COMPARISON OF ENERGY CULVERTS TO STANDARD THREE CELL BOX CULVERTS

A Thesis

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by

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ABSTRACT

This hydraulic model study was undertaken to compare the hydraulic characteristics of the energy culvert with those of a conventional three cell box culvert.

The energy culvert is basically a chute with a lowered floor. The approach walls to the chute converge gradually as the floor drops with the exit walls diverging as the floor rises.

The flow pattern in the energy culvert involved converging a flow of water and increasing the specific energy by setting the chute floor below the normal channel bed to produce increased velocities. With the larger velocities, a smaller cross sectional area than a comparable three cell box culvert was required. At the outlet from the culvert, the velocities were reduced sufficiently to prevent erosion in the downstream channel by providing a reverse curve ramp to raise the water back to normal channel bed elevation. This reverse curve ramp reduced the high velocities rather quickly and minimized the turbulence when the lateral distribution of the water occurred. The distinct advantage of this design is that the discharge may be doubled with only a small corresponding increase in head water levels.

It was found that the energy culvert was significantly more efficient hydraulically, and capable of passing a larger range of discharges under high tailwater conditions.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the Water Resources Department of Civil Engineering at the University of Manitoba for the assistance of two undergraduate students for six weeks during testing. Mr. H.E. Cowley, Assistant Bridge Engineer for the Manitoba Department of Highway's Bridge Branch also aided in discussing the three cell box culvert and bridges in general. The guidance of Prof. V.J. Galay, the author's supervisor, was appreciated throughout this study.

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LIST OF SYMBOLS

L	length [feet]
E	energy [feet]
w	width of chute [feet]
n	Manning's roughness coefficient
y_n	normal depth of flow [feet]
cfs	cubic feet per second
fps	feet per second
Q	discharge [cfs]
q	unit discharge [cfs/ft. of width]
$\frac{V^2}{2g}$	velocity head [feet]
z	distance from datum to culvert floor [feet]
F_r	Froude number
P.T.H.	Provincial Trunk Highway
Prov. Rd.	Provincial Road

CHAPTER I

INTRODUCTION

a) Statement of problem

The present design of culverts generally necessitates the use of multiple barrel culverts or a bridge where a low head is essential. With the present culvert design, a large head is sometimes required to pass an unexpected or much larger than design discharge. In cases such as these, the road is occasionally overtopped and may be washed out. It would be advantageous to avoid this problem and find a more efficient manner to pass a large volume of water under a road with a low allowable difference in water levels. It would also be very convenient if the structure could pass a much larger flow with only a small increase in head water levels. This was found to be possible in an energy culvert which uses the type of behavior concept of a constant total energy and a varying specific energy.

b) Previous work

Previous work in the design of an energy culvert has been carried out by Dr. G.R. McKay of the University of Queensland, Brisbane, Australia (REFERENCE 1). Several culverts utilizing this concept have now been constructed in Queensland.

c) Limit of undertaking

This study was limited to the testing of three hydraulic models. The first model was a replica of a three cell culvert design presently being used on all major roads in the province of Manitoba. The cells in each culvert vary from 3' to 12' square with the capacity of the structures being up to 3000 cfs. The model tested had three 7' x 7' cells with the total rated capacity of the culvert being 885 cfs. Two other models were built to verify the theory of the energy culvert. Each of these two models had different chute widths to further examine the hydraulic characteristics of an energy culvert.

The testing of these models was limited to flows up to a maximum of 2100 cfs and to a high and low tailwater level corresponding to two greatly different values of Manning's roughness coefficient.

d) Justification of topic

The possible substitution of a bank of 6 or 8 corrugated metal pipes, a large standard three cell culvert or a small bridge by a more efficient energy culvert, justifies the development and testing of a new culvert design that in theory appears to be more efficient than present designs. There is some indication that there may be a financial saving in using an energy culvert. However, the main consideration would be the potential reduction of the hazard created by the road being overtopped.

e) Preview

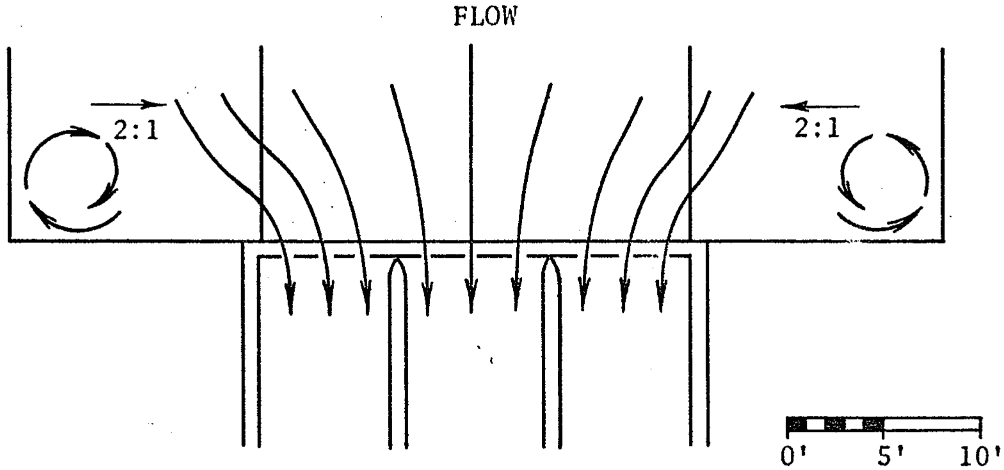
In this thesis the theory for the energy culvert will be presented. This theory will be verified from studies of three hydraulic models and a seties of comparative tests. It will be shown that the idea of converging a flow of water, increasing the specific energy, then decreasing the specific energy and diverging the flow was more efficient within givenenergy limits than the conventional three cell box culvert theory.

CHAPTER II

THEORY

a) The hydraulic design of a three cell culvert

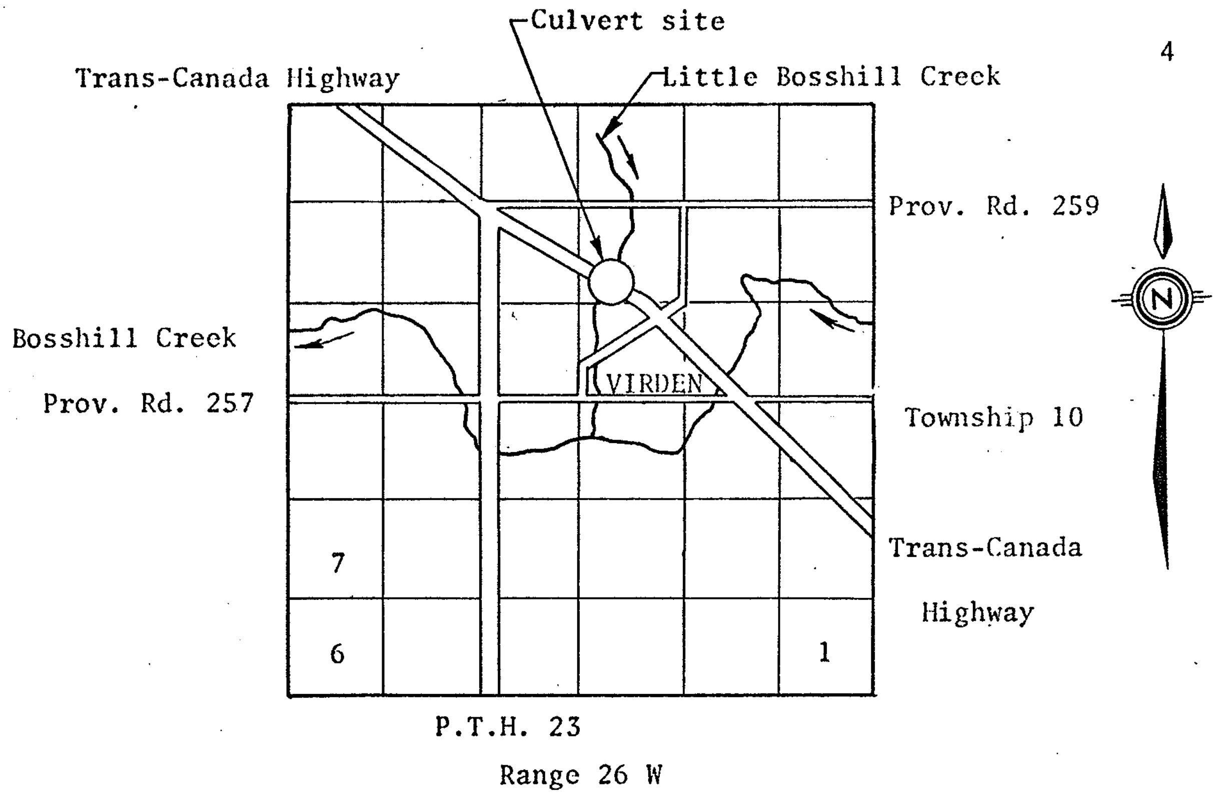
In the design of various types of conduits, the United States Bureau of Public Roads nomographs (FIGURE 1,APPENDIX A) are used as a fast graphical solution for calculating the discharge capacity of a culvert. The rated capacity of the three cell culvert was based on the capacity of a single cell, which was multiplied by three. The field observations indicates that more water would pass through the centre cell than through the two outside cells (FIGURE 2-1) because of the contraction effects producing a higher velocity in the enetre cell. When the uneven flow distribution was considered, it was thought that the average discharge would be close to that predicted by the nomograph.



Flow pattern in 3 cell culvert

FIGURE 2-1

For comparison purposes, a model of an actual three cell culvert was built. A model was made from an existing culvert FIGURE 5, APPENDIX A), located on the Little Bosshill Creek where it crossed the Trans-Canada Highway at Virden, Manitoba as seen in FIGURE 2-2. The difference in elevation between the crown of the road (1445.6') and the maximum headwater level (1442.7') allowed a head factor of 2.9' before the road was overtopped.

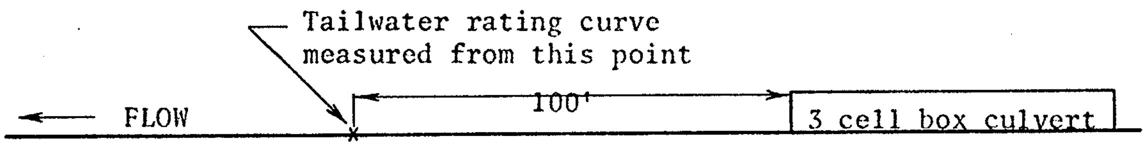


Location plan of culvert site

FIGURE 2-2

In the design of the field structure, the headwater elevation was established at 1442.7' by the Highway Department. The design head difference of 1.0' between the headwater and tailwater elevations was subtracted from 1442.7' resulting in a tailwater elevation of 1441.7'. The head difference was set at 1.0' partly because of the very low head limitation and also because it is a standard design requirement by the Water Control Department.

In the Little Bosshill Creek, the Manning's roughness factor was then calculated to be 0.0545, which was supported by field observations of the creek. The tailwater rating curve was calculated from a point about 100' downstream from the structure at elevation 1433.13' (FIGURE 2-3). The rating curve was calculated for several values of channel roughness as seen in FIGURE 2-4. The roughness of finished concrete for the structure was assumed to be 0.012 for design purposes.



Tailwater rating curve location

FIGURE 2-3

From the Bureau of Public Roads nomograph (FIGURE 1, APPENDIX A), a table of theoretical discharges for the actual three cell culvert for a given head difference was prepared (TABLE 1, APPENDIX B). The expected discharge at 1.0' head was 885 cfs while the 2% design discharge was 825 cfs. The three cell culvert model was built to duplicate the hydraulic characteristics mentioned previously, as closely as laboratory conditions would permit.

b) Energy culvert theory

i) Energy equation application

The design of the energy culvert (FIGURE 2-5) was based on the application of the energy equation which was derived from FIGURE 2-6.

$$E = \frac{V^2}{2g} + y + z \qquad (1)$$

For this equation to apply, the following assumptions were made for a two dimensional flow system.

1) steady flow
2) irrotational flow
3) no velocity variation across the cross section
4) incompressible flow
5) no energy added or subtracted from the system

For use in the design of an energy culvert, substitute the unit discharge $q = Q/w$ and equation (1) becomes a modified energy equation.

$$E = \frac{q^2}{2g\,y^2} + y + z \qquad (2)$$

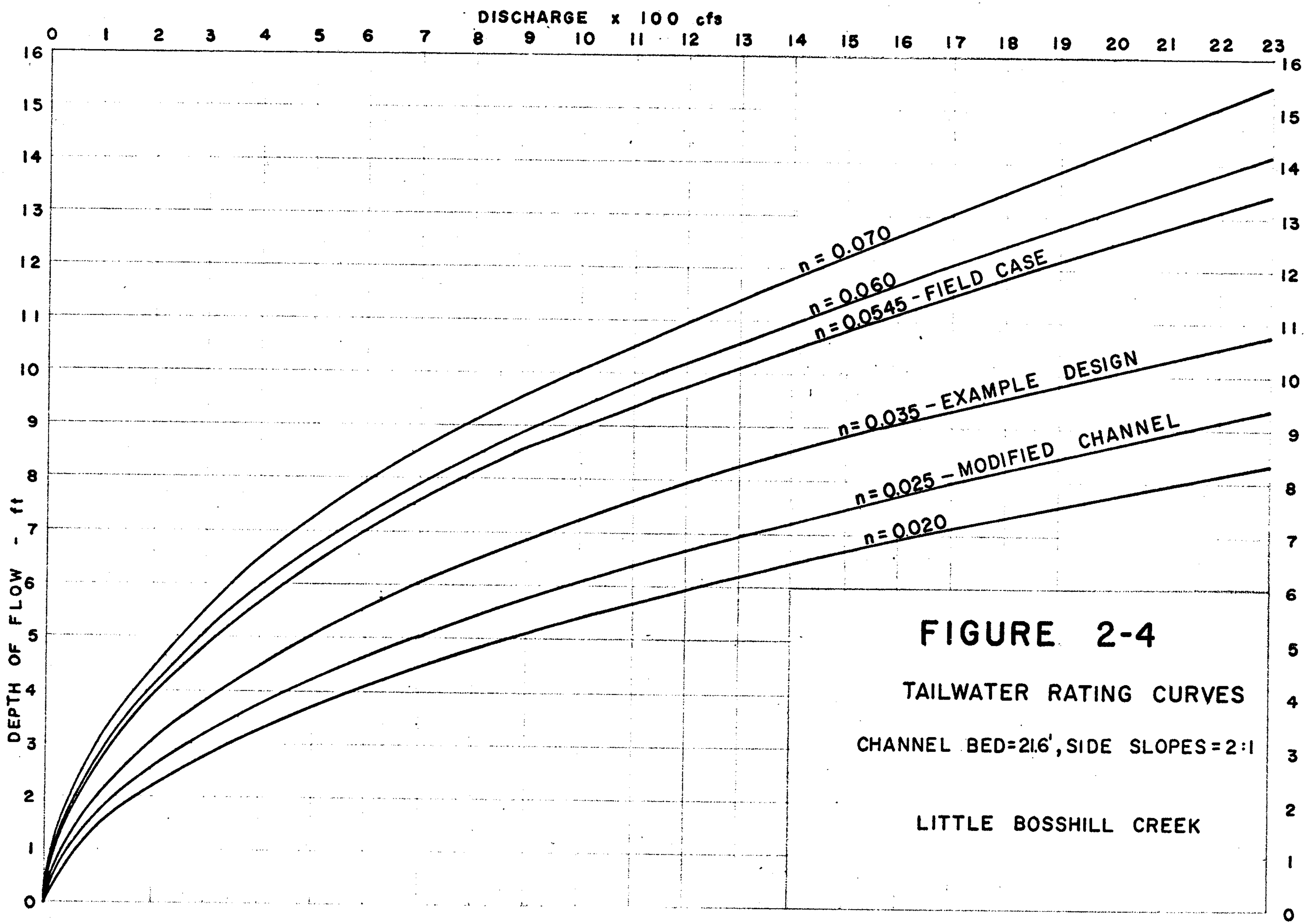
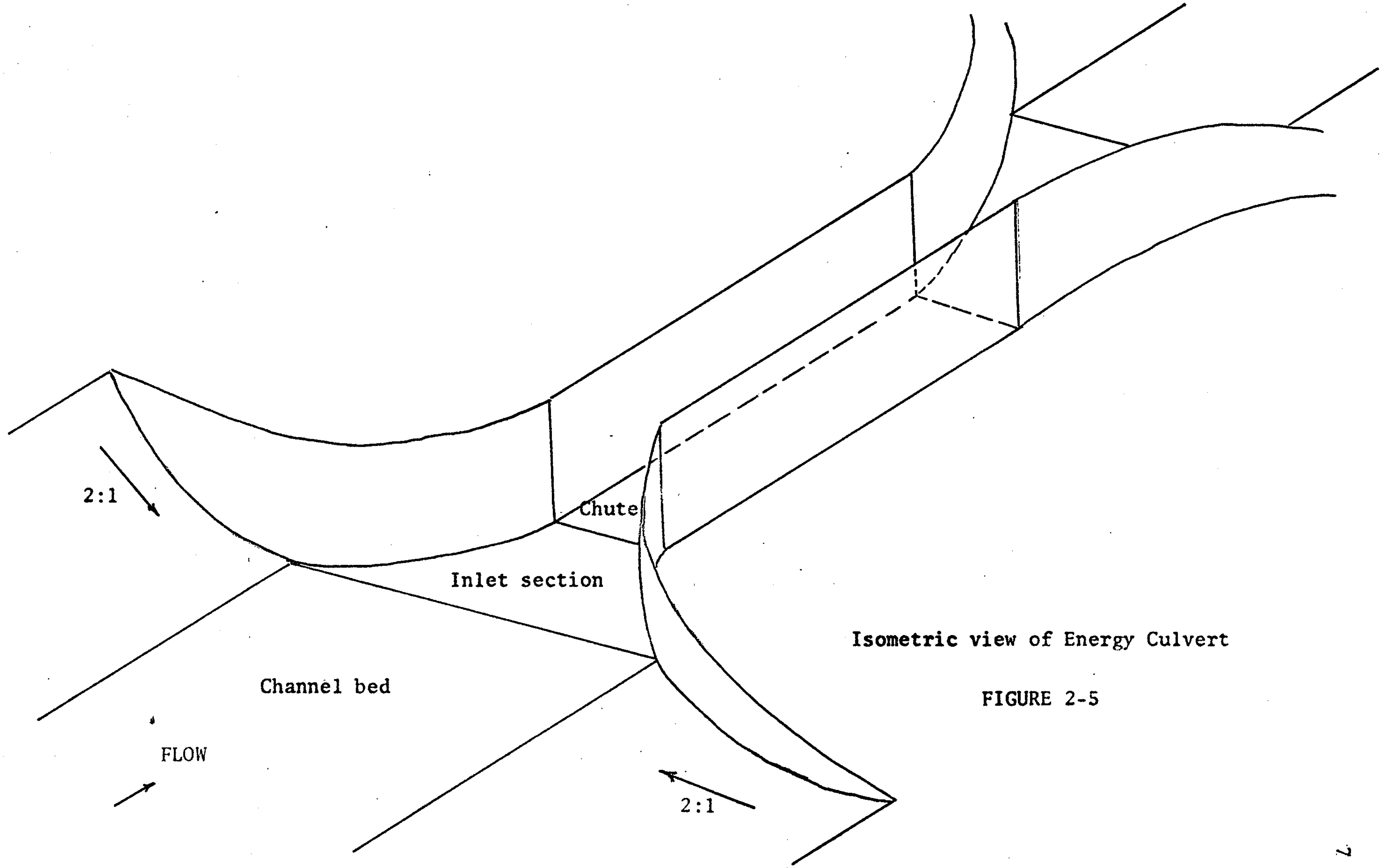


FIGURE 2-4

TAILWATER RATING CURVES

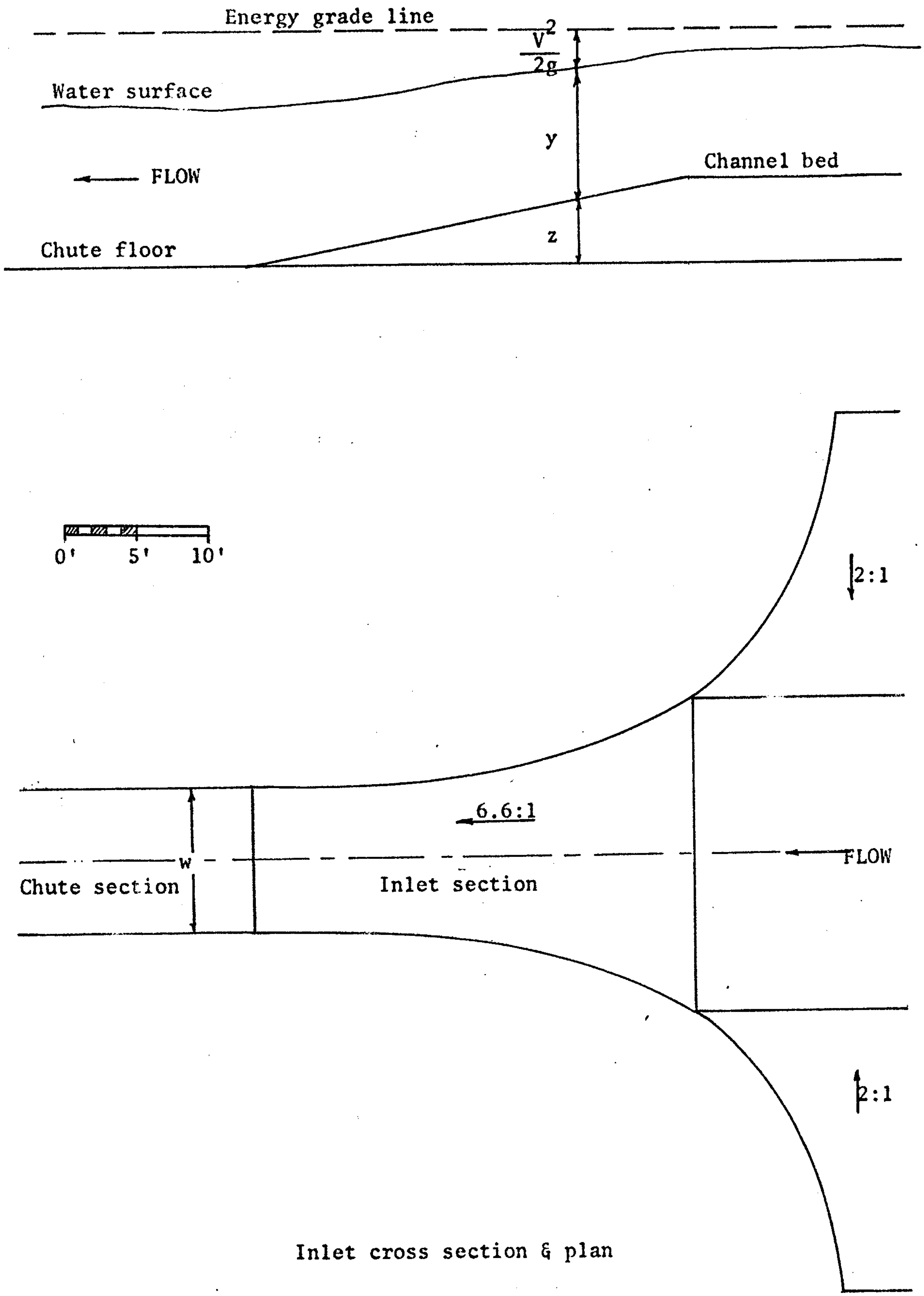
CHANNEL BED=21.6', SIDE SLOPES = 2:1

LITTLE BOSSHILL CREEK



Isometric view of Energy Culvert

FIGURE 2-5



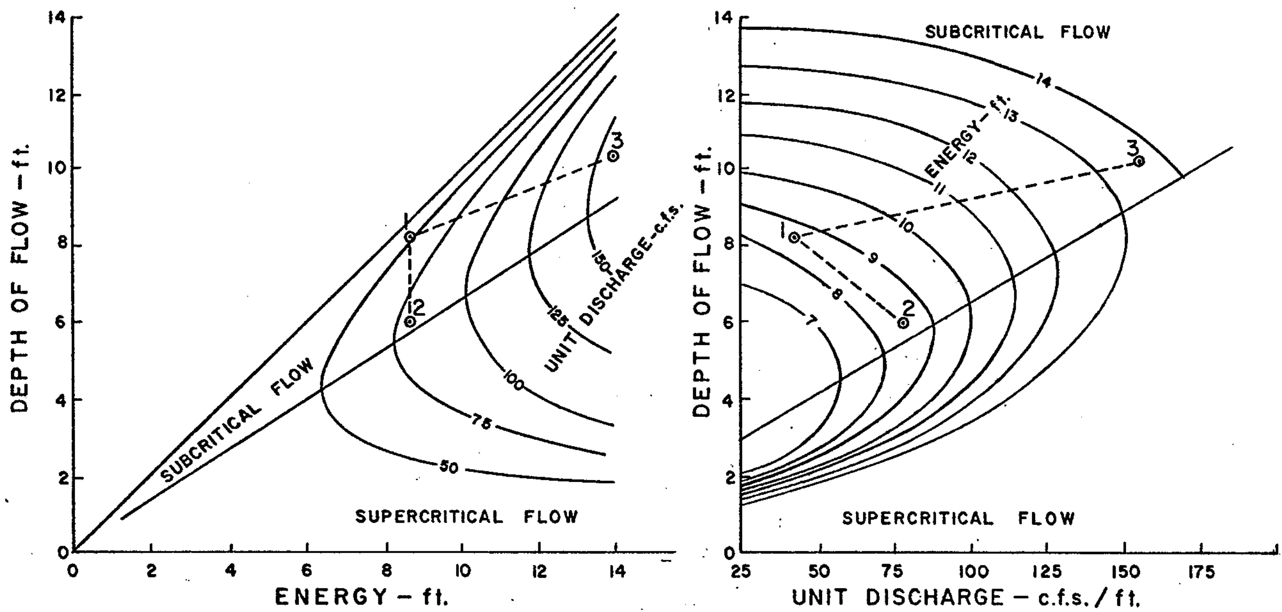
Inlet cross section & plan

FIGURE 2-6

This equation essentially is based on the Law of Conservation of Energy which states that energy cannot be created or destroyed but only converted from one form to another. In this culvert some of the potential energy of the water in the channel was converted to kinetic energy because the culvert chute elevation was less than the channel bed elevation.

ii) Basic flow concept

The basic flow concept of the energy culvert can most easily be explained by means of a three dimensional specific energy diagram as seen in FIGURE 2-7.



Three dimensional specific energy diagram

FIGURE 2-7

In the design of constrictions, there is generally no drop in the chute floor elevations. Since there is no increase in total energy, the constriction could force the water into a supercritical flow condition, but this is avoided in order that a hydraulic jump does not occur. The design of a culvert without a drop in chute elevation would mean an increase in unit discharge as shown in FIGURE 2-7 from point 1 to point 2. Because there was no increase in total energy, to avoid supercritical flow conditions, the maximum unit discharge would be greatly restricted. The energy culvert avoided this problem by setting the chute floor below the channel bed. Dropping the chute floor elevation has the effect of increasing the total energy, thus increasing the maximum unit discharge as represented in FIGURE 2-7 from point 1 to point 3. In adding energy to the flow of water, the subcritical flow condition was maintained at all times. At the outlet of the structure, the chute floor was raised back to normal channel bed elevation which resulted in a rapid recovery of velocity head. This energy recovery produced lower velocities in the downstream channel. This would not be possible in a normal constriction having no drop in the chute floor. It is the increase in total energy that allows a much larger unit discharge or a narrower chute to be used to full advantage.

iii) Application of basic flow concept

In order to apply the theory mentioned above to determine the flow characteristics through the energy culvert, the following approach was taken. The first step to solving the modified energy equation (2) for the inlet section was to predetermine the inlet and chute floor elevations, and to assume a chute width, thus fixing the unit discharge from which the depth of flow could be calculated. If the inlet walls and floor were linear in shape, the resulting water surface profile would be curved. However, to obtain a linear water surface profile, either the floor or walls would be curved. At the time, it was much easier to deal with a linear water surface so the inlet walls were curved and the inlet floor was linear.

Another approach to the solution of equation (2) could be taken by fixing the depth of flow at the chute entrance and calculating the unit discharge and the corresponding chute width. In this case the amount of energy required to produce the given depth of flow would be calculated and the elevation of the chute floor thus found.

It was impossible to avoid the continuously curved floor of the outlet due to the requirement of almost total energy recovery. At the outlet, the water was rapidly forced up the curved floor to a higher elevation as it was desirable to convert much of the kinetic energy to potential energy as soon as possible before the flow spread out too much.

After the velocities had been reduced considerably, the diverging of the flow over the entire cross section may proceed with a minimum of losses. Whether or not a hydraulic jump will occur depends on the design of the structure.

The specific energy diagram (FIGURE 2, APPENDIX A) was used to provide a very fast graphical solution to the modified energy equation (2). Since there were a large number of calculations, the graph was heavily relied upon.

c) Energy culvert design calculations

i) Introduction

The calculations performed in determining the water surface profiles were based on another modified energy equation. One of the initial assumptions for this equation to be valid was the concept of a two dimensional flow system. The hydraulic model system was a three dimensional flow system, thus some minor discrepancies between the theoretical calculations and the test results were expected.

In the energy culvert design, the flow condition in all cases was to be subcritical. For design purposes it was much easier to design for the critical flow condition to be reached at the entrance to the chute and then increase the total energy by setting the chute deeper to keep the flow in the subcritical region of the specific energy diagram. Once this amount of energy has been established, the shape of the walls was set and the water surface profile was re-calculated.

ii) Chute width selection

In selecting the width of the chute a problem was encountered as to what width would be reasonable. One could not pick a value at random and hope that it would work. It was thought that an energy culvert chute width of 1/2 to 1/3 that of the box culvert would be reasonable as a beginning point. The energy culvert chute widths of 7.5' and 10' were chosen for an accurate comparison study to the 7' x 7' box culvert.

To aid in the selection of a chute width, or a culvert capacity, a graph based on the critical flow conditions of chute width vs total energy vs discharge was prepared with the use of unit discharges.

We have for the rectangular chute section

$$y_c = \sqrt[3]{\frac{q^2}{g}} = \sqrt[3]{\frac{Q^2}{w^2 g}} = 2/3\ E$$

$$\text{or} \quad E = 3/2\ [Q^2/w^2 g]^{1/3}$$

$$\text{expanding} \quad E^3 = [3/2]^3\ [Q^2/w^2 g] = [27/8]\ [Q^2/w^2 g]$$

$$w^2\ E^3 = 27/8\ [Q^2/g] = 0.105\ Q^2$$

$$\text{rearranging} \quad w^2 = 0.105\ [Q^2/E^3] \qquad (3)$$

A graph (FIGURE 3, APPENDIX A) was prepared from equation (3). This graph shows the amount of energy required for a given width and given discharge at critical flow conditions.

iii) Subcritical width, energy & discharge relationship

The graph previously mentioned may be used for critical conditions only, however, for design purposes this condition would be avoided. Thus it was essential to know what occurred at subcritical flow conditions. Two graphs were prepared accordingly. The first graph (FIGURE 2-8) for 885 cfs, and the second graph (FIGURE 2-9) for 1800 cfs. The first discharge of 885 cfs was equal to the design discharge of the three cell culvert, while the second discharge of 1800 cfs was approximately double the design discharge in order that the structure could be studied at very large flows.

These graphs show the depth of flow and available energy relationship for various chute widths. These culvert width charts are the same as a specific energy diagram except that instead of labeling the family of curves with its own unit discharge, each curve was labeled with the corresponding chute width that was required to produce that unit discharge.

For example, from FIGURE 2-8, for a total energy of say 14', the minimum chute width required to pass 885 cfs and remain as critical or subcritical flow was 5.5'. If the energy level was increased, a smaller minimum width could be selected, but if the energy level de-

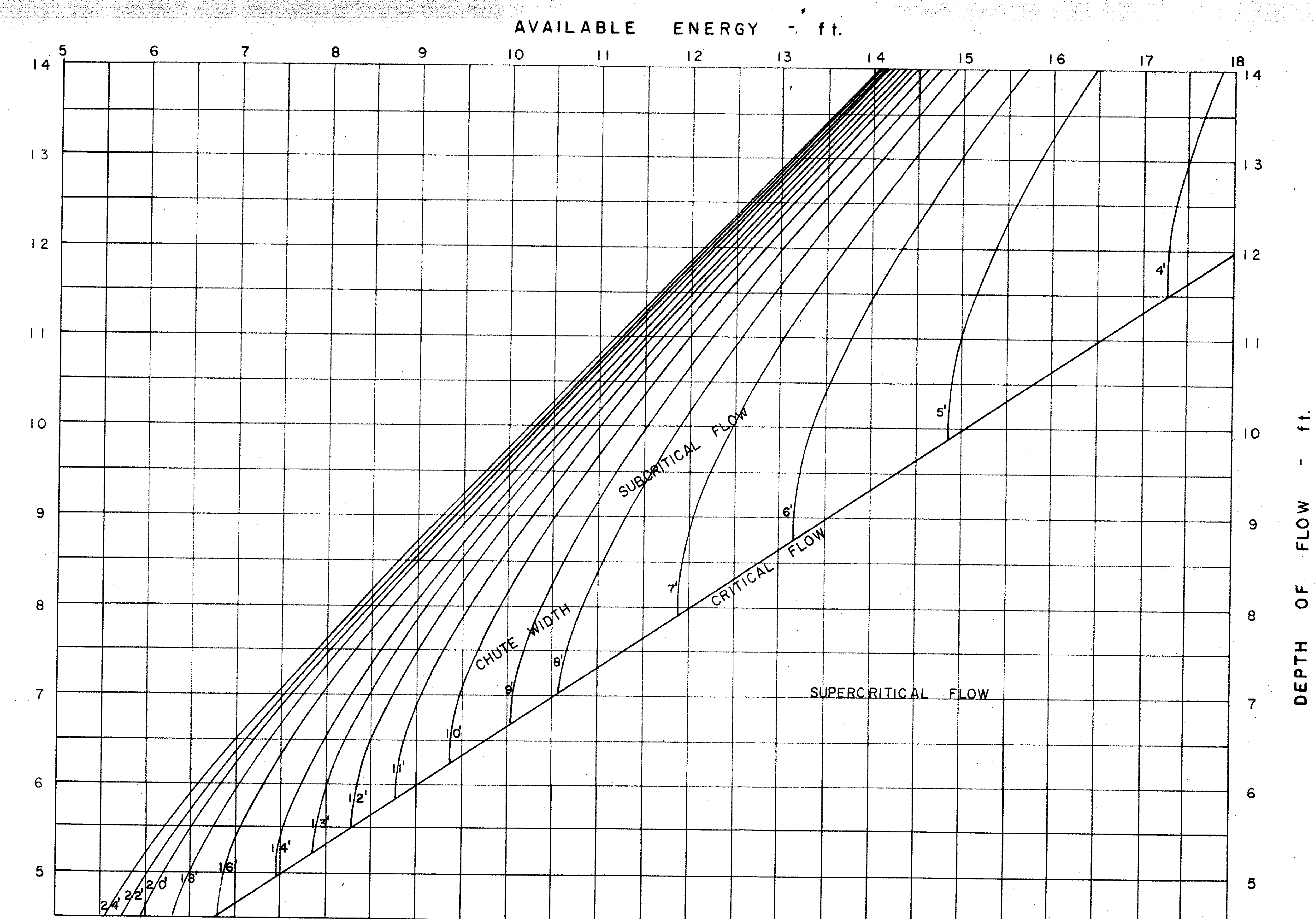


FIGURE 2-8 SUBCRITICAL FLOW - WIDTH, DISCHARGE, & ENERGY RELATIONSHIP	CULVERT WIDTH CHART FOR 885 cfs

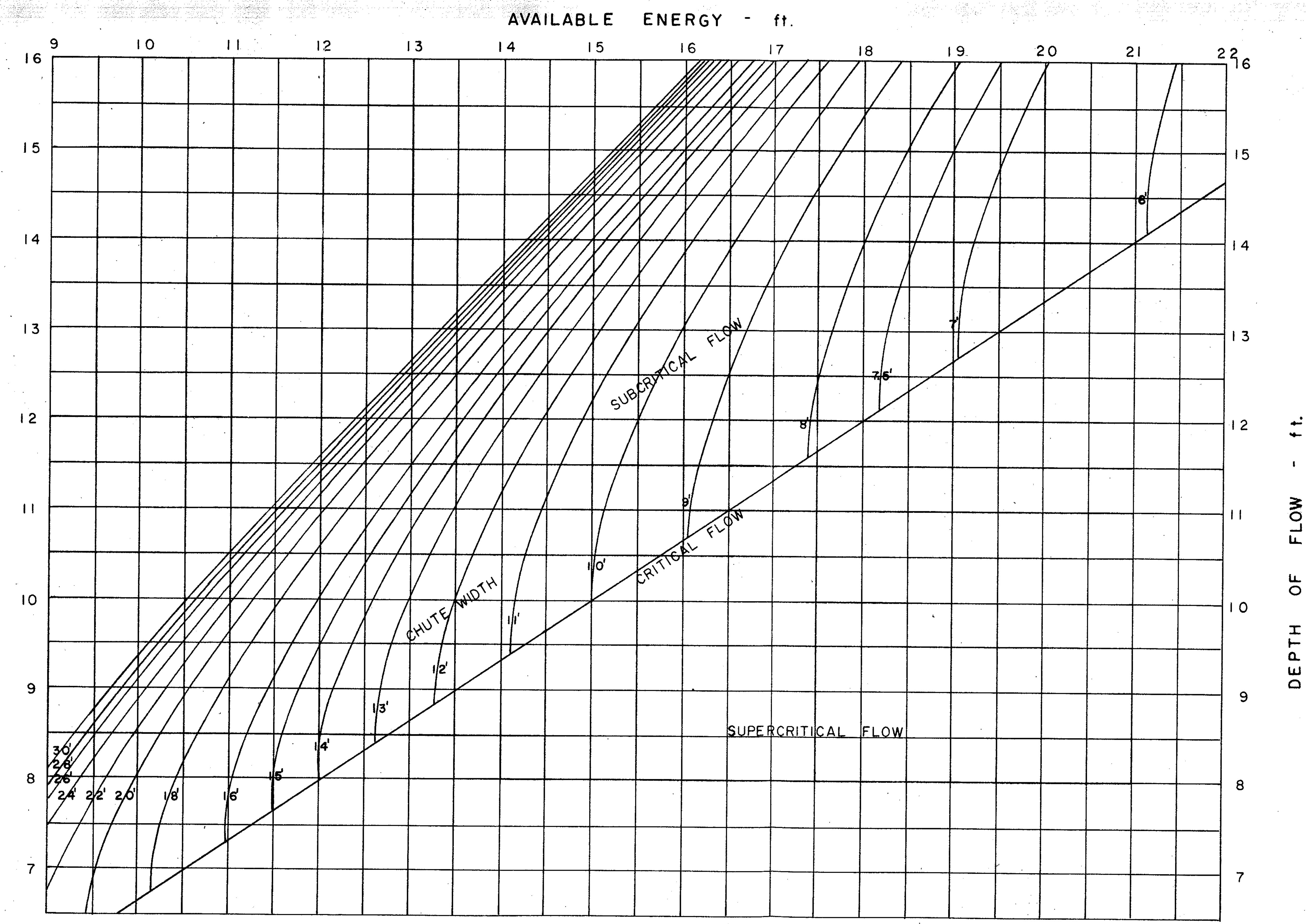


FIGURE 2-9
SUBCRITICAL FLOW - WIDTH, DISCHARGE, & ENERGY RELATIONSHIP

CULVERT WIDTH CHART FOR 1800 cfs

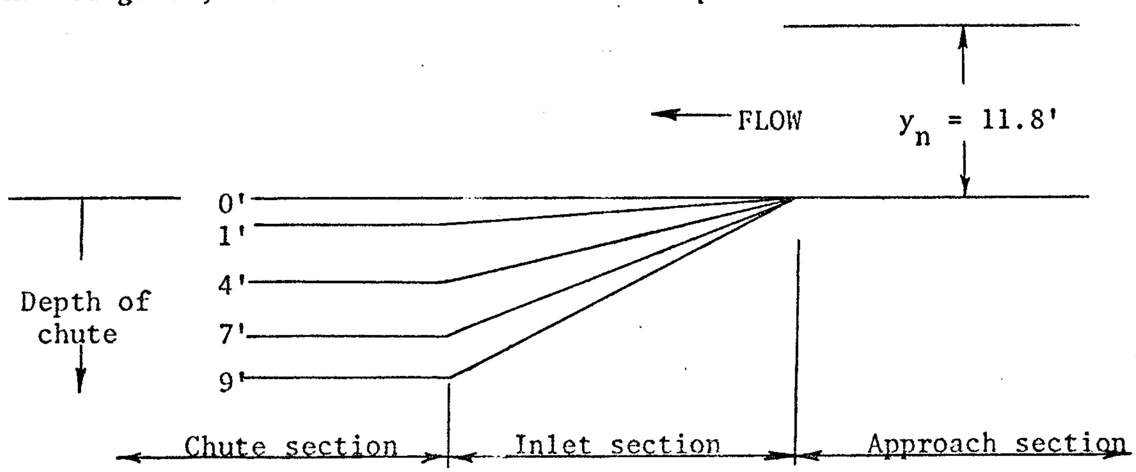
creased, a much larger minimum chute width would be selected. Thus the selected chute widths of 7.5' and 10' were well within the subcritical region of the graph as long as at least 12' of total energy were available.

In FIGURE 2-9, the discharge was doubled to 1800 cfs. Thus for example, at an energy level of say 17.5', the minimum chute width would be 8.0-. At any width less than 8.0', a backwater curve would form due to the choke effect of the chute width.

From hydraulic principles it may be shown that water flowing in a chute will use all the energy that was available to it through an adjustment of its depth of flow or velocity for any given width of the chute. In reading FIGURES 2-8, & 2-9, the plot of that width would fall at the point where the sloping line corresponding to that width meets the vertical line corresponding to the amount of available energy. The resulting depth of flow would then be read on the right hand side of the graph.

The amount of available energy equals the tailwater depth plus the velocity head plus the amount that the chute floor was set below the channel bed. Thus, an obvious problem of how much the culvert should be set below the channel bed for a certain flow and chute width must have some solution. By choosing any two of the three variables, the third one is fixed for critical conditions.

FIGURE 2-10 shows various chute depths that may be selected for the prototype. From this figure, TABLE II-1 was prepared to show various minimum chute widths for a discharge of 1800 cfs at n = 0.0545. It may be seen from TABLE II-1 that by setting the chute below the cha-nel grade, a smaller chute width was required.



Depth of chute

FIGURE 2-10

TABLE II-1

Minimum chute width for countersink

Depth of culvert	Minimum width
0'	14.4'
1'	12.7'
4'	9.2'
7'	7.9'
9'	6.3'

iv) Initial design calculations

In the initial design calculations a channel bed roughness of 0.0545 was used, which was the roughness of the Little Bosshill Creek. However, as a check on design performance, a channel bed roughness of 0.025 was also used. This roughness corresponds to that of creeks with smooth beds or no vegetation along the banks. This value also corresponds to that of man made channels or ditches.

With a chute width of 7.5' and a channel roughness factor of 0.025, from FIGURE 3, APPENDIX A, the required total energy was found to be 11.40' and from FIGURE 2-4, the normal depth of flow was 6.04'. Therefore, subtracting the two values, the chute was to be lowered 5.36' or approximately 5.4' below the channel bed.

The exact amount of the losses were unknown and could only be estimated. Since some turbulence was expected in the chute and at the outlet in addition to losses due to friction, these were generously allowed for in the energy balance estimate in TABLE II-2

The basic difference in centre line profiles between the three ce-l box culvert and the energy culvert after energy losses were taken into account may be seen in FIGURE 2-11. In addition to the profiles, elevations at all major points were included in this figure.

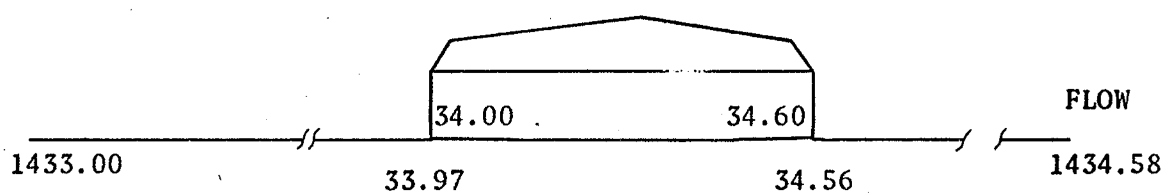
v) Inlet section calculations

The depth of the chute has been set at 5.4' but the length of the inlet section remained to be determined. A slope of 6:1 was initially considered for the inlet floor, which would make the length equal to 33'. As an approximation, the inlet length was selected at 30'.

TABLE II-2

Energy balance

Location	Energy
Drop at inlet	+5.40'
Drop of chute	+0.60'
Gain in specific energy	+6.00'
Rise at outlet	-4.54'
Net energy recovery	+1.46'
Losses (estimated)	-1.46'
Energy balance	0



3 cell 7' x 7' box culvert

Centre line profiles of box & energy culverts

FIGURE 2-11

The curved shape of the inlet walls was the only remaining problem to be solved. A linear water surface profile was assumed beginning with the normal depth of flow at the inlet and ending with the critical depth of flow at the chute entrance.

The available energy and depth of flow were then measured from this figure, and, from the specific energy diagram the unit discharge and consequently the required width were calculated. Upon plotting the results, it was discovered that the curve of the inlet wall was bery irregular and not as smooth as expected. The curve was then modified to follow a smoothly continuous path, and this modified curve was selected as the final shape. The points that form this curve upon which the energy culvert inlet and outlet walls were based was listed in TABLE 2, APPENDIX B.

After establishing the final wall shape, the unit discharge, and the available energy, and the depth of flow were calculated. This final curve was also applied to the 10' wide energy culvert without any change.

The water surface profile calculations for the inlet section were summarized in TABLE 3, APPENDIX B, for the 7.5' wide chute at discharges of 885 cfs and 1200 cfs. The results for the 885 cfs discharge were plotted in FIGURE 2-12, but the results for the 1200 cfs discharge represent the critical values for the 7.5' width at high tailwater levels and consequently were not plotted. TABLE 4, APPENDIX B, was a summation of the water surface profile calculations for the 10' wide chute at discharges of 885 cfs and 1800 cfs, which were also plotted in FIGURE 2-12.

From FIGURE 2-12 at 885 cfs, the 10' wide chute had a slightly greater depth of flow than the 7.5' wide chute. However, in doubling the discharge, the water level increase at the chute entrance for the 10' model was calculated to be 1.9' [22% of the total depth], while the water level increase at the entrance to the structure was 3.0' (FIGURE 2-12). In the prototype design, approximately 2' to 3' would be added to the top of the inlet and outlet walls as freeboard, so that the capacity of the structure may be doubled without any extra major concrete construction. It was this ability to handle a doubled discharge with only a small corresponding increase in upstream water

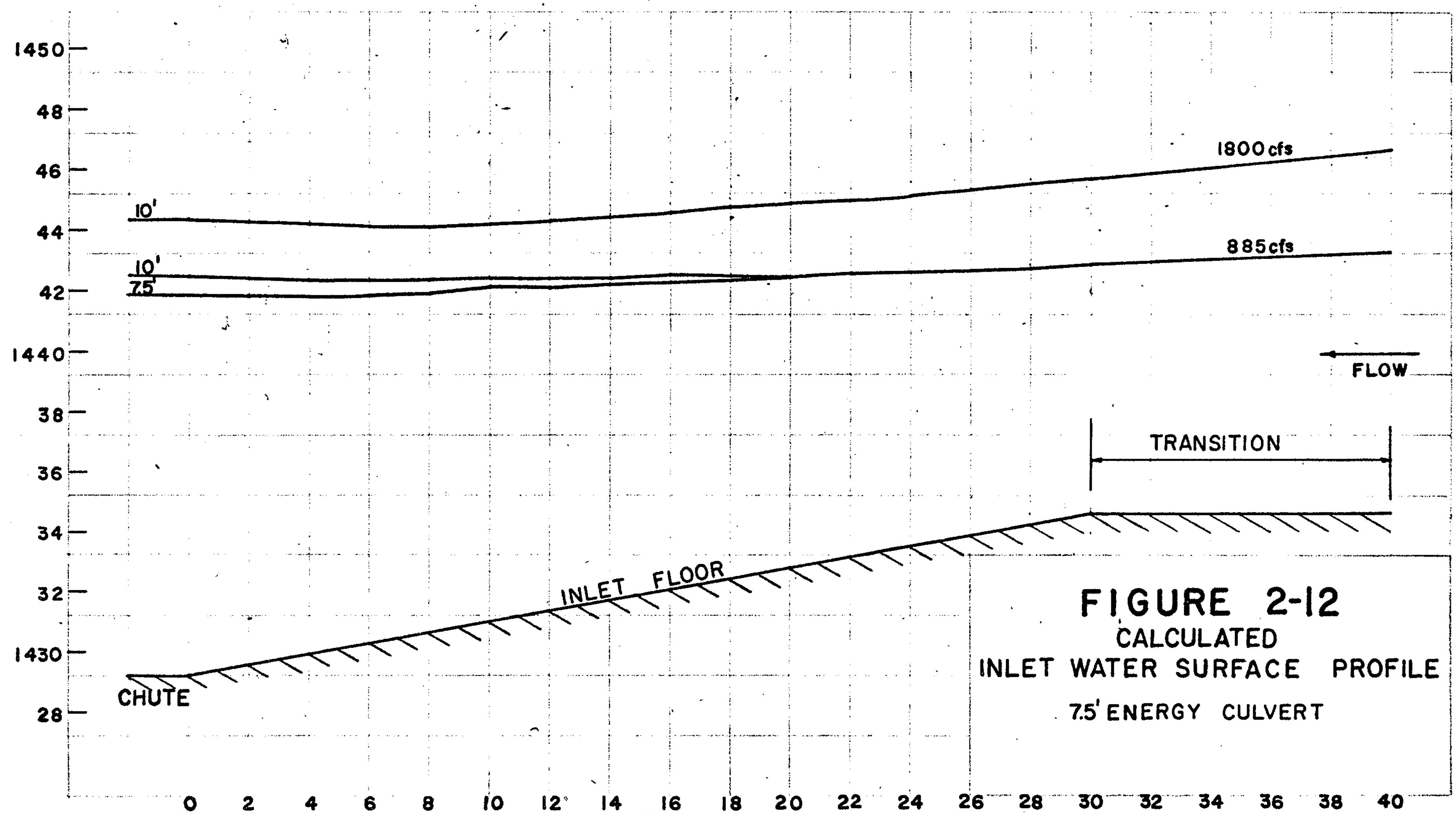


FIGURE 2-12
CALCULATED
INLET WATER SURFACE PROFILE
7.5' ENERGY CULVERT

levels that makes this design extremely advantageous. As there was little energy dissipation in the contraction of a flow of water, no turbulence was expected in the inlet section. The shape of the walls were not critical in the inlet section and any minor changes that did occur were negligible.

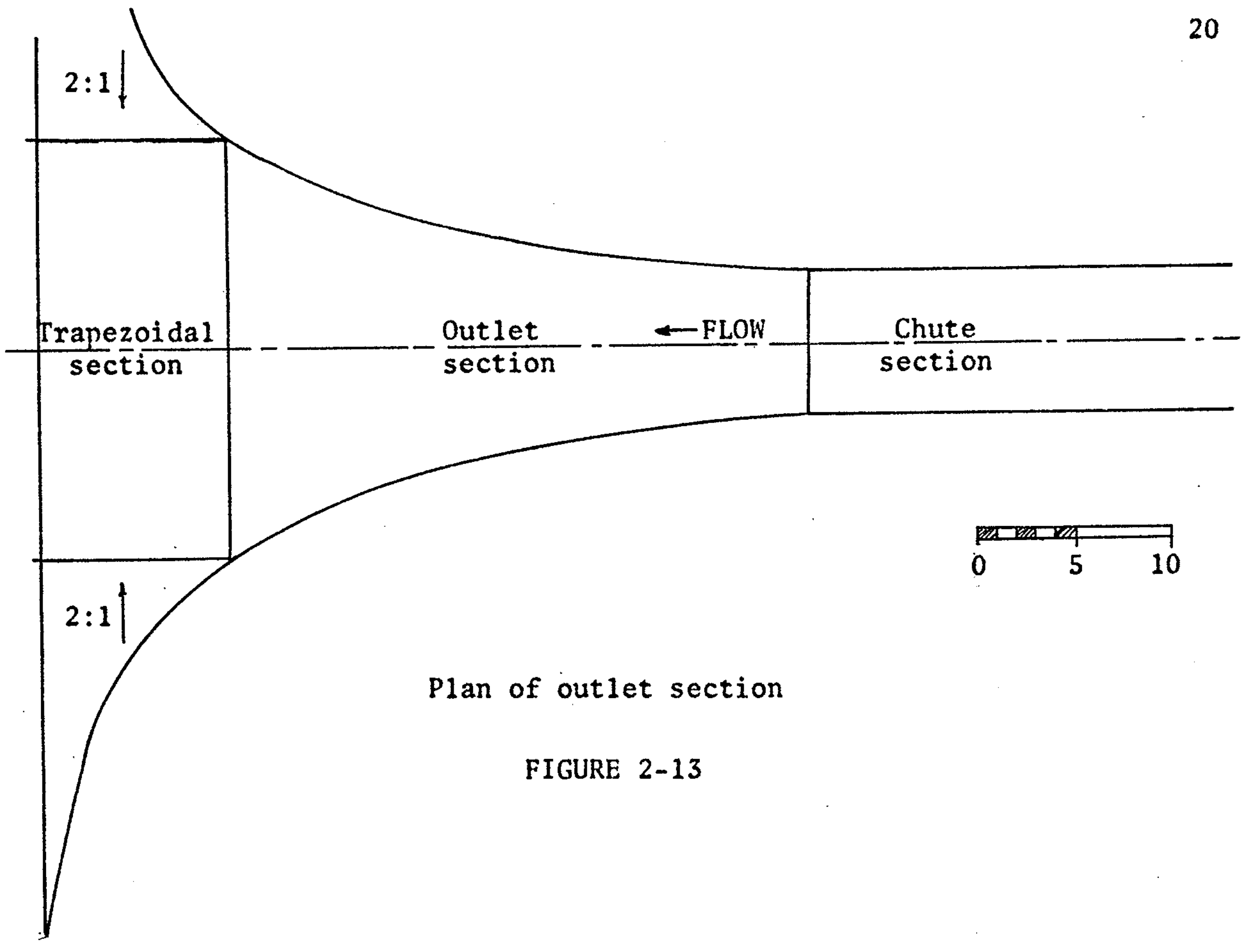
vi) Curvature of outlet floor

In the outlet design, the floor consisted of a reverse curve originated by Dr. McKay (REFERENCE 1) to reduce turbulence by converting kinetic energy to potential energy. At the exit, the water was moving too rapidly to be released into the downstream channel without severe bank erosion. To reduce the outlet velocities, an energy conversion was essential.

A reverse curve ramp was selected for the outlet floor because of its continuous change of slope, thus continuous energy recovery no matter where its point of inflection may occur. The point of inflection in this design was selected at one third of the outlet length (10") from the chute in such a manner so that the outlet floor had risen 62% while only one third of the lateral expansion had occurred. This was done to reduce velocities and the available energy quickly before too much expansion of the outlet section had taken palce. At the beginning of the transition from the rectangular to the trapezoidal cross section, the floor rise and chute expansion had reached the calculated limits. TABLE 5, APPENDIX B, shows a comparison on a percentage basis between the length of the chute, the amount of rise of the chute floor and the width of the outlet section.

vii) Outlet section calculations

For symmetry, the outlet walls were identical to those of the inlet section (FIGURE 2-13). The total amount of energy was known and the shape of the outlet floor was determined as previously discussed. Once these factors were known, the unit discharge and the water surface profile were quickly determined. TABLE 6, APPENDIX B, is a summation of the calculations for the 7.5' wide energy culvert at a discharge of 885 cfs. TABLE 7, APPENDIX B, is a summation of the calculations for the 10' wide energy culvert at 885 cfs and 1800 cfs. The results of TABLES 6 & 7, APPENDIX B, were plotted along with the centre line profile of the outlet floor in FIGURE 2-14.



Plan of outlet section

FIGURE 2-13

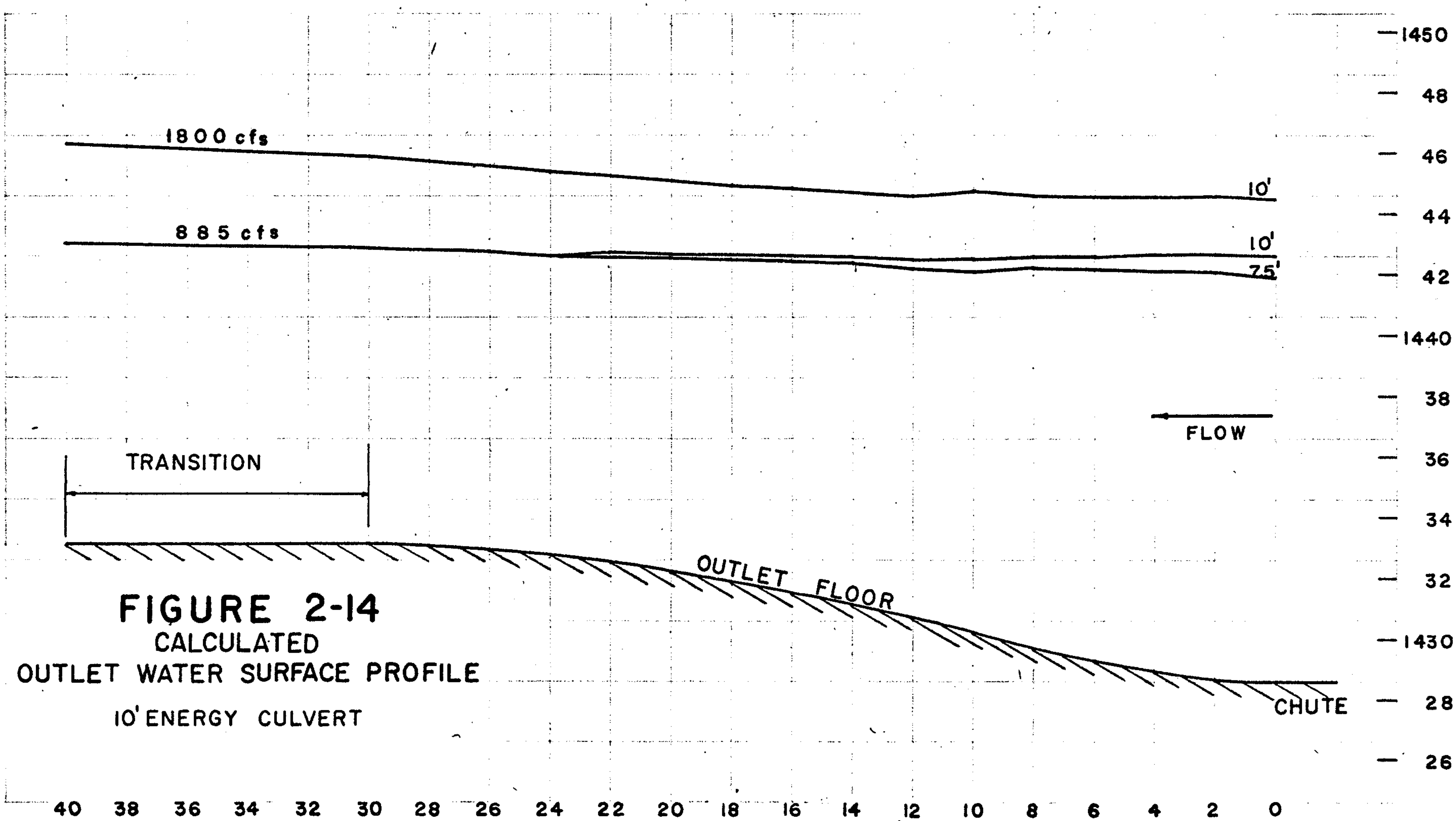


FIGURE 2-14
CALCULATED
OUTLET WATER SURFACE PROFILE
10' ENERGY CULVERT

CHAPTER III

EXPERIMENTAL STUDY

a) Model scales

One of the problems in building a model is to make it act in exactly the same way as the protype. Complete similarity in the model is sometimes difficult or impossible to obtain because the force ratios must be identical at all points in the model simultaneously (REFERENCE 6). A true or undistorted hydraulic model would have all the significant characteristics of the prototype reduced in size (geometric similarity) and would satisfy the design restrictions (kinematic and dynamic similarity). To keep the model geometrically undistorted, the scale ratio had to be same both horizontally and vertically. This meant that the length ratio for all dimensions was identical.

To satisfy the design restrictions, kinematic similtude was first considered. This included the correct operation of the model and proper simulation of the currents and discharges at all times. Kinematic similtude was said to exist if the paths of homologous moving particles were geometrically similar, and if the ratios of the velocities of these particles were equal.

Dynamic similtude was said to exist between geometrically and kinematically similar systems if the ratios of all homologous forces in the model and prototype were identical.

In dynamic similtude the most important dimension was force. The similarity of forces such as shear ratio, pressure ratio, and force ratio are important in most model studies.

The major factors that occur in a model are gravity, surface tension, viscous forces or friction, large velocities, and elasticity. Complete similtude between the model and the prototype was impossible to obtain because each model factor must equal its prototype factor in magnitude, force, and direction simultaneously on one model. However, in most cases one or two of the factors predominates while the others have only a relatively weak effect on the particular study (REFERENCE 3).

The purpose of the hydraulic study will govern which of the previous factors would be the most important. Therefore, to obtain the correct model scales, these factors must be equated between the model and the prototype. The model was then operated in such a manner to obtain kinematic similtude with respect to the predominating force.

Since there were no surface tension forces, high velocities, and significant friction, the Weber, Mach and Reynolds numbers respectively may be eliminated. The force due to gravity or the Frode number predominated in the following scale ratios.

$$[F]_m = [F]_p \qquad \text{where } F = \text{Froude no.}$$
$$m = \text{model}$$
$$p = \text{prototype}$$

$$[V/(gL)^{1/2}]_m = [V/(gL)^{1/2}]_p$$

$$\text{also} \quad [g]_m = [g]_p \quad \text{or} \quad [g]_r = 1.0$$

The site conditions for the three cell box culvert consisted of a channel width of approximately 60', while the testing flume in the hydraulics laboratory had a width of 3.0'. The length ratio was then selected at 20.

$$[L]_r = 20$$

velocity	$[V]_r$	=	$[(L)_r]^{1/2}$	=	4.47
time	$[T]_r$	=	$[(L)_r]^{1/2}$	=	4.47
acceleration	$[a]_r$	=	1.0		
discharge	$[Q]_r$	=	$[(L)_r]^{5/2}$	=	1790

Since the Euler numbers were a common factor

$$[E]_m = [E]_p \qquad \text{where } E = \text{Euler no.}$$

pressure	$[p]_r$	=	$[L]_r$
force	$[F]_r$	=	$[(L)_r]^3$
Manning's 'n'	$[n]_p$	=	$[(L)_r]^{1/6}\ [n]_m$
	$[n]_p$	=	$1.648\ [n]_m$

Slope of the channel was estimated to be 0.10% or 0.001.

b) Testing apparatus

The major piece of apparatus was a 2.5' x 3' x 46' recirculating flume with glass side panels in thedownstream half and steel side panels in the upstream half (FIGURE 3-1). The water entered the flume through one of two 6" mains from a sump 10' x 30' x 20' deep located in the lower floor of the hydraulics laboratory.

Water surface profiles were measured by means of a point gauge located on a four wheeled carriage. This carriage ran on pre-leveled rails which were supported by the top edge of the flume. A neon light and a 90 volt battery were used in an electronic circuit to indicate when the point gauge touched the water surface. This made the reading of the point gauge much faster and easier. The water velocities in the flume were measured by a Kent Mini-Flow Probe, which was a minerature propeller fixed on the end of a rod for measuring velocities in hydraulic models.

c) Testing procedure

The testing procedure involved controlling the tailwater depth in the channel about 100' downstream from the structure by means of a drain valve corresponding to the tailwater rating curve (FIGURE 2-4) for values of n = 0.025 and n = 0.0545. Various discharges up to 2000 cfs were used for all hydraulic models at both high and low tailwater conditions. The water surface profile and velocity measurements were then taken, the latter being only on selected flows.

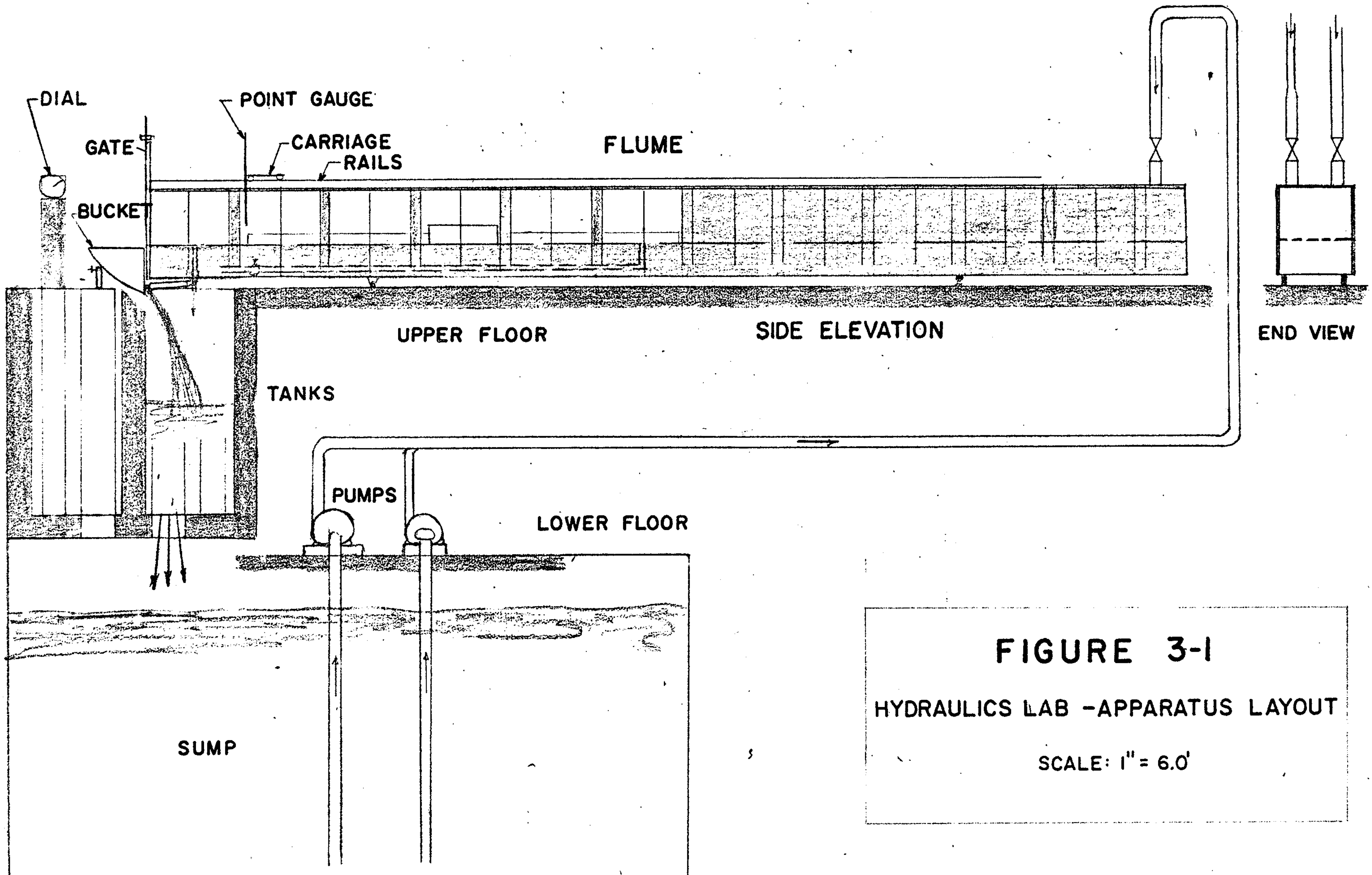


FIGURE 3-1

HYDRAULICS LAB - APPARATUS LAYOUT

SCALE: 1" = 6.0'

During testing, the location and number of standing waves and hydraulic jumps were noted.

The water surface profile was measured every 20' from the structure up to 160' distant. On the three cell model, the profiles inside the centre and outside culvert barrel and in the channel itself were measured by the use of 30 open manometer tubes. FIGURE 4, APPENDIX A, shows the general arrangement of the manometer tube locations. On the energy culvert, the profiles were taken as above in addition to every 5' in the inlet and outlet sections as well as every 10' within the chute. Velocity measurements were taken continuously from the inlet section to the outlet section for selected discharges. From these measurements the Froude number at each point was calculated, and an average value was obtained for each test.

d) Preparation of the three cell culvert

The three cell box culvert was constructed from plans supplied by the Department of Highways. The model was made from plywood and finished with latex and enamel paint. For further details see APPENDIX C.

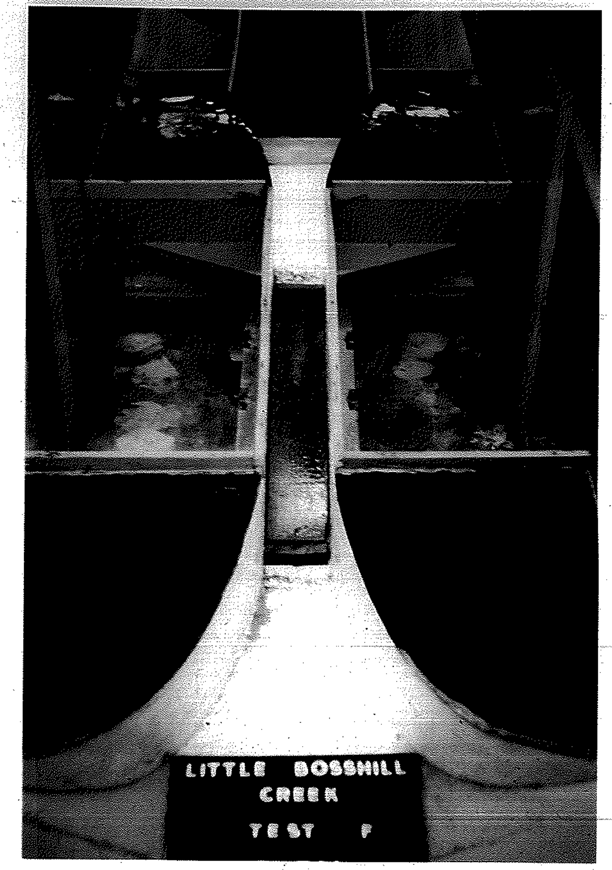
e) Preparation of the energy culvert

The base for the energy culvert was prepared from plywood while paraffin was used to finish off the curved surfaces. Latex paint was used to give a smooth finish to the model. A further discussion may be found in APPENDIX C.

f) Reduced available energy in the chute

The sedimentation within the chute section during low flows and ice formation in the chute during the winter must be examined if this structure was to be considered for use in Canada. It was essential to know what would happen to the water surface profile when the amount of available energy was reduced. It was expected that the water levels would rise in the inlet and outlet sections, but the amount of this rise was unknown.

This energy reduction was accomplished by placing a 3/4" thick plywood strip on the bottom of the chute (PHOTOGRAPH 1) for the 7.5' and 10' wide chute models. The floor of the chute was raised by 1.46' in this manner (FIGURE 8, APPENDIX A).



Chute insert for reduced available energy tests

PHOTOGRAPH 1

CHAPTER IV

TEST RESULTS

a) Three cell box culvert

In TABLE IV-1 the test results have been summarized and plotted in FIGURE 4-1. The complete water surface profiles have been plotted in FIGURES 6-1, 6-2, and 6-3.

TABLE IV-1

3 cell 7' x 7' box culvert test results

n = 0.0545

Test	Discharge cfs	Upstream elevation ft	Downstream elevation ft	Head difference ft
C-1	256	1437.77	1437.70	0.18
C-2	574	1440.31	1440.08	0.23
C-3	764	1441.55	1441.24	0.85
B-12	892	1442.45	1441.87	0.58
C-5	975	1442.88	1442.28	0.60
C-6	1150	1443.88	1443.00	0.88
K-2	1312	1444.70	1443.54	1.16
K-4	1480	1445.48	1444.16	1.32
K-6	1640	1446.20	1444.58	1.67
K-8	1870	1447.34	1445.22	2.12
K-10	2015	1448.44	1446.00	2.44

n = 0.025

K-1	1320	1441.98	1440.30	1.68
K-3	1485	1442.42	1440.62	1.80
K-5	1640	1442.84	1441.14	1.70
K-7	1790	1443.40	1441.62	1.78
K-9	2010	1444.24	1442.06	2.18

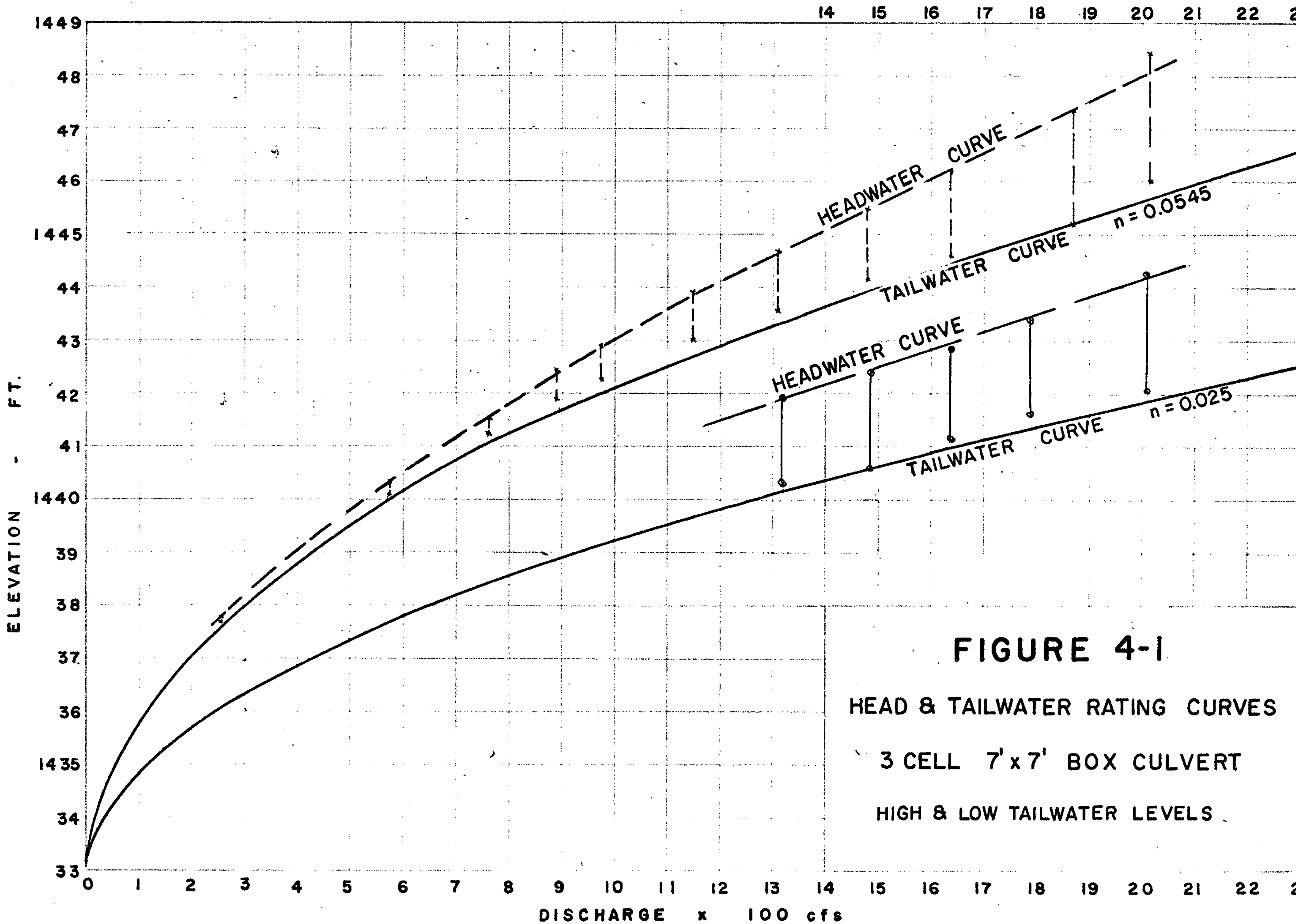


FIGURE 4-1

HEAD & TAILWATER RATING CURVES

3 CELL 7' x 7' BOX CULVERT

HIGH & LOW TAILWATER LEVELS

b) 7.5' wide energy culvert

The test results have been summarized in TABLE IV-2 for this series of tests and plotted in FIGURE 4-2. The complete water surface profiles have been plotted in FIGURES 6-4 to 6-9 inclusive.

TABLE IV-2

7.5' wide energy culvert test results

n = 0.0545

Test	Discharge cfs	Froude no.	Upstream elevation ft	Downstream elevation ft	Head difference ft
D- 1	239	0.290	1437.72	1437.70	0.02
D-22	423		1439.10	1438.76	0.34
D- 2	548	0.425	1440.85	1440.00	0.85
D-18	690	0.480	1441.36	1440.56	0.80
D- 3	795	0.500	1442.02	1441.04	0.98
D- 6	853	0.520	1442.60	1441.68	0.92
D-10	942		1443.30	1442.26	1.06
D-13	1130	0.580	1444.50	1442.90	1.60
H- 2	1300	0.637	1445.60	1443.36	2.24
H- 4	1473	0.619	1446.66	1444.10	2.56
H- 6	1600	0.669	1447.50	1444.48	3.02
H- 8	1870	0.702	1449.24	1445.40	3.84
H-10	2010	0.754	1450.08	1445.92	4.16

n = 0.025

D-24	230		1437.00	1435.94	1.06
D-23	421		1437.92	1436.88	1.06
D-20	573		1438.50	1437.52	0.98
D-17	700	0.730	1439.74	1438.00	1.74
D- 5	770		1440.38	1438.58	1.80
D-19	1005		1442.30	1439.90	2.40
D-15	1140		1443.20	1438.90	4.30
H- 1	1325		1445.06	1440.30	4.76
H- 3	1480		1446.00	1440.92	5.08
H- 5	1608		1446.92	1440.92	6.00
H- 7	1850		1450.00	1441.50	8.50
H- 9	2010		1450.10	1441.86	8.24

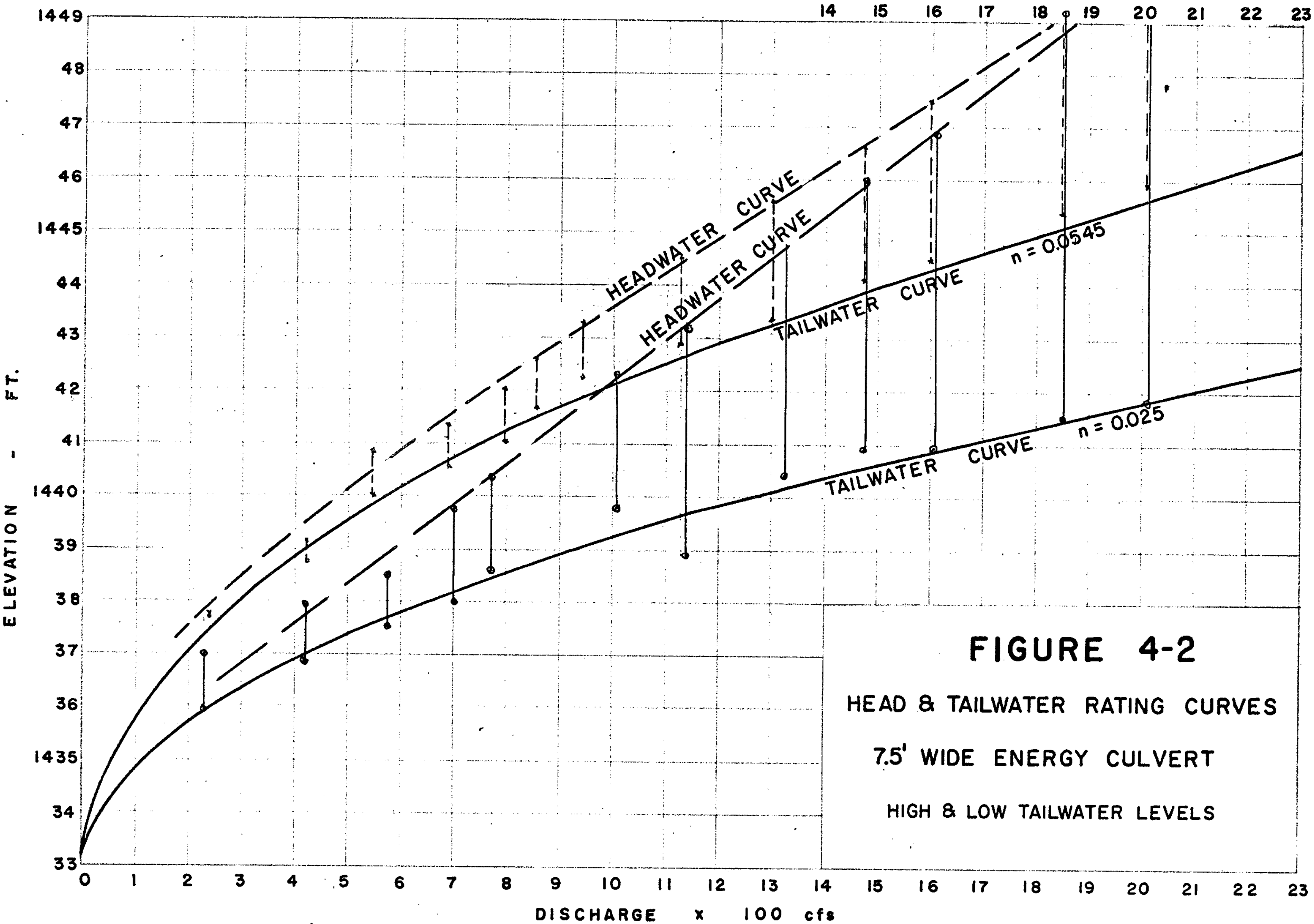


FIGURE 4-2

HEAD & TAILWATER RATING CURVES

7.5' WIDE ENERGY CULVERT

HIGH & LOW TAILWATER LEVELS

c) 7.5' energy culvert with reduced available energy

The test results have been summarized in TABLE IV-3 at high tailwater levels only. The summarized results were plotted in FIGURE 4-3 and the complete water surface profiles were plotted in FIGURES 6-10 & 6-11. TABLE IV-4 shows the normal and raised chute floor elevations and the amount to which the chute was raised.

TABLE IV-3

7.5' wide chute with reduced available energy

Test	Discharge cfs	Froude no.	Upstream elevation ft	Downstream elevation ft	Head difference ft
F-1	855		1442.70	1441.58	1.12
F-2	1120		1444.36	1442.70	1.66
J-5	1290	0.679	1446.32	1443.32	2.02
J-4	1472	0.669	1447.60	1443.96	3.64
J-3	1610	0.730	1448.50	1444.54	3.96
J-2	1790		1449.90	1445.24	4.66
J-1	2060		1451.76	1445.84	5.92

TABLE IV-4

Reduced energy chute elevations

Point	New elevation ft	Old elevation ft	Chute raised ft
17	1430.08	1430.14	0.04
18	1429.34	1429.30	0.04
18.5	1430.68	1429.28	1.40
19	1430.68	1429.26	1.42
20	1430.62	1429.22	1.40
21	1430.62	1429.16	1.46
22	1430.62	1429.14	1.48
23	1430.56	1429.10	1.46
24	1430.30	1429.04	1.26
25	1429.12	1429.06	0.06

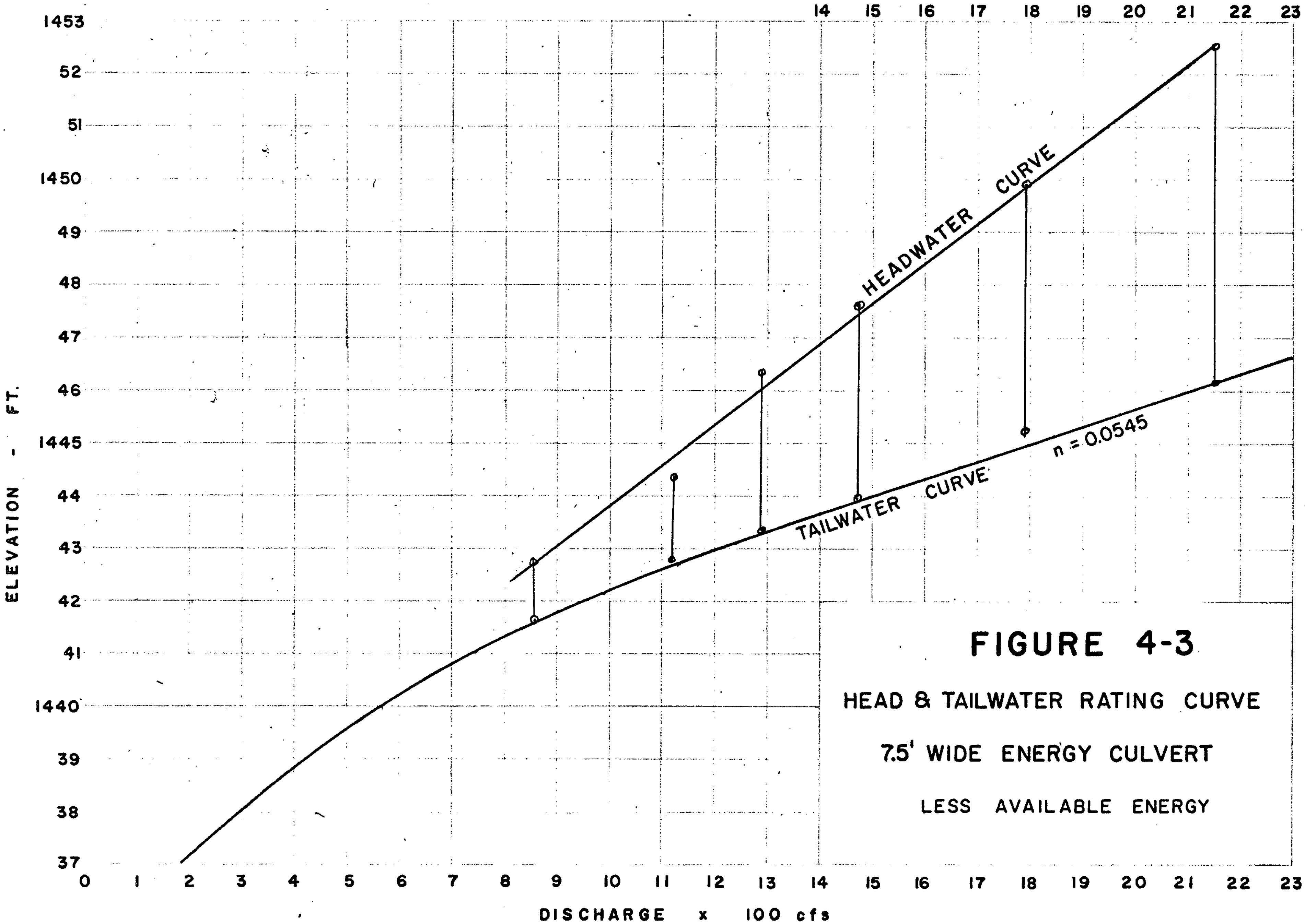


FIGURE 4-3

HEAD & TAILWATER RATING CURVE

7.5' WIDE ENERGY CULVERT

LESS AVAILABLE ENERGY

d) 10' wide energy culvert

The test results have been summarized in TABLE IV-5 for high and low tailwater conditions. The summarized results have been plotted in FIGURE 4-4, and the complete water surface profiles have been plotted in FIGURES 6-12 to 6-14 inclusive.

TABLE IV-5

10' wide energy culvert test results

n = 0.0545

Test	Discharge cfs	Froude no.	Upstream elevation ft	Downstream elevation ft	Head difference ft
M- 2	345		1438.60	1438.54	0.06
M- 4	580	0.324	1440.58	1440.24	0.34
M- 6	890	0.401	1442.06	1441.64	0.42
M- 8	1200	0.435	1443.90	1443.06	0.84
M-10	1400	0.473	1444.80	1443.80	1.00
M-12	1580	0.497	1445.48	1444.32	1.16
M-14	1790	0.531	1446.40	1444.96	1.44
M-16	2050	0.560	1447.76	1445.92	1.74

n = 0.025

M- 1	357		1437.60	1436.82	0.78
M- 3	580		1438.60	1437.80	0.80
M- 5	900		1440.08	1438.90	1.18
M- 7	1200		1441.60	1439.88	1.72
M- 9	1408		1442.60	1440.40	2.20
M-11	1600		1443.66	1441.00	2.66
M-13	1800		1444.86	1441.28	3.58
M-15	2070		1446.08	1442.00	4.08

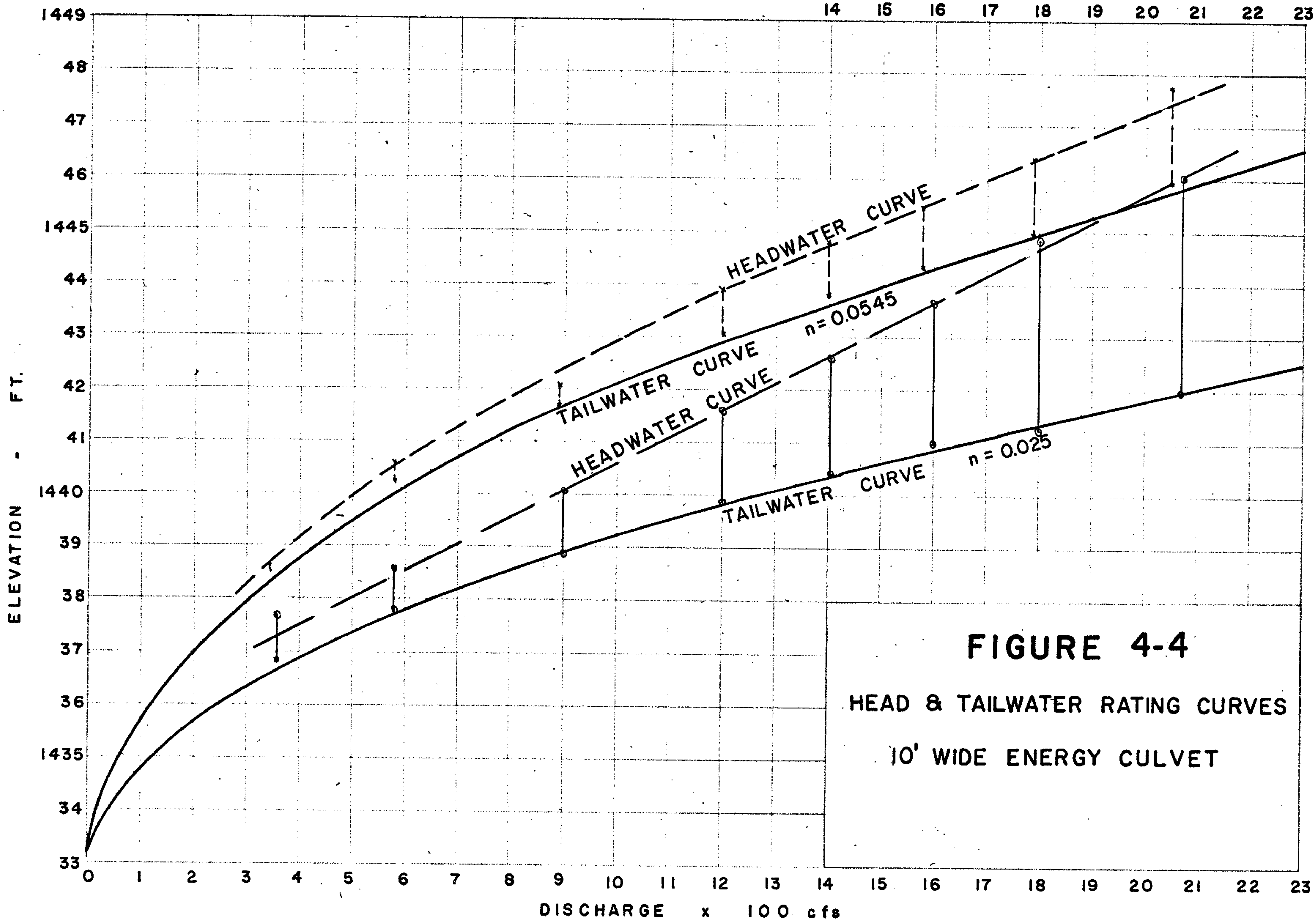


FIGURE 4-4

HEAD & TAILWATER RATING CURVES

10' WIDE ENERGY CULVET

e) 10' energy culvert with reduced available energy

The test results have been summarized in TABLE IV-6 at high tailwater levels only. The summarized results were plotted in FIGURE 4-5 while the complete water surface profiles were plotted in FIGURE 6-15.

TABLE IV-6

10' wide chute with reduced available energy

n = 0.0545

Test	Discharge cfs	Froude no.	Upstream elevation ft	Downstream elevation ft	Head difference ft
N-1	329		1438.28	1438.16	0.19
N-2	554		1440.12	1439.92	0.20
N-3	926	0.455	1442.42	1441.80	0.60
N-4	1130	0.470	1443.94	1442.86	1.08
N-5	1400	0.521	1444.94	1443.74	1.20
N-6	1600	0.571	1445.96	1444.42	1.54
N-7	1760	0.610	1446.60	1444.90	1.70
N-8	2020	0.614	1447.92	1445.78	2.14

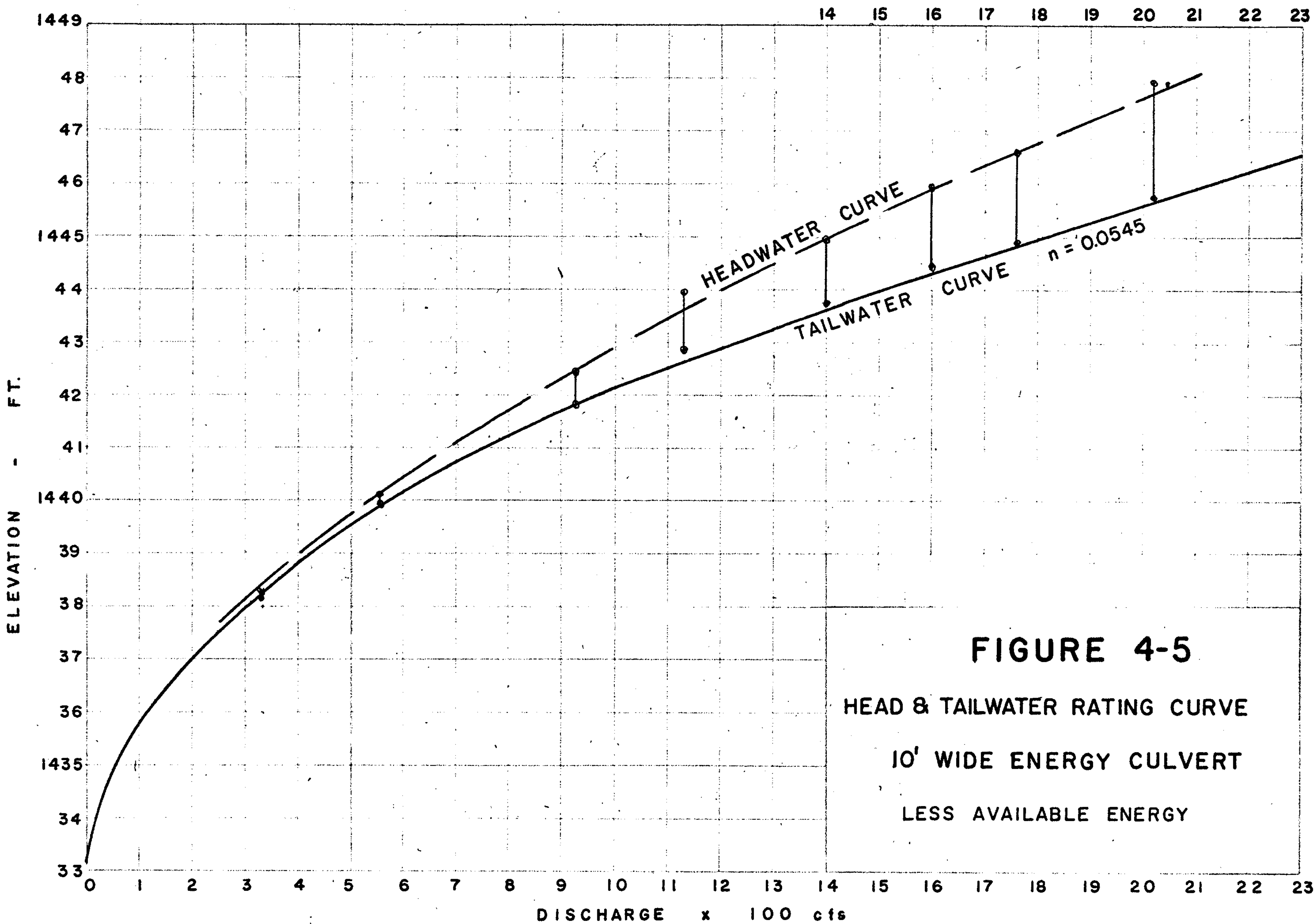


FIGURE 4-5

HEAD & TAILWATER RATING CURVE

10' WIDE ENERGY CULVERT

LESS AVAILABLE ENERGY

f) General observations

i) Three cell box culvert

During large high tailwater flows, the upstream water surface was generally smooth and free of turbulence. Two vortices formed over the barrel inlets at flows over 1600 cfs and grew larger as the discharge increased. On the downstream side of the structure, three large boils were formed about 10' away from the exit at about the same discharge (PHOTOGRAPH 2).

The recorded cross sectional velocity distribution in the downstream section showed a distinct line of separation or boundary between the high velocity flow and the relatively still water. Potassium permanganate dye was injected into the channel to find eddy currents and areas of relatively calm water as in PHOTOGRAPH 2, where the dye was introduced upstream. The dye in the fast moving water had been swept away while a large amount of it remained in the eddy currents. The eddies that formed were much larger on one side of the channel than on the other which was caused by the current swinging to one side of the channel as it left the three cell structure.

ii) 7.5' wide energy culvert

In this energy culvert model, several large standing waves were observed in the chute. The first stationary wave shifted downstream from a place 10' from the chute inlet to one half way down the chute as the discharge passed 1300 cfs (PHOTOGRAPH 3).

When the chute floor was elevated 1.46', the water surface became rougher and slightly higher in elevations. Other details of the tests were summarized in TABLE IV-7.

iii) 10' wide energy culvert

The 10' wide culvert had a very smooth water surface at high tailwater conditions and a rough water surface profile at low tailwater conditions. When the chute floor was raised 1.46' as previously mentioned, the water surface profile at high tailwater levels was very smooth up to 1400 cfs, beyond which the profile became rougher (PHOTOGRAPH 4). Other observation details of the tests were summarized in TABLE IV-8.

iv) Outlet turbulence

The outlet turbulence for the three cell culvert model at high tailwater consisted mainly of boils formed downstream from the structure. During low tailwater levels at flows over 1000 cfs, supercritical flow and shock waves were present, followed by a hydraulic jump in the downstream channel.

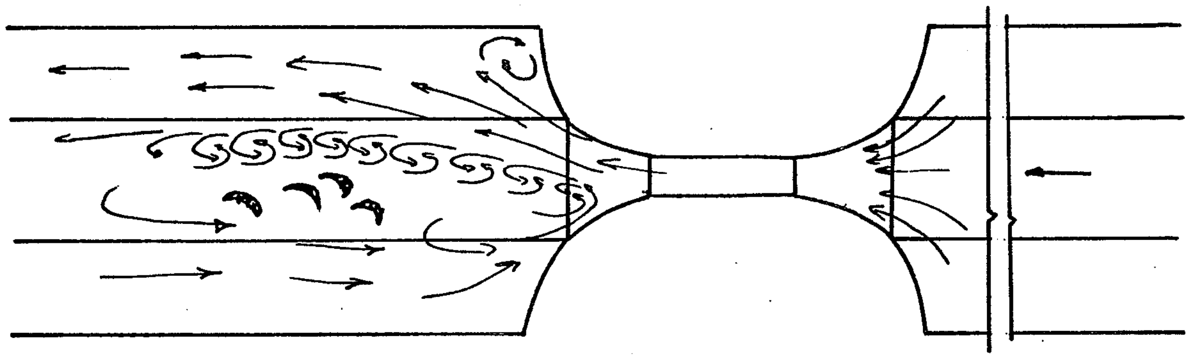
For the two energy culverts during very low flows, a hydraulic jump occurred at the inlet section, which was drowned out at larger flows. Small standing waves were observed in the chute at low flows, which grew larger and fewer as the discharge increased. At low tail-water conditions, a hydraulic jump was noted at the structure outlet for approximately 900 cfs and upward. When the jump had formed, it was discovered that by raising the tailwater about 1', the jump changed to a large standing wave with a very small jump about 3' wide at the centre of the wave. It was observed that once the jump had formed, the water surface downstream was relatively smooth, indicating a substantial dissipation of energy. When the initial standing wave had formed instead of a jump, a series of standing waves occurred downstream at about 20' in amplitude and up to 3' in height. This indicated that little energy had been dissipated so that erosion in the downstream channel would soon follow.

v) Choke effect

For the 7.5' wide chute at low tailwater levels, a choke or constriction was observed for large flows when the chute seemed to be too narrow to pass the discharge. This was also observed in the same model at high tailwater levels for a larger flow. The same choke effect was present in the 10' wide chute at low tailwater levels around the same discharge, however, no choke effect was observed at high tailwater conditions.

vi) Sedimentation

Sand and other sediment was introduced into the flume from the debris in the sump. However, it was observed that during testing, no sediment of any kind settled within the structure. A few crescent shaped sand dunes formed in the downstream channel on the less turbulent side (FIGURE 4-6). During larger flows, much heavier objects such as plastic letters with steel inside them were introduced into the flow at the inlet, however, they were immediately swept away and deposited downstream.



Outlet turbulence in energy culvert

FIGURE 4-6

TABLE IV-7

Observations of 7.5' wide culvert tests

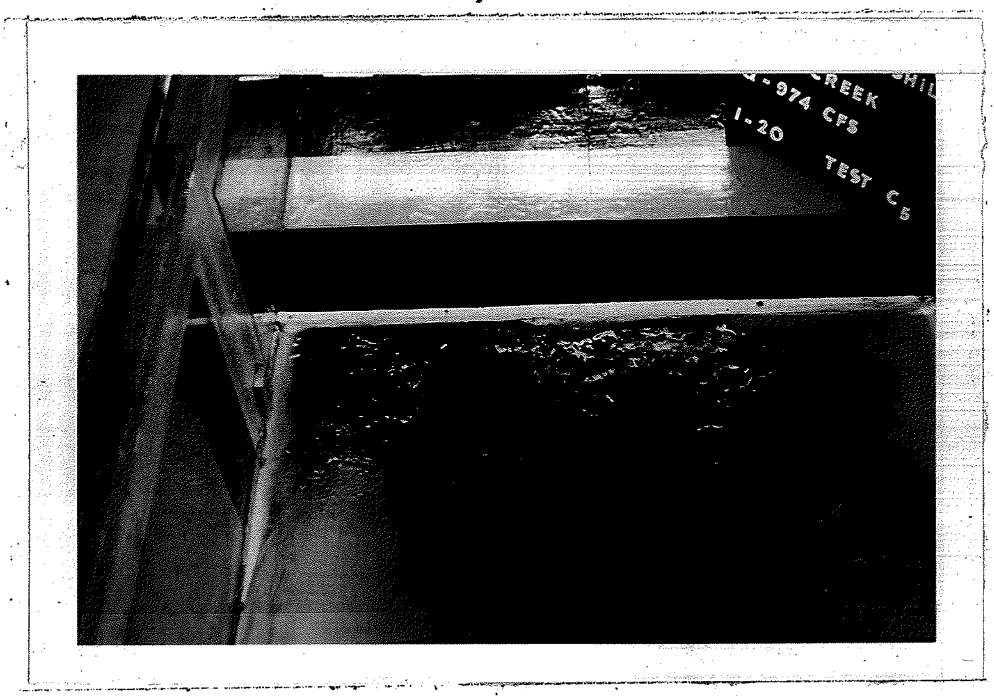
Condition	High tailwater	Low tailwater	Less energy at high tailwater
Hydraulic jump eliminated at inlet	none	500 cfs	none
First standing wave	600 cfs	420 cfs	----
One standing wave remaining	1300 cfs	1000 cfs	1120 cfs
Above wave drowned out	2000 cfs	2000+cfs	2000 cfs
Hydraulic jump began at outlet	1300 cfs	1140 cfs	1120 cfs

TABLE IV-8

Observations of 10' wide culvert tests

Condition	High tailwater	Low tailwater	Less energy at high tailwater
Hydraulic jump eliminated at inlet	none	1000 cfs	------
First standing wave	1200 cfs	900 cfs	1400 cfs
Two waves remaining	2000 cfs	-----	------
One wave remaining	2000+cfs	2070 cfs	1600 cfs
Hydraulic jump began at outlet	none	1400 cfs	1760 cfs

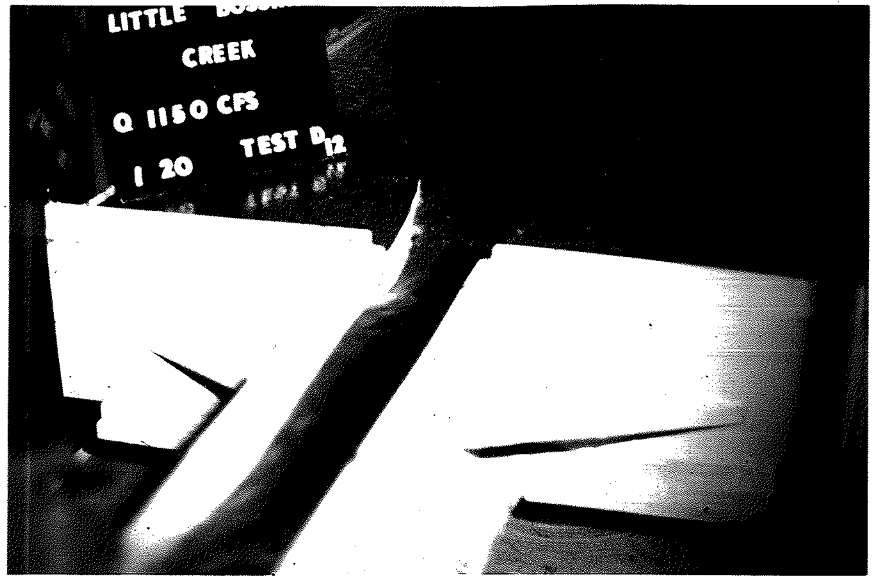
FLOW



Boils downstream of box culvert

PHOTOGRAPH 2

FLOW



Main current moving to right of channel

PHOTOGRAPH 3

Standing waves in chute during large flows

PHOTOGRAPH 4

CHAPTER V

DISCUSSION

a) Comparison of test results

i) 3 cell, 7.5' & 10' models at n = 0.0545

At high tailwater conditions, the three hydraulic models were compared with respect to the headwater elevations at given flows (FIGURE 5-1). In this figure, the lower line represents the tailwater elevation that was controlled by a valve during testing. The upper three lines represent the headwater elevations for each model that were a result of controlling the tailwater pool elevation. The graph was briefly summarized in TABLE V-1 for three selected discharges. The column on the right side of the table shows a percentage comparison of the head difference in each model with the smallest being 100%.

At 885 cfs, there was not much head difference between the three models as seen in FIGURE 5-1. At this point a comparison between the models was difficult for any accuracy. The 10' wide energy culvert was clearly more efficient than the other models at this high tailwater condition. At 1600 cfs, the headwater of the 7.5' wide culvert was well over the road at elevation 1445.6', while the headwater of the three cell box culvert was just barely over the road. The 7.5' energy culvert could be ignored at 2000 cfs because of the excessive head difference which was almost twice that of the three cell culvert.

The 10' energy culvert and the three cell culvert were closely compared at all flows, with the 10' chute being slightly better hydraulically. The critical discharge limit of the 7.5' wide energy culvert was 1200 cfs, beyond which a choke effect was expected.

ii) 3 cell, 7.5' & 10' models at n = 0.025

The three models were compared as before, except at low tailwater conditions this time. The results of the comparison tests were plotted in FIGURE 5-2 with the headwater elevations plotted on their respective curves above the tailwater curve. The distance from the tailwater curve to the headwater curve represents the head difference

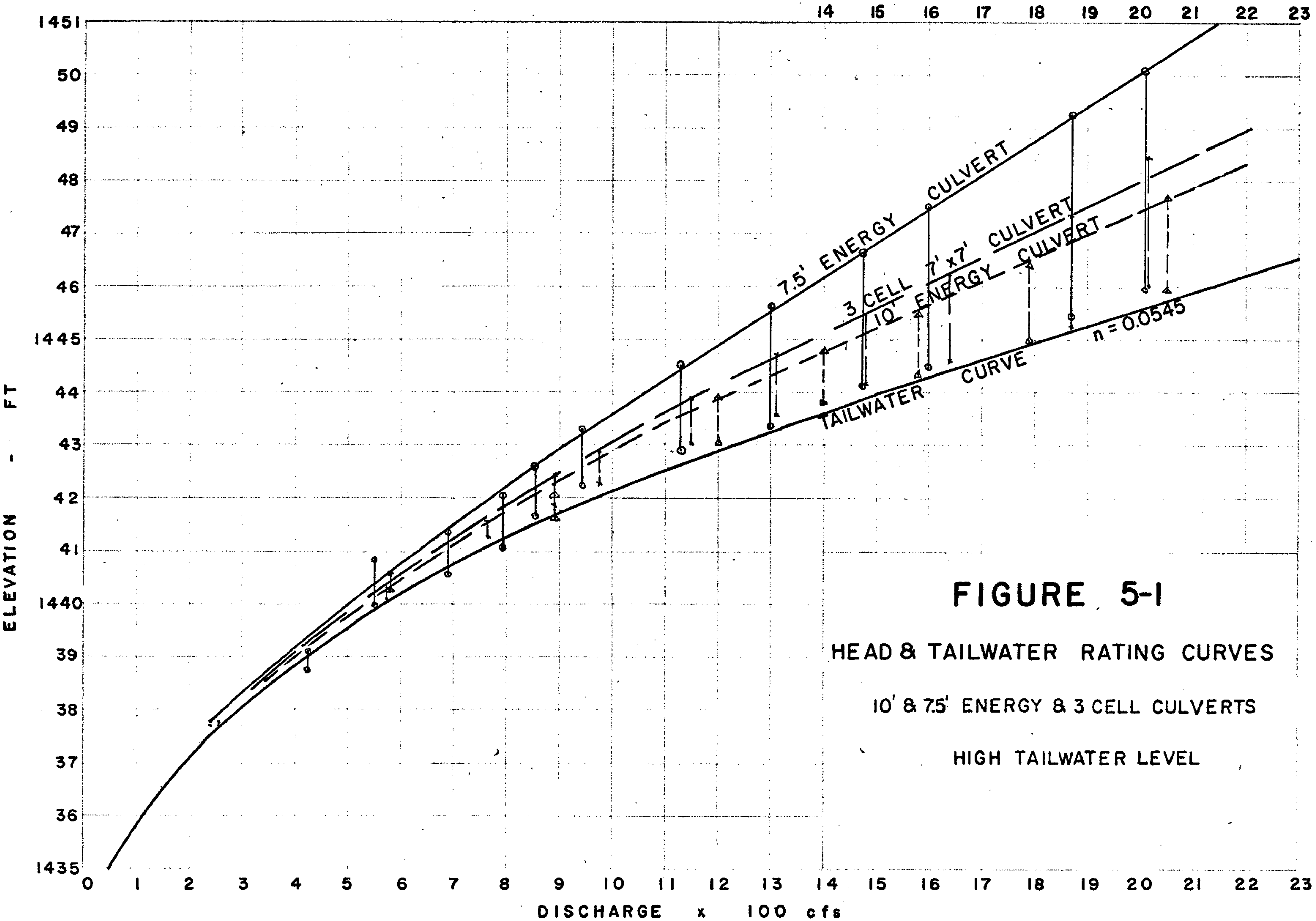


FIGURE 5-1

HEAD & TAILWATER RATING CURVES

10' & 7.5' ENERGY & 3 CELL CULVERTS

HIGH TAILWATER LEVEL

required by the model at the given flow. TABLE V-2 was a comparison summary of FIGURE 5-2 for three selected flows.

TABLE V-1

Head difference comparison at n = 0.0545

Discharge cfs	Model	Head difference ft	Percentage comparison %
900	7.5' chute	1.15	230
	3 cell	0.71	142
	10' chute	0.50	100
1800	7.5' chute	3.68	246
	3 cell	2.00	133
	10' chute	1.50	100
2000	7.5' chute	4.34	254
	3 cell	2.36	138
	10' chute	1.71	100

Upon first glance at FIGURE 5-2, it was obvious that the 7.5' wide energy culvert required a much greater head difference than either of the two other models. However, up to 1200 cfs there was very little difference in head between the three cell and 10' wide culverts, but at 1800 cfs the difference became significant with the three cell model requiring the lowest head. At the maximum flow of 2000 cfs, the head difference between the two models was only 1.55', but this was not too significant as the depth of flow was 11'.

iii) 7.5' & 10' energy culverts at reduced energy

These models were examined to see what difference there would be if the amount of available energy were reduced 1.46'. This may be analogous to a corresponding amount of sediment or else lowering the culvert 3.94' instead of 5.40' below the normal channel bed. The test comparison results were plotted in FIGURE 5-3 and briefly summarized in TABLE V-3.

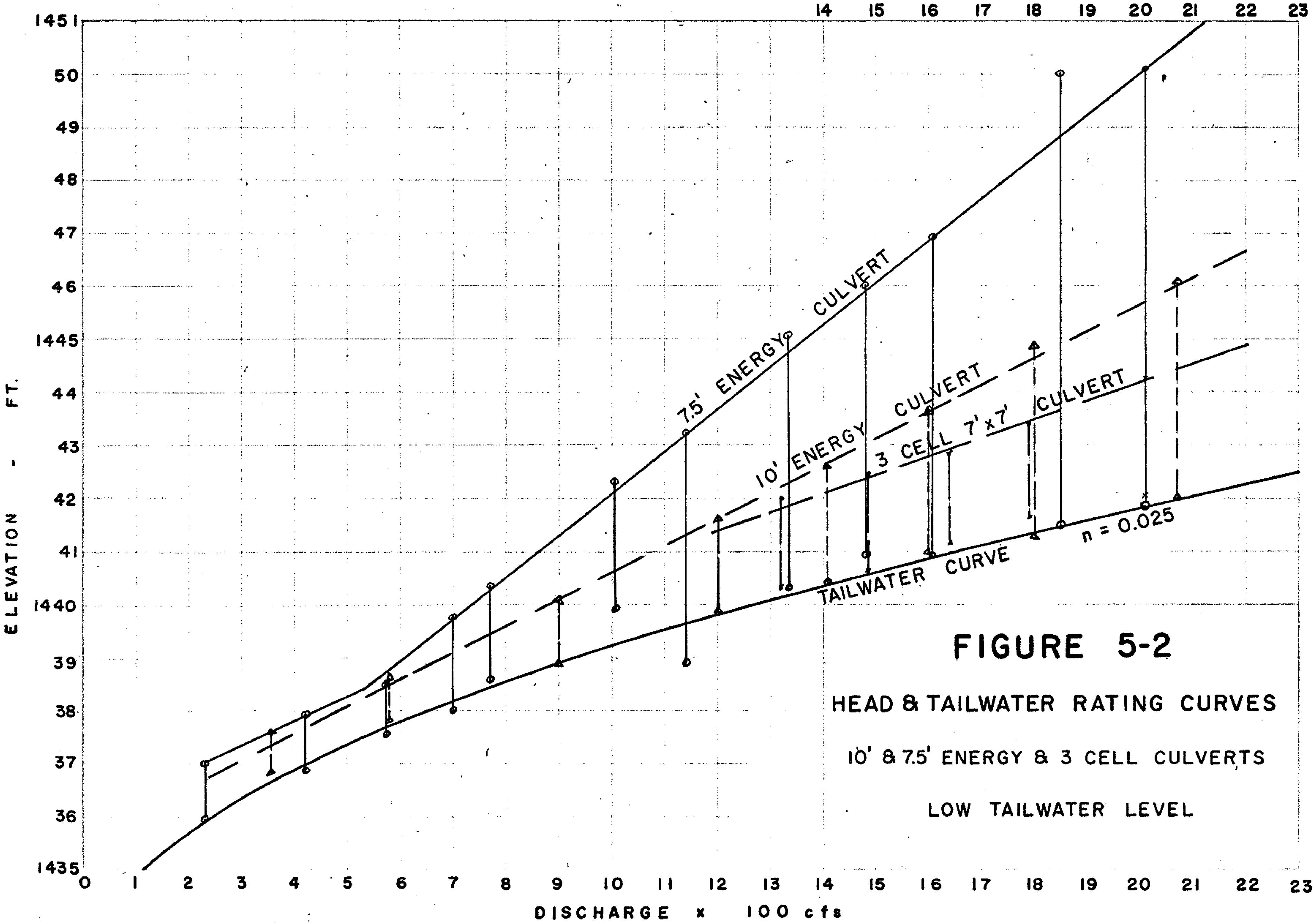


FIGURE 5-2

HEAD & TAILWATER RATING CURVES

10' & 7.5' ENERGY & 3 CELL CULVERTS

LOW TAILWATER LEVEL

TABLE V-2

Head difference comparison at n = 0.025

Discharge cfs	Model	Head difference ft	Percentage comparison %
900	7.5' chute	2.55	239
	10' chute	1.15	109
	3 cell	1.05	100
1800	7.5' chute	7.00	342
	10' chute	3.28	160
	3 cell	2.05	100
2000	7.5' chute	8.00	356
	10' chute	3.80	169
	3 cell	2.25	100

TABLE V-3

7.5' & 10' culvert head comparison at n = 0.0545

Model	Discharge cfs	Flow condition	Head difference ft	Percentage comparison %
7.5' chute	900	reduced energy	1.25	114
		normal	1.10	100
	1800	reduced energy	4.78	226
		normal	3.80	100
10' chute	900	reduced energy	0.61	135
		normal	0.45	100
	1800	reduced energy	1.80	129
		normal	1.40	100

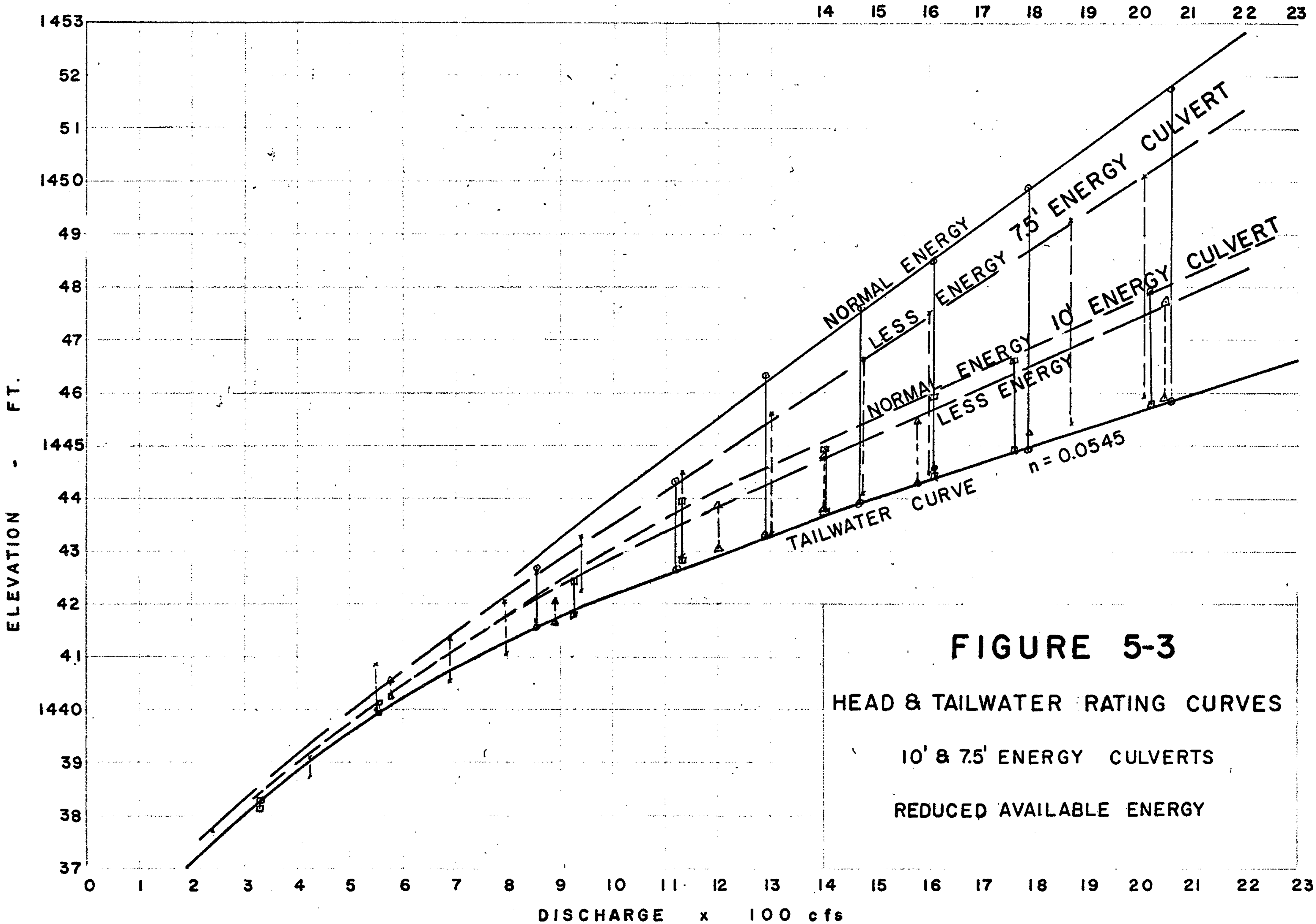


FIGURE 5-3

HEAD & TAILWATER RATING CURVES

10' & 7.5' ENERGY CULVERTS

REDUCED AVAILABLE ENERGY

The bottom line in FIGURE 5-3 represents the predetermined tailwater curve while the first pair of curves above this represent the headwater elevations for the 10' energy culvert. The bottom curve of this pair was the water surface at the normal chute floor, and the upper curve was the water surface at the higher chute floor elevation. The top pair of curves represent the headwater elevations for the 7.5' energy culvert. The bottom curve was for the normal chute floor level, while the top curve was for the raised chute floor.

At low flows in the neighborhood of 700 cfs, there was no noticable difference between the two energy levels for both culverts. As expected at larger flows, the difference between the two energy levels was significant enough to draw intresting conclusions. When a reduced amount of energy was used, the 10' wide chute performed better than the 7.5' wide chute at all discharges. This meant that the water surface elevation rose less for the 10' wide culvert than for the 7.5' wide culvert as seen in FIGURE 5-3.

b) 3 cell model performance vs prototype

From model testing, the actual head difference required by the structure did not compare very well with the theoretical head difference at an entrance coefficient of 0.5 as seen in TABLE V-4.

TABLE V-4

Head differences for 3 cell culvert

Discharge	Test result difference	Theoretical head difference	
		$K_e = 0.2$	$K_e = 0.5$
cfs	ft	ft	ft
900	0.60	0.80	1.00
1150	0.90	1.30	1.70
1480	1.32	2.10	2.80
1640	1.67	2.60	3.40
2010	2.44	4.00	5.00

From TABLE V-4, it may be seen that the Bureau of Public Roads nomograph was not a good guide to obtain the correct values for the required head difference. Nevertheless these nomographs are still used as a basic aid in design offices today.

The design error occurred when the discharge was calculated for one cell and then multiplied by three for the structure. The result was close for low flows, but it was estimated that the entrance coefficient for the middle cell almost approached zero due to the smooth contraction of the flow. The entrance coefficient (K_e) for the side barrels was reduced considerably as only the outside edges of the barrels were affected by the flow contraction. If the selected coefficient was 0.2 instead of the recommended value of 0.5, a better correlation was found between the results from test results and TABLE V-4. Thus the discharge as calculated from the nomograph for a single cell cannot be multiplied by any number of times to get the approximate capacity of a structure. These charts may only be used for a single cell or for a series of cells where there are no contraction interferences between them. This structure was rated at 900 cfs by its designers but model testing showed that its actual capacity was 1230 cfs or 25% overdesigned. It is in this area that hydraulic models are the most valuable as they show the discrepancies that exist between theory and practice as well as clarifying assumptions.

From TABLE V-5, it may be seen that the inlet velocities for the three cell culvert differed from the outlet velocities, especially at larger discharges. This large difference was due mainly to the overestimated losses. Since the total drop in the channel bed across the structure was 1.4', if 1.0' of this was converted to energy, the resulting velocity increase would be approximately 8 ft./second. Thus, by estimating the losses at a greatly reduced value, the uneven distribution would decrease.

c) Energy culvert behavior

i) 7.5' & 10' energy culverts

1) Velocity distribution

The major problem with these structures was the excessive turbulence at the outlet because the velocities did not decrease to the degree that was expected. To compare the inlet and outlet velocities more easily, TABLE V-5 was prepared from the testing records.

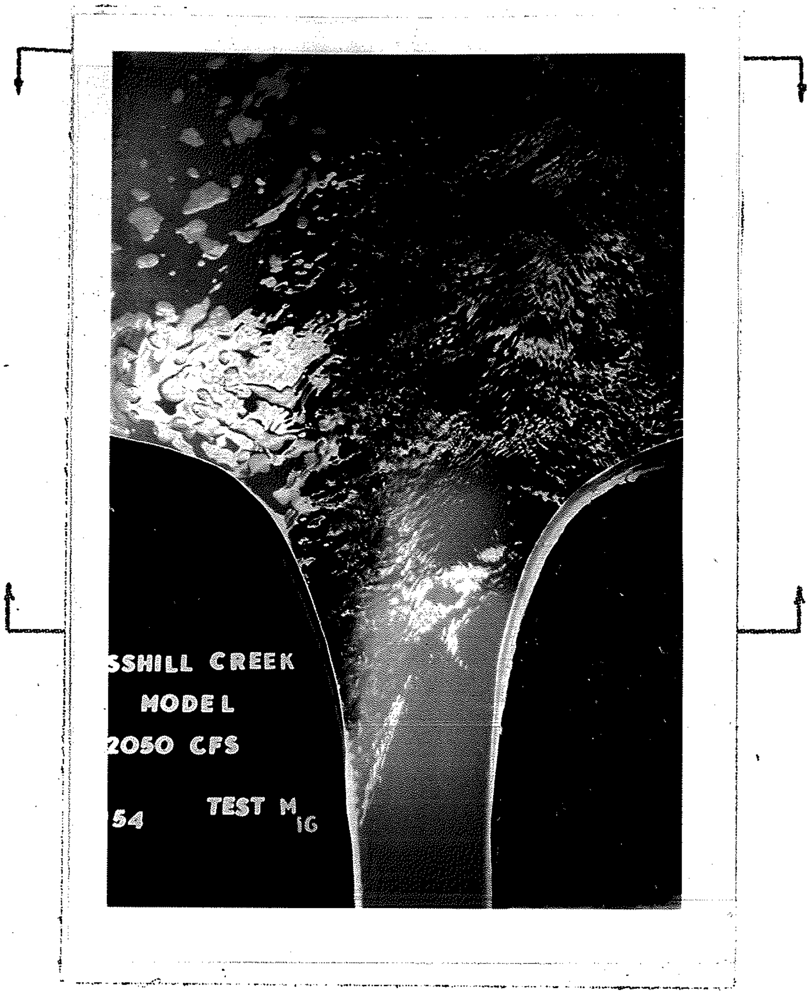
TABLE V-5

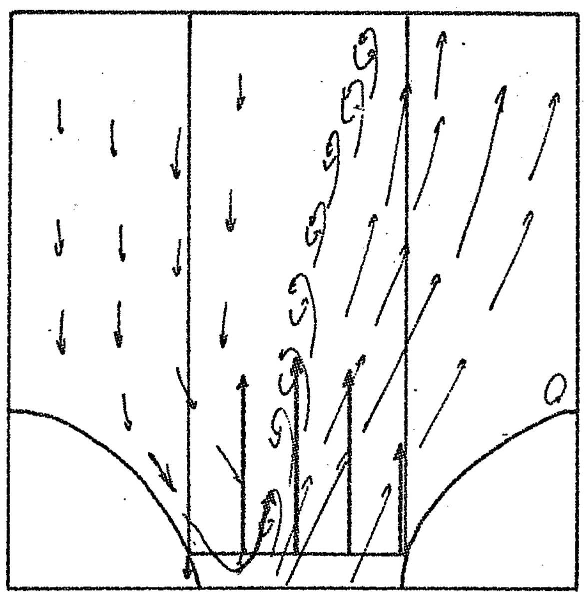
Velocities at structure inlet and outlet

Discharge	7.5' chute		Discharge	10' chute		Discharge	Three cell	
	Inlet	Outlet		Inlet	Outlet		Inlet	Outlet
cfs	fps	fps	cfs	fps	fps	cfs	fps	fps
548	4.8	6.7	580	4.0	5.2	574	---	---
853	4.3	9.9	890	6.1	6.7	892	---	---
1130	5.7	10.0	1200	6.7	7.5	1150	4.3	8.3
1600	6.5	14.5	1500	7.2	9.8	1640	4.3	11.9
2010	6.7	17.7	2050	8.6	11.6	2015	4.5	15.3

Since the drop for the energy culverts in the channel bed from upstream to downstream of the structure was 1.46', from the above table it was evident that the energy losses were over estimated. Most of this drop was converted to kinetic energy but not converted back to potential energy as intended. The greater difference between velocities for the 7.5' model at larger flows was due to the backwater effect created by the narrow chute width. Energy losses in the culvert were quite small and the slope of the chute would be sufficient to overcome them. At larger flows the excessive outlet velocities produced considerable turbulence in the form of boils, standing waves and large eddies.

Due to the high velocities the lateral distribution of the water from the chute took place only to the end of the rectangular cross section or top of the outlet floor. From this point the flow continued out in the channel in a block (PHOTOGRAPH 5); the distinct rectangular shape finally dispersing about 100-150' downstream. During very low discharges the main thread of the current moved to one side of the channel while the water on the other side was relatively tranquil in a very large eddy. At about 500 cfs the main thread of the current



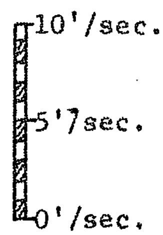


Energy culvert downstream turbulence

PHOTOGRAPH 5

Velocity vector

scale:



swung over to the other side of the channel which created a large eddy on the opposity side (PHOTOGRAPH 5), and remained there as the flow increased.

This phenomena remained to be completely explained, but the current moving to one side may result from the fact that the fast moving water encountered a relatively still pool of water. To maintain its energy, the water forced itself to one side of the channel, thus minimizing the friction losses encountered along the boundary of the fast and slow moving water. At the side of the channel where the velocities were the largest, the water surface profile was lower and rougher. It was this fast current leaving the structure and moving downstream without dissipation that would cause massive erosion of the banks. This scour would be minimized by reducing the total drop from one side of the structure to the other to a minimum of 0.6' or less from the previous value of 1.46'.

2) Doubled discharge

From Chapter II, the theory pointed out that for the 10' wide chute by doubling the discharge, only a small increase in head would result at the structure inlet and outlet. Since the effect of doubling the discharge was considered important, it was looked at in more detail. TABLE V-6 summarized the test results for high tailwater conditions.

TABLE V-6

Head difference for doubled discharge

Energy culvert width	Energy	Inlet to outlet of structure for 900 cfs to 1800 cfs		Inlet to outlet of chute for 900 cfs to 1800 cfs	
		inlet	outlet	inlet	outlet
ft		ft	ft	ft	ft
7.5	normal	6.66	4.04	5.16	2.00
7.5	reduced	7.28	3.50	5.52	2.14
10	normal	4.26	3.24	3.30	3.30
10	reduced	4.18	3.04	2.38	2.32

The above table shows the result of the choke effect on the water levels for the 7.5' wide energy culvert. For the 10' wide model, the test results produced higher water levels than expected. This was due to the fact that the theory was developed on the assumption of a two dimensional flow. The model testing brought in a third dimension, the width. Since the effects of contraction and expansion in this direction were not considered, it has been shown that the effect was significant enough to be a major design factor. In TABLE V-6, the values for the 7.5' wide chute may be ignored as the upper discharge was past the critical limit for this model; however, for the 10' model, the differences were less when the available energy was reduced. It must also be remembered that the initial water levels for the reduced energy tests were much higher than for the other tests.

3) Reduced available energy

With reduced available energy, the water surface elevations for doubling the discharge were much greater than the expected 1.4' to 2', especially in the chute region. It must be mentioned here that for both models, this reduced amount of energy would be considered as an alternate design.

During testing it was observed that shock waves which accompany supercritical flow conditions appeared in the chute at approximately 900 cfs. The flow in these areas was not near the critical region so that conclusions as to whether the flow actually was supercritical were not considered.

ii) 7.5' energy culvert

This model performed approximately as the theory predicted, however, its efficiency near the critical discharge may be open to discussion. The fact that it was operated near and past the limiting discharge gave more support to the testing and discussion of the 10' wide energy culvert.

iii) 10' energy culvert

Based on experience from the previous model, the 10' wide chute energy culvert performed much better than expected. At high tailwater conditions, a hydraulic jump was expected at the outlet but none occurred, which meant that the critical capacity of the model was not reached. When the flow does reach this capacity, the structure would act as a choke and a backwater effect would occur.

No choke effect was noticed with this model and none was expected within the given range of discharges. With a 2 1/2' increase in chute width, the discharge at which critical depth would occur (critical discharge) more than doubled from 1350 cfs to 2900 cfs at high tailwater conditions.

d) Cost estimates

i) Introduction

From previous considerations, the energy culvert application depends on its cost compared to that of similar structures. The structures to which this design was compared to were a therr cell 7' x 7' box culvert, three cell 10' x 10' box culvert, corrugated arch pipe, corrugated round pipe, timber bridge and a concrete deck bridge. Further details may be seen in APPENDIX D, while the data was summarized in TABLE V-7.

TABLE V-7

Cost estimate summation

Structure	900 cfs	1800 cfs
3 cell 7' x 7' box	$ 18,000	
3 cell 10' x 10' box		$ 30,000
7.5' energy culvert	$ 16,000	
10' energy culvert		$ 20,000
Corrugated metal pipe		
- round pipe	$ 18,200	$ 36,400
- arch pipe	$ 21,000	$ 42,000
Bridge		
- timber	$ 11,000	$ 11,000
- concrete deck	$ 30,000	$ 30,000

ii) Cost comparison

From TABLE V-7 the timber bridge was by far the most economical structure that could be built for any discharge, however, this bridge would not be selected for use on a major road. The corrugated metal pipes require too much channel width for an economical installation. If the flow was definitely below 900 cfs, then the best structure to build would be the three cell culvert, but if the flow was expected to be over 1200 cfs, then the 10' wide energy culvert would be the best structure to consider for construction. For the same discharge, the 10' wide culvert costs 2/3 of the cost of the concrete deck bridge or the 10' x 10' box culvert.

e) Adaptation to field use

The construction of an energy culvert would not be difficult as there were no unique structural problems and the curved concrete walls and floor were the only complex concrete forming problems. The curved inlet walls would be approximated by four straight sections, thus eliminating some of the concrete work. The outlet walls would have to be curved to a point one half the distance up the channel side slope. A linear section would then replace the curved section as the effect of the curved wall at this point was insignificant (FIGURE 5-4).

It must be noted that if such an energy culvert was constructed, it would be the ideal location for a streamflow recording gauge because of the rectangular cross section of the structure. Some adjustment would have to be made for the possibility of silting during low flows because these low flows are sometimes very important. The stage recording device could be connected directly to the concrete chute wall to provide easy access for constant measurement.

One variation in this design would be the use of sheet steel piling for the walls instead of concrete. They would be driven deep enough so that gabions could be used for the floor instead of a concrete slab, thus the structure could be built without concrete. The gabions would be anchored to the piling in some manner to prevent movement. In this way an energy culvert could be placed in a river bed during low flows without interrupting the flow or requiring a by-pass channel.

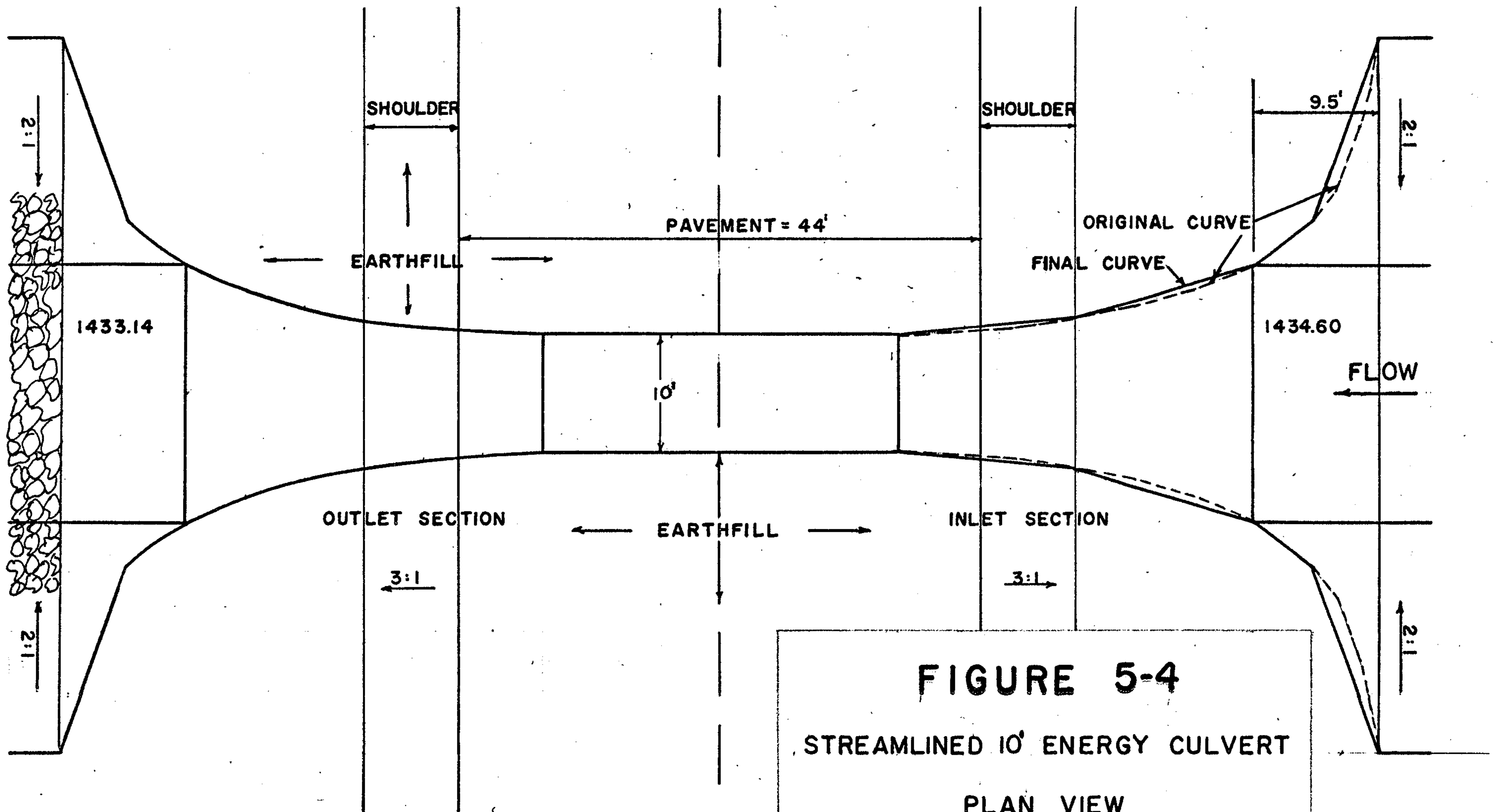


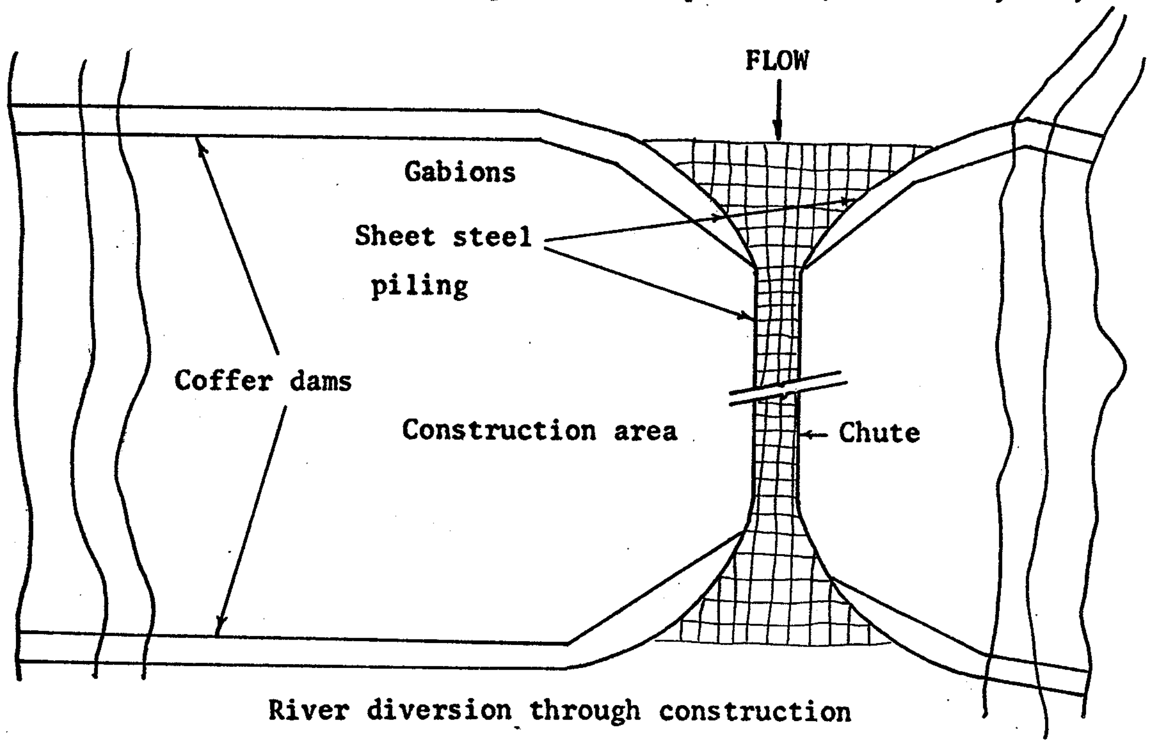
FIGURE 5-4

STREAMLINED 10' ENERGY CULVERT

PLAN VIEW

1 mm = 5.0'

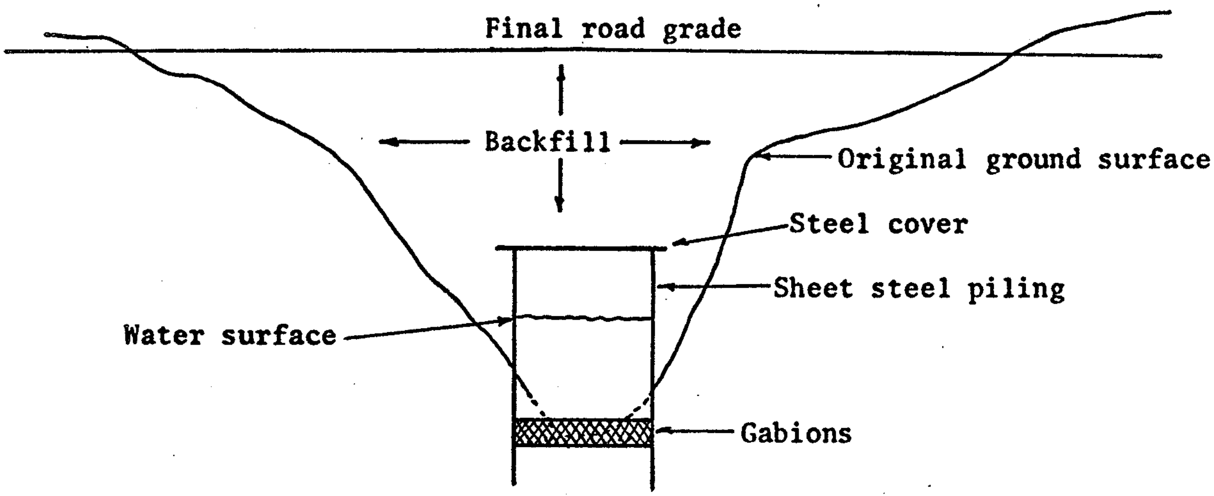
Using the gabions and sheet metal piling, water may be diverted around to through a dam during the construction phase. With some planning, the structure could be built so that the danger of damage from excessive flows may be minimized. Here the primary use of this structure would be to reduce the width of the river to a minimum to allow as much construction as possible to proceed (FIGURE 5-5, 5-6).



River diversion through construction

FIGURE 5-5

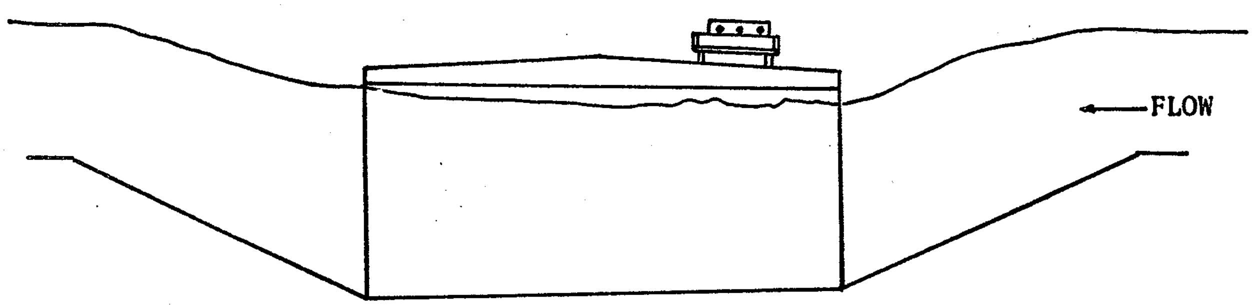
Another use would be in the elimination of the bridge over a shallow river in a deep valley. A bridge would normally be required, but this may be eliminated by the use of an energy culvert and backfill. The structure would be placed in the river bed during a low flow period or during the winter, and then backfilled to the desired road grade. The steel cover on the culvert would allow sufficient clearance for a free water surface at all times, much the same as the chute ceiling on an energy culvert. In this way the tremendous costs of a bridge may be avoided and a first class structure provided at a reasonable cost (FIGURE 5-6).



Energy culvert in a valley

FIGURE 5-6

An additional use of this culvert may come from a functional as well as scenic effect. This effect comes from the fact that the water surface in the chute was considerably lower than the headwater surface elevation. If the road bed was placed at the correct elevation, the car passengers could drive along the highway and see water in a channel at a higher elevation on both sides of the road (FIGURE 5-7). Additional model testing would be required to determine the best chute width, inlet and outlet lengths and shapes to obtain the maximum scenic effect.



Scenic effect of energy culvert

FIGURE 5-7

The most useful application of the concrete energy culvert would be where low flows exist throughout most of the year, but extremely high flows occurred during the spring runoff. It is in a case such as this that the energy culvert would be hydraulically more efficient over a large range of discharges instead of restricted to a narrow range around the design capacity as many structures may be.

The structure could be designed for only 80% of the maximum expected flow, relying on a backwater effect or ponding of water upstream if the conditions would allow. The inlet walls would be given much more attention during the design phase than the outlet walls in this case. The walls would be 2' to 4' higher than the water levels to be sure that the backwater created by the choke effect of the chute was contained within them and not allowed to spill out and cause massive erosion.

f) Final design procedure

Due to the difficulties in attempting the design calculations of an energy culvert for the first time, an example of the final design procedure was presented in detail in APPENDIX E. This example was for a design flow of 1200 cfs, an 11.0' wide chute and a channel roughness of 0.035.

g) Comparison to previous work

A paper was presented to the Main Road Department of Queensland, Australia (REFERENCE 9), in which the second part dealt with the energy culvert concept as presented by Dr. G.R. McKay (REFERENCE 1). From this paper, the energy culvert presented, was designed so that the critical depth occurred at the entrance to the chute. Upon comparing the worked example in the paper at a discharge of 640 cfs, chute width equal to 10.0', with FIGURE 3, APPENDIX A, the difference in required energy levels was 0.06'. This was considered an excellent comparison of the design principles.

To obtain a smooth water surface, it was found that only a small portion of the actual capacity of the structure should be used, providing that a hydraulic jump does not form at the outlet. Therefore, the problem of eliminating standing waves in the chute would be easily solved by increasing the chute width considerably.

h) Choke effect

A choke effect occurs when a constriction in a channel is severe enough to influence or control the water levels upstream, the result of which is a backwater curve. If the chute width was held constant and the discharge increased, the unit discharge and critical depth both increased. It followed that within the contraction, the specific energy would also increase, resulting in increased water levels to form a backwater curve. This resulted in additional available energy to force the flow through the contraction. The water levels would adjust themselves according to the amount of energy required and the discharge.

In the 7.5' energy culvert model, there was insufficient energy to pass more than 1350 cfs at high tailwater levels, without the formation of a backwater curve. If more energy was made available by lowering the chute to a greater depth, the head build up would be delayed until a larger limiting flow was reached.

It has been noted that throughout the observations and discussions that a hydraulic jump formed at much lower flows for the low tailwater condition than for the high tailwater condition. It was well known that a hydraulic jump that formed at low tailwater would be drowned out if the tailwater level was raised sufficiently. The formation of the jump depends on the level of the water surface in the downstream channel which in turn depends on the roughness of the channel. It must be noted here that the jump did not form in the model testing until the critical discharge of the particular model had been exceeded. Therefore, in designing this structure, no hydraulic jump would occur as long as the flow does not exceed the critical limit. If the flow was expected to exceed the limit, additional downstream protection in the form of heavy rip-rap must be considered.

The 7.5' wide chute reached its limiting discharge at 850 cfs for n = 0.025, and 1350 cfs for n = 0.0545; the 10' wide chute at 1350 cfs and 2900 cfs respectively.

i) Sedimentation

When any culvert has a sunken centre section or chute, there would be soil and debris settling out during low flows. This probability was examined by introducing sand into the flow of water through the energy culvert during testing. At no time for flows over approximately 100 cfs did any sand settle within the structure. This was due to the large velocities and continuous surfaces that did not provide any pockets where eddies could form and deposit material.

To check the result of sedimentation on the water surface profiles, the amount of available energy was reduced 1.46' as previously discussed (FIGURE 8, APPENDIX A). With a deposit of 1.46' of material, the water surface elevation increased 0.40'. This meant that an area of 1.06' times the chute width was subtracted from the cross sectional area of the flow, and to pass the same discharge, the velocity had to increase. Assuming that a large amount of soil had been deposited at low flows, when a larger flow occurred, erosion would begin. The amount to which it continued would depend on the ease with which the material eroded and the discharge.

The problem of debris collecting in front of the culvert, such as logs, would be solved only by removal. Small floating debris would be passed downstream on the open water surface instead of collecting at the inlet as occurs in other culverts.

j) Ice problem

The probability of ice forming in the chute during the winter must be considered in this climate. There was also a good possibility that the water standing in the chute would freeze through to the bottom of the chute. There was also a good possibility that ice pressure may damage the chute section if it was not considered in the design. The longitudinal ice pressure in the chute would be relieved by the sloping inlet and outlet floors. The lateral ice pressure would be taken care of by providing heavy reinforcing in the concrete walls in addition to the three concrete collars shown in FIGURES 5 & 6, APPENDIX A. To prevent ice build up, the water could be pumped out of the chute in the fall, but this would not last long as ground water seepage would soon fill it in again.

In the spring, the ice within the culvert would be the last to melt, resulting in a temporary decrease in capacity. When the water flowed over the ice at a velocity of about 6 fps, the ice would melt very quickly due to the large temperature gradient from the water in the stream to the ice in the culvert. In the energy culvert, the maximum velocities were recorded near the bottom of the chute. The ice that formed at or near the bottom of the chute would be in the fastest thread of the current during the spring thaw. Complete melting would probably occur within a week or two, depending on the temperature, thus the full culvert capacity would be restored before the spring runoff reached its peak in April. More detailed investigation into spring break-up would be essential to study the freezing problem in detail.

With this structure there would always be a free water surface, so that when spring came and an early flow of water occurred, the structure would act as a single cell culvert. This single cell would act partly as an energy culvert with only a small drop in the chute floor elevation if any. The original capacity of the structure would be restored as soon as the ice had melted.

CHAPTER VI

CONCLUSIONS

a) Summary

i) 3 cell & 10' wide energy culvert

In comparing the three cell box culvert and the 10' wide energy culvert, the energy culvert was a more efficient means of passing water under a road for all discharges up 2000 cfs for high tailwater conditions. However, at low tailwater conditions, the three cell culvert performed the best, which was due to its large corss sectional area.

ii) 7.5' & 10' wide energy culverts

The 10' wide energy culvert did not have a choke effect at large flows as the 7.5' wide chute experienced, but, the operating flow range for the latter culvert was much less than that of the 10' wide chute model. The 10' energy culvert performed best at a high tailwater flow condition corresponding to a large channel roughness.

iii) 7.5' & 10' wide energy culverts at two energy levels

In the event of sedimentation or ice forming in either culvert, no problems were expected. With an increase in flow, the sediment that settled out would erode out and the ice would quickly melt.

In reducing the amount of available energy, it was found that the water surface was slightly higher and smoother with higher velocities.

iv) Energy culvert at doubled discharge

When the discharge was increased 100% in the 10' wide culvert, the upstream head was increased 3.0' or 25%. From this, the capacity of a structure may be greatly increased without re-designing the structure.

b) Conclusions

The energy culvert has been found to be more efficient, passing the same discharge as a three cell culvert with only half the flow area. The centre section may be shortened up to 50% by beginning the inlet and outlet sections within the road section, thus reducing the overall structure length and consequently the cost by 20%.

The inlet walls should be approximated by three or four straight sections, while the outlet walls in the transitional section may also be approximated by two or three straight sections, without interferring significantly with the flow pattern. The drop at the inlet section should equal the rise at the outlet section to give a lower exit velocity and reduce the turbulence downstream.

c) Recommendations

1) It is strongly recommended that erosion control studies be made with the energy culvert model in a sand bed channel. This study could examine means for a more efficient energy re-conversion and reduction of turbulence. Studies on proper placement of rip rap should also be included at the same time.

2) The range of discharges from 50 to 600 cfs should be examined for chute widths of 3.0' to 6.0'. This type of structure would find common usage in replacing a large bank of small (3' diameter) culverts. The flow range of 2000 to 5000 cfs should also be looked at for chute widths of 10' up to 20'. Although this size of structure may not find a great deal of application, it may be very good in some cases.

3) The curved floor of the outlet should be kept basically unchanged. One slight improvement would be to raise the floor a bit faster with respect to the distance from the structure for a more efficient energy conversion.

Another structure modification to examine would be the shorter chute length and linear inlet and outlet walls. Several different chute depths should also be examined to see if the water surface profile was lowered much less than the chute floor, and if there was an economical limit to the depth of the chute.

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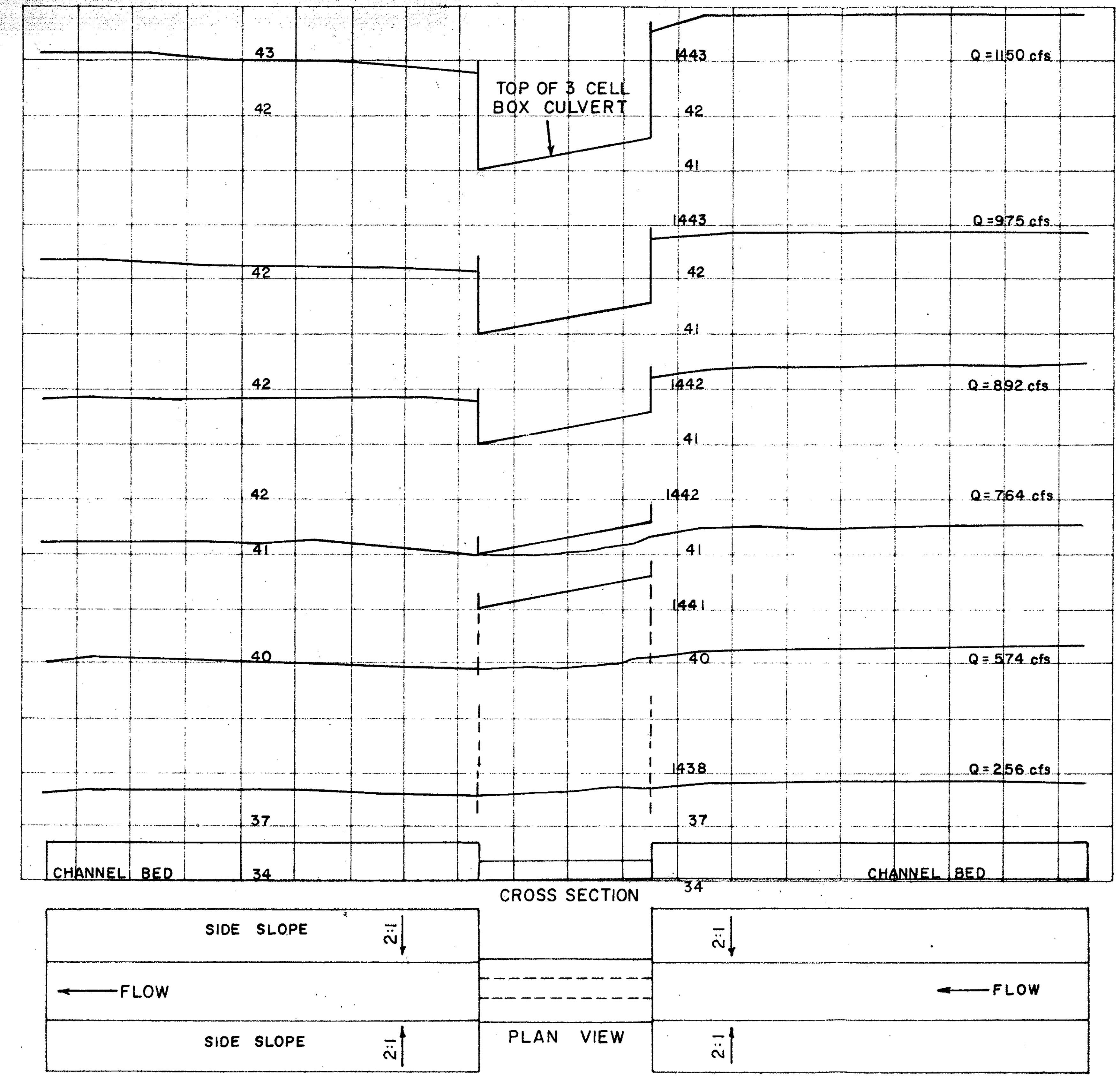

FIGURE 6-1

HIGH TAILWATER LEVELS n = 0.0545

3 CELL 7' x 7' BOX CULVERT

WATER SURFACE PROFILES

SCALE: VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S LOWE NOV/69

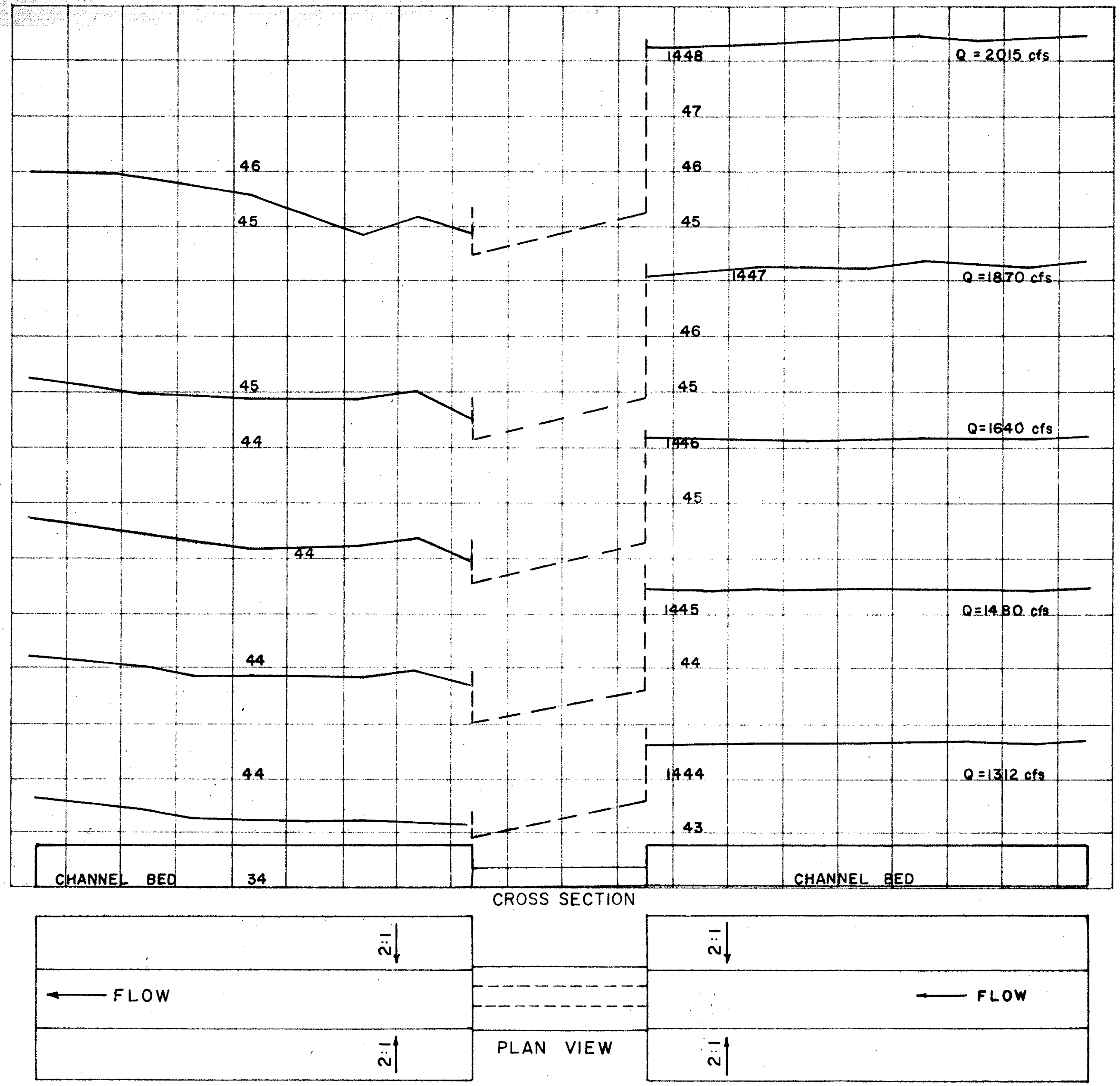

FIGURE 6-2

HIGH TAILWATER LEVELS n = 0.0545

3 CELL 7' x 7' BOX CULVERT

WATER SURFACE PROFILES

SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S LOWE NOV / 69

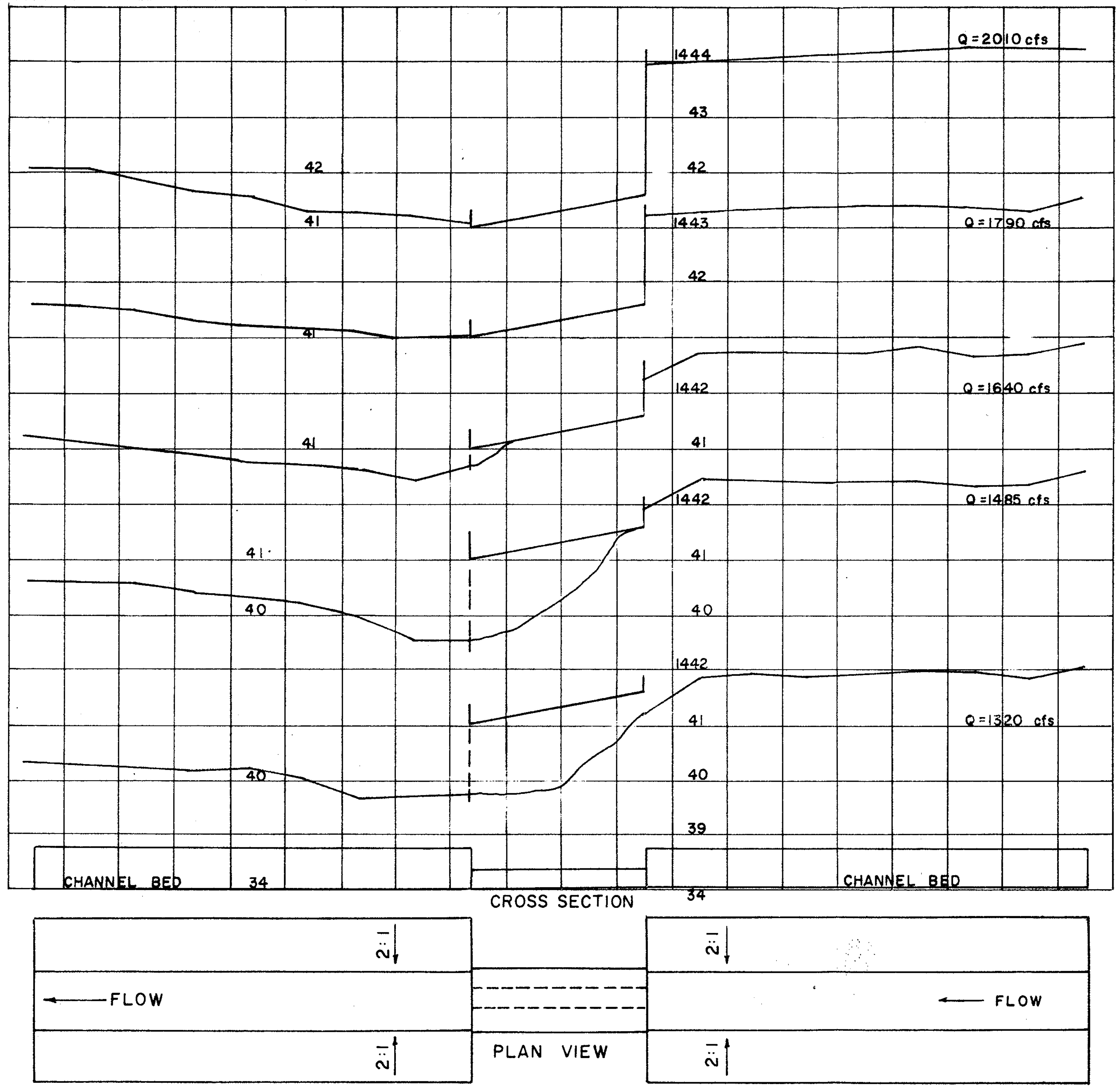

FIGURE 6-3

LOW TAILWATER LEVELS n = 0.025

3 CELL 7'x7' BOX CULVERT

WATER SURFACE PROFILES

SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S. LOWE NOV/69

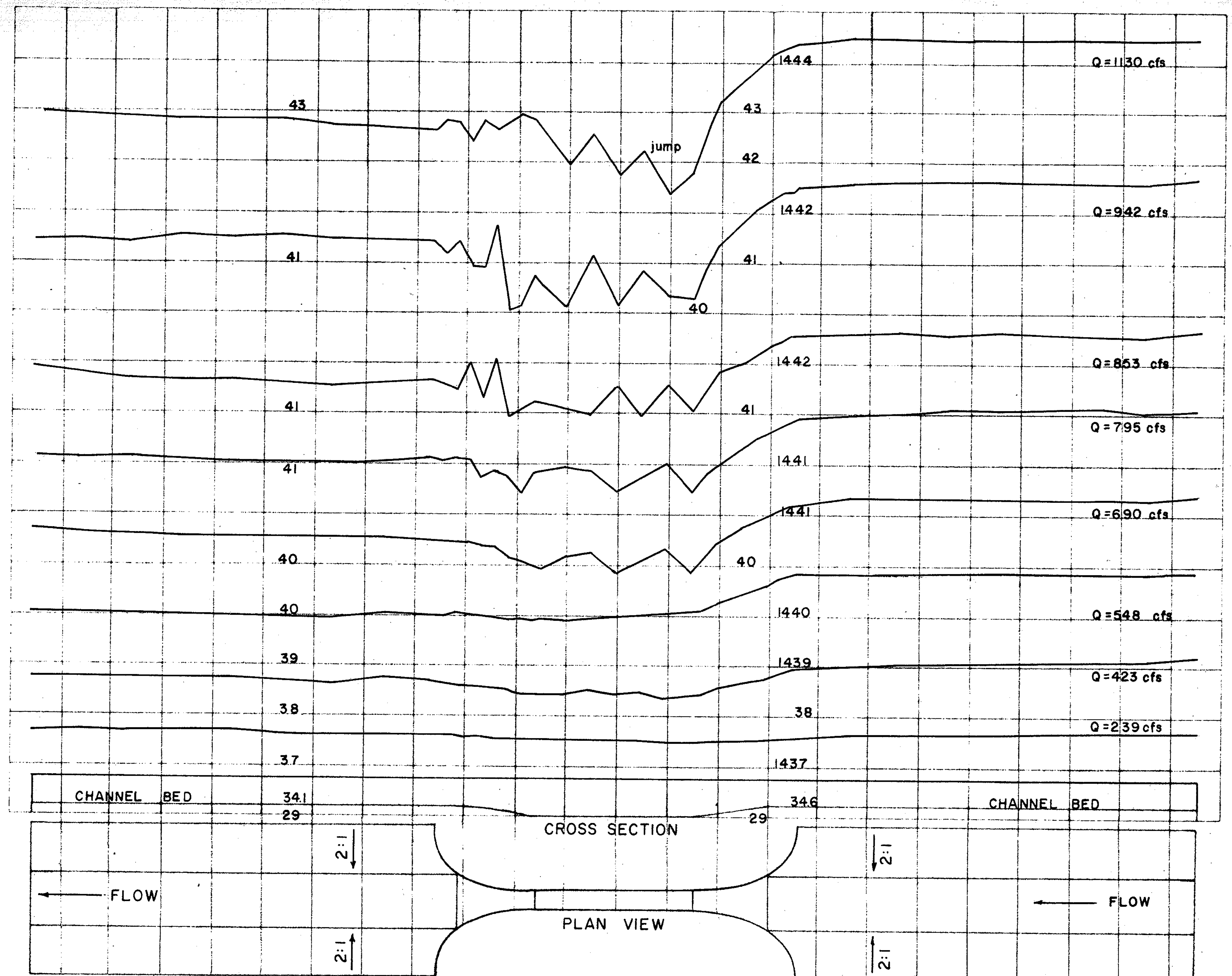

FIGURE 6-4

HIGH TAILWATER LEVELS n = 0.0545

7.5' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S LOWE NOV / 69

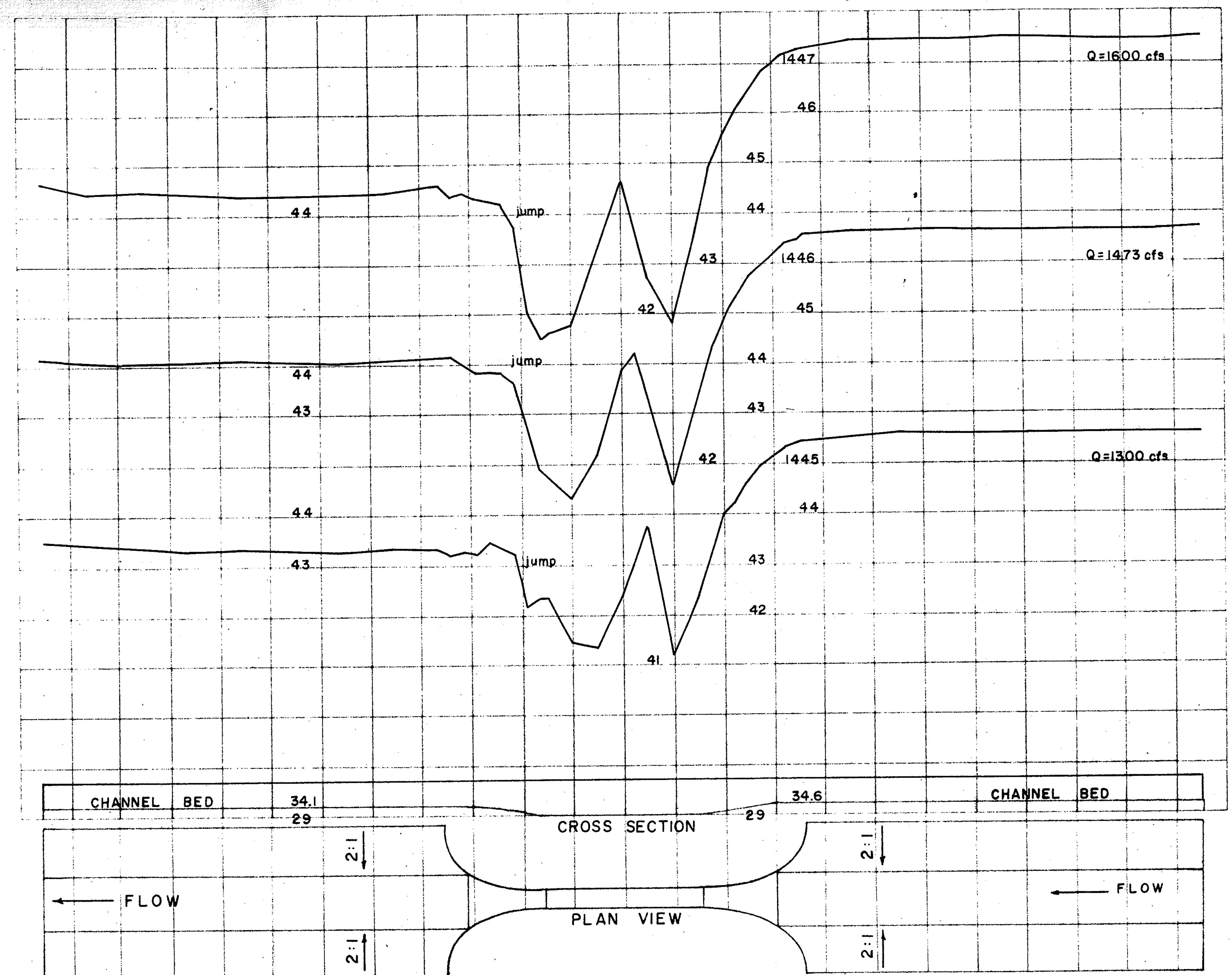

FIGURE 6-5

HIGH TAILWATER LEVELS n = 0.0545

7.5' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20'

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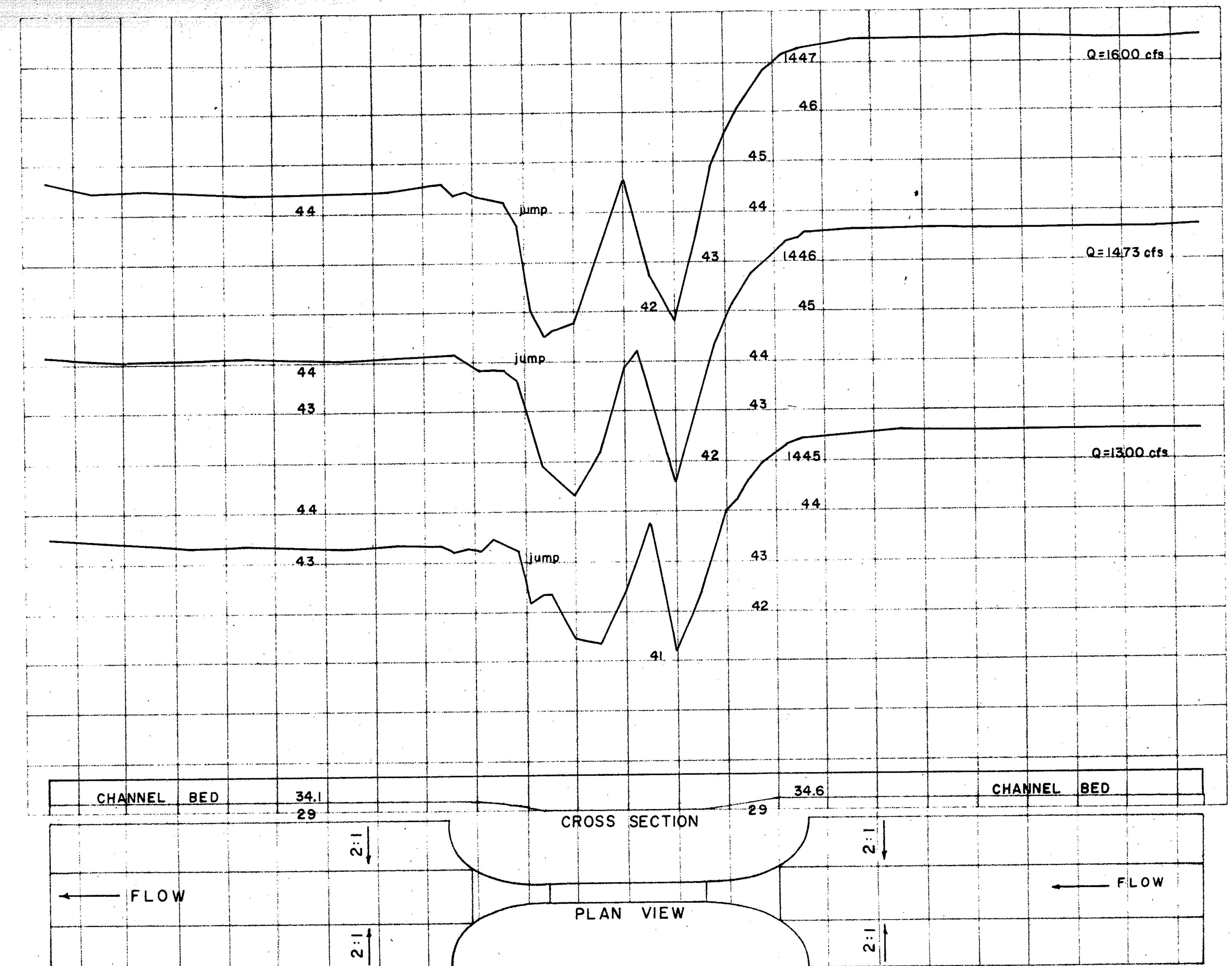

FIGURE 6-5

HIGH TAILWATER LEVELS n = 0.0545

7.5' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20'

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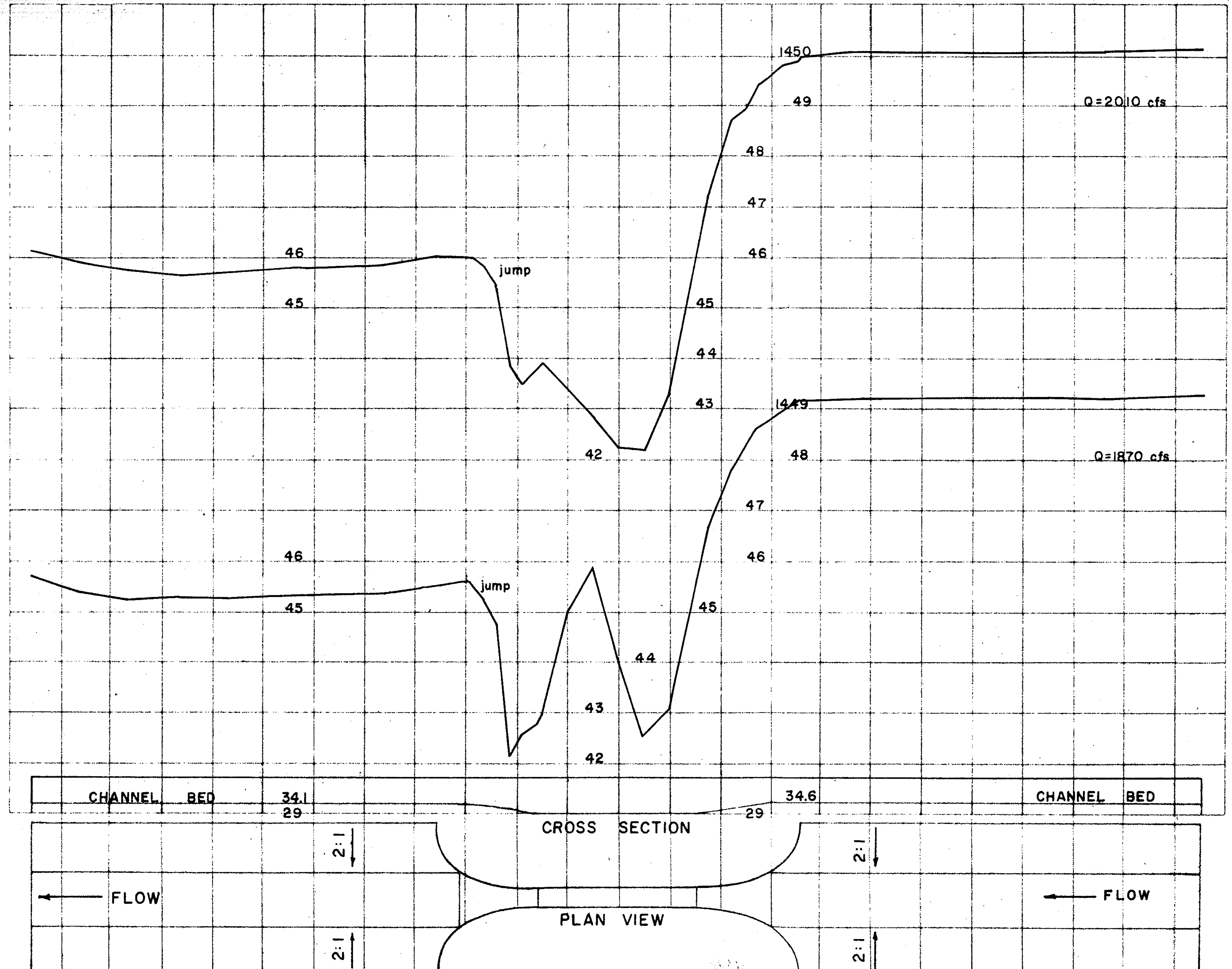


FIGURE 6-6

HIGH TAILWATER LEVELS n = 0.0545

7.5' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S LOWE NOV / 69

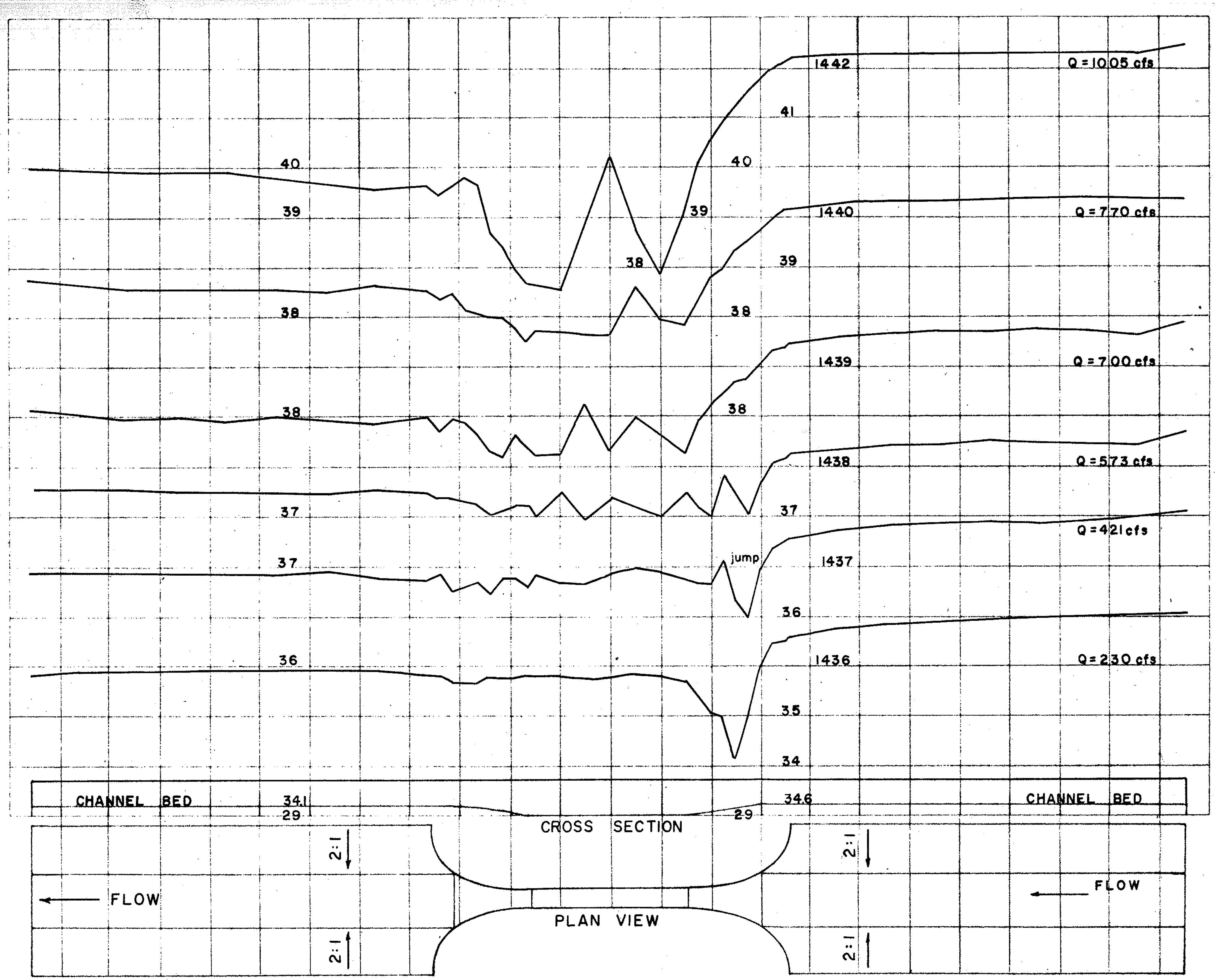


FIGURE 6-7

LOW TAILWATER LEVELS n = 0.025

7.5' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S LOWE NOV / 69

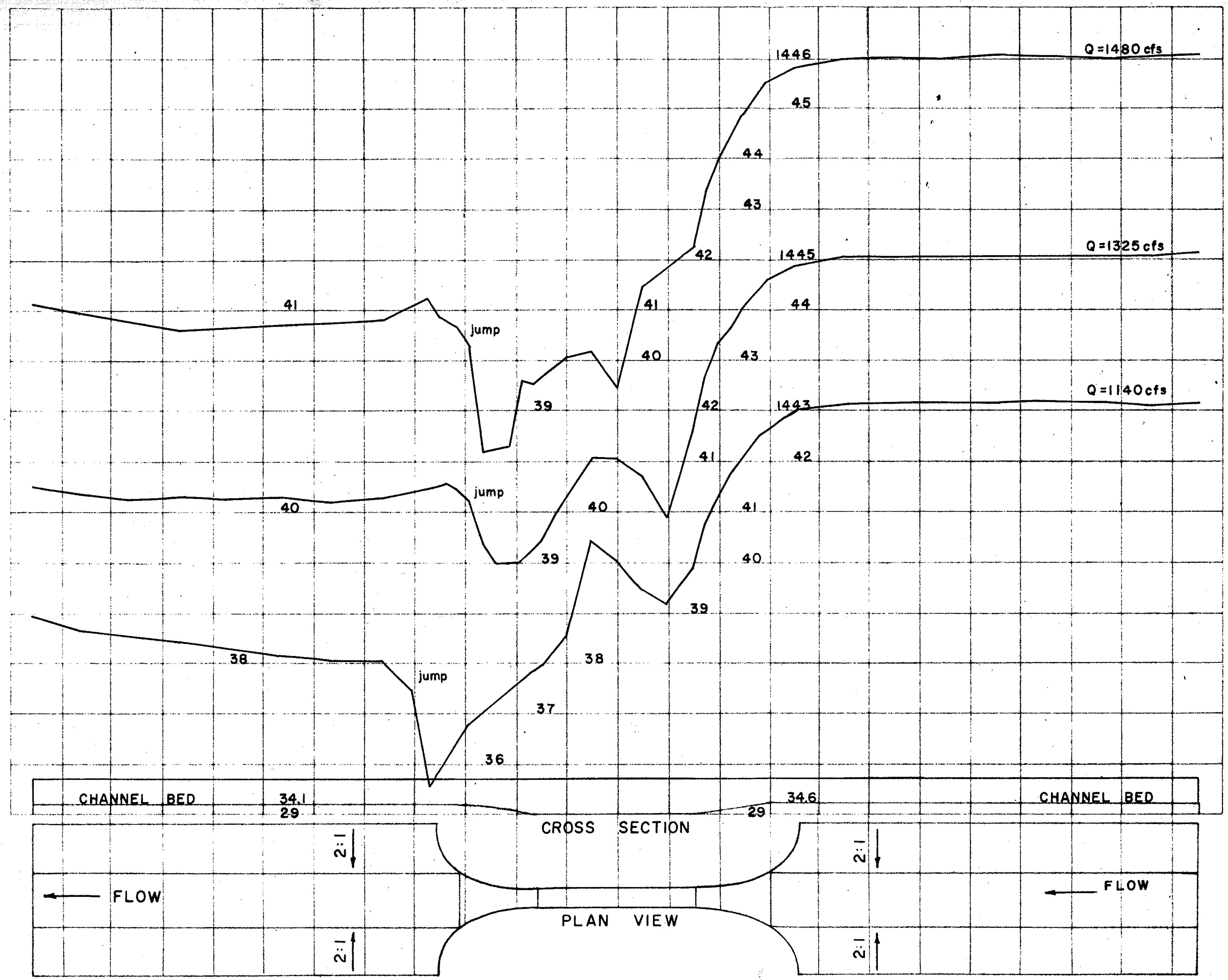


FIGURE 6-8 LOW TAILWATER LEVELS n = 0.025	**7.5' ENERGY CULVERT** WATER SURFACE PROFILES SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20' DRAWN BY S LOWE NOV / 69

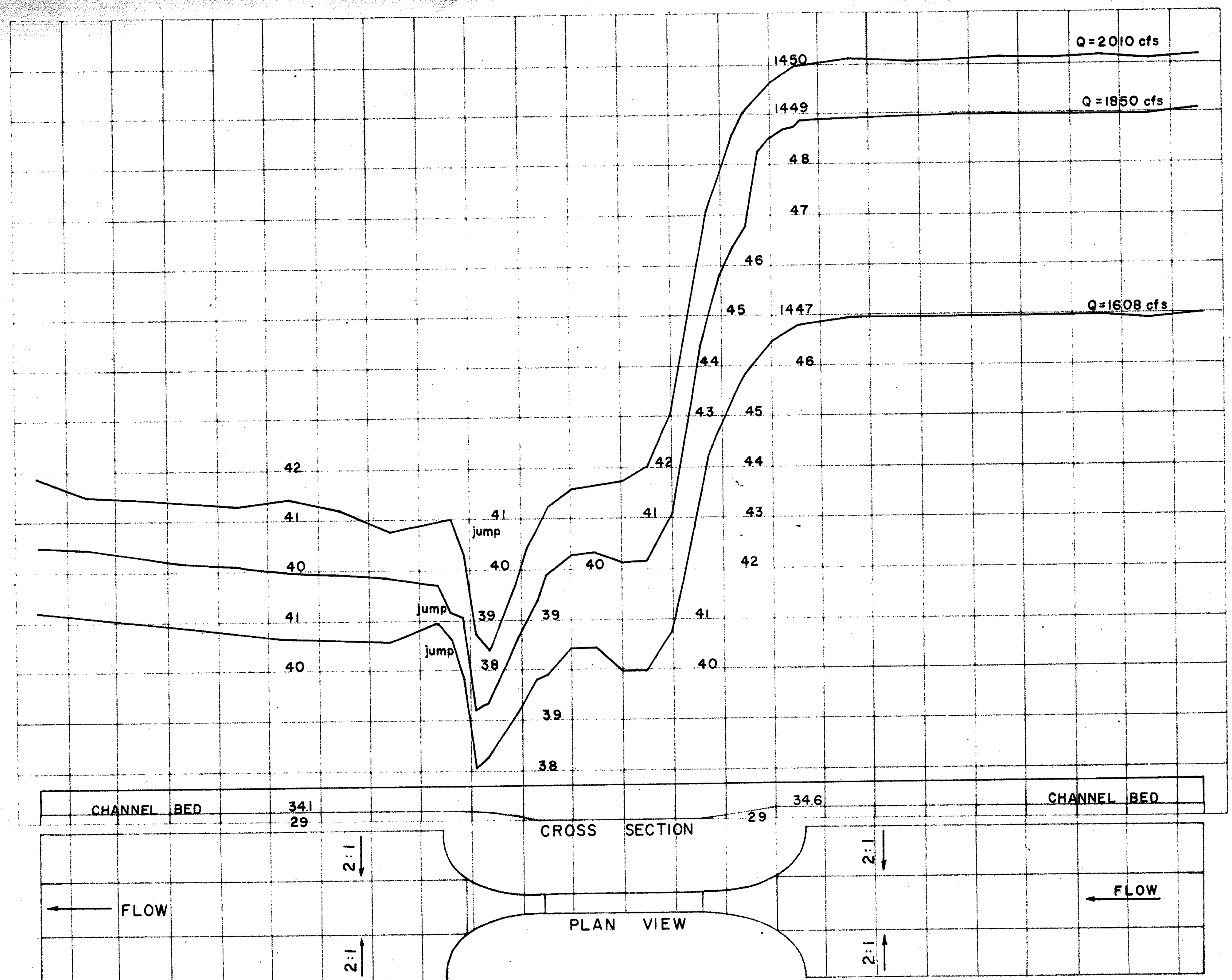


FIGURE 6-9

LOW TAILWATER LEVELS n= 0.025

7.5' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S LOWE NOV / 69

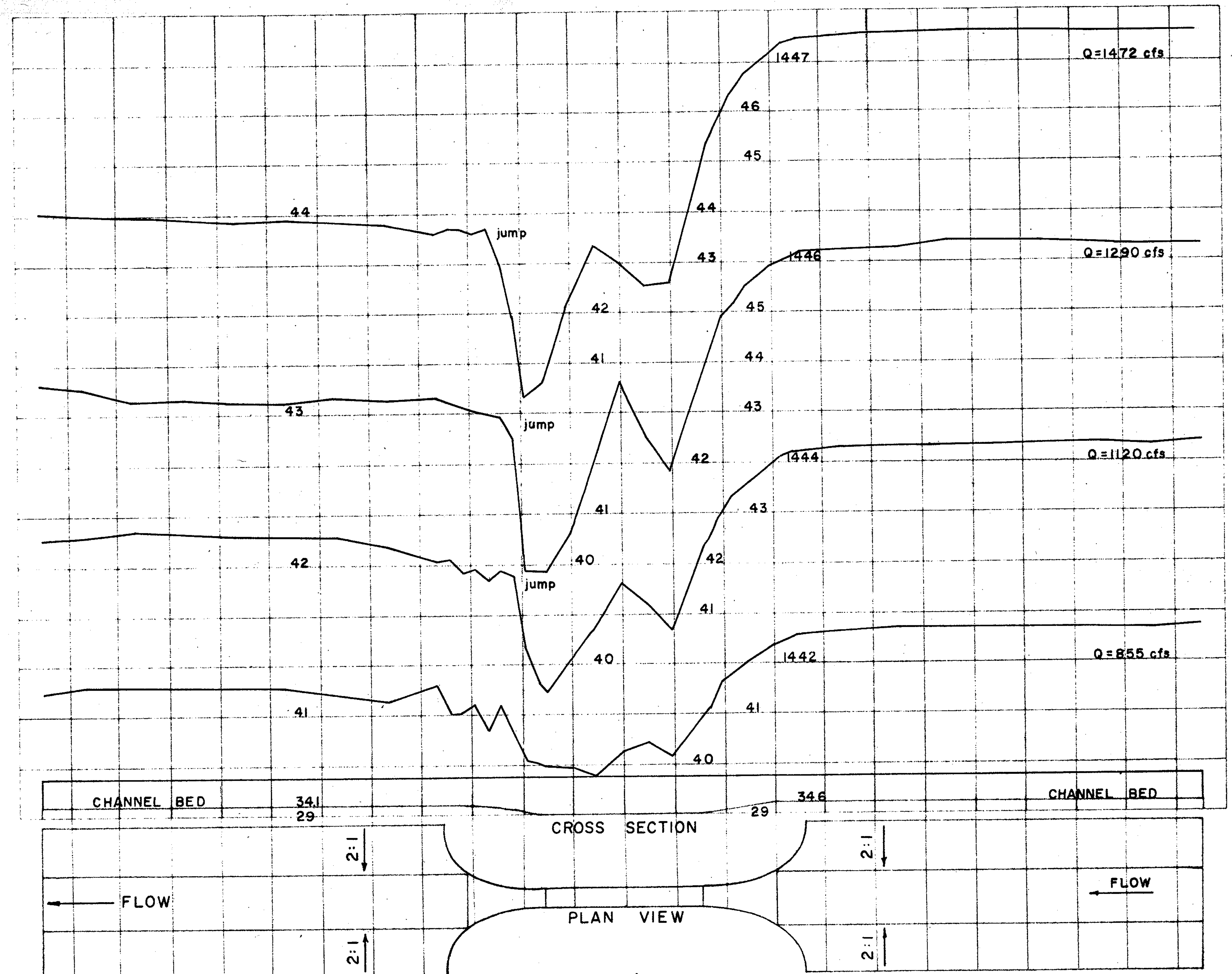


FIGURE 6-10

HIGH TAILWATER LEVELS n=0.0545

LESS AVAILABLE ENERGY

7.5' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE VERTICAL 1" = 1', HORIZONTAL 1" = 20'

DRAWN BY S LOWE NOV / 69

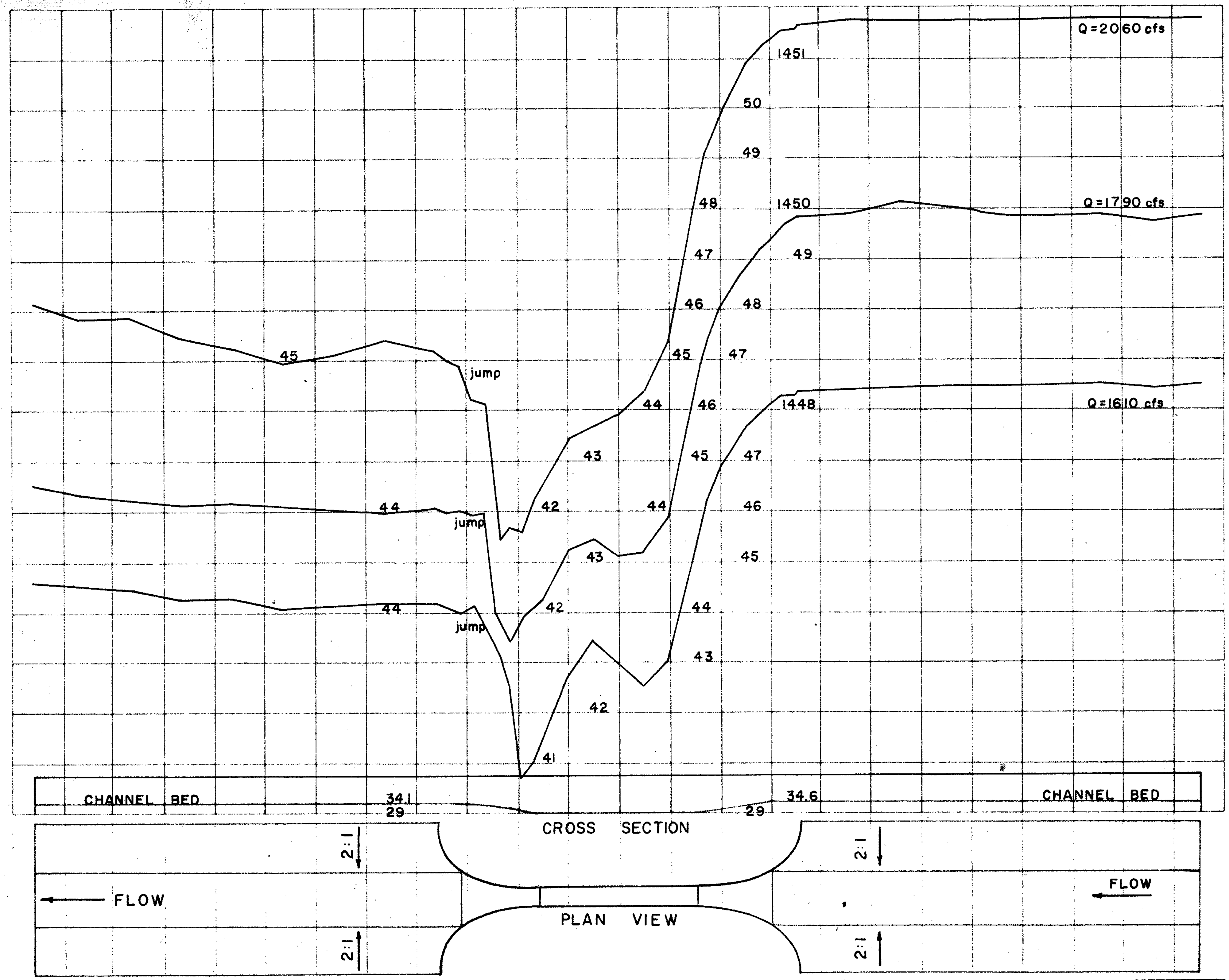


FIGURE 6-11

HIGH TAILWATER LEVELS n=0.0545

LESS AVAILABLE ENERGY

7.5' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S. LOWE NOV / 69

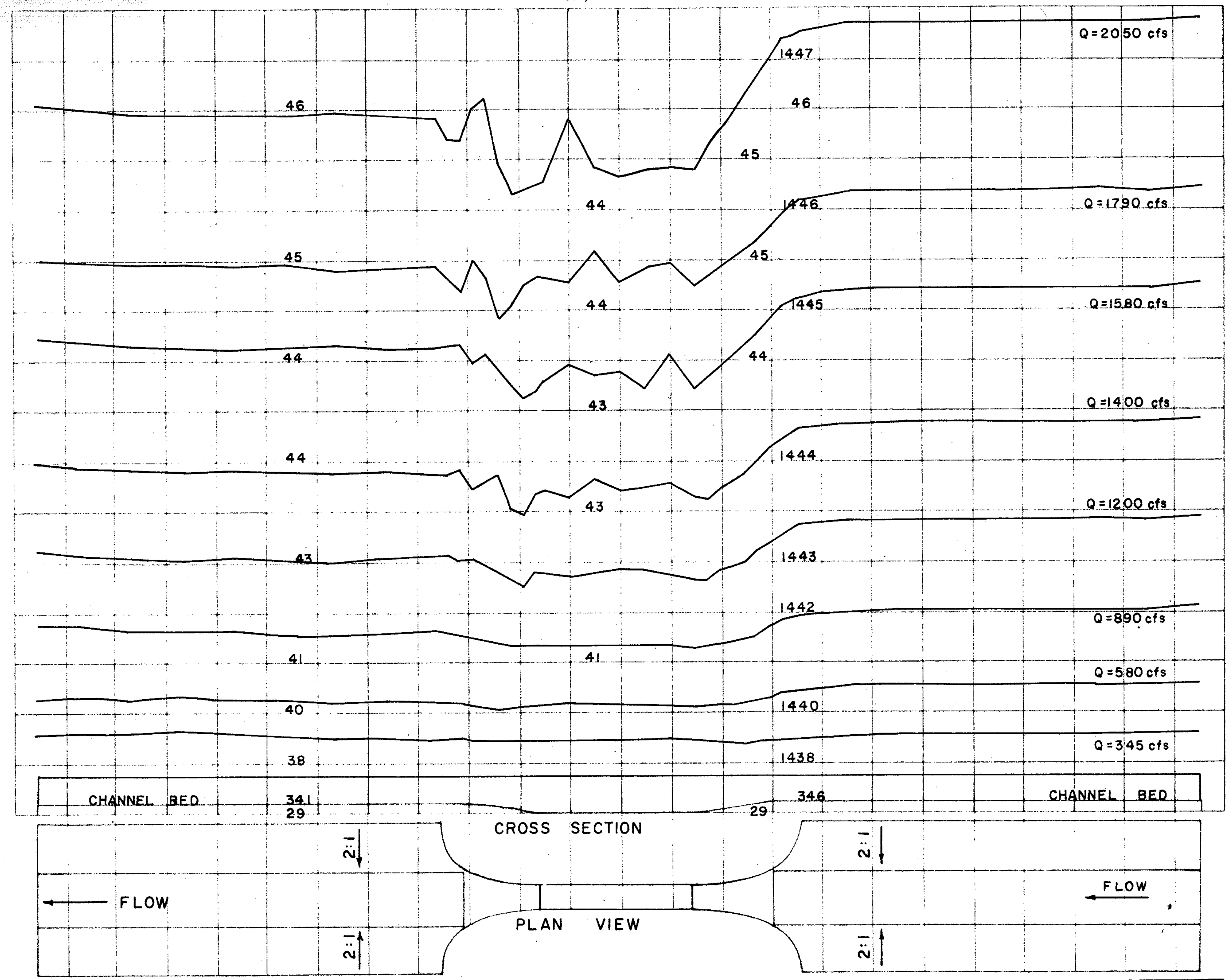


FIGURE 6-12

HIGH TAILWATER LEVELS n=0.0545

10' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S. LOWE NOV / 69

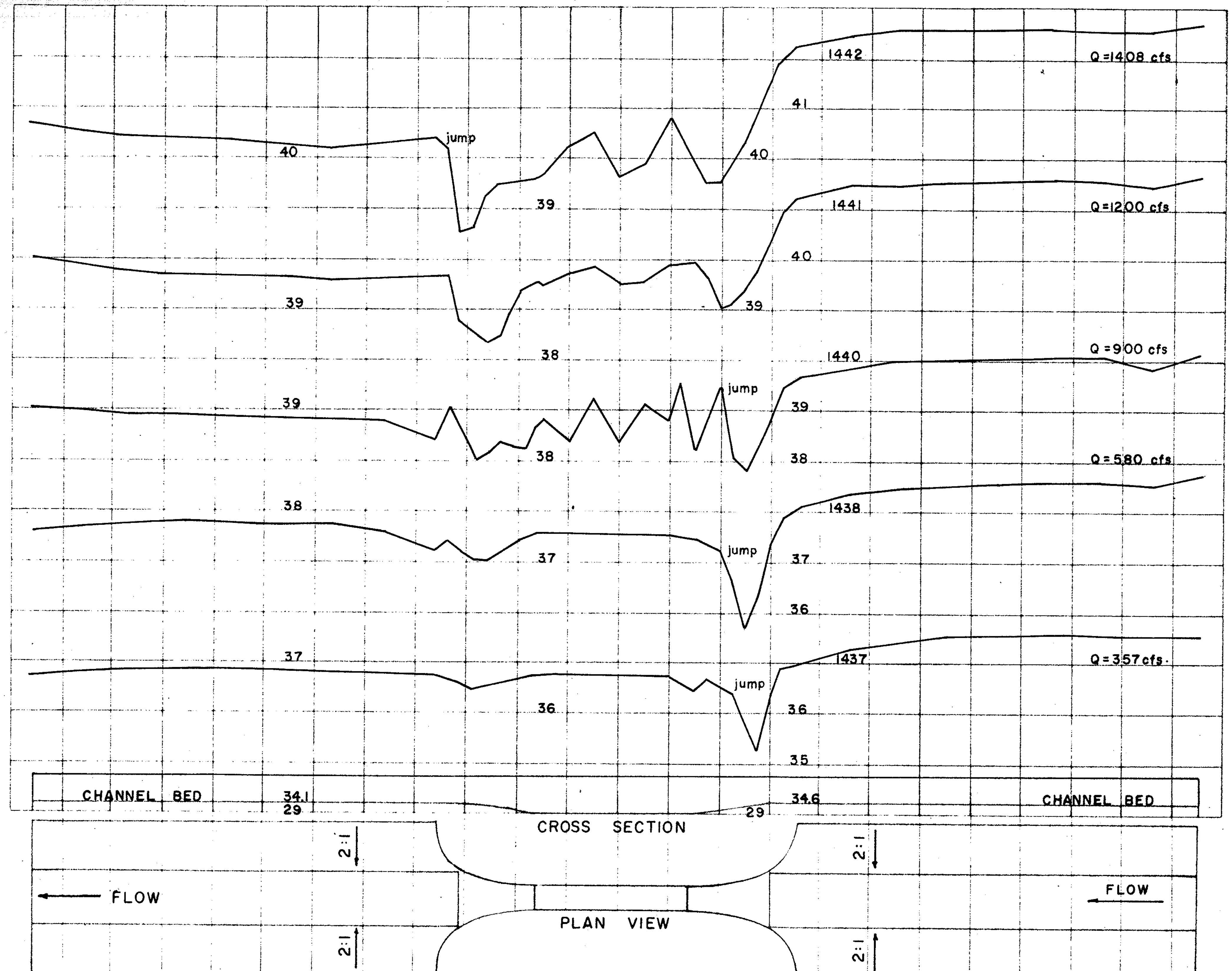


FIGURE 6-13

LOW TAILWATER LEVELS n=0.025

10' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S LOWE NOV / 69

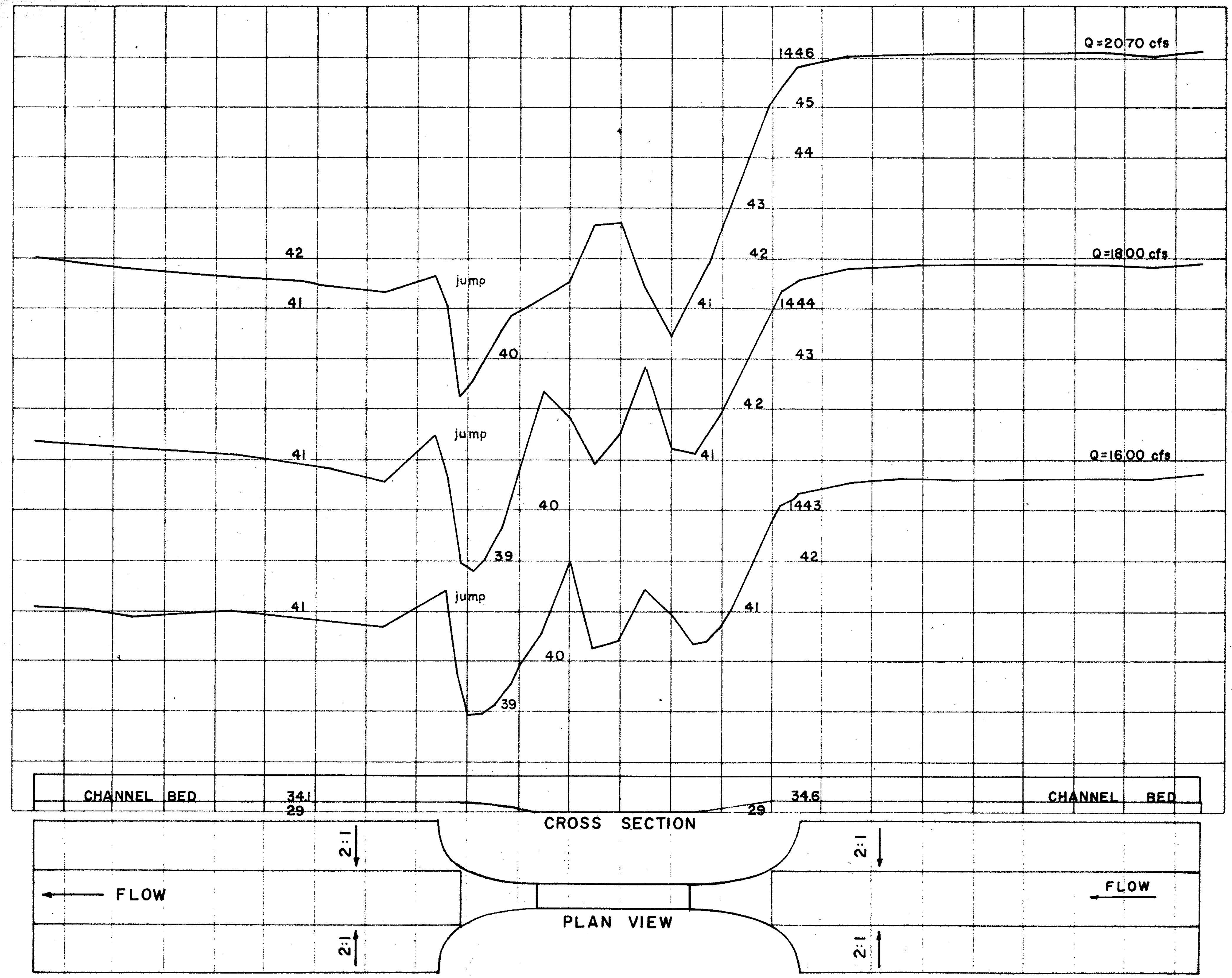


FIGURE 6-14

LOW TAILWATER LEVELS n=0.025

10' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S. LOWE NOV / 69

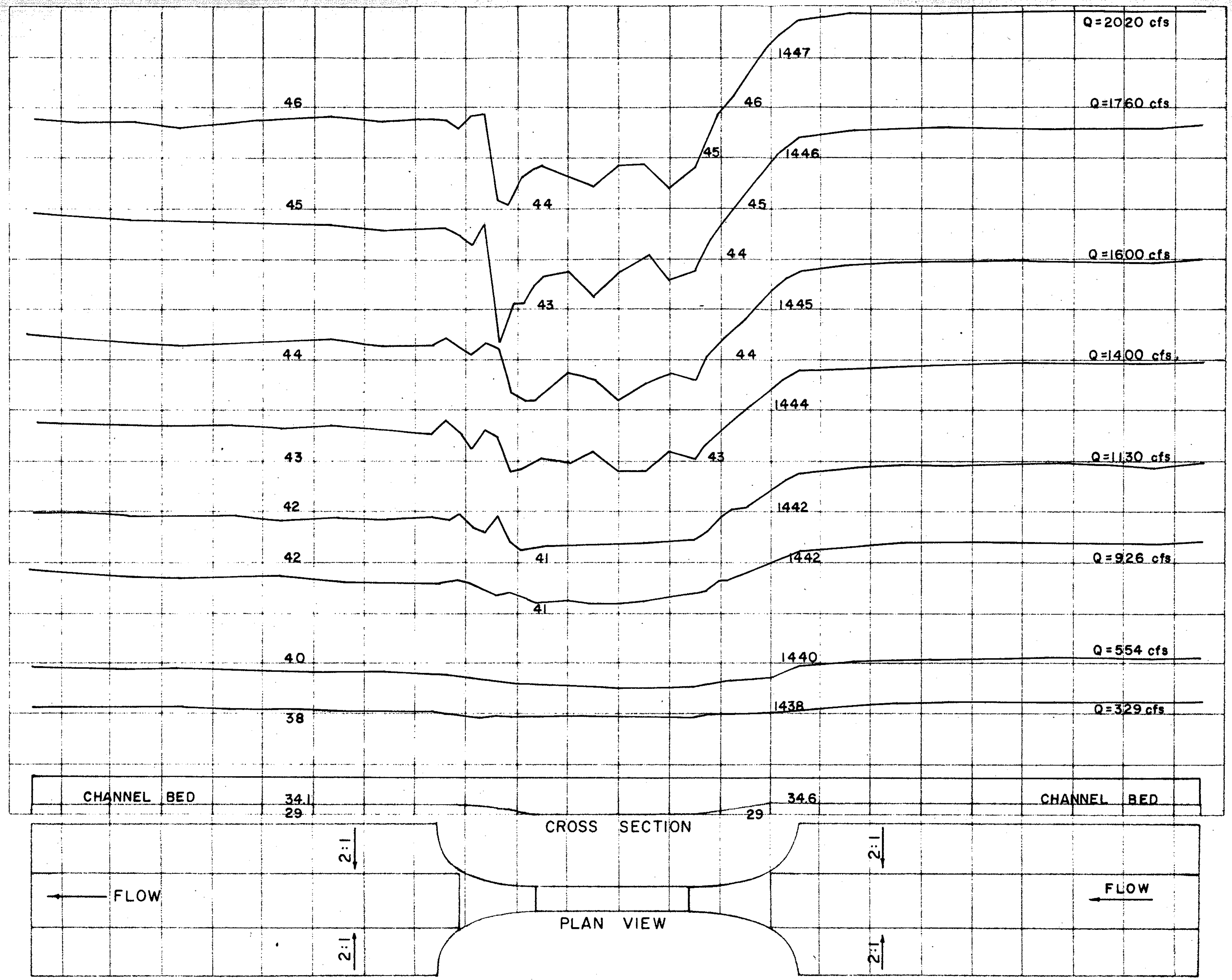


FIGURE 6-15

HIGH TAILWATER LEVELS n=0.0545

LESS AVAILABLE ENERGY

10' ENERGY CULVERT

WATER SURFACE PROFILES

SCALE : VERTICAL 1 = 1', HORIZONTAL 1 = 20'

DRAWN BY S. LOWE NOV / 69

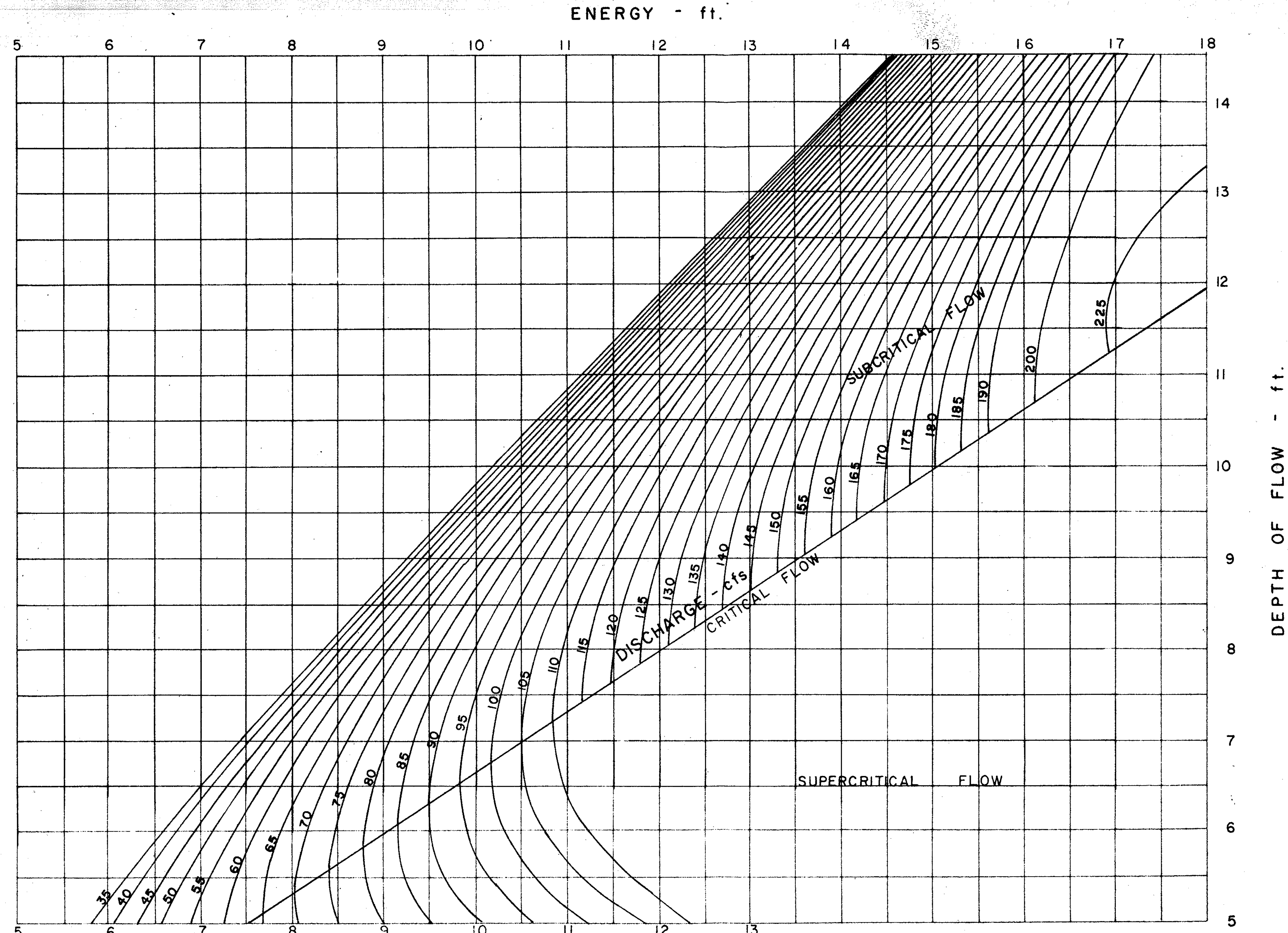


FIGURE 2

ENERGY, DEPTH, & UNIT DISCHARGE RELATIONSHIP

SPECIFIC ENERGY DIAGRAM

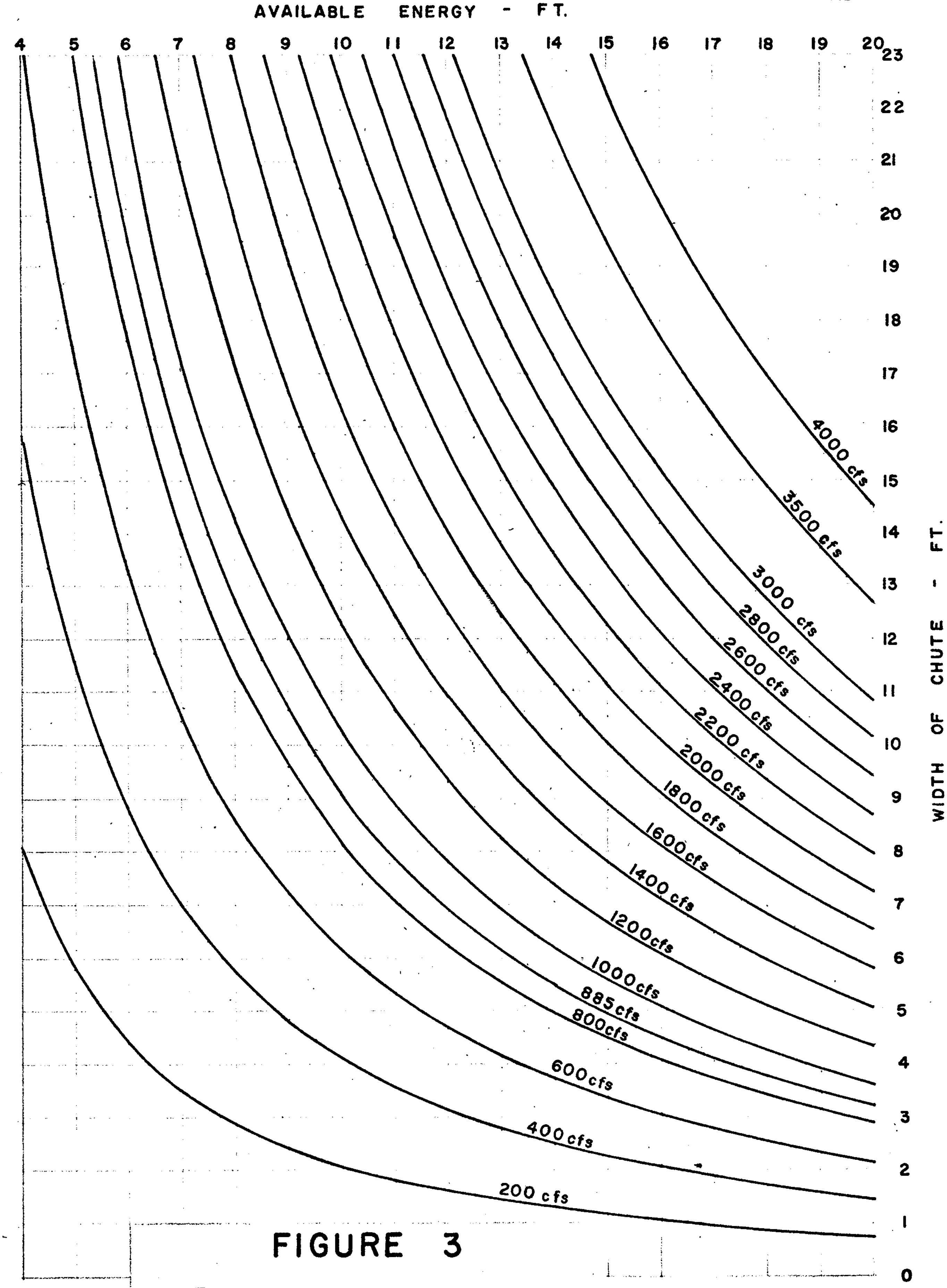


FIGURE 3

WIDTH-ENERGY RELATIONSHIP FOR CRITICAL DISCHARGE CONDITIONS FOR ENERGY CULVERT

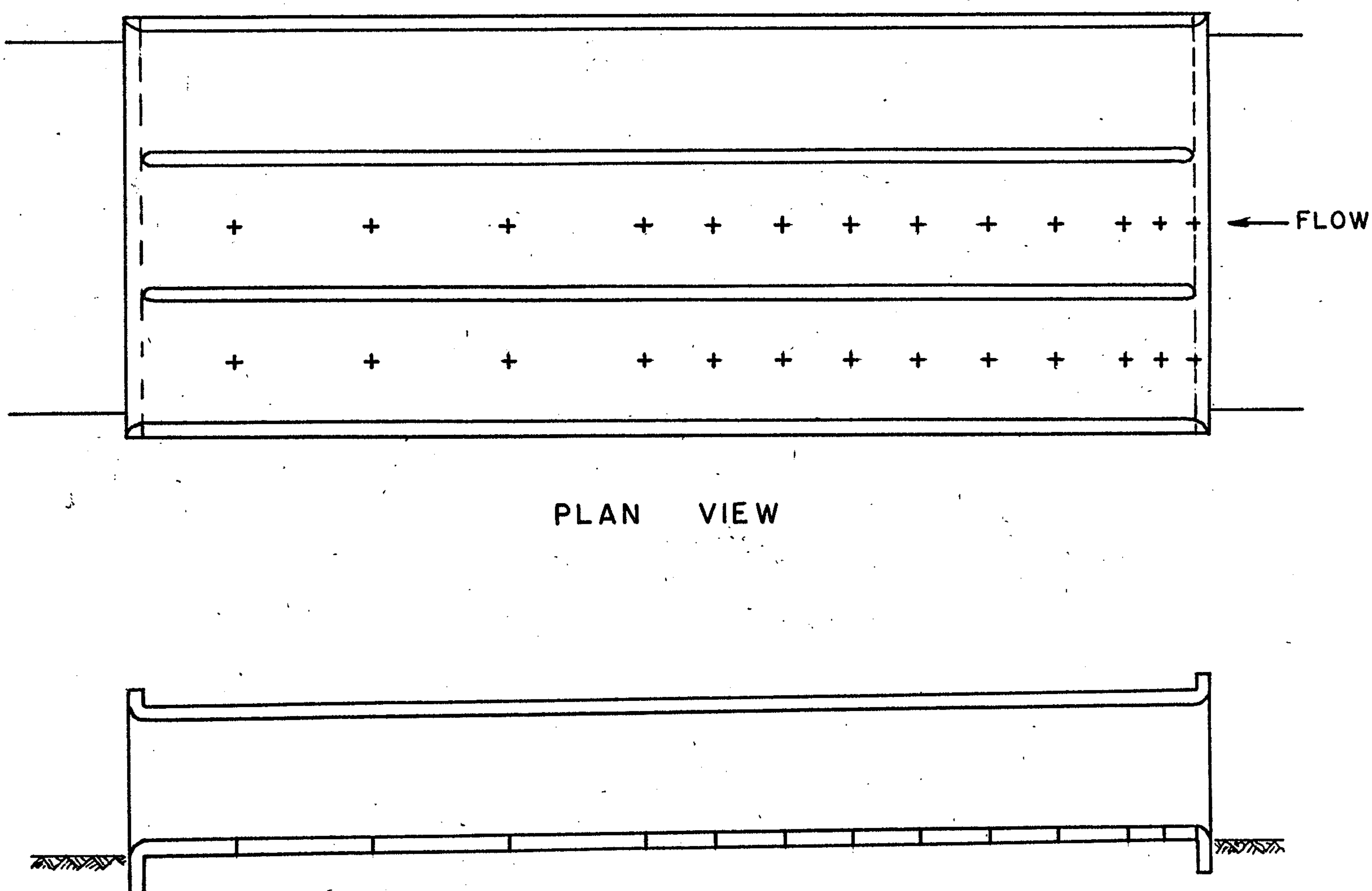
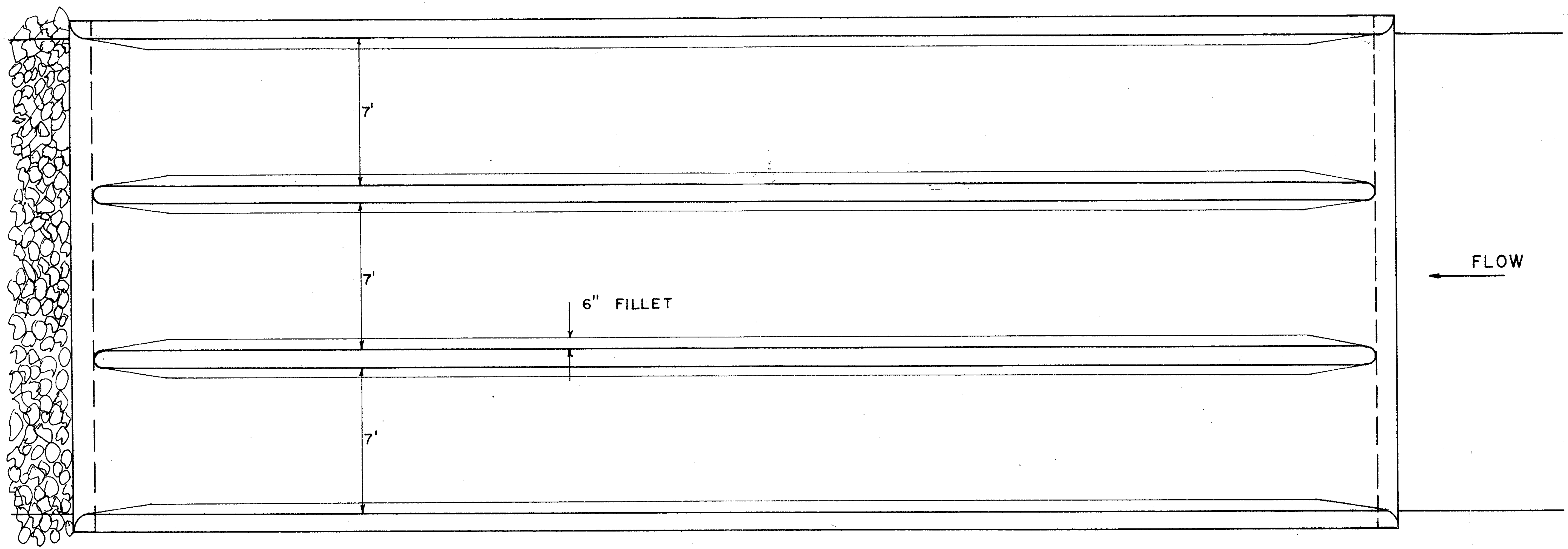


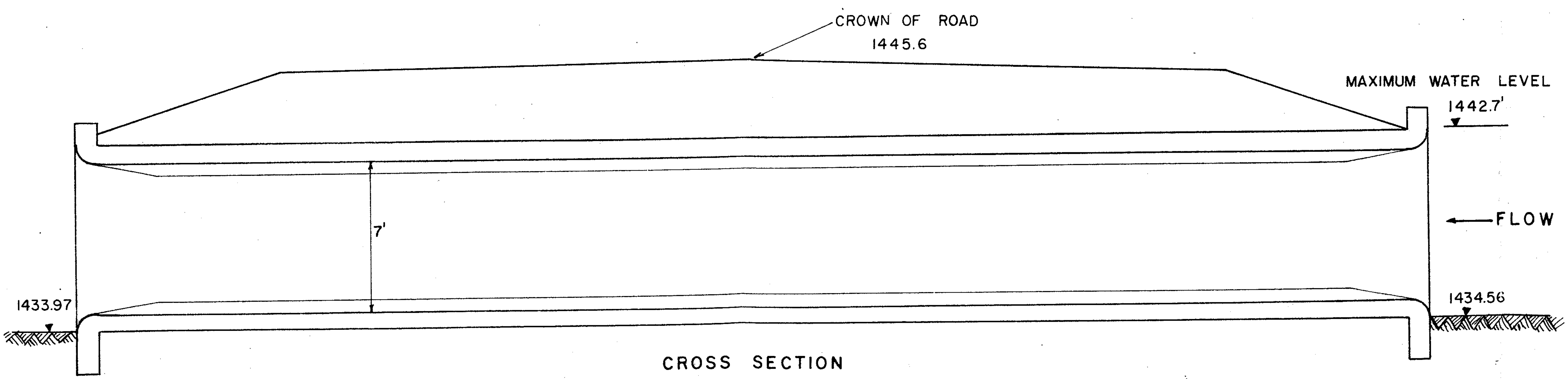
FIGURE 4

OPEN MANOMETER TUBE LOCATION

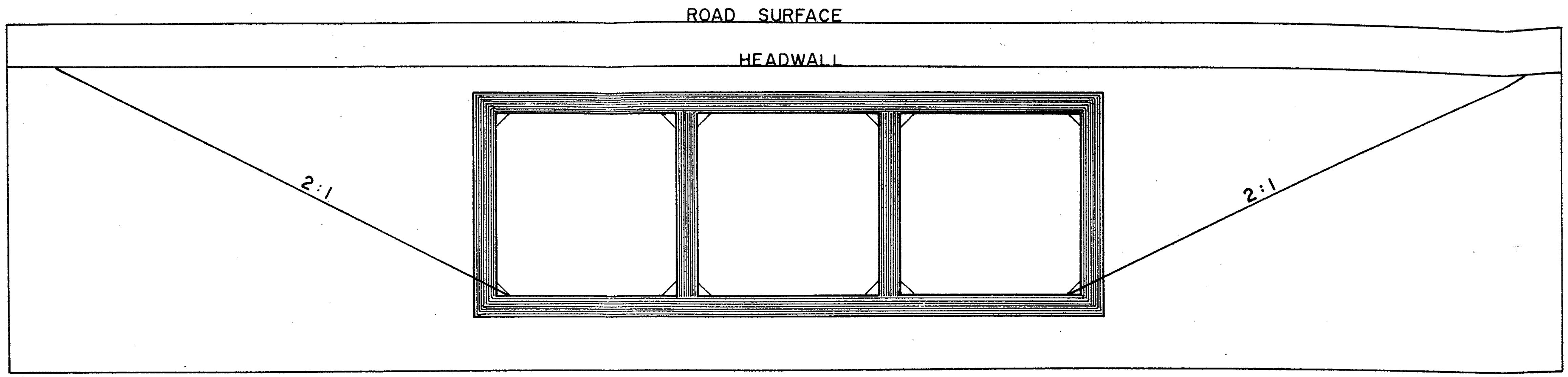
SCALE: 1" = 10'



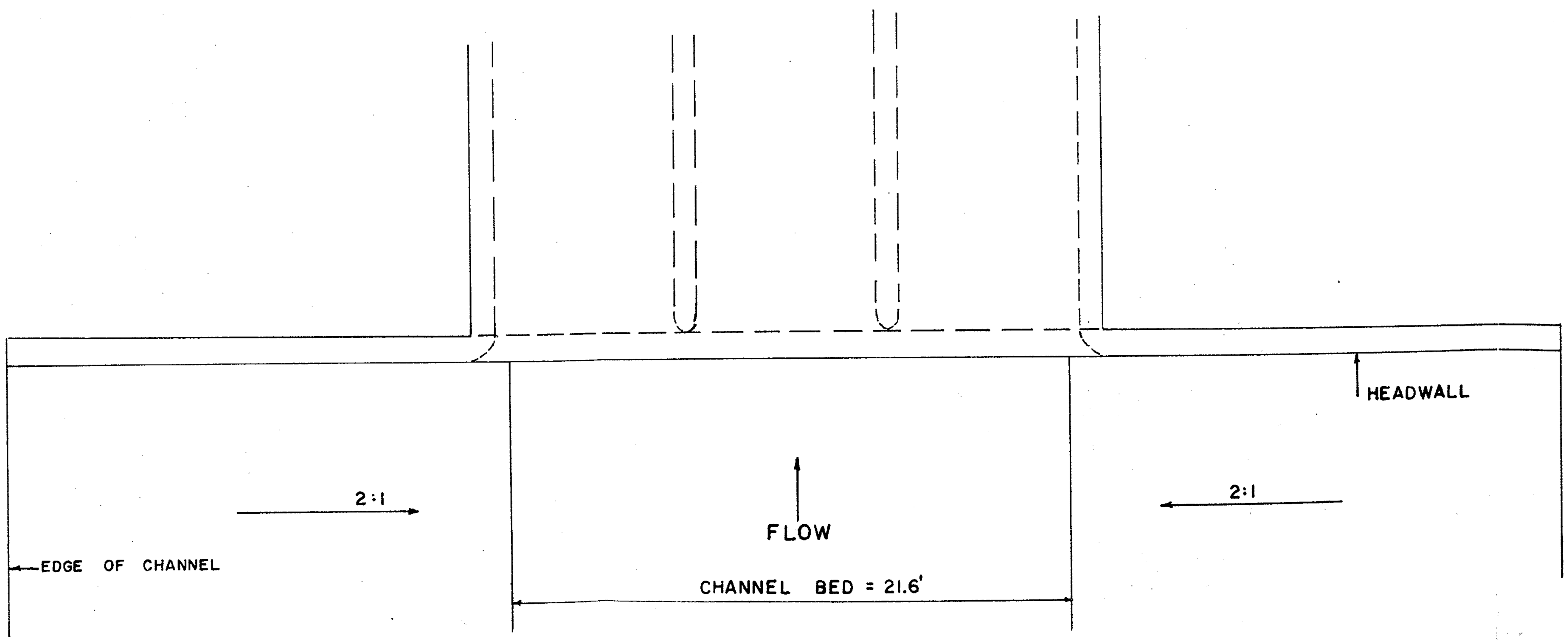
PLAN VIEW



CROSS SECTION

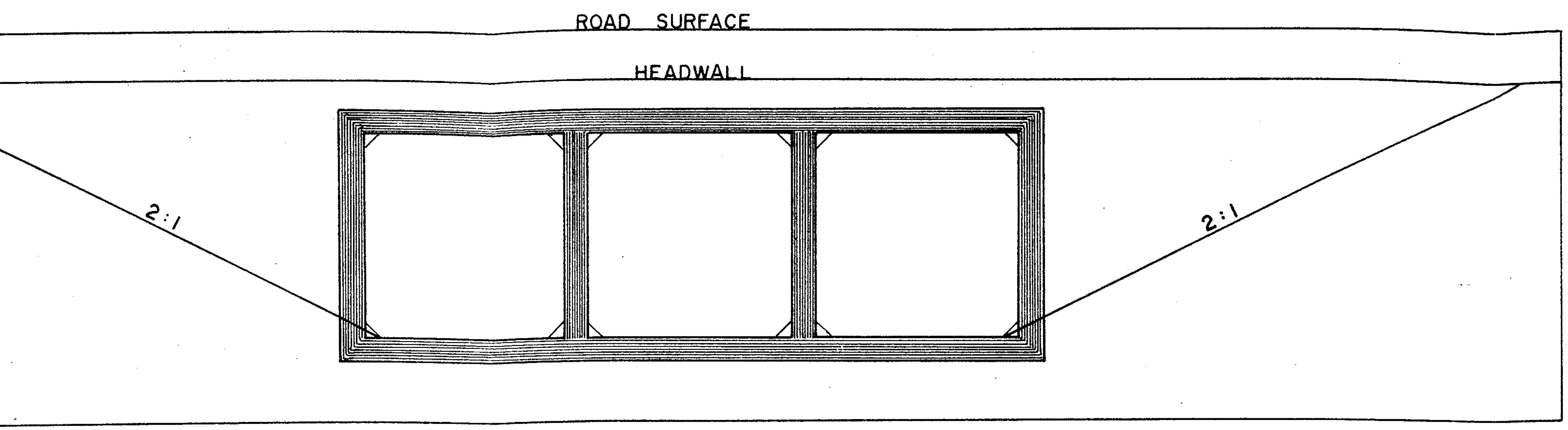


FRONT ELEVATION

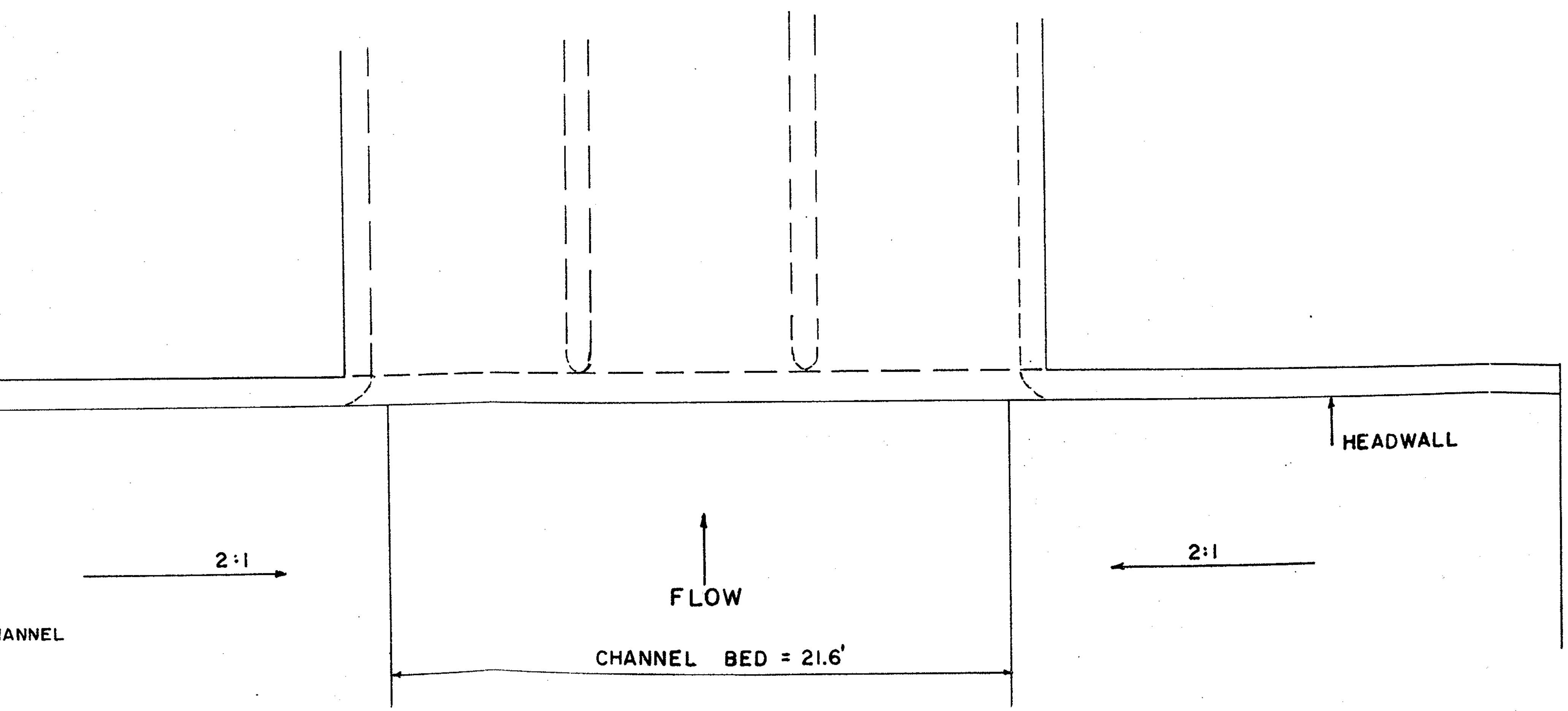


ENTRANCE PLAN

FIGURE
3 CELL 7'x7' BO
GENERAL F
SCALE : 1" = 5.0'
DRAWN BY S. LOWE



FRONT ELEVATION



ENTRANCE PLAN

FIGURE 5
3 CELL 7' x 7' BOX CULVERT
GENERAL PLAN
SCALE : 1" = 5.0'
DRAWN BY S. LOWE / NOV 69

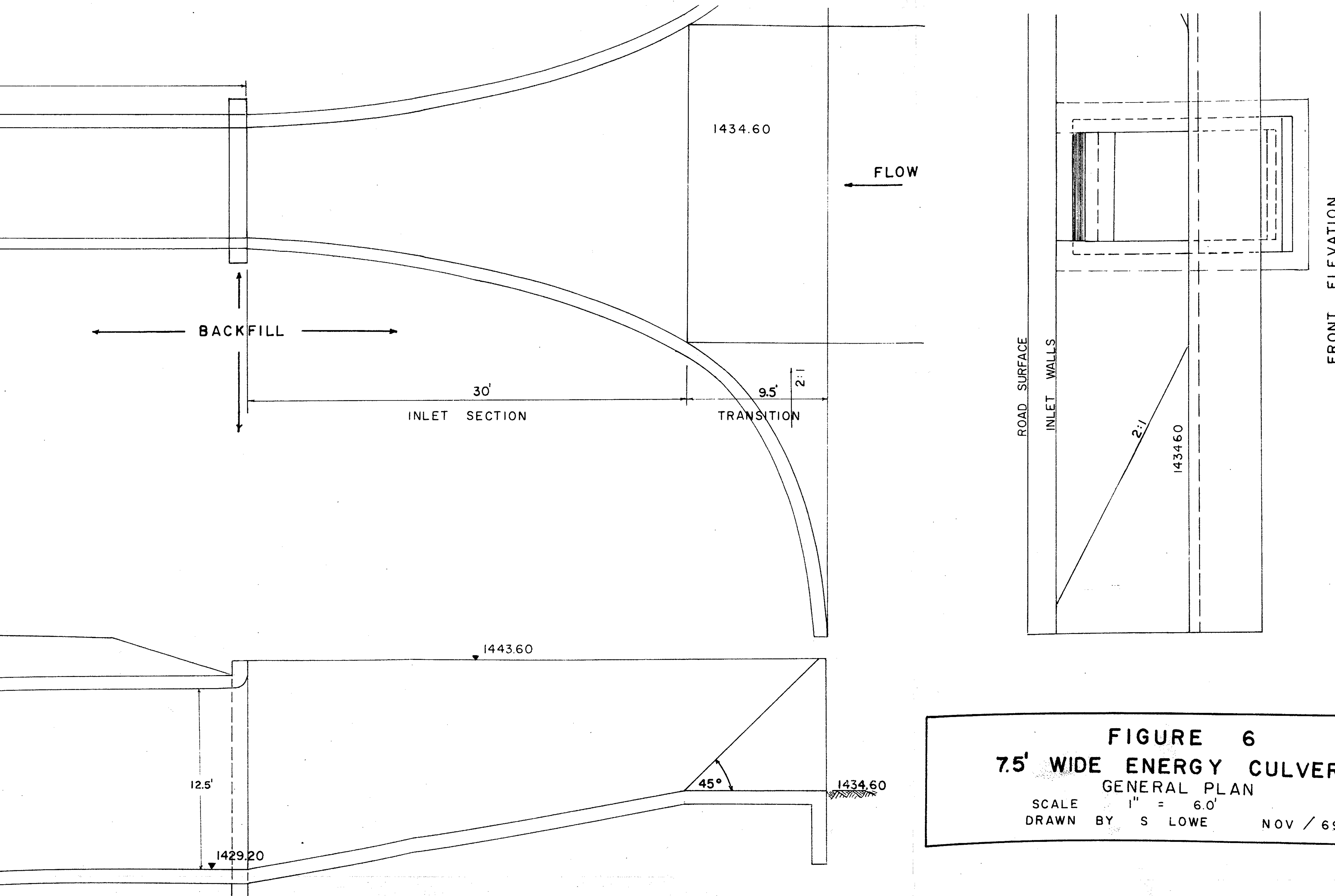


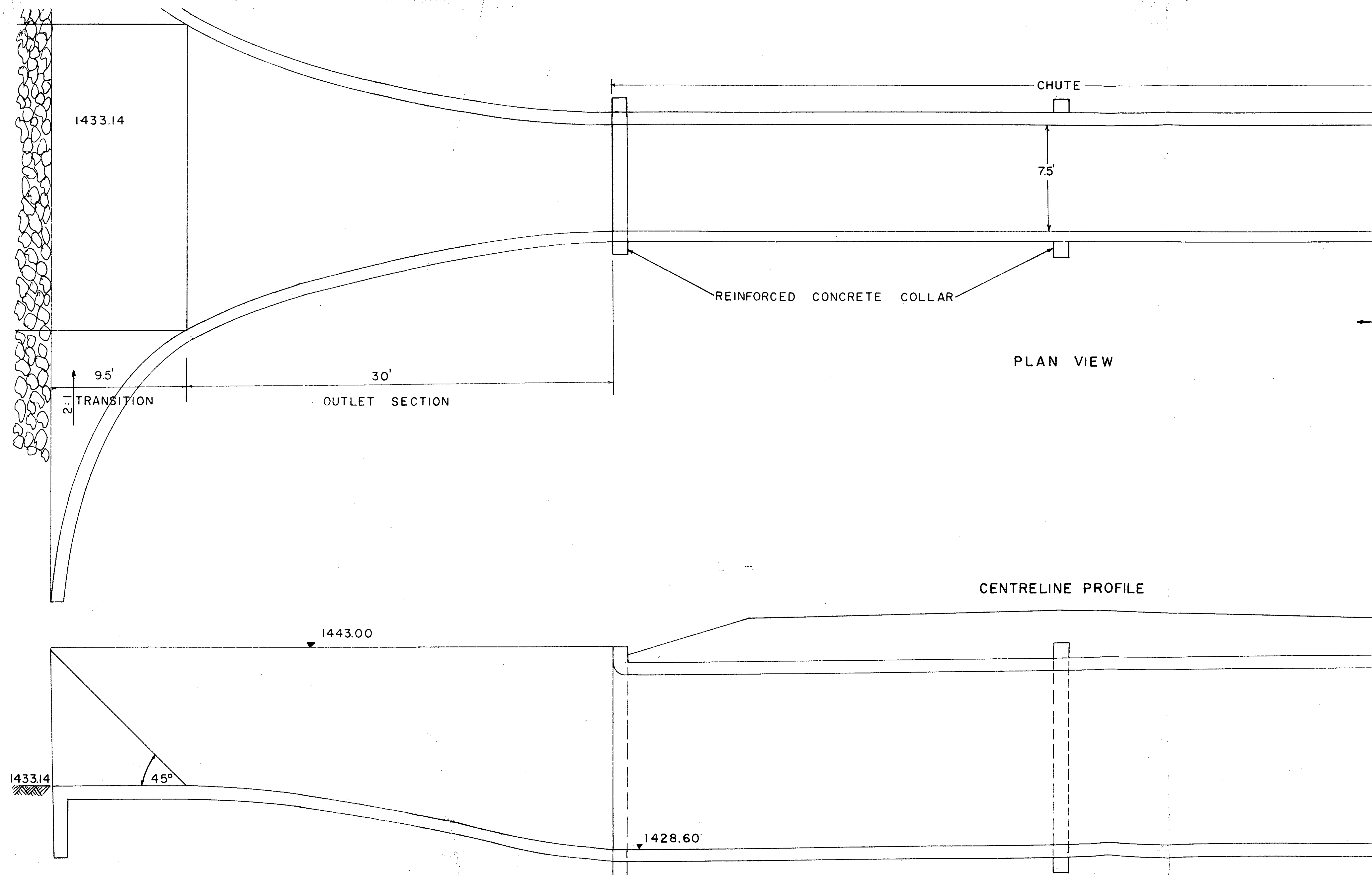
FIGURE 6

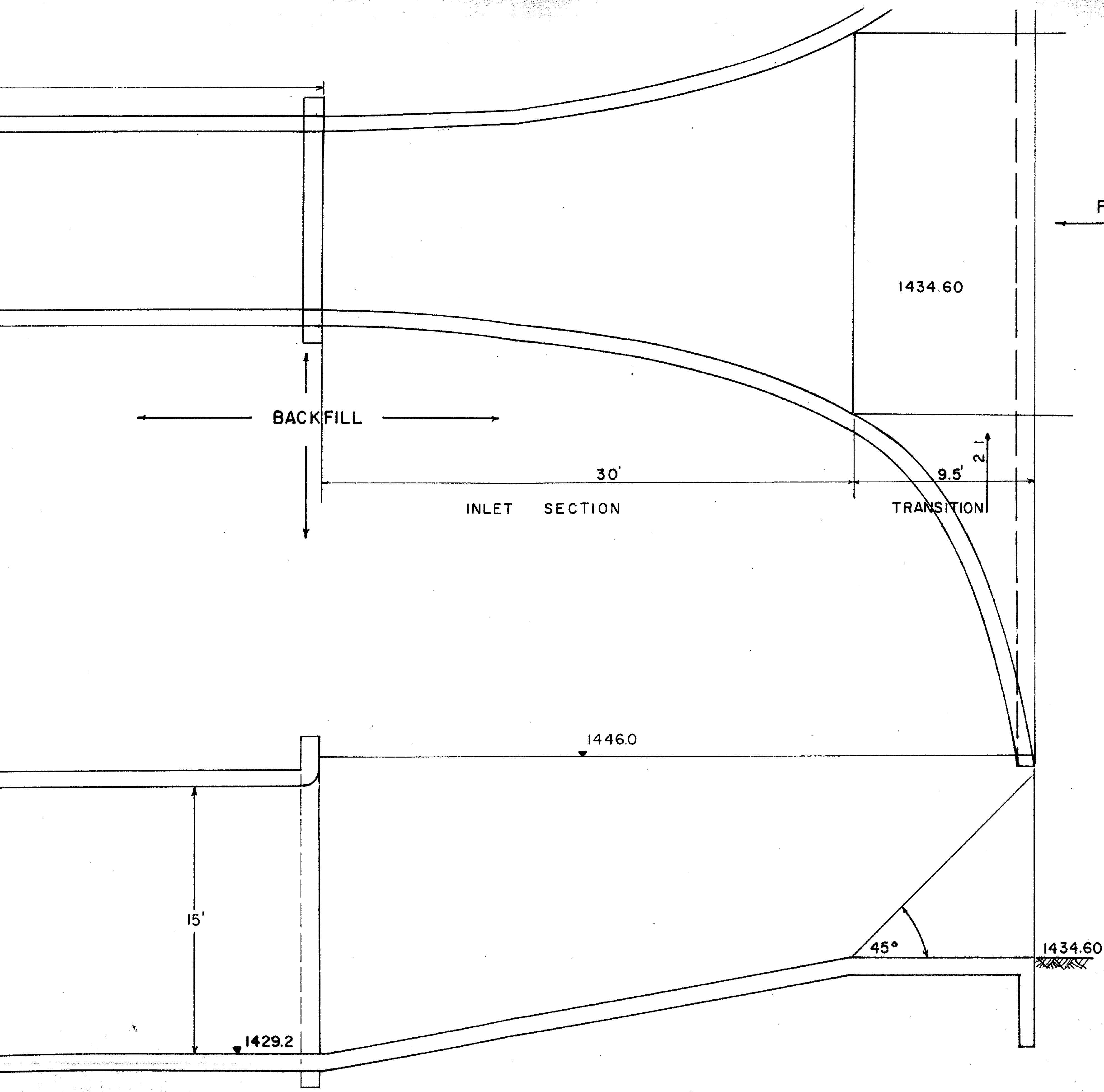
7.5' WIDE ENERGY CULVERT

GENERAL PLAN

SCALE 1" = 6.0'

DRAWN BY S LOWE NOV / 69


CHUTE
1433.14
7.5'
REINFORCED CONCRETE COLLAR
PLAN VIEW
9.5'
30'
2:1
TRANSITION
OUTLET SECTION
CENTRELINE PROFILE
1443.00
1433.14
45°
1428.60'



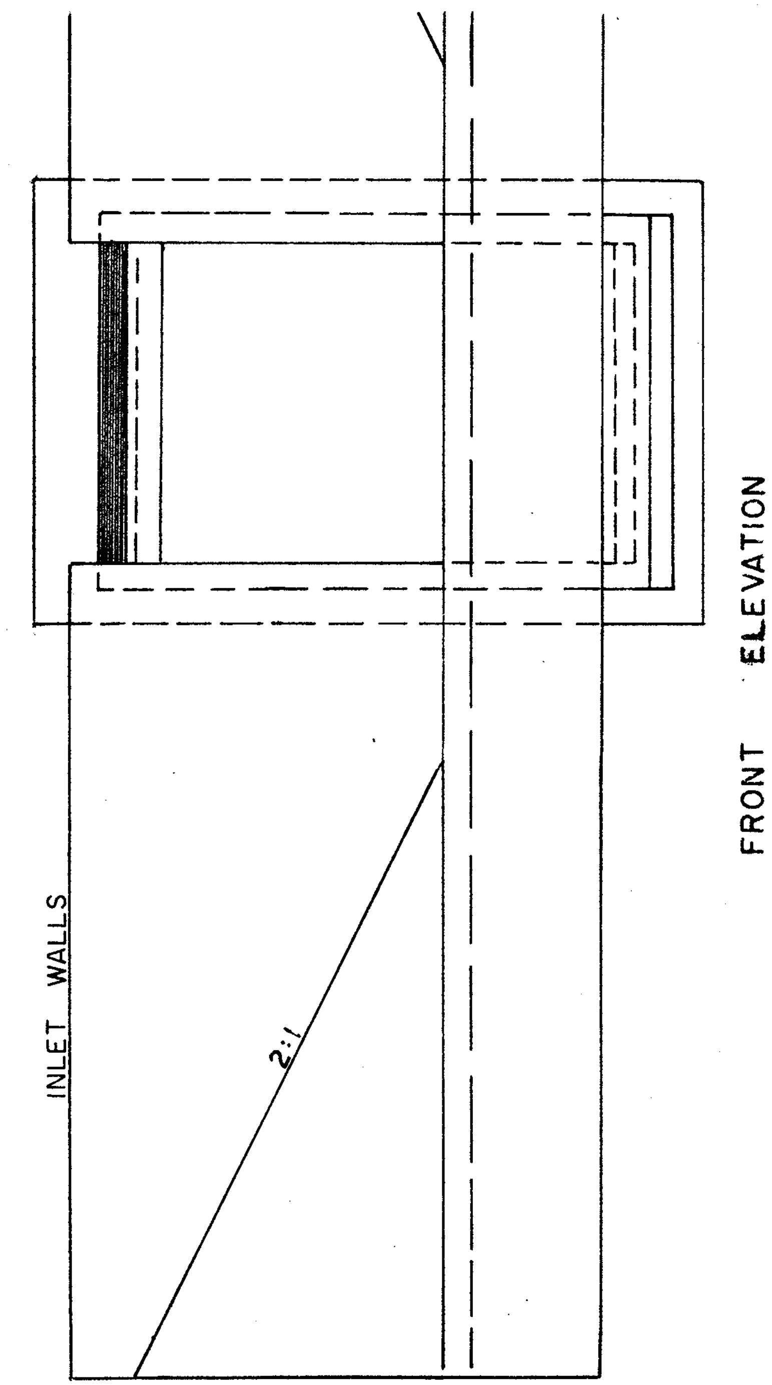
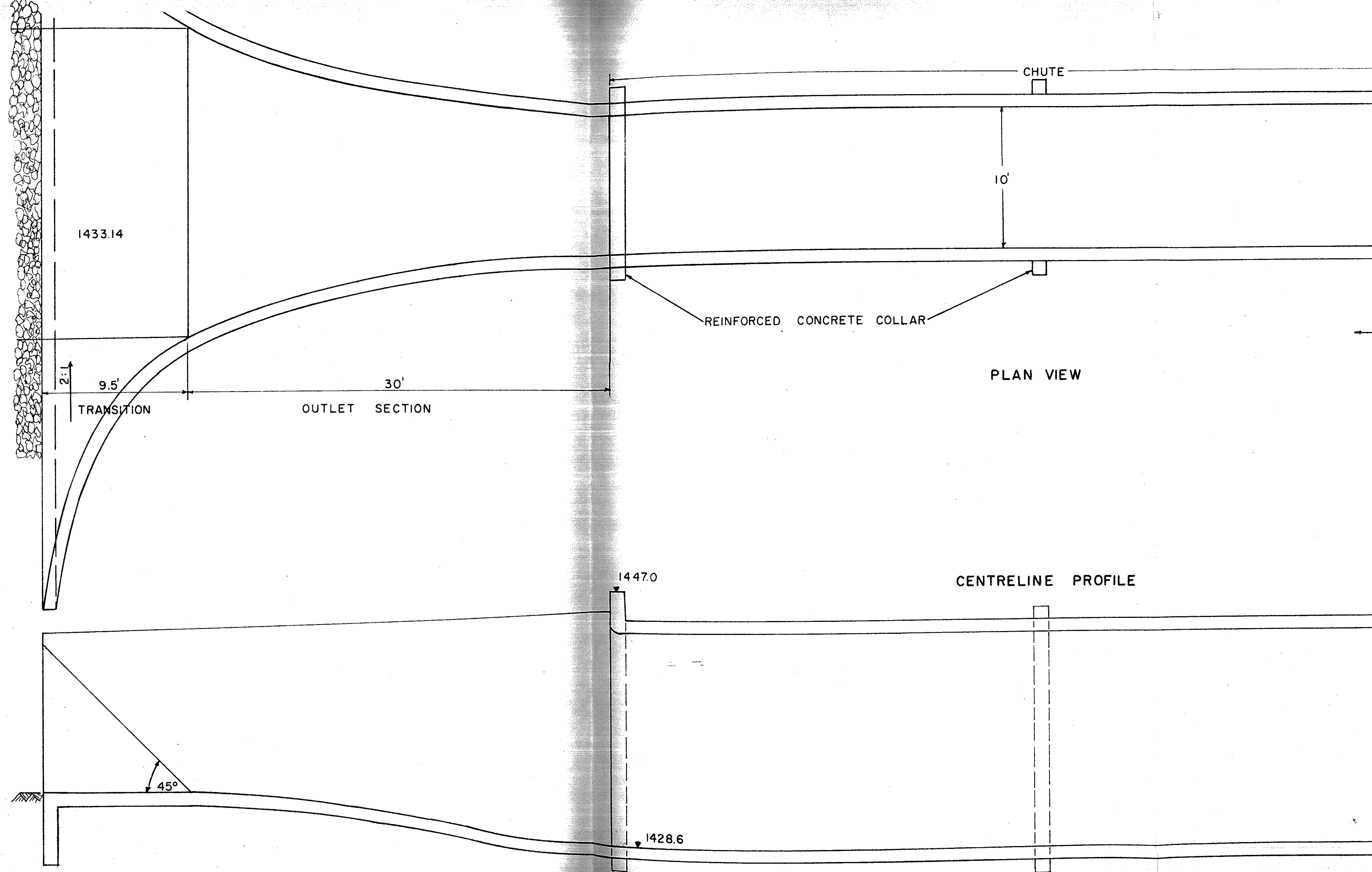


FIGURE 7
10' WIDE ENERGY CULVERT
GENERAL PLAN
SCALE : 1" = 6.0'
DRAWN BY S. LOWE NOV 69


CHUTE
10'
1433.14
REINFORCED CONCRETE COLLAR
PLAN VIEW
2:1
9.5'
30'
TRANSITION
OUTLET SECTION
1447.0
CENTRELINE PROFILE
45°
1428.6

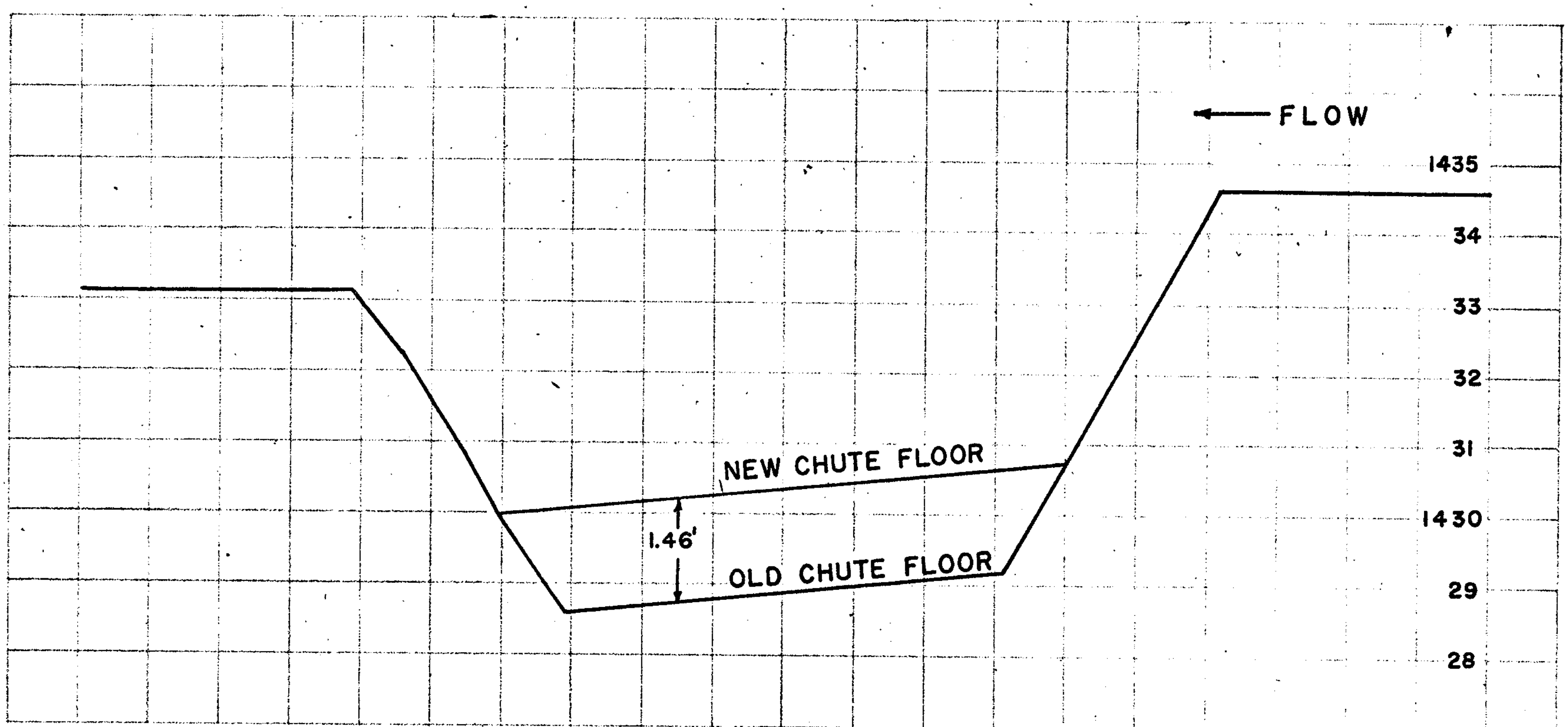


FIGURE 8

CROSS SECTION OF ENERGY CULVERT

WITH ENERGY REDUCTION

SCALE : HORIZ 1mm = 10'

APPENDIX B

TABLES

TABLE 1

Required head difference for 3 cell culvert

Head difference ft	$K_e = 0.5$		$K_e = 0.2$	
	Discharge 1 cell cfs	Discharge 3 cells cfs	Discharge 1 cell cfs	Discharge 3 cells cfs
0.8	265	795	300	900
0.9	280	840	320	960
1.0	295	885	340	1020
1.1	315	945	360	1080
1.2	330	990	370	1110
1.3	340	1020	385	1155
1.4	350	1050	400	1200
1.6	370	1110	420	1260
1.8	400	1200	450	1350
2.0	425	1275	475	1425
2.2	440	1320	500	1500
2.4	460	1380	525	1575
2.6	480	1440		
2.8	495	1485		
3.0	510	1530	580	1740
3.2	540	1620		
3.4	550	1650		
3.6	560	1680		
3.8	580	1740		
4.0	600	1800	670	2010
4.2	610	1830		
4.4	620	1860		
4.6	630	1890		
4.8	650	1950		
5.0	670	2010		

TABLE 2

Width of inlet & outlet sections

Distance ft	7.5' chute width ft	10' chute width ft
0	7.50	10.00
1	7.67	10.03
2	7.74	10.13
3	7.84	10.17
4	8.00	10.20
5	8.10	10.33
6	8.33	10.37
7	8.55	10.53
8	8.77	10.67
9	9.10	10.92
10	9.40	11.13
11	9.67	11.35
12	10.10	11.67
13	10.40	11.95
14	10.90	12.27
15	11.27	12.58
16	11.70	12.92
17	12.31	13.33
18	12.67	13.68
19	13.10	14.03
20	13.60	14.50
21	14.10	14.92

distance ft	7.5' chute width ft	10' chute width ft
22	14.68	15.42
23	15.30	16.00
24	16.00	16.58
25	16.78	17.25
26	17.70	18.08
27	18.50	18.88
28	19.40	19.67
29	20.40	20.63
30	21.60	21.60
31	22.70	22.70
32	24.10	24.00
33	25.50	25.43
34	27.70	26.95
35	29.45	29.00
36	32.60	31.20
37	36.50	34.70
38	43.50	39.00
39		44.90
39.5	60.00	
40	60.00	52.20
40.5	60.00	60.00

TABLE 3

7.5' wide chute inlet calculations

Dist from inlet	Width of chute	885 cfs Unit discharge	885 cfs Energy	885 cfs Depth of flow	1200 cfs Unit discharge	1200 cfs Energy	1200 cfs Depth of flow
ft	ft	cfs/ft	ft	ft	cfs/ft	ft	ft
0	7.50	118.0	14.00	12.26	160.0	15.26	12.86
2	7.74	114.3	13.60	12.28	155.0	14.89	12.51
4	8.00	110.5	13.25	11.90	150.0	14.54	12.17
6	8.33	106.0	12.90	11.62	144.0	14.21	11.90
8	8.77	101.0	12.53	11.30	137.0	13.84	11.68
10	9.40	94.0	12.28	11.17	127.8	13.44	11.56
12	10.10	87.6	11.80	10.78	119.0	13.11	11.40
14	10.90	81.0	11.45	10.55	110.0	12.74	11.26
16	11.70	75.6	11.10	10.25	102.5	12.38	11.05
18	12.67	70.0	10.73	9.96	94.6	12.04	10.87
20	13.60	65.0	10.38	9.68	88.2	11.66	10.58
22	14.68	60.4	10.02	9.36	81.8	11.32	10.38
24	16.00	55.5	9.64	9.08	75.0	10.94	10.08
26	17.70	50.0	9.28	8.78	67.7	10.95	9.82
28	19.40	45.5	8.93	8.46	61.7	10.24	9.60
30	21.60	41.0	8.59	8.22	55.5	9.89	9.35

TABLE 4

10' wide chute inlet calculations

		885 cfs			1800 cfs		
Dist from inlet ft	Width of chute ft	Unit discharge cfs/ft	Energy ft	Depth of flow ft	Unit discharge cfs/ft	Energy ft	Depth of flow ft
0	10.00	88.5	14.00	13.32	180.0	17.35	15.19
2	10.13	87.4	13.60	12.88	177.5	17.00	14.75
4	10.20	86.8	13.25	12.50	176.0	16.63	14.28
6	10.37	85.5	12.90	12.16	173.5	16.30	13.86
8	10.67	83.0	12.53	11.77	169.0	15.91	13.46
10	11.13	79.5	12.28	11.57	161.5	15.56	13.25
12	11.67	75.9	11.80	11.08	154.3	15.20	13.00
14	12.27	72.2	11.45	10.77	146.8	14.85	12.87
16	12.92	68.5	11.10	10.50	139.2	14.50	12.58
18	13.68	64.7	10.73	10.12	131.8	14.12	12.35
20	14.50	61.0	10.38	9.73	124.1	13.79	12.15
22	15.42	57.5	10.02	9.43	116.7	13.41	11.93
24	16.58	53.5	9.64	9.12	108.7	13.06	11.72
26	18.08	49.0	9.28	8.81	99.6	12.71	11.57
28	19.67	45.0	8.93	8.50	91.5	12.35	11.35
30	21.60	41.0	8.59	8.22	83.4	12.00	11.14

TABLE 5

Rise, length & chute width for outlet

Length ft	Percent of length %	Rise of outlet ft	Percent of rise %	Width of outlet ft	w-7.5' ft	Percent (w-7.5') of width %
0	0.0	0.00	0.0	7.50	0.00	0.0
1	3.4	0.07	1.5	7.67	0.17	1.2
2	6.7	0.13	2.9	7.74	0.24	1.7
3	10.0	0.27	5.9	7.84	0.34	2.4
4	13.4	0.40	8.8	8.00	0.50	3.5
5	16.7	0.52	11.5	8.10	0.60	4.3
6	20.0	0.70	15.4	8.33	0.83	5.9
7	23.4	0.88	19.4	8.55	1.05	7.4
8	26.7	1.08	23.8	8.77	1.27	9.0
9	30.0	1.37	30.2	9.10	1.60	11.3
10	33.4	1.62	35.7	9.40	1.90	13.5
11	36.7	1.92	42.3	9.67	2.17	15.4
12	40.0	2.16	47.6	10.10	2.60	18.4
13	43.4	2.38	52.4	10.40	2.90	20.6
14	46.7	2.58	56.8	10.90	3.40	24.1
15	50.0	2.77	61.0	11.27	3.77	26.7
16	53.4	2.94	64.8	11.70	4.20	29.8
17	56.7	3.12	68.7	12.31	4.81	34.1
18	60.0	3.30	72.7	12.67	5.17	36.7
19	63.4	3.43	75.6	13.10	5.60	39.7
20	67.7	3.58	78.9	13.60	6.10	43.3
21	70.0	3.73	82.2	14.10	6.60	46.8
22	73.4	3.87	85.2	14.68	7.18	50.9
23	76.7	3.97	87.4	15.30	7.80	55.3
24	80.0	4.08	89.9	16.00	8.50	60.3
25	83.4	4.20	92.5	16.78	9.28	65.8
26	86.7	4.28	94.3	17.70	10.20	72.3
27	90.0	4.36	96.0	18.50	11.00	78.0
28	93.4	4.43	97.6	19.40	11.90	84.4
29	96.7	4.46	98.2	20.40	12.90	91.5
30	100.0	4.54	100.0	21.60	14.40	100.0

TABLE 6

7.5' wide chute outlet calculations

Distance from outlet	Width of chute	885 cfs		
		Unit discharge	Energy	Depth of flow
ft	ft	cfs/ft	ft	ft
0	7.50	118.0	14.60	13.37
2	7.74	114.3	14.50	13.35
4	8.00	110.5	14.25	13.15
6	8.33	106.0	13.90	12.84
8	8.77	101.0	13.55	12.55
10	9.40	94.0	12.90	11.92
12	10.10	87.6	12.45	11.43
14	10.90	81.0	12.05	11.25
16	11.70	75.6	11.65	11.02
18	12.67	70.0	11.30	10.65
20	13.60	65.0	11.00	10.40
22	14.68	60.4	10.75	10.20
24	16.00	55.5	10.50	10.01
26	17.70	50.0	10.30	9.90
28	19.40	45.5	10.15	9.80
30	21.60	41.0	10.05	9.67

TABLE 7

10' wide chute outlet calculations

		885 cfs			1800 cfs		
Dist from outlet ft	Width of chute ft	Unit discharge cfs/ft	Energy ft	Depth of flow ft	Unit discharge cfs/ft	Energy ft	Depth of flow ft
0	10.00	88.5	14.60	13.98	180.0	17.95	15.88
2	10.13	87.4	14.50	13.95	177.5	17.85	15.85
4	10.20	86.8	14.25	13.63	176.0	17.60	15.60
6	10.37	85.5	13.90	13.25	173.5	17.25	15.26
8	10.67	83.0	13.55	12.92	169.0	16.90	14.90
10	11.13	79.5	12.90	12.25	161.5	16.25	14.58
12	11.67	75.9	12.45	11.75	154.3	15.80	13.90
14	12.27	72.2	12.05	11.43	146.8	15.40	13.57
16	12.92	68.5	11.65	11.17	139.2	15.00	13.40
18	13.68	64.8	11.30	10.77	131.8	14.65	13.10
20	14.50	61.0	11.00	10.48	124.1	14.35	12.92
22	15.42	57.5	10.75	10.25	116.7	14.05	12.78
24	16.58	53.5	10.50	10.07	108.7	13.85	12.73
26	18.08	49.0	10.30	9.92	99.6	13.65	12.70
28	19.67	45.0	10.15	9.83	91.5	13.50	12.70
30	21.60	41.0	10.05	9.77	83.4	13.40	12.75

APPENDIX C

MODEL CONSTRUCTION & TESTING APPARATUS

a) Model construction

i) Preparation of the three cell culvert

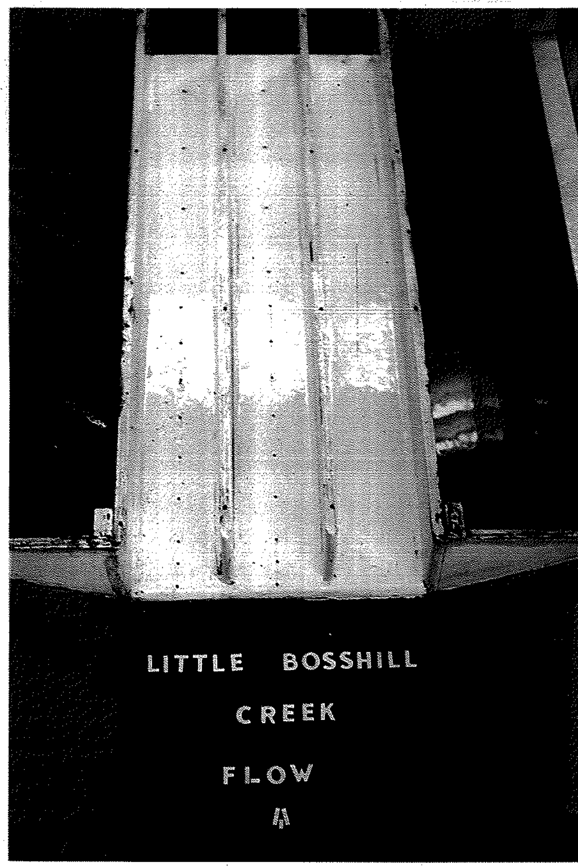
Initially the upstream and downstream channel sections were constructed from a 3/4" plywood sheet, 8' long, which also served as the channel bed. Side slopes for the channel were selected at 2:1 and supported by wedges on the base, leaving a channel bed width of 21.6'. Since the roughness of the base was insufficient to duplicate field conditions, mosquito netting was nailed to the channel bed. The bed was painted deep blue and the channel sides were painted pale green to easily distinguish between the channel bed and side slopes in color photographs. This channel section corresponded to a prototype section 160' long and 60' wide. This length of channel was selected as sufficient to obtain uniform flow conditions.

FIGURE 5, APPENDIX A, shows the general plan of the three cell box culvert on Little Bosshill Creek. Using the model length ratio of 20, the resulting model was 31.5" long and 13" wide, with side and end supports to hold it in the flume. Brass fittings for the open manometer tubes were countersunk in the bottom of the culvert and connected to the manometer tube stand by 300' of plastic tubing.

The three cell culvert was cut from 1/2" plywood and given two coats of waterproofing. The sides were then glued and screw-nailed to the bottom section and the 6" fillets added. The irregularities in the wood surface were filled with plastic wood and sanded. Two coats of latex paint and one coat of enamel paint were applied to give the model a smooth surface. The culvert section was securely fixed in the flume to the upstream and downstream sections by eight bolts while wedges were used to hold the channel sections in place (PHOTOGRAPH 6). All joints that did not fit tightly or leaked during testing were sealed with caulking compound or asphalt.

It was desired to see what occurred when sandbags were placed on the shoulder of the road and the discharge through the structure was doubled. This test was used to correlate the theoretical head difference and the actual head difference required to pass a given flow.

A 60' long section of highway was cut from 1/4" plywood, glued to the appropriate supports, and then placed on top of the three cell



Intermediate construction of three cell model

PHOTOGRAPH 6

culvert. It was then painted to resemble the prototype and caulked to prevent leakage. The resulting assembly very closely resembled the structure at Little Bosshill Creek (PHOTOGRAPH 7).

ii) Preparation of the energy culvert

The 7.5' wide energy culvert (FIGURE 6, APPENDIX A), was begun by preparing a base section upon which the chute walls and inlet and outlet sections were supported. This base also served as the floor of the chute or centre section. Next, the inlet approach and outlet exit sections were supported at their correct elevations above the base on blocks. The linear inlet floor was cut from 1/2" plywood and shaped

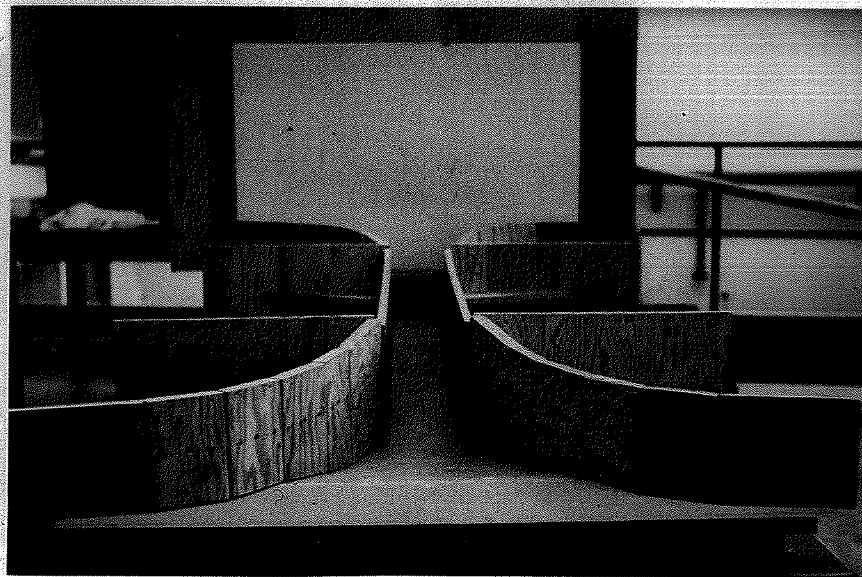
Final construction of three cell culvert

PHOTOGRAPH 7

to meet the base and approach sections with a very small transition. The headwalls and chute walls were added to the model with the appropriate bracing. It was decided that in order to obtain a more exact and workable shape, the curved walls of the inlet and outlet sections in addition to the outlet floor would be formed from paraffin.

Since the outlet floor was to be a reverse curve, a linear wood section was nailed to the base and to the elevated exit section, upon which the curved floor was formed. A template had been cut from sheet metal and trimmed to the exact shape of the outlet floor curve plotted in FIGURE 2-14. This template was used to strike off the final floor surface after the paraffin was allowed to harden.

For the inlet and outlet walls, a rough curve was made from small wood sections, braced together, and nailed in place on the inlet and outlet floors (PHOTOGRAPH 8). A strip of sheet metal 6" wide was clamped and braced in an approximate position that the final curve would take when finished. Paraffin was melted and poured between the sheet metal and the wood sections and allowed to harden sufficiently before the metal form was removed. This procedure was repeated for the other three walls and required 20 lb. of wax.



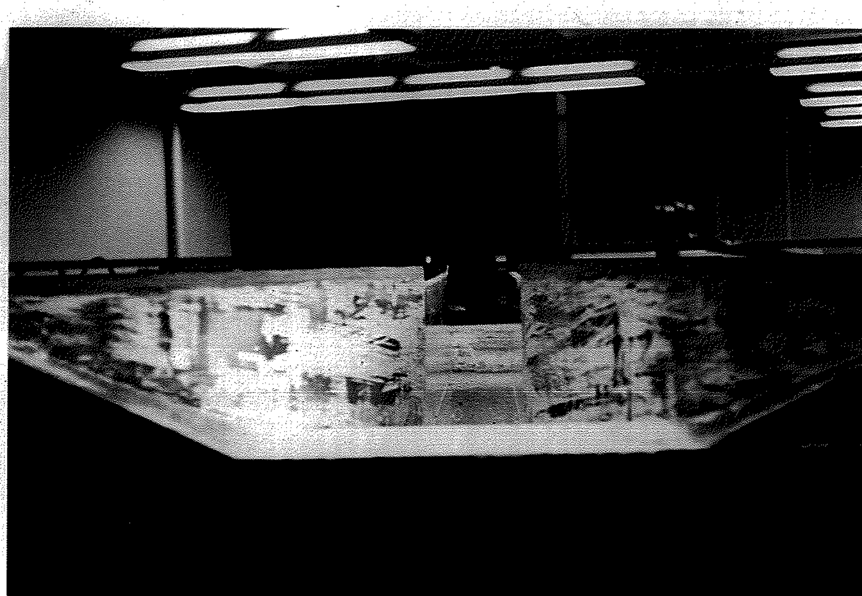
Initial construction of energy culvert

PHOTOGRAPH 8

To bring the walls to their final shape, another template was cut from sheet metal and trimmed to the shape of the curved wall plotted from the points in TABLE 2, APPENDIX B. The walls were then shaved with a small plastic tool to remove excessive wax until the template fitted all sections properly. The model was given one coat of latex paint to show up the imperfections in the paraffin surface, and then these imperfections were removed. The side slopes of the channel were continued towards the model until they intersected the vertical curved walls.

A triangular shaped block of wax was poured on both sides of the inlet approach and outlet exit sections (PHOTOGRAPH 9) and trimmed approximately to the 2:1 slope of the channel sides. A cover made from 1/4" plywood was placed between the headwall and the curved walls of the inlet and outlet sections to resemble backfill in the prototype design.

The energy culvert model was given a coat of latex paint and white enamel paint to duplicate the roughness of concrete. FIGURE 5, APPENDIX A shows the general layout of this model. The model was placed in the

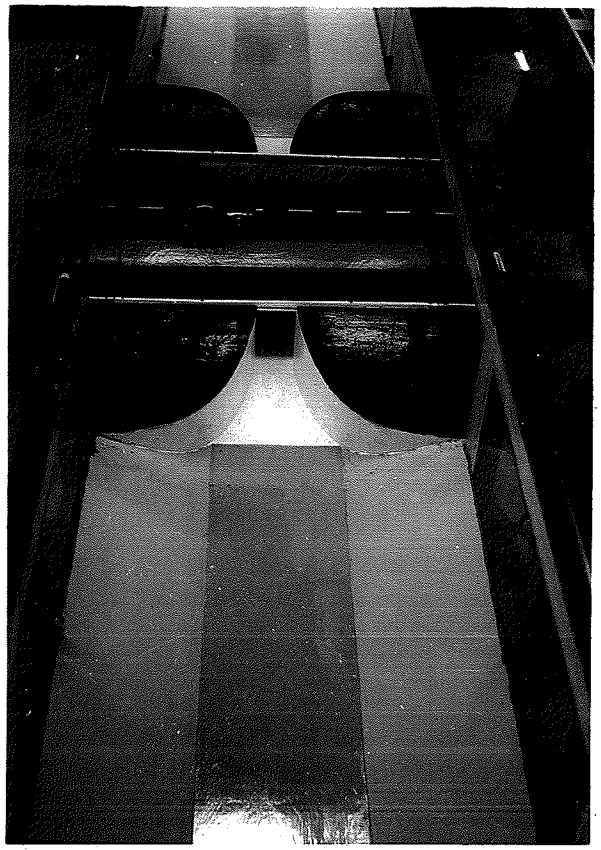


Intermediate construction of energy culvert

PHOTOGRAPH 9

flume and the channel sections were fitted tightly against it but were not bolted together. The 2:1 side slopes on the model were trimmed to match the channel side slopes and repainted. All joints that did not fit tightly or leaked during testing were filled with caulking compound or paraffin and repainted. The road section was added to the model (PHOTOGRAPH 10) but was removed immediately before testing commenced. At larger flows, the inlet, chute and outlet walls were extended vertically to maintain the same smooth streamlined shape. Open manometer tubes were not used in the testing of this model as all surface elevations at all discharges were taken with a point gauge.

The 10' wide energy culvert (FIGURE 6, APPENDIX A) was constructed from the 7.5' wide energy culvert by modifying only the width of the inlet, outlet and chute. The floors of the inlet, chute and outlet remained unchanged. The curved walls and chute walls were removed and the chute walls were re-secured to the base 10' apart. The curved walls were secured at both sides of the chute entrance and exit, then rotated so that the channel width at 30' from the chute was exactly 21.6'. The walls were then secured to the inlet and outlet



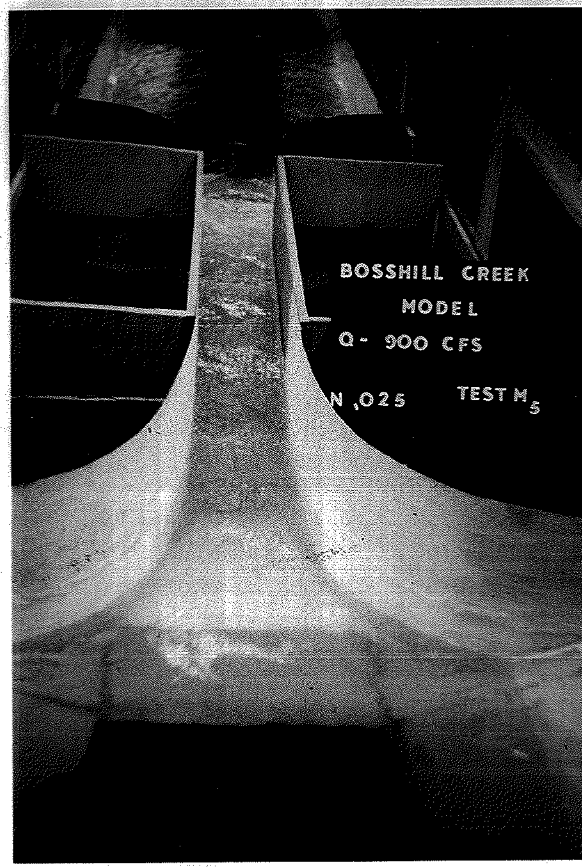
Final construction of energy culvert

PHOTOGRAPH 10

floors and all cracks were sealed with wax. The entire hydraulic model was given an additional coat of paint because the previous coat of paint had lost its brightness. The walls of the inlet, chute, and outlet were laso extended upward by means of a plywood base and sheet metal in preparation for very large flows (PHOTOGRAPH 11).

b) Testing apparatus

In the flume, a baffle made from three 2" layers of a nylon mesh packing material, was used to produce uniform flow conditions at the top end of the tank. At the lower end of the flume, a 2.5' x 3'



Upward extension of inlet & chute walls

PHOTOGRAPH 11

gate on a rising stem lifter, was mounted on 2" angle iron to the tank. Below the gate, a compressed air powered directional bucket was located. This bucket distributed water from the flume into one of two tanks located between the upper and lower floors of the hydraulics laboratory. Each tank had a float measuring device, which was connected to a dial and pointer located on a pedistal 5' above the floor. The tanks had been calibrated in terms of total volume, or cubic feet for a given number of turns of the pointer, the full capacity being approximately 300 cubic feet. To empty the tanks, a water pressure controlled lifting cylinder was located in each tank. When opened, the contents of the tanks emptied directly below into the sump. A stop watch was used to record the amount of time required to fill a given volume of the north tank.

In the bottom of the flume, there were two 2" holes with connecting pipes installed underneath the flume to the lower end where control valves were located. The first hole, about the middle of the tank, was used to drain any leakage from the model that occurred during testing. The second hole, located at the lower end of the flume, controlled the level of the tailwater pool because the lifting mechanism for the slide gate was not sensitive enough for continuous testing.

The recirculating water was drawn up from the sump by one of two pumps, each powered by a 25 horsepower motor. The smaller capacity pump being due to a constant speed motor under full load; the larger capacity pump being a variable speed motor under a full load. The smaller pump was very difficult to prime and was only used for discharges up to 700 cfs. The output of this pump at any discharge was constant, while the output from the other pump varied considerably with a small discharge. With a large discharge, this variation in the larger pump decreased sufficiently for reliable use.

The water from the pumps was conveyed to the flume by means of a 6" main for the larger pump, and a 4" main for the smaller pump. The discharge released into the flume was controlled by valves located on the two 6" mains entering the upper end of the tank.

The Kent Mini-Flow Probe consisted of a probe or rod about 1 1/2' long with a small propeller mounted at the bottom of the probe. At the top of the rod, a two prong electrical connection was mounted for a chord which connected the probe to the recording box. On the box was a dial, a battery test switch, and a two position speed selector switch. When placed in the water, the propeller turned and the dial needle pointed to a number which corresponded to a velocity on an accompanying chart. The probe was attached to the point gauge by means of a special clamp and the recording box was placed on the carriage for convenient observation.

APPENDIX D

COST ESTIMATES

Cost Estimate for Comparison

a) Introduction

The following unit prices used in the cost estimate comparison were recommended by H.E. Cowley, Assistant Bridge Engineer for the Manitoba Department of Highways' Bridge Branch. With easy access to the site, the unit price of concrete was \$80/cu. yd. The cost of steel reinforcing and placing, backfill and other items were included in the unit price of \$100/cu. yd. for concrete without too much error.

The unit price of \$9/sq.ft. of deck for a timber bridge and \$25/sq.ft. for a concrete deck bridge were recommended for estimating purposes. These unit prices include the labor and materials required to finish the project.

The cost of a timber bridge was by far the cheapest compared to any alternate design, however, it was the policy of the Highway Department's not to build a timber structure on the Trans-Canada or provincial trunk highways. It was considered good practice to place only a first class bridge on a major road.

In the use of corrugated metal pipes, it was part of the Highway's policy to place not more than two pipes over 6' in diameter at one site. This was done for space and hydraulic considerations. The typical installation was two 14' x 8'9" arch pipes or something similar at one crossing. This rule does not apply for small pipes as a large bank of 3' diameter corrugated metal pipes was common in many places.

b) Three cell box culvert

i) 7' x 7' box culvert with wall thickness = 0.833'

Volume of floor & top	2 x 63 x 24.3 x .833/27	94.6 cu.yd.
Volume of sides	4 x 63 x 7 x .833/27	54.5 cu.yd.
Volume of headwalls	2[54 x 11.75 - 24.3 x 8.67] x .833/27	26.2 cu.yd.
		175.3 cu.yd.

Total concrete volume = 175.3 cu. yds. Select 180.0 cu. yds.

Cost at \$100/cu.yd. \$ 18,000

ii) 10' x 10' box culvert with 1.0' wall thickness

Volume of floor & top	2 x 63 x 34 x 1/27	159.0 cu.yd.
Volume of sides	4 x 63 x 10 x 1/27	93.5 cu.yd.
Volume of headwalls	2[60 x 16 - 34 x 10] 1/27	46.0 cu.yd.
		298.5 cu.yd.

Total concrete volume = 298.5 cu. yds. Select 300.0 cu. yds.

Cost at $100/cu.yd. $ 30,000

c) 7.5' wide energy culvert

i) Normal chute length with 0.833' wall thickness

Chute

Volume of floor	2 x 63 x 9.17 x .833/27	35.7 cu.yd.
Volume of walls	2 x 63 x 12 x .833/27	46.8 cu.yd.
Chute volume		82.5 cu.yd.

Inlet & outlet sections

Volume of walls	4[12.7 + 8.3]/2 x 30 x .833/27	39.0 cu.yd.
	4 x 23 x 8.3 x .833/27	23.6 cu.yd.
Volume of floors	2[30 x (7.5 + 21.6)/2 +10 x (21.6 + 60)/2] x .833/27	52.2 cu.yd.
		114.8 cu.yd.

Volume of concrete	chute	82.5 cu. yds.
	inlet & outlet	114.8 cu. yds.
		197.3 cu. yds.

Select 200.0 cu. yds.

Cost at $100/cu.yd. $ 20,000

ii) Reduce chute length by 50%

Volume of concrete	chute	41.2 cu. yds.
	inlet & outlet	114.8 cu. yds.
		156.0 cu. yds.

Select 160.0 cu. yds.

Cost at $100/cu.yd. $ 16,000

d) 10' wide energy culvert

i) Normal chute length with 0.833' wall thickness

Chute

Volume of floor	2 x 63 x 11.67 x .833/27	45.4 cu.yd.
Volume of walls	2 x 63 x 17.17 x .833/27	66.8 cu.yd.
Chute volume		112.2 cu.yd.

Inlet & outlet sections

Volume of walls	4[16.7 + 11.4]/2 x 30 x .833/27	52.2 cu.yd.
	4 x 23 x 11.4 x .833/27	32.4 cu.yd.
Volume of floors	2[30 x (10 + 21.6)/2 + 10 x (21.6 + 60)/2] x .833/27	54.4 cu.yd.
		139.0 cu.yd.

Volume of concrete	chute	112.2 cu. yds.
	inlet & outlet	139.0 cu. yds.
		251.2 cu. yds.

Select 255.0 cu. yds.

Cost at \$100/cu.yd. \$ 25,500

ii) Reduce chute length by 50%

Volume of concrete	chute	56.1 cu. yds-
	inlet & outlet	139.0 cu. yds.
		195.1 cu. yds.

Select 200.0 cu. yds.

Cost at \$100/cu.yd. \$ 20,000

e) Corrugated metal pipe

i) Standard round pipe

8' in diameter, #8 gauge costs \$42,47/linear ft.
(includes erection & backfill to 1/3 diameter)

Cost of pipe \$43.47 /ft. + 10% tax	\$46.62 /ft.
installation = 30%	\$13.99 /ft.
Total cost of pipe	\$60.61 /ft.

Length of pipe = 63' + 2[5 x 3] + 4 couplers at 2' each = 98.0'

select length = 100.0'

At 900 cfs with 1.0' head, three 8' diameter pipes were required

Cost = 3 x 100 x $60.61 = $ 18,183

Say $18,200

At 1800 cfs with 1.0' head, six 8' diameter pipes were required

Cost = 6 x 100 x $60.61 = $ 36,366

Say $ 36,400

ii) Multiplate arch pipe

At 1.0' head difference the required size of the arch pipes were 12'10" span by 8'4" rise.

Cost of pipe $73.17 /ft + 10% tax	$80.50 /ft.
installation = 30%	$24.10 /ft.
Total cost of pipe	$104.60 /ft.

Length of pipe = 100'

At 900 cfs with 1.0' head, two arch pipes were required.

Cost = 2 x 100 x $104.60 = $ 20,920

Say $ 21,000

At 1800 cfs with 1.0' head, four arch pipes were required.

Cost = 4 x 100 x $104.60 = $ 41,840

Say $ 42,000

f) Bridges

Recommended by the Bridge Branch

span length = 40'

roadway width = 30' for a major road

i) Timber bridge

Cost = 1200 sq.ft. at $9 / sq.ft. = $ 10,800

ii) Concrete deck bridge

Cost = 1200 sq.ft. at $25 / sq.ft. = $ 30,000

APPENDIX E

FINAL DESIGN PROCEDURE

Final Design Procedure

a) Introduction

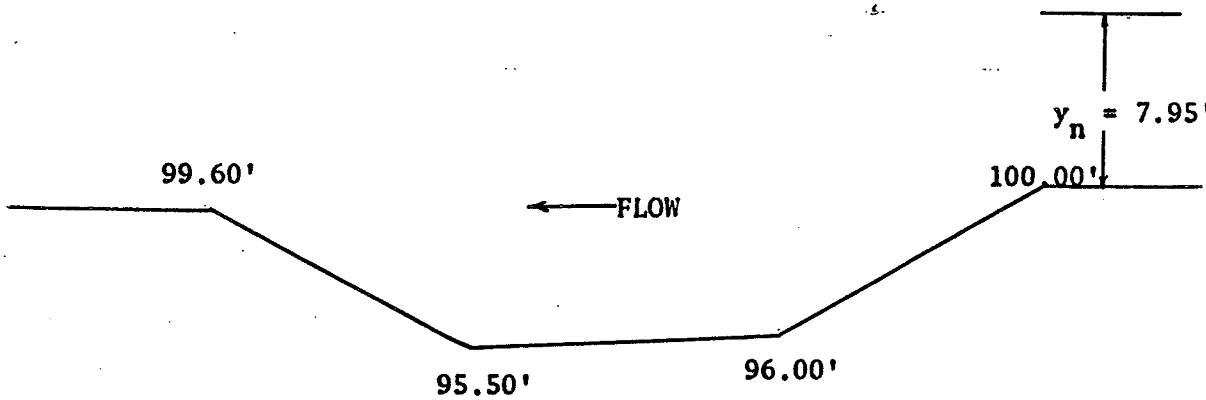
To determine a design procedure for the energy culvert, the following information was given: the 2% discharge was 1200 cfs; Manning's n = 0.035; channel bed width = 21.6'; channel side slopes = 2:1; width of road and shoulders = 60'; inlet and outlet section lengths optional; limit to which the chute may be lowered was 6'; linear sections were to be used wherever possible and cost saving modifications may be used.

b) Preliminary design calculations

From the channel dimensions, a tailwater rating curve may be prepared for a roughness coefficient of 0.035 (FIGURE 2-4), and a specific energy diagram must be obtained (FIGURE 2, APPENDIX A). With the tailwater rating curve at 1200 cfs, the normal depth of flow was 7.95' and the velocity head was about 0.04', thus fixing the channel energy at 8.00'. At this time there was a choice of setting the chute width or fixing the depth to which the chute may be lowered. In this case, it was decided to set the chute depth at 4.00' below the channel bed. Therefore, the total available energy at the entrance to the chute would be 8.00' + 4.00' = 12.00'. From FIGURE 3, APPENDIX A, the critical width for the chute would be 9.35'. With a width of 10.00', the maximum discharge would be 1260 cfs, which does not allow very much of a safety factor to remain in the subcritical flow condition. At a chute width of 11.00', the maximum discharge would be 1410 cfs, which was more reasonable, but one may select a 12.00' width for extra precaution. In this design, the 11.00' chute width was considered sufficient.

The length of the inlet section was arbitrary but should be limited from 25' to 35'. Since the drop of the inlet was 4.00', the inlet length was selected at 28.0', which resulted in a slope of 7:1 of the inlet floor.

The energy losses in the structure must be estimated before the energy grade line may be established. Friction energy losses should be in the order of 0.40' in total and the chute should have a drop in elevation of 0.50' over its entire length. A cross section of the energy culvert with the pertinent elevations is shown in FIGURE E-1. The energy losses were estimated to occur at the rate of 0.00' in the inlet section, 0.10' in the chute section, 0.20' in the outlet section, and 0.10' in the downstream transition from a rectangular to a trapezoidal shape. There would be heavy energy losses in the channel downstream from the structure, but these were not considered in the design.



Energy culvert cross section

FIGURE E-1

In order to draw the linear water surface profile, the depth of flow at the entrance to the chute and also the depth of flow at the inlet to the structure must be calculated. From the specific energy diagram (FIGURE 2, APPENDIX A), at E = 12.00', width = 11.00', and q = 109 cfs/ft., the depth of flow at the chute entrance was found to be 10.20'. However, the depth of flow at the structure entrance must be found from the specific energy diagram because the inlet width was restricted to 21.60'. The corresponding unit discharge of 55.5 cfs/ft. and the total energy of 8.00' resulted in a flow depth of 7.05', which was plotted with the other flow depth found and joined with a straight line in FIGURE E-2. From FIGURE E-2, the depth of flow and the amount of available energy were measured at regular intervals of 4.0' and the results listed in TABLE E-I. This table shows the preliminary calculations for the inlet width and the widths that were selected in the final design of this section.

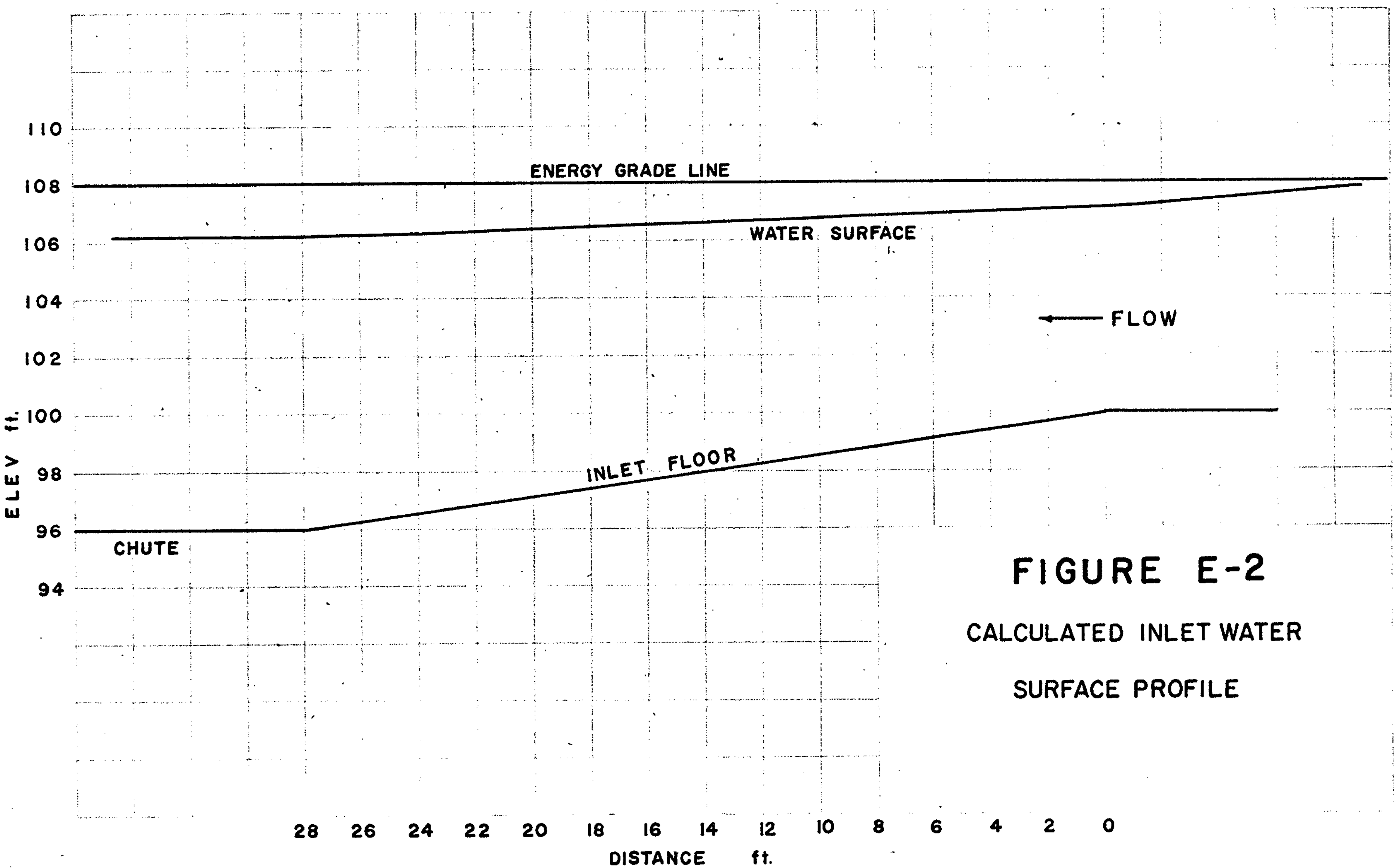
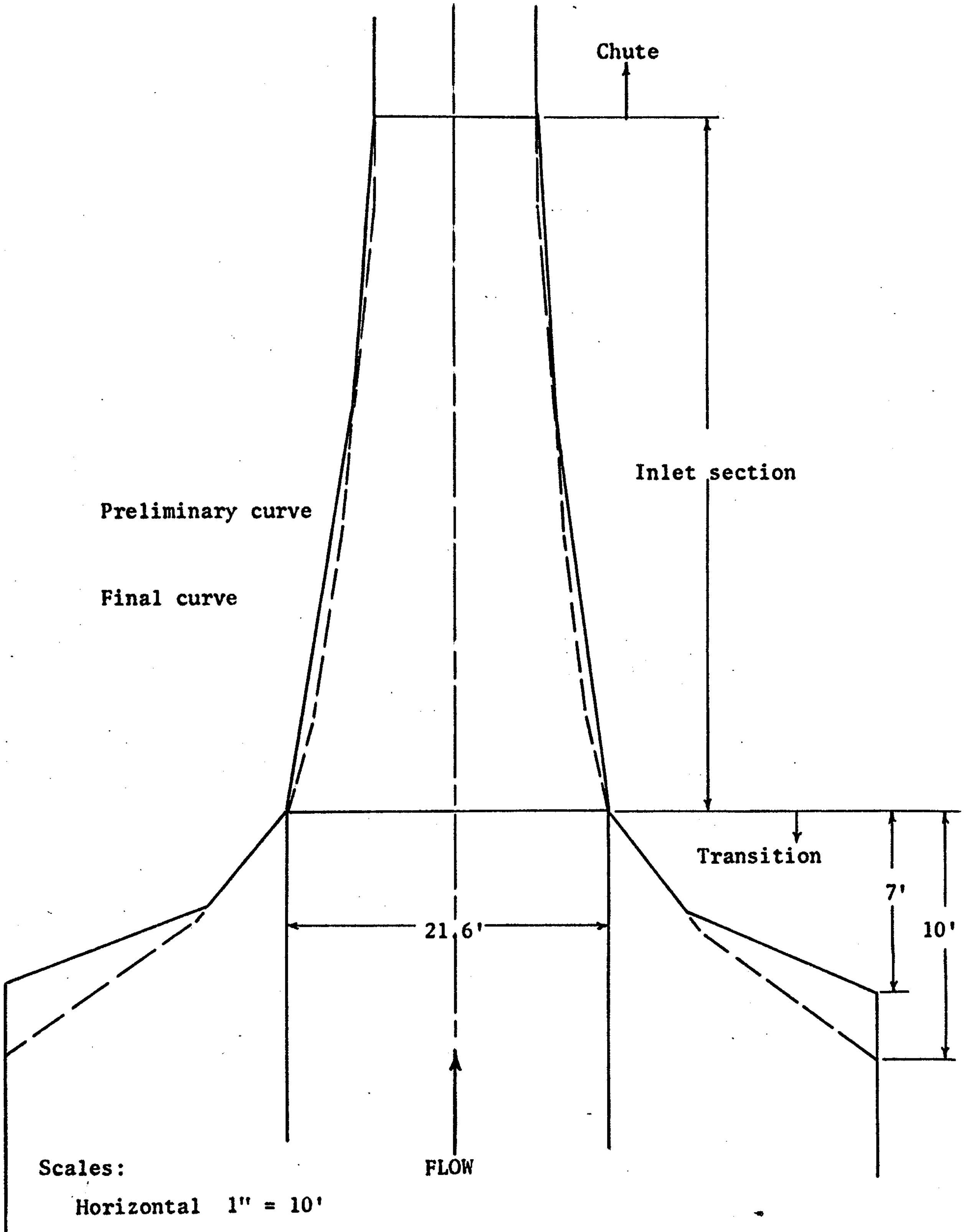


FIGURE E-2

CALCULATED INLET WATER

SURFACE PROFILE



Scales:
Horizontal 1" = 10'
Vertical 1" = 6'

Plan of inlet section with modification

FIGURE E-3

TABLE E-I

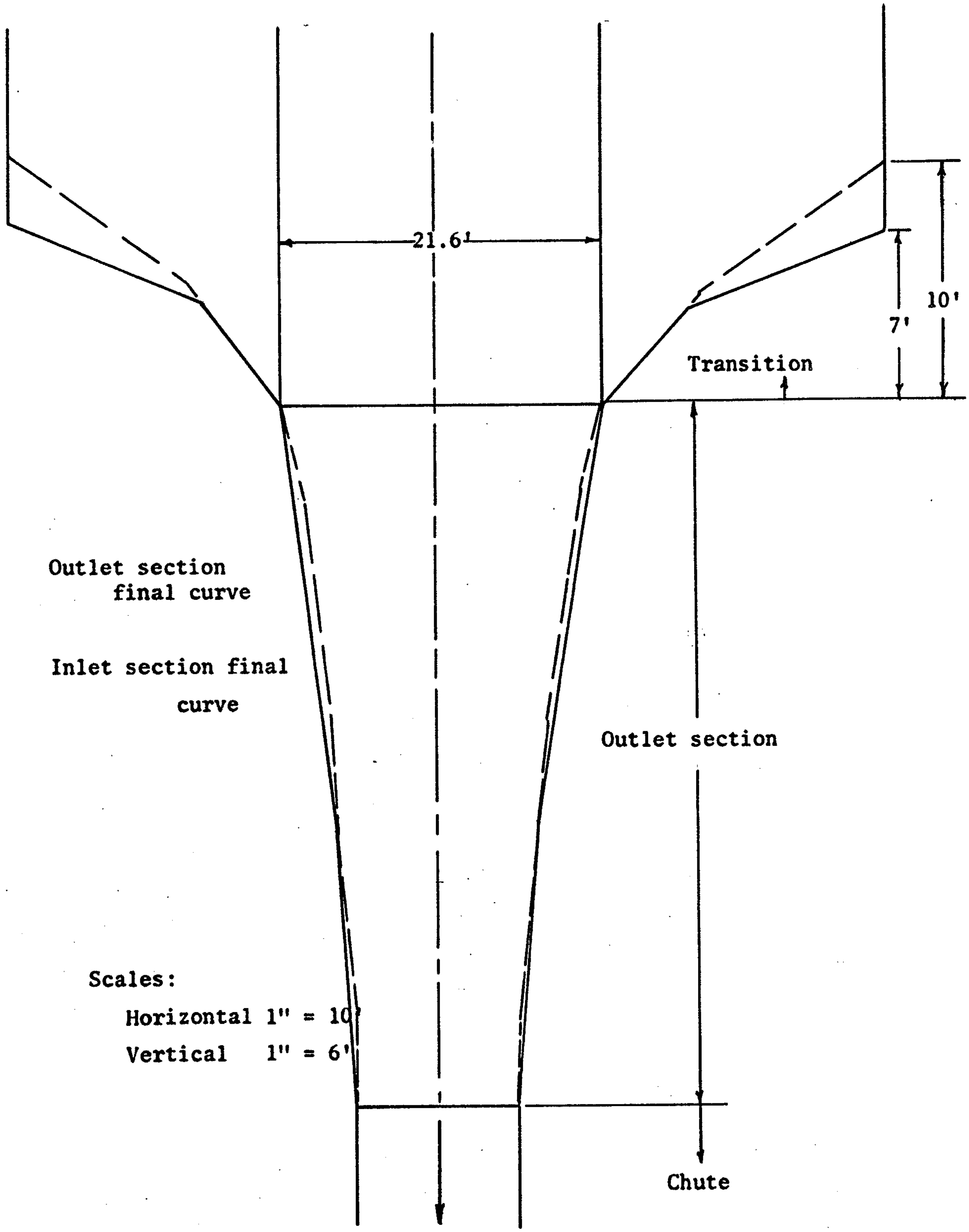
Preliminary inlet width calculations

Distance from inlet ft	Depth of flow ft	Available energy ft	Unit discharge cfs/ft	Required width ft	Final design width ft
0	7.05	8.00	55.5	21.60	21.60
4	7.50	8.70	66.0	18.20	20.25
8	7.95	9.25	73.0	16.43	18.60
12	8.40	9.85	82.0	14.64	17.10
16	8.70	10.35	89.0	13.50	15.50
20	9.35	10.90	94.0	12.78	13.40
24	9.70	11.40	102.0	11.76	12.40
28	10.20	12.00	109.0	11.00	11.00

The calculated values for the preliminary inlet widths were plotted in dashed lines in FIGURE E-3. The inlet widths as calculated to this point were only rough values, and the solid lines in FIGURE E-3 show the final shape of the inlet walls. From this diagram, the resulting preliminary curve was not as smooth as desired but it will be examined in more detail at a later time.

At the transition sections, the inlet and outlet widths were not calculated, but the shape of the walls should be a continuation of the initial curve. Here a linear section may be used to replace the curved walls near the channel sides as the curvature of the walls in this section do not aid in spreading the flow over the entire cross section. The outlet walls, however, will retain the curved shape (FIGURE E-4) so that the preliminary width calculations were not wasted.

For symmetry, the length of the outlet was set at 28', the same as the inlet, and the amount of rise of the chute floor as determined from FIGURE E-1 was 4.10'. To determine the shape of the outlet floor, the problem was to create a reverse curve or else use from TABLE 3,



Plan of outlet section with modification

FIGURE E-4

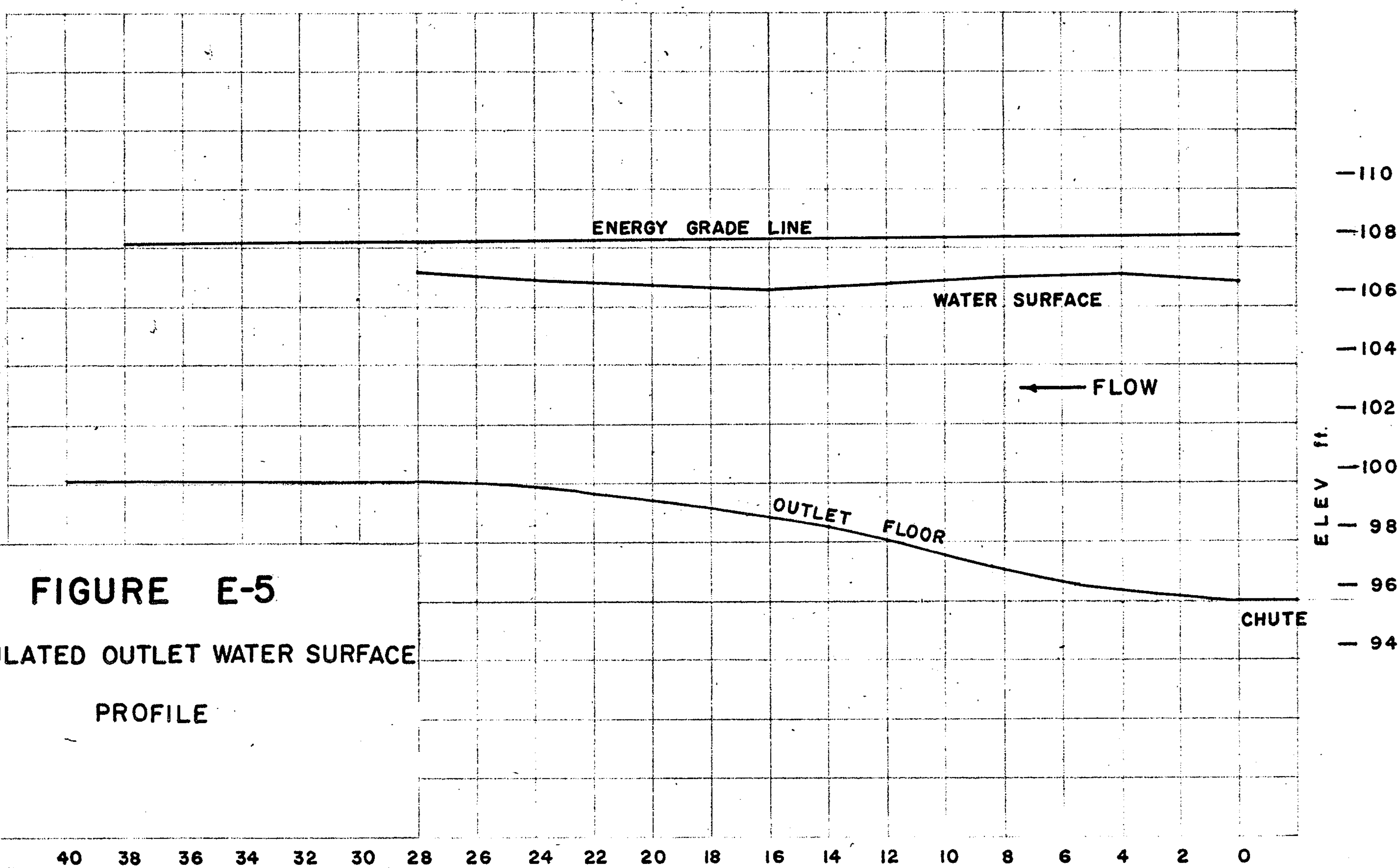


FIGURE E-5

CALCULATED OUTLET WATER SURFACE PROFILE

APPENDIX B, the distance from the chute and the amount of rise on a percentage basis and modify the result if so desired. The curvature of the floor in this design was constructed from the latter method, and the results of the calculations may be found in TABLE E-II and plotted in FIGURE E-5.

TABLE E-II

Outlet floor shape calculations

Percent of distance %	Distance from chute ft	Percent of rise %	Rise of floor ft
0	0.0	0.0	0.00
10	2.8	5.9	0.24
20	5.6	15.4	0.63
30	8.4	30.2	1.22
40	11.2	46.7	1.92
50	14.0	61.0	2.50
60	16.8	72.7	2.98
70	19.6	82.2	3.37
80	22.4	89.9	3.69
90	25.2	96.0	3.93
100	28.0	100.0	4.10

The design may not proceed further until the location of the water surface elevations with respect to the outlet retaining walls is known. The energy grade line and outlet widths have already been established, so that the depth of flow was the only unknown. From FIGURE E-5, the amount of energy and width or unit discharge at any point were known so that from the specific energy diagram, the depth of flow may be calculated as in TABLE E-III. These water surface profile calculations may be considered the final ones as the shape of the outlet was to remain unchanged.

TABLE E-III

Final outlet water surface profile calculations

Distance from outlet ft	Design width ft	Unit discharge cfs/ft	Available energy ft	Depth of flow ft
0	11.00	109.0	12.40	10.80
4	11.76	102.0	12.10	10.67
8	12.78	94.0	11.30	9.90
12	13.50	89.0	10.35	8.72
16	14.64	82.0	9.50	7.75
20	16.43	73.0	8.90	7.35
24	18.20	66.0	8.40	7.05
28	21.60	55.5	8.10	7.10

There remains some details in the preliminary design, but the major features have been covered. The height of the inlet and outlet walls should be 2.0' to 3.0' above the predicted water levels, but may not necessarily be horizontal due to the lower water levels within the chute than at the entrance and exit of the structure.

Once the wall elevations have been established, the depth of the chute must be determined so as to continuously provide a free water surface at all discharges. The lowest elevation of the chute ceiling should be above that of the normal depth of flow of the design discharge in the upstream channel (FIGURE E-6). This again may be modified if the design was expected to be exceeded to any great degree.

c) Final design calculations

The final design procedure should begin with a complete re-evaluation of the preliminary design, its capacity, inlet and outlet walls, and the water surface profiles.

The capacity of the structure may be estimated in the following manner. The minimum possible chute width from FIGURE 3, APPENDIX A, at an energy level corresponding to 1800 cfs was 11.0', thus the structure would be operating at 66% of its capacity at the design discharge. One may say that the structure was 33% overdesigned, but it must be remembered that as one moves away from the critical discharge into the subcritical flow region, the standing waves that occur become smaller and less likely to have an effect on the flow pattern in the chute. It was desirable to reduce the height of these waves to provide a much smoother water surface as they may be in the order of 2' to 3' in height.

From the previous discussion, the height of the chute ceiling may be set at the depth of flow for 1200 cfs. But, because the critical discharge of the structure was 1800 cfs, it does not mean that the chute could not pass more water with the aid of a backwater curve. For example, if enough energy were available, it was desired to pass 2400 cfs through this structure. For this discharge, the normal depth of flow was 11.0', while the total energy in the channel would be 11.4' and 15.4' in the chute entrance. But, from FIGURE 3, APPENDIX A, this flow through an 11.00' wide chute requires at least 17.0' of energy. Therefore, this flow would be passed as soon as the backwater effect had built up a head of 1.6' which would result in a flow depth at the chute entrance of 12.5'.

The shape of the inlet walls may be approximated by four linear sections as in FIGURE E-3 shown by the solid lines. The outlet walls should remain in the curved shape as determined from TABLE E-I but the transition section may be altered slightly as shown in FIGURE E-6. When the shape of the inlet walls were changed, the inlet water surface profiles must be re-calculated as shown in TABLE E-IV.

To reduce costs, the length of the chute may be reduced considerably by starting the converging and diverging of the inlet and outlet sections within the road section. For this design, extend the inlet and outlet 15.0' inside the roadway thus reducing the chute length from a possible 60.0' to a more reasonable 30.0' (FIGURE E-6).

d) Summation

The final design procedure presented here was only a first approximation to the prototype that would be constructed. The width of the inlet and outlet sections was calculated only every 4', which would be reduced to every foot in the working design. The water

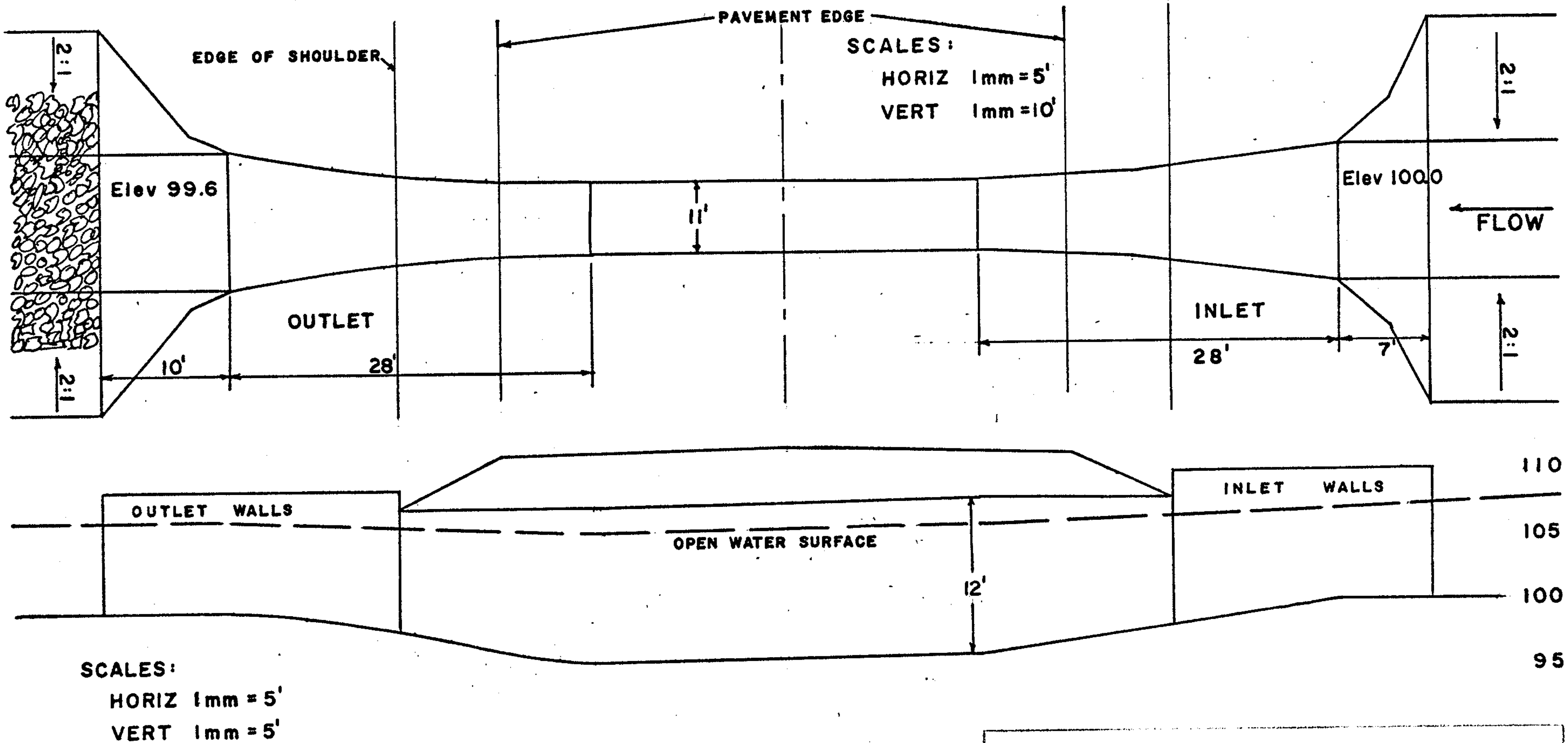


FIGURE E-6

GENERAL PLAN

CALCULATED EXAMPLE

SCALES AS SHOWN

surface profiles would also be looked into in much greater detail at several discharges, not only the maximum expected flow. Also consideration must be given to the opssibility of serious erosion in the downstream channel in addition to adequate rip rap protection. The structural design of the walls and floor would be the next important approximation in the working design. This second approximation may change the dimensions of the structure to some degree where it would no longer be a feasable design.

As this design is new in Canada, the first few structures that would be built, must be looked on as experimental until they have proven satisfactory during operation over a period of several years.

TABLE E-IV

Final inlet water surface profile calculations

Distance from inlet ft	Required width ft	Design width ft	Unit discharge cfs/ft	Available energy ft	Depth of flow ft
0	21.60	21.60	55.5	8.00	7.05
4	18.20	20.25	59.4	8.70	7.82
8	16.43	18.60	64.5	9.25	8.33
12	14.64	17.10	70.2	9.85	8.90
16	13.50	15.50	77.5	10.35	9.27
20	12.78	13.40	89.5	10.90	9.55
24	11.76	12.40	96.8	11.40	9.92
28	11.00	11.00	109.0	12.00	10.20