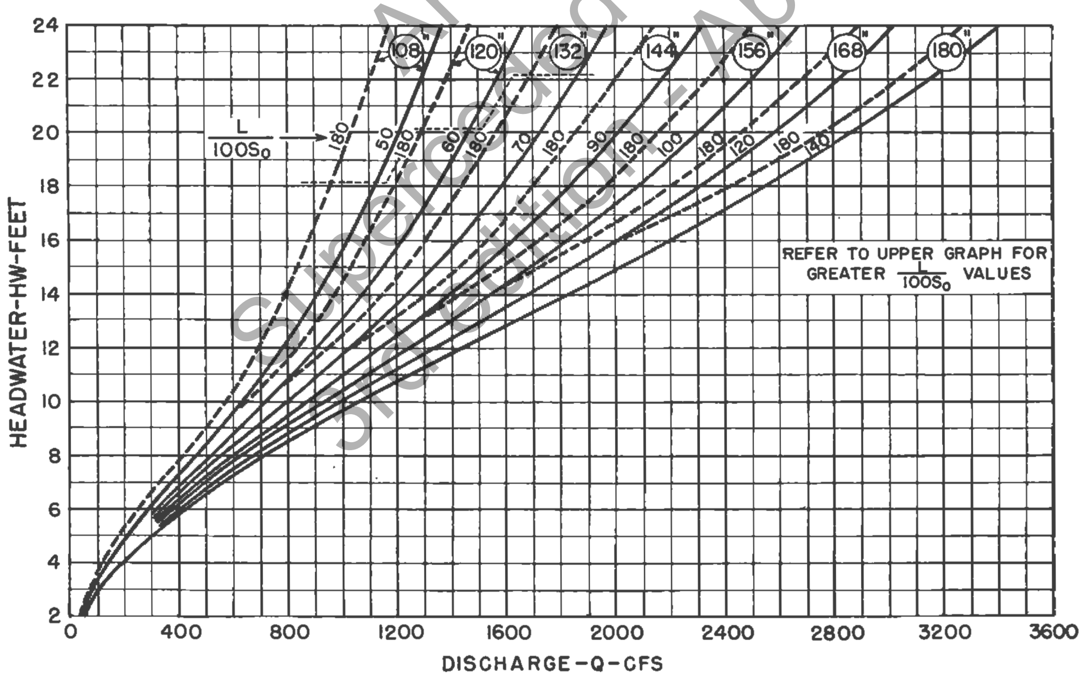
CULVERT CAPACITY
STRUCTURAL PLATE
CIRCULAR CORR. METAL PIPE
HEADWALL ENTRANCE
60" TO 108" ○

CHART 32





EXAMPLE

⊗ GIVEN:
1500 CFS., AHW=17.6 FT
L=180 FT., S_0=0.006

⊗ SELECT 144"
HW=16.5 FT.

CULVERT CAPACITY
STRUCTURAL PLATE
CIRCULAR CORR. METAL PIPE
HEADWALL ENTRANCE
108" TO 180" ○

"UREAU OF PUBLIC ROADS JAN. 1963

VII H. Structural Plate Pipe-Arch
Corrugated Culverts

<u>2-in. by 6-in. corrugation</u>

18-inch Radius Corner Plates

<u>Charts 33 and 34</u>, are for structural plate pipe-arch with inlet face normal to the axis and projecting to or beyond the toe of fill. The charts may also be used for mitered inlets, and the other inlet variations listed under sec. VII E for standard (1/2" x 2-2/3") circular corrugated metal pipe with projecting entrance.

<u>Charts 35 and 36,</u> are for a full-height headwall at 90° to the culvert axis, extending at least 1/12 D above the pipe crown and of sufficient length to retain the fill slopes clear of the waterway opening. The charts may also be used with all inlet variations listed under sec. VII E for standard circular corrugated metal pipe with headwall entrance, except that metal end-sections are not available.

The capacity charts for pipe-arches of corrugated structural plate include headwater curves for outlet control computed for 0.01 invert slopes, as was done for the circular pipe with 2" x 6" corrugations. It is advisable to install all such culverts at slope of 0.01 or more, if feasible. The factors involved are discussed briefly in sec. VII G.

Headwater depth for pipe-arch culverts with invert slopes significantly less than 0.01 may be read from the capacity charts and increased as provided in the instructions sec.VII G for structural plate circular pipe.

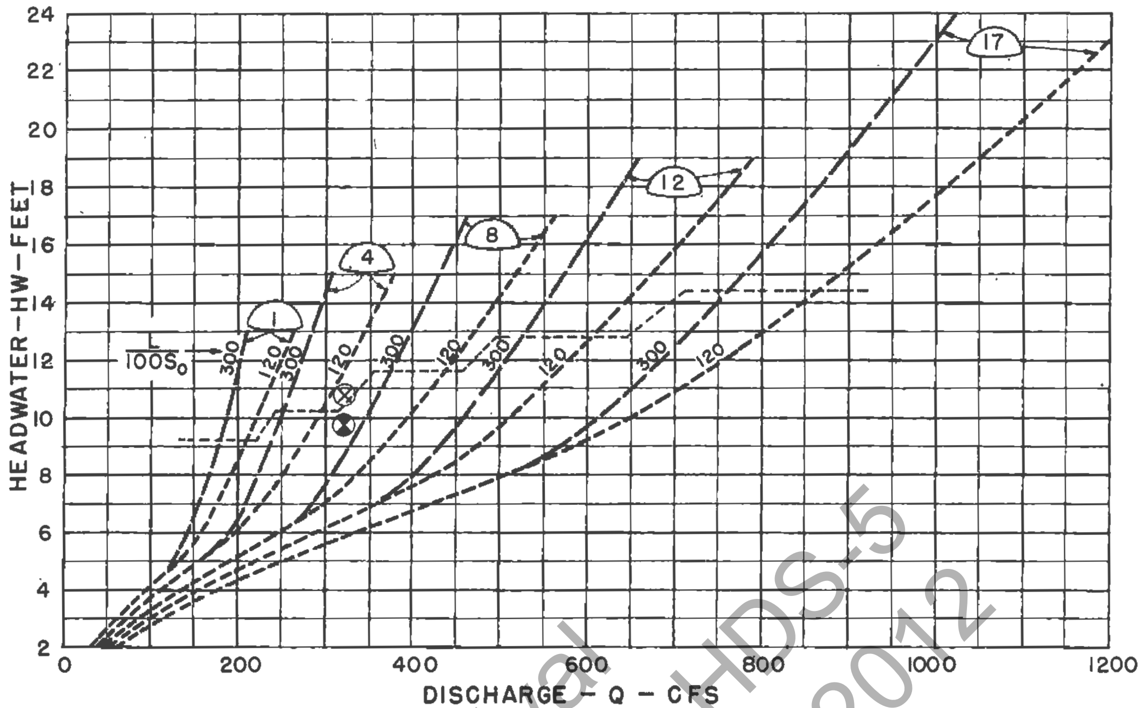
The culvert capacity charts include 8 of the 34 standard sizes available in structural plate pipe-arches. Sizes not included in the charts may be selected by use of the methods given in sec. IV, case 6. The actual inside maximum dimensions, crest-to-crest of corrugations, are given in the following table, with the inside perimeter and area of each section.

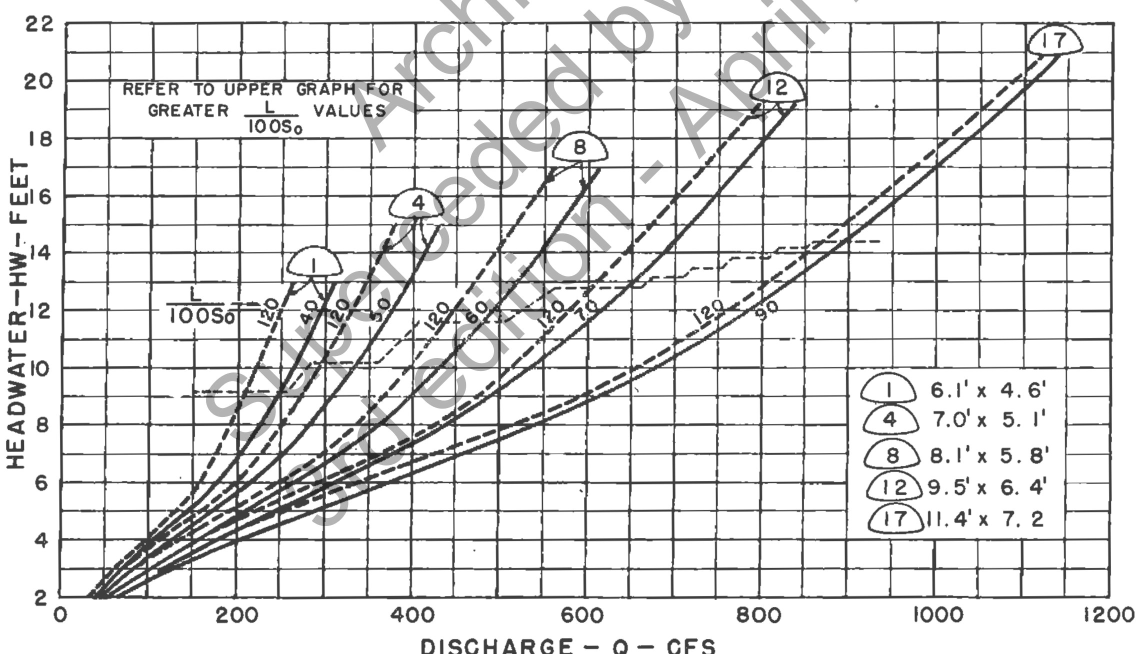
STRUCTURAL PLATE PIPE-ARCHES - 18" CORNER RADIUS

Section No.	Span ft.	Rise ft.	Perimeter ft.	Area s.f.
* 1	6.08	4.58	9.46	22.1
2	6.33	4.76	9.81	24.1
3	6.77	4.91	10.28	26.1
* 4	7.02	5.09	10.64	28.4
5	7.25	5.27	10.99	30.6
6	7.70	5.42	11.46	32.9
7	7.93	5.60	11.82	35.4
* 8	8.15	5.78	12.17	38.0
9	8.62	5.92	12.64	40.4
10	8.83	6.11	12.98	43.1
11	9.32	6.26	13.48	45.8
*12	9.52	6.44	13.82	48.7
13	9.72	6.62	14.16	51.6
14	10.22	6.77	14.64	54.5
15	10.70	6.91	15.15	57.5
16	10.92	7.09	15.48	60.7
*17	11.40	7.24	16.00	63.9
18	11.62	7.42	16.32	67.2
19	11.82	7.61	16.65	70.7
20	12.32	7.75	17.17	74.1
21	12.52	7.93	17.48	77.6
22	12.70	8.12	17.81	81.3
*23	12.87	8.31	18.15	85.2
24	13.40	8.44	18.64	88.7
25	13.93	8.58	19.17	92.6
26	14.12	8.77	19.47	96.5
27	14.28	8.96	19.80	100.7
28	14.82	9.10	20.33	104.8
*29	15.33	9.23	20.86	108.7
30	15.53	9.42	21.17	113.1
31	15.70	9.61	21.48	117.5
32	15.87	9.80	21.80	122.2
33	16.42	9.93	22.32	126.5
*34	16.58	10.12	22.64	131.3

* Pipe-arch size included in charts

CHART 33

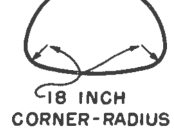




EXAMPLE

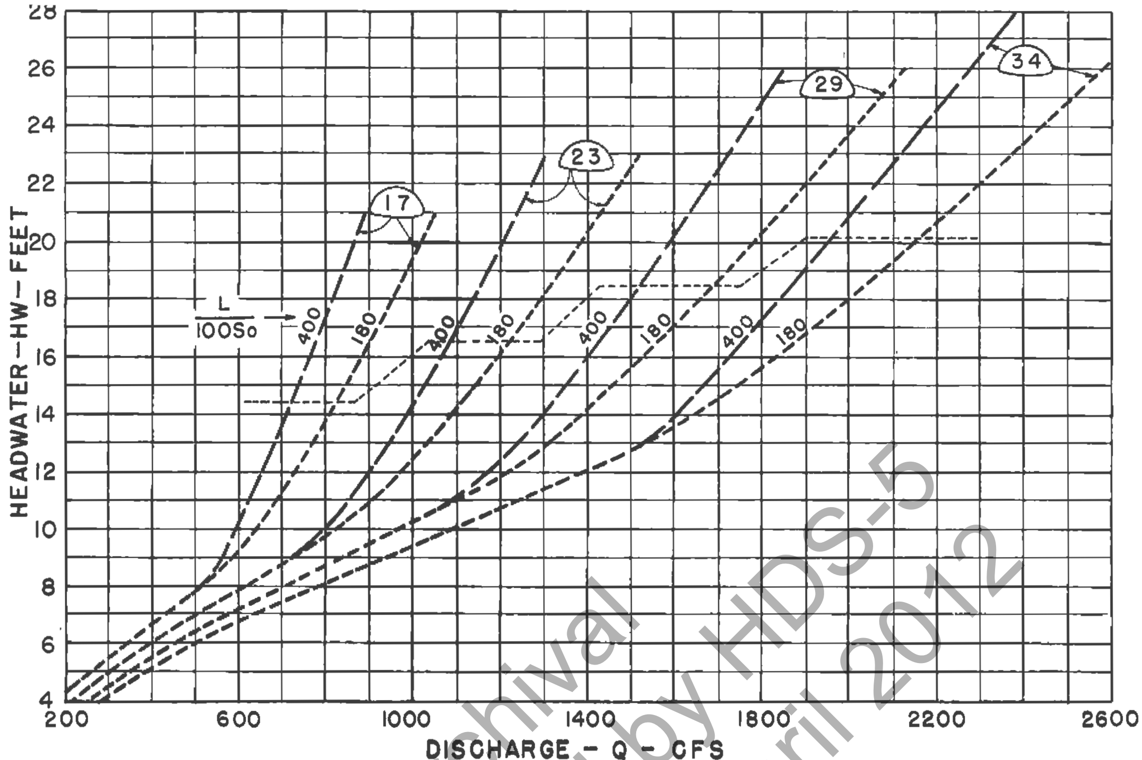
⊗ GIVEN:
320 CFS., AHW = 10.8 FT.
L = 158 FT., S_0 = 0.009

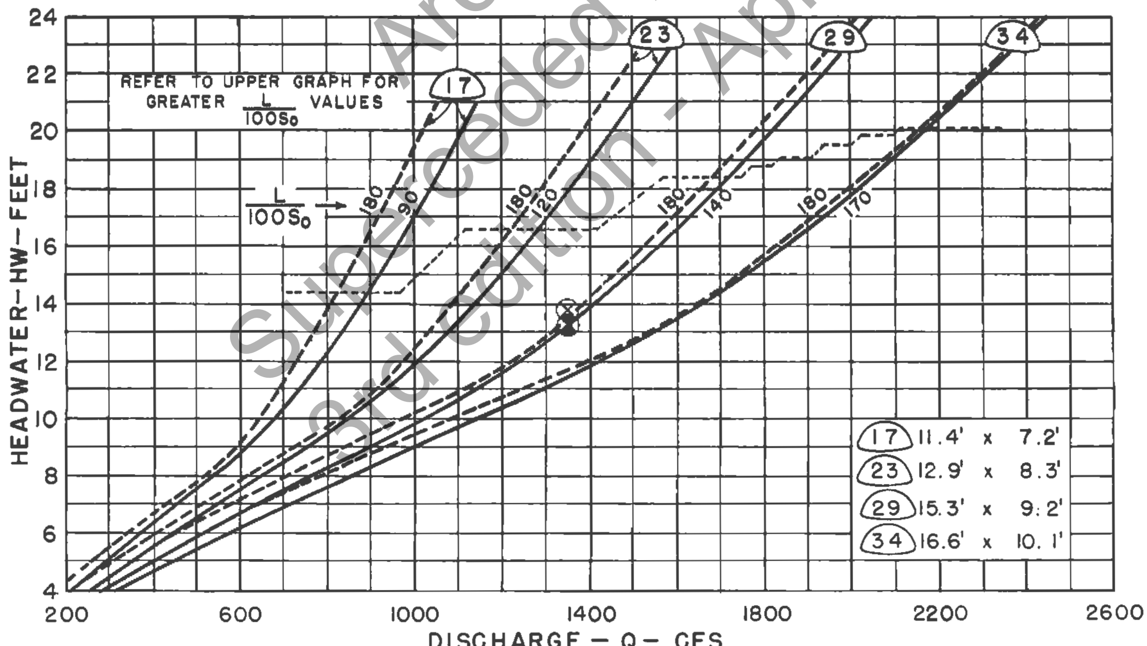
SELECT No. 6
7.7' x 5.4'
HW = 9.7 FT.



CULVERT CAPACITY STRUCTURAL PLATE CORR. METAL PIPE-ARCH PROJECTING ENTRANCE 4.6' TO 7.2' RISE

CHART 34

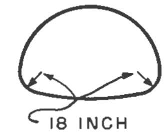




EXAMPLE

⊗ GIVEN:
1350 CFS., AHW = 13.8 FT.
L = 278 FT., S_0 = 0.022

⊗ SELECT No. 29
15.3' x 9.2'
HW = 13.2 FT.



CULVERT CAPACITY
STRUCTURAL PLATE
CORR. METAL PIPE-ARCH
PROJECTING ENTRANCE
7.2' TO 10.1' RISE

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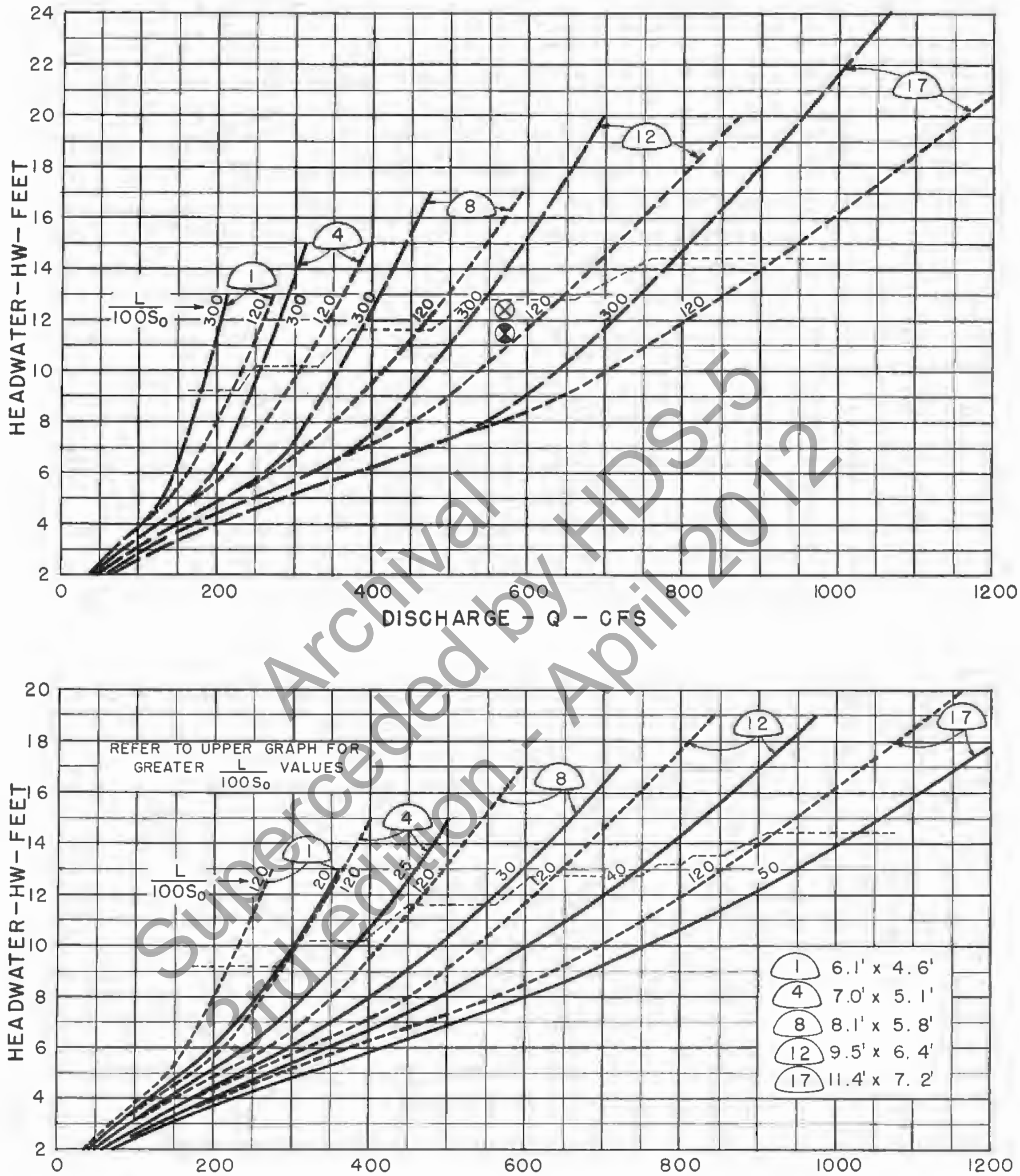
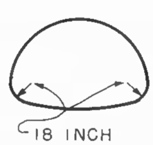
CHART 35



EXAMPLE

⊗ GIVEN:
570 CFS., AHW = 12.4 FT.
L = 110 FT., S = 0.007

SELECT No. 12
9.5' x 6.4'
HW = 11.5 FT.



18 INCH CORNER-RADIUS

CULVERT CAPACITY STRUCTURAL PLATE CORR. METAL PIPE-ARCH HEADWALL ENTRANCE 4.6' TO 7.2' RISE

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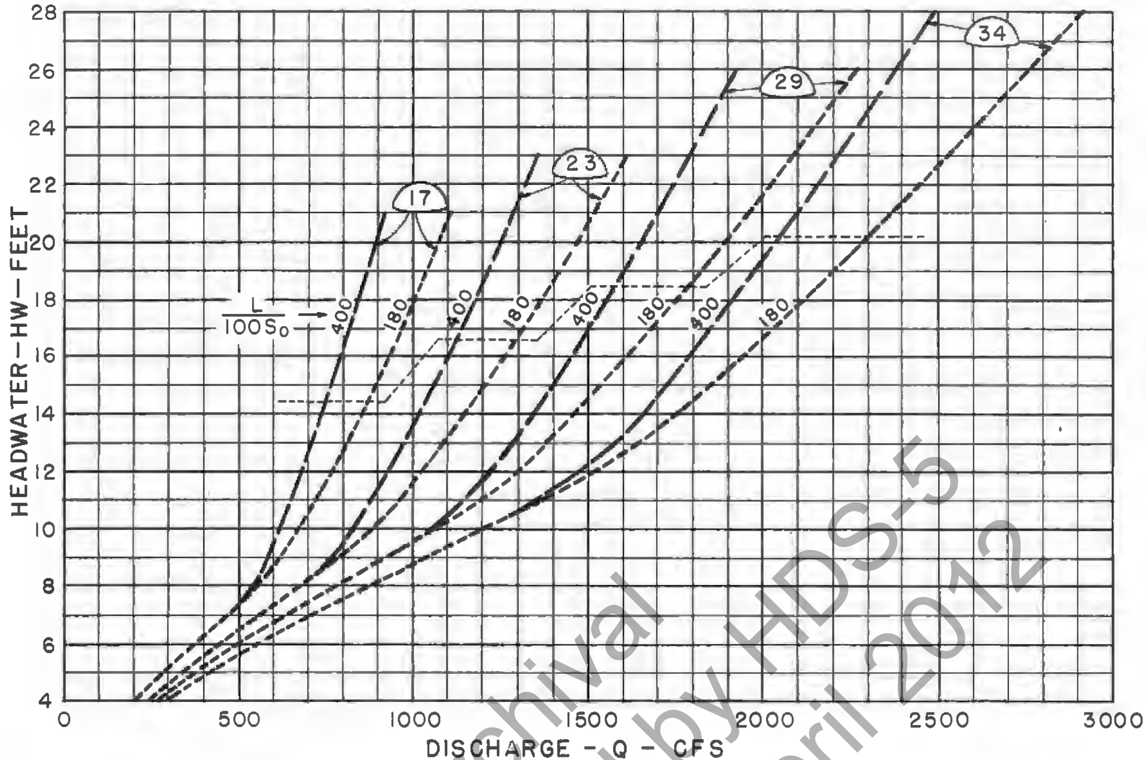
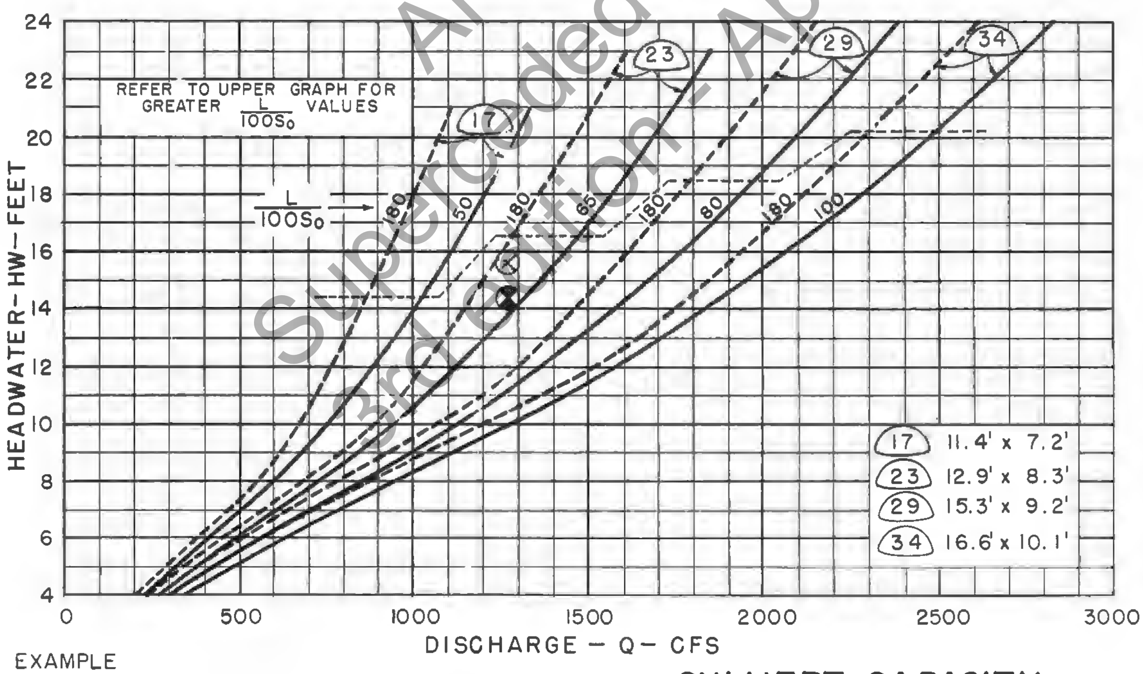
CHART 36

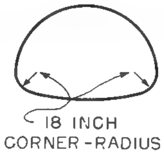




EXAMPLE

⊗ GIVEN:
1270 CFS., AHW = 15.6 FT.
L = 126 FT., S = 0.013

SELECT No. 23
12.9' x 8.3'
HW = 14.4 FT.
(OR 12.7' x 8.1' HW = 15.3 FT.)



CULVERT CAPACITY
STRUCTURAL PLATE
CORR. METAL PIPE-ARCH
HEADWALL ENTRANCE
7.2' TO 10.1' RISE

BUREAU OF PUBLIC ROADS JAN. 1963

VIII. APPENDIX

A. Hydraulic Principles and Compilation of Charts

A-1 Notation

A — Area of a cross-section of flow, in sq. ft.

A_b — Area of culvert barrel opening, in sq. ft.

AHW — The allowable headwater depth, in ft. above the culvert invert at the inlet. The depth corresponding to the upstream water surface elevation which the designer considers would be dangerous to exceed at a particular site. It is usually that elevation above which damage from flooding of adjacent property or the roadway would result in damage greater than some acceptable value.

B — Span of box culvert, or maximum horizontal dimension of an oval pipe or a pipe-arch, in ft.

D — Height of any culvert barrel opening, such as a box culvert, pipe, or pipe arch; also circular pipe diameter, in ft.

(Diameter of pipe is commonly used in inches, and for this reason the charts show pipe sizes in inches, although all calculations are made in foot units).

d_c — Critical depth, in ft. (in a culvert barrel, as used here). The depth of flow at which depth plus velocity head is a minimum. See critical depth charts in HEC No. 5.

HW — Depth of headwater at a culvert, in ft.

The difference in elevation from the culvert invert at the inlet to the water surface of the headwater pool required to discharge any given rate of flow through a culvert.

k_e — Entrance loss coefficient for full flow. Values in HEC No. 5.

L — Length of culvert, in ft., measured along the culvert axis and face-to-face of headwalls, or end-to-end of projecting pipe. Lengths of culverts with mitered ends are usually measured at one-half height.

n — Manning's roughness coefficient.

Q — Rate of flow through a single barrel culvert, or per barrel in a multiple culvert in cubic feet per second, cfs.

S_f — Head loss per ft. of length of culvert due to friction.

S_o — Slope of the invert of a culvert barrel with reference to a horizontal plane, in ft. per ft. of length; thus the sine of the slope angle.

$100\ S_o$ Invert slope in percent, or ft. of fall per 100 ft. of culvert length.

TW Tailwater depth, in ft.
The depth of flow in the outlet channel below a culvert, as referenced to the invert of the culvert at its outlet.

V Mean velocity of flow at any depth in feet per second, fps. That is, Q divided by cross-sectional area of flow A.

V_c Mean velocity of flow at critical depth, in fps.

$\frac{V^2}{2g}$ Velocity head, in ft.; kinetic energy of flow.

A-2 Inlet Control Flow

Inlet control flow is defined as flow through a culvert with the depth of headwater controlled by the inlet. The area, shape and edge detail of the inlet face affect the depth of headwater required. In inlet control, conditions of flow downstream and the roughness, length and slope of the culvert barrel do not affect the depth of headwater.

It is necessary to determine the discharge capacity of the various inlet types experimentally. The headwater-discharge curves of the culvert capacity charts are obtained by scaling up the data from laboratory tests of model culverts, principally those tests conducted for the Bureau of Public Roads by the National Bureau of Standards.

The capacity charts for each culvert type apply to a particular inlet type and inlet edge detail. A series of sizes of culverts of that type make up the inlet control (solid line) curves of each chart. These solid line curves apply only to inlet control flow, although a headwater curve for outlet control flow will correspond very closely to the inlet control curve if a length and slope combination are selected to give that result.

A-3 Outlet Control Flow

Outlet control flow is defined as culvert operation with headwater controlled by conditions at the culvert outlet. The depth of flow at the outlet, either critical depth or tailwater depth, plus velocity head, establishes the total head above the invert at the plane of the culvert outlet. Headwater depth, measured above the invert at the entrance, includes the total head at the outlet, resistance loss for flow in the barrel, and head loss at the entrance. In the calculation procedure it is necessary to subtract the difference in elevations between the inlet and outlet inverts in changing the measurement datum from the control section at the outlet to the inlet. In this way, the headwater depths for inlet and outlet control operation are measured from a common reference point at the inlet. Measurement of headwater from the same reference point is essential to the construction of the capacity charts containing both inlet and outlet control headwater curves.

The outlet control curves of the culvert capacity charts are based upon critical depth at the outlet end of the culvert barrel. Any greater depth of flow in the culvert barrel, as might be caused by depth of flow in the outlet channel, will result in an increase of total head at the outlet and an increase of headwater depth, p. 10-8.

To compute the outlet control curves of the capacity charts, a particular length of culvert was selected, and a slope less than critical slope was assigned. The values used for various culverts are given in detail in A-5 following. A discharge rate was selected, and critical depth computed. Then the usual step method for non-uniform flow calculations was used to compute the depth of flow throughout the length of the culvert. The depth at the inlet determines the mean velocity at this point, and thus the velocity head. The head loss at the entrance is $k_e V^2/2g$, where the entrance loss coefficient k_e is obtained from Table 1 of HEC No. 5. Headwater depth for each particular culvert and discharge rate is the sum of depth and velocity head at the inlet, plus entrance head loss. The fall of the barrel is taken into account in the backwater calculations.

A greater rate of flow, a longer culvert, or a flatter slope can result in the backwater profile, which begins at critical depth at the outlet, reaching the top of the culvert barrel downstream from the inlet. Upstream from this point the barrel flows full. The length of barrel flowing full is found by subtracting the length of free surface flow of the backwater profile from the total length of culvert. Above the free surface length, the hydraulic grade line rises from its position at the crown at a rate equal to the resistance slope for full flow minus the invert slope. Therefore, at the plane of the inlet the hydraulic grade line is above the inlet invert by the amount

$$h_1 = D + (S_f - S_o)\ (L - L_2)$$

where S_f is the friction slope in full flow and L_2 is the length of the backwater profile from outlet depth to the point of full flow. Headwater depth is obtained by adding velocity head and entrance loss to the height h_1 of the hydraulic grade line.

A pipe, or any culvert section with an arched soffit, will always involve some length of free surface flow at the outlet, however short it may be at the higher rates of flow. This occurs because critical depth is always less than the height of the barrel. Box culverts present a different condition.

Flat soffit cross-sections, such as box culverts, result in critical depth reaching the top of the box at a sufficient rate of discharge. The discharge rate for d_c equal to D is within the common range of use.

of box culverts for highway drainage. Therefore, the culvert capacity chart headwater curves for outlet control involve cases where the culvert flows full at the outlet.

Where a box culvert flows full at the outlet, the flow tends to spread as it leaves the culvert, and this results in a convex upward curvature of the surface as the flow turns downward. As a result, the pressure of the flow on the floor is decreased, and it would follow that the hydraulic grade line for flow in the barrel would pierce the plane of the outlet at some point below the top of the barrel. Ample experimental evidence is available to confirm this conclusion. However, highway culverts are normally used for a range of discharge rates, in proportion to size, that just reaches into those producing the conditions discussed above. A substantial lowering of the hydraulic grade line can occur only at discharge rates greater than can normally be permitted for highway culverts. In addition, the extent of lowering of the hydraulic grade line is reduced if the channel width is only moderately greater than the culvert span, because the flow spreads to a lesser degree.

For these reasons the chart headwater curves were computed on the basis of the hydraulic grade line at the outlet of box culverts being at the top of the barrel for discharge rates giving critical depth equal to or greater than box height. Headwater depth was calculated by the same method used for all culverts with a partial length of full flow, except that the total length was used to compute the rise of the hydraulic grade line.

A-4 Resistance Factors

In backwater profile calculations and in determining the friction slope in full flow, the Manning equation was used, with resistance factors appropriate for the culvert material in each case. The available experimental data were used to determine the Manning n for each material. The values of the following table were used to compute headwater curves for outlet control flow:

Concrete box culverts	n = 0.012
Concrete pipe culverts	n = 0.012

Standard (1/2") corrugated metal,
Unpaved, n varies with size:

Pipe Diam. in.	18	24	36	48	60	72	96
Pipe-Arch Span, in.		29	43	58	72	--	--
n	0.0247	.0245	.0240	.0237	.0234	.0231	.0228

Structural plate (2") corrugated metal,
Unpaved, n varies with size:

Pipe Diam. ft.	5	7	9	13	15
Pipe-Arch span, ft.	6.1	8.2	11.4	16.6	--
n	0.0328	.0320	.0314	.0305	.0302

The culvert capacity charts do not include curves for corrugated metal pipe or pipe-arch culverts with paved inverts. The curves are used for paved invert culverts by reducing the length of the culvert and using the charts with $L/100S_o$ computed for the reduced length (Sec. IV). This compensates for the smaller loss of head by resistance, because of a smoother surface for a part of the perimeter. The value of n varies with depth of flow, and was computed on the basis of n = 0.012 for the paved portion in making the trial computations to determine the length reduction to be used.

A-5 Chart Curves

A wide range of conditions of culvert operation will be included in the band of headwater depths between the inlet control curve for a particular size and kind of culvert and an outlet control curve for a long culvert of the same size at a small slope. Curves for culverts on a zero slope are not shown because highway culverts 200 ft. or more in length are usually not built on a level grade.

The lengths and slopes used in constructing the outlet control curves of the charts were selected with the objective of obtaining a wide range of use of the charts, while avoiding chart curves that are difficult to read. Difficulties in reading headwater will result if the outlet control curve crosses the curves of the next smaller size. Therefore, the lengths that could be used in the charts, at the flatter slopes, were limited. However, the culvert length used to construct the chart outlet control curve does not limit use of the charts to culverts of this particular length. The charts can be used for reliable determinations of size or headwater for culverts of other lengths and slopes by use of the culvert $L/100S_o$ ratio. The lengths and slopes used in the charts for the various culvert materials are given in the paragraphs below.

a. <u>Concrete Culverts</u>. Charts for concrete box and concrete pipe culverts include the inlet control curve for each size, and in most cases, an outlet control curve for a culvert 240 feet long on a 0.002 slope (0.2%). This length and slope give $L/100S_o$ equal to 1,200, and this appears in the charts. For examples, refer to Chart Nos. 1, 4, 11 and 13. For the larger sizes the length was increased to 300 feet, then 400 feet, and finally the outlet control curve was omitted since it plotted close to the inlet control curve.

b. <u>Standard Corrugated Metal Culverts</u>. The chart headwater curves for standard corrugated metal pipe and pipe-arch culverts involve a modification of the system used for concrete box and pipe culverts. The greater resistance losses in the rough pipe increases the depth of headwater above that for the same size concrete pipe in <u>outlet control</u> at the same discharge rate. Therefore, the culvert length used to construct curves must be decreased, or the slope increased, or both. Otherwise the outlet control curve for one size will cross the inlet control curve of the next smaller size.

The method used for circular pipe was to plot the curves in two separate graphs. The lower graph contains the inlet control curve and an outlet control curve for a culvert of intermediate length. Lengths of 120, 150 and 180 feet were used for the intermediate curves for such culverts, together with 0.8 or 0.6% slopes. The upper graph repeats this outlet control curve, and adds another curve, beginning at a length of 180 feet at 0.4% slope for small sizes, and increasing to 240 feet at 0.4%, and finally to 300 feet at 0.3% for the largest sizes. For examples, refer to Chart Nos. 19, 20 and 21.

The above arrangement of chart curves permits interpolation for intermediate sizes between those represented by the curves. (See sec. IV, cases 4, 5 and 6.) Because all sizes of standard corrugated metal pipe-arches (above the minimum used) are included in the capacity charts, interpolation is not necessary. Therefore, charts 25 to 28 combine the inlet control curve and two outlet control curves for a size in one graph. Separation of curves is obtained by combining sizes 1 and 3, 2 and 4, etc.

c. <u>Structural Plate Culverts</u>. The chart headwater curves for structural plate corrugated metal pipe and pipe-arches are presented in a two-graph system as for the standard circular C.M. pipe culverts. The resistance factors for structural plate (2" x 6" corrugation) are still greater than for the standard 1/2-inch corrugation depth, as is shown above. Therefore, it was found advisable to use a flow line slope of 0.010 (1.0%) for culverts operating in outlet control. The intermediate curve, for outlet control, is based on lengths of 120 feet, or 180 feet for larger sizes. The upper outlet control curve for each size is computed for a length of 300 feet, or 400 feet for the larger sizes.

A-6 Interpolation for Headwater

The capacity charts may be applied to a wide range of site conditions. This is accomplished by using the culvert L and S_o as an $L/100S_o$ value to read headwater by interpolating between the chart curves. Because greater length causes an increase of headwater, and a steeper invert slope decreases headwater, the quotient $L/100S_o$ serves to indicate the relative headwater depth for a given culvert size.

Application of interpolation to the chart curves, as described in sec. II C, requires that the inlet control curve be assigned an $L/100S_o$ number and treated as an outlet control curve. This is possible, even though length and slope do not affect headwater depth in inlet control, because there is also a combination of length and slope which gives an outlet control headwater curve generally coinciding with the inlet control curve over most of the discharge range. Using this particular length and slope, as found by solution of simultaneous equations for headwater, $L/100S_o$ was calculated and shown on each inlet control curve where an outlet control curve is also shown for that size. Therefore, the inlet control curve (solid line) is also an outlet control curve for use in interpolating for headwater depths between chart curves.

The interpolation method for determining headwater depth was discontinued where it was found that length and slope became relatively insignificant factors. This was found to occur with the larger size concrete culverts. At certain sizes, determined by check calculations, the charts for concrete box and concrete pipe culverts contain only the inlet control curve for each size, shown as a solid line (see Chart 5 or 12). This is satisfactory for application to a wide range of lengths and slopes because the culvert length giving an almost identical headwater curve, at one particular slope, was always greater than 300 feet, and for most sizes the length was greater than 400 feet.

The range of application of this single curve for a size was found by a series of trial calculations that established the highest $L/100S_o$ value that could be shown on the chart curve and still be used without significant error in reaching the chart. The criteria used was that the true headwater curve for any long culvert in outlet control, with $L/100S_o$ equal to or less than the chart value, would always be within 5 percent or less of the discharge shown by the chart curve at equal headwater depth, within the limit that headwater does not exceed 2D. This limit of twice the barrel height D, in feet, is shown in the charts by a dotted line in steps across the curves for the various sizes. Therefore, the single curve may be used to determine headwater depth, or capacity at a given headwater depth, with assurance that discharge capacity will not be over-estimated by more than 5 percent at points below the dotted stepped line, provided of course, that the culvert $L/100S_o$ does not exceed the chart value.

For culvert lengths no greater than were used to construct the charts, the accuracy of a headwater determination made from a capacity chart will be good, particularly at all headwater depths less than 2D, and within the limit that $L/100S_o$ does not exceed the value shown in the chart. The effect of various lengths and slopes upon headwater depth is examined further in Appendix B.

APPENDIX

VIII B. Accuracy of Chart Solutions

B-1 General Considerations

The culvert capacity charts provide one of the several methods that are available for making hydraulic calculations related to flow through highway culverts. The purpose of all these methods is to select a culvert of sufficient capacity to carry the design flood peak without requiring a headwater depth exceeding some limit fixed by site conditions. A culvert size is found to be satisfactory through some procedure for calculating the depth of headwater required to discharge the design flood. A number of trial solutions will give one or more culverts meeting the requirements.

No exact solution for a culvert design problem is possible, in view of the fact that the flood magnitude must be estimated. The selection of an acceptable probability of occurrence of a greater flood or an average frequency, does not guarantee that the flood rate estimate is correct. One could not be certain, for example, that the flood of 50-year average recurrence interval on a certain stream was 300 cfs., and was not in fact 270 or 330 cfs. The difference in headwater depth would be minus or plus one foot, or less, from that required for a discharge rate of 300 cfs.

In routine application of any hydraulic design method for determining headwater depth, a finding of headwater below the allowable limit would indicate an acceptable culvert, and headwater above the limit would be cause for rejection of consideration of that culvert size. However, it may be noted from the example cited above that a culvert that would give headwater one foot or less over the limit at 330 cfs would carry 300 cfs within the headwater limit. The difference of ten percent in capacity at the design headwater limit is not necessarily a serious factor, in view of the difficulties one faces in estimating the magnitude of future floods.

The points mentioned above are major considerations in culvert design. However, the accuracy of the capacity charts will be considered here from the standpoint of the reliability of a headwater determination made from the chart for a certain size of culvert at a specific discharge rate.

The capacity charts are used to determine headwater depth for a given culvert and rate of flow. In this determination the $L/100S_o$ ratio for the particular culvert is used to interpolate between the chart curves, and in some cases to read headwater on a curve. There is no implication that $L/100S_o$, in itself, may be used to calculate the depth of headwater. This ratio is useful only for application to charts containing headwater curves plotted for a particular size of culvert of one type, including an outlet control curve for a particular culvert length and slope. The $L/100S_o$ ratios must be given for the chart curves. However, the $L/100S_o$ ratio is a logical indicator for headwater depth because greater length increases headwater and greater slope decreases it, at least down to the slope limit for beginning of inlet control operation. Interpolation for headwater depth between an inlet control curve and an outlet control curve of a chart means that the inlet control curve is actually used as if it were an outlet control case. This is satisfactory procedure, as was explained in Appendix A-6.

The accuracy of a headwater depth read from a culvert capacity chart on the basis of the $L/100S_o$ ratio varies with the depth of headwater relative to the barrel height D. If inlet control is certain because of the low $L/100S_o$ ratio, then headwater depth read on the inlet control curve is exact over the entire range of headwater, provided, of course, that the chart applies to the culvert inlet type. However, if $L/100S_o$ requires interpolation between chart curves because it exceeds the value given on the inlet control curve of the chart, then the relative depth of headwater is a significant factor in regard to accuracy of results.

The length of a culvert may vary over a wide range for any given $L/100S_o$ ratio. Culvert lengths exceeding those used to construct the charts (Appendix A-5) are the principal factor causing errors in headwater depth as read from a chart on the basis of $L/100S_o$. Length of the culvert becomes a more significant factor as headwater depth increases. For a given culvert, higher headwater depths are caused by greater discharge rates, and larger rates of flow result in a greater rate of head loss from resistance loss per foot of length. The unit rate of loss varies as the square of the discharge rate. Therefore, culvert length will cause larger relative increases in headwater at greater discharge rates, and thus at greater depths of headwater.

B-2 Effects of Relative Headwater Depths

The degree of reliability of a headwater depth determined from a culvert capacity chart may be placed in one of three general classifications. It should be understood that errors in the headwater determination can occur only with outlet control flow. However, the charts are used without requiring any procedure for a fully reliable determination of whether the control section is at the inlet or the outlet. The omission of such difficult procedures is one of the principal advantages of the culvert capacity chart method.

Because many culvert length and slope combinations do not show beyond doubt that inlet control will govern, the degree of reliability of headwater read from a chart will be considered as a general problem applicable to all cases. From this standpoint, the reliability of a headwater depth read from a chart on the basis of $L/100S_o$ can be evaluated in regard to the relative depth of headwater as follows:

HW < 1.3D	Good accuracy, even when read above the chart curves by extrapolating up to 1.5 times the upper curve $L/100S_o$.
HW 1.3 to 2 D	Good accuracy, if $L/100S_o$ is within the chart limit.
HW > 2 D	HW may deviate considerably from the chart solution for certain lengths and slopes.

The accuracy of the capacity charts within the above ranges of headwater is discussed more fully in the following paragraphs.

a. <u>HW less than 1.3 D</u>. Headwater depths less than 1.3 D permit considerable latitude in use of the charts. In plotting headwater curves with a wide range of lengths and slopes, it was found that the curves were closely spaced until headwater submerges the inlet. At greater headwaters, culverts longer and steeper than used to construct the chart, were found to give headwater curves diverging from the chart curves. A typical illustration is given in Fig. 2, page 10-86, which shows headwater curves for 48-inch CMP culverts of several different lengths and slopes.

   Fig. 2 shows that headwater curves for culverts of various lengths all follow an almost identical pattern until headwater reaches some value in the range of 1.25 to nearly 1.5 D. These are cases where the culvert slope is small so that outlet control occurs even at small discharge rates. The limit for a restricted effect of length upon headwater has been defined as 1.3 D for design purposes.

   This 1.3 D value cannot be an exact headwater figure because it is affected by entrance loss, resistance factor, and length and slope of the culvert. However, 1.3 D serves well as a depth marking the end of a headwater zone where length and slope have limited effect; and therefore, the chart curves may be extrapolated to find HW for $L/100S_o$ values beyond the maximum given in the chart if the actual HW is determined to be less than 1.3 D. Note the example given in sec. II C.

b. <u>HW 1.3 D to 2 D</u>. For headwater depths in the range of 1.3 D to 2 D, the possible spread of headwater curves for culverts of lengths other than were used to construct the charts rules out the use of headwaters above those acquired from the $L/100S_o$ value shown on the higher chart curve for each size. The cause for headwater curves deviating from the pattern of the chart curves, and the degree of deviation, may best be explained be consideration of an example.

   Except for the one case of a zero slope, the lengths and slopes for the headwater curves shown on Fig. 2 were selected to give

$L/100S_o$ ratios of either 300 or 600, the values shown in Chart No. 20 for this particular size and entrance type. For comparison, the chart curves are also shown in Fig. 2 by heavy lines. The chart outlet control curves represent culverts 120 feet long at 0.4 percent slope and 240 feet long at the same slope.

It may be noted that there is a tendency for the headwater curves for culverts with $L/100S_o$ of 600 to group around the chart curve of the same value, and a similar tendency for culverts with $L/100S_o$ of 300. A closer examination will show that headwater curves of equal $L/100S_o$ go above the chart curves if L is greater than for the chart curve, and are displaced to the right if L is less. For example, the headwater curve for a culvert 120 ft. long and at 0.002 slope ($L/100S_o$ = 600) lies very close to the chart curve for $L/100S_o$ equal to 300. In fact the curves are parallel, and offset by the difference of fall of the inverts, that is, by 0.24 ft.

In applications to culvert design, this means that the actual capacity of a culvert of given $L/100S_o$ will be greater than shown by the chart curve at a certain headwater level if the actual headwater curve position is to the right of the chart curve. Conversely, the actual capacity is less than indicated if the actual headwater curve would lie to the left of, or above, the chart curve.

The first condition results in a conservative, and therefore acceptable, choice of culvert size. As may be seen in Fig. 2, the under-estimation of capacity is negligible for headwater depths less than 5 ft., and may be as large as 10 percent or more at 8 ft. of headwater. For concrete culverts, where the outlet control curve of the chart, for a still longer culvert, lies much closer to the inlet control curve, the degree of possible under-estimation of capacity becomes much smaller.

Therefore, the design problems of concern will be those in which the actual headwater curve lies above the chart curve. In Fig. 2 it will be seen that this condition occurs for headwater depths above 1.5 D. This is generally the condition that exists in all charts, but identification of a particular minimum level is not required in application of the general design procedure. A more essential need is to define an upper headwater level, below which the possible error of <u>over-estimation</u> of capacity is sufficiently small as to be acceptable.

It is obvious that the spread of outlet control headwater curves increases with discharge, and thus with headwater depth. Therefore, a headwater limit, below which the errors will be acceptably small, may be found by trial calculations for headwater curves for a variety of culvert lengths, with slopes

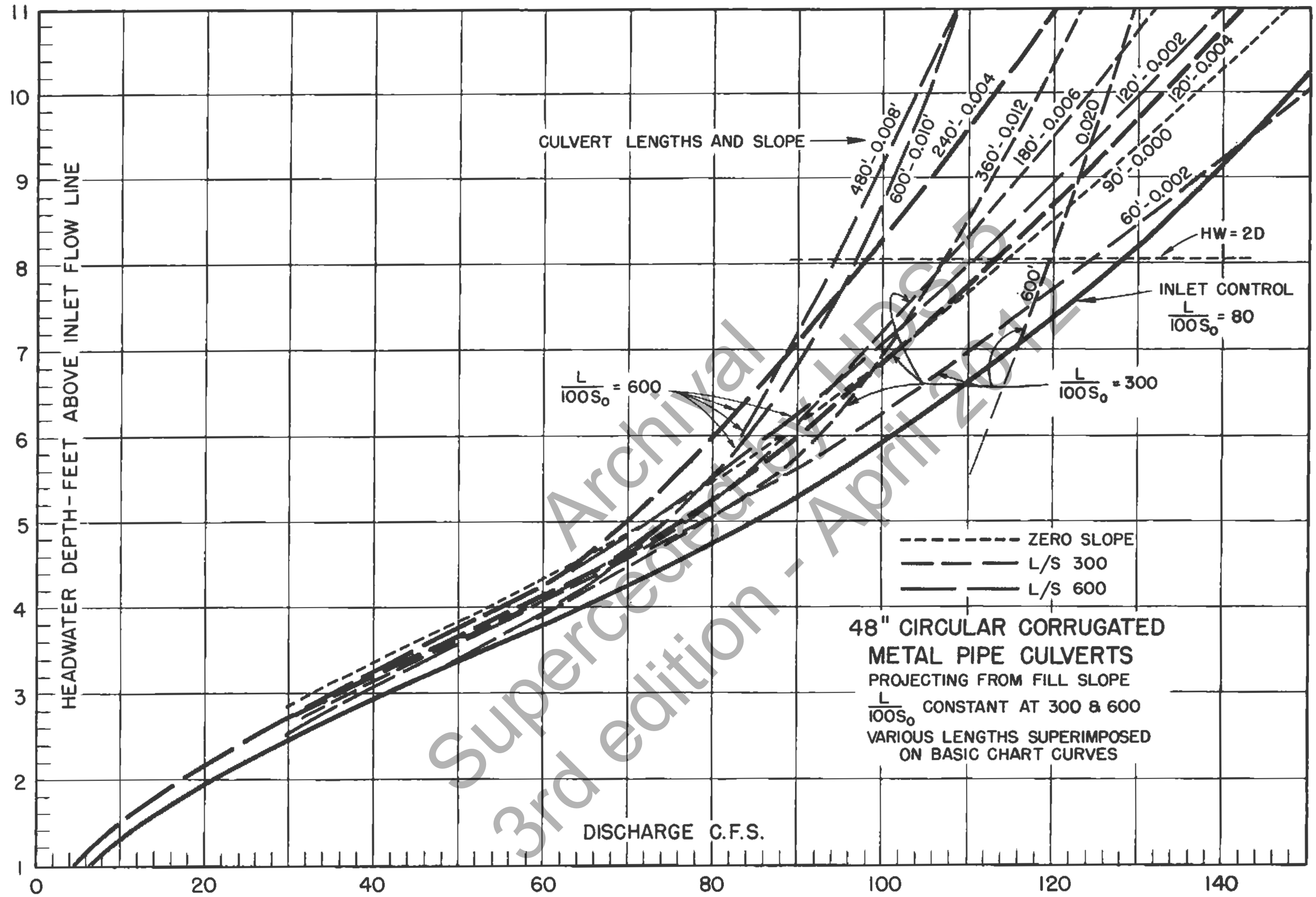

CULVERT LENGTHS AND SLOPE
480'-0.008'
600'-0.010'
240'-0.004
360'-0.012
180'-0.006
0.020
120'-0.002
120'-0.004
90'-0.000
60'-0.002
HW = 2D
INLET CONTROL
$\frac{L}{100S_0}$ = 80
$\frac{L}{100S_0}$ = 600
$\frac{L}{100S_0}$ = 300
600'
ZERO SLOPE
L/S 300
L/S 600
48" CIRCULAR CORRUGATED
METAL PIPE CULVERTS
PROJECTING FROM FILL SLOPE
$\frac{L}{100S_0}$ CONSTANT AT 300 & 600
VARIOUS LENGTHS SUPERIMPOSED
ON BASIC CHART CURVES
HEADWATER DEPTH-FEET ABOVE INLET FLOW LINE
DISCHARGE C.F.S.
1
2
3
4
5
6
7
8
9
10
11
0
20
40
60
80
100
120
140

Figure 2

selected to keep $L/100S_o$ equal to or less than a chart curve value.

The above procedure was applied to many of the sizes included in the culvert capacity charts. A headwater limit of 2 D was selected because, at that headwater depth, it was found that the over-estimation of discharge capacity would not exceed 5 or 6 percent if the culvert $L/100S_o$ was no greater than that shown on the outlet control curve of the chart.

Similar trial calculations established that the charts for culvert sizes shown only by a single solid line curve, the inlet control curve, may be used with confidence for culverts with $L/100S_o$ within the chart limit and headwater below 2 D.

c. <u>HW greater than 2 D</u>. Headwater depths greater than 2 D define a zone where certain culvert lengths will give headwater-discharge curves deviating considerably from the pattern shown by the capacity chart curves. As illustrated in Fig. 2, the headwater curves for various culverts, with $L/100S_o$ the same as for the culverts used to plot the chart curves, actually do depart considerably from these chart curves in the range of headwater depths above twice the culvert height. The actual headwater depth for a specific case may be either greater or less than would be read from the chart by use of the general method based on $L/100S_o$. The possibility of error and its magnitude increase in relation to the difference between the culvert length and the length used in construction of the charts.

The headwater curve for a 600-ft. long culvert at 0.02 slope ($L/100S_o = 300$) in Fig. 2 illustrates a condition encountered with longer culverts. That part of the curve below the inlet control curve is shown as a lightweight dashed line to signify that it is not a valid representation of headwater in this range.

The following will explain the factors involved in this example. Critical slope for a culvert barrel increases with increasing discharge rate. Therefore, a certain slope, found to be less than critical at the design discharge, may still be greater than critical at small or intermediate discharge rates, so that on a rising flood hydrograph the culvert will begin operating with inlet control. That is, the headwater depth will follow the solid line curve of the capacity chart, as is shown for the 600-ft. culvert at 2% slope in Fig. 2. At a discharge rate of 116 cfs. the operation changes to outlet control with a steeply rising headwater curve. This is a typical condition, and further evidence of the necessity for checking headwater determinations where HW is greater than 2 D. For a discharge of 116 cfs. critical depth in a 48-inch pipe is 3.3 ft. or 0.82 D, and the friction slope for flow at either 0.82 D or full flow is 0.022 ft. per ft., or more than the barrel slope in this case. Therefore, the free surface flow condition of inlet control cannot be maintained at greater discharge rates, with the result that the culvert operation will convert to outlet control.

From Fig. 2 it is evident that headwater depth read from the culvert capacity chart for a 600-ft. culvert at 2% slope, i.e., $L/100S_o$ = 300, will be correct at only one point, that for Q = 123 cfs. For all lesser discharge rates headwater will be less than read on the chart curve for $L/100S_o$ of 300, and for all greater discharge rates the actual headwater depth will be greater than read from the chart.

Below a headwater of 2 D, the error is on the safe side, in that the capacity of the culvert is under-estimated at all headwater depths below 9 ft. for this particular example. These situations can be recognized and steps taken to obtain a more correct solution for headwater depth if it is considered worthwhile.

The significant factor in all such cases is that a long culvert is involved. The chart curve for 300 $L/100S_o$ is computed for L = 180 ft. and S_o = 0.006, as explained in Appendix A-5. The 600-ft. long culvert of the example far exceeds all lengths used in the chart, where the usual length for the upper curve of $L/100S_o$ of 600 was 240 ft., and only 180 ft. was used for the intermediate curve. Where long culverts are involved, as compared to lengths used to construct the charts, the procedure of HEC No. 5 should be used.

In application of the capacity charts to culvert design, it is not normally necessary to use the nomographs to check headwater depth for these long culverts, provided the indicated headwater does not exceed 2 D. For the case considered above, the actual capacity of the 48-inch corrugated metal culvert can be as much as 14% greater than read on the chart curve for 300 $L/100S_o$, at HW of 7.1 ft. Also, the maximum error in headwater, read at 8 ft., would be 1.2 feet.

The above is admittedly an extreme case, but even so the next smaller culvert size (42-in.) would be entirely unacceptable in most cases because of excessive headwater depth. The fact that an alternate selection of a smaller size culvert cannot be made in the situations where the capacity charts underestimate the discharge capacity (or over-estimate headwater) is a strong argument against being concerned with this type of error in use of the charts. The problems of real concern are only those where headwater depth read from the chart may be less than the real value. Such situations, with significant degrees of error, occur only for headwater depths greater than 2 D.

In order to obtain satisfactory accuracy in the determination of headwater from a culvert capacity chart, the instructions specify (sec. III) that headwater should be below 2 D, otherwise the headwater should always be checked by use of HEC No. 5. It is essential that this check also be made for cases involving culvert sizes shown by only the inlet control curve. The $L/100S_o$ ratio shown on these curves is sufficiently large to include possible long lengths which can result in errors in the range of headwater depths exceeding twice the culvert opening height.

B-3 Culverts on Level Grade

The instructions for use of the charts provide for selection of culvert size if the culvert invert is on a zero slope, so that $L/100S_o$ cannot be computed. Fig. 2 includes the headwater curve for a culvert 90 ft. long at zero slope, obtained from backwater profile calculations It will be noted that a zero slope has no marked effect upon headwater depth for a relatively short culvert (L/D equals 22.5), even for a corrugated metal culvert with a relatively high resistance factor.

Instructions for use of the charts (sec. IV, case 7) can be tested for the culvert included in Fig. 2. Assigning a fictitious slope of 0.004, $L/100S_o$ is 225 and $L \times S_o$ equals 0.36 ft. Headwater obtained by interpolation from the chart and addition of the fictitious fall of the invert is compared to a precise calculation in the table below.

Q	Chart HW 225 $L/100S_o$	HW + 0.36'	Actual HW
50	3.58	3.94	3.84
80	5.08	5.44	5.46
110	7.36	7.72	7.72

APPENDIX

VIII C. Chart Listing

The Culvert Capacity Charts are arranged in groups applying to each culvert material and shape. Two sets of charts are included, one for each of two entrance types used with that kind of culvert. The following charts are included.

Charts	Culvert Type	Entrance	Size Range
1 to 5	Concrete Box	Headwall	Rectangles 1.5 to 6 ft. high; and
6 to 10	Concrete Box	Wingwall	Square 1.5 to 12 ft.
11, 12	Concrete Pipe, Circular	Square-Edged	18 to 180 inch Diameter
13, 14	Concrete Pipe, Circular	Groove-Edged	
15	Concrete Pipe, Oval, long axis horizontal	Square-Edged	23" x 14" to 91" x 58"
16	Same	Groove-Edged	
17	Concrete Pipe, Oval, long axis vertical	Square-Edged	14" x 23" to 53" x 83"
18	Same	Groove-Edged	
19 to 21	Standard (1/2") C.M. Pipe	Projecting	18 to 120 inch Diameter
22 to 24	Standard (1/2") C.M. Pipe	Headwall	
25, 26	Std. (1/2") C.M. Pipe-Arch	Projecting	25" x 16" to 72" x 44"
27, 28	Std. (1/2") C.M. Pipe-Arch	Headwall	
29, 30	Structural Plate (2") C.M. Pipe, Circular	Projecting	60 to 180 inch Diameter
31, 32	Same	Headwall	
33, 34	Structural Plate (2") C.M. Pipe-Arch*	Projecting	6.1' Span by 4.6' High, to
35, 36	Same	Headwall	16.6' Span by 10.1' High

*18-inch corner radius; these charts do not include the 31-inch corner radius Pipe-Arches.