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BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION

BLACKSTONE RIVER, MASSACHUSETTS

DESIGN MEMORANDUM NO. 3

HYDRAULIC AND STRUCTURAL DESIGN

Corps of Engineers, U.S. Army - Office of the Division Engineer

New England Division - Boston, Mass.

FEBRUARY 1957

49

ARMY NED BOSTON

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
150 CAUSEWAY STREET
BOSTON 14, MASS.

ADDRESS REPLY TO:
DIVISION ENGINEER

REFER TO FILE NO.
NEDGW

28 February 1957

SUBJECT: Submission of Design Memorandum, Worcester Diversion, Blackstone River Basin, Massachusetts

TO: Chief of Engineers
Department of the Army
Washington 25, D. C.
ATTENTION: ENGWE

1. In accordance with paragraph 4214.12 of Orders and Regulations, there are submitted herewith for review and approval 10 copies of Design Memorandum No. 3, "Hydraulic and Structural Design" for the Worcester Diversion, Blackstone River Basin, Massachusetts."

2. Project plans and specifications are currently being prepared by an architect-engineer and in accordance with paragraph 4215.10 of Orders and Regulations will be reviewed and approved by this office. The project will be advertised as soon thereafter as possible, but not before approval of the above-mentioned design memorandum is received. It is therefore requested that review of the design memorandum be expedited.

3. Completed copies of the plans and specifications will be forwarded to the Office of the Chief of Engineers on or about the date of advertisement. Necessary modification, if any, will be incorporated in the project by addendum or by change order depending upon the time available.

FOR THE DIVISION ENGINEER:

Miles L. Wachendorf
MILES L. WACHENDORF
Lt. Colonel, Corps of Engineers
Executive Officer

Incl
Design Memo No. 3
(cys 1-10, incl.)

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FLOOD CONTROL PROJECT

WORCESTER DIVERSION

BLACKSTONE RIVER, MASSACHUSETTS

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2	General Design Memorandum	26 Sept 1956	19 Oct 1956
3	Hydraulic and Structural Design	28 Feb 1957	
4	Concrete Materials	9 Oct 1956	2 Nov 1956
5	Geology and Soils	12 Dec 1956	18 Jan 1957

WORCESTER DIVERSION

BLACKSTONE RIVER, MASSACHUSETTS

DESIGN MEMORANDUM NO. 3

HYDRAULIC AND STRUCTURAL DESIGN

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CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON 14, MASS.

FLOOD CONTROL PROJECT

WORCESTER DIVERSION
BLACKSTONE RIVER BASIN
MASSACHUSETTS

DESIGN MEMORANDUM NO. 3

HYDRAULIC AND STRUCTURAL DESIGN

February 1957

A. INTRODUCTION

1. Purpose. - The purpose of this memorandum is to present the basic hydraulic and structural design features of the Worcester Diversion Project. It presents the results of investigations and analyses, including the criteria, basic data, assumptions and computations of the hydraulic and structural features. The first part of this memorandum covers the hydraulic design and the second part covers the structural design. Hydrologic criteria and subsurface conditions for the project are presented in Design Memorandum No. 1, Hydrologic Analysis and in Design Memorandum No. 5, Geology and Soils.

2. Scope. - This memorandum covers the following structures: the control dam, intake, tunnel, stilling basin and return channel.

PART I - HYDRAULIC DESIGN

B. CONTROL DAM

3. General. - A general description and functioning of the control dam across Leesville pond, a short distance below the diversion intake, is given in Design Memorandum No. 1, page 15, in which a project design discharge of 12,000 c.f.s. was established. A flow of 6,000 c.f.s. would be diverted through the tunnel and 6,000 c.f.s. would pass over the control dam when the lake pool is at elevation 497. Plan and sections of the control dam are shown on Plate 3-2.

4. Discharge Coefficient and Length of Crest. - The weir discharge is affected by tailwater at high flows and the amount of this submergence is obtained from Plate No. 1-8 of Design Memorandum No. 1. Computations showing the method used in determining the discharge coefficient are shown in the Appendix. A 175-foot length of crest is required in order to pass 6,000 c.f.s. with a head of 5 feet, freeboard of 1'-0" and with head water at elevation 497. The earth section has been designed to pass flows over the embankment.

5. Shape of Crest. - Since the design head on the dam is equal to or more than one-half the weir height, the crest profile will be a standard Ogee crest for a 5-foot head as shown on Table 1 of Manual Part CXVI, Chapter 3 - Hydraulic Design Spillways.

C. INTAKE

6. General. - The location and details of the diversion intake are shown on Plates Nos. 3-2, 3-3 and 3-10. The intake prevents flood water below elevation 487 from entering the diversion. It will pass an increasing flow above this elevation as the pond rises with a design discharge of 6,000 c.f.s. at elevation 492.

7. Type of Spillway. - The intake is a partial morning glory spillway of shallow depth with a circular weir crest extending over an angle of 180 degrees. The invert of the spillway at the point of tangency with the tunnel was established at 451.80 in order to have the excavation for the initial section of tunnel in compact glacial till rather than partially in till and partially in rock.

8. Discharge Coefficient and Length of Weir. - The crest coefficient for the morning glory has been determined on the same basis as for a full morning glory in accordance with Engineering Manual Part CXVI, Chapter 3, Plates 39 and 40. The method of determining the discharge coefficient and length of weir is given in the Appendix. The entire area upstream of the spillway structure and the control dam will be excavated to elevation 482.

9. Crest Shape. - The shape of crest conforms to the equation for the standard crest of Ogee spillways as shown in Table 1, page 7 of the Manual.

10. Entrance and Bend Losses. - The losses through the intake have been taken as .19 of the tunnel velocity head. Plate 1 of Part CXVI, Chapter 2 - Reservoir Outlet Structures - was used as a guide in the determination of this coefficient.

D. TUNNEL

11. General. - A 16-foot diameter concrete circular conduit 4,205 feet long will convey flows from the intake to the stilling basin at the downstream end. The plan, profile and details of the tunnel are indicated on Plates 3-3, 3-4 and 3-5. The hydraulic characteristic curves for this tunnel are shown on Plate 3-12 and computations for the curves are shown in the Appendix. An "n" value of .011 was assumed which is under the .012 recommended in the manual, but which is considered conservative by the Waterways Experiment Station. The tunnel slope is greater than that required for critical discharge and all flows will be free up to the 6,000 c.f.s. design discharge. Pressure flow occurs at about 6,000 c.f.s. and above.

12. Functioning of Intake and Tunnel. - On low and moderate discharges it is expected that a jump or wave will form at the elbow of the intake from where the water surface will form a drop down curve to about uniform flow at normal depth. On high discharges the water surface may rise to such an elevation in the intake that the higher head may cause greater discharge temporarily which in turn would be followed by a lower head. This condition could be repeated and cause pulsations or surges in the tunnel and stilling basin. The 150-foot stilling basin and 800 feet of the return channel in rock would minimize any possible damage from the surges.

E. OUTLET STILLING BASIN

13. Design Criteria. - The stilling basin design is illustrated on Plate No. 3-3 and 3-11. The stilling basin is designed in accordance with hydraulic criteria described in the Manual CXVI, Chapter 2. Flow through the intake and tunnel is unregulated. The intake with a weir having the possibility of a higher discharge coefficient and a tunnel with a friction coefficient "n" less than .011 may result in much higher discharges through the stilling basin than the design discharge of 6,000 c.f.s. The design would be adequate for 7,000 c.f.s. flow through the basin.

14. Trajectory and Flare. - The 2'-0" parabolic drop 70 feet long between the invert of the tunnel and the stilling basin floor is paved.

The flare ratio does not exceed the criteria of twice the Froude number for a discharge of 6,000 c.f.s. on the assumption of a 40-foot wide stilling basin.

15. Stilling Basin Floor. - Jump heights and tailwater depths have been computed for various flows and drawn on Plate 3-11 to indicate the relationship between the two depths. Hydraulic computations are shown in the Appendix.

16. Length of Stilling Basin. - The 150-foot length of basin is about eight times the depth after jump which is conservative for discharges exceeding 6,000 c.f.s.

The basin will be paved for only 50 feet at which point the velocity in the jump would be reduced to about 10 feet per second. A concrete sill with the top at elevation 407.18 will extend across the basin at Station 47+20.

17. Analysis of Flow Conditions. - Velocities at the portal, beginning of the hydraulic jump and at the end of the basin for several discharges are shown with corresponding tailwater elevations on Plate No. 3-11.

F. RETURN CHANNEL

18. General. - The return channel extending from the end of the stilling basin at Station 47+20 to the Blackstone River generally follows the bed of Hull Brook and is divided into three main reaches. The first reach from Station 47+20 to about Station 55+00 is entirely in rock, with a bottom width of 40 feet, side slopes of 4 vertical on 1 horizontal and a channel bottom slope of .0025.

The second reach extends from the end of the channel in rock to the Massachusetts Turnpike Crossing and is in earth with a bottom width of 35 feet with side slopes of 1 vertical on 2½ horizontal. The bottom width for this reach has been reduced from the 50-foot width shown in the General Design Memorandum as a result of more detailed hydraulic calculations. The earth slopes will be protected with 2'-6" of rock fill. The bottom channel slope is .000964 to meet the invert of the existing Turnpike Crossing.

The third reach from the break in bottom grade at the Turnpike Crossing extends to Station 154+20 with a bottom width of 50 feet and side slopes of 1 vertical on 2½ horizontal. It is covered with 2'-6" of rock fill. The bottom channel slope is .000589. In order to pass normal flood flows under the NY, NH & H Railroad and to flare the outlet into the Blackstone River, the bottom width is increased from 50 feet to 80 feet by a transition between Stations 154+20 and 156+20. The span of the railroad bridge will be 80 feet. The hydraulic characteristic curves of these sections with an "n" value of .035 are shown on Plate No. 3-12.

19. Design Discharge. - The design discharge of the return channel was established as 6,000 c.f.s plus the flood flow of 800 c.f.s. from the 4.15 square miles of drainage area adjacent to Hull Brook. 500 c.f.s. of this flow is assumed to enter the upper end of the second reach and the remaining 300 c.f.s. is assumed

to enter just below the Massachusetts Turnpike Crossing. The tailwater in the Blackstone River at the outlet of the return channel was assumed to be elevation 413 with the stream bed at about elevation 397. A tailwater rating curve of the Blackstone River of the return channel outlet is shown on Plate No. 3-13.

20. Water Profile in Return Channel. - A backwater curve computation with the above assumptions gave a water depth of 15.5 feet or elevation 422.68 at Station 47+20. This backwater curve was computed in accordance with the Waterways Experiment Station, Hydraulic Design Criteria on Open Channel Flow, Sheets 010-2 and to 010-5/3. The detail calculations are shown in the Appendix. The backwater curve profile and the velocities of flow in the reaches have been plotted on Plate 3-12. It has been assumed that an "n" value of .035 throughout the reaches allows for losses through all bridge openings except at Greenwood Street and the NY, NH & H Railroad. The losses at these points have been computed and are shown in the Appendix.

PART II - STRUCTURAL DESIGN

G. DESIGN CRITERIA

21. Design Criteria. - a. General. - All working stresses conform to those specified in the Engineering Manual for Civil Works, Part CXXI, Chapter I, "Stresses and Criteria for Structural Design", dated May, 1953. Loading conditions, design assumptions and other design criteria are based on the following applicable parts of the Engineering Manual for Civil Works issued by the Office of the Chief of Engineers: Standard Practice for Concrete (Part CXX, October 1953); Gravity Dam Design (Part CXXII, October 1952); Structural Design of Spillways and Outlet Works (Part CXXIV, December 1952) and Design of Miscellaneous Structures (Part CXXIX, Chapter 1, Tunnels, June, 1952, and Chapter 2, Conduits, Culverts and Pipes, June, 1948). Accepted engineering practice has been employed in cases which the Engineering Manual for Civil Works does not cover.

b. Concrete. - The Civil Works Manual exposure classification "A" (applicable to structures subject to moderately severe weather exposure) has been used for all concrete. The following table lists the concrete and reinforced concrete working stresses used in the design of structures.

Description	Unit Stress (p.s.i.)
Flexure - f'_c = 3,000 p.s.i.	
Extreme fiber stresses in compression	1,050
Extreme fiber stresses in tension (plain concrete)	90
Shear - (v)	
Beams - no web reinforcement	90
Bond - (u)	
Deformed Bars	210
Modular Ratio - (n) = 10	

c. Reinforcement. - (1) Grade and Working Stresses. - All reinforcement in the structures, including temperature and shrinkage reinforcement, is designed for the working stresses of new billet steel, intermediate grade, deformed bars with an allowable stress of 18,000 p.s.i. in flexural tension. The reinforcement will conform to the requirements of ASTM Specification A15-54T for "Billet Steel Bars for Concrete Reinforcement", deformed, Intermediate Billet.

(2) Spacing. - The clear distance between parallel bars will not be less than $1\frac{1}{2}$ times the diameter of round bars except that in no case will the clear distance between parallel bars be less than 1 inch, or $1\frac{1}{2}$ times the maximum coarse aggregate size.

(3) Minimum Cover for Main Reinforcement. -

Type	Minimum Cover (Inches)
All reinforcing adjacent to earth or rock	4
All other reinforcing	3

(4) Splices. - All splices will be lapped 30 diameters to develop by bond, the total working strength of the bars. Splices in the main reinforcement at points of maximum moment will be avoided in the design.

(5) Temperature and Shrinkage Reinforcement. - Temperature and shrinkage reinforcement will be provided in slabs and walls where the main reinforcement extends in only one direction. This reinforcement, based on deformed bars, will provide for a minimum ratio of steel area to concrete area (bd) of 0.002 with a maximum spacing between bars of 18 inches.

22. Basic Data and Assumptions. -

a. Controlling Elevations (m.s.l.)

Top of control dam	498
Control dam spillway crest	492
Intake structure spillway crest	487
Tunnel invert at exit portal	407
Stilling basin floor	405

b. Loads. - (1) Dead Loads. - The following unit weights for materials have been used:

Material	UNIT WEIGHT, pcf		
	Saturated	Dry	Submerged
Rock Fill	135	115	72
Gravel Bedding and Pervious Fill	141	125	78
Impervious Fill	150	138.8	87.5
Foundation Till	150	138.8	87.5
Foundation Sand	128	106	66
Foundation Rock		175	
Concrete (plain and reinforced)		150	

(2) Live Loads. - The following live loads have been used:

Water 62.5 lbs. per cu. ft.

c. External Water Pressure. - In cases where hydrostatic pressure affects the design of a structure, it has been assumed to act over the entire area in question under the full head. Specific uplift assumptions for each structure are given in the section where the structure is treated separately.

d. Earth Pressure. - Pressures against the tunnel have been determined by the methods outlined in Part CXXIX, Chapter 2, Conduits, Culverts and Pipes, using Case I.

H. CONTROL DAM

23. Description. - The control dam is shown on Plate 3-2. The Ogee spillway section will be constructed on the glacial till or compact silty sand. A concrete vertical key at the upstream end of the Ogee section will be carried down into glacial till to form a cutoff.

The area immediately downstream from the Ogee section will be covered with a concrete slab. The area further downstream from the slab will have a layer of rock fill 2'-6" thick, the lower part of which will be comprised of the finer sizes.

The non-overflow section and the training walls at the abutment will be designed as gravity sections. The non-overflow section will extend into the impervious section of the earth dam. The fill adjacent to the training wall will be free draining to prevent excessive thrusts due to possible pressure from frost action in the glacial till.

The diversion cofferdams will form the upstream and downstream pervious zones of the permanent embankment. The impervious center section will be constructed from the glacial till. The entire embankment will be covered with rock fill from the tunnel excavation.

24. Stability Analysis. - The dam has been analyzed for stability and sliding; first, with head water assumed at crest level with no tailwater; second, with 5 feet of head water over the crest and tailwater 2.5 feet above the crest; finally, with 5 feet of head water over the crest and tailwater 2.5 feet below the crest.

The sliding factor of the Ogee section under the first assumption is .3; under the second assumption is .15 and for the final assumption is .6. The vertical key will be reinforced to further increase the factor of safety against sliding.

25. Sluice Gates - Operating Mechanism. - Two 5' x 5' cast iron sluice gates will be provided in the control dam in order to pass low flows. These gates are designed for seating pressure with a differential in head not exceeding 10 feet. The seats will be of bronze.

The operating floor stand will be of sufficient capacity to operate the gate properly under the 10-foot head differential with provision for crank and power operation. It will have a bronze operating nut and tapered roller anti-friction bearing.

The portable power operator mechanism will have a small gasoline engine, reversing transmission and an adjustable release clutch with the reversing transmission being driven by a chain drive from the gasoline engine. The floor stand will have special brackets for fastening the operating mechanism to the stand.

I. INTAKE STRUCTURE

26. General. - The intake and transition section is shown on Plate 3-10. The location of the intake structure has been revised from that shown in the General Design Memorandum to provide a better working space between the intake and the railroad track. It is founded on rock and is designed as a cylindrical structure to resist the horizontal water and earth loads acting on the perimeter. The opening through the side for flow to the tunnel is circular in section and decreases to a 16-foot diameter at the tunnel. This circular section will be reinforced by circumferential reinforcing at the inside face.

The main cylindrical ring will be reinforced horizontally to transfer the main ring stresses to the adjacent concrete above and below the water passage opening.

The side walls forming the bell mouth of the transition section proper will be supported on the main structural ring of the intake.

A joint with rubber water stop has been provided at the juncture of the intake with the tunnel in the glacial till.

27. Uplift. - The bottom slab in the vicinity of the invert is subject to considerable uplift. To resist this force dowels have been designed anchoring the slab to the underlying rock. The entire structure is stable for uplift with external water pressure to elevation 492 without an internal water load.

28. Crest. - The overhanging crest has been designed as a cantilever to carry the load of concrete and water.

29. Debris Barrier and Log Boom. - The debris barrier in front of the intake structure will be A.R.E.A. 115# steel rails spaced 12 ft. center to center. They will be located on the circumference of a circle concentric with the intake and about 30 feet from the crest. These rails will be driven deep into the glacial till with their top at elevation 493.

A log boom will be located across the stream just above the control dam and intake as shown on the drawings. The logs will be about 10 inch diameter at the tip and about 18 feet long and connected together by boom chains. A steel cable shall pass through the chains on each log and the ends of the cable will be fastened to substantial anchors at each end.

J. TUNNEL

30. General. - The cross sections and profile of the 16 ft. diameter tunnel are shown on Plates 3-3, 3-4 and 3-5. The thickness of tunnel lining as indicated on Plate 2-6 of Design Memorandum No. 2 has been increased. The minimum thickness of lining shown in "Typical Rock Section - Unsupported" has been increased from 1'-0" to 1'-3" and the lining shown in "Typical Earth Section" has been increased from 2'-1" to 2'-1½". The tunnel extends from the intake structure to the stilling basin and is in compact glacial till for about 405 feet, in weathered phyllitic rock for about 225 feet and in relatively sound phyllite for approximately 3,575 feet. Most of the 3,575 feet of tunnel in rock will not require any form of support during construction. For short stretches of weathered or severely broken zones, provision is made for installing either steel ribs, roof bolts or applications of gunite. Probable areas of increased rock tunnel loading are discussed on page 7 of Design Memorandum No. 5, Geology and Soils.

The easterly portal of tunnel has been located in relatively sound bedrock, well into the hillside, where approximately 50 feet of rock cover is available over the tunnel portal.

31. Design Loading. - The design of the tunnel follows the criteria set forth in the Engineering Manual, Part CXXIX, Chapter 1, "Tunnels", and Chapter 2, "Design of Miscellaneous Structures, Conduits, Culverts and Pipes". The following loading conditions govern the design of the tunnel.

a. Tunnel in Earth. -

Maximum vertical load = Weight of 65 ft. of submerged earth.

Horizontal load = 50% of vertical load.

Maximum hydrostatic pressure = 65 ft. head of water over crown.

b. Tunnel in Rock. -

Maximum hydrostatic pressure = 175 ft. head of water over crown.

c. Temporary Supports for Tunnel in Earth. -

Vertical load = Weight of 22.5 ft. of submerged earth.

Maximum hydrostatic pressure = 65 ft. head of water over crown.

d. Temporary Supports for Tunnel in Rock. -

Vertical load = Weight of 10 ft. of fractured, blocky, seamy rock.

32. Design Analysis. - An analysis for a circular concrete tunnel lining has been made similar to that for a modified circular culvert in "Concrete Culverts and Conduits" of the Portland Cement Association.

Coefficients have been computed for moment, shear and thrust for uniform vertical earth load, uniform horizontal earth load and triangular horizontal earth load at points on the shell 15 degrees apart for a tunnel of radius r and thickness of lining t.

Computations combining the weight of tunnel lining with outside water load to crown have been made for a 16-foot diameter tunnel with lining thicknesses of 1'-0", 1'-6", 2'-0" and 2'-6". The weight of the lining balances the buoyancy at 2'-6" thickness. For thickness less than 2'-6" the excess buoyancy has been assumed as distributed equally to each of the six top voussoirs and which approximates a trapezoidal reaction.

Applicable combinations of these data have been used to design the 16' diameter tunnel. The design of the tunnel in rock is computed on Sheet B-23 and the design of the tunnel, both for reinforced and unreinforced concrete in earth, is computed on Sheet B-24.

Moments and shears for thicknesses shown are taken from computations or interpolated from moment or force diagrams in the Appendix.

The computations for structural steel tunnel supports are on Sheets B-25 and B-26 in the Appendix.

K. STILLING BASIN

33. General. - The stilling basin is shown on Plates 3-3 and 3-11. The rock on the bottom and sides of the basin from the tunnel portal for 120 feet will be paved with reinforced concrete.

34. Anchors. - The floor slab and side walls are anchored to the rock by a regularly spaced layout of anchor bars. These bars are designed to resist a contained water pressure from ground water found in the rock equal to the elevation of the top of the walls.

The downstream section of the stilling basin will be unpaved for about 100 feet where the velocities of flow are substantially reduced.

TABLE I

DETAILED FEDERAL COST ESTIMATE
(1956 Price Level)

ENR Construction Cost Index 697 (1913 = 100)

No. Item	Description	Quantity	Unit	Unit Price	Estimated Amount
1	Preparation of Site	1	Job	L.S.	$ 30,000
2	Control and Diversion of Kettle Brook	1	Job	L.S.	15,000
3	Common Excavation - Intake	1	Job	L.S.	20,000
4	Common Excavation - General				
	a. First 650,000 cu. yds.	650,000	Cu. Yds.	0.60	390,000
	b. Over 650,000 cu. yds.	50,000	Cu. Yds.	.50	25,000
5	Rock Excavation - Open Cut				
	a. First 120,000 cu. yds.	120,000	Cu. Yds.	3.50	420,000
	b. Over 120,000 cu. yds.	20,000	Cu. Yds.	3.25	65,000
6	Mucking Rock Overbreak in Open Cut	1,500	Cu. Yds.	1.00	1,500
7	Tunnel Excavation - All Earth				
	a. First 4,500 cu. yds.	4,500	Cu. Yds.	20.00	90,000
	b. Over 4,500 cu. yds.	500	Cu. Yds.	18.00	9,000
8	Tunnel Excavation - Part Earth-Part Rock				
	a. First 2,500 cu. yds.	2,500	Cu. Yds.	20.00	50,000
	b. Over 2,500 cu. yds.	200	Cu. Yds.	18.00	3,600
9	Tunnel Excavation - Rock				
	a. First 36,000 cu. yds.	36,000	Cu. Yds.	20.00	720,000
	b. Over 36,000 cu. yds.	4,000	Cu. Yds.	18.00	72,000
10	Tunnel Excavation - Rock, Ordered Enlargement	70	Cu. Yds.	20.00	1,400
11	Tunnel Excavation - Mucking Rock Overbreak Material	3,300	Cu. Yds.	2.00	6,600

TABLE I (Cont'd)

No. Item	Description	Quantity	Unit	Unit Price	Estimated Amount
12	Structural Supports in Tunnel				
	a. First 400 Full Circle	400	Each	$660.00	$264,000
	b. Over 400 Full Circle	100	Each	660.00	66,000
13	Structural Supports in Tunnel				
	a. First 30 Half Circle and Legs	30	Each	582.00	17,460
	b. Over 30 Half Circle and Legs	15	Each	582.00	8,730
14	Liner Plates - 16" x 3'-1-11/16"				
	a. First 8,600	8,600	Each	29.40	252,840
	b. Over 8,600	900	Each	29.40	26,460
15	Liner Plates 16" x 9-27/64"	600	Each	7.50	4,500
16	Lagging 6" Channel 8.2				
	a. First 4,000	1,000	Lin. Ft.	4.10	4,100
	b. Over 4,000	250	Lin. Ft.	4.10	1,025
17	Tie Bars	180	Each	3.50	630
18	Rock Bolts for 8-Foot Setting				
	a. First 100	100	Each	15.00	1,500
	b. Over 100	50	Each	15.00	750
19	Concrete in Tunnel - Reinforced				
	a. First 2,750 cu. yds.	2,750	Cu. Yd.	50.00	137,500
	b. Over 2,750 cu. yds.	150	Cu. Yd.	40.00	6,000
20	Concrete in Tunnel - Unreinforced				
	a. First 12,500 cu. yds.	12,500	Cu. Yd.	50.00	625,000
	b. Over 12,500 cu. yds.	700	Cu. Yd.	40.00	28,000
21	Concrete (Backfill) in Tunnel	3,300	Cu. Yd.	12.00	39,600
22	Concrete - Control Dam Intake Structure Stilling Basin				
	a. First 7,000 cu. yds.	7,000	Cu. Yd.	45.00	315,000
	b. Over 7,000 cu. yds.	500	Cu. Yd.	20.00	10,000

TABLE I (Cont'd)

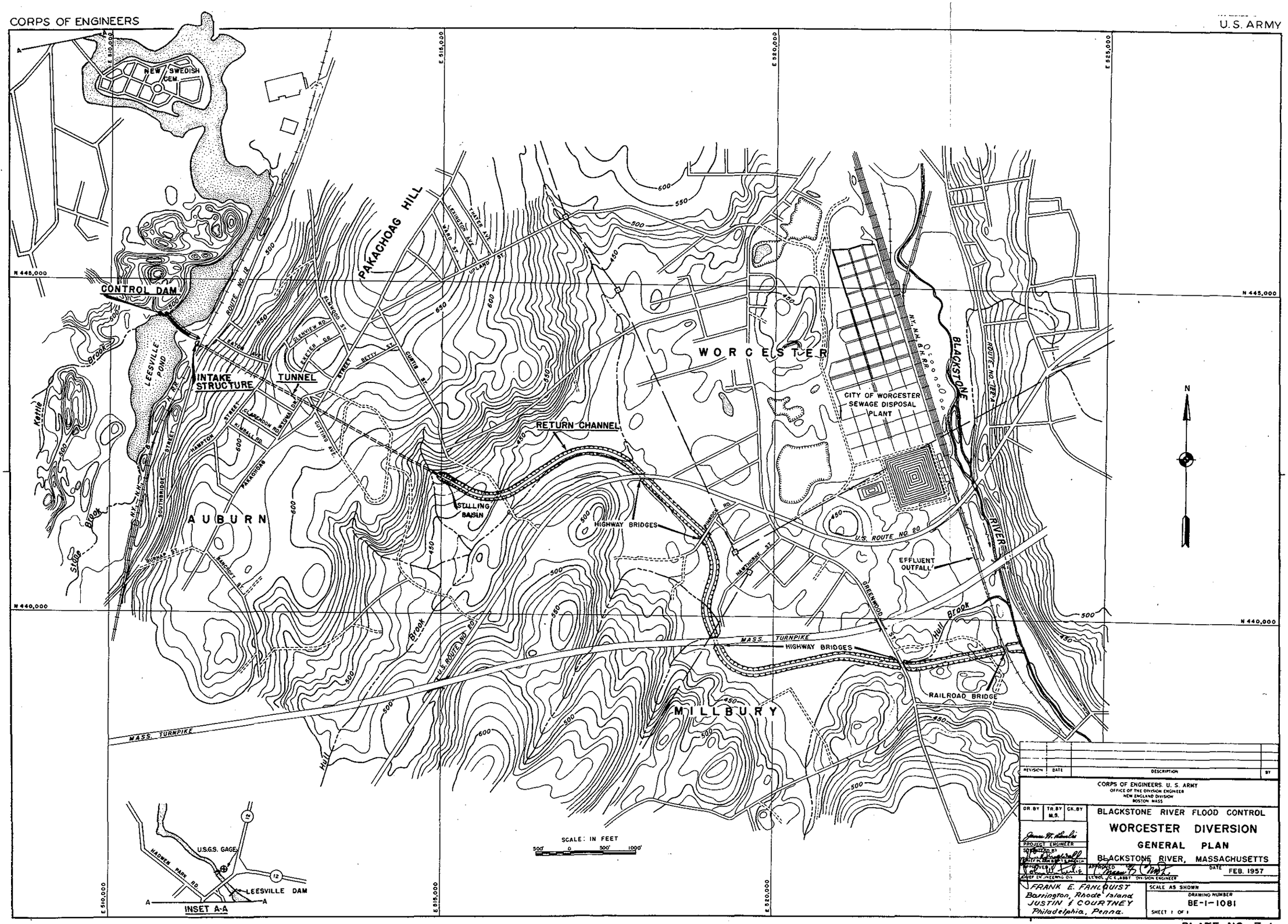
No. Item	Description	Quantity	Unit	Unit Price	Estimated Amount
23	Concrete Backfill - Stilling Basin	150	Cu. Yd.	$ 10.00	$ 1,500
24	Reinforcing Steel	225,000	Lbs.	.20	45,000
25	Portland Cement	30,000	Bbl.	5.70	171,000
26	Tunnel Consolidation Grouting-Mobilization and Demobilization	1	Job	L.S.	2,000
27	Tunnel Consolidation Grouting - Drilling 3" Explor. Holes (NX)	100	Lin. Ft.	7.00	700
28	Tunnel Consolidation Grouting - Drilling $1\frac{1}{2}$" Grout Holes	250	Lin. Ft.	3.50	875
29	Tunnel Consolidation Grouting - 2" Pipe for Grout Holes	187	Lb.	1.10	206
30	Tunnel Consolidation Grouting - Portland Cement	150	Cu. Ft.	1.60	240
31	Tunnel Consolidation Grouting - Sand in Consolidating Grouting	20	Cu. Ft.	1.00	20
32	Tunnel Consolidation Grouting - Placing Grout	200	Cu. Ft.	3.75	750
33	Tunnel Consolidation Grouting - Connection to Grout Holes	25	Each	2.00	50
34	Anchors - Intake Structure	89	Each	91.00	8,099
35	Anchors - Stilling Basin	400	Each	51.60	20,640
36	Impervious Fill Embankment	5,000	Cu. Yd.	.50	2,500
37	Pervious Fill Embankment	20,000	Cu. Yd.	.50	10,000

TABLE I (Cont'd)

No. Item	Description	Quantity	Unit	Unit Price	Estimated Amount
38	Rock Fill - Earth Dam	3,700	Cu. Yd.	$ 1.25	$ 4,625
39	Rock Fill - Return Channel	125,000	Cu. Yd.	1.25	156,250
40	Sluice Gates and Hoists	1	Job	L.S.	7,500
41	Rubber Water Stops	8,000	Lin. Ft.	4.00	32,000
42	Debris Barrier - 115 lb. A.R.E.A. Rail	21	Each	150.	3,150
43	Log Boom	1	Job	L.S.	1,500
44	Chain Link Fencing and Gates	1	Job	L.S.	11,200
		Sub Total			$4,208,000
		Contingencies at 15%			631,000
	Total Construction Cost				$4,839,000
	Relocations (NY, NH & H Railroad Bridge)				131,000
	Engineering and Design				305,000
	Supervision and Administration				395,000
	TOTAL FEDERAL COST				$5,670,000

CORPS OF ENGINEERS

U.S. ARMY



REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS.

DR. BY | TR. BY M.S. | CK. BY

BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION

GENERAL PLAN

BLACKSTONE RIVER, MASSACHUSETTS

PROJECT ENGINEER

SUBMITTED BY

CHIEF PLANNING & REPORTS BRANCH

APPROVED

CHIEF ENGINEERING DIV.

APPROVED

LT. COL. J.C. ELABBY DIVISION ENGINEER

DATE FEB. 1957

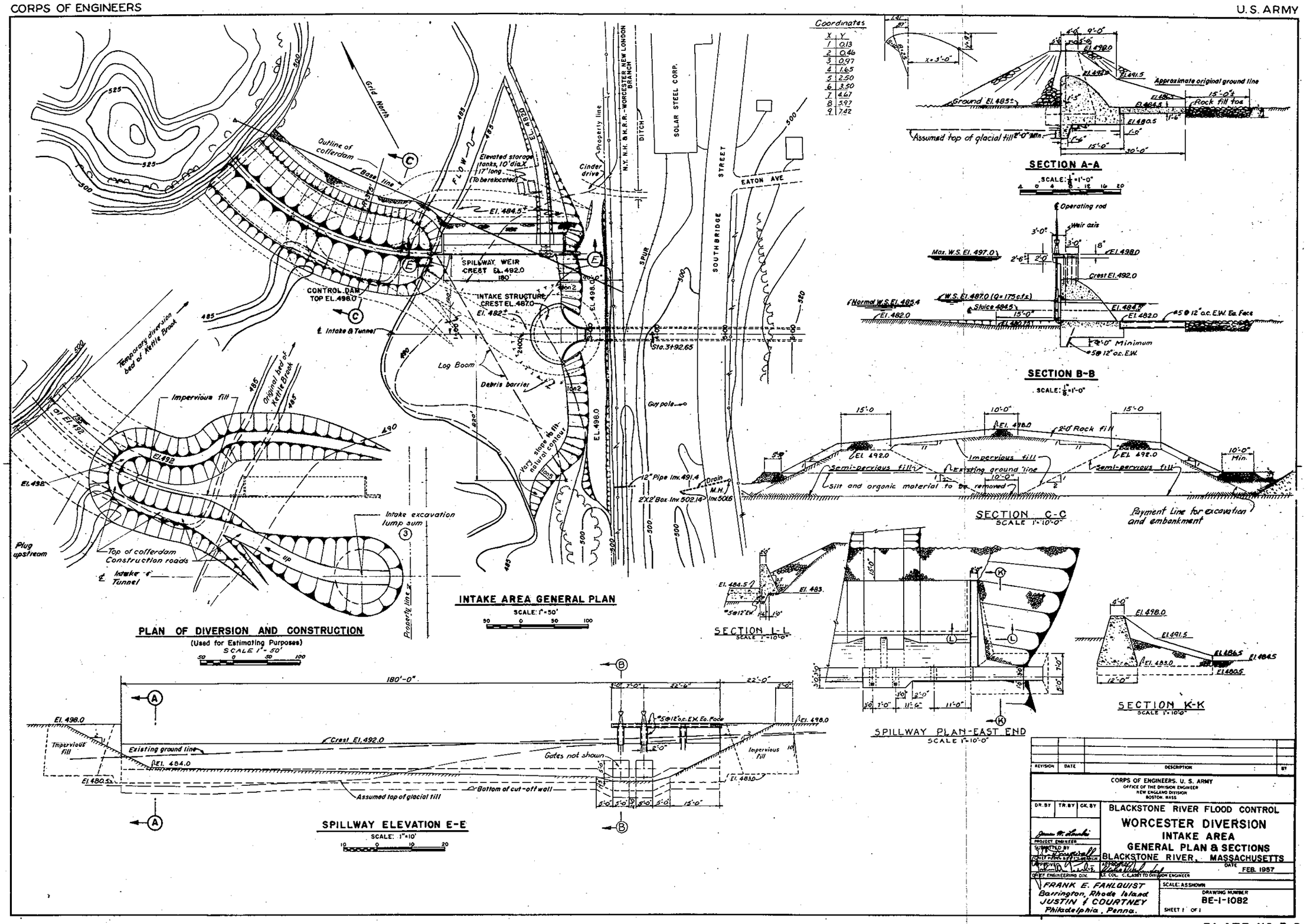
FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.

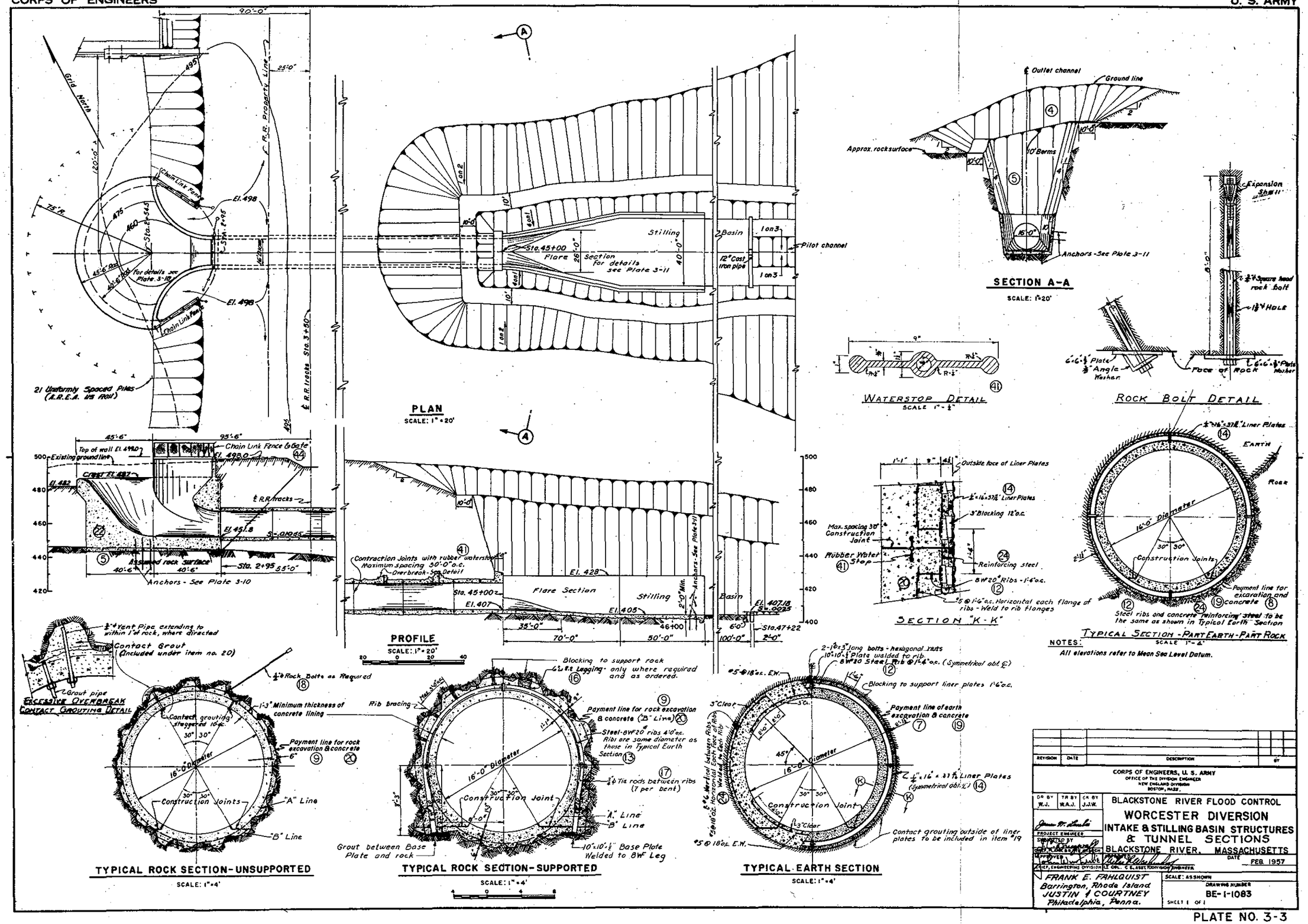
SCALE AS SHOWN

DRAWING NUMBER BE-1-1081

SHEET 1 OF 1

PLATE NO. 3-1


Coordinates
X Y
1 0.13
2 0.46
3 0.97
4 1.65
5 2.50
6 3.50
7 4.67
8 5.97
9 7.42
Grid North
Outline of cofferdam
Base line
Elevated storage tanks, 10' dia. X 17' long (To be relocated)
FLOW
El. 484.5
SPILLWAY WEIR CREST EL. 492.0 180'
CONTROL DAM TOP EL. 498.0
INTAKE STRUCTURE CREST EL. 487.0
El. 482
℄ Intake & Tunnel
Log Boom
Debris barrier
Temporary diversion bed of Kettle Brook
Impervious fill
Original bed of Kettle Brook
Vary slope to fit natural contour
Intake excavation lump sum
Plug upstream
Top of cofferdam Construction roads
Intake ℄ Tunnel
Property line
N.Y. N.H. & H.R.R.-WORCESTER NEW LONDON BRANCH
DITCH
SOLAR STEEL CORP.
SOUTHBRIDGE STREET
EATON AVE
SPUR
Cinder drive
Guy pole
Sta. 31+92.65
12" Pipe Inv. 491.4
Drain M.H.
2'X2' Box Inv. 502.14
Inv. 501.6
EL. 498.0
INTAKE AREA GENERAL PLAN
SCALE: 1"=50'
PLAN OF DIVERSION AND CONSTRUCTION
(Used for Estimating Purposes)
SCALE 1"=50'
Approximate original ground line
Ground El. 485±
Rock fill toe
Assumed top of glacial till 2'-0" Min.
SECTION A-A
SCALE: 1/8"=1'-0"
℄ Operating rod
Weir axis
Max. W.S. El. 497.0
El. 498.0
Crest El. 492.0
Normal W.S. El. 485.4
W.S. El. 487.0 (Q=175 cfs)
Sluice 484.5
El. 482.0
#5 @ 12" o.c. E.W. Ea. Face
2'-0" Minimum
#5 @ 12" o.c. E.W.
SECTION B-B
SCALE: 1/8"=1'-0"
2'-0" Rock fill
Impervious fill
Existing ground line
Semi-pervious fill
Silt and organic material to be removed
Payment Line for excavation and embankment
SECTION C-C
SCALE 1"=10'-0"
El. 484.5
El. 483
#5 @ 12" E.W.
SECTION L-L
SCALE 1"=10'-0"
SPILLWAY PLAN-EAST END
SCALE 1"=10'-0"
El. 498.0
El. 491.5
El. 486.5
El. 484.5
El. 483.0
El. 480.5
SECTION K-K
SCALE 1"=10'-0"
180'-0"
Crest El. 492.0
Existing ground line
El. 484.0
Gates not shown
Impervious fill
Assumed top of glacial till
Bottom of cut-off wall
SPILLWAY ELEVATION E-E
SCALE: 1"=10'
REVISION DATE DESCRIPTION BY
CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS.
DR. BY TR. BY CK. BY
PROJECT ENGINEER
SUBMITTED BY
CHIEF ENGINEERING DIV.
APPROVED BY
LT. COL. C.E. ASST TO DIVISION ENGINEER
BLACKSTONE RIVER FLOOD CONTROL
WORCESTER DIVERSION
INTAKE AREA
GENERAL PLAN & SECTIONS
BLACKSTONE RIVER, MASSACHUSETTS
DATE FEB. 1957
FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.
SCALE: AS SHOWN
DRAWING NUMBER
BE-1-1082
SHEET 1 OF 1



REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS.

DR BY	TR BY	CK BY
W.J.	W.A.J.	J.J.W.

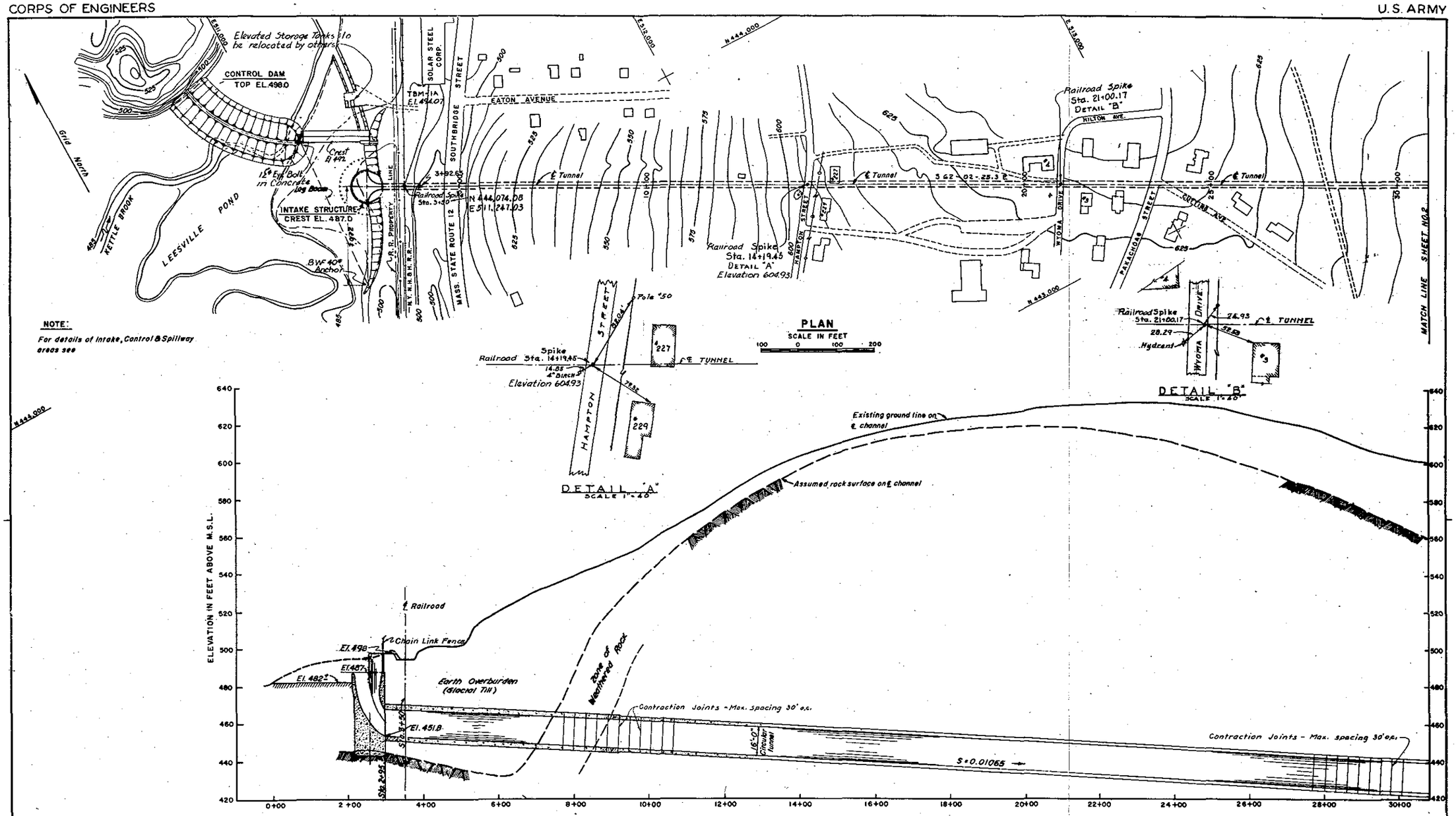
PROJECT ENGINEER
SUBMITTED BY
CHIEF, DESIGN & SPECIFICATION BRANCH
APPROVED
CHIEF, ENGINEERING DIVISION — LT. COL., C.E., ASST. DIVISION ENGINEER

FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.

BLACKSTONE RIVER FLOOD CONTROL
WORCESTER DIVERSION
INTAKE & STILLING BASIN STRUCTURES & TUNNEL SECTIONS
BLACKSTONE RIVER, MASSACHUSETTS

DATE FEB 1957
SCALE: AS SHOWN
DRAWING NUMBER BE-1-1083
SHEET 1 OF 1

PLATE NO. 3-3



NOTES:

All elevations refer to Mean Sea Level Datum.
Contour interval 5 feet.
Views of local interests will be ascertained to determine final disposition of spoil piles.
For typical return channel sections see Plate No. 3-5, 3-7, 3-8
Assumed rock surface based on subsurface and seismic explorations

REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON MASS

DR BY M.O. | TR BY W.A.J. | CK BY J.J.W.

PROJECT ENGINEER

SUBMITTED BY
CHIEF PLANN. & REP. BRANCH

APPROVED
CHIEF ENGINEERING DIV.

APPROVED
LT. COL. C.E., ASST TO DIVISION ENGINEER

FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.

BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION
PLAN & PROFILE NO. 1

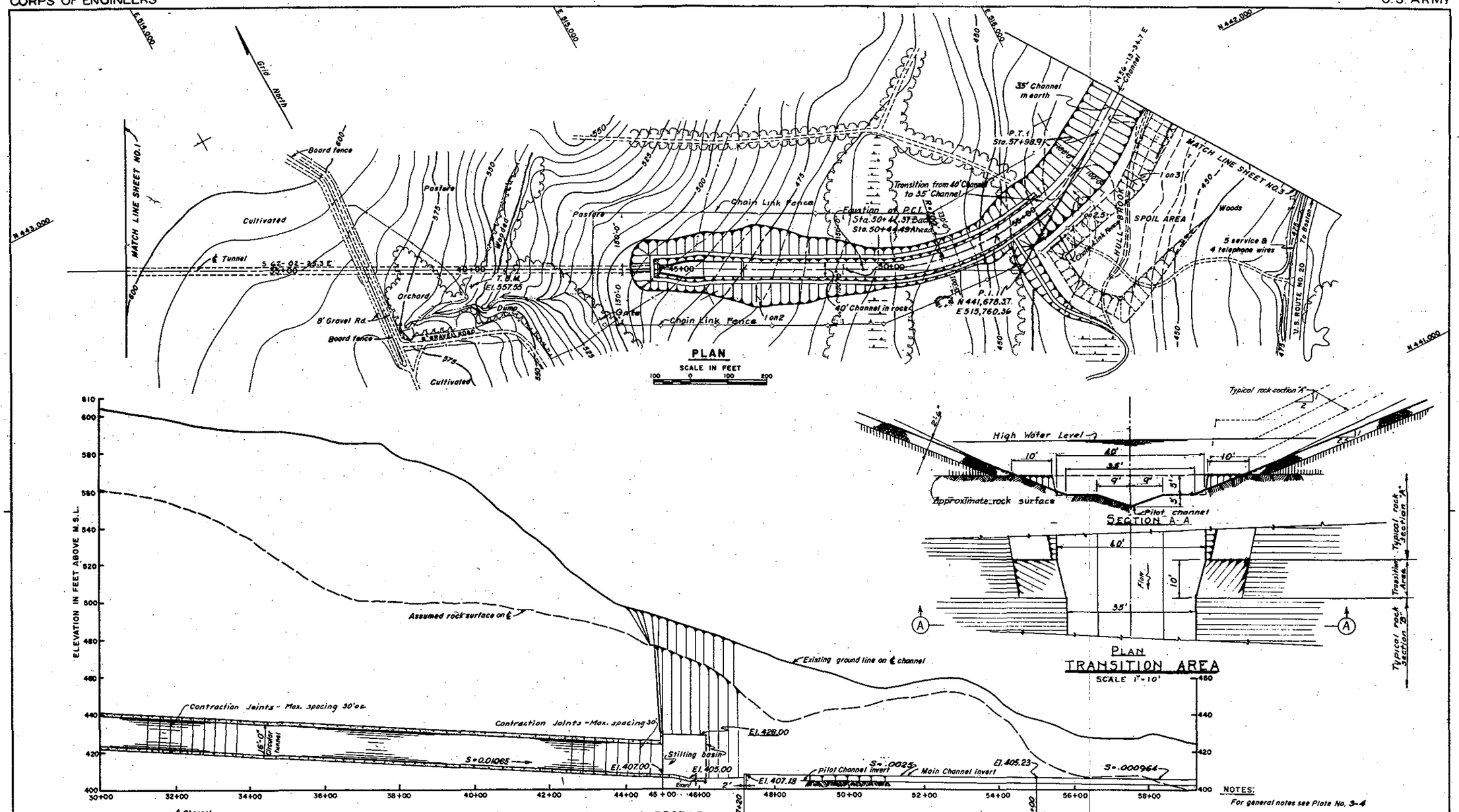
BLACKSTONE RIVER, MASSACHUSETTS

DATE FEB. 1957

SCALE: AS SHOWN

DRAWING NUMBER BE-1-1084

SHEET 1 OF 6



NOTES:
For general notes see Plate No. 3-4

REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS.

DR. BY W.J. TR. BY W.A.J. CK. BY J.J.W.

BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION

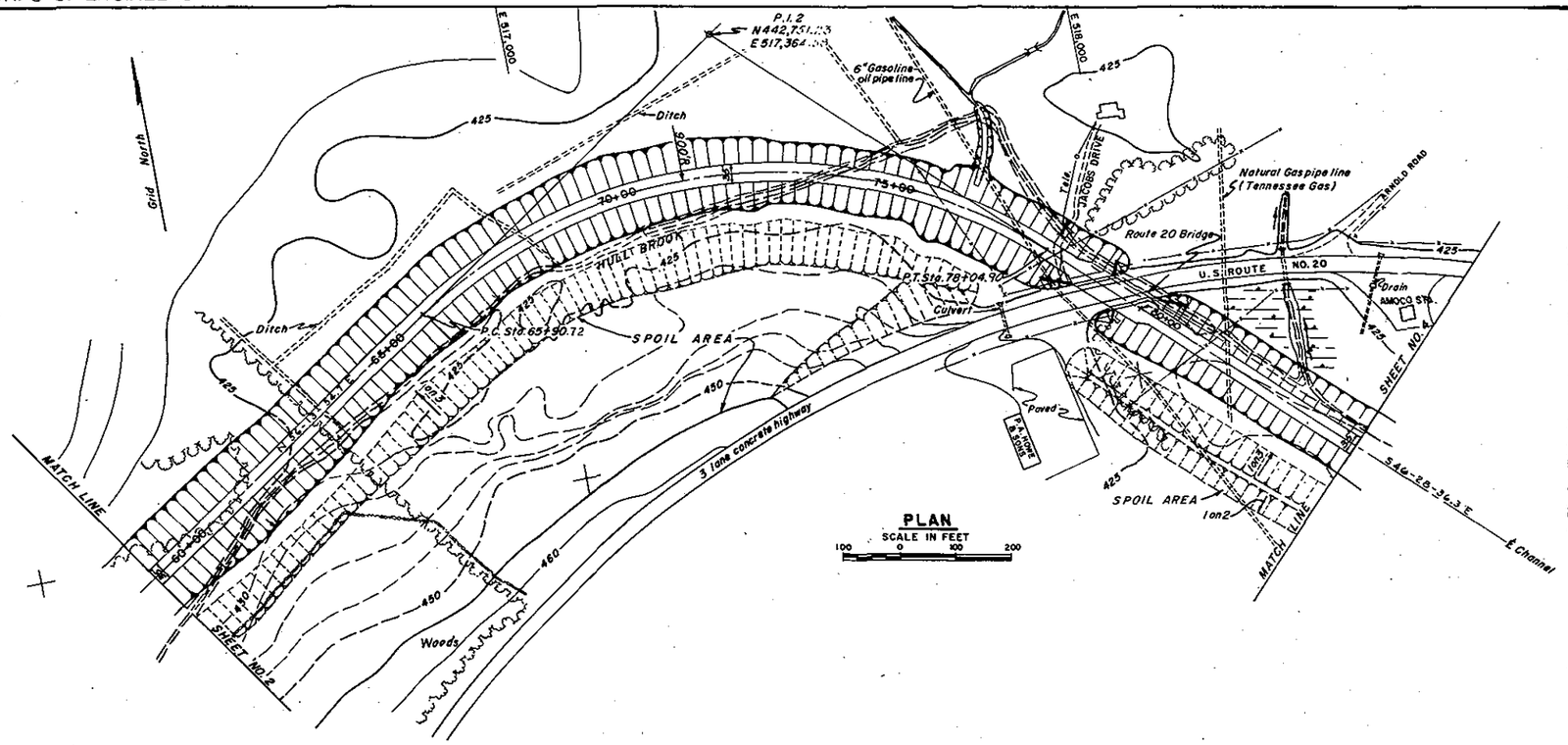
PLAN & PROFILE NO. 2

BLACKSTONE RIVER, MASSACHUSETTS

PROJECT ENGINEER
SUPERVISED BY CHIEF, PLANNING & REPORTS BRANCH
APPROVED CHIEF ENGINEERING DIV.
APPROVED LT. COL. C.E., ASST. TO DIVISION ENGINEER
DATE FEB. 1957

FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.

SCALES: AS SHOWN
DRAWING NUMBER BE-1-1085
SHEET 2 OF 6



NOTES:

For general notes see Plate No. 3-4

REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS

DR. BY C.O.D. | TR. BY S.F.C. | CK. BY C.O.D.

BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION

PLAN & PROFILE NO. 3

BLACKSTONE RIVER, MASSACHUSETTS

PROJECT ENGINEER

SUBMITTED BY:

APPROVED

CHIEF ENGINEERING DIV.

APPROVED

LT. COL. C.E. ASST. DIVISION ENGINEER

DATE FEB. 1957

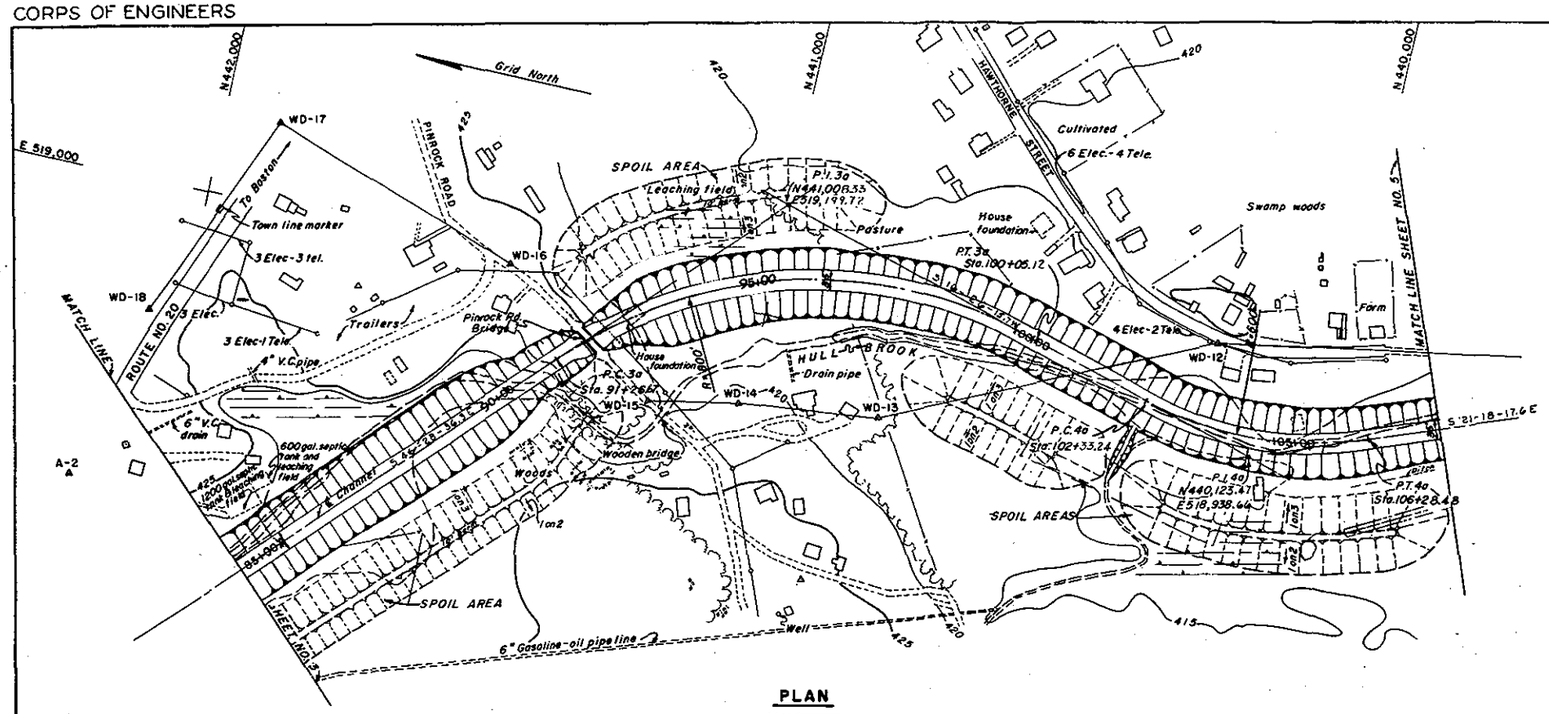
FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.

SCALES: AS SHOWN

DRAWING NUMBER BE-1-1086

SHEET 3 OF 6

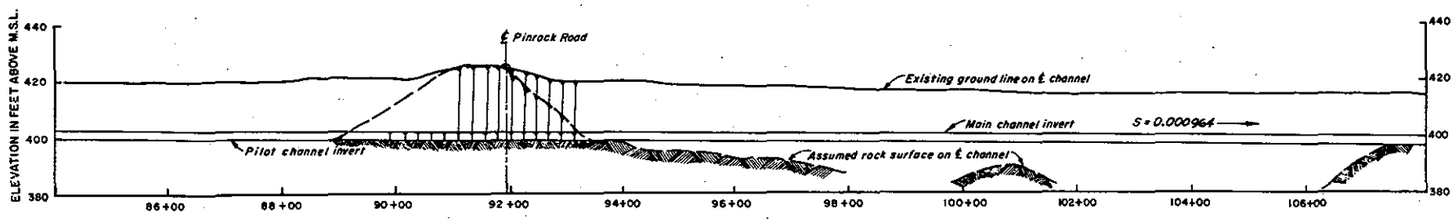
PLATE NO. 3-6



PLAN

SCALE IN FEET

100 0 100 200



PROFILE

SCALES: HOR. 1" = 100'
VERT. 1" = 20'

NOTES:

For general notes see Plate No. 3-4

REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON MASS

DR. BY R.T.B. | TR. BY S.F.C. | CK. BY C.O.D.

BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION

PLAN & PROFILE NO. 4

BLACKSTONE RIVER, MASSACHUSETTS

PROJECT ENGINEER
SUBMITTED BY
CHIEF PLANN & SPECIFICATION
APPROVED
CHIEF ENGINEERING DIV.
APPROVED
LT. COL. C.E. ASST. DIVISION ENGINEER
DATE FEB. 1957

FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.

SCALE AS SHOWN

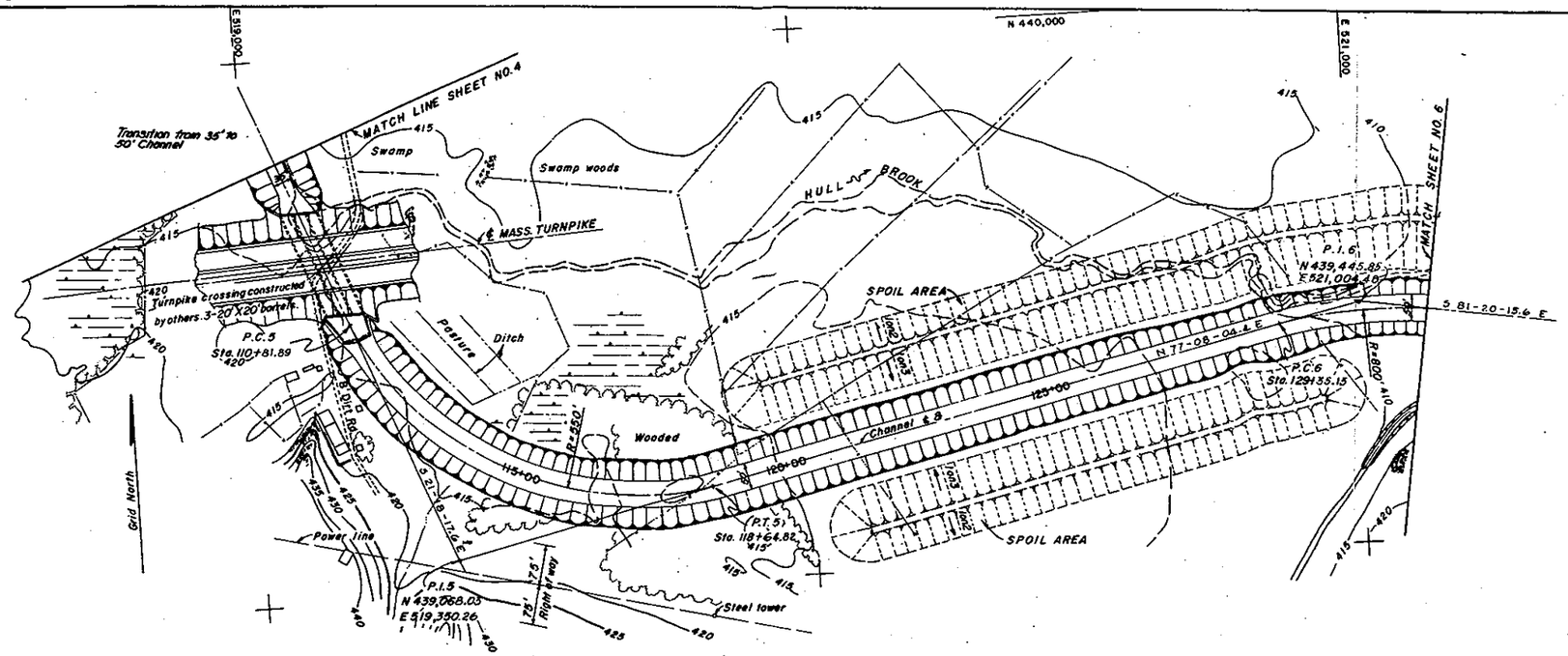
DRAWING NUMBER
BE-1-1087

SHEET 4 OF 6

PLATE NO. 3-7

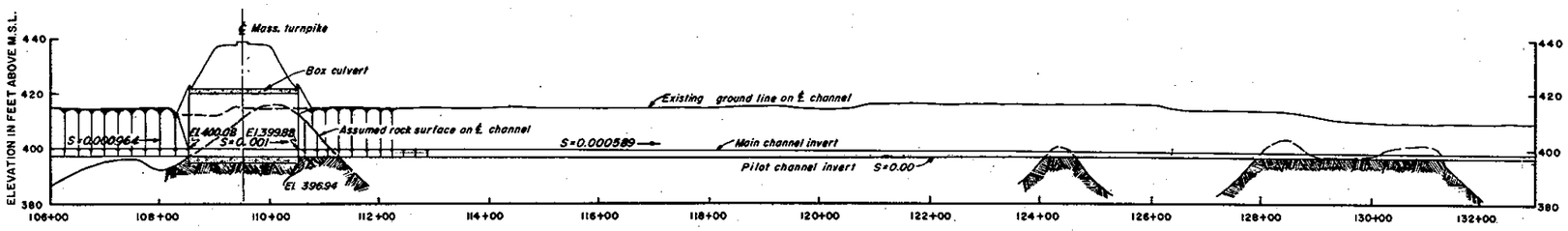
CORPS OF ENGINEERS

U.S. ARMY



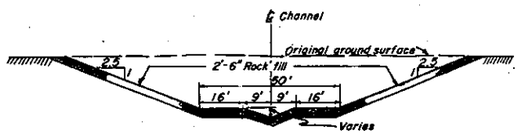
PLAN

SCALE, IN FEET 100 0 100 200



PROFILE

SCALES: HOR. 1"=100' VERT. 1"=20'



TYPICAL SECTION

FROM THE MASSACHUSETTS TURNPIKE TO THE BLACKSTONE RIVER

SCALE: 1"=20'

20 0 20 40

NOTES:

For general notes see Plate No. 3-4

REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON MASS

DR. BY M.A.F.	TR. BY S.F.C.	CK. BY C.O.D.	BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION

PLAN & PROFILE NO. 5

BLACKSTONE RIVER, MASSACHUSETTS

DATE FEB. 1957

PROJECT ENGINEER

SUBMITTED BY: CHIEF, DESIGN BRANCH

REVIEWED: CHIEF ENGINEERING DIV.

APPROVED: LT. COL. C.E. ASST. DIVISION ENGINEER

FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.

SCALE AS SHOWN

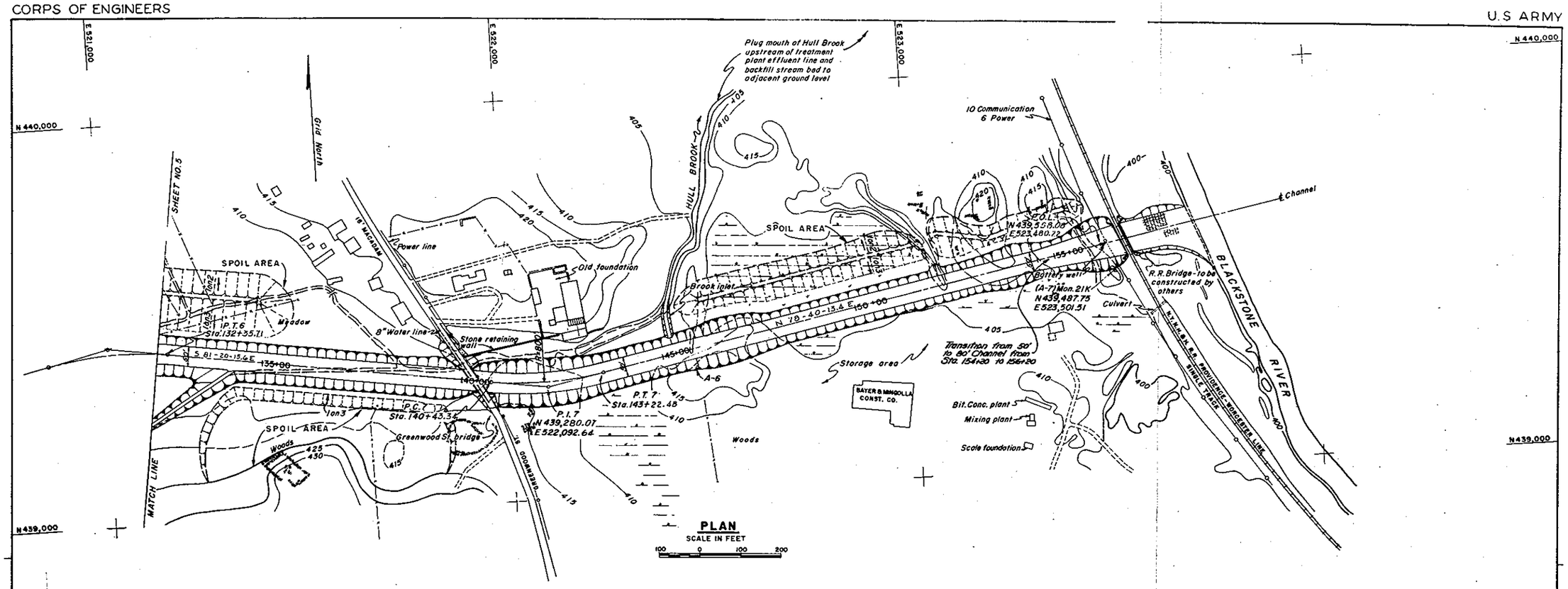
DRAWING NUMBER BE-1-1088

SHEET 9 OF 6

PLATE NO. 3-8

CORPS OF ENGINEERS

U.S ARMY



NOTES:

For general notes see Plate No. 3-4

REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS U S ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON MASS

DR. BY M.A.F. | TR. BY S.F.C. | CK. BY C.O.D.

BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION

PLAN & PROFILE NO. 6

BLACKSTONE RIVER, MASSACHUSETTS

PROJECT ENGINEER

SUBMITTED BY

CHIEF PLANN. BR. T.S. BRANCH

APPROVED

CHIEF ENGINEERING DIV.

APPROVED

LT. COL. C.E. ASST. DIVISION ENGINEER

DATE FEB. 1957

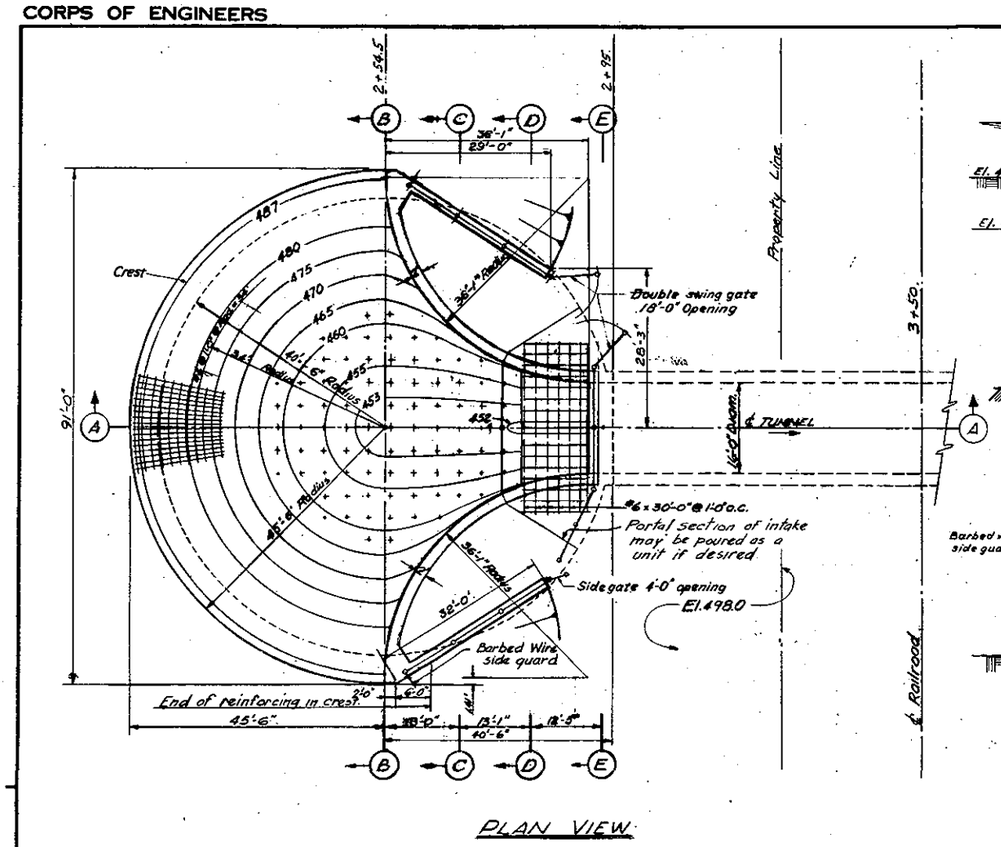
FRANK E. FAHLQUIST
Barrington, Rhode Island
JUSTIN & COURTNEY
Philadelphia, Penna.

SCALES: AS SHOWN

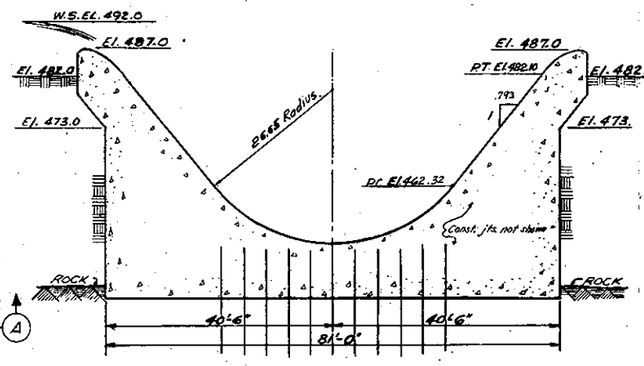
DRAWING NUMBER BE-1-1089

SHEET 6 OF 6

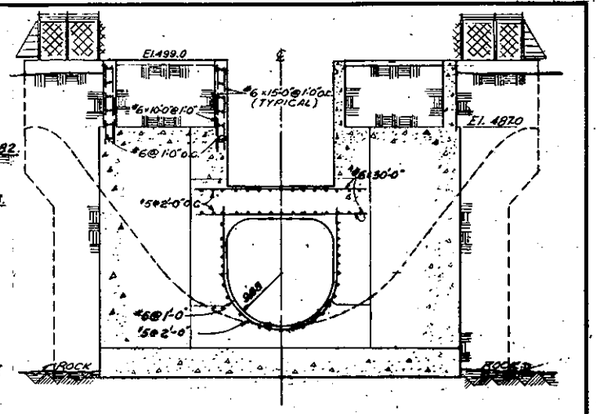
PLATE NO. 3-9



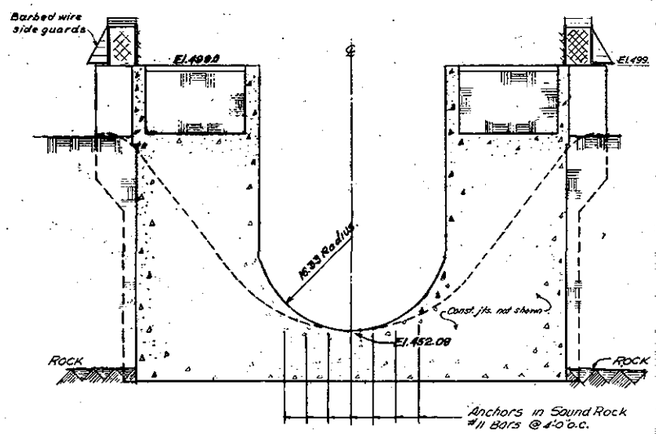
PLAN VIEW



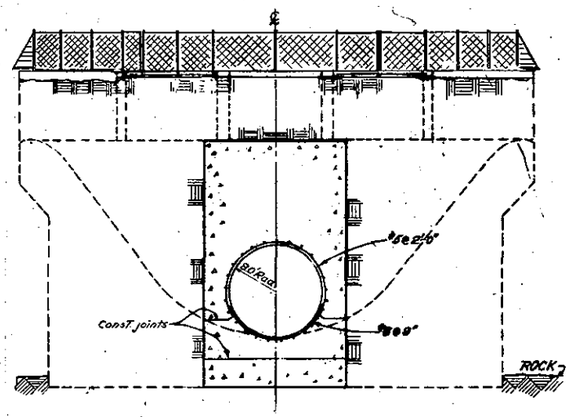
SECTION "B-B"



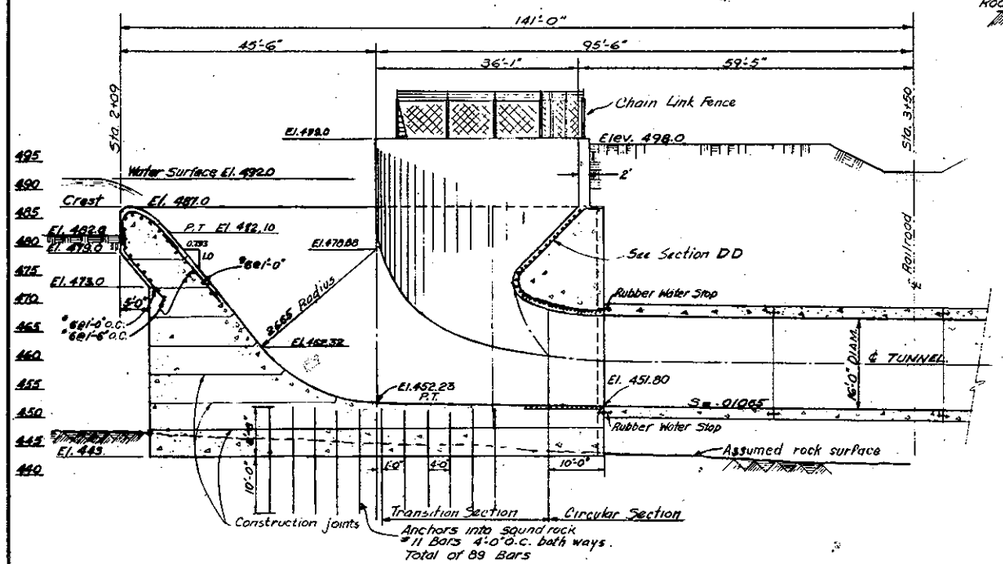
SECTION D-D



SECTION C-C



SECTION E-E



SECTION "A-A"

See Plate No. 3-14 for the alignment and elevations of spillway and transition profiles of the intake structure

REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS.

DR. BY TJA | TR. BY WJ | CK. BY ABR

PROJECT ENGINEER

SUBMITTED BY: CHIEF, PLANN. & REPORTS BRANCH

APPROVED: CHIEF ENGINEERING DIV.

APPROVED: LT. COL. C. ELMER ROBINSON, ENGINEER

BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION INTAKE STRUCTURE

BLACKSTONE RIVER MASSACHUSETTS

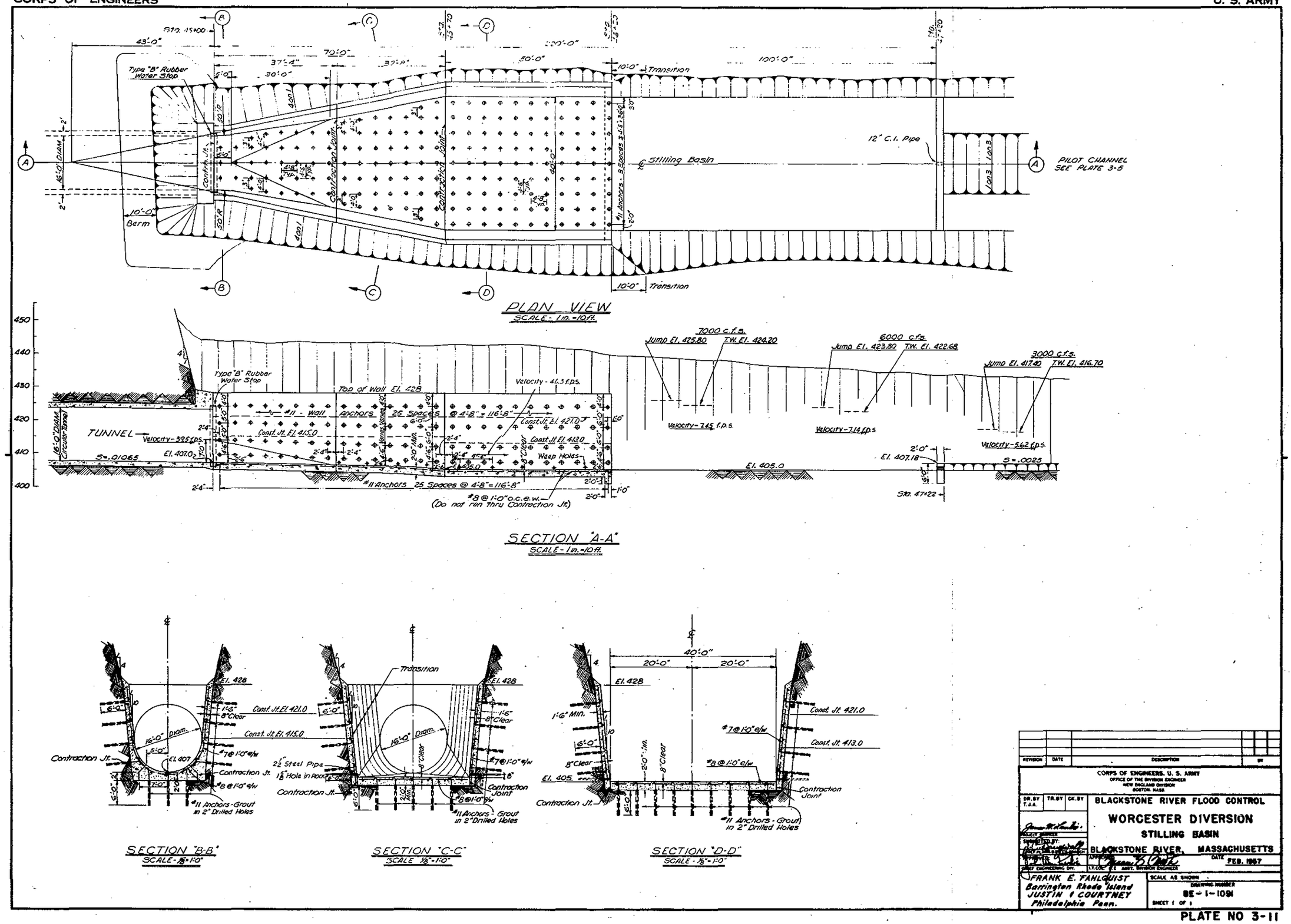
DATE FEB. 1957

FRANK E. FAHLQUIST
BARRINGTON - RHODE ISLAND
JUSTIN & COURTNEY
PHILADELPHIA - PA.

SCALE 1 in. = 10 ft.

DRAWING NUMBER 8E-1-1090

SHEET 1 OF 1



REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS.

DR. BY T.J.A. | TR. BY | CK. BY

BLACKSTONE RIVER FLOOD CONTROL

WORCESTER DIVERSION

STILLING BASIN

BLACKSTONE RIVER, MASSACHUSETTS

APPROVED: LT. COL. C.E. ASST. DIVISION ENGINEER

DATE FEB. 1957

SUBJECT ENGINEER

SUBMITTED BY:

CHIEF ENGINEERING DIV.

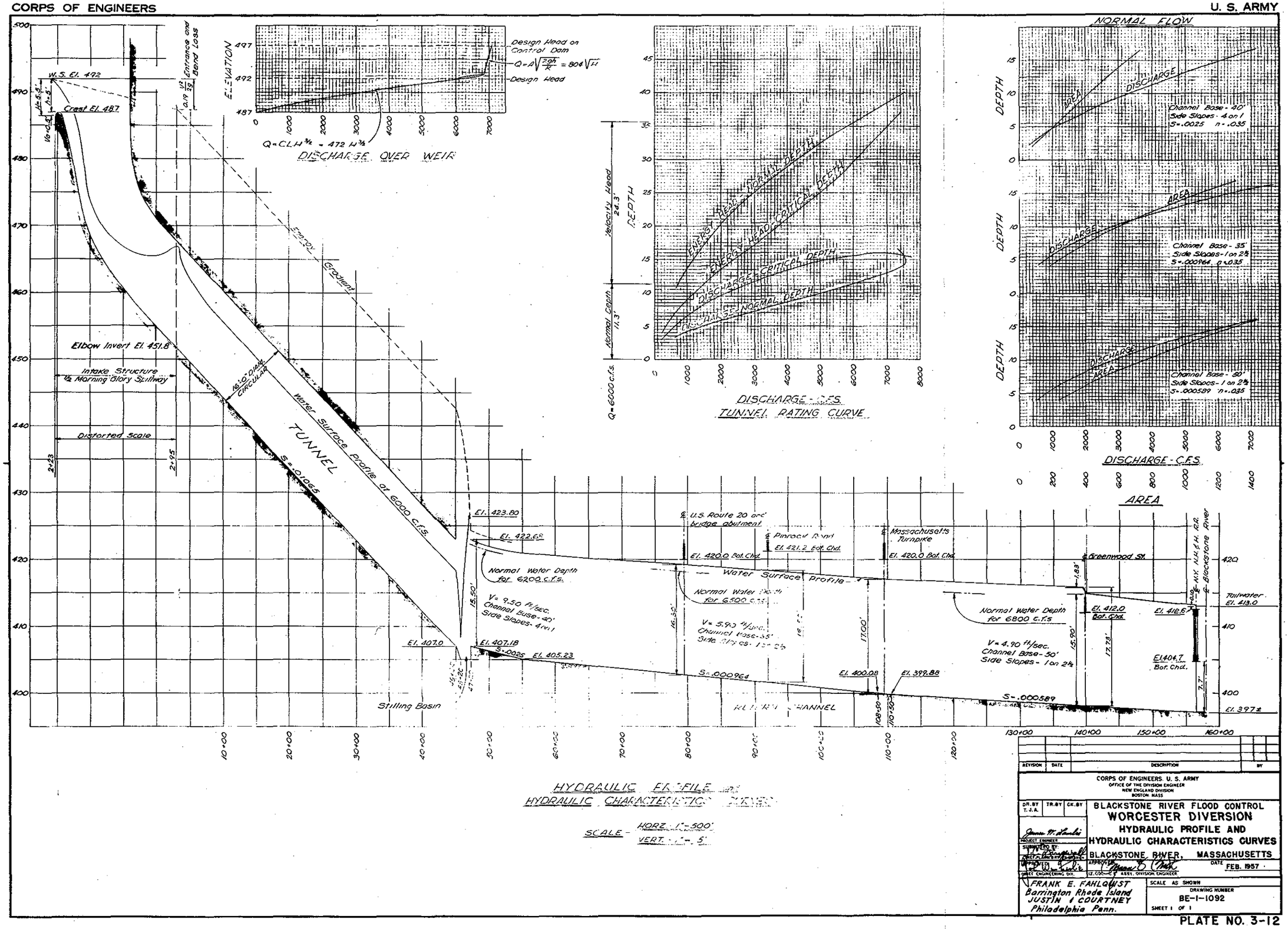
FRANK E. FAHLQUIST
Barrington Rhode Island
JUSTIN & COURTNEY
Philadelphia Penn.

SCALE AS SHOWN

DRAWING NUMBER BE-1-1091

SHEET 1 OF 1

PLATE NO 3-11



REVISION	DATE	DESCRIPTION	BY

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OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS.

DR. BY T. J. A. | TR. BY | CK. BY

PROJECT ENGINEER

SUBMITTED BY: CHIEF, DESIGN BRANCH

APPROVED: CHIEF, ENGINEERING DIV.

APPROVED: LT. COLONEL, CORPS OF ENGINEERS, ASST. DIVISION ENGINEER

DATE FEB. 1957

BLACKSTONE RIVER FLOOD CONTROL
WORCESTER DIVERSION
HYDRAULIC PROFILE AND HYDRAULIC CHARACTERISTICS CURVES
BLACKSTONE RIVER, MASSACHUSETTS

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Philadelphia Penn.

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DRAWING NUMBER BE-1-1092

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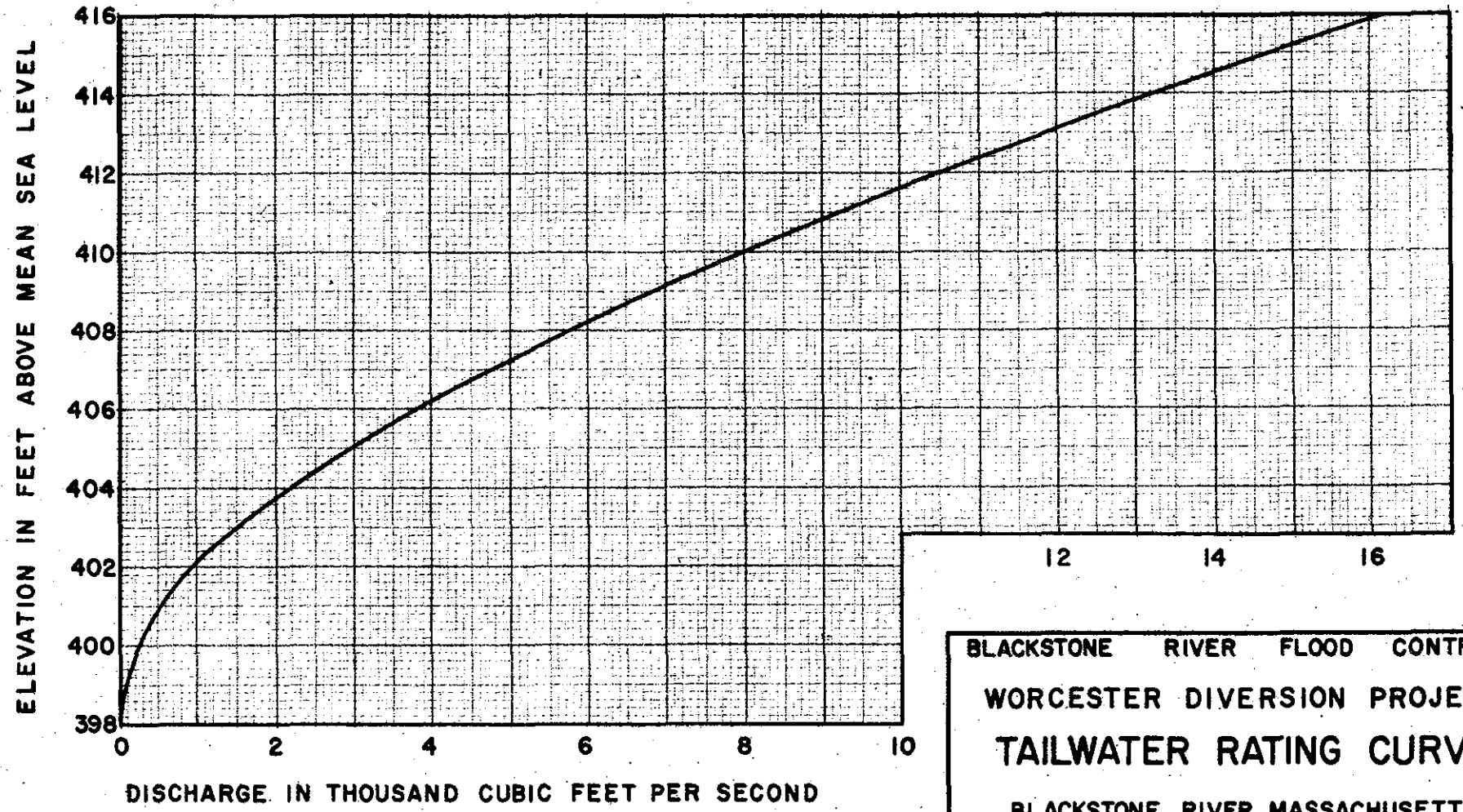


NOTE: This curve applies at section 3000 feet downstream from bridge, U.S. Highway No. 20.

BLACKSTONE RIVER FLOOD CONTROL

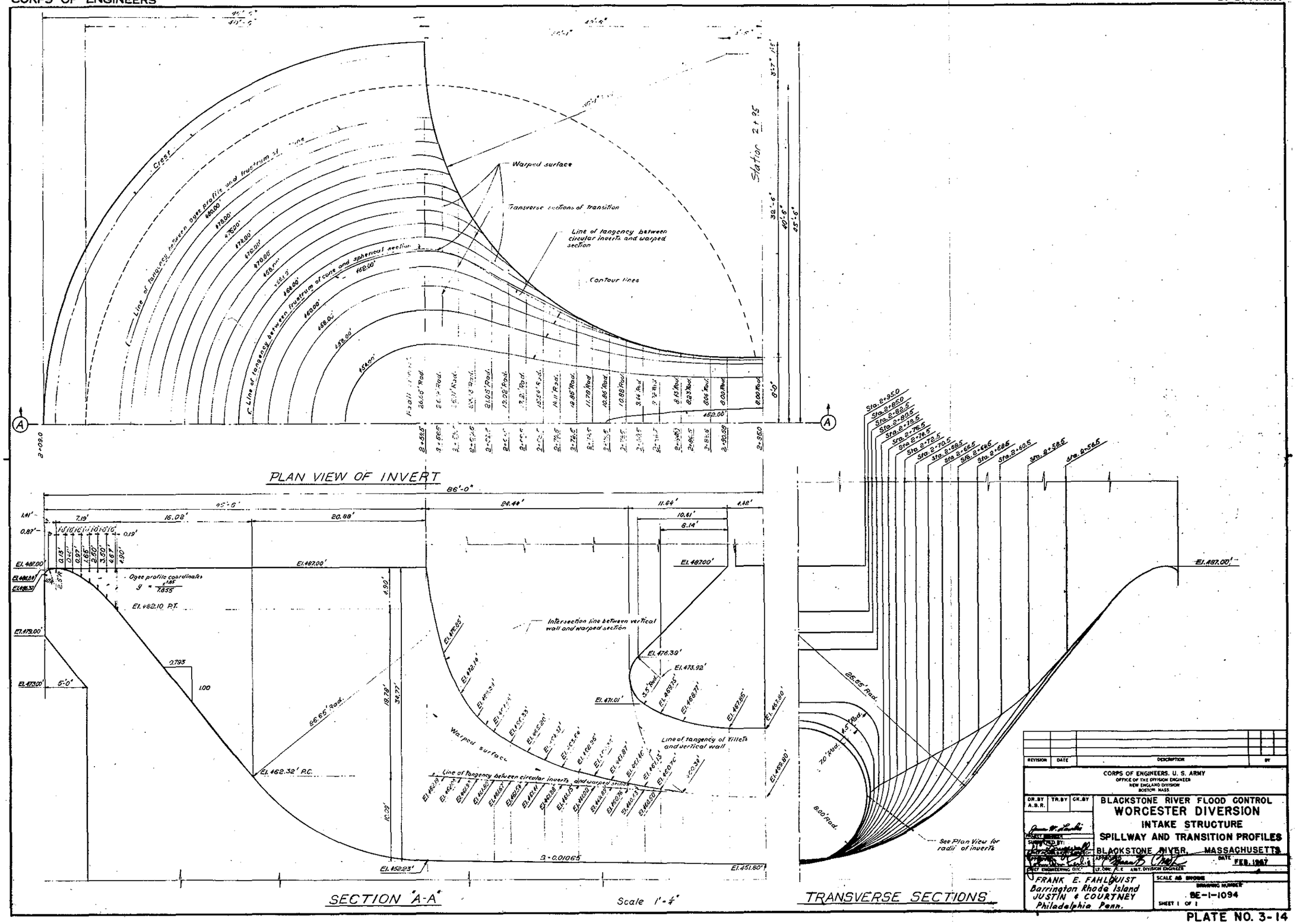
WORCESTER DIVERSION PROJECT

TAILWATER RATING CURVE

BLACKSTONE RIVER, MASSACHUSETTS

NEW ENGLAND DIVISION BOSTON, MASS.

JUNE 1956


PLAN VIEW OF INVERT
Crest
Line of tangency between gate profile and frustrum of cone
Line of tangency between frustrum of cone and spherical section
Warped surface
Transverse sections of transition
Line of tangency between circular inverts and warped section
Contour lines
Station 2+95
SECTION "A-A"
Scale 1"=4'
Ogee profile coordinates
Intersection line between vertical wall and warped section
Line of tangency of fillets and vertical wall
Line of tangency between circular inverts and warped section
TRANSVERSE SECTIONS
See Plan View for radii of inverts
CORPS OF ENGINEERS, U. S. ARMY
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NEW ENGLAND DIVISION
BOSTON, MASS.
BLACKSTONE RIVER FLOOD CONTROL
WORCESTER DIVERSION
INTAKE STRUCTURE
SPILLWAY AND TRANSITION PROFILES
BLACKSTONE RIVER, MASSACHUSETTS
FEB. 1947
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Barrington Rhode Island
JUSTIN & COURTNEY
Philadelphia Penn.
BE-1-1094
SHEET 1 OF 1

APPENDIX A

TYPICAL HYDRAULIC DESIGN COMPUTATIONS

INDEX TO SHEETS

Title	Page No.
Control Dam - Coefficient of Discharge	A-1
Intake Structure - Crest length	A-2
Intake Structure - Crest shape	A-3
Intake Structure - Discharge curve	A-4 and A-5
Outlet Tunnel - Critical discharge	A-6
Outlet Tunnel - Discharge at normal depths	A-7
Stilling Basin - Hydraulic jump computations	A-8
Stilling Basin - Hydraulic jump computations	A-9
Stilling Basin - Hydraulic jump computations	A-10
Stilling Basin - Hydraulic jump computations	A-11
Return Channel - Uniform flow 40' base channel	A-12
Return Channel - Uniform flow 35' base channel	A-13
Return Channel - Uniform flow 50' base channel	A-14
Return Channel - Open channel flow Backwater computations	A-15

Coefficient of Discharge-

Reference: Engineering Manual Part CXVI

Chapter 3 - Plate No 5 & No-9-

$Q = CLH^{3/2}$

Plate 5 $He/Hd = 5/5 = 1.00$ $C = 4.03$

$h_s = 4.2$ See Design Memo #1. Plate 1-8

Plate -9- $h_s/He = 4.2/5.0 = 0.84$

Ratio of submergence = 0.80

$4.03 \times .80 = 3.20$

$C = 3.20$

$Q = 6000$ C.F.S

$C = 3.2$

$H = 5$ $H^{3/2} = 11.18$

$L = \frac{Q}{CH^{3/2}} = \frac{6000}{3.2 \times 11.18} = 168.$

Two Piers = 4.

Contractions + Misc = 8

180' TOTAL LENGTH.

Actual crest length shown on drawing for the control dam 176 feet.

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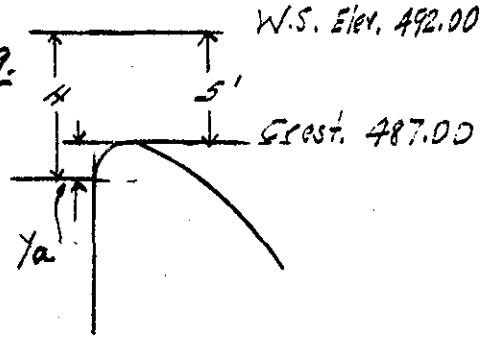
Worcester Diversion - One-Half Morning Glory

Spillway Design

Coefficient of discharge determined on basis of morning glory type.
Engineering Manual - Part CXVI - Chapter 3
Hydraulic Design - Spillways



Discharge Coefficient Plate 39.

$Y_a/H = 0.11 - 0.10\ H/R$

$h = 5'\quad R = 45.5'$

$Y_a = 5(0.11 - 0.10\ \frac{5}{45.5})$

$Y_a = 0.5$

$H = h + Y_a = 5.0 + 0.5 = 5.5'$

$H/R = 5.5/45.5 = 0.121$

From Plate 40 $C = 3.335$ Use 3.30

Crest length

$Q = CLH^{3/2}$ Plate 39

$L = \frac{Q}{CH^{3/2}} = \frac{6000}{3.30\ (5.5)^{3/2}} = 141$ Ft.

$L' = L + 2k_a H$, Plate 14

$= 141 + 2(.18)(5.5) = 142.98$

Crest length = 143 Feet. $Q = (3.30 \times 143) = 471.9 \times H^{\frac{3}{2}}$

$\pi R = 142.98$

180° Spillway $R = \frac{142.98}{3.1416} = 45.5$ Ft without piers

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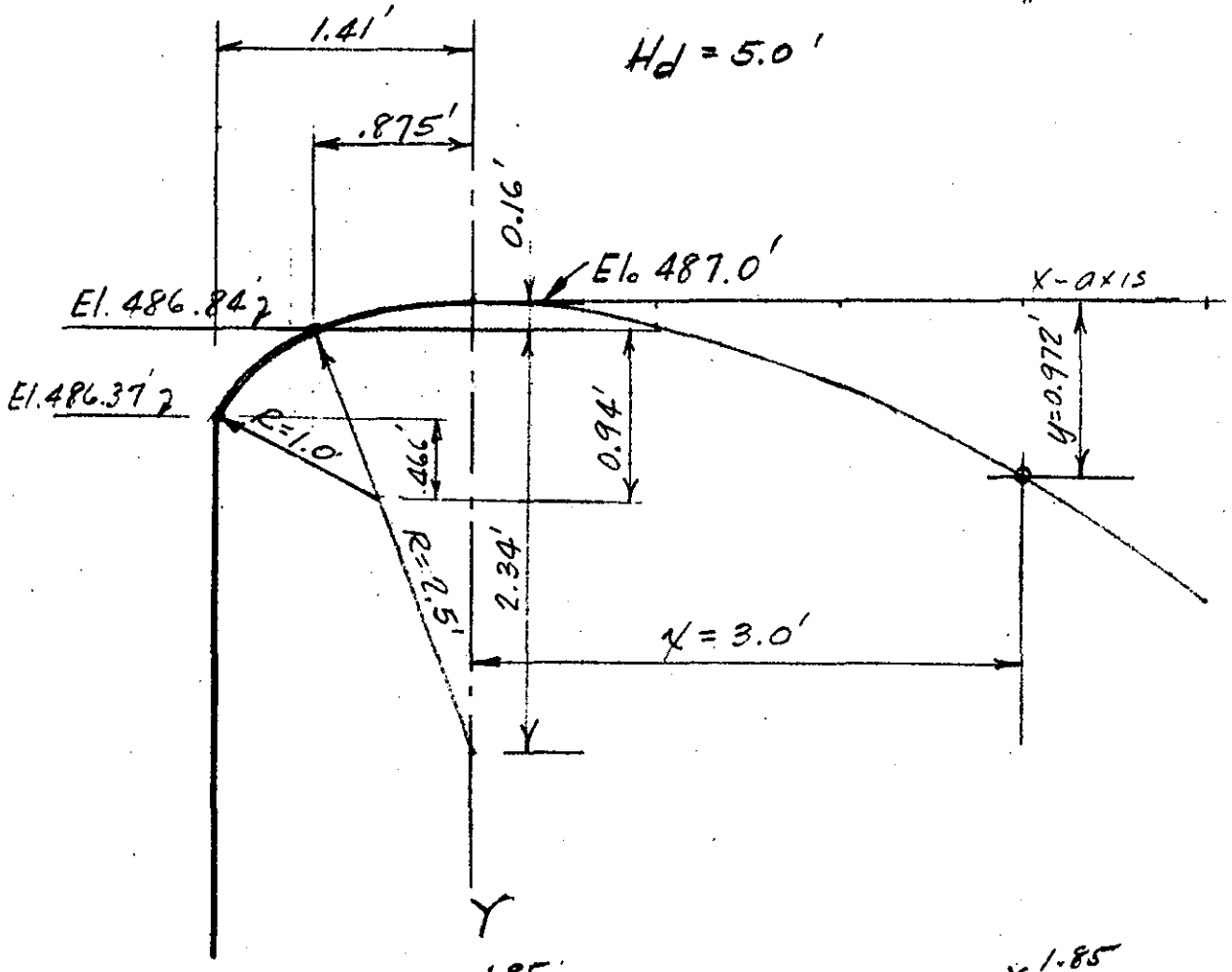
Worcester Diversion - Intake

Spillway Profile determined on basis of Ogee type.
- Ref: pgs 6 & 7 Engr. Manual
Table No 1 Part CXVI Chapt. 3.



$$y = \frac{x^{1.85}}{2H_d^{0.85}} \qquad H_d = 5 \therefore y = \frac{x^{1.85}}{7.855}$$

X	$X^{1.85}$	y
1	1.000	.127
2	3.605	.459
3	7.633	.972
4	12.996	1.654
5	19.638	2.500
6	27.515	3.503
7	36.596	4.667
8	46.851	5.965
9	58.257	7.42
10	70.795	9.008
11	84.444	10.75

Coordinates for ogee section

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Worcester Diversion - One Half Morning Glory

Spillway Design - Discharge Curve.

$Q = CLH^{3/2}$

$C = 3.30 \quad L = 143 \text{ Ft} \quad H = 5.5 \text{ Ft.}$

Elev.	H	$H^{3/2}$	$Q = CLH^{3/2} = 472 H^{3/2}$	Q
487	- - - -	- - - -		
488	1.5	1.837	3.30 X 143 X 1.837	860
489	2.5	3.953	3.30 X 143 X 3.953	1865
490	3.5	6.548	3.30 X 143 X 6.548	3090
491	4.5	9.546	3.30 X 143 X 9.546	4510
492	5.5	12.900	3.30 X 143 X 12.900	6100
493	6.5	16.570	3.30 X 143 X 16.570	7820
494	7.5	20.540	3.30 X 143 X 20.540	9700

Continuation of Discharge Curve. Spillway Design Discharge controlled by wier to Elev. 492.00 - above this elevation by capacity of tunnel under pressure.

$$k = V^2/2g + k_e + k_b + k_f$$

k_e = entrance loss

k_b = bend "

k_f = friction "

$V^2/2g$ = Velocity Head

Unit = $1.00\ V^2/2g$

$k_e = .32\ V^2/2g$

$k_b = .38\ V^2/2g$ } Maximum

$k_f = 2.33\ V^2/2g$

Total $= 4.03\ V^2/2g$

Reference: Engineering Manual. Part CXVI chapter-3. Hydraulic Design. Reservoir Outlet Structures.

$$Q = A\sqrt{\frac{2gH}{K}}$$

$$k_f = \frac{29.1\,(n^2)\,L}{R^{4/3}}$$

$$k_f = \frac{29.1 \times (.011)^2 \times 4195}{(4)^{4/3} = 6.35} = 2.33$$

$L = 4195$
$D = 16$
$n = .011$
$R = 4.0$
$A = 201.06$

Elev	H	$A\sqrt{\frac{2g}{K}}$	$\sqrt{H}$	$Q = 804\sqrt{H}$
492	73	804.	8.54	6850
493	74	"	8.60	6900
494	75	"	8.66	6960
495	76	"	8.72	7000
496	77	"	8.77	7040
497	78	804.	8.83	7100

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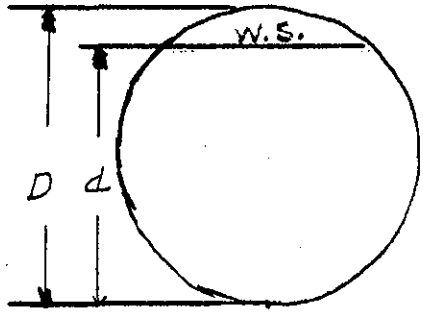
T Worcester Diversion - Outlet Tunnel

Critical Discharge & Velocities - Depths for 16' Foot Diameter Tunnel flowing partly full.

Reference - King's Hydraulic's & Reclamation - Hydraulic & Excavation Tables - Page 48 & 48a.



d/D	d_c	$V_c^2/2g$	V_c	Area	Q_c	$He = D + V^2/2g$
0.2	3.2	1.12	8.48	28.6	230	4.32
0.3	4.8	1.73	10.54	50.7	535	6.53
0.4	6.4	2.40	12.42	75.1	935	8.80
0.5	8.0	3.24	14.43	100.6	1440	11.24
0.6	9.6	4.02	16.06	125.9	2015	13.62
0.7	11.2	5.13	18.14	150.3	2735	16.33
0.8	12.8	6.75	20.83	172.5	3600	19.35
0.9	14.4	9.98	25.30	190.7	4825	24.38
0.95	15.2	14.30	30.30	197.4	5950	29.5
0.96	15.3	15.80	31.90	198.0	6320	31.1

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Worcester Diversion- Outlet Tunnel

Discharge at Normal Depths for 16 Foot Diameter Tunnel - Reference. Hydraulic Design Chart 224-8 Open Channel Flow

$Q = C_n C_k$ $\quad C_n = \frac{1.486\, S^{1/2}}{n}$ $\quad C_k = AR^{2/3}$ $\quad y_0 = d$

$n = .011$
$S = .01065$

d/D	d	Area	R	$R^{2/3}$	C_k	C_n	Q
0.2	3.2	28.6	1.93	1.55	44.3	14	620
0.3	4.8	50.7	2.72	1.95	99.0	14	1385
0.4	6.4	75.1	3.42	2.27	171.0	14	2390
0.5	8.0	100.6	4.00	2.52	254.0	14	3550
0.6	9.6	125.9	4.45	2.71	340.0	14	4760
0.7	11.2	150.3	4.75	2.83	426.0	14	5970
0.8	12.8	172.5	4.80	2.85	492.0	14	6890
0.9	14.4	190.7	4.76	2.83	540.0	14	7550
0.95	15.2	197.4	4.58	2.76	545.0	14	7620
0.96	15.3	198.0	4.52	2.73	540.0	14	7550

Velocity for 3000 CFS = 32.71 ft per Sec.
Velocity " 6000 CFS = 39.60 ft " Sec.
Velocity " 7000 CFS = 40.50 ft " "

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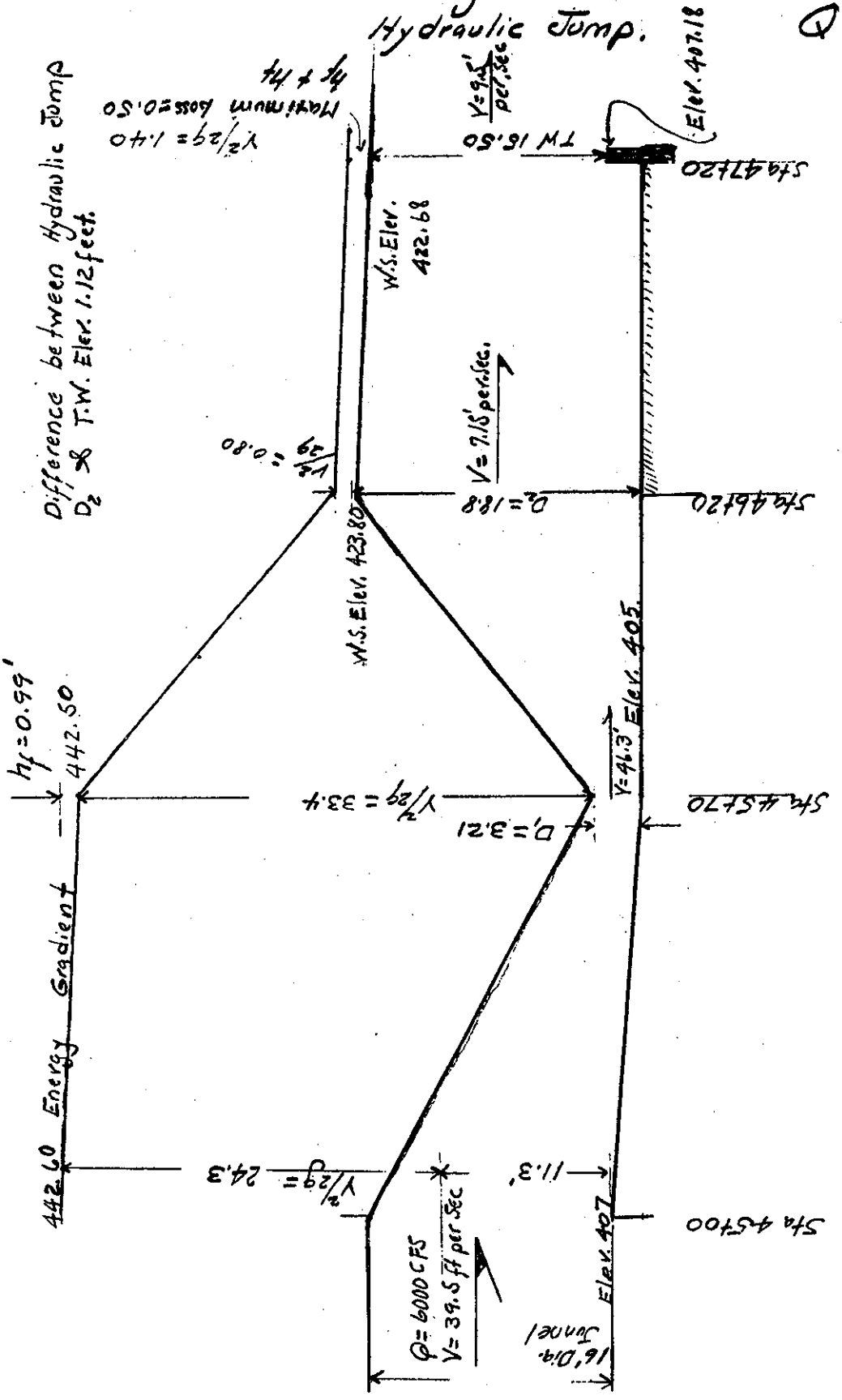
Worcester Diversion - Stilling Basin

Hydraulic Jump.

Q = 6000 C.F.S.



Hydraulics $Q = 3000$ CFS

Energy at Tunnel portal = Depth + $V^2/2g$

Velocity from Page A-7 = 32.70 ft per sec. $V^2/2g = 16.7$

Depth " " A-7 = 7.50 ft.

Elev. Energy Gradient = 407.00 + 7.50 + 16.7 = 431.20

$V_1 = \sqrt{2g(H - h_f)} = \sqrt{64.32(24.26 - 0.67)} = 38.9$ ft per sec.

$h_f = \frac{Ln^2V^2}{2.2082\, r^{4/3}} = \frac{70 \times .013^2 \times 35.8^2}{2.2082 \times (5.89)^{4/3}} = 0.67$

D_1 was determined to be 1.92 ft by previous trial computations.
V = average velocity r = average n = .013

Froude Number = $F_1 = \frac{V_1}{\sqrt{gD_1}} = \frac{38.9}{\sqrt{32.2 \times 1.92}} = 4.96$

D_1 was determined by $Q = AV_1$ $3000 = A \times 38.9$
$A = 77$ Sq. Ft.

B = 40 ft. side slopes 10 vertical on 1 horizontal

$\frac{D_2}{D_1} = 6.5$ Ref. Bureau of Reclamation Hydraulic Laboratory Report No. Hyd-399

Conjugate Tailwater depth

$D_2 = 6.5 \times 1.915 = 12.4$

Elev. of Tailwater = 405.00 + 12.4 = 417.40

Elev. Energy Gradient = 1.92 + 23.60 + 405.00 = 430.52 + h_f 0.67 = 430.19

Length of Basin = 6 × 12.4 = 74.5 feet

Concrete section 50 ft. remainder in rock cut.

$Q = 6000$ C.F.S.

Energy at Tunnel portal = Depth + $V^2/2g$

Velocity & Depth from Page 7

Velocity = 39.50 ft per sec. Depth = 11.3 ft. $V^2/2g = 24.3$

Elev. Energy Gradient = 407.00 + 11.3 + 24.3 = 442.60

By previous trial computations D_1 was determined to be 3.20 ft.

$V_1 = \sqrt{2g(H - h_f)} = \sqrt{64.32(34.39 - 0.99)} = 46.3$

From average velocity and average r n = .013

$h_f = \frac{L n^2 V^2}{2.2082\, r^{4/3}} = \frac{70 \times (.013)^2 \times (42.9)^2}{2.2082 \times (5.89)^{4/3}} = 0.99$

D_1 was determined to be 3.20 by $Q = AV_1 = 6000 = A\,46.3$
$A = 130$

Base = 40 Ft. Side slopes 10 vertical on 1 horizontal

$F_1 = \frac{V_1}{\sqrt{g D_1}} = \frac{46.3}{\sqrt{32.2 \times 3.20}} = 4.56$

$\frac{D_2}{D_1} = 5.85$ Ref: Bureau of Reclamation Hydraulic Laboratory Report No. Hyd. 399

Conjugate Tailwater depth

$D_2 = 5.85 \times 3.20 = 18.80$ ft. Elev. 405.00 + 18.80 = 423.80

$\frac{L}{D_2} = 5.95 = 5.95 \times 18.80 = 112$ ft.

Concrete section 50 Ft. remainder in rock cut.

Elev. Energy Gradient. 3.20 + 33.30 + 405.00 = 441.50

441.50 + h_f 0.99 = 442.49

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Worcester Diversion - Stilling Basin

Hydraulics

$Q = 7000$ CFS

Energy at Tunnel portal = depth + $V^2/2g$

Velocity and depth from Page 7

Velocity = 40.50 ft per Sec. Depth = 12.8 $V^2/2g = 25.5$

Elev. Energy gradient = 407.00 + 12.8 + 25.5 = 445.30

By previous computations D_1 was determined to be 3.60 ft.

$V_1 = \sqrt{2g(H - h_f)} = \sqrt{64.32(36.69 - 0.99)} = 47.90$ ft per Sec.

From average velocity and average r - $n = .013$

$$h_f = \frac{L\, n^2 V^2}{2.2082\, r^{4/3}} = \frac{70 \times (.013)^2 \times (44.2)^2}{2.2082 \times (5.89)^{4/3}} = 0.99 \text{ ft.}$$

D_1 was determined to be 3.60 by $Q = AV = 7000 = A\,47.50$

$A = 147$

Base = 40 Ft. Side slopes 10 vert. on 1 horizontal

$$F_1 = \frac{V_1}{\sqrt{g D_1}} = \frac{47.9}{\sqrt{32.2 \times 3.60}} = 4.44$$

$\frac{D_2}{D_1} = 5.75$ Ref: Bureau of Reclamation Hydraulic Laboratory Report No Hyd. 399

Conjugate Tailwater depth

$D_2 = 5.75 \times 3.60 = 20.8$ Elev = 405.00 + 20.8 = 425.80

$\frac{L}{D_2} = 5.9 = 5.90 \times 20.8 = 124$ ft.

Concrete section 50 Ft remainder in rock cut.

Elev. Energy gradient 3.60 + 35.70 + 405.00 = 444.30

444.30 + 0.99 h_f = 445.29

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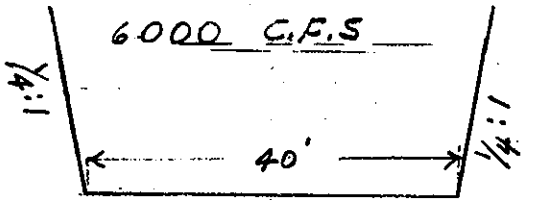
Worcester Diversion Channel

Uniform Flow.
Reference. Hydraulic Tables - Second Edition
War Department - Corps of Engineers
Hydraulic Computations - 40' B. Channel - 1/4:1 SS

S=.0025 n=.035



B	D	T	R	A	V	Q
40	2	41	1.84	81	3.19	258
	4	42	3.40	164	4.80	786
	6	43	4.75	249	6.00	1550
	8	44	5.95	336	6.97	2350
	10	45	7.01	425	7.78	3350
	12	46	7.97	516	8.49	4390
	14	47	8.84	609	9.08	5510
	14.9		9.20	651	9.30	6050
40	15.0	47.5	9.25	656.25	9.48	6250
	16	48	9.65	704	9.61	6750
	16.5	48.25	9.83	728	9.72	7070

Required Capacity
6200 C.F.S.

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Worcester Diversion Channel

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Uniform flow.
Hydraulic Computations - 35' Base channel 2½:1 SS.

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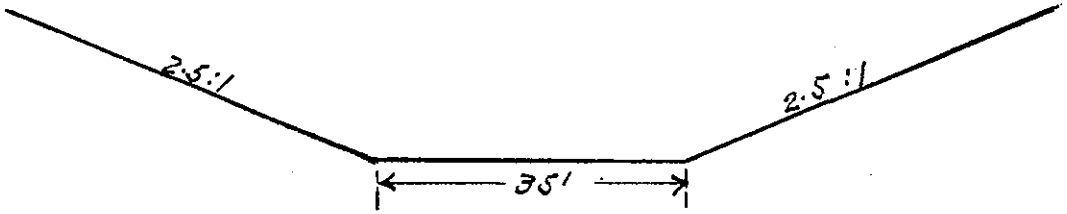
Slope = .00096 ft/ft n = .035



B	D	T	R	A	V	Q
35	4	55	3.18	180	2.86	504
	6	65	4.46	300	3.60	1080
	8	75	5.64	440	4.15	1825
	10	85	6.75	600	4.73	2830
	12	95	7.83	780	5.17	4050
	14	105	8.90	980	5.65	5550
	14.5	107.5	9.10	1038	5.73	5925
	15	110	9.40	1067.5	5.85	6360
	15.25	111.25	9.52	1115.6	5.90	6582
	15.5	112.5	9.64	1143.7	5.95	6800
	16.0	115	9.90	1200	6.06	7300
	16.5	117.5	10.2	1258.25	6.25	7875

Required Capacity
6500 cfs

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SHEET NO. F-14 OF

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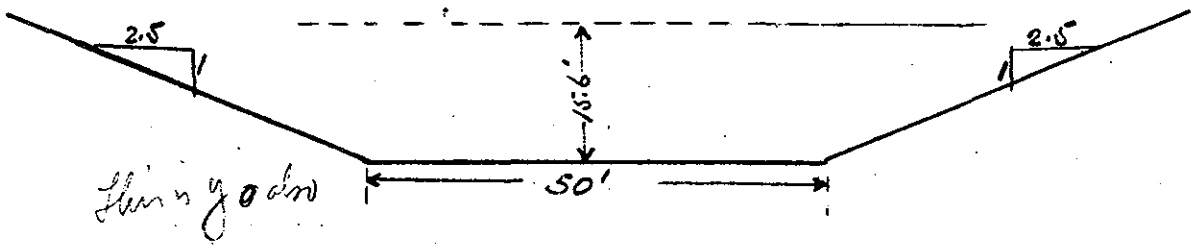
Worcester Diversion - Return Channel

Uniform Flow.
Discharge - Velocity - Area - Curves 50' Base Channel
Side slopes - 2½:1 S = .000589 M = .035

Reference - Hydraulic Tables - Corps of Engineers
2nd Edition.
Hydraulic computations.

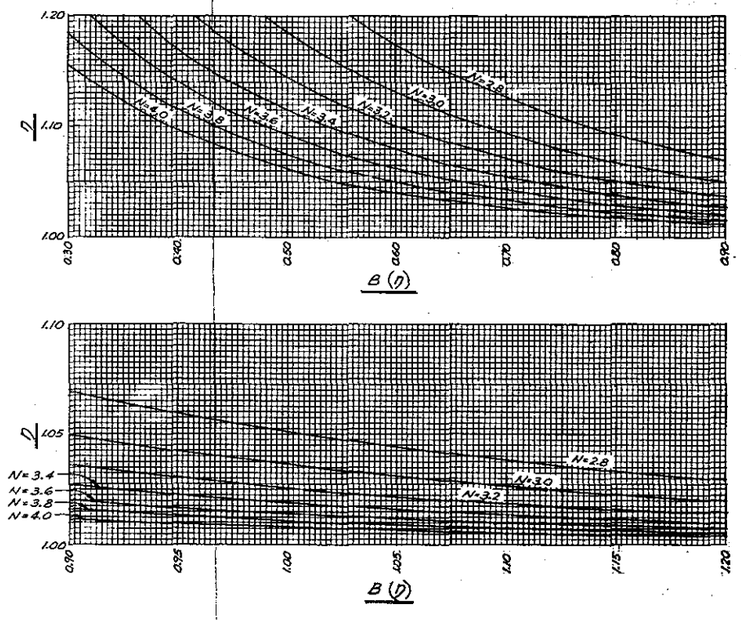


B	D	T	R	A	V	Q
50	4	70	3.35	240	2.30	552
50	6	80	4.74	390	2.90	1130
50	8	90	6.02	560	3.40	1900
50	10	100	7.22	750	3.85	2890
50	12	110	8.38	960	4.10	3940
50	14	120	9.50	1190	4.60	5480
50	15	125	10.04	1312	4.78	6240
50	15.6		10.40	1389	4.90	6800
50	16.0	130	10.6	1440	4.96	7150

Required Capacity
6800 C 75

OPEN CHANNEL FLOW
BACKWATER COMPUTATIONS
by the GRAPHICAL METHOD

Station	Reach L from sta. 158+00	Depth y	Normal Depth y_o	Critical Depth Hydraulic Design Charts 610-6/2, 610-8 y_c	Hydraulic Exponent Design Chart 010-2 N	$\eta = \frac{y}{y_o}$	$\beta = \left(\frac{y_c}{y_o}\right)^N$	$1-\beta$	$I = \frac{L S_o}{y_o}$	η_2	$y_2 = \eta_2 y_o$	S_o	Discharge	Grade Elev.	W.S. Elev.	Channel Sections	Remarks
						Hydraulic Design Criteria - Open Channel Flow Reference: Sheets 010-1, 010-2 to 010-5/3. Hydraulic Design Charts 010-1, 010-2, 010-3, 010-4, 010-5 to 010-5/3.											
158+00	—	16.00	15.6	6.0	3.7	—	—	—	—	—	—			397.0±	413.00	B=80' D=15.6 Side Slopes 1 on 2.5	N.Y. N.H. & H Railroad Bridge submerged by tailwater. Loss of head due to overflowing railroad grade estimated at 0.10 foot.
156+60	140	16.00	15.6	6.0	3.7	$\frac{16.00}{15.60}=1.025$	$\left(\frac{6.00}{15.60}\right)^{3.7}=(0.38)^{3.7}$ = .0280	1.0000 − .0280 = .9720	$\frac{140 \times .000589 = .082}{15.60} = .0053$	1.025	16.00			397.08	413.08		
156+20	180	16.10	15.6	6.0	3.7	$\frac{16.10}{15.60}=1.03$	$\left(\frac{6.00}{15.60}\right)^{3.7}=(0.38)^{3.7}$ = .0280	1.0000 − .0280 = .9720	$\frac{180 \times .000589 = .106}{15.60} = .0068$	1.025	16.00			397.19	413.19	Transition from B=80' to B=50'. Avg. B=65'. D=15.6 Side Slopes 1 on 2.5	
Transition 154+20	380	16.10	15.6	6.5	3.8	$\frac{16.10}{15.60}=1.03$	$\left(\frac{6.5}{15.60}\right)^{3.8}=(0.42)^{3.8}$ = .0370	1.0000 − .0370 = .9630	$\frac{380 \times .000589 = .224}{15.60} = .014$	1.029	16.05			397.30	413.35		Greenwood Street 50' Span Bridge Opening 50'×14'=700□'
139+50	1850	16.10	15.6	7.5	3.9	$\frac{16.10}{15.60}=1.03$	$\left(\frac{7.5}{15.6}\right)^{3.9}=(0.48)^{3.9}$ = .0570	1.0000 − .0570 = .9430	$\frac{1850 \times .000589 = 1.09}{15.60} = .07$	1.025	16.00	S = .000589	Q = 6800 cfs.	398.17	414.17	B=50' D=15.6 Side Slopes 1 on 2.5	
139+00	1900	16.10	15.6	7.5	3.9	$\frac{16.10}{15.60}=1.03$	$\left(\frac{7.5}{15.6}\right)^{3.9}=(0.48)^{3.9}$ = .0570	1.0000 − .0570 = .9430	$\frac{1900 \times .000589 = 1.12}{15.60} = .072$	1.022	15.90			398.20	414.10	Head Loss = H = 1.83 $\sqrt{H} = \frac{Q}{CA\sqrt{2g}} = \frac{6800}{.90 \times 700 \times 8.02} = 1.35$	
139+00	1900	—	—	—	—	—	—	—	—	—	17.73			398.20	415.93		
139+00	Reach L from Sta. 139+00	17.73	15.6	7.5	3.9	—	—	—	—	—	—			398.20	415.93	B=50' D=15.6 Side Slopes 1 on 2.5	
129+00	1000	17.73	15.6	7.5	3.9	$\frac{17.73}{15.60}=1.14$	$\left(\frac{7.5}{15.6}\right)^{3.9}=(0.48)^{3.9}$ = .0570	1.0000 − .0570 = .9430	$\frac{1000 \times .000589 = 0.59}{15.60} = .038$	1.125	17.55			398.79	416.34		
119+00	2000	17.73	15.4	7.5	3.9	$\frac{17.73}{15.40}=1.15$	$\left(\frac{7.5}{15.4}\right)^{3.9}=(0.49)^{3.9}$ = .0620	1.0000 − .0620 = .9380	$\frac{2000 \times .000589 = 1.18}{15.4} = .077$	1.120	17.25			399.38	416.63		
110+50	2850	17.73	15.25	7.5	3.9	$\frac{17.73}{15.25}=1.16$	$\left(\frac{7.5}{15.25}\right)^{3.9}=(0.49)^{3.9}$ = .0620	1.0000 − .0620 = .9380	$\frac{2850 \times .000589 = 1.68}{15.25} = .110$	1.115	17.00			399.88	416.88		
110+50	Reach L from Sta. 110+50	17.00	15.25	7.5	3.9	—	—	—	—	—	—	S = .001	Q = 6500 cfs.	399.88	416.88	3-20'×20' Square Openings	Mass. Turnpike Area Each Opening 400 Sq. ft.
108+50	200	17.00	15.25	7.2	2.9	$\frac{17.00}{15.25}=1.11$	$\left(\frac{7.2}{15.25}\right)^{2.9}=(0.47)^{2.9}$ = .1120	1.0000 − .1120 = .8880	$\frac{200 \times .001 = 0.20}{15.25} = .013$	1.115	17.00			400.08	417.08		
108+50	Reach L from Sta. 108+50	17.00	15.25	7.2	2.9	—	—	—	—	—	—			400.08	417.08	B=35' D=15.25 Side Slopes 1 on 2.5	Pinrock Road B=50' D=15.25 Vertical Sides
102+15	635	17.00	15.25	8.40	4.1	$\frac{17.00}{15.25}=1.11$	$\left(\frac{8.40}{15.25}\right)^{4.1}=(0.55)^{4.1}$ = .0862	1.0000 − .0862 = .9138	$\frac{635 \times .000964 = .61}{15.25} = .04$	1.095	16.70			400.69	417.39		
92+15	1635	17.00	15.25	8.40	4.1	$\frac{17.00}{15.25}=1.11$	$\left(\frac{8.40}{15.25}\right)^{4.1}=(0.55)^{4.1}$ = .0862	1.0000 − .0862 = .9138	$\frac{1635 \times .000964 = 1.58}{15.25} = .103$	1.080	16.45			401.66	418.11		
91+65	1685	17.00	15.25	8.0	2.8	$\frac{17.00}{15.25}=1.11$	$\left(\frac{8.0}{15.25}\right)^{2.8}=(0.52)^{2.8}$ = .1600	1.0000 − .1600 = .8400	$\frac{1685 \times .000964 = 1.62}{15.25} = .106$	1.083	16.50	S = .000964	Q = 6500 cfs.	401.70	418.20		
79+70	2880	17.00	15.25	8.40	4.1	$\frac{17.00}{15.25}=1.11$	$\left(\frac{8.40}{15.25}\right)^{4.1}=(0.55)^{4.1}$ = .0862	1.0000 − .0862 = .9138	$\frac{2880 \times .000964 = 2.78}{15.25} = .183$	1.060	16.15			402.86	419.01		U.S. Route 20 B=50' D=15.25 Vertical Sides
79+20	2930	17.00	15.25	8.00	2.8	$\frac{17.00}{15.25}=1.11$	$\left(\frac{8.0}{15.25}\right)^{2.8}=(0.52)^{2.8}$ = .1600	1.0000 − .1600 = .8400	$\frac{2930 \times .000964 = 2.82}{15.25} = .185$	1.070	16.30			402.90	419.20		
67+00	4150	17.00	15.25	8.40	4.1	$\frac{17.00}{15.25}=1.11$	$\left(\frac{8.40}{15.25}\right)^{4.1}=(0.55)^{4.1}$ = .0862	1.0000 − .0862 = .9138	$\frac{4150 \times .000964 = 4.00}{15.25} = .262$	1.045	15.95			404.08	420.03		
55+00	5350	17.00	15.25	8.40	4.1	$\frac{17.00}{15.25}=1.11$	$\left(\frac{8.40}{15.25}\right)^{4.1}=(0.55)^{4.1}$ = .0862	1.0000 − .0862 = .9138	$\frac{5350 \times .000964 = 5.15}{15.25} = .338$	1.035	15.75			405.23	420.98		
55+00	Reach L from Sta. 55+00	15.75	15.25	8.40	4.1	—	—	—	—	—	—	S = .0025	Q = 6500 cfs.	405.23	420.98	B=40' D=15.00 Side Slopes 4 on 1	Rock Cut
47+20	780	15.75	15.00	9.40	3.6	$\frac{15.15}{15.00}=1.05$	$\left(\frac{9.40}{15.00}\right)^{3.6}=(0.625)^{3.6}$ = .1640	1.0000 − .1640 = .8160	$\frac{780 \times .0025 = 1.95}{15.00} = .130$	1.030	15.50			407.18	422.66		



Basic Equation

$$B(\eta) = -\int_0^{\eta} \frac{d\eta}{\eta^{N-1}}$$

Where:

$\eta = \frac{y}{y_o}$

N = Hydraulic Exponent (3.3 for wide rectangular channels)

OPEN CHANNEL FLOW

η vs $B(\eta)$

Reference – Hydraulic Design Chart 010-3

REVISION	DATE	DESCRIPTION	BY

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIVISION ENGINEER
NEW ENGLAND DIVISION
BOSTON, MASS.

DR. BY T.J.A. | TR. BY | CK. BY

SUBMITTED BY: CHIEF, PLANN. & REPTS. BRANCH

APPROVED: CHIEF ENGINEERING DIV.

BLACKSTONE RIVER FLOOD CONTROL
WORCESTER DIVERSION
RETURN CHANNEL FLOW
BACKWATER COMPUTATIONS

BLACKSTONE RIVER, MASSACHUSETTS

APPROVED: COL. C.E. DIVISION ENGINEER

DATE FEB. 1957

JUSTIN & COURTNEY
PHILADELPHIA - PENNA.

SCALE

DRAWING NUMBER

SHEET 1 OF 1

APPENDIX B

TYPICAL STRUCTURAL DESIGN COMPUTATIONS

INDEX TO SHEETS

Title		Page No.
Control Dam -	Center of gravity	B-1
	Stability analysis	B-2 and B-3
Intake Structure -	Uplift computations	B-4
	Ring stress analysis of intake	B-5
	Cantilever crest	B-6
	Cantilever wall	B-7
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Tunnel -	Coefficients for Moments - Thrusts - Shears - Geometric Elements	B-9
	Uniform Vertical Earth Load	B-10
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	Triangular Horizontal Earth Load	B-12
	Moments - Thrusts - Shears	
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APPENDIX B (Cont'd)

	Title	Page No.
Tunnel	- Thrusts and Shears - Force Diagrams	
	Coefficients	
	Uniform Vertical Earth Load	B-18
	Uniform Horizontal Earth Load	B-19
	Triangular Horizontal Earth Load	B-20
	16' Diameter Tunnel - Triangular Water Load to Crown on Outside with Tunnel Weight and Excess Buoyancy Reaction	
	2'-6" and 2'-0" Lining	B-21
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	Design of 16' Diameter Tunnel in Rock for Unreinforced Concrete Linings of 1'-0", 1'-3" and 1'-6"	B-23
	Design of 16' Diameter Tunnel in Earth for Unreinforced 2'-10" Lining and Reinforced 2'-2" Lining	B-24
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	Design of Temporary Tunnel Supports for Earth	B-26
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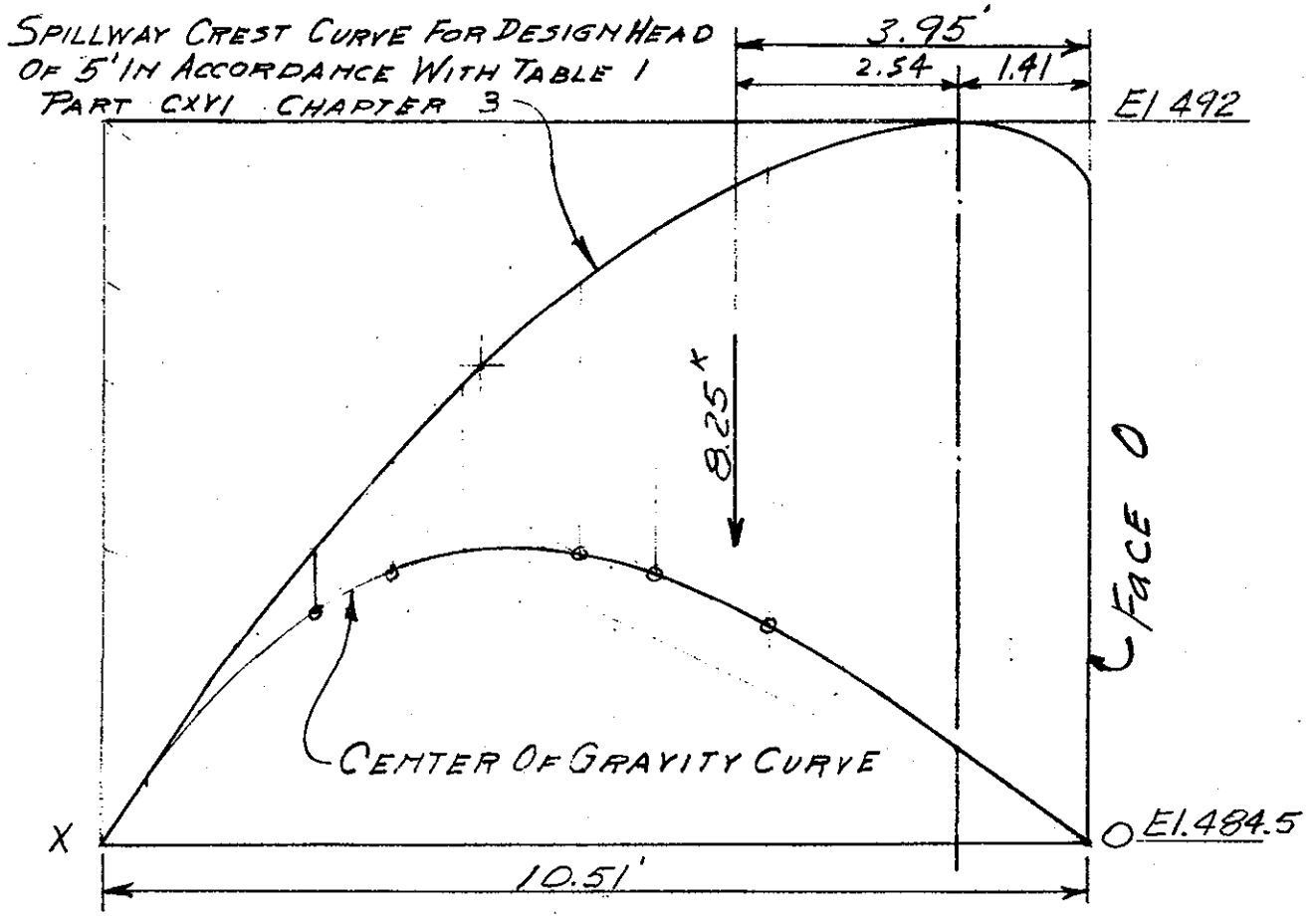
Control Dam - Stability Analysis

Center of Gravity of Ogee Section



Planimeter Readings

Area Weir = 892

Area C. of G. Curve = 335

4□" = 260 Planimeter

Scale 4½" = 16□'

Center of Gravity

$\frac{335}{892} \times 10.51 = 3.95'$ downstream from face ("O")

Weight per foot

$\frac{892}{260} \times 16 \times .15 = 8.25^K$

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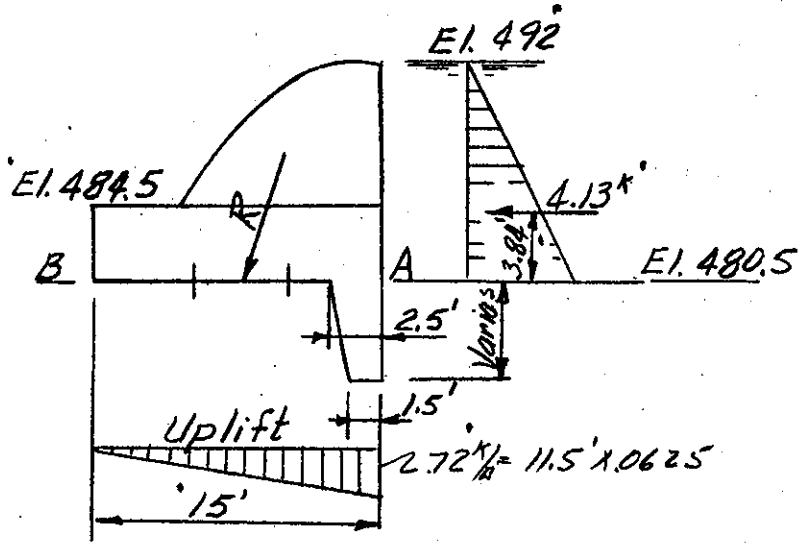
Control Dam ~ Stability Analysis



Case I
Headwater - El. 492.0', Full Uplift - Neglect slab
Tailwater - None', No Uplift'

Resultant - Moments about A	Force Horiz.	Force Vert.	Arm	Mom
Concrete Weir (by planimeter)		8.25k	3.95'	32.6'k
" Cutoff (1.5+2.5)/2 x 5 x .15		1.5	1.02	1.53
" Slab 4 x 15 x .15		9.0	7.5	67.5
Uplift .0625 x 11.5 x 15/2		-5.4	5.0	-27.0
H.W. Pressure .0625 x 11.5²/2	4.13k		3.84'	15.9
	ΣH = 4.13k	ΣV = 13.35k		ΣM = 90.53'k

$\frac{\Sigma M}{\Sigma V} = \frac{90.53}{13.35} = (7.15)$ From A (6.78) $a = \frac{15}{2} - (7.15) = (.35')$ 0.72' (6.78)

Sliding Factor

$\frac{\Sigma H}{\Sigma V} = \frac{4.13}{13.35} = .31$ Say .3

Soil Pressure

$\frac{P}{A} \pm \frac{Pa}{S} = \frac{13.35}{15}\left(1 \pm \frac{.35 \times 6}{15}\right) =$ 1.01 k/□' at A (0.72) 1.15
.77 k/□' at B .63

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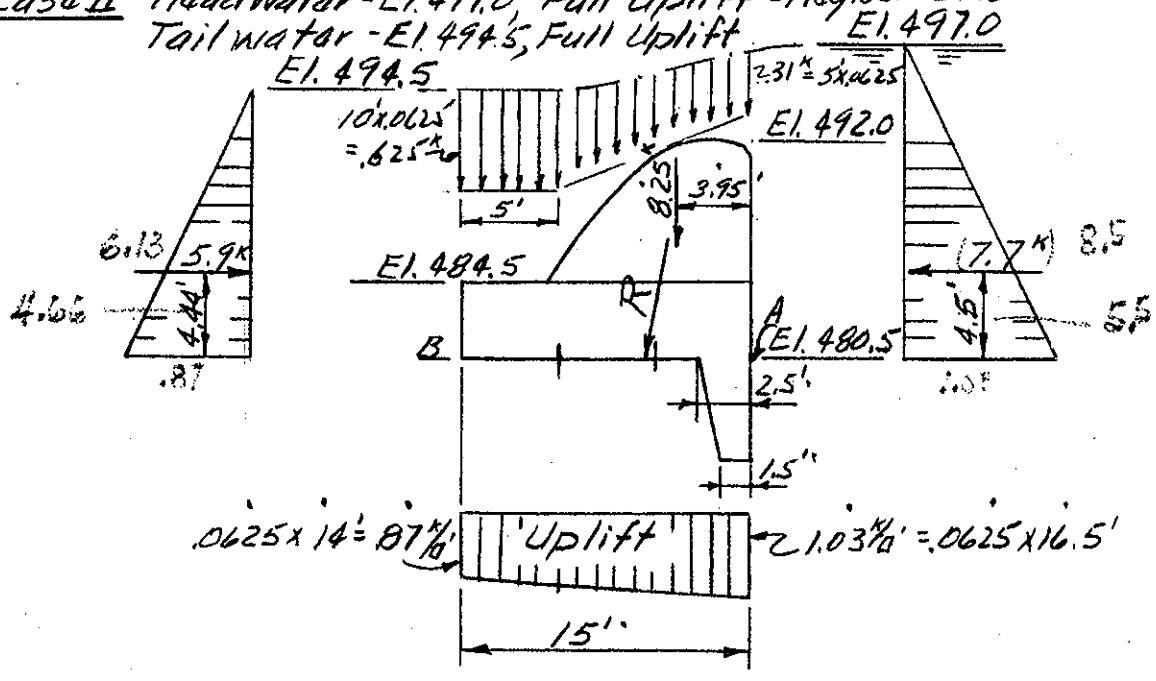
Control Dam ~ Stability Analysis
Case II - Headwater - El. 497.0, Full Uplift - Neglect Slab
Tailwater - El. 494.5, Full Uplift



Resultant - Moments about A	Force Horiz	Force Vert.	Arm	Mom
Concrete Weir (by planimeter)		8.25 K	3.95'	32.6 'K
" Cutoff (1.5+2.5)/2 x 5 x .15		1.5	1.02	1.53
" Slab 4 x 15 x .15		9.0	7.5	67.5
Tailwater .0625 x 10 x 5		3.12	12.5	39.0
" .0625 x 10 x 10/2		3.12	6.66	20.8
" .0625 x 10 x 5/2		1.56	3.33	5.2
Uplift .0625 x 16.5 x 15/2		-7.71	5.0	-38.6
" .0625 x 14 x 15/2		-6.57	10.0	-65.7
T.W. Pressure .0625 x 14²/2	-6.13 K		4.66	-28.5
" .0625 x 2.5²/2	.19		12.33	2.34
H.W. Pressure .0625 x 16.5²/2	8.50		5.5	46.7
" .0625 x 5²/2	-.78		13.16	-10.26
	ΣH = 1.78 K	ΣV = 12.27 K		ΣM = 72.11 'K
				72.61

$$\frac{\Sigma M}{\Sigma V} = \frac{72.61}{12.27} = 5.9' \text{ From A}$$

$$e = \frac{15}{2} - 5.9 = 1.6'$$

Soil Pressure

$$\frac{P}{A} \pm \frac{Pe}{S} = \frac{12.27}{15}\left(1 \pm \frac{1.6 \times 6}{15}\right)$$

$$= 1.34 \text{ K/□' at A}$$
$$.28 \text{ K/□' at B}$$

Sliding Factor

$$\frac{\Sigma H}{\Sigma V} = \frac{1.78}{12.27} = .145 \text{ say } .15$$

FOR CASE III SEE B27.

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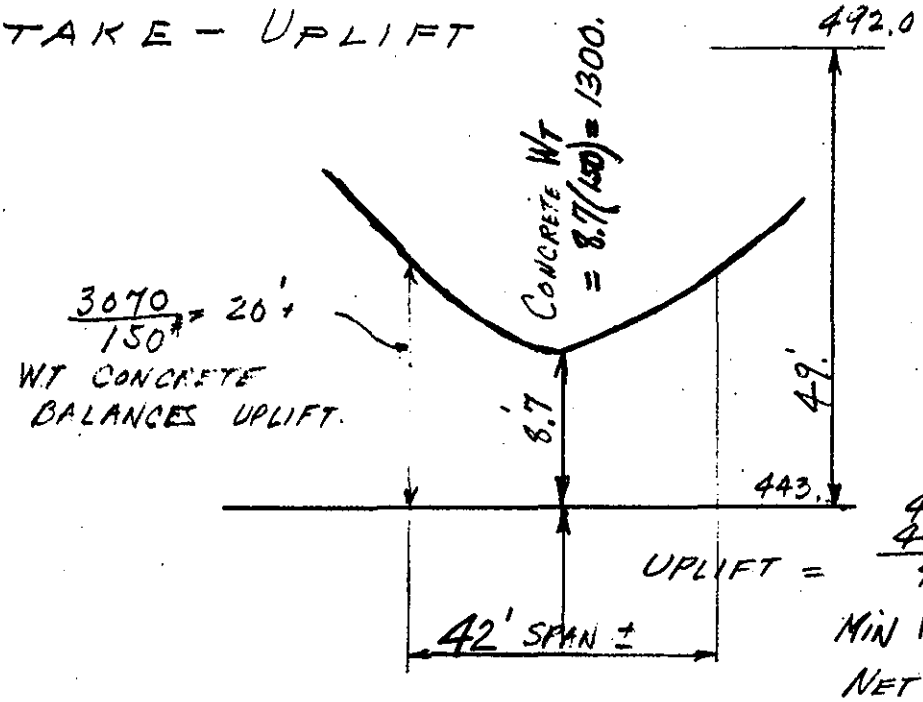
INTAKE - UPLIFT



UPLIFT = $\frac{492 - 443}{49}(62\frac{1}{2}) = 3070$ #

MIN WT CONCRETE = 1300

NET UPLIFT = 1770.#

$M = \frac{1770}{8} \times 42^2 = 375.^{'k}$ THIS IS M IF LOAD IS UNIFORM HOWEVER LOAD IS PARABOLIC.

STRESS IN CONCRETE IF NO REINFORCING $d = 114''$ $= \frac{375^{'k} \times 12}{\frac{6d^2}{6} = 26000}$

$= 172.$ #

PUT ANCHORS IN THE LOW INVERT AREA.

USE $1\frac{1}{2}''$ DIA BARS. @ 18000# = 1.56#(18000#) = 28000#

$\therefore \frac{28000}{1770} = 15.9$ SQ FT. = ABOUT 4' CC.

USE 4' CC.

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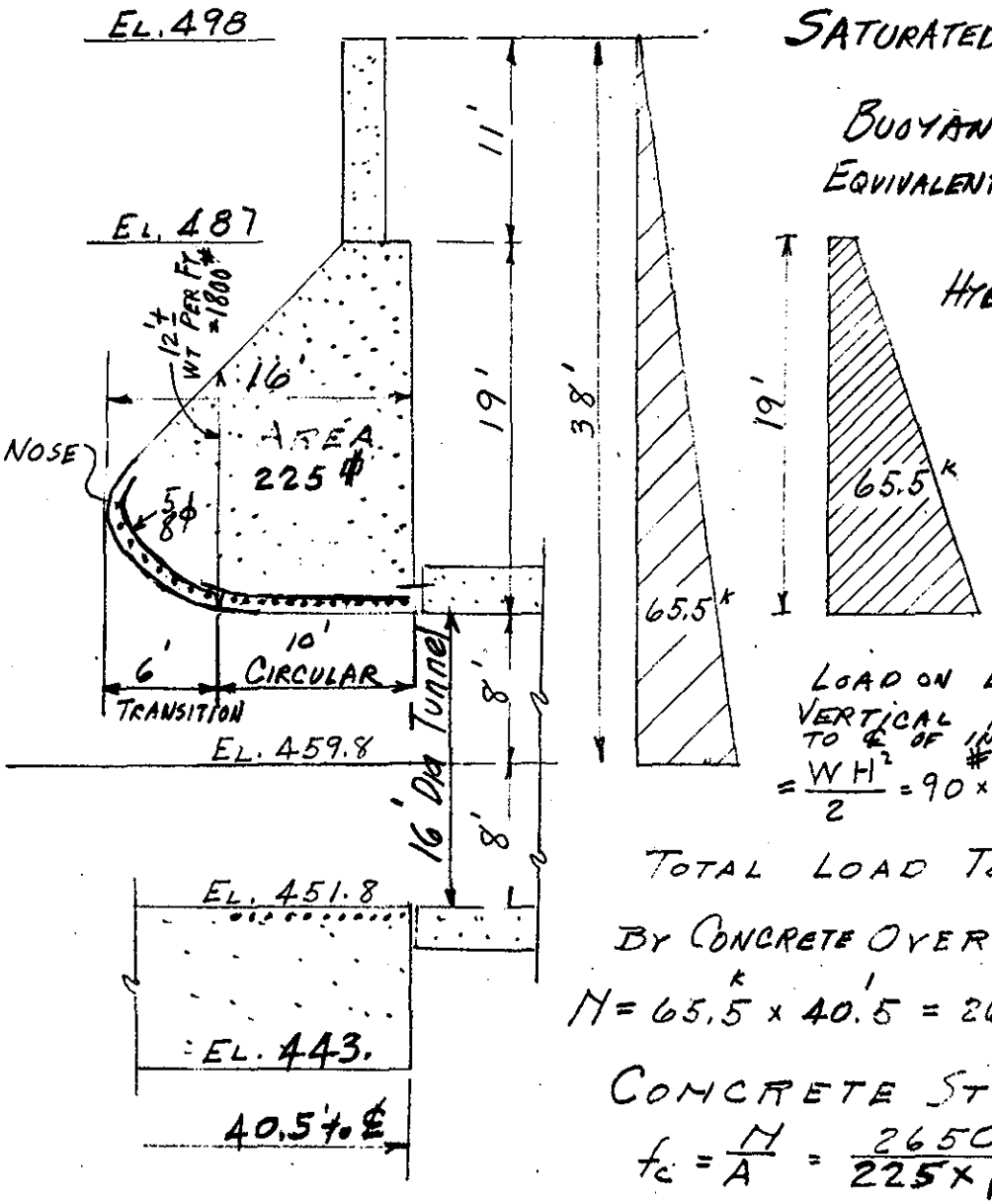
INTAKE - STRESS AT TUNNEL



SATURATED WT TILL = 150#
BUOYANT WEIGHT 62#
88#

EQUIVALENT LIQUID PRESSURE
$= \frac{1}{3}\,88 = 30^{\#}$

HYDROSTATIC = 62#
92#

SAY 90.#

LOAD ON EVERY FOOT OF VERTICAL PROJECTION OF INTAKE TO ℄ OF INTAKE.

$= \frac{WH^2}{2} = 90^{\#} \times \frac{38^2}{2} = 65.5^k$

TOTAL LOAD TO BE CARRIED BY CONCRETE OVER OPENING

$M = 65.5^k \times 40.5' = 2650.^k$

CONCRETE STRESS

$f_c = \frac{M}{A} = \frac{2650.000}{225 \times 144} = 82\ ^{\#}/_{S.I.}$

ACTING AREA		CONCRETE STRESS
PERCENT	SQ. FT.	LBS. PER. SQ. IN.
100%	225	82
50 %	113	163
33⅓ %	75	246

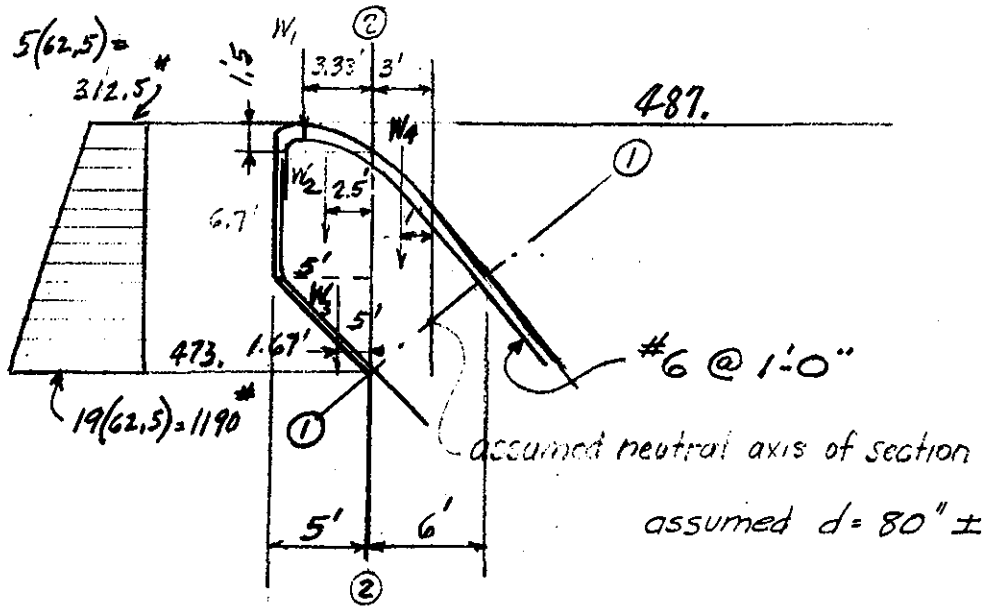
STEEL IN NOSE $W_T = \frac{1800 + 480}{12} \times 6 = 6600^{\#}$

$M = \frac{6600}{10} \times 20 = 132^{'k}$ $d = 29''$

$A_s = \frac{132.}{1.3 \times 60} = 1.7^{\#}$ USE 3/4 ϕ ABOUT 1'-0" SPRED AROUND CURVE OF NOSE

USE CIRCUMFERENTIAL STEEL AROUND CIRCULAR SECTION TO ASSIST IN TRANSMITTING STRESSES OVER AND UNDER CIRCULAR OPENING

F CLIENT CORPS OF ENGINEERS – U.S. ARMY
WORCESTER DIVERSION
INTAKE – CANTILEVER CREST



assumed d = 80" ±

DESIGN FOR TENSION STEEL ON INSIDE OF CANTILEVER

	Weight	×	Arm	=	Moment 2-2	Moment 1-1
$W_1 = \frac{1}{2} \times 1.5 \times 5 \times \frac{150}{1000}$	$= .56^k$	×	3.33	=	1.87	
			6.33			3.54
$W_2 = 5 \times 6.7 \times \frac{150}{1000}$	$= 5.02^k$	×	2.5		12.55	
			5.5			27.60
$W_3 = \frac{1}{2} \times 5 \times 5 \times \frac{150}{1000}$	$= 1.88^k$ / 1.46^k	×	1.67		3.14	
		×	4.67			8.78
$W_4 = \frac{1}{2} \times 6 \times 10 \times \frac{150}{1000}$	$= 4.5^k$	×	1			4.50
			ΣM_{2-2} =		$17.56^{'k}$	
			ΣM_{1-1} =			$= 44.42^{'k}$

SECTION 1-1 M

$A_s = \frac{M}{f_s jd} = \frac{44.42 \times 12}{18 \times .875 \times 80} = 0.423 \square''/'$

USE #6 @ 12" o.c. = .44 □"/'

SHEAR $= \frac{7460}{12 \times \frac{7}{8} \times 80} = 10\#/\square''$ OK

DESIGN FOR TENSION STEEL ON OUTSIDE OF CANTILEVER

$M_H = .312(14)7 + .878(14)(\frac{1}{2})\frac{14}{3} = 30.5 + 28.7 = 59.2$

$M_V = 1.05(5)\frac{5}{2}$ $\quad A_s = \frac{27.8}{1.380} = .27$ #PER FT $\quad = \frac{13.}{72.2}$ 1k

USE = 34"φ 1'-0" M CONCRETE $= \frac{44.4}{27.8}$ 1k

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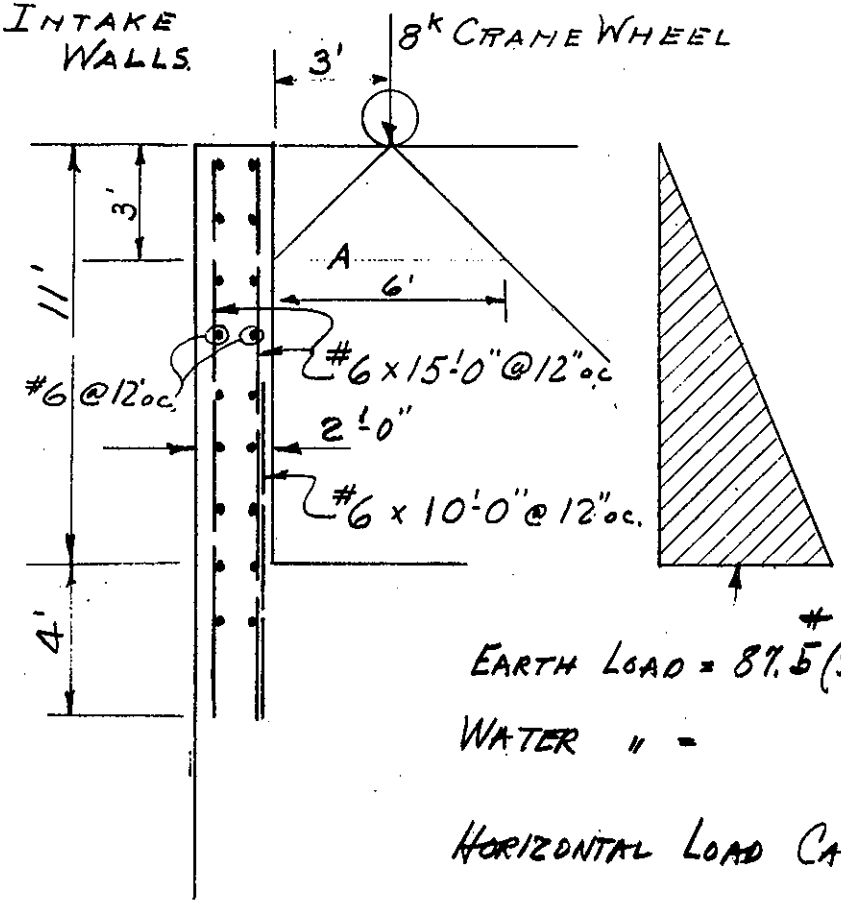
CT. WORCESTER DIVERSION CANTILEVER WALL

INTAKE WALLS



HORIZ LOAD CAUSED BY CRANE

$P = \frac{8000}{6 \times 6} \times .29$

$= 64\ \#/\square'$

$\frac{(64+7)}{2} = 35 \pm\ \#/\square'$

AVERAGE LOAD CAUSED BY CRANE

$P = \frac{8000 \times .3}{22 \times 14} = 8 \pm\ \#/\square'$

EARTH LOAD = $87.5^{\#}$ (SUBMERGED) $\times .3 = 30^{\#/\square'}$ HORIZ

WATER " = $60^{\#/\square'}$ "

$90^{\#/\square'}$ "

HORIZONTAL LOAD CAUSED BY CRANE = $35^{\#/\square'}$

MOMENTS

CRANE LOAD = $\frac{35\ 8^3}{6} = 3.^{1k}$

MOMENTS DUE TO WATER + SUBMERGED EARTH

$M = \frac{WH^3}{6} = 90\ \frac{11^3}{6} = 20^{1k}$ TOTAL $M = 23^{1k}$ $d = 12''$

∴ 2' WALL AMPLE

$A_s = \frac{23}{1.29 \times 21} = .85^{\square''}$

USE #6 @ 6" o.c. V.O.F.

TEMP $A_s = .0025 \times 12 \times 24 = .72^{\square''}$

USE #6 @ 12" o.c. H.E.F.

Stilling Basin - Design Computations

Uplift - Floor.

W.S. Elev. 428.00 - Base of concrete in floor El. 403.00
Pressure Head = 25 ft - Use this H over entire base.

Uplift pressure 25' x 62.5 # □' = 1560 # □'
Weight of concrete 2' x 150# □' = 300 # □'

Net Uplift - P = 1260 # □'

Anchor Bars into rock base to stabalize uplift pressure

Spaced 4' 6" x 4' 8" = Area 21 Sq. Ft.
Uplift P = 1260 # □' x 21 Sq. Ft = 26500 lbs.
Use No 11 Bars. $\frac{26500\#}{1.56 \text{ sq. in.}}$ = 17,000 p.s.i. stress in steel.

Investigation of Slab for Bending & Cantilever stresses

$M = \frac{WL^2}{12} = \frac{1260 \times (4'6" \times 4'8")}{12} = \frac{1260 \times 21}{12} = 2205$ ft lbs.

Design as a two way slab. Take 1/2 Moment 1.102 kps.

From Concrete Design Handbook d = 3"

$As = \frac{M}{f_s j d} = \frac{1102 \times 12}{18000 \times .875 \times 14} = 0.06$ sq. inches steel

Check cantilever bending at contraction joints.

Moment = 1260 # (wt) x (2'4" Area) x 1'2" arm = 3400 ft. lbs.

From Concrete Design Handbook d = 4 1/2"

$As = \frac{M}{f_s j d} = \frac{3400 \times 12}{18,000 \times .875 \times 14"} = 0.06$ sq. inches steel.

Use d = 8".

Temperature steel - Floor & Walls.

.0025 x Area. Floor .0025 x 24" x 12" = 0.72 Sq. Inches
Use No 6 Bars. @ 1'-0"

Walls .0025 x 18" x 12" = 0.54 " "
Use No 6 Bars @ 1'-0"

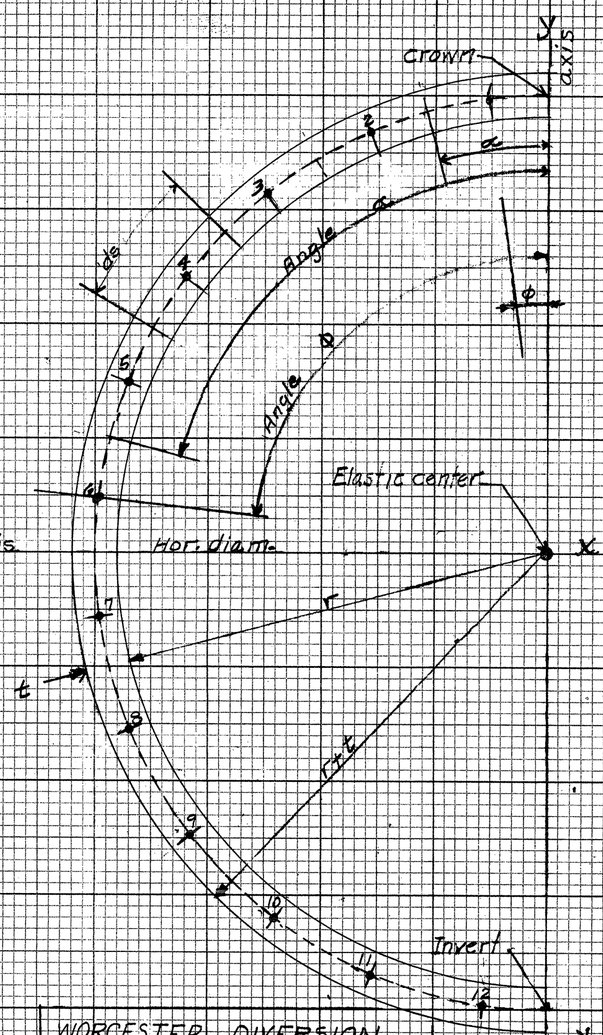
Temperature steel ample for bending & cantilever stresses.

Anchors in Walls:

Spaced the same as the floor except for 1st row below top of wall.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Point		Coordinate		Voussoir	Coordinate		Projection of Voussoir		ds	t	t^3	a	ay	ay^2
		y	x		y	x								
No.	Angle ϕ	$(r+t/2)$ Cosine	$(r+t/2)$ Sine	Angle α	$(r+t/2)$ Cosine	$(r+t/2)$ Sine	$(r+t/2)$ y_p	$(r+t/2)$ x_p	$(r+t/2) = \frac{r}{24}\pi$			$\frac{(r+t/2)}{t^3}$ $12\frac{ds}{t^3}$	$\frac{(r+t/2)^2}{t^3}$	$\frac{(r+t/2)^3}{t^3}$
Crown	0°	+1.000	0.000	crown	+1.000	0.000								
1	7.5°	+0.991	-0.131	15°	+0.966	-0.259	+0.034	-0.259	0.2618	1.00	1.00	3.142	+3.113	3.085
2	22.5°	+0.924	-0.383	30°	+0.866	-0.500	+0.100	-0.241	0.2618	1.00	1.00	3.142	+2.903	2.682
3	37.5°	+0.793	-0.609	45°	+0.707	-0.707	+0.159	-0.207	0.2618	1.00	1.00	3.142	+2.492	1.976
4	52.5°	+0.609	-0.793	60°	+0.500	-0.866	+0.207	-0.159	0.2618	1.00	1.00	3.142	+1.913	1.165
5	67.5°	+0.383	-0.924	75°	+0.259	-0.966	+0.241	-0.100	0.2618	1.00	1.00	3.142	+1.203	0.461
6	82.5°	+0.131	-0.991				+0.259	-0.034	0.2618	1.00	1.00	3.142	+0.412	0.054
Hor. Dia	90.0°			90°	0.000	-1.000								
7	82.5°	-0.131	-0.991				0.259	+0.034	0.2618	1.00	1.00	3.142	-0.412	0.054
8	67.5°	-0.383	-0.924	75°	-0.259	-0.966	-0.241	+0.100	0.2618	1.00	1.00	3.142	-1.203	0.461
9	52.5°	-0.609	-0.793	60°	-0.500	-0.866	-0.207	+0.159	0.2618	1.00	1.00	3.142	-1.913	1.165
10	37.5°	-0.793	-0.609	45°	-0.707	-0.707	-0.159	+0.207	0.2618	1.00	1.00	3.142	-2.492	1.976
11	22.5°	-0.924	-0.383	30°	-0.866	-0.500	-0.100	+0.241	0.2618	1.00	1.00	3.142	-2.903	2.682
12	7.5°	-0.991	+0.131	15°	-0.966	-0.259	-0.034	+0.259	0.2618	1.00	1.00	3.142	-3.113	3.085
Invert	0°	-1.000	-0.000	Invert	-1.000	0.000								
											Totals	37.704	0	+18.846

$$\text{Elastic Center} = \frac{\Sigma\, ay}{\Sigma\, a} = \frac{0.000\,(r+t/2)^2 t^{-3}}{37.704\,(r+t/2)^2 t^{-3}} = 0.000$$



WORCESTER DIVERSION.
TUNNEL GEOMETRIC ELEMENTS

FRANK E. FAHLQUIST
BARRINGTON, RHODE ISLAND

SHEET No. B-9

JUSTIN & COURTNEY
PHILA. PA. JAN 1957

	30	31	32	33	35	36	37	38	39	40	41	42
No.	Vertical Earth Load	Σ V Load	Moment Arms	M_v	m Σ M_v	ma	may	$M_o + m$	$H_o y$	Moment M	Thrust N	Shear V
Equation	P	P	(r+t/2)	P(r+t/2)	P(r+t/2)	$P(r+t/2)t^2$	$P(r+t/2)t^3$	P(r+t/2)	P(r+t/2)	P(r+t/2)	P	P
Method	(#9/2)	Σ(#30)	(Col. No. 4) $X_n - X_{n-1}$	(#31)×(#32)	Σ(#33)	(#13)×(#35)	(#36)×(#3)	M_o+(#35)	H_o×(#3)	(#38)+(#39)	See Sheet B-18	
Crown								+0.1268	−0.0089	+0.119	+0.009	000
1	+0.130	0.130			(−0.004)			+0.1228	−0.0088	+0.118	+0.017	0.064
			−0.252	−0.0328								
2	+0.120	0.250			−0.0328	−0.1031	−0.0953	+0.0940	−0.0082	+0.086	+0.080	0.172
			−0.226	−0.0565								
3	+0.103	0.353			−0.0893	−0.2806	−0.2225	+0.0376	+0.0071	+0.031	+0.191	0.233
			−0.184	−0.0650								
4	+0.080	0.433			−0.1543	−0.4848	−0.2952	−0.0274	−0.0055	−0.033	+0.318	0.230
			−0.131	+0.0567								
5	+0.050	0.483			−0.2110	−0.6630	−0.2533	−0.0842	0.0035	−0.088	+0.427	0.165
			+0.067	+0.0323								
6	+0.017	0.500			−0.2433	−0.7644	−0.1001	−0.1165	0.0012	−0.118	+0.488	0.057
Hor. Dia.										−0.121	+0.500	0.000
7	−0.022	0.478			−0.2433	−0.7707	+0.1010	−0.1165	−0.0012	−0.115	+0.483	0.072
			+0.067	+0.0320								
8	−0.064	0.414			−0.2113	−0.6639	+0.2536	−0.0845	+0.0034	−0.081	+0.409	0.175
			+0.131	+0.0542								
9	−0.096	0.318			−0.1571	−0.4936	+0.3066	−0.0303	+0.0054	−0.025	+0.286	0.230
			+0.184	+0.0585								
10	+0.110	0.208			−0.0986	−0.3098	+0.2457	+0.0282	+0.0071	+0.035	+0.155	0.212
			+0.226	+0.0470								
11	+0.110	0.098			−0.0516	−0.1621	+0.1498	+0.0752	+0.0082	+0.083	+0.053	0.146
			+0.252	+0.0247								
12	+0.097	0			−0.0269	−0.0845	−0.0837	+0.0999	+0.0088	+0.109	−0.002	0.048
Invert										+0.116	−0.009	0.000
					Totals	−4.7805	+0.1680					

$$M_o = -\frac{\Sigma ma}{\Sigma a} = -\frac{-4.7805}{+37.704} = +0.1268$$

$$H_o = -\frac{\Sigma may}{\Sigma ay^2} = -\frac{+0.1680}{+18.846} = -0.0089$$

FRANK E. FAHLQUIST
BARRINGTON, RHODE ISLAND

JUSTIN & COURTNEY
PHILADELPHIA, PENNA.
JAN. 1957

WORCESTER DIVERSION
TUNNEL COEFFICIENTS FOR
MOMENT, THRUST & SHEAR.
UNIFORM VERTICAL EARTH LOAD
SHEET No. B-10

	1	23	24	25	26	35	36	37	38	39	40	41	42
	No.	Horizontal Earth load	ΣH Loads	Moment Arms	M_H	m ΣM_H	ma	may	$M_o + m$	$H_o y$	Moment M	Thrust N	Shear V
Equation		$w(r+t/2)$	$w(r+t/2)$	$(r+t/2)$	$w(r+t/2)^2$	$w(r+t/2)^2 t^{-3}$	$w(r+t/2)^4 t^{-3}$	$w(r+t/2)^4 t^{-3}$	$w(r+t/2)^2$	$w(r+t/2)^2$	$w(r+t/2)^2$	$w(r+t/2)$	$w(r+t/2)$
Method		(#8) (All +)	Σ(#23)	(Col No. 3) $y_n - y_{n-1}$	(#24)×(#23)	Σ(#26)	(#35)×(#13)	(#36)×(#3)	(M_o + #35)	(H_o × #3)	(#38)+(#39)	See Sheet B-19	
	Crown								+0.7479	-0.9971	-0.249	+0.997	0
	1	+0.034	+0.034		0.000	0.000	0.000	0.000	+0.7479	-0.9881	-0.240	0.97	0.13
				-0.067									
	2	0.100	0.134		-0.0023	-0.0023	-0.0072	-0.0667	+0.7456	-0.9213	-0.1776	0.84	0.35
				-0.131									
	3	0.159	0.293		-0.0176	-0.0199	-0.0625	-0.0496	+0.7280	-0.7907	-0.063	0.62	0.45
				-0.184									
	4	0.207	0.500		-0.0539	-0.0738	-0.2319	-0.1412	+0.6741	-0.6072	+0.067	0.32	0.23
				-0.226									
	5	0.241	0.741		-0.1130	-0.1868	-0.5869	-0.2248	+0.5611	-0.3819	+0.179	0.14	0.35
				-0.252									
	6	+0.259	+1.000		-0.1867	-0.3735	-1.1735	-0.1537	+0.3744	-0.1306	+0.244	0.02	0.12
	Hor. Dia.			-0.262							+0.243	0.00	0.00
	7	+0.259	+1.259		-0.2620	-0.6355	-1.9767	+0.2616	+0.1129	+0.1306	+0.243	0.02	0.12
				-0.252									
	8	0.241	1.500		-0.3173	-0.9528	-2.9937	+1.1466	-0.2049	+0.3819	+0.177	0.14	0.35
				-0.226									
	9	0.207	1.707		-0.3380	-1.2918	-4.0588	+2.4718	-0.5439	+0.6072	+0.063	0.29	0.23
				-0.184									
	10	0.159	1.866		-0.3141	-1.6059	-5.0455	+4.0011	-0.8580	+0.7907	-0.067	0.62	0.43
				-0.131									
	11	0.100	1.966		-0.2445	-1.8504	-5.8139	+5.3720	-1.1025	+0.9213	-0.181	0.84	0.35
				-0.067									
	12	+0.034	+2.000		-0.1317	-1.9821	-6.2276	+6.1716	-1.2342	+0.9881	-0.246	0.97	0.13
	Invert										-0.255	+1.003	0
						TOTALS	-28.1782	+18.7887					

$$M_o = -\frac{\Sigma ma}{\Sigma a} = -\frac{-28.1782}{37.704} = +0.7479$$

$$H_o = -\frac{\Sigma may}{\Sigma ay^2} = -\frac{+18.7887}{18.846} = -0.9971$$

FRANK E. FAHLQUIST
BARRINGTON, RHODE ISLAND
JUSTIN & COURTNEY
PHILADELPHIA, PENNA.
JAN. 1957

WORCESTER DIVERSION
TUNNEL COEFFICIENTS FOR
MOMENT, THRUST & SHEAR.
UNIFORM HORIZONTAL EARTH LOAD
SHEET No. B-11

	1	22	23	24	25	26	35	36	37	38	39	40	41	42
	No.	Intensity = Y Co-ord. From ℄ Crown	Horizontal Earth Load (H)	ΣH	Moment Arms	Moment (M_H)	m ΣM_H	ma	may	$M_o + m$	$H_o y$	Moment (M)	Thrust (N)	Shear (V)
Equation		$T(r+t)$	$T(r+t)^2$	$T(r+t)^2$	$(r+\frac{t}{2})$	$T(r+t)^2(r+\frac{t}{2})$	$T(r+t)^2(r+\frac{t}{2})$	$\frac{T(r+t)^2(r+\frac{t}{2})^2}{t^3}$	$\frac{T(r+t)^2(r+\frac{t}{2})^3}{t^3}$	$T(r+t)^2(r+\frac{t}{2})$	$T(r+t)^2(r+\frac{t}{2})$	$T(r+t)^2(r+\frac{t}{2})$	$T(r+t)^2$	$T(r+t)^2$
Method		1-#3	#22×#8	Σ#23	$Y_n - Y_{n-1}$	#25×#24	Σ#26	#26×#13	#27×#3	M_o+#26	H_o×#3	#29+#30	See Sheet B-20	
	Crown									+ .415	- .639	- .224	+ .64	0
	1	.009	.0003	.0003		0	0	0	0	+ .415	- .633	- .218	+ .63	- .08
					- .067									
	2	.076	.0076	.0079		0	0	0	0	+ .415	- .590	- .175	+ .58	- .24
					- .131									
	3	.207	.0329	.0408		- .0010	- .0010	- .0031	- .0025	+ .418	- .506	- .092	+ .48	- .37
					- .184									
	4	.391	.0809	.1217		- .0075	- .0085	- .0267	- .0163	+ .401	- .389	+ .022	+ .34	- .44
					- .226									
	5	.617	.1487	.2704		- .0275	- .0360	- .1131	- .0434	+ .379	- .244	+ .135	+ .17	- .41
					- .253									
	6	.869	.2251	.4955		- .0684	- .1044	- .328	- .0429	+ .311	- .083	+ .228	+ .04	- .25
	Hor. Dia.	1.000			(-.130)	(-.0645)	(-.1689)			(+.246)	(0)	+ .246	0	- .14
					- .260									
	7	1.130	.2925	.7880		- .1289	- .2333	- .734	+ .0954	+ .182	+ .083	+ .265	0	0
					- .253									
	8	1.383	.3335	1.1215		- .1992	- .4325	- 1.360	+ .521	- .017	+ .244	+ .227	+ .12	+ .29
					- .226									
	9	1.609	.3330	1.4545		- .254	- .6865	- 2.159	+ 1.315	- .271	+ .389	+ .116	+ .39	+ .52
					- .184									
	10	1.793	.2850	1.7395		- .268	- .9545	- 3.000	+ 2.475	- .539	+ .506	- .033	+ .76	+ .58
					- .131									
	11	1.924	.1924	1.9319		- .227	- 1.1815	- 3.720	+ 3.44	- .766	+ .590	- .176	+ 1.11	+ .46
					- .067									
	12	1.991	.0677	1.9986		- .1293	- 1.3108	- 4.120	+ 4.08	- .896	+ .633	- .263	+ 1.32	+ .17
	Inv.	2.000		(2.00)	(-.009)	(-.018)	(-1.3288)			- .914	+ .639	- .276	+ 1.36	0
								- 15.664	+ 12.021					

$$M_o = \frac{-\Sigma ma}{\Sigma a} = -\frac{-15.66}{37.7} = +.415$$

$$H_o = -\frac{\Sigma may}{\Sigma ay^2} = -\frac{12.02}{18.85} = -.639$$

FRANK E. FAHLQUIST
BARRINGTON, RHODE ISLAND
JUSTIN & COURTNEY
PHILADELPHIA, PENNA.
JAN. 1957

WORCESTER DIVERSION TUNNEL COEFFICIENTS FOR MOMENT, THRUST & SHEAR TRIANGULAR HORIZONTAL EARTH LOAD.

SHEET No. B-12

	1	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40C	41C	42C	40	41	42
	No.	Distance Top of shell to center of shell extrados	Load Intensity	Horizontal Loads	ΣH Loads	Moment Arms	M_H	ΣM_H	Vertical Water Load	Vertical Buoyancy Reaction	Total Vertical Load	ΣV Loads	Moment Arms	M_V	ΣM_V	m	ma	may	$M_o + m$	$H_o y$	Moment	Thrust	Shear	Moment	Thrust	Shear
Equation		$(r+t)$	$(r+t)$	$(r+t)^2$	$(r+t)^2$	$(r+\frac{t}{2})$	$(r+t)^2(r+\frac{t}{2})$	$(r+t)^2(r+\frac{t}{2})$	$(r+t)^2$	$(r+t)^2$	$(r+t)^2$	$(r+t)^2$	$(r+\frac{t}{2})$	$(r+t)^2(r+\frac{t}{2})$	$(r+t)^2(r+\frac{t}{2})$	$(r+t)^2(r+\frac{t}{2})$	$(r+t)^2(r+\frac{t}{2})^2$	$(r+t)^2(r+\frac{t}{2})^2 y$	$(r+t)^2(r+\frac{t}{2})^2$	$(r+t)^2(r+\frac{t}{2})$	$(r+t)^2(r+\frac{t}{2})$	$(r+t)^2(r+\frac{t}{2})$	$(r+t)^2$	$(r+t)^2$	—	See Sheet B-21	
Method		$1-(^*3)$	$62.5\times(^*21)$	$(^*8)\times(^*22)$	$\Sigma(^*23)$	(Col. No. 3) $y_n - y_{n-1}$	$(^*24)\times(^*25)$	$\Sigma(^*26)$	$(^*9)\times(^*22)$	See Note:	$(^*27)+(^*29)$	$\Sigma(^*30)$	(Col. No. 4) $X_n - X_{n+1}$	$(^*31)\times(^*32)$	$\Sigma(^*33)$	$(^*27)+(^*34)$	$(^*13)\times(^*35)$	$(^*36)\times(^*3)$	$30.86+(^*35)$	$-31.\times(^*3)$	$(^*38)+(^*39)$	See Sheet No. B-21			1.02 (*40c)	.11 (*41c)	.111 (*42c)
																					ft. lb.	lb.	lb.	ft. kips.	kips.	kips
	Crown	0						0							0		0									
																			+30.86	−31.00	−.14	+31.0	1.5	−.14	3.41	.17
	1	0.009	0.56	0.02	0.02	−0.067		0	+0.15	+8.16	+8.31	+8.31	−0.252	−0.14	−0.14	−0.14	0.44	−0.44	+30.72	−30.72	0	+31.0	1.5	0	3.41	.17
	2	0.076	4.75	0.48	0.50	0.131	0	0	+1.14	+8.16	+9.30	+17.61	−0.226	−2.09	−2.23	−2.23	7.01	−6.48	+28.63	−28.64	.01	+33.0	1.5	−.01	3.75	.17
	3	0.207	12.94	2.06	2.56	−0.184	−0.07	−0.07	+2.68	+8.16	+10.84	+28.45	−0.184	−3.98	−6.21	−6.28	−19.73	−15.65	+24.58	−24.58	0	+38.0	1.5	0	4.20	.17
	4	0.391	24.44	5.06	7.62	−0.226	−0.47	−0.54	+3.89	+8.16	+12.05	+40.50	−0.131	−5.23	−11.44	−11.98	−37.64	−22.92	+18.88	−18.88	0	+43.5	1.0	0	4.80	.11
	5	0.617	38.56	9.29	16.91	−0.252	−1.72	−2.26	+3.86	+8.16	+12.02	+52.52	−0.067	−5.31	−16.75	−19.01	−59.73	−22.88	+11.85	−11.87	−.02	+50.5	.5	−.02	5.55	.06
	6	0.869	54.31	14.07	30.98	(−0.131)	−4.26	−6.52	+1.85	+8.17	+10.02	+62.54	(−0.009)	−3.82	−20.27	−26.79	−84.7	−11.03	+4.07	−4.06	+.01	+38.1	0	+.01	6.40	0
	Hor. Dia.						(−4.04)	(−10.58)					0	(−0.56)	(−20.83)	(−31.41)	—	—	−0.55	0	−.55	+62.7	0	−.56	6.90	0
	7	1.131	70.69	18.31	49.29	−0.252	−8.12	−14.64	−2.40	+8.15	+5.75	+68.29	+0.067	0	−20.27	−34.91	−109.69	+14.37	−4.05	+4.06	+.01	+66.0	0	+.01	7.27	0
	8	1.363	86.44	20.83	70.12	−0.226	−12.42	−27.06	−8.64	+8.15	−0.49	+67.80	+0.131	+6.58	−15.69	−42.75	−134.32	+51.44	−11.89	+11.87	−.02	+73.0	0	−.02	8.05	0
	9	1.609	100.56	20.82	90.94	−0.184	−15.85	−42.91	−15.99	+8.15	−7.84	+59.96	+0.184	+8.88	−6.81	−49.72	−156.22	+95.14	−18.86	+18.88	+.02	+80.	0	+.02	8.72	0
	10	1.793	112.06	17.82	108.76	−0.131	−16.73	−59.64	−23.20	+8.15	−15.05	+44.91	+0.226	+11.03	+4.22	−55.62	−174.73	+138.09	−24.56	+24.58	+.02	+87.2	0	+.02	9.65	0
	11	1.924	120.25	12.02	120.78	−0.067	−14.25	−73.89	−28.98	+8.15	−20.83	+24.08	+0.252	+10.15	+14.37	−59.52	−187.01	+172.80	−28.66	+28.64	−.02	+90.0	0	−.02	9.90	0
	12	1.991	124.44	4.23	125.00	−0.005	−8.09	−81.98	−32.23	+8.15	−24.08	0	+0.130	+6.07	+20.44	−61.54	−193.36	+191.62	−30.68	+30.72	+.04	+93.0	0	+.04	10.23	0
	Invert	2.000					−0.56	−82.54						0	+20.44	−62.10	—	—	−31.10	+31.00	−.10	+94.0	0	−.10	10.34	0
									−97.87	+97.87		$M_L = \frac{5.31}{2} \times \frac{.131}{4} = .136$														
																			−1163.45	+584.06						

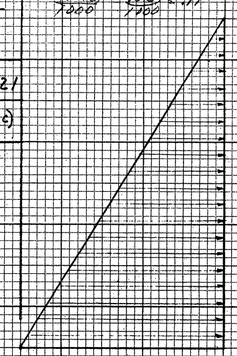
Note:
1.-Buoyancy: The resultant of the total water load is 97.87 acting up.
2.-A reaction equal & opposite in direction to the buoyancy is distributed uniformally around the shell.
3 This reaction is exactly equal to the weight of the tunnel shell when $r = 8'-0''$ and $t = 2\frac{1}{2}''$

$$M_o = -\frac{\Sigma ma}{\Sigma a} = -\frac{-1163.45}{37.724} = +30.86$$

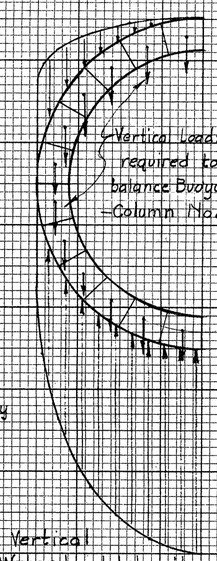
$$H_o = -\frac{\Sigma may}{\Sigma ay^2} = -\frac{584.06}{18.848} = -31.00$$

when $r=8$ and $t=2.5$ $\frac{(r+t)^2}{1000}\left(r+\frac{t}{2}\right) = \frac{(10.5)^2}{1000} \times 8.25$

$\frac{(r+t)^2}{1000} = \frac{(10.5)^2}{1000} = .111$



Horizontal Water Load Intensity -Column No. 22-



FRANK E. FAHLQUIST
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WORCESTER DIVERSION TUNNEL
16' DIAMETER -30" LINING
TRIANGULAR WATERLOAD TO CROWN ON OUTSIDE AND BUOYANCY REACTION UNIFORMLY AROUND SHELL
SHEET No. B-13

1	24	27	28	28a	29	30	31	32	33	34	35	36	37	38	39	40	41	42
No.	ΣH Loads	ΣM_H	Vertical Water Load	Weight of Tunnel Shell	Vertical Buoyancy Reaction	Total Vertical Load	ΣV Loads	Moment Arms	M_V	ΣM_V	m	ma	may	$M_o + m$	$H_o y$	Moment	Thrust	Shear
Method	$(r+t)^2$(Coef.) on Sheet B-13 Column #24 $= \frac{100}{1000}$(Coef.)	$(r+t)^2(r+\frac{t}{2})$ x(Coef.) on Sheet B-13 Column #27 $= \frac{900}{1000}$(Coef.)	$(r+t)^2$(Coef.) on Sheet B-13 Column #28 $= \frac{100}{1000}$(Coef.)	$\frac{2\pi R t}{24} \times 150$ $= \frac{2\pi(r+\frac{t}{2})t}{24} \times 150$ $= \frac{707}{1000}$	* Uniform Distribution on Top $= \frac{1}{6} \times 1.303$	(#28)+(#29)	Σ(#30)	$(r+\frac{t}{2})$(Coef) on Sheet B-13 Column #32 $= 9$(Coef)	(#31)x(#32)	Σ(#33)	(#27)+(#34)	$a = \frac{(r+\frac{t}{2})(\text{Coef})}{t^3}$ on Sheet B-9 Column #13 $= 9.53$(#35)	$y = (r+\frac{t}{2})$(Coef) on Sheet B-9 Column #3 $= 9 \times (\frac{t}{2}) \times$(#36)	M_o - See Below $= 29.08 +$(#35)	$y = (r+\frac{t}{3})$(Coef) on Sheet B-9 Column #8 $= 9$(#3) x 3.10	(#38)+(#39)	See Sheet No. B-21	
	kips.	ft. kips	kips	kips	kips	kips	kips	ft.	ft. kips	ft kips	ft. kips			ft. kips	ft. kips	ft. kips	kips	kips
Crown	0	0	0	0	0	0	0		0	0	0	0	0	+29.08	-27.90	+1.18	3.10	0
1	.002	0	+0.015	+0.707	+0.217	+0.939	+0.939	-2.27	-0.20	-0.20	+0.20	-0.71	-6.33	+28.88	-27.65	+1.23	3.20	0.05
2	.050	0	+0.114	+0.707	+0.217	+1.038	+1.977	-2.03	-2.13	-2.33	-2.33	-8.23	-68.39	+26.75	-25.76	+0.99	3.45	0.10
3	.256	-0.063	+0.268	+0.707	+0.217	+1.192	+3.169	-1.66	-4.01	-6.34	-6.40	-22.62	-161.28	+22.68	-22.10	+0.58	3.95	0.15
4	.762	-0.49	+0.389	+0.707	+0.217	+1.313	+4.482	-1.18	-5.26	-11.60	-12.09	-42.73	-234.16	+16.99	-16.99	0	4.65	0.15
5	1.69	-2.03	+0.386	+0.707	+0.217	+1.310	+5.792	-0.60	-5.29	-16.89	-18.92	-64.86	-230.67	+10.16	-10.69	-0.53	5.56	0.10
6	3.058	-5.87	+0.185	+0.707	+0.218	+1.110	+6.902		-3.47	-20.36	-26.23	-92.70	-109.37	+2.85	-3.66	-0.81	6.40	0.10
Mid																	6.90	0.10
7	4.73	-13.18	-0.240	+0.707	0	+0.467	+7.369	+0.60	0	-20.36	-33.54	-118.53	+139.86	-4.46	+3.66	-0.80	7.20	0.10
8	7.01	-24.55	-0.864	+0.707	0	-0.157	+7.212	+1.18	+4.42	-15.94	-40.29	-142.38	+491.21	-11.71	+10.69	-0.52	7.80	0.15
9	9.09	-38.62	-1.599	+0.707	0	-0.892	+6.320	+1.66	+8.51	-7.43	-46.05	-162.74	+891.81	-16.97	+16.49	+0.02	8.35	0.25
10	10.87	-53.78	-2.320	+0.707	0	-1.613	+4.707	+2.02	+10.49	+3.06	-50.72	-179.24	+1297.98	-21.64	+22.10	+0.46	8.80	0.25
11	12.08	-66.50	-2.898	+0.707	0	-2.191	+2.516	+2.27	+9.51	+12.57	-53.93	-190.59	+1583.80	-24.85	+25.76	+0.91	9.10	0.15
12	12.50	-78.78	-3.223	+0.707	0	-2.516	0		+5.71	+18.28	-55.50	-196.14	+1749.57	-26.46	+27.65	+1.13	9.20	0.05
Invert															+27.90	+1.18	9.80	0
			Totals	-9.787	+8.484	+1.303						-1223.47	+5324.03					

Algebraic Sum Col. No. 28 = Buoyancy = 9.787

Buoyancy - Shell Wt. = Req'd Reaction

9.787 - 8.484 = 1.303

$$H_o = -\frac{\Sigma\, may}{\Sigma\, ay^2} = -\frac{+5324.03}{1717.52} = -3.10$$

$$M_o = -\frac{\Sigma\, ma}{\Sigma\, a} = -\frac{-1223.47}{42.42} = +29.08$$

WORCESTER DIVERSION TUNNEL

16' DIAMETER - 24" LINING

TRIANGULAR WATER LOAD TO CROWN ON OUTSIDE AND

TUNNEL WEIGHT + EXCESS BUOYANCY REACTION

FRANK E. FAHLQUIST
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PHILADELPHIA, PA.

SHEET No. B-14

No.	27 ΣM_H	28 Vertical Water Load	28a Weight of Tunnel Shell	29 Vertical Buoyancy Reaction	30 Total Vertical Load	31 ΣV	32 Moment Arms	33 M_V	34 ΣM_V	35 m	36 ma	37 may	38 $M_o + m$	39 $H_o y$	40 Moment	41 Thrust	42 Shear
Method	$(r+t)^2(r+\frac{t}{2})$ x(Coef.) on Sheet B-13 Column #27 $= \frac{788}{1000}$(Coef.)	$(r+t)^2$(Coef. on Sheet B-13 Column #28 $= \frac{102}{1000}$(Coef.)	$\frac{2\pi R t}{24}$ 150 # $\frac{2\pi(r+\frac{t}{2})t}{24}$ 150 $= \frac{515}{1000}$	Uniform Distribution on Top $= \frac{1}{6} \times 2.630$ (#28)+(#28a)+(#29)		Σ(#30)	$(r+\frac{t}{2})$(Coef.) on Sheet B-13 Column #32 = 8.75(Coef.)	(#31)x(#32)	Σ(#33)	(#27)+(#34)	$a = \frac{(r+\frac{t}{2})}{t^3}$(Coef.) on Sheet B-9 Column #13 = 8.15(#35)	$y = (r+\frac{t}{2})$(Coef.) on Sheet B-9 Column #3 = 8.15(#3)(#36)	M_o - See Below = 26.3 + (#35)	$y = (r+\frac{t}{2})$(Coef.) on Sheet B-9 Column #3 = 8.15(#3) 2.78	(#38)+(#39)	See Sheet No. B-22	
	ft. kips	kips	kips	kips	kips	kips	ft.	ft. kips	ft. kips	ft. kips			ft. kips	ft. kips	ft. kips	kips	kips
CROWN	0	0	0					0	0	0	0	0	+ 26.30	- 24.29	+2.01	2.78	0
1	0	+.0135	+.515	+.438	+0.966	+.966		- 0.28	- 0.28	-0.28	-2.28	-19.77	+ 26.02	- 24.07	+1.95	2.80	0.10
							-2.20										
2	0	+.1025	+.515	+.438	+1.055	+2.021		- 2.12	- 2.40	- 2.40	-19.55	-157.57	+ 23.90	-22.37	+1.53	3.10	0.35
							-1.98										
3	.05	+.2410	+.515	+.438	+1.194	+3.215		- 4.00	- 6.40	- 6.45	-52.55	-364.70	+ 19.85	-19.26	+0.59	3.70	0.52
							-1.61										
4	- 0.43	+.350	+.515	+.438	+1.303	+4.518		- 5.18	- 11.58	- 12.03	- 98.01	- 582.39	+ 14.27	-14.80	-0.53	4.50	0.50
							-1.15										
5	- 1.79	+.347	+.515	+.439	+1.301	+5.819		- 5.16	- 16.74	- 18.53	- 150.96	- 505.72	+ 7.77	- 9.30	-1.53	5.40	0.48
							-0.59										
6	-5.15	+.167	+.515	+.439	+1.121	+ 6.940		- 3.43	- 20.17	- 25.32	- 206.28	- 237.22	+ 0.98	- 3.19	-2.21	6.35	0.20
							0								-2.35	6.95	0.15
Top Dia.																	
7	-11.58	- .216	+.515	0	+0.299	+ 7.239		0	- 20.17	- 31.77	- 258.83	+ 297.66	- 5.47	+ 3.19	-2.28	7.10	0.10
							+0.59										
8	- 21.40	- .776	+.515	0	- 0.261	+ 6.978		+ 4.27	- 15.90	- 37.20	- 303.07	+1015.28	- 10.90	+ 9.30	-1.60	7.60	0.35
							+1.15										
9	-33.80	-1.420	+.515	0	- 0.905	+ 6.073		+ 8.03	- 7.87	- 41.07	- 334.60	+1783.42	- 14.77	+14.80	+0.03	7.90	0.45
							+1.61										
10	- 47.20	- 2.09	+.515	0	- 1.575	+ 4.498		+9.78	+ 1.91	- 45.29	- 368.98	+2560.72	- 18.99	+19.27	+0.28	8.15	0.40
							+1.98										
11	- 58.40	- 2.60	+.515	0	- 2.085	+ 2.403		+8.91	+ 10.82	- 47.58	- 387.63	+3124.30	- 21.28	+22.31	+1.04	8.30	0.35
							+2.20										
12	- 64.70	- 2.92	+.515	0	- 2.405	0		+5.29	+16.11	- 48.59	- 395.86	+3432.11	- 22.29	+24.07	+1.78	8.40	0.10
INVERT													- 22.29	24.29	+2.00	8.55	0
	TOTALS	- 8.81	+6.18	+2.63							-2578.60	+10406.11					

Algebraic Total Col. No. 28 = Buoyancy = 8.81

Buoyancy - Wt. Shell = Req'd Reaction

8.81 - 6.18 = 2.63

$$H_o = -\frac{\Sigma may}{\Sigma ay^2} = -\frac{+10406.11}{3747.38} = -2.776$$

$$M_o = -\frac{\Sigma ma}{\Sigma a} = -\frac{-2578.60}{98.04} = +26.30$$

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PHILADELPHIA, PA.

WORCESTER DIVERSION TUNNEL
16' DIAMETER - 18" LINING
TRIANGULAR WATER LOAD TO CROWN ON OUTSIDE
AND
TUNNEL WEIGHT EXCESS BUOYANCY REACTION

SHEET No. B-15

No.	24 ΣH Loads	27 ΣM_H	28 Vertical Water Load	28a Weight of Tunnel Shell	29 Vertical Buoyancy Reaction	30 Total Vertical Load	31 ΣV Loads	32 Moment Arms	33 M_r	34 ΣM_r	35 m	36 ma	37 may	38 $M_o + m$	39 $H_o y$	40 Moment	41 Thrust	42 Shear
Method	$(r+t)^2$(Coef.) on Sheet B-13 Column #24 $= \frac{81}{1000}$(Coef.)	$(r+t)^2(r+\frac{t}{2})$ x (Coef.) on Sheet B-13 Column #27 $= \frac{689}{1000}$(Coef.)	$(r+t)^2$(Coef.) on Sheet B-13 Column #28 $= \frac{81}{1000}$(Coef.)	$\frac{2\pi R t}{24} \cdot 150$ $= \frac{334}{1000}$	Uniform Distribution on Top $= \frac{1}{6} \times 3.919$	(#29)+(#28a)+(#29)	Σ(#30)	$(r+\frac{t}{2})$(Coef.) on Sheet B-13 Column #32 $= 8.5$(Coef.)	(#31)×(#32)	Σ(#33)	(#27)+(#34)	$a = \frac{(r+\frac{t}{2})}{t^3}$(Coef.) on Sheet B-9 Column #13 $= 26.7$(#35)	$y = (r+\frac{t}{2})$(Coef.) on Sheet B-9 Column #3 $= 8.5$(#3)(#36)	M_o - See Below $= 24.23$(#35)	$y = (r+\frac{t}{2})$(Coef.) on Sheet B-9 Column #3 $= 8.5(\frac{t}{3}) \times 2.51$	(#38)+(#39)	See Sheet No B-22	
	Kips	Ft. Kips	Kips	Kips	Kips	Kips	Kips	Ft	Ft Kips	Ft Kips	Ft Kips			Ft Kips	Ft. Kips	Ft Kips	Kips	Kips
Crown	0	0	0											+ 24.23	- 21.34	+ 2.89	2.51	0
1	+ .002	0	+ 0.012	+ 0.334	+ 0.653	+ .999	+ .999	- 2.14	- 0.27	- 0.27	- 0.27	- 7.21	- 60.71	+ 23.96	- 21.13	+ 2.83	2.58	+ .20
2	+ .040	0	+ 0.092	+ 0.334	+ 0.653	+ 1.079	+ 2.078	- 1.92	- 2.14	- 2.41	- 2.41	- 64.35	- 505.15	+ 21.82	- 19.70	+ 2.12	2.90	+ .45
3	+ .209	- 0.05	+ 0.217	+ 0.334	+ 0.653	+ 1.204	+ 3.282	- 1.56	- 3.99	- 6.40	- 6.45	- 172.22	- 1160.76	+ 17.78	- 16.92	+ 0.86	3.53	+ .58
4	+ .618	- 0.37	+ 0.315	+ 0.334	+ 0.653	+ 1.302	+ 4.584	- 1.11	- 5.12	- 11.52	- 11.89	- 317.46	- 1644.44	+ 12.34	- 13.00	- 0.66	4.42	+ .70
5	+ 1.37	- 1.56	+ 0.513	+ 0.334	+ 0.653	+ 1.300	+ 5.884	- 0.57	- 5.09	- 16.61	- 18.17	- 485.14	- 1581.56	+ 6.06	- 8.18	- 2.12	5.40	+ .62
6	+ 2.5	- 4.49	+ 0.150	+ 0.334	+ 0.654	+ 1.138	+ 7.022	0	- 3.35	- 19.96	- 24.45	- 652.82	- 724.63	- 0.22	- 2.79	- 3.01	6.50	+ .43
Hor. Dia.																- 3.25	7.00	0
7	+ 3.98	- 10.08	- 0.194	+ 0.334	0	+ 0.140	+ 7.162	+ 0.57	0	- 19.96	- 30.04	- 802.07	+ 890.30	- 5.81	+ 2.79	- 3.02	7.10	- .15
8	+ 5.70	- 18.63	- 0.700	+ 0.334	0	- 0.366	+ 6.796	+ 1.11	+ 4.08	- 15.88	- 34.51	- 921.42	+ 3003.83	- 10.28	+ 8.18	- 2.10	7.36	- .46
9	+ 7.35	- 29.54	- 1.296	+ 0.334	0	- 0.961	+ 5.835	+ 1.56	+ 7.54	- 8.34	- 37.88	- 1011.40	+ 5239.05	- 13.65	+ 13.00	- 0.65	7.50	- .58
10	+ 8.7	- 41.06	- 1.879	+ 0.334	0	- 1.545	+ 4.290	+ 1.92	+ 9.10	+ 0.76	- 40.30	- 1076.01	+ 7252.31	- 16.07	+ 16.92	+ 0.85	7.52	- .64
11	+ 9.8	- 50.87	- 2.347	+ 0.334	0	- 2.013	+ 2.277	+ 2.14	+ 8.24	+ 9.00	- 41.87	- 1117.93	+ 8775.75	- 17.64	+ 19.70	+ 2.06	7.55	- .40
12	+ 10.2	- 56.44	- 2.611	+ 0.334	0	- 2.277	0		+ 4.81	+ 13.87	- 42.57	- 1136.62	+ 9570.34	- 18.34	+ 21.13	+ 2.79	7.56	- .13
Invert		- 56.83							0	+ 13.87	- 42.96	—	—	- 18.73	+ 21.34	+ 2.85	7.61	0
	Totals		- 7.927	+ 4.008	+ 3.919													

Algebraic Sum of Col. No 28 = Buoyancy = 7.927

Buoyancy = Shell Wt. + Req'd Reaction

7.927 − 4.008 = 3.919

$M_x = \frac{.999}{2} \times \frac{2.14}{4} = .267$

$H_o = -\frac{\Sigma may}{\Sigma ay^2} = -\frac{29{,}054.33}{11{,}576.2} = -2.51$

$M_o = -\frac{\Sigma ma}{\Sigma a} = -\frac{-7764.65}{320.44} = +24.23$

−7,764.65 +29,054.33

(from Mom. Curve)

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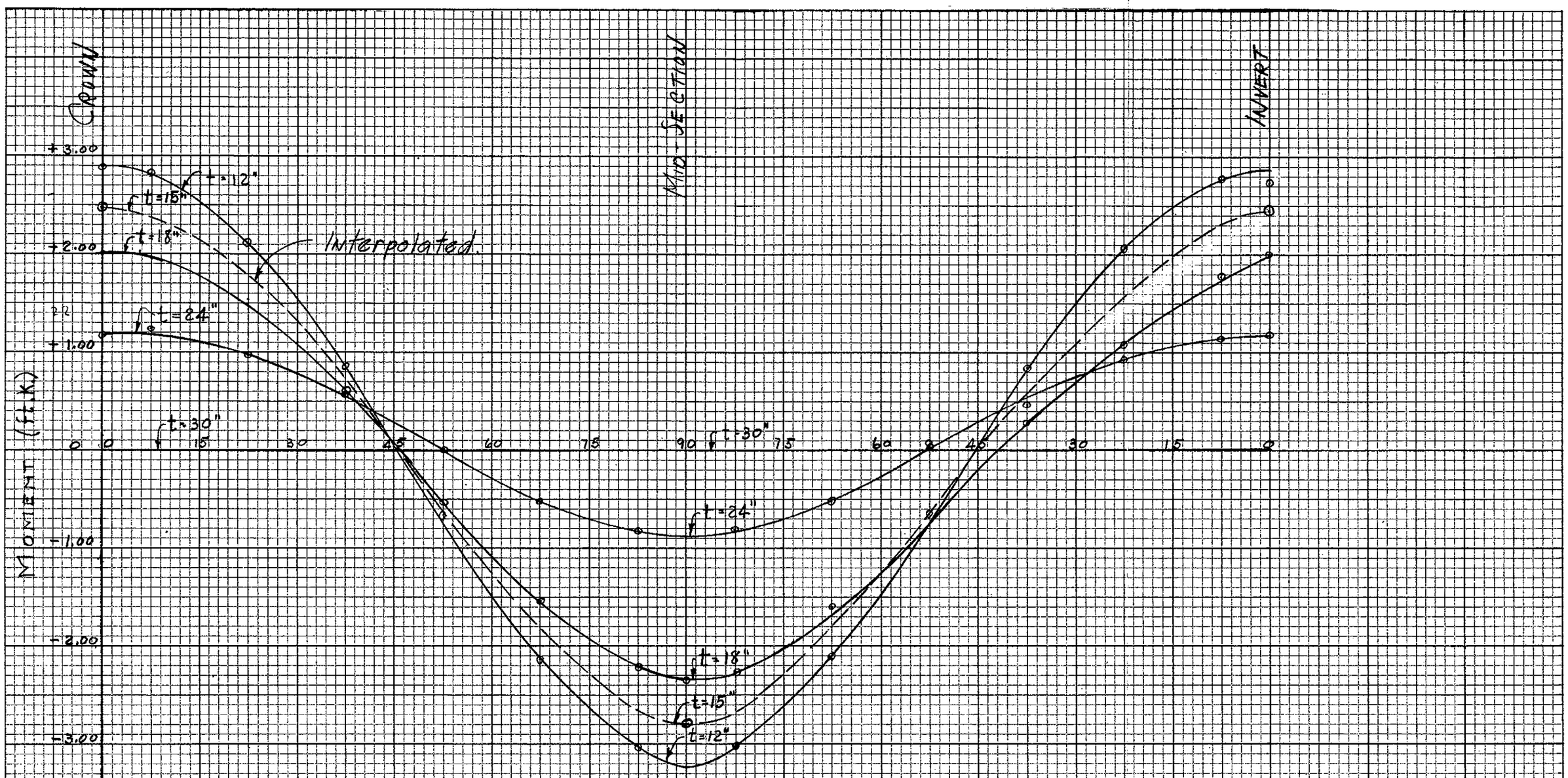
WORCESTER DIVERSION TUNNEL

16 ft DIAMETER − 12" LINING

TRIANGULAR WATER LOAD TO CROWN ON OUTSIDE AND TUNNEL WEIGHT + EXCESS BUOYANCY REACTION

SHEET No B-16



WORCESTER DIVERSION
16' DIA. TUNNEL
MOMENT DIAGRAMS FOR
2'-6" 2'-0" 1'-6" & 1'-0" LINING
Triangular Water Load to Crown Outside
And Buoyancy Reaction Distributed Around
The Shell.

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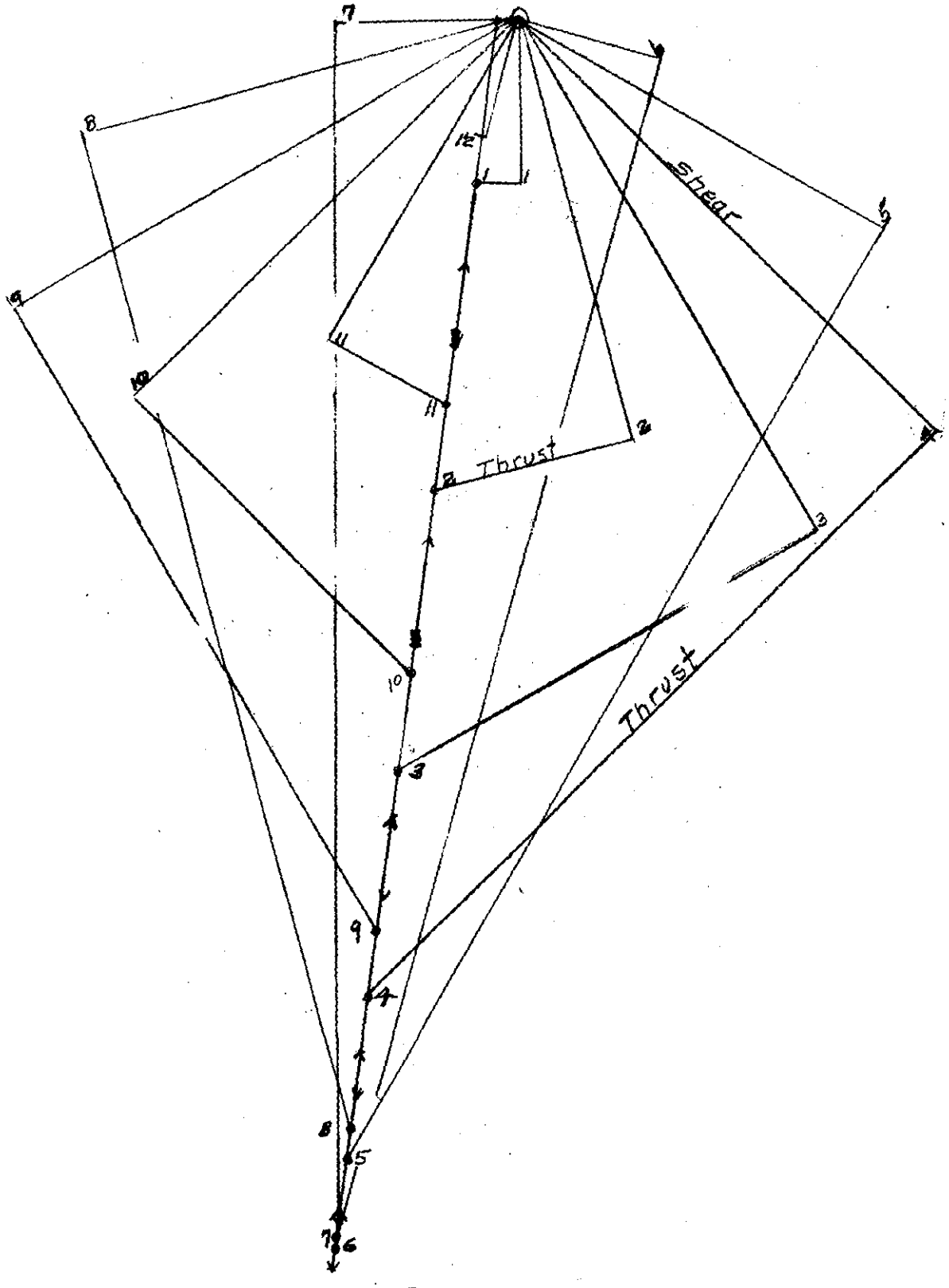
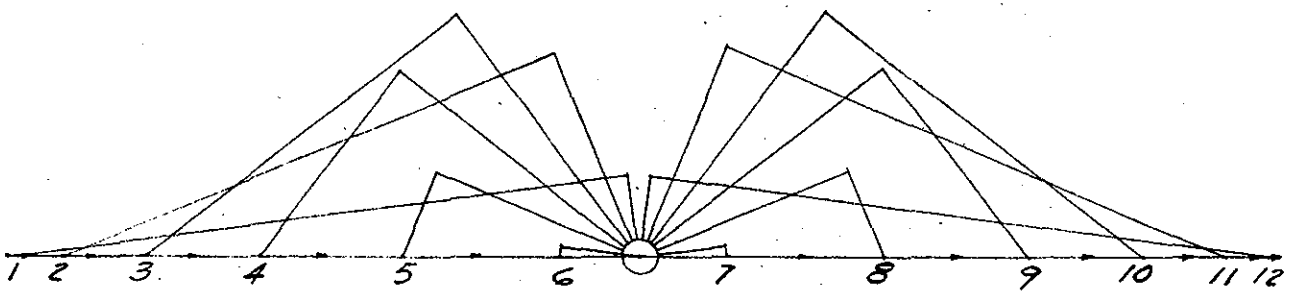
BARRINGTON, RHODE ISLAND
JUSTIN & COURTNEY
PHILADELPHIA, PA.

SHEET No. B-17



F.E.F
14C

THRUSTS & SHEARS
FORCE DIAGRAMS
Uniform Vertical Earth Load
Scale 1" = 0.60

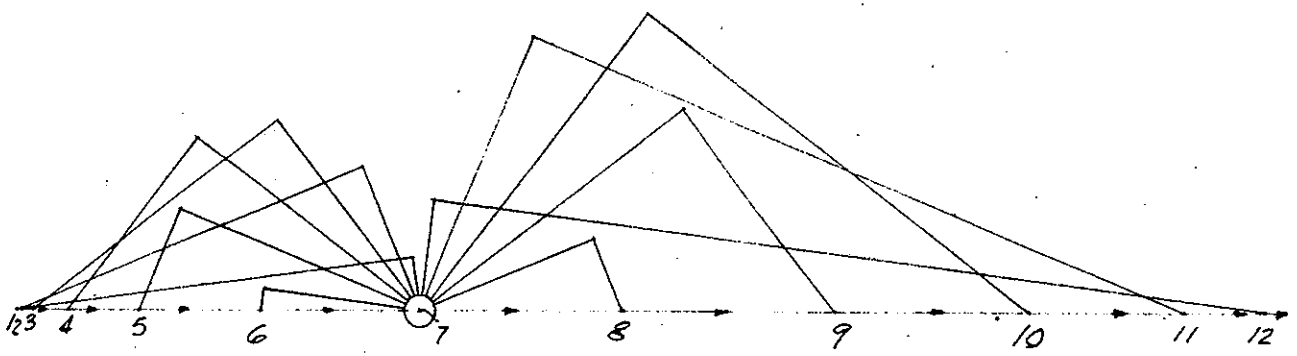


THRUSTS & SHEARS
FORCE DIAGRAMS
Uniform Horizontal Earth Load

SCALE: 1" = 0.30 UNITS
UNITS ARE COEFFICIENTS OF $w(r+\frac{t}{2})$

F.E.F.
J.+C.

B19



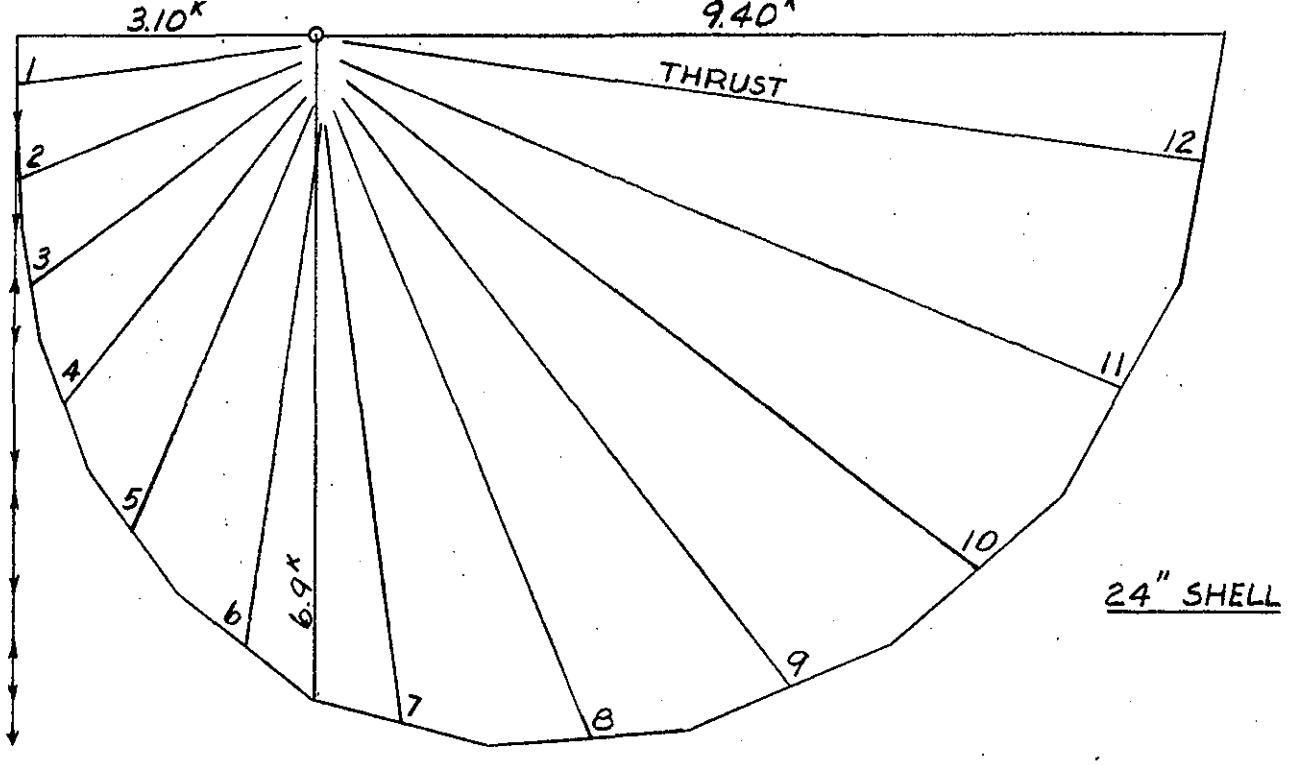
THRUSTS & SHEARS
FORCE DIAGRAMS
Triangular Horizontal Earth Load

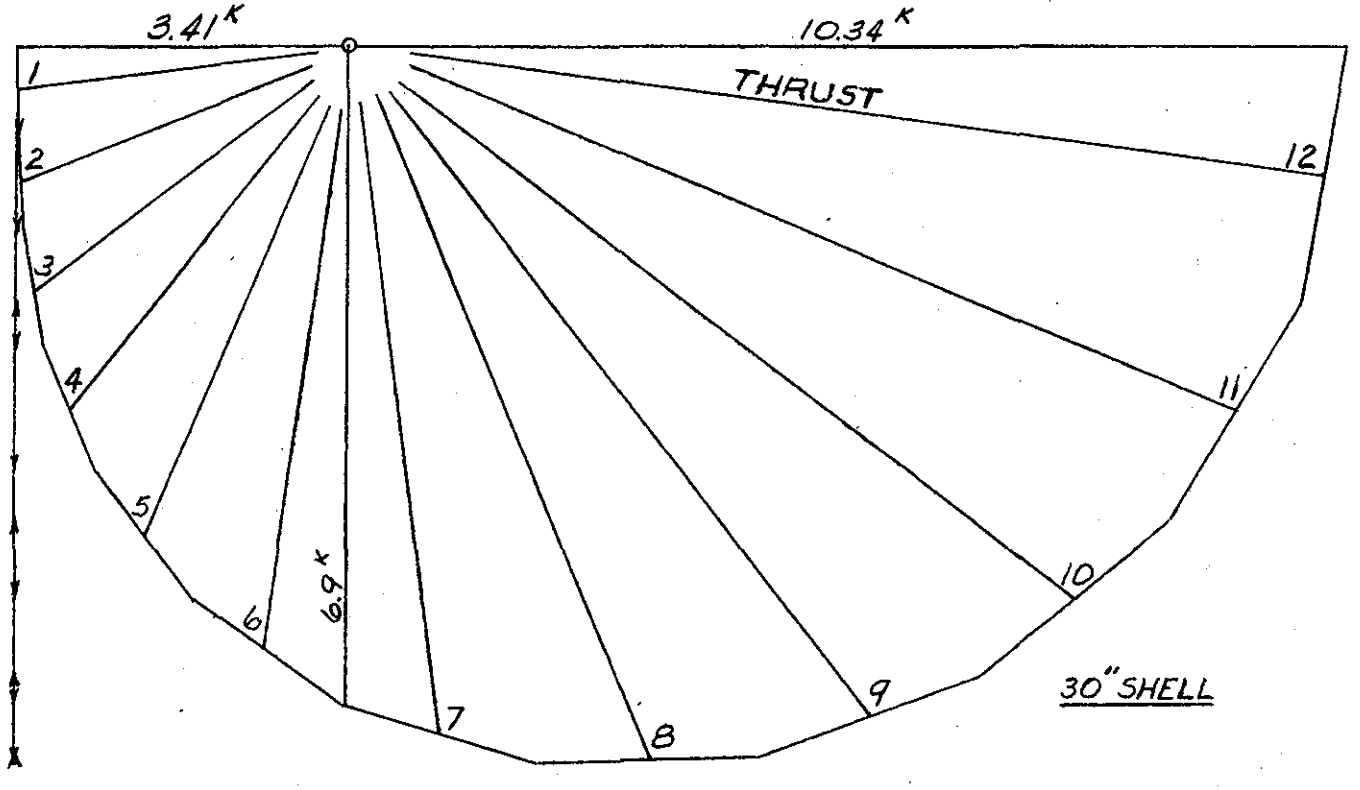
SCALE: 1" = 0.30 UNITS

UNITS ARE COEFFICIENTS OF $T(r+\frac{t}{2})^2$

F.E.F.
J.+C.

B20





WORCESTER DIVERSION

TUNNEL — 16 FT. DIAMETER

TRIANGULAR WATER LOAD TO CROWN ON OUTSIDE

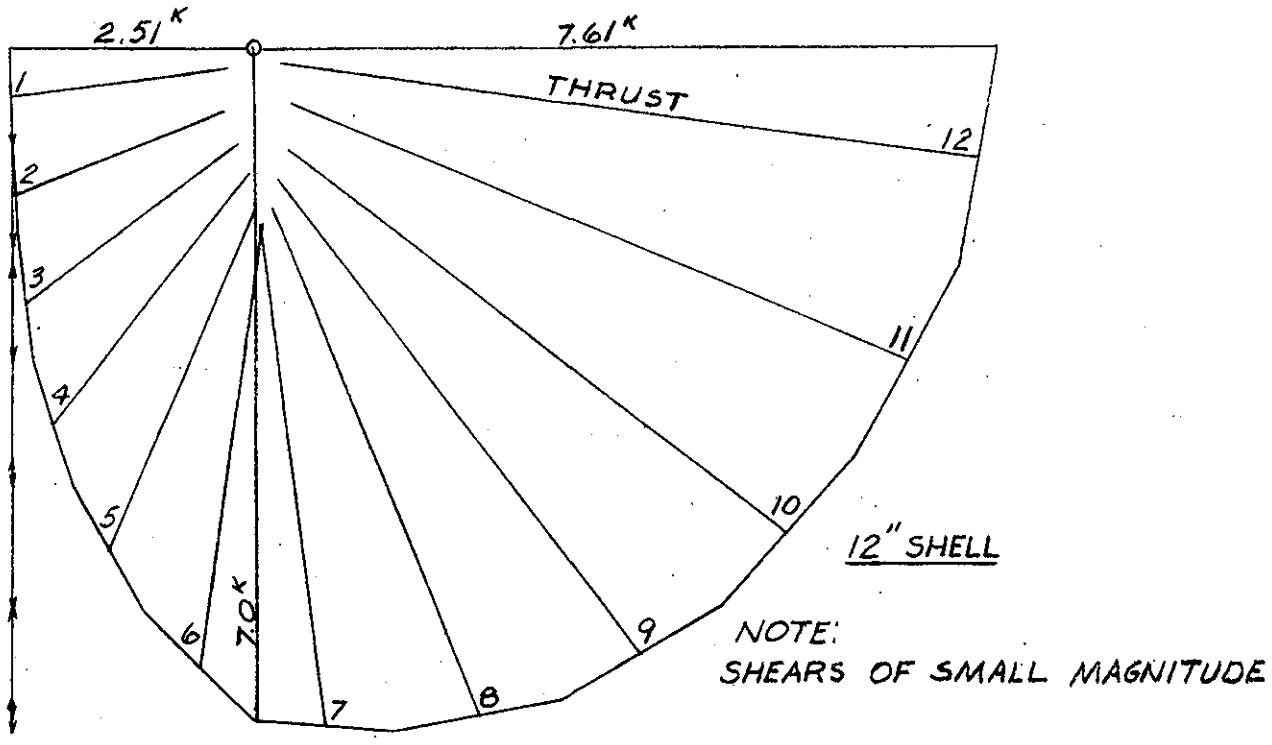
WITH

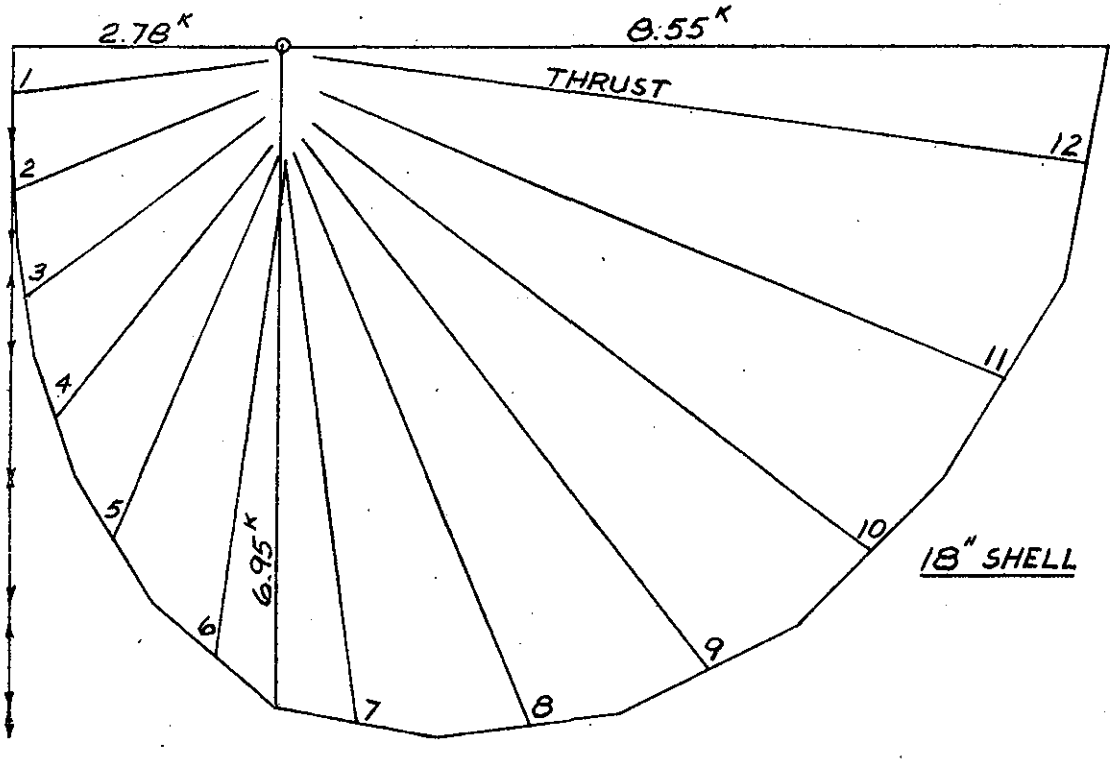
TUNNEL WEIGHT & EXCESS BOUYANCY REACTION

THRUSTS & SHEARS — FORCE DIAGRAMS

FRANK E. FAHLQUIST — JUSTIN & COURTNEY

JANUARY 1957 — SHEET NO. B-21





WORCESTER DIVERSION

TUNNEL — 16 FT. DIAMETER

TRIANGULAR WATER LOAD TO CROWN ON OUTSIDE

WITH

TUNNEL WEIGHT & EXCESS BOUYANCY REACTION

THRUSTS & SHEARS — FORCE DIAGRAMS

FRANK E. FAHLQUIST — JUSTIN & COURTNEY

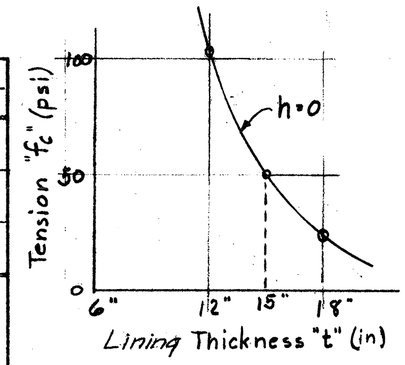
JANUARY 1957 — SHEET NO. B-22

CASE FOR h = 0' ; t = 1.0'

	CROWN		MID-SECTION		INVERT	
	M (ft.K)	N (KIPS)	M (ft.K)	N (KIPS)	M (ft.K)	N (KIPS)
TUNNEL SHELL & WATER BELOW CROWN	+2.89	2.51	-3.25	7.00	+2.85	7.61
WATER ABOVE CROWN $M = 0$; $N = \frac{wh(r+t)}{1000}$	0	0	0	0	0	0
TOTAL	2.89	2.51	3.25	7.00	2.85	7.61
DIRECT STRESS $f_N = 1000N \div 144t$	1000 × 2.51 ÷ 12×12 = 17#		1000 × 7.0 ÷ 12×12 48#		1000 × 7.61 ÷ 12×12 53#	
BENDING STRESS $f_M = 6000M \div 144t^2$	6000 × 2.89 ÷ 12×12 = - 120#		6000 × 3.25 ÷ 12×12 - 135#		6000 × 2.85 ÷ 12×12 - 119#	
COMBINED STRESS MAX. & MIN.	+197#	-103#	+183#	-87#	+172#	-66#

CASE FOR h = 0' ; t = 1.5'

	CROWN		MID-SECTION		INVERT	
	M (ft.K)	N (KIPS)	M (ft.K)	N (KIPS)	M (ft.K)	N (KIPS)
TUNNEL SHELL & WATER BELOW CROWN	+2.01	2.78	-2.35	6.95	+2.00	8.55
WATER ABOVE CROWN $M = 0$; $N = \frac{wh(r+t)}{1000}$	0	0	0	0	0	0
TOTAL	2.01	2.78	2.35	6.95	2.00	8.55
DIRECT STRESS $f_N = 1000N \div 144t$	1000 × 2.78 ÷ 12×18 = 13#		1000 × 6.95 ÷ 12×18 32#		1000 × 8.55 ÷ 12×18 40#	
BENDING STRESS $f_M = 6000M \div 144t^2$	6000 × 2.01 ÷ 18×18 = - 37#		6000 × 2.35 ÷ 18×18 - 44#		6000 × 2.00 ÷ 18×18 - 37#	
COMBINED STRESS MAX. & MIN.	+ 50#	-24#	+76#	-12#	+77#	+ 3#



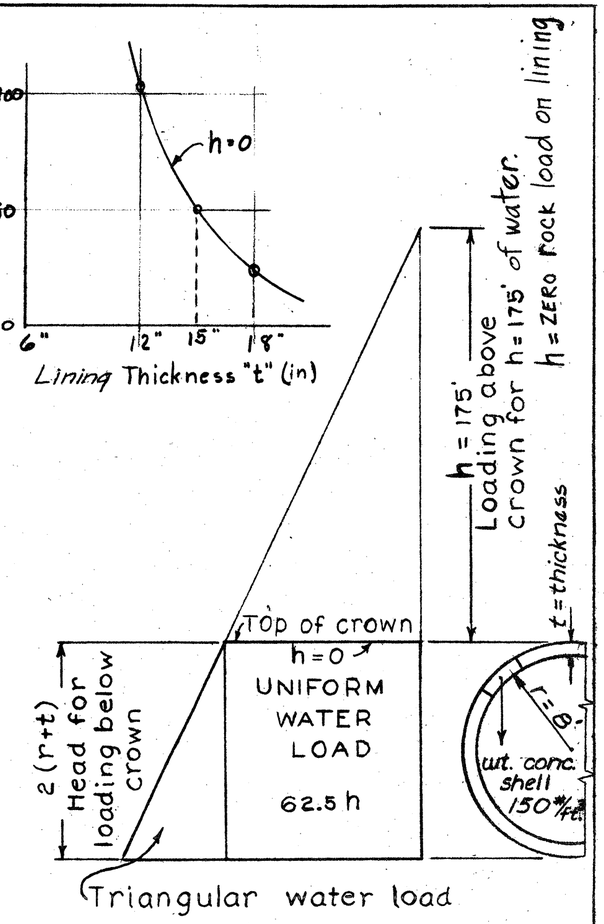
CASE FOR h = 0' ; t = 1.25

	CROWN		MID-SECTION		INVERT	
	M (ft.K)	N (KIPS)	M (ft.K)	N (KIPS)	M (ft.K)	N (KIPS)
TUNNEL SHELL & WATER BELOW CROWN	+2.45	2.64	-2.80	6.98	+2.45	8.08
WATER ABOVE CROWN $M = 0$; $N = \frac{wh(r+t)}{1000}$	0	0	0	0	0	0
TOTAL	2.45	2.64	2.80	6.98	2.45	8.08
DIRECT STRESS $f_N = 1000N \div 144t$	1000 × 2.64 ÷ 12×15 = 15#		1000 × 6.98 ÷ 12×15 39#		1000 × 8.08 ÷ 12×15 45#	
BENDING STRESS $f_M = 6000M \div 144t^2$	6000 × 2.45 ÷ 15×15 = -65#		6000 × 2.80 ÷ 15×15 -74#		6000 × 2.45 ÷ 15×15 - 65#	
COMBINED STRESS MAX. & MIN.	+80#	-50#	+113#	-35#	+110#	-20#

CASE FOR h = 175' ; t = 1.25'

	CROWN		MID-SECTION		INVERT	
	M (ft.K)	N (KIPS)	M (ft.K)	N (KIPS)	M (ft.K)	N (KIPS)
TUNNEL SHELL & WATER BELOW CROWN	+2.45	2.65	-2.80	6.98	+2.45	8.08
WATER ABOVE CROWN $M = 0$; $N = \frac{wh(r+t)}{1000}$	0	(62.5×1.62)* 101.25	0	(62.5×1.62)* 101.25	0	(62.5×1.62)* 101.25
TOTAL	2.45	109.90	2.80	108.23	2.45	109.33
DIRECT STRESS $f_N = 1000N \div 144t$	1000 × 109.90 ÷ 12×15 578#		1000 × 108.23 ÷ 12×15 608#		1000 × 109.33 ÷ 12×15 607#	
BENDING STRESS $f_M = 6000M \div 144t^2$	6000 × 2.45 ÷ 15×15 65#		6000 × 2.80 ÷ 15×15 75#		6000 × 2.45 ÷ 15×15 65#	
COMBINED STRESS MAX. & MIN.	+643#	+513#	+683#	+533#	+672#	+542#

* $h(r+t) \div 1000 = \frac{175 \times 9.25}{1000} = 1.62$



FRANK E. FAHLQUIST
BARRINGTON, RHODE ISLAND
JUSTIN & COURTNEY
PHILADELPHIA, PENNA.

WORCESTER DIVERSION
DESIGN OF
16 FOOT DIAMETER TUNNEL IN ROCK
FOR UNREINFORCED CONCRETE LININGS OF
1'-0", 1'-3" AND 1'-6"

JANUARY 1957 SHEET No. B-23

26" REINFORCED CONCRETE TUNNEL IN EARTH

EQUATIONS

LOADING	Data From Sheet	Column	General	Substitutions	Constants	Crown Moment C_M	Crown Moment M(ft.k)	Crown Thrust C_N	Crown Thrust N(kips)	Horz. Mid. Section Moment C_M	Horz. Mid. Section Moment M(ft.k)	Horz. Mid. Section Thrust C_N	Horz. Mid. Section Thrust N(kips)	Invert Moment C_M	Invert Moment M(ft.k)	Invert Thrust C_N	Invert Thrust N(kips)
			$r=8'$ $t=2.17'$ $h=65$	$(r+t)=10.17$ $(r+\frac{t}{2})=9.08$													
Tria. Water, Shell Wt. and Buoyancy Reaction	B-14	41	Absolute Values of Thrust – Estimated			—	+ 0.8	—	+ 3.2	—	- 0.6	—	+ 6.9	—	+ 0.8	—	+ 9.6
	B-17	—	Absolute Values of Moment – Estimated														
Uniform Water Above The Crown	—	—	$N=\frac{h(r+t)}{1000}C_N$	$\frac{65\times10.17}{1000}C_N$	$0.66C_N$			+ 62.5	+ 41.3			+ 62.5	+ 41.3			+ 62.5	+ 41.3
	—	—	$M=\frac{h(r+t)(r+t_2)}{1000}C_M$	$\frac{65\times10.17\times9.08}{1000}C_M$	$6.00C_M$	0	0			0	0			0	0		
Uniform Vertical Submerged Earth Load	B-10	41	$N=PC_N$	$115.68C_N$	$115.68C_N$			+0.009	+ 1.0			+ 0.50	+ 57.8			-0.009	- 1.0
	B-10	40	$M=P(r+\frac{t}{2})C_M$	$115.68\times9.08\times C_M$	$1050.41C_M$	+0.119	+125.0			-0.121	-127.1			+0.115	+120.8		
Uniform Horizontal Submerged Earth Load	B-11	41	$N=w(r+t)C_N$	$2.844\times10.17\times C_N$	$28.92C_N$			+0.997	+ 28.8			0	0			+1.003	+ 29.0
	B-11	40	$M=w(r+t)(r+\frac{t}{2})C_M$	$2.844\times10.17\times9.08\times C_M$	$262.62C_M$	-0.249	- 65.4			+0.243	+ 63.8			-0.255	- 67.0		
Triangular Horizontal Submerged Earth Load	B-12	41	$N=T(r+t)^2C_N$	$.0438\times10.17^2\times C_N$	$4.53C_N$			+0.64	+ 2.9			0	0			+1.36	+ 6.2
	B-12	40	$M=T(r+t)^2(r+\frac{t}{2})C_M$	$.0438\times10.17^2\times9.08\times C_M$	$41.09C_M$	-0.224	- 9.2			+0.246	+ 10.1			-0.275	- 11.3		
Total							+ 51.2		+ 77.2		- 53.8		+106.0		+ 43.3		+ 85.1
Maximum Concrete Fiber Stress	Direct		$f_a=\frac{1000}{A}N$	—	—	$f_a=\frac{1000}{314}N=\frac{77,200}{314}=$			246 Lbs/Sq.In.	$f_a=\frac{1000}{320}N=\frac{106,000}{320}=$			331 Lbs/Sq.In.	$f_a=\frac{1000}{314}N=\frac{85,100}{314}=$			271 Lbs/Sq.In.
	Bending		$f_b=\frac{12000}{S}M$	—	—	$f_b=\frac{12000}{1360}M=\frac{12000}{1360}51.2=$		451.2	Do.	$f_b=\frac{12000}{1400}M=\frac{12000}{1400}53.8=$		462	Do.	$f_b=\frac{12000}{1360}M=\frac{12000}{1360}43.3=$		382	Do.
	Total			f_a+f_b				698	Do.			793	Do.			653	Do.
ACI (1956) Building Code	Stress ÷ Allowable = $f_a \div F_a$					$\frac{f_a}{F_a}=246\div550=$		.447		$\frac{f_a}{F_a}=331\div581=$		.570		$\frac{f_a}{F_a}=271\div550=$		.493	
	Stress ÷ Allowable = $f_b \div F_b$					$\frac{f_b}{F_b}=451\div1050=$		.430		$\frac{f_b}{F_b}=462\div1050=$		.440		$\frac{f_b}{F_b}=382\div1050=$		.364	
	Total					(#5@18"o.c.)		.877		(#6@6"o.c.)		1.010		(#5@18"o.c.)		.857	

34" UNREINFORCED CONCRETE TUNNEL IN EARTH

EQUATIONS

LOADING	Data From Sheet	Column	General	Substitutions	Constants	Crown Moment C_M	Crown Moment M(ft.k)	Crown Thrust C_N	Crown Thrust N(kips)	Horz. Mid. Section Moment C_M	Horz. Mid. Section Moment M(ft.k)	Horz. Mid. Section Thrust C_N	Horz. Mid. Section Thrust N(kips)	Invert Moment C_M	Invert Moment M(ft.k)	Invert Thrust C_N	Invert Thrust N(kips)
			$r=8'$ $t=2.83$ $h=65$	$(r+t)=10.83$ $(r+\frac{t}{2})=9.42$													
Tria. Water, Shell Wt. and Buoyancy Reaction	B-14	41	$N=\frac{(r+\frac{t}{2})t}{1000}C_N$	$\frac{10.83^2}{1000}C_N$	$0.12C_N$			+ 31.0	+3.4			+62.7	+ 7.4			+94.0	+11.0
	B-17	—	Absolute Values of Moment – Estimated			—	0			—	0			—	0		
Uniform Water Above The Crown	—	—	$N=\frac{h(r+t)}{1000}C_N$	$\frac{65\times10.83}{1000}C_N$	$0.71C_N$			+ 62.5	+44.0			+62.5	+44.0			+62.5	+44.0
	—	—	$M=\frac{h(r+\frac{t}{2})(r+\frac{t}{2})}{1000}C_M$	$\frac{65\times10.83\times9.42}{1000}C_M$	$6.63C_M$	0	0			0	0			0	0		
Uniform Vertical Earth Load	B-10	41	$N=PC_N$	$123.19\times C_N$	$123.19C_N$			+0.009	+ 1.1			+0.50	+ 61.5			-0.009	- 1.1
	B-10	40	$M=P(r+\frac{t}{2})C_M$	$123.19\times9.42\times C_M$	$1160.46C_M$	+0.119	+ 138.1			-0.121	- 140.4			+0.115	+133.5		
Uniform Horizontal Earth Load	B-11	41	$N=w(r+t)C_N$	$2.844\times10.83\times C_N$	$30.76C_N$			+0.997	+ 30.7			0	0			+1.003	+ 30.8
	B-11	40	$M=w(r+t)(r+\frac{t}{2})C_M$	$2.844\times10.83\times9.42\times C_M$	$289.73C_M$	-0.249	- 72.1			+0.243	+ 70.4			-0.255	- 73.9		
Triangular Horizontal Earth Load	B-12	41	$N=T(r+t)^2C_N$	$.0438\times10.83^2\times C_N$	$5.13C_N$			+0.64	+ 3.3			0	0			+1.36	+ 7.0
	B-12	40	$M=T(r+t)^2(r+\frac{t}{2})C_M$	$.0438\times10.83^2\times9.42\times C_M$	$48.34C_M$	-0.224	- 10.8			+0.246	+ 11.9			-0.275	- 13.3		
Total							+ 55.2		+ 82.7		- 58.1		+112.9		+ 46.3		+ 91.7
Maximum Concrete Fiber Stress	Direct		$f_a=\frac{1000}{A}N$	$\frac{1000}{12\times34}N$	$2.45N$			202.6	Lbs/Sq.In.			276.6	Lbs/Sq.In.			224.7	Lbs/Sq.In.
	Bending		$f_b=\frac{6000}{d^2}M$	$\frac{6000}{34^2}M$	$5.20M$			287.0	Do.			302.1	Do.			240.8	Do.
Combined Concrete Fiber Stress			Maximum	$f_c=f_a+f_b$				489.6	Do.			578.7	Do.			465.5	Do.
			Minimum	$f_c=f_a-f_b$				−84.4	Do.			−25.5	Do.			−16.1	Do.

Design of Reinforcing Steel for Tunnel Shell 26" Thick

Crown and Invert

Use #5 @ 18" o.c. Ea Way, Outside Face

$p_g = \frac{A_s}{A_g} = \frac{.21}{12\times26} = .00067$ $\quad g = \frac{26-4}{26} = .85$

$(n-1)\,p_g = 9\times.00067 = .006$

* (Table No. 27) $D = 6.0$

Equivalent Area $A = 12\times26 + 9\times.21 = 314''$

* Section Modulus $S = \frac{At}{D} = \frac{314\times26}{6} = 1360$

Allowable Concrete Stress - Axial (A.C.I. Code)

$F_a = .8\,(0.225 f'_c + f_s p_g)$

$F_a = .8\times.225\times3000 + .8\times18000\times.00067$

$F_a = 550$ #/□"

Allowable Concrete Stress - Bending (Exposure "A")

$F_b = .35 f'_c = .35\times3000 = 1050$ #/□"

Horz. Mid. Section

Use #6 @ 6" o.c. Circumferential, Inside Face

#5 @ 18" o.c. Longitudinal, Inside Face

$p_g = \frac{A_s}{A_g} = \frac{.88}{12\times26} = .00282$ $\quad g = .85$

$(n-1)\,p_g = 9\times.00282 = .0254$

$D = 5.95$

$A = 12\times26 + 9\times.88 = 320$ □"

$S = \frac{At}{D} = \frac{320\times26}{5.95} = 1400$

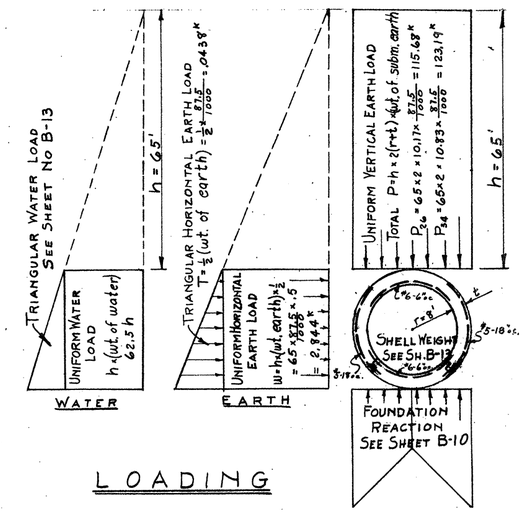
$F_a = .8\times.225\times3000 + .8\times18000\times.00282 = 581$ #/□"

$F_b = 1050$ #/□"

* Table No 27 in Reinf. Conc. Design Handbook of A.C.I.

Section Modulus $S = \frac{I}{C}$ substitute factors from equations $I = AR^2$ and $D = \frac{t^2}{2R}$ and $C = \frac{t}{2}$

$$S = \frac{I}{C} = \frac{A\frac{t^2}{2D}}{\frac{t}{2}} = \frac{At}{D}$$



LOADING

WORCESTER DIVERSION TUNNEL

Design With 65' Earth & Ground Water Load

26" Shell - Reinforced Concrete

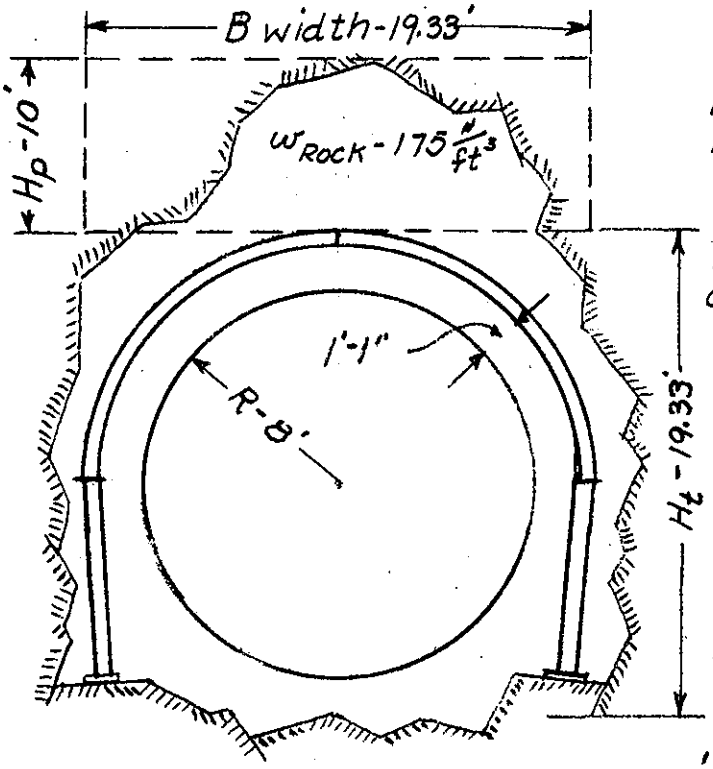
34" Shell - Unreinforced Concrete

Frank E. Fahlquist
Barrington, Rhode Island.

Justin & Courtney
Philadelphia, Penna.

January 1957

Sheet No. B-24



Reference "Rock Tunneling with Steel Supports", by Proctor & White.

Assumed rock conditions — fractured, blocky and seamy phyllite and schist. Steeply bedded at right angles to tunnel.

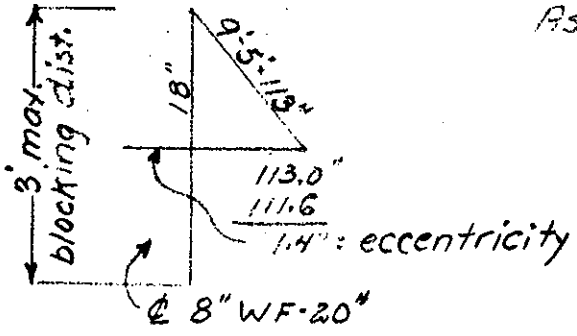
Rock load (height of fall out) P. 91

$H_p = 0.25(B+H_t)$
$= 0.25(19.33+19.33)$
$= 9.7'$ Use 10'

Assume rib spacing of 4.0'.
∴ Load per rib per foot of tunnel width
$= 10' \times 175^{\#} \times 4' = 7000^{\#}$

Refer to Table 1, p.238. For B width of 20' and 46" block spacing, an 8" I beam @ 18.4# has capacity of 6950#, per foot of tunnel width at a stress equal to 24,000 #.

Design For 18,000 # Stress



Assume 3' blocking distance.

$113^2 = 12769$
$18^2 = 324$
$111.6^2 = 12445$

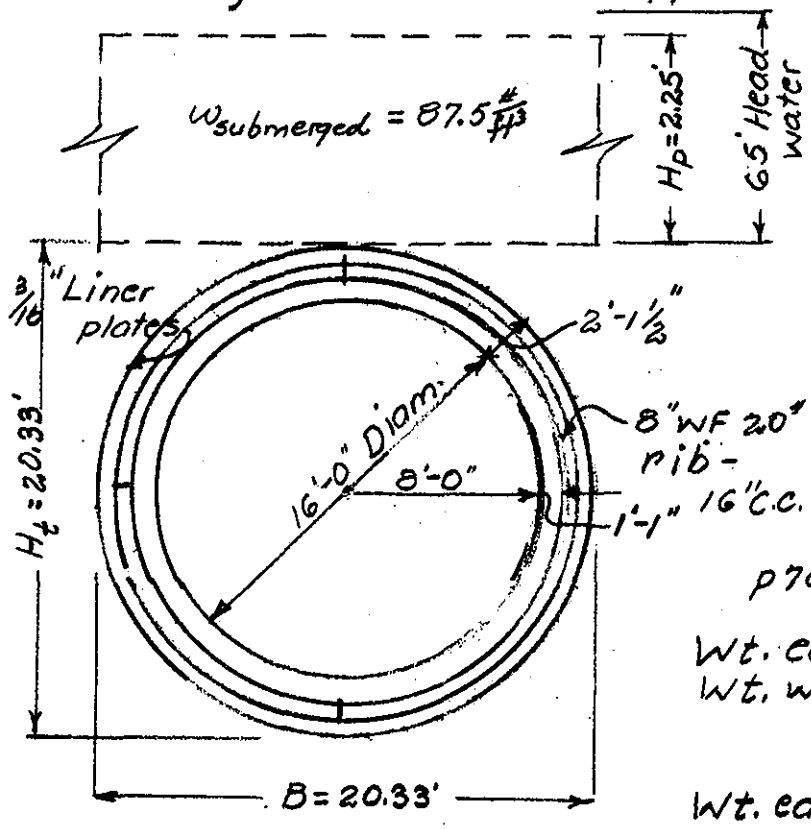
$$\text{Stress in rib} = \frac{\text{Thrust}}{\text{Area}} + \frac{M}{\text{Sec. Mod.}}$$
$$= \frac{7^K \times 9.67}{5.55} + \frac{67500(1.4")}{17}$$
$$= 12200 + 5550 = 17750^{\#}$$

Use 8" WF 20# ribs with blocking dist. of 3'-0", Maximum. Make ribs same radius for both earth and rock tunnel.

For post: Load $= 7^K \times 9.67 = 68^K$. $\frac{l}{R} = \frac{12 \times 8}{1.2} = 80$ $f_s = 13{,}300^{\#}$
Capacity of 8" WF 20# $= 13{,}300^{\#} \times 5.55 = 73^K$.

OF CLIENT Worcester Diversion - Earth Tunnel.

Design of Steel Rib Support.



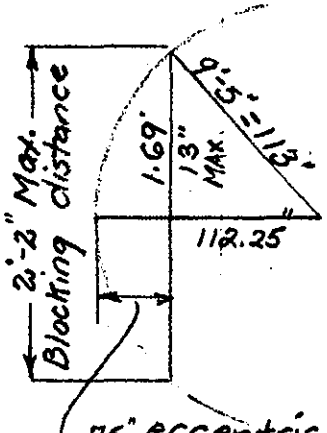
Reference: "Rock Tunneling with Steel Supports" by Proctor & White.

p70. $H_p = .54(B + H_t) = 22.5'$

Wt. earth = 22.5' × 87.5# = 1960#
Wt. water = 6.5' × 62.5# = 4040#
Total = 6000#

Wt. earth & water per rib = 1.33 × 6^k = 8^k

Assume 2'-2" blocking distance on ribs for liner plate support.



$113^2 = 12769$
$13^2 = 169$
$112.25^2 = 12{,}600$

Assume 8" WF 20# rib
Gross area = 5.88 □"
Hole 3/8 × 7/8 = .33 □"
5.55 □"

$$\text{Stress in rib} = \frac{\text{Thrust}}{\text{Net Area } I} + \frac{\text{Mom.}}{\text{Sec. Mod. } I}$$

$$= \frac{8000(10.17)}{5.55} + \frac{81500 \times .75''}{17}$$

$$= 14{,}650^{\#} + 3580^{\#} =$$

$$= 18{,}200^{\#}$$

Earth tunnel open for considerable time before placing concrete lining,

∴ Under above loading, ribs would be stressed to about 18,000#

Also - grout packing will be placed on exterior of liner plates. This will produce zero blocking space for overburden.

CLIENT U.S. Army Engineers

Worcester Diversion

Control Dam ~ Stability Analysis

Case III Headwater El. 497.0, Full Uplift
Tailwater El. 489.5, Full Uplift

Resultant Location - Moments about A

		Force Horiz.	Force Vert.	Arm	Mom
Concrete Wall			8.25^k	3.95'	32.6$^{'k}$
" Cutoff	(1.5+2.5)/2 x 5 x .15		1.5	1.02	1.53
" Slab	4 x 15 x .15		9.0	7.5	67.5
Tailwater	.0625 x 5 x 5 Assumed 4' on Dam.		1.56	12.5	19.5
Concrete Apron	.09 x 2 x 4 (Submerged)		.72	17.0	12.24
Uplift	.0625 x 16.5 x 15/2		-7.71	5.0	-38.5
	.0625 x 9 x 15/2		-4.22	10.0	-42.2
T.W. Pressure	.0625 x 9²/2	-2.53^k		3.0	-7.6
H.W. "	.0625 x 16.5²/2	8.5		5.3	45.0
" "	.0625 x 5²/2	-.78		13.16	-10.25
		$\Sigma H = 5.19^k$	$\Sigma V = 9.1^k$		$\Sigma M = 87.52'^k$

79.82 8.8 8.8 1.3 79.82

$$\frac{\Sigma M}{\Sigma V} = \frac{(87.52)}{9.1} = (9.6)' \text{ From A}, \quad a = (9.6) - \frac{15}{2} = (2.1)$$

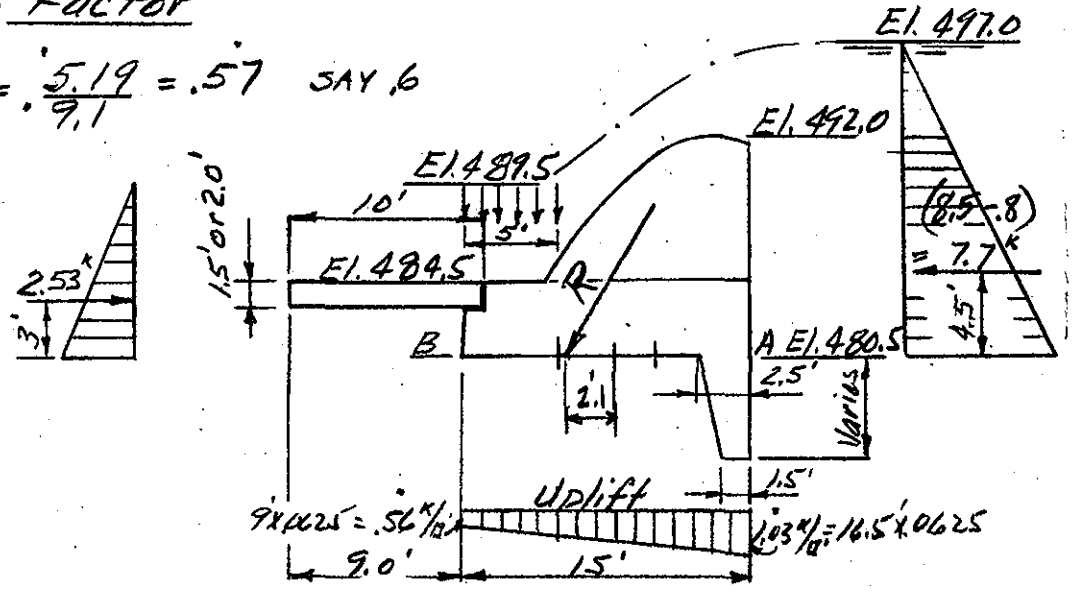
Soil Pressure

1.3

$$\frac{P}{A} \pm \frac{Pa}{S} = \frac{9.1}{15}\left(1 \pm \frac{6 \times (2.1)}{15}\right) = 1.1^k/\square' \text{ at B} \quad 0.93$$
$$0.096^k/\square' \text{ at A} \quad 0.29$$

Sliding Factor

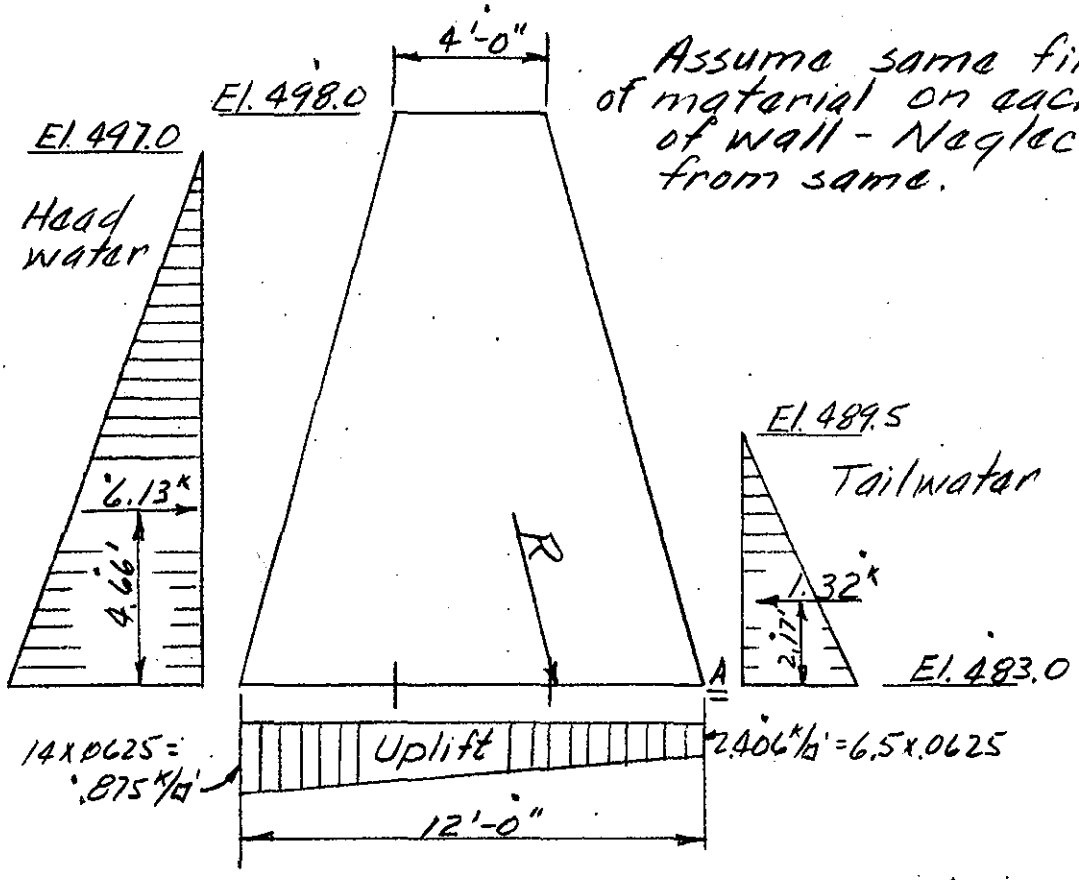
$$\frac{\Sigma H}{\Sigma V} = \frac{5.19}{9.1} = .57 \quad \text{SAY } .6$$



CLIENT U.S. Army Engineers

T. Worcester Diversion Control Dam ~ Retaining Wall

Assume same fill height of material on each side of wall - Neglect forces from same.



.97
83
14
4.66

Moments about A		Forces Vert.	Forces Horiz	Arm	Mom
Concrete -	4 x 1.5 x 1.5	9.0^k		6.0'	54.0 ^'k
	4 x 1.5 x 1.5	9.0		6.0'	54.0
H.W. Thrust	.0625 x 14²/2		-6.13^k	4.66	-28.6
T.W. Thrust	.0625 x 6.5²/2		+1.32	2.17	2.86
Uplift	.875 x 12/2	-5.25		8.0	-42.0
	.406 x 12/2	-2.44		4.0	-9.76
H.W. Wt.	.0625 x 14 x 3.73/2	1.63		10.49	17.1
T.W. Wt.	.0625 x 6.5 x 1.73/2	.35		.57	.2
		ΣV 12.29^k	ΣH 4.81^k		ΣM 47.8 ^'k

$\frac{\Sigma M}{\Sigma V} \frac{47.8}{12.29} = 3.9'$ From A, $a = \frac{12}{2} - 3.9 = 2.1'$

Sliding Factor

$\frac{\Sigma H}{\Sigma V} \frac{4.81}{12.29} = .39$

Soil Pressure

$\frac{P}{A} \pm \frac{Pa}{S} = \frac{12.29}{12}\left(1 \pm \frac{2.1 \times 6}{12}\right) = 2.07$ k/□' at A
$.03T$ k/□' Upstream

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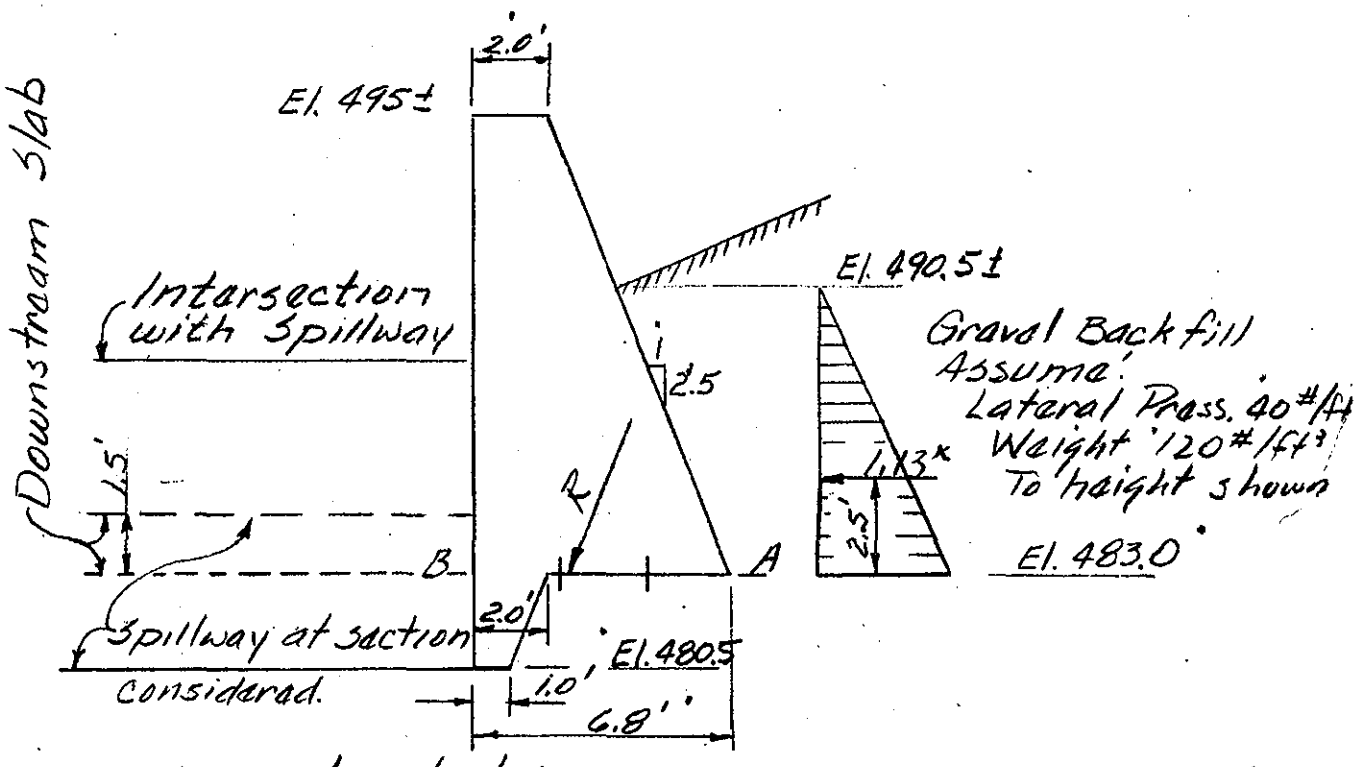
SHEET NO. B-29 OF
DATE 2/21/57
COMP. BY J.J.W.
CHECKED BY E.M.L.

OF CLIENT U.S. Army Engineers
CT Worcester Diversion
Control Dam ~ Retaining Wall



Moments about A		Force Vert	Force Horiz.	Arm	Mom
Concrete	2 x 12 x .15	3.6K		5.8'	20.9'K
	12 x 4.8/2 x .15	4.42		3.2'	14.1
Cutoff	1 x 2.5 x .15	.37		6.3'	2.3
	1 x 2.5 x .15/2	.19		5.46	1.03
Earth	12 x 7.5 x 3/2	1.35		1.0	1.35
	12 x 1.5 x 3/2	.27		1.0	.27
Lateral Press.	.04 x 7.5²/2		1.13K	2.5	2.82
		ΣV = 10.2K	ΣH = 1.13K		42.77'K

$\frac{\Sigma M}{\Sigma V} = \frac{42.77'^K}{10.2^K} = 4.2'$ From A $\quad e = \frac{6.8}{2} - 4.2 = .8'$

Soil Pressure

$\frac{P}{A} \pm \frac{Pe}{S} = \frac{10.2}{6.8}\left(1 + \frac{.8 \times 6}{6.8}\right)$

$= 1.6$ K/□' at ~~A~~ B 2.56

$= 1.4$ K/□' at ~~B~~ A 0.44

Sliding Factor

$\frac{\Sigma H}{\Sigma V} = \frac{1.13}{10.2} = .1.1$ say .15