US Army Corps of Engineers

HYDRAULICS LABORATORY

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SCOUR PROTECTION FOR DAM NO. 7 MONONGAHELA RIVER, PENNSYLVANIA

Hydraulic Model Investigation

by

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Lock and Dam No. 7, Monongahela River is a navigation project located 85 miles from the mouth of the river near the Pennsylvania-West Virginia state line. The dam is an uncontrolled fixed-crest type with a short horizontal spillway apron for energy dissipation. Model tests were conducted on a 1:25-scale section model of the dam, spillway apron, and a section of the river wall of the lock. The purpose of the model study was to determine sizing and configuration of materials necessary to protect the area immediately downstream from the spillway apron from additional scour.

A scour protection plan consisting of large grout-filled fabric bags placed downstream of the spillway apron and along the river wall of the lock and a 3-ft-high sloping end sill placed on the existing spillway apron was developed. This plan provided scour protection for all flow conditions anticipated at the project.

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PREFACE

The model investigation reported herein was authorized by the Office, Chief of Engineers (OCE), US Army, on 19 December 1983, at the request of the US Army Engineer District, Pittsburgh (ORP).

The studies were conducted by personnel of the Hydraulics Laboratory (HL), US Army Engineer Waterways Experiment Station (WES), during the period October 1985 to October 1986 under the direction of Mr. F. A. Herrmann, Jr., Chief, Hydraulics Laboratory, and under the general supervision of Mr. J. L. Grace, Jr., Chief, Hydraulic Structures Division. The tests were conducted by Messrs. T. E. Murphy, Jr., and J. E. Hite, Jr., Locks and Conduits Branch, under the supervision of Mr. J. F. George, Chief, Locks and Conduits Branch. This report was prepared by Mr. Hite.

The model was constructed by Mr. Bobby Blackwell under the supervision of Mr. Sid Leist, Engineering and Construction Services Division.

Messrs. Bruce McCartney of OCE; Laszlo Varga of the US Army Engineer Division, Ohio River; Ed Kovanic, Robert W. Schmitt, Joe Coletti, Ray Povirk, and Walt Leput, ORP, visited WES during the course of the model study to observe model operation and correlate results with design studies.

COL Dwayne G. Lee, CE, is the Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.2831685	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609344	kilometres
pounds (mass)	0.4535924	kilograms

SCOUR PROTECTION FOR DAM NO. 7
MONONGAHELA RIVER, PENNSYLVANIA

Hydraulic Model Investigation

PART I: INTRODUCTION

Background

1. Lock and Dam No. 7, Monongahela River is located 85 miles* from the mouth of the river near the Pennsylvania-West Virginia state line (Figure 1). The overall length of the dam from the river wall of the lock to the abutment is 610 ft. It is an unreinforced concrete dam with a shear key channeled into the foundation near the upstream face as shown in Figure 2.

2. The dam was constructed between 1923 and 1926 and is an uncontrolled fixed-crest type with a horizontal spillway apron for energy dissipation. Diver's inspections of the downstream face of the dam and the streambed immediately below the dam indicated that the apron has been undercut almost all the way across the entire length. The depth of the undercut varies from a few in. to 6 ft below the apron. There is concern that further structural damage will occur if the area downstream from the dam is not protected against future scour.

Purpose of Model Study

3. The purpose of the model study was to develop a scour protection plan that would repair the area immediately downstream from the dam and prevent future scouring of this area. Also, the model was used to determine the flow conditions that caused the most severe scour.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

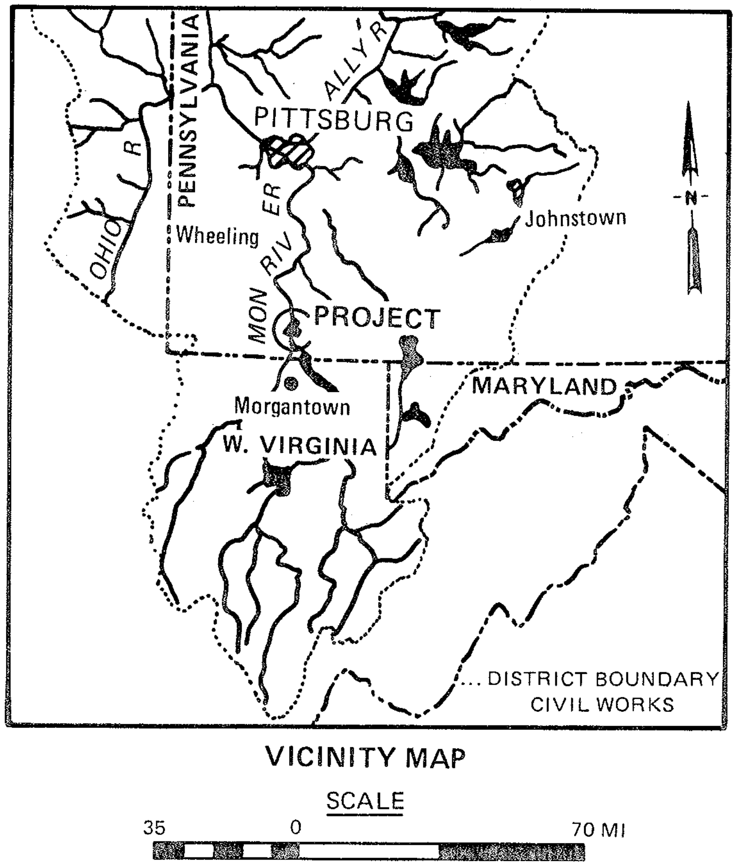


Figure 1. Vicinity map

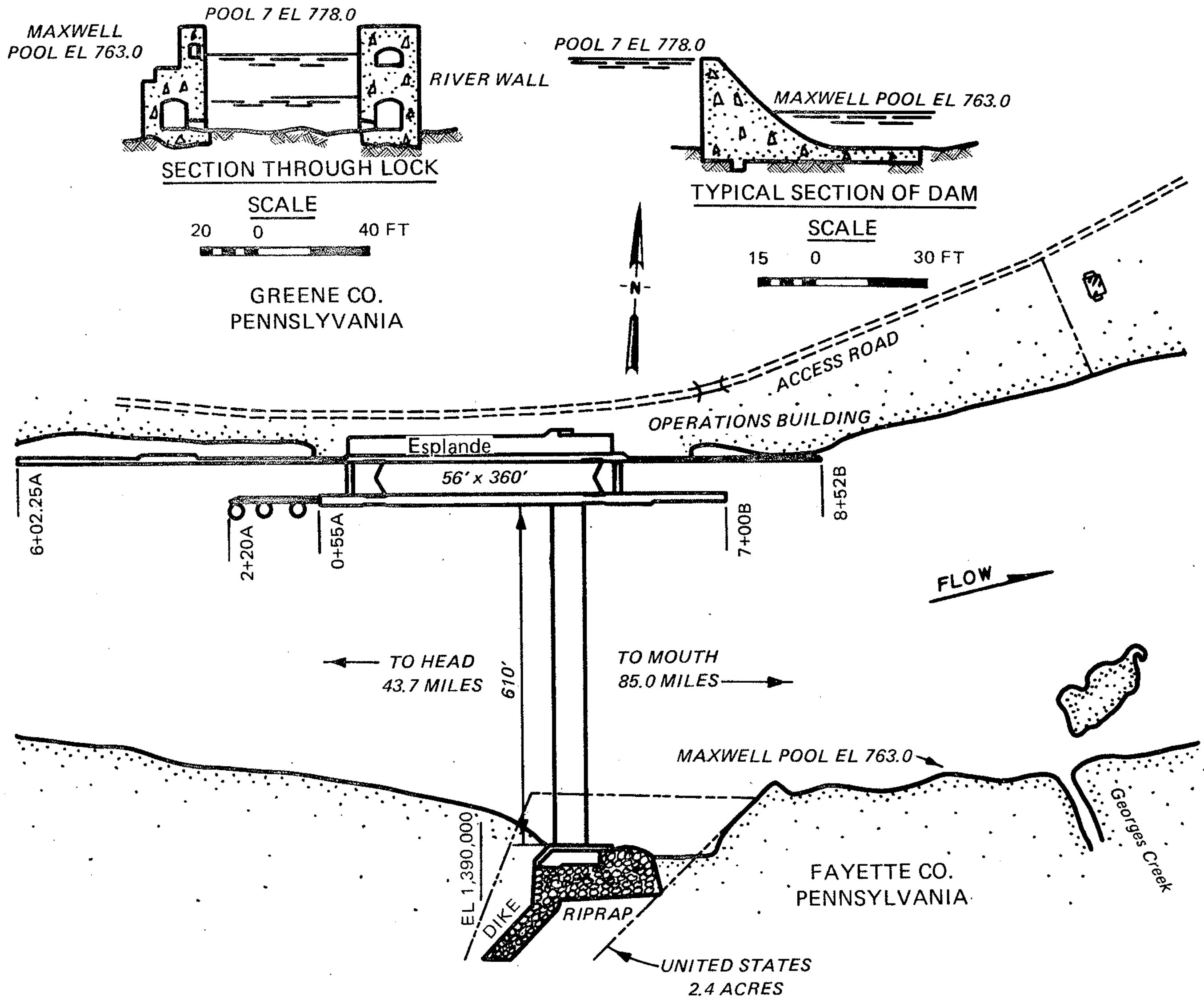


Figure 2. Plan and elevation view

PART II: THE MODEL

Description

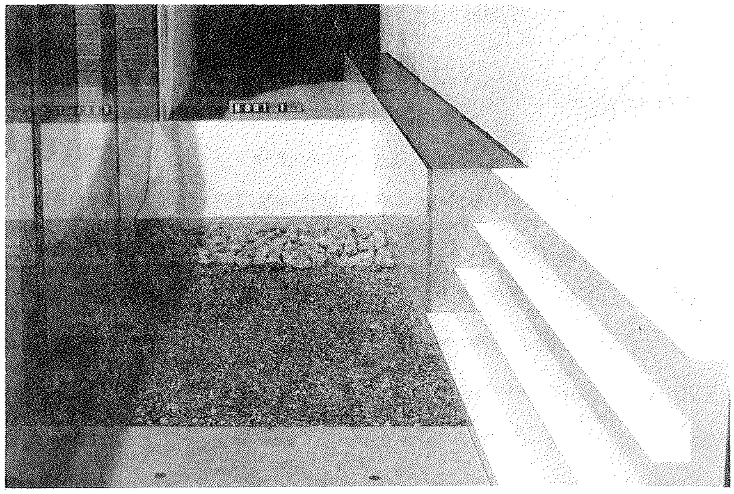
4. The model (Figure 3) was constructed to an undistorted scale of 1:25 and reproduced a 78-ft-long section of the uncontrolled fixed-crest weir and spillway apron, and a 22-ft-wide section of the river wall of the lock. Approximately 200 ft of the river wall of the lock was constructed upstream from the dam and 300 ft downstream from the dam. A 200 ft length of topography upstream from the dam, the proposed riprap protection, and 400 ft of the exit channel downstream from the dam were also reproduced. The fixed-crest weir, spillway apron, and a portion of the downstream side of the river wall of the lock were fabricated of sheet metal. The upstream topography and the remaining portions of the river wall of the lock were constructed of plastic-coated plywood. A 50-ft-section of the exit channel immediately downstream of the dam was molded with riprap and sand, followed by 140 ft of pea gravel and the remaining 210 ft reproduced with plastic coated plywood.

Model Appurtenances

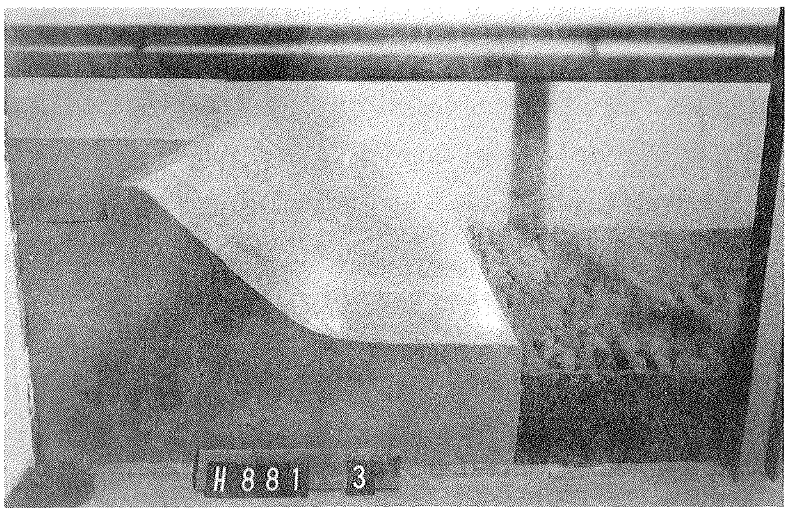
5. Water used in operation of the models was supplied by a circulating system. Discharges in the model, measured with venturi meters installed in the inflow lines, were baffled when entering the model. Water-surface elevations and soundings over the sand and riprap beds were measured with point gages. Velocities were measured with pitot tubes mounted to permit measurement of flow from any direction and at any depth. The tailwater in the lower end of the model was maintained at the desired depth by means of an adjustable tailgate. Different designs, along with various flow conditions, were recorded photographically.

Scale Relations

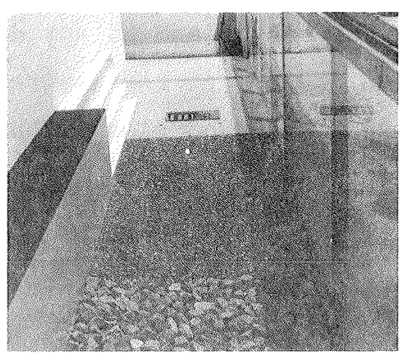
6. The accepted equations of hydraulic similitude, based on the Froudian criteria, were used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General



a. Looking upstream



b. Side view



c. Looking downstream

Figure 3. General view of model

relations for the transference of model data to prototype equivalents are presented below:

Characteristic	Dimension*	Model:Prototype
Length	L_r	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3,125
Volume	$V_r = L_r^3$	1:15,625
Weight	$W_r = L_r^3$	1:15,625
Time	$T_r = L_r^{1/2}$	1:5

*Dimensions are in terms of length.

Because of the nature of the phenomena involved, certain model data can be accepted quantitatively, while other data are reliable only in a qualitative sense. Measurements in the model of discharges, water-surface elevations, velocities, and resistance to displacement of riprap material can be transferred quantitatively from model to prototype by means of the above scale relations. Evidence of scour of the model sand bed, however, is to be considered only as qualitatively reliable since it has not yet been found possible to reproduce quantitatively in a model the relatively greater extent of erosion that occurs in the prototype with fine-grained bed material. Data on scour tendencies provided a basis for determination of the relative effectiveness of the different designs and indicated the areas most subject to attack.

PART III: TESTS AND RESULTS

7. Initial tests were conducted with the type 1 riprap plan shown in Plate 1. This plan consisted of 3- to 4-ft-diameter stones placed horizontally for 50 ft downstream from the end of the spillway apron. The bottom of the rock was placed at el 748*, with the top of the rock offset a minimum of 2 ft below the top of the spillway apron, el 754. A high velocity plunging jet exiting the spillway apron was observed for discharges up to 85,000 cfs (unit discharge, q, of 139.3 cfs/ft). Discharge rating curves are shown in Plate 2.

This plunging jet flow continued over the type 1 riprap causing instability of the stone protection for discharges between 20,000 and 85,000 cfs. The worst flow condition for riprap stability appeared to be with a discharge of around 85,000 cfs. Several stones were unstable and some were displaced from the riprap bed. Plunging flow conditions with the type 1 riprap plan for discharges of 20,000 cfs (unit q of 32.8 cfs/ft), 50,000 cfs (unit q of 82.0 cfs/ft), and 85,000 cfs (unit q of 139.3 cfs/ft) are shown in Photo 1 and riding jet flow conditions for discharges of 100,000 cfs (unit q of 164.0 cfs/ft) and 160,000 cfs (unit q of 262.3 cfs/ft) are shown in Photo 2. Once the riding jet flow occurred, the attack on the area downstream from the dam was reduced and the type 1 riprap plan remained stable. Velocities measured for these flow conditions are shown in Plates 3-7. Maximum velocities observed over the stone protection occurred with a discharge of 85,000 cfs and ranged from 9.0 to 11.0 ft/sec. These velocities and associated turbulence were sufficient to displace the stones in the type 1 riprap plan.

8. The type 1 riprap plan was replaced with the type 2 riprap plan which consisted of 4- to 5-ft-diameter stones, Plate 8, placed horizontally for 50 ft downstream from the end of the spillway apron. The bottom of the rock was placed at el 747.0, with the top of the rock offset a minimum of 2 ft below the top of the spillway apron, as shown in Plate 8. Test results indicated that with a discharge of 85,000 cfs and tailwater el of 783.5 the type 2 riprap plan was unstable.

9. A 3-ft-high sloping end sill was placed on the spillway apron with

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* All elevations (el) and stages cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

the downstream face of the sill located 3 ft upstream from the end of the spillway apron. Stones 3 to 4 ft in diameter were placed horizontally for 50 ft downstream from the end of the spillway apron. This was designated the type 3 scour protection plan and is shown in Plate 9. The bottom of the rock was placed at el 750, with the top of the rock not exceeding the spillway apron elevation of 754. With this plan in place, the stone protection was unstable for the discharge (slightly higher than 85,000 cfs) that occurred during the flow transition from surface jet flow to plunging jet flow. Excessive turbulence over the riprap also occurred as the jet flow transitioned from plunging to surface flow. This condition caused slight fluttering of the rock, but was not as severe as the transition from surface to plunging flow.

10. With a discharge of 85,000 cfs, and a tailwater slightly above normal tailwater el 783.5, the jet flow rode the surface of the tailwater and caused no harmful turbulence over the riprap. As the tailwater was lowered, the jet began to plunge, and before it conformed to the crest shape, it attacked the area downstream from the spillway apron. This flow transition from surface jet to plunging jet flow and attack on the riprap are illustrated in Plate 10. It is during these type flow transitions that excessive turbulence was observed over the riprap bed.

11. The type 4 scour protection plan, shown in Plate 11, utilized the same size stone (3-4 ft diameter) and end sill as the type 3 scour protection plan, but the top of the rock was offset a minimum of 2 ft below the top of the spillway apron as shown in Plate 11. The bottom of the rock was placed at el 748. This plan was tested with a discharge of 85,000 cfs during the flow transition and the same instability observed with the type 3 plan was also experienced with the type 4 plan. The rock size was increased to 4- to 5-ft-diameter stones (type 5 scour protection plan, shown in Plate 12). This plan was tested with a discharge of 85,000 cfs during the transition flow and slight movement of a few stones was observed. Flow conditions with the type 5 scour protection plan for discharges of 20,000, 50,000, 85,000, 100,000, and 160,000 cfs are shown in Photo 3, respectively. The end sill was less effective in deflecting the plunging jet to the surface with increasing discharges. Velocities measured with the type 5 scour protection plan for a discharge of 85,000 cfs are shown in Plate 13. Velocities over the stone protection were reduced and were in an upstream direction as seen by comparing

Plates 13 and 5.

12. The type 6 scour protection plan consisted of a double layer of 4- to 5-ft-diameter stone to increase interlocking with the bottom of the stones placed at el 747.0 and a 3-ft-high sloping end sill placed 3 ft upstream from the end of the spillway apron, as shown in Plate 14. This design was tested with a discharge of 85,000 cfs and very slight movement of a few of the stones was observed. The 3-ft-high end sill was moved to the end of the apron to form the type 7 protection plan shown in Plate 15 and slight movement again was observed for flow condition with a discharge of 85,000 cfs.

13. The topography in some areas downstream from the dam prevented two layers of large stone as utilized in the types 6 and 7 scour protection plans from being placed such that the stone would not project above the spillway apron el 754. Thus, this approach was abandoned. Tests were then conducted using grout-filled fabric bags 20 ft long, by 6.75 ft wide, by 2.75 ft thick for scour protection. The first of these plans was the type 8 scour protection plan shown in Plate 16. The bags were placed perpendicular to the flow for a distance of 40.5 ft downstream from the end of the spillway apron with the top of the bags at el 754. A test conducted with a discharge of 50,000 indicated slight movement of the bags. An additional test conducted for 1 hour (prototype) with a discharge of 85,000 cfs revealed that the bags moved 2 to 3 ft downstream and some were observed to flutter at all times during the test.

14. The type 9 scour protection plan, Plate 17, was tested next. The bags were placed longitudinally with the flow for a distance of 40 ft downstream from the apron with the top of the bags placed at el 754. The top of the bags were placed at el 754 due to the depth limitation caused by the topography in certain areas. This plan was tested with discharges of 50,000 and 85,000 cfs and constant fluttering of the bags was observed. This instability increased during the flow transition at 85,000 cfs and although no bags were washed downstream, this was considered failure.

15. The type 10 scour protection plan consisted of the same bag configuration as the type 9 plan, with the addition of a 3-ft-high sloping end sill placed at the end of the spillway apron, Plate 18. With this design in place, the bags remained stable for all discharges and for the flow transition at 85,000 cfs. Flow conditions with the type 10 scour protection plan for discharges of 50,000 and 85,000 cfs are shown in Photo 4. The bags also

remained stable with the end sill placed 3 ft upstream from the end of the spillway apron, type 11 scour protection plan shown in Plate 19.

16. The grout-filled bags were tested with 1 row placed against the downstream face of the dam perpendicular to the flow, type 12 scour protection plan, and the bags remained stable. Although the bags were considered stable, this was not a desirable protection plan due to the potential for excessive scour close to the structure. The type 13 scour protection plan used this bag configuration with the addition of a 3-ft-high end sill placed 3 ft upstream from the end of the spillway apron and the bags were stable, but again this was considered minimal protection.

17. Diver's reports had indicated scour along the river wall of the lock. Velocities were measured along the base of the lock wall for discharges of 20,000, 50,000, and 85,000 cfs as shown in Plates 20-22. These velocities ranged from 4.0 to 14.5 ft/sec along the wall and the higher velocities observed are sufficient to cause scour in an erodible material. With the end sill placed at the end of the spillway apron, the velocities were generally in an upstream direction as shown in Plates 23-25. These velocities would not cause scour problems.

18. Additional rating curve information received from the Pittsburgh District revealed that the tailwater was lower for some discharges. Additional tests were conducted with the type 10 scour protection plan to verify the adequacy of the plan with these lower tailwaters. Plunging flow conditions were observed up to a discharge of 105,000 cfs with a tailwater el of 785. The revised rating curve is shown in Plate 2 along with the original rating curve. The type 10 scour protection plan was tested for all flow conditions including the flow transition with discharges slightly higher and lower than 105,000 cfs and remained stable for all conditions.

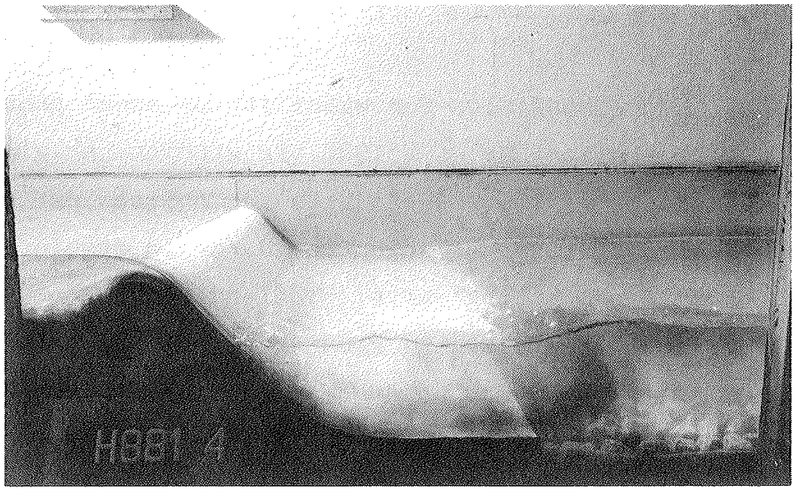
19. The type 14 scour protection plan shown in Plate 26 incorporated the elements of the type 10 plan with the addition of 3 bags placed along the river wall of the lock. The number of bags placed along the river wall will depend on the location and extent of the existing scoured areas. If certain areas along the wall are severely scoured, bags should probably be used to repair these areas. The addition of the end sill significantly reduced the velocities along the base of the river wall. Three bags were placed along the lock wall downstream of the protection below the dam in the type 14 scour

protection plan to observe scouring tendencies adjacent to and at the termination of the bags. The plan was tested and remained stable for all discharges. Photo 5 shows the exit channel after 7.5 hours (prototype) with a discharge of 20,000 cfs, and 10 hours (prototype) with a discharge of 85,000 cfs. Only slight scour of the model bed downstream of the bags was observed and virtually no model scour occurred around the bags along the lock wall.

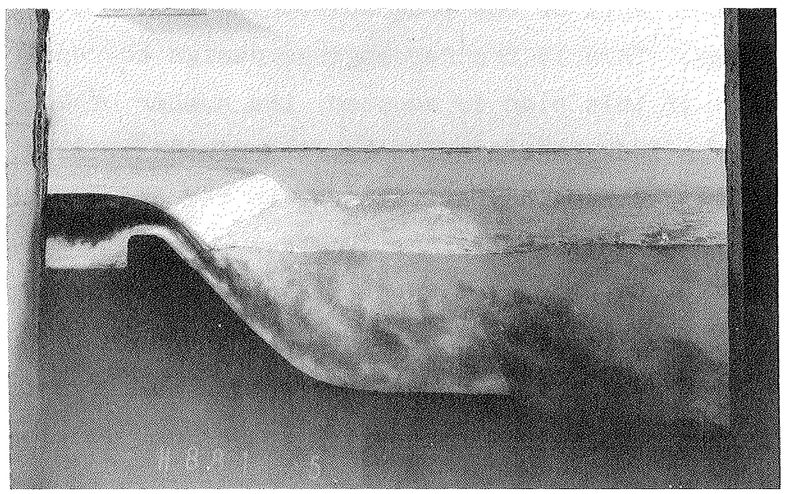
PART IV: SUMMARY AND RECOMMENDATIONS

20. The most severe condition for stability of scour protection material occurred with a discharge of 85,000 cfs with the original rating curve and with a discharge of 105,000 cfs with the revised rating curve. Two riprap plans were tested, neither of which would remain stable for all flow conditions with the original rating curve. The addition of a 3-ft-high sloping end sill deflected the plunging flow away from the area immediately downstream from the spillway apron but 4- to 5-ft-diameter stones were still unstable. Large grout-filled fabric bags 20 ft long by 6.75 ft wide by 2.75 ft thick remained stable when the 3-ft-high sloping end sill was placed on the spillway apron. The type 14 scour protection plan, Plate 26, provided adequate scour protection for the area below the dam as well as for a 60 ft length along the river wall of the lock downstream from the bags that were placed below the dam. This is the recommended design to repair Dam No. 7 Monongahela River. If this plan is adopted, the number of bags placed along the river wall of the lock beginning at the end of the spillway apron should be a minimum of five and possibly all the way to the end of the wall if severe scour currently exists along the entire length.

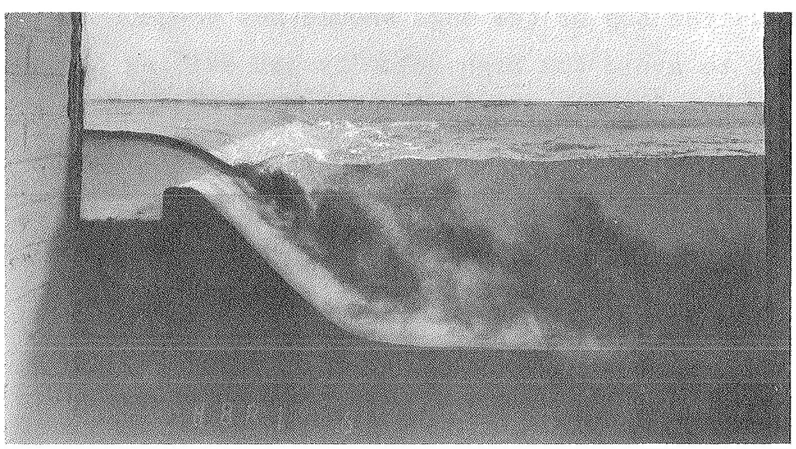
21. In placing the grout-filled fabric bags, past prototype experience has shown that it is desirable for the bottom of the bags to conform to the surface on which they rest to help prevent cracking and efforts should also be made to reinforce the bags within themselves and to couple them to each other. A properly designed granular filter is necessary to prevent loss of material underneath the bags. The material underneath the bags should consist of a graded granular material large enough to prevent piping through the voids of adjacent bags. The top of the bags should not project above the spillway apron el of 754.0 to avoid the high velocity jet exiting the apron.



a. Discharge 20,000 cfs, tailwater el 769.7

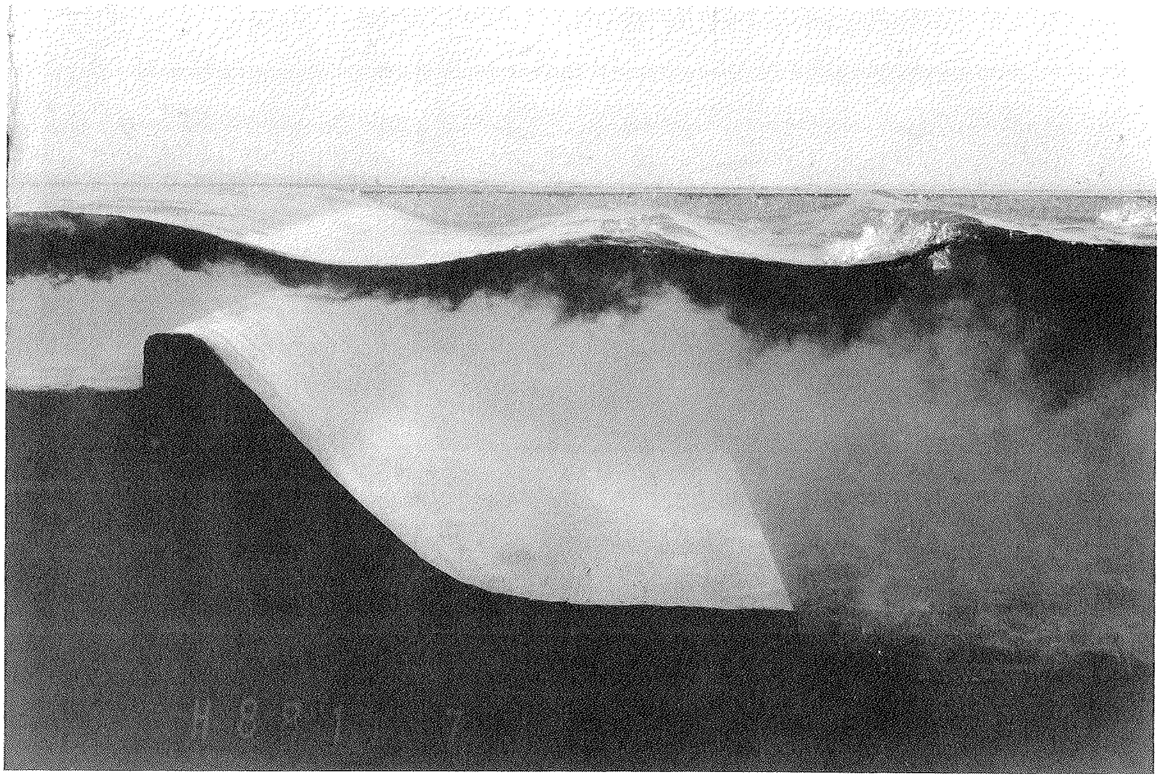


b. Discharge 50,000 cfs, tailwater el 776.5

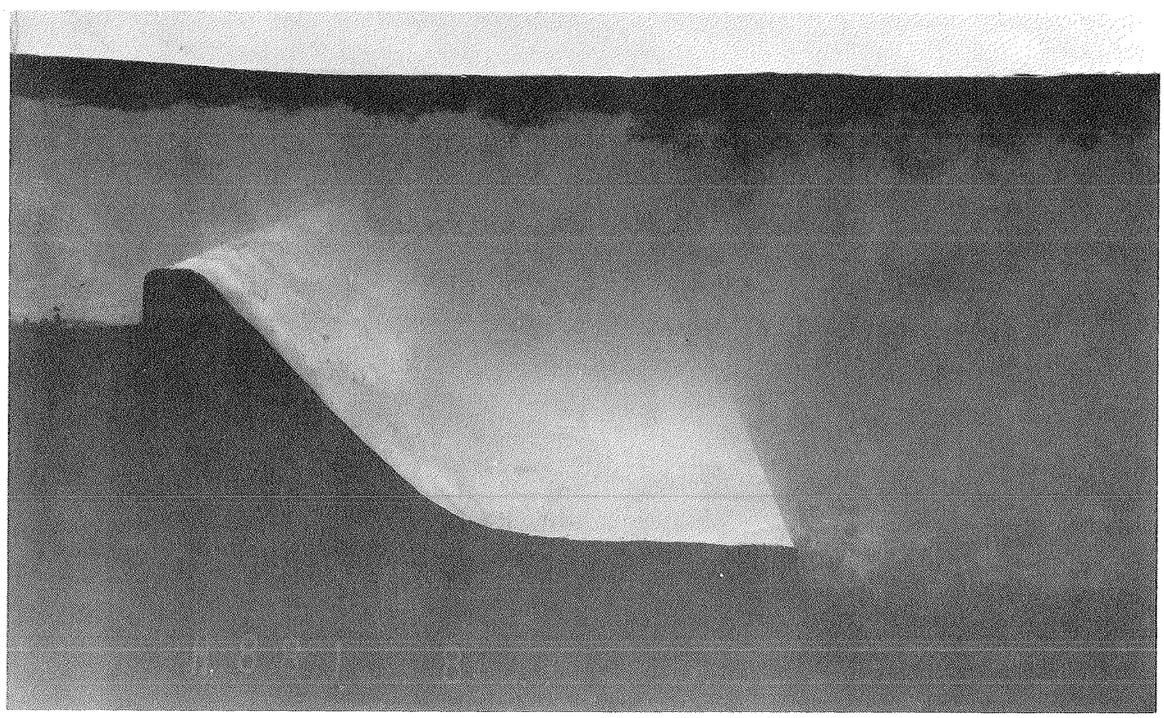


c. Discharge 85,000, tailwater el 783.5

Photo 1. Plunging jet flow conditions

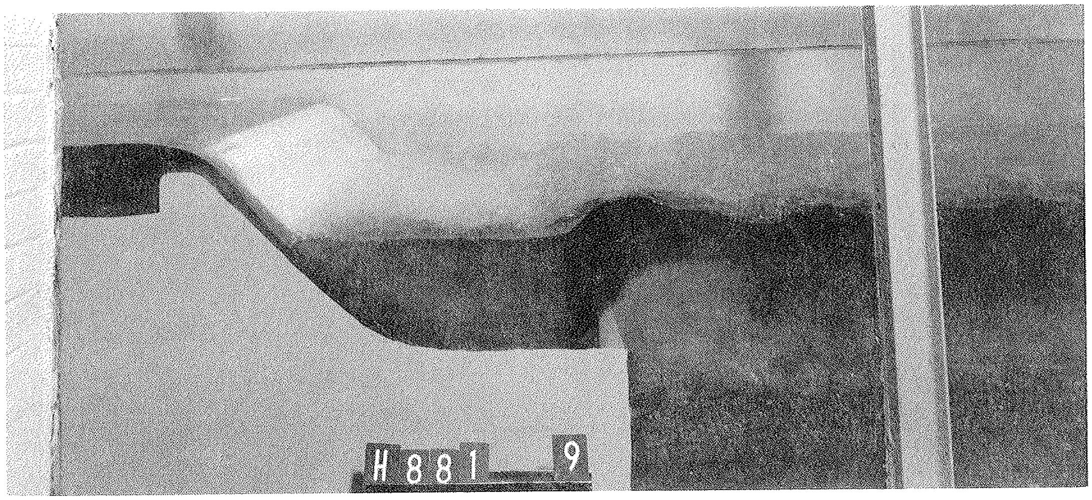


a. Discharge 100,000 cfs, tailwater el 786.5

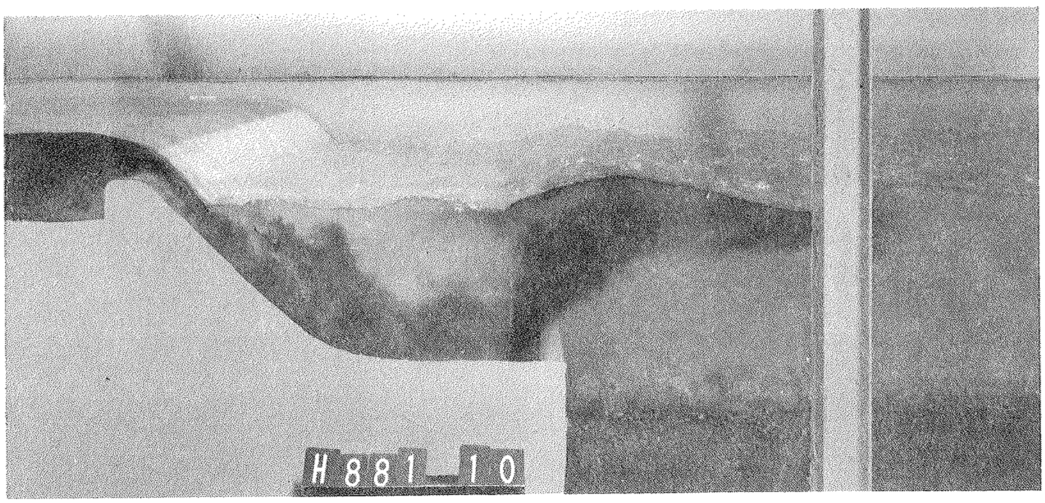


b. Discharge 160,000 cfs, tailwater el 796.5

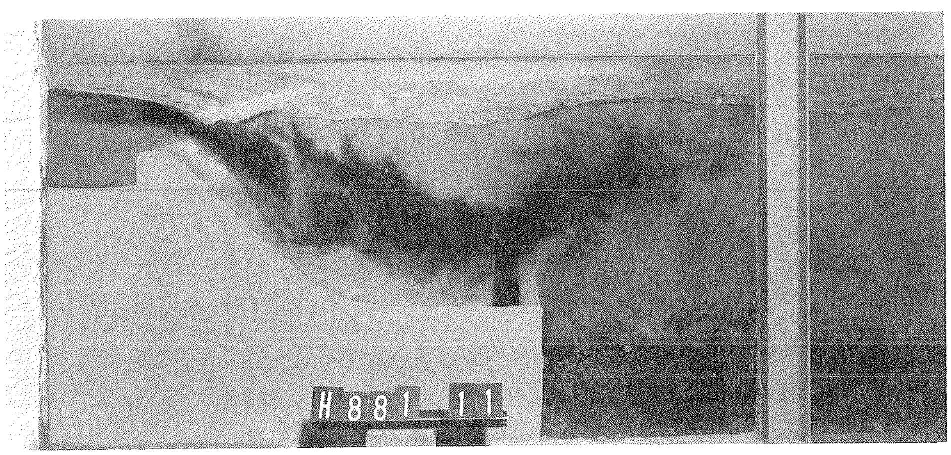
Photo 2. Riding jet flow conditions



a. Discharge 20,000 cfs, tailwater el 769.7

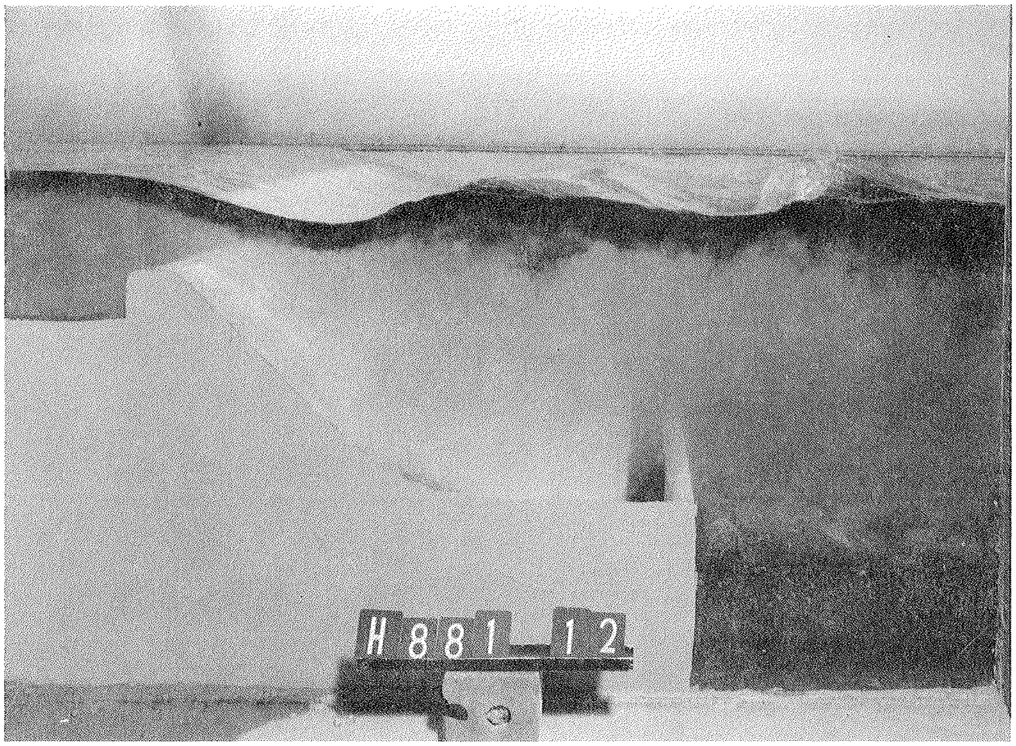


b. Discharge 50,000 cfs, tailwater el 776.5

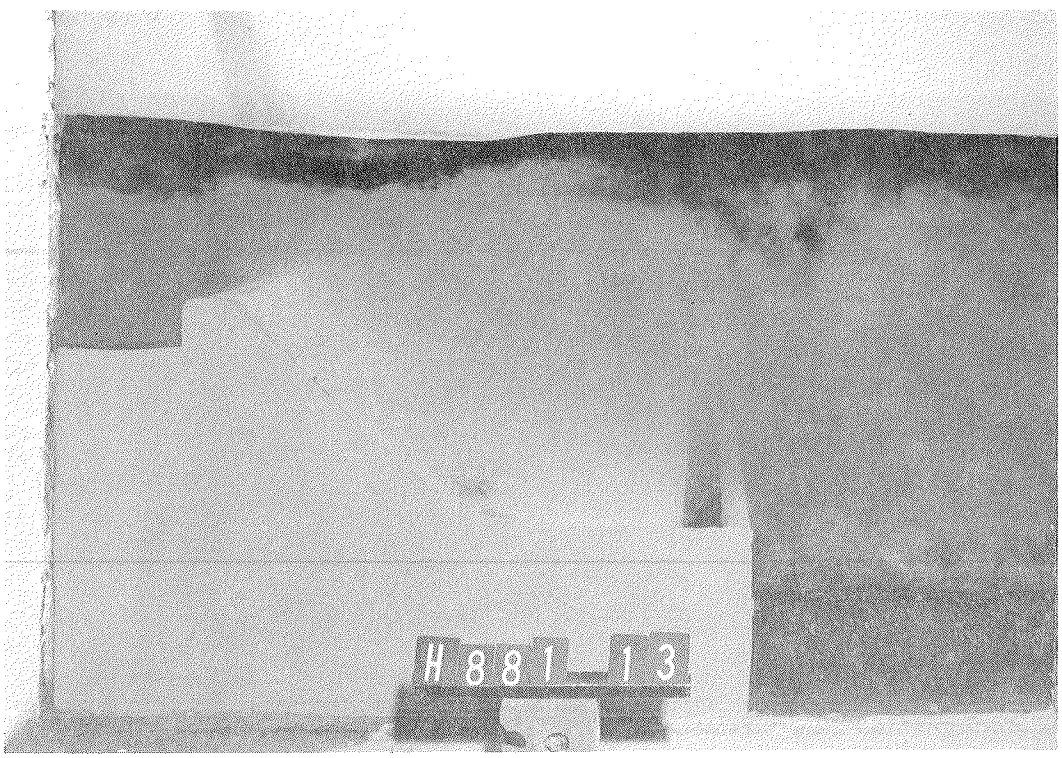


c. Discharge 85,000 cfs, tailwater el 783.5

Photo 3. Flow conditions with type 5 scour protection plan (Continued)

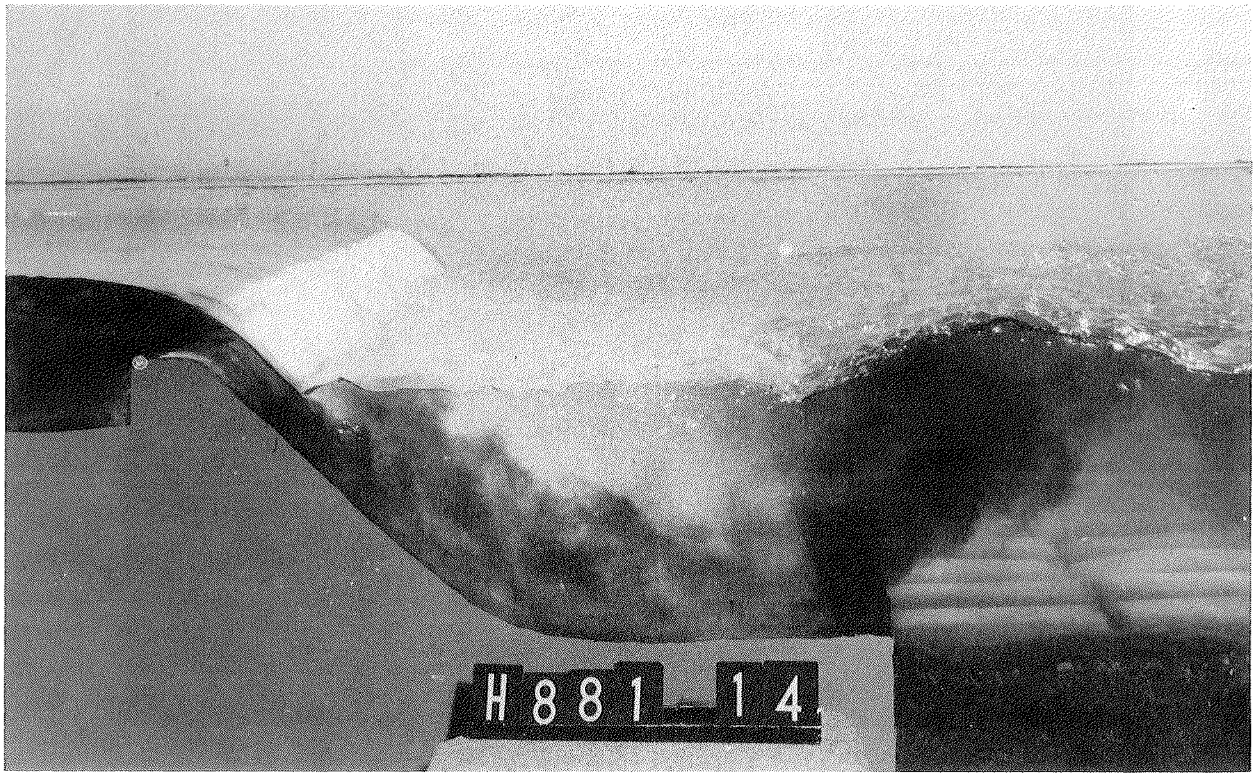


d. Discharge 100,000 cfs, tailwater el 786.5

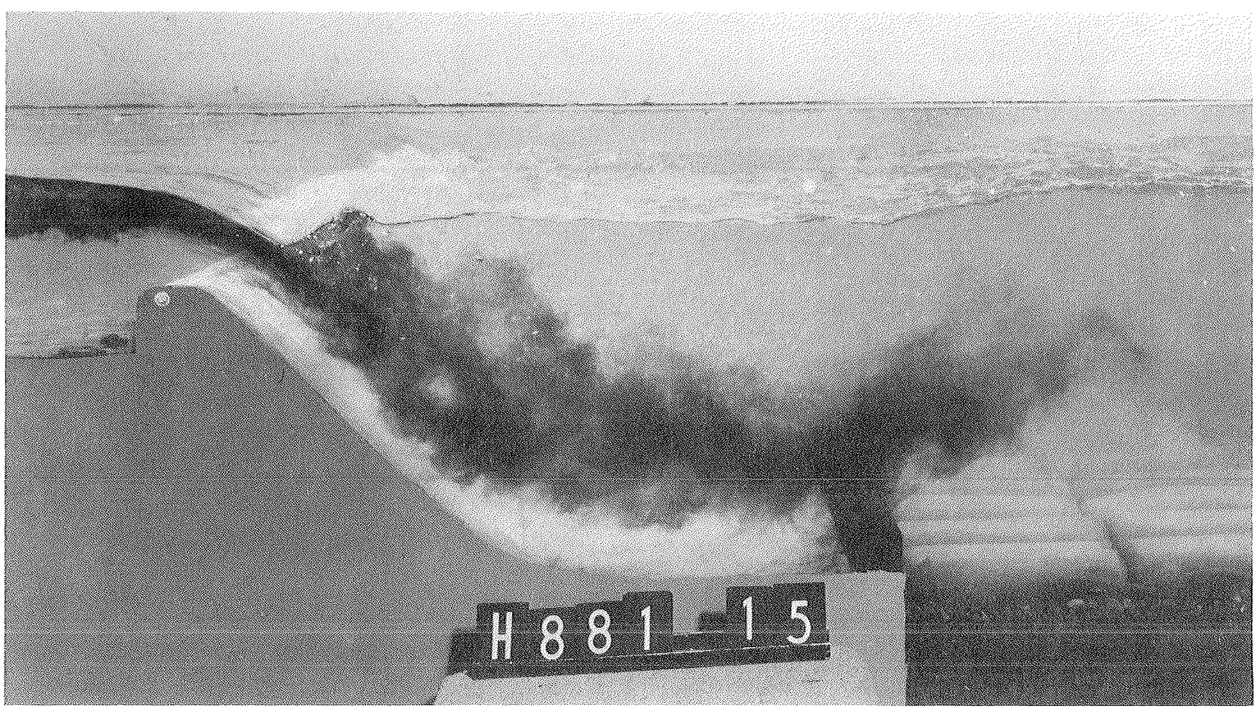


e. Discharge 160,000 cfs, tailwater el 796.5

Photo 3. (Concluded)



a. Discharge 50,000 cfs, tailwater el 776.5



b. Discharge 85,000 cfs, tailwater el 783.5

Photo 4. Flow conditions with the type 10 scour protection plan

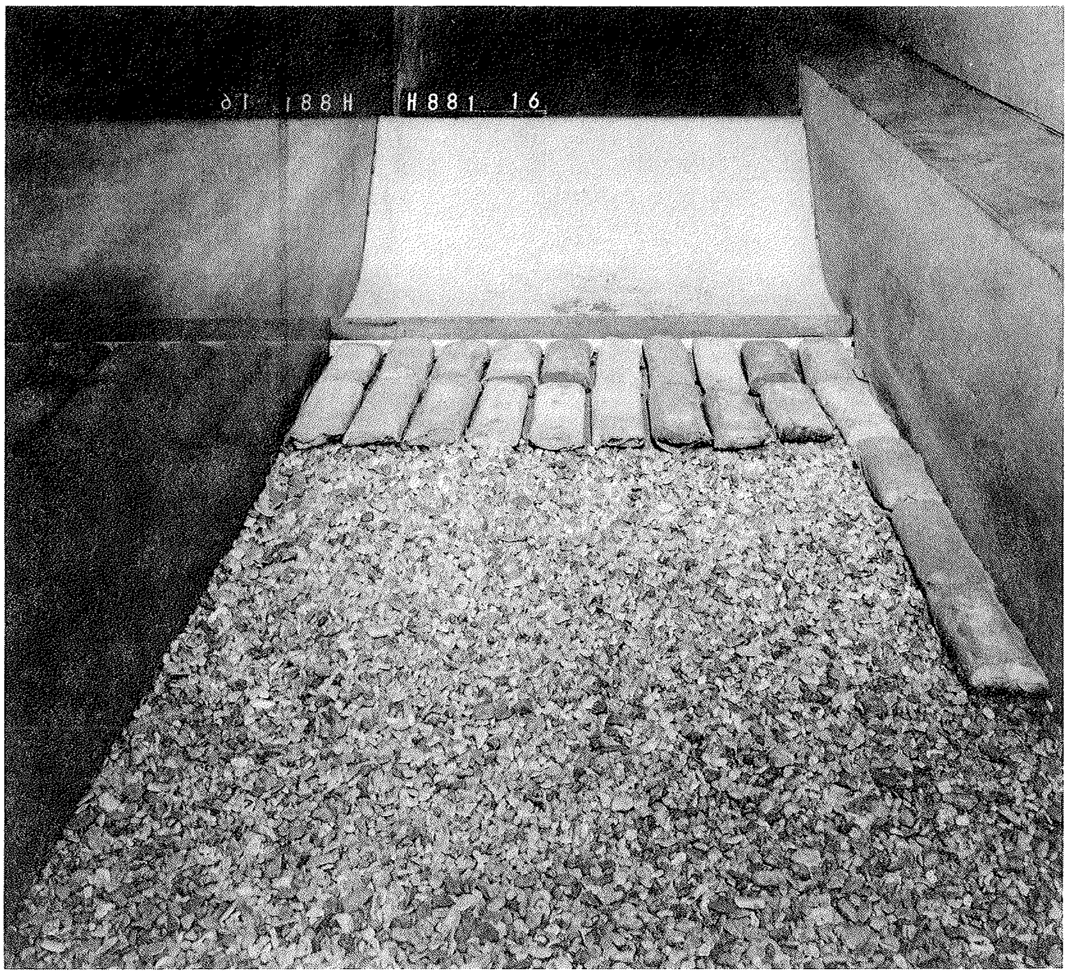
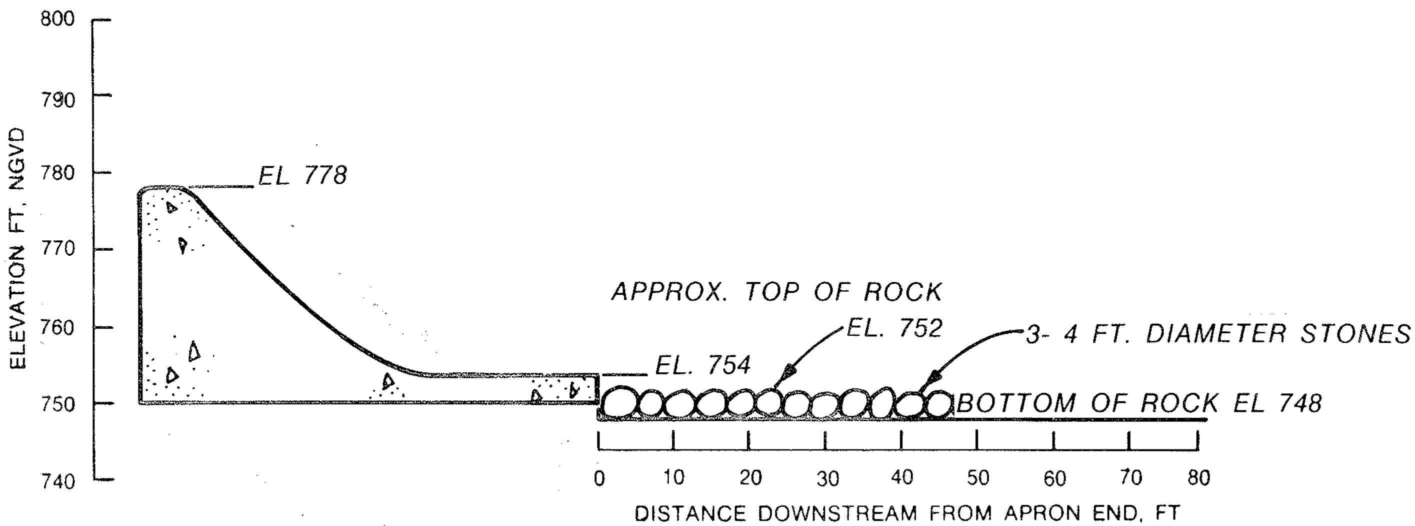
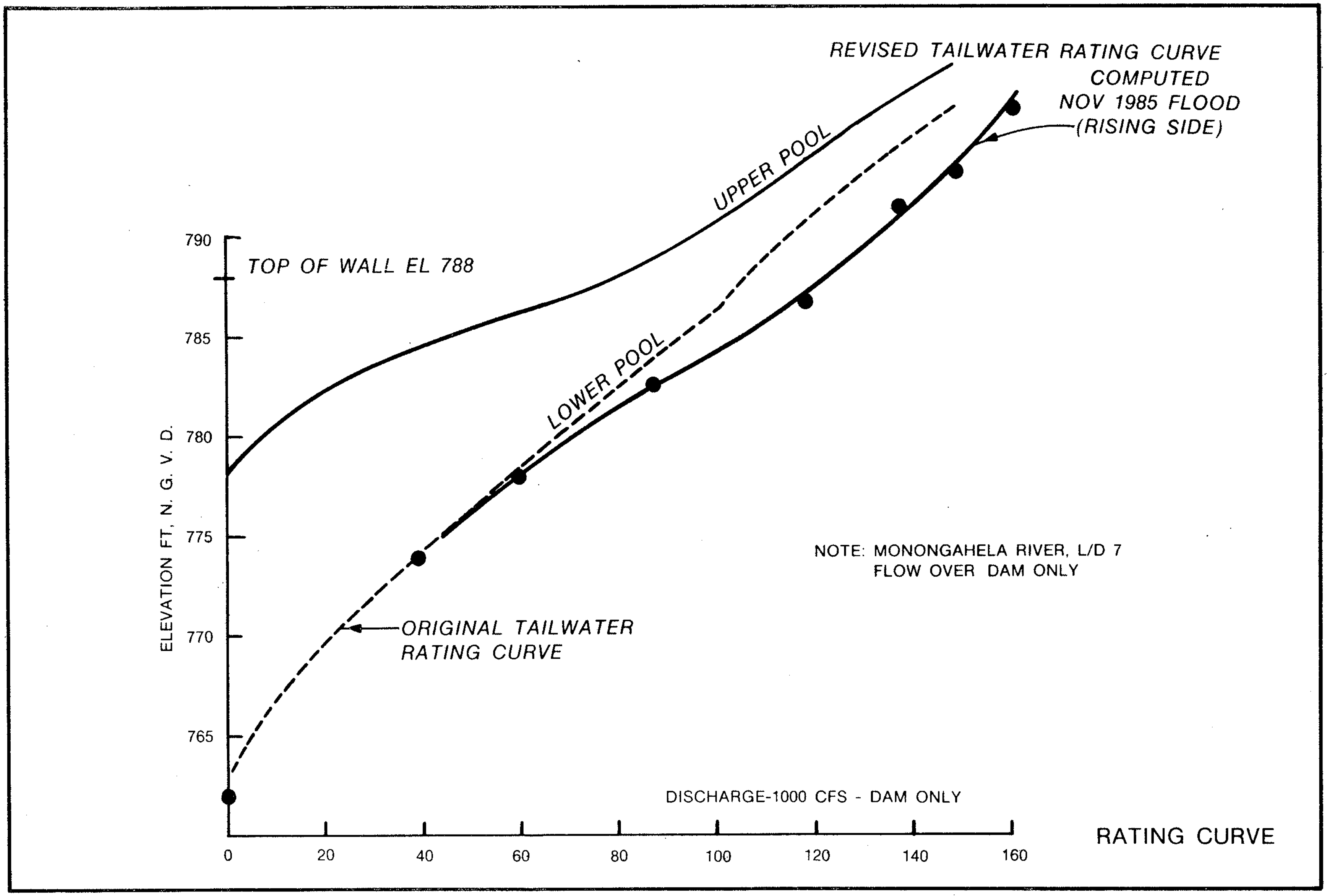


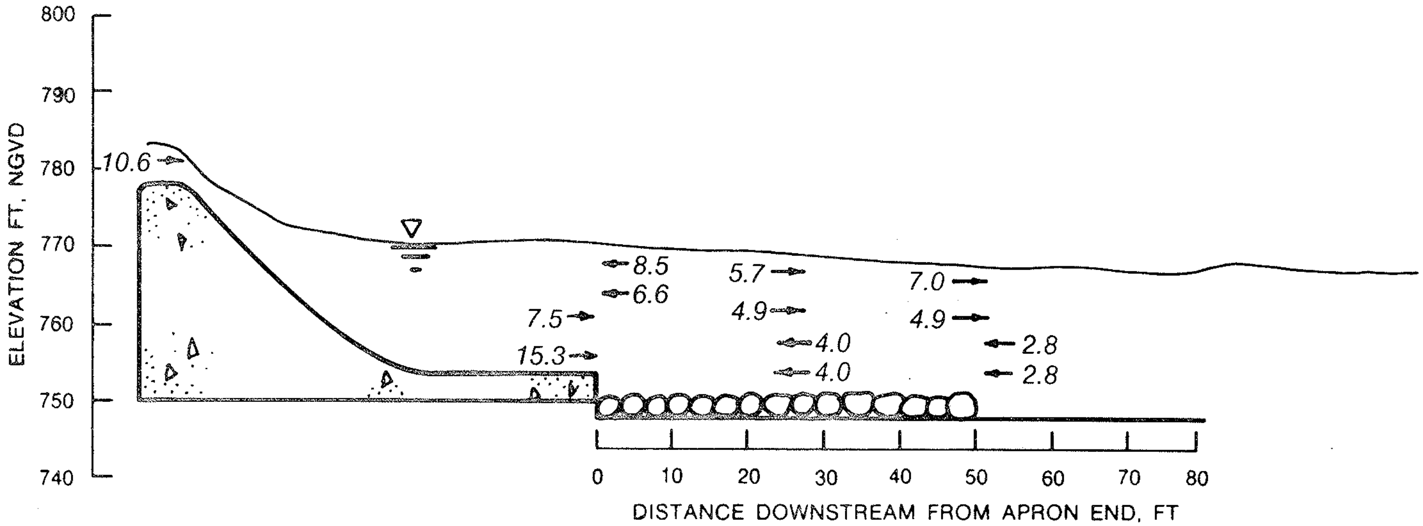
Photo 5. Type 14 scour protection plan



TYPE 1 RIPRAP PLAN

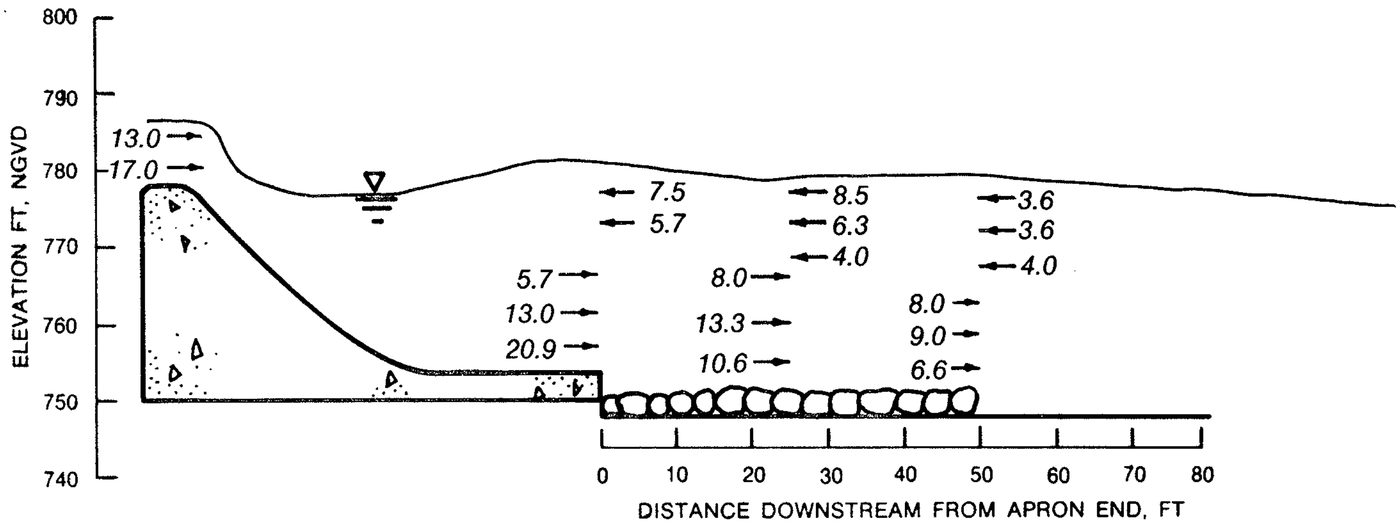
PLATE 2


REVISED TAILWATER RATING CURVE
COMPUTED
NOV 1985 FLOOD
(RISING SIDE)
UPPER POOL
LOWER POOL
TOP OF WALL EL 788
ORIGINAL TAILWATER
RATING CURVE
NOTE: MONONGAHELA RIVER, L/D 7
FLOW OVER DAM ONLY
ELEVATION FT, N. G. V. D.
790
785
780
775
770
765
DISCHARGE-1000 CFS - DAM ONLY
0
20
40
60
80
100
120
140
160
RATING CURVE



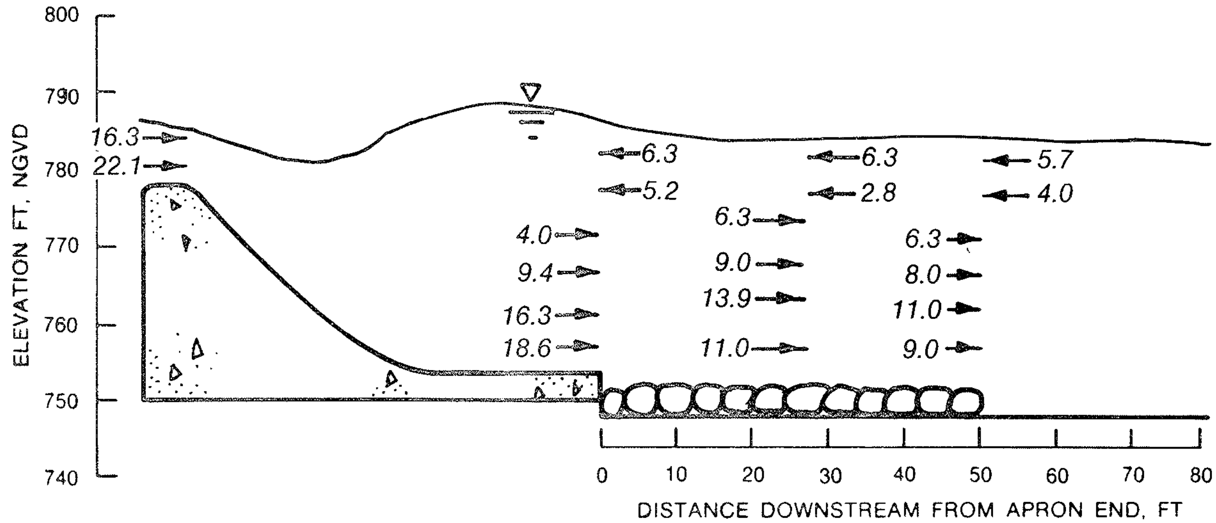
NOTE: VELOCITY AND WATER SURFACE PROFILES TAKEN ALONG MODEL CENTERLINE

VELOCITIES
TYPE 1 RIPRAP PLAN
DISCHARGE - 20,000 CFS
TW EL - 769.7



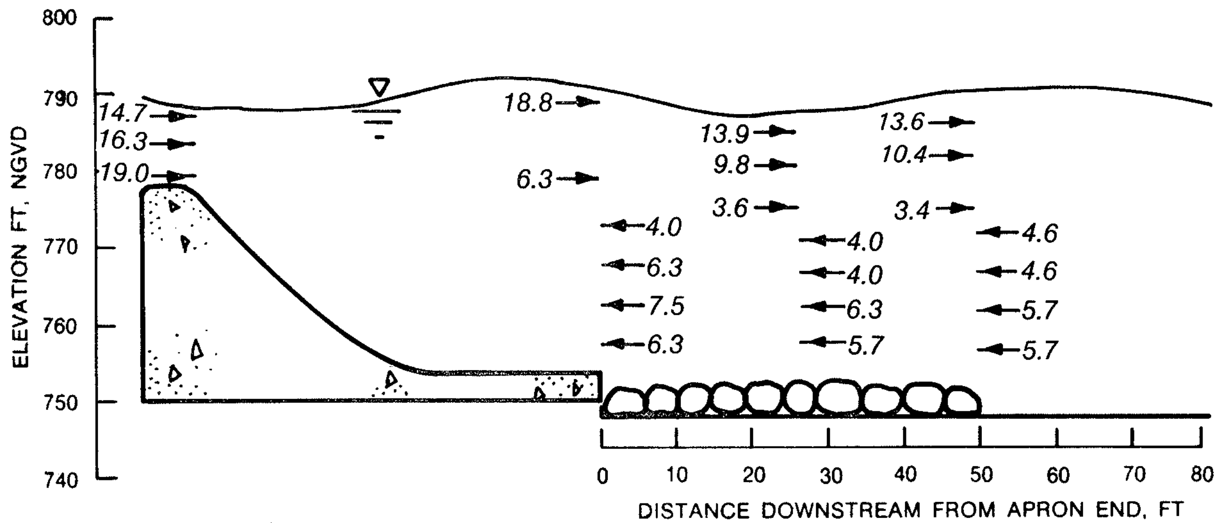
NOTE: VELOCITY AND WATER SURFACE PROFILES TAKEN ALONG MODEL CENTERLINE

VELOCITIES
TYPE 1 RIPRAP PLAN
DISCHARGE - 50,000 CFS
TW EL - 776.5



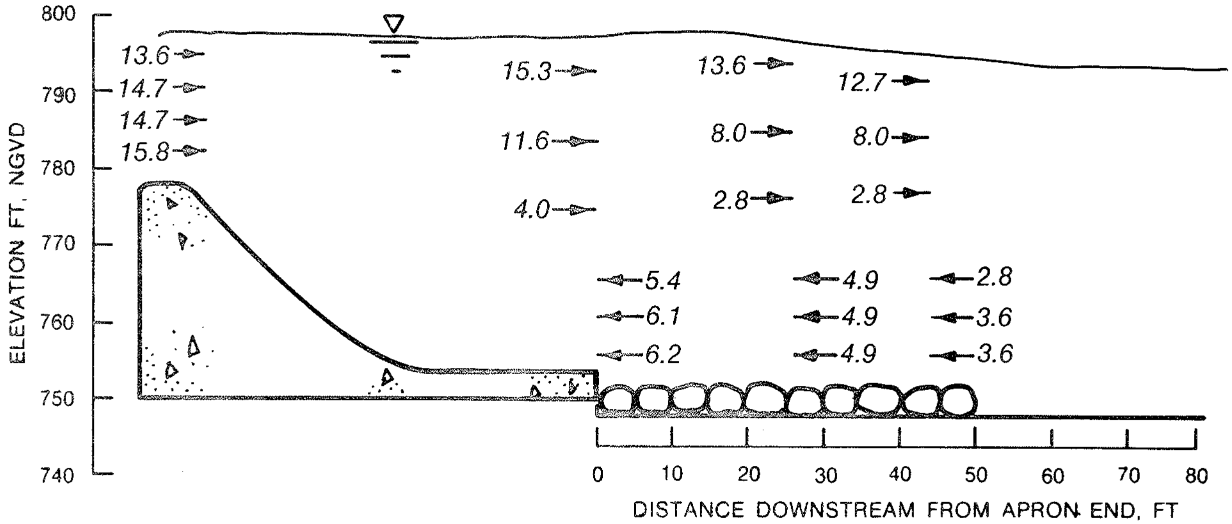
NOTE: VELOCITY AND WATER SURFACE PROFILES
TAKEN ALONG MODEL CENTERLINE

VELOCITIES
TYPE 1 RIPRAP PLAN
DISCHARGE - 85,000 CFS
TW EL - 783.5



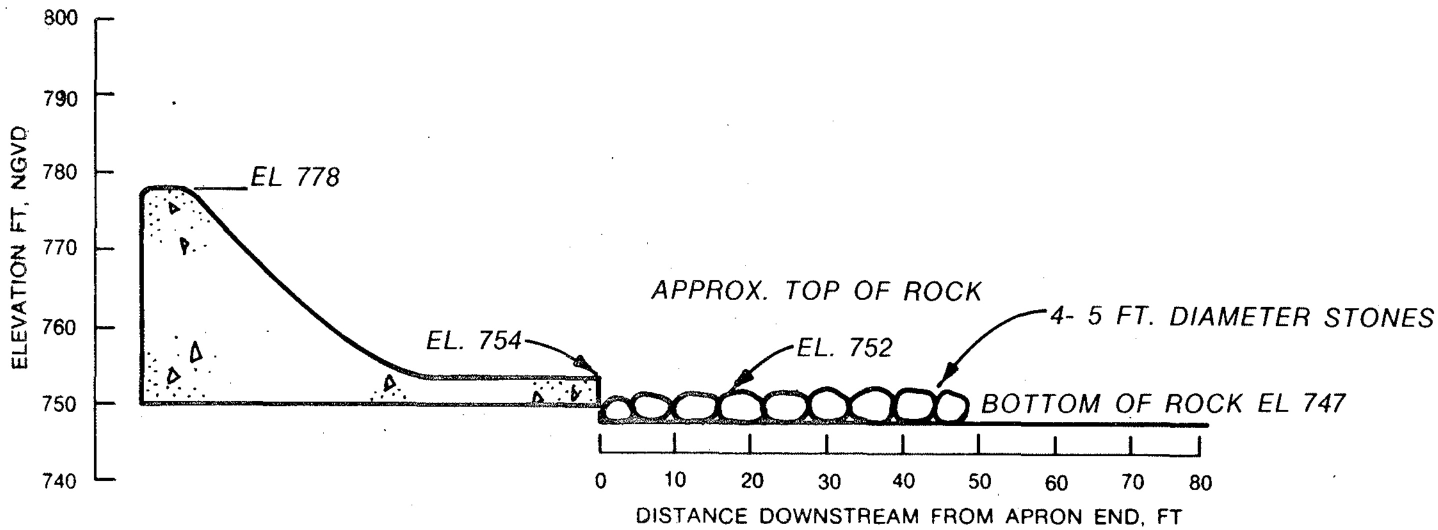
NOTE: VELOCITY AND WATER SURFACE PROFILES TAKEN ALONG MODEL CENTERLINE

VELOCITIES
TYPE 1 RIPRAP PLAN
DISCHARGE - 100,000 CFS
TW EL - 786.5

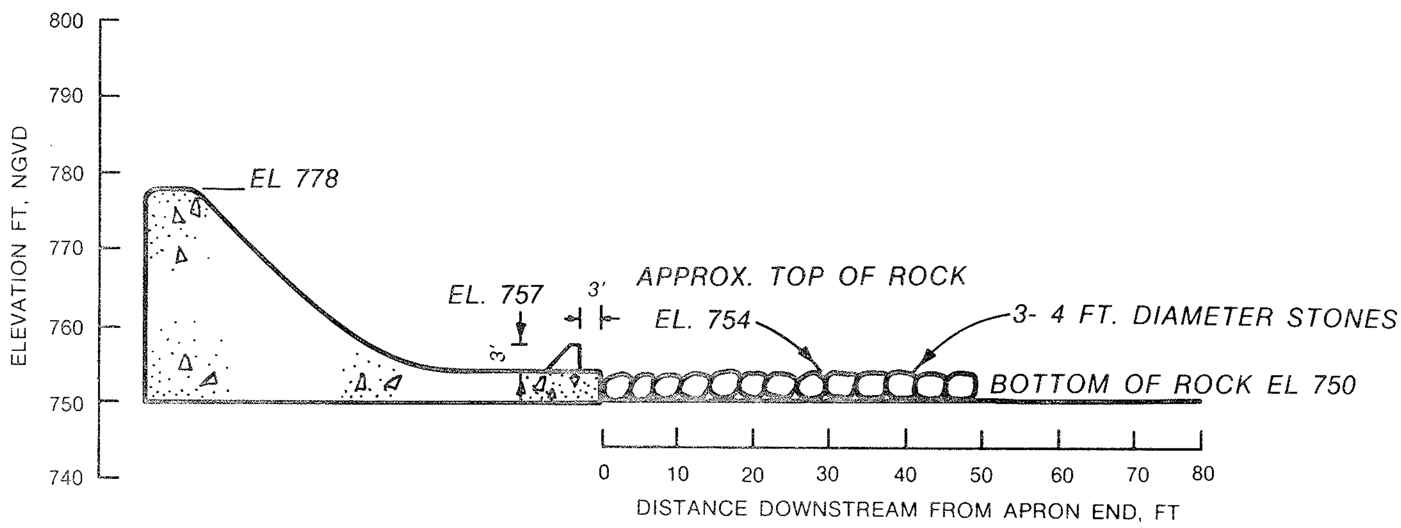


NOTE: VELOCITY AND WATER SURFACE PROFILES TAKEN ALONG MODEL CENTERLINE

VELOCITIES
TYPE 1 RIPRAP PLAN
DISCHARGE - 160,000 CFS
TW EL - 796.5

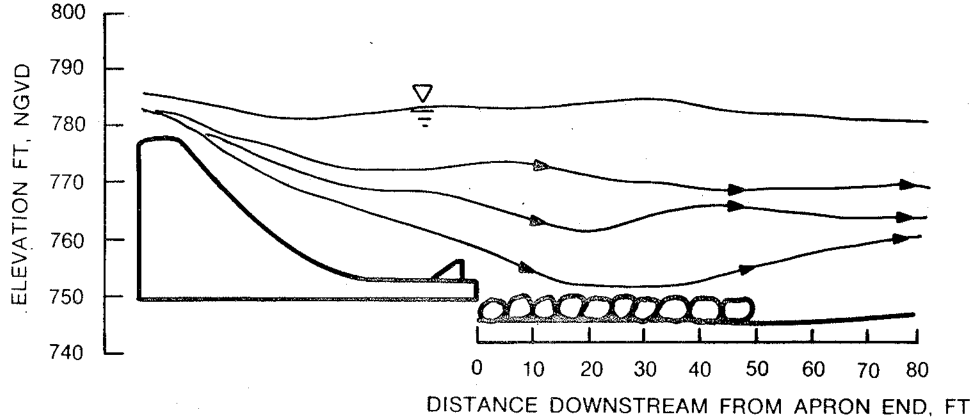


TYPE 2 RIPRAP PLAN

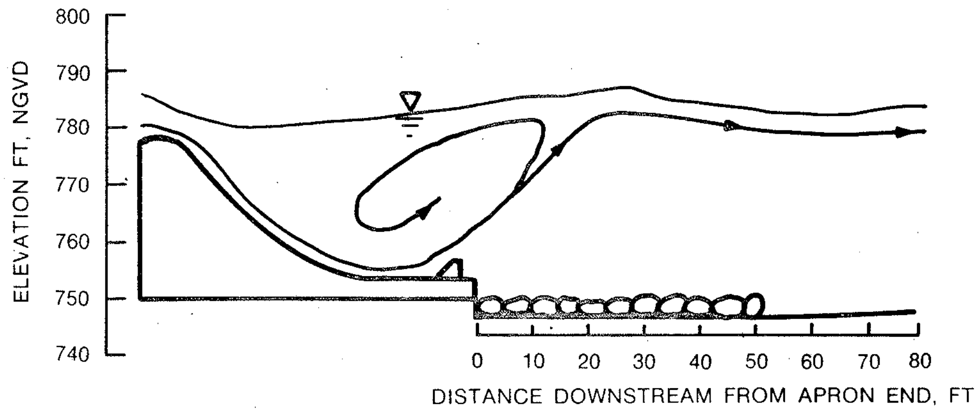


TYPE 3 SCOUR PROTECTION PLAN

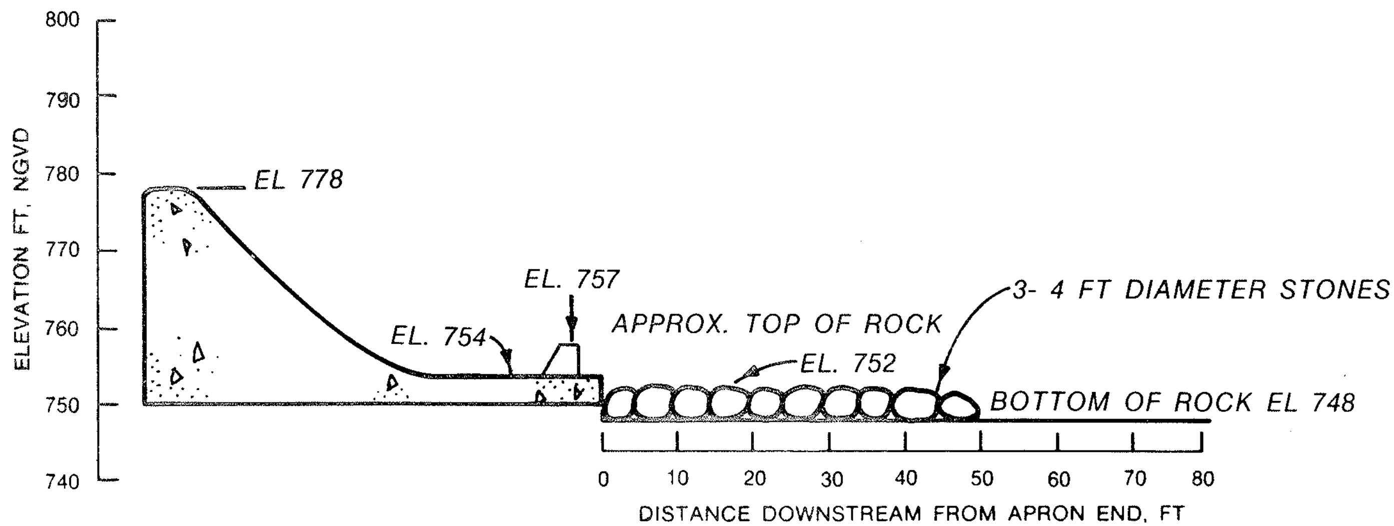
PLATE 10



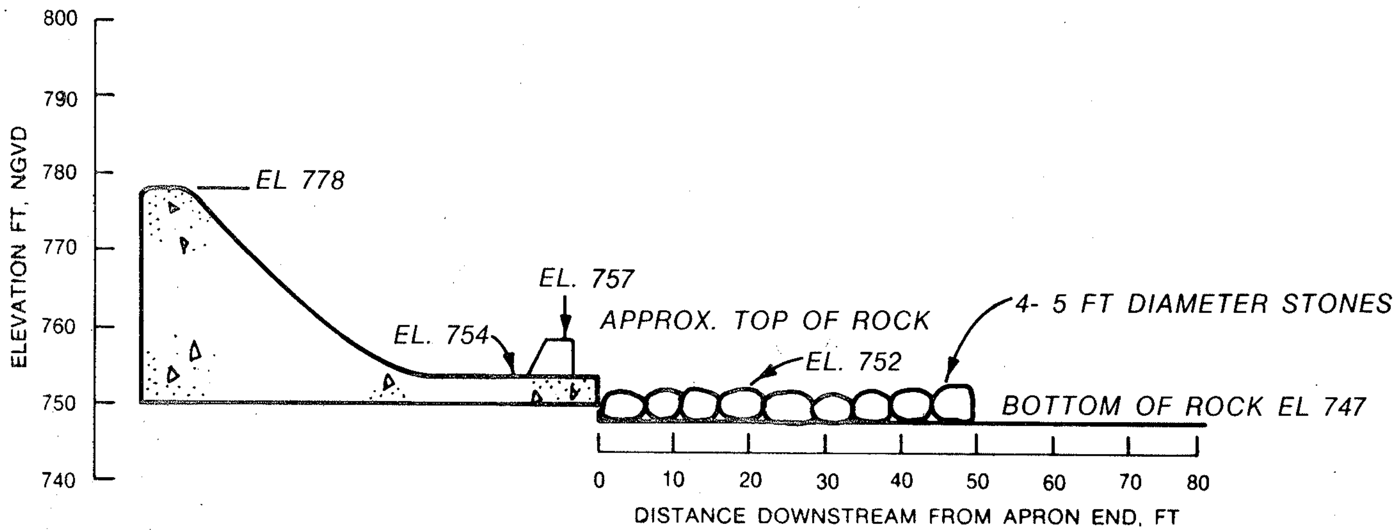
TRANSITION BETWEEN SURFACE AND PLUNGING FLOW
DISCHARGE- SLIGHTLY > 85,000 CFS
TW EL- SLIGHTLY > 783.5



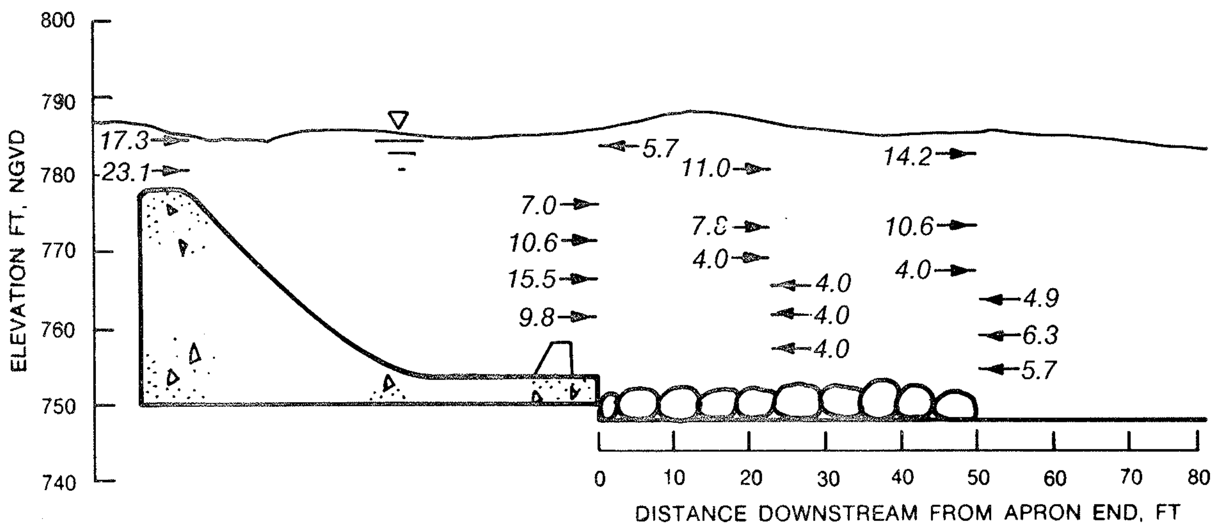
FLOW CHARACTERISTICS
TYPE 3 SCOUR PROTECTION PLAN



TYPE 4 SCOUR PROTECTION PLAN

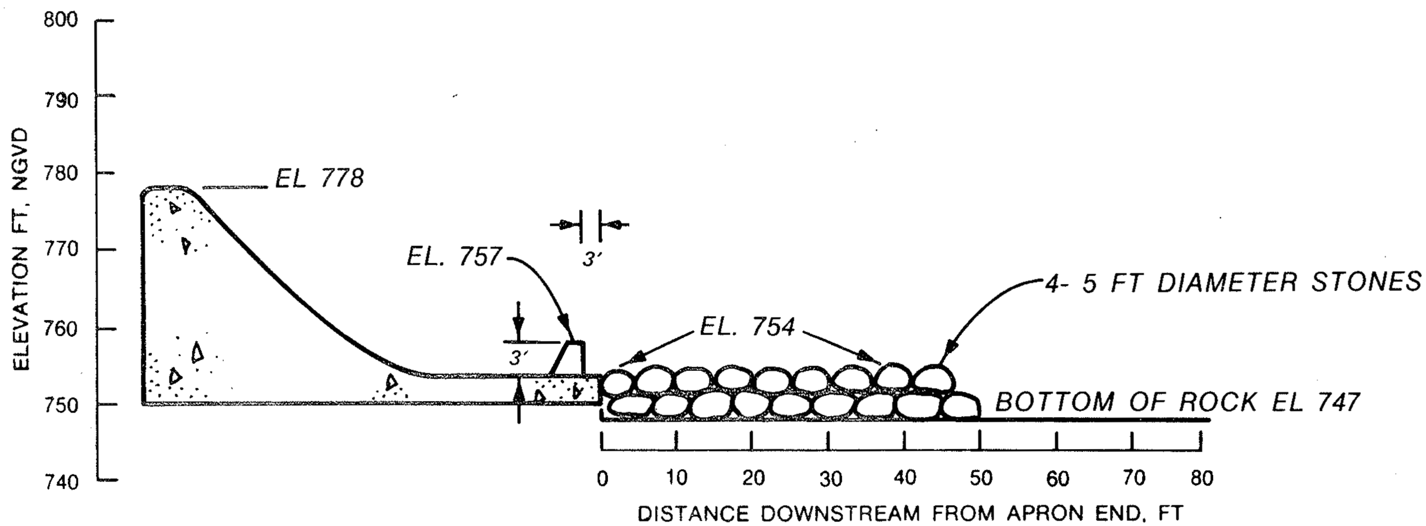


TYPE 5 SCOUR PROTECTION PLAN

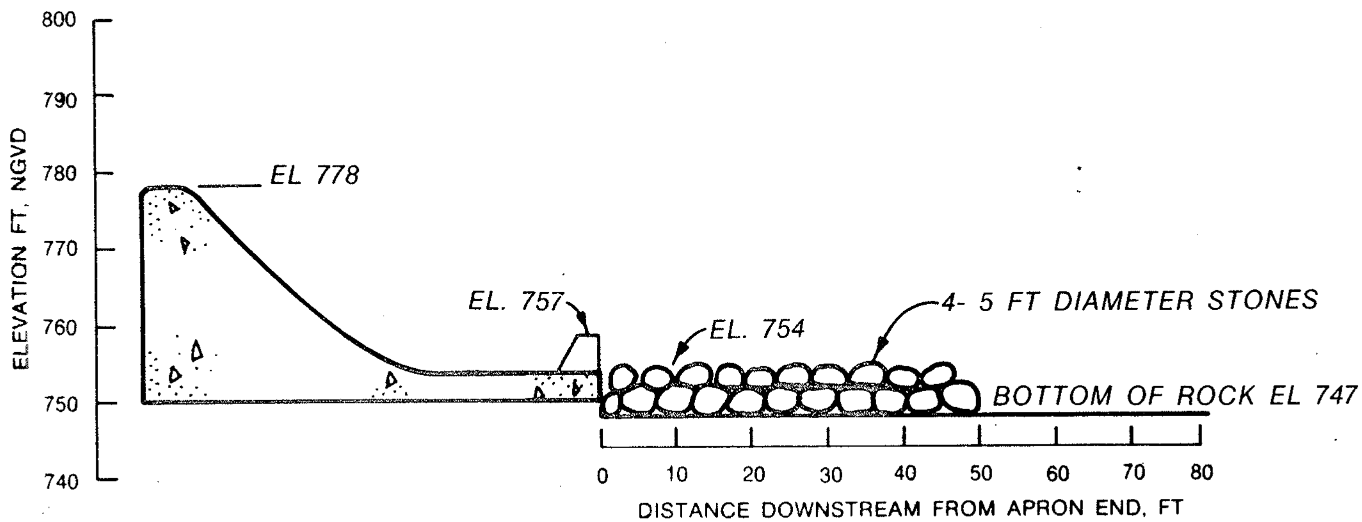


NOTE: VELOCITY AND WATER SURFACE PROFILES TAKEN ALONG MODEL CENTERLINE

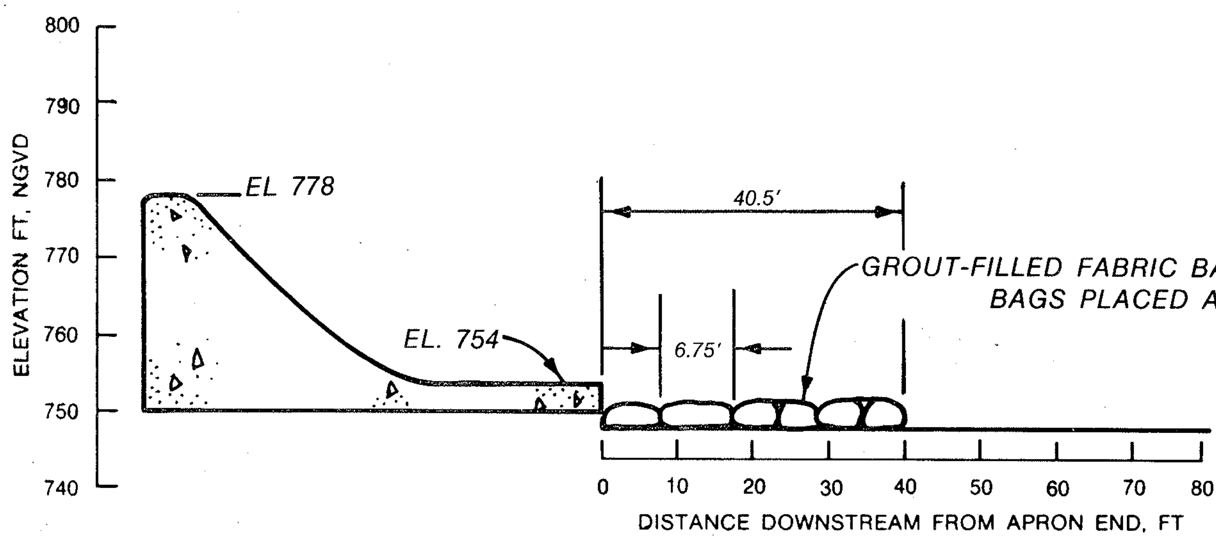
VELOCITIES
TYPE 5 SCOUR PROTECTION PLAN
DISCHARGE - 85,000 CFS
TW EL - 783.5



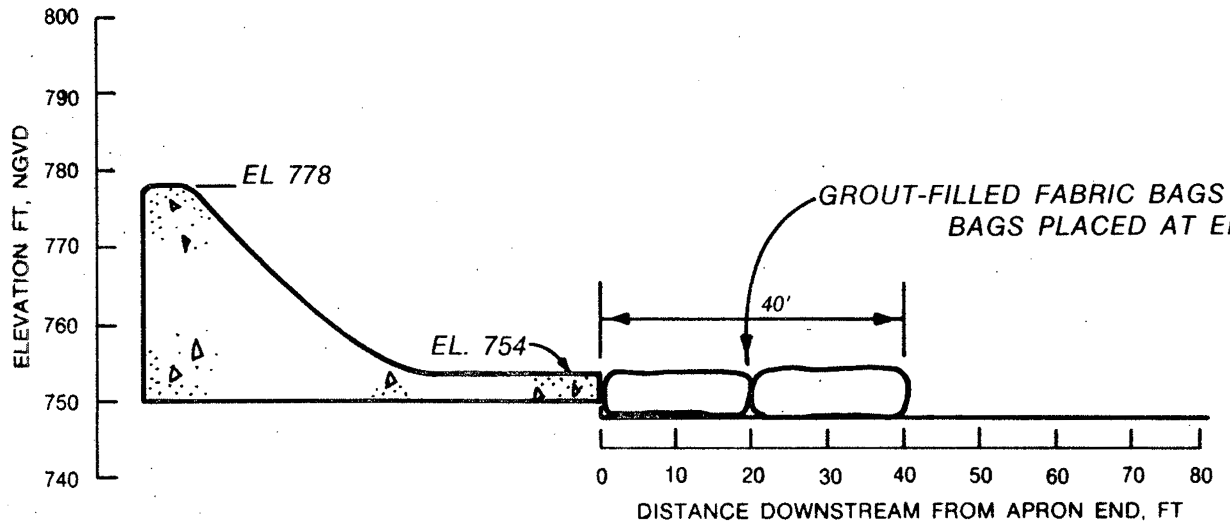
TYPE 6 SCOUR PROTECTION PLAN



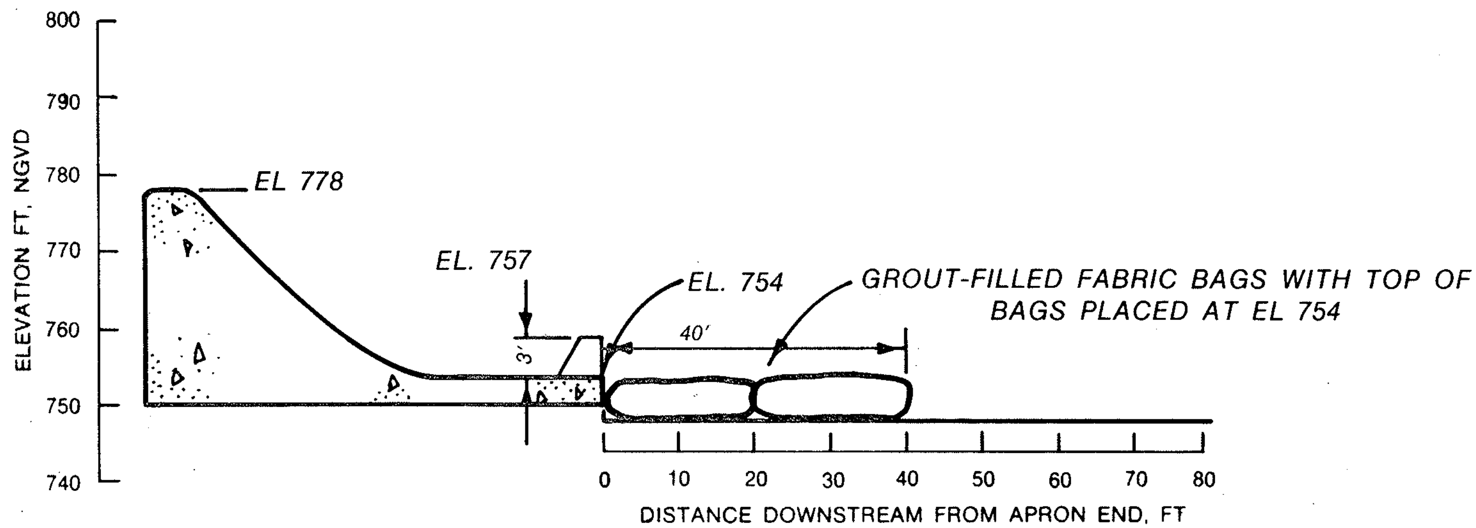
TYPE 7 SCOUR PROTECTION PLAN



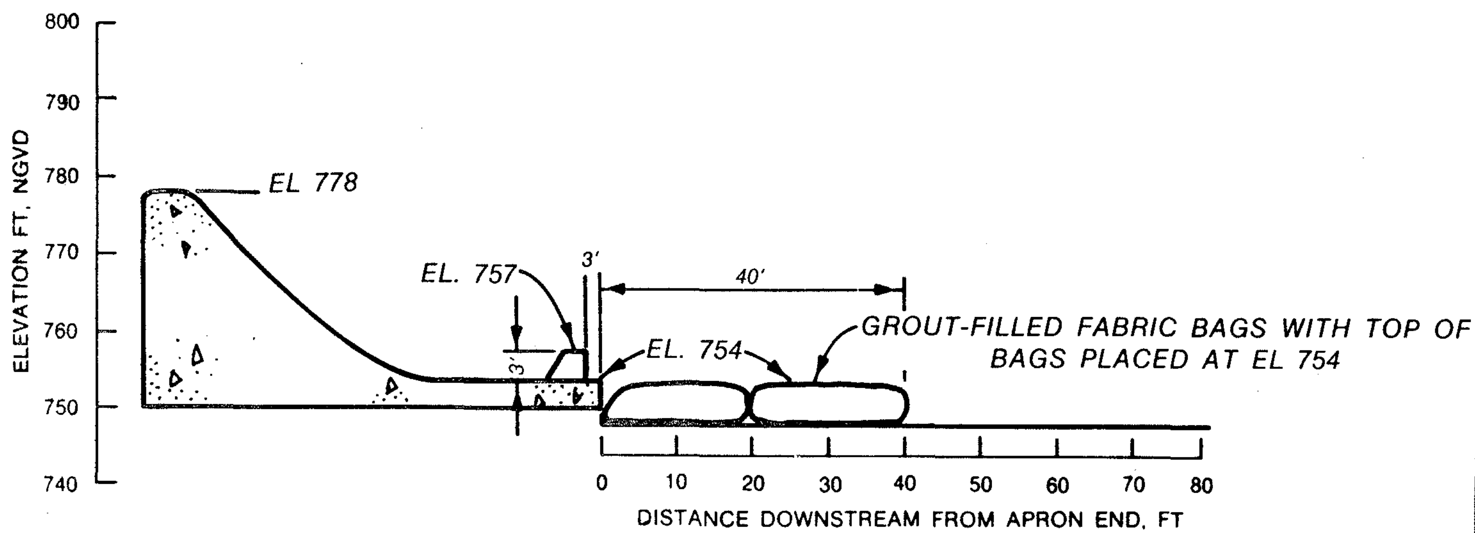
TYPE 8 SCOUR PROTECTION PLAN



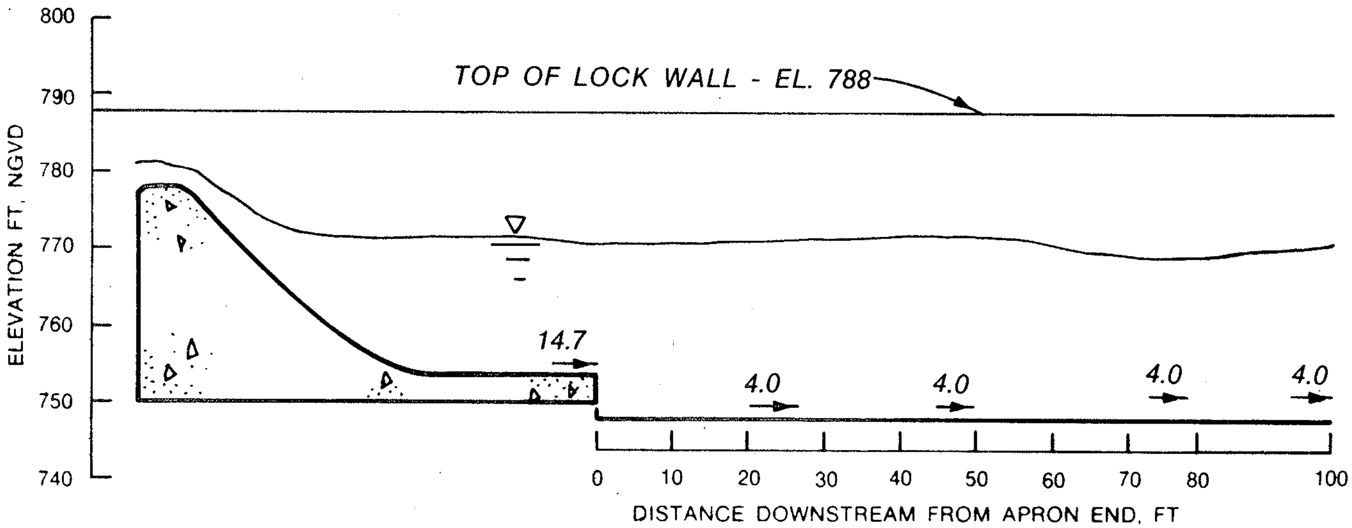
TYPE 9 SCOUR PROTECTION PLAN



TYPE 10 SCOUR PROTECTION PLAN

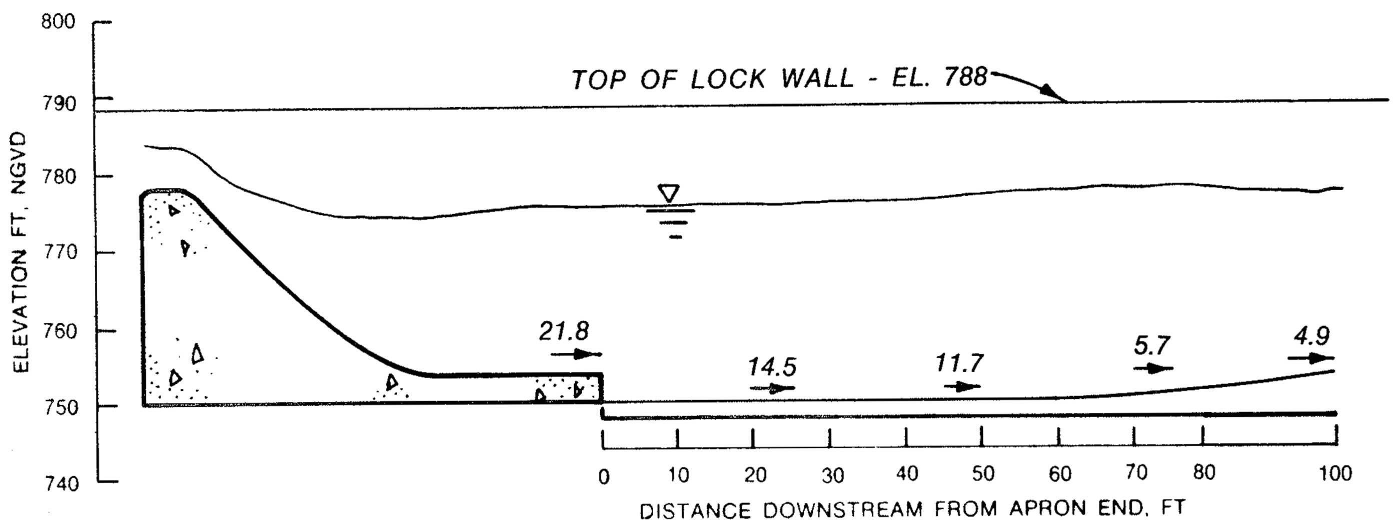


TYPE 11 SCOUR PROTECTION PLAN



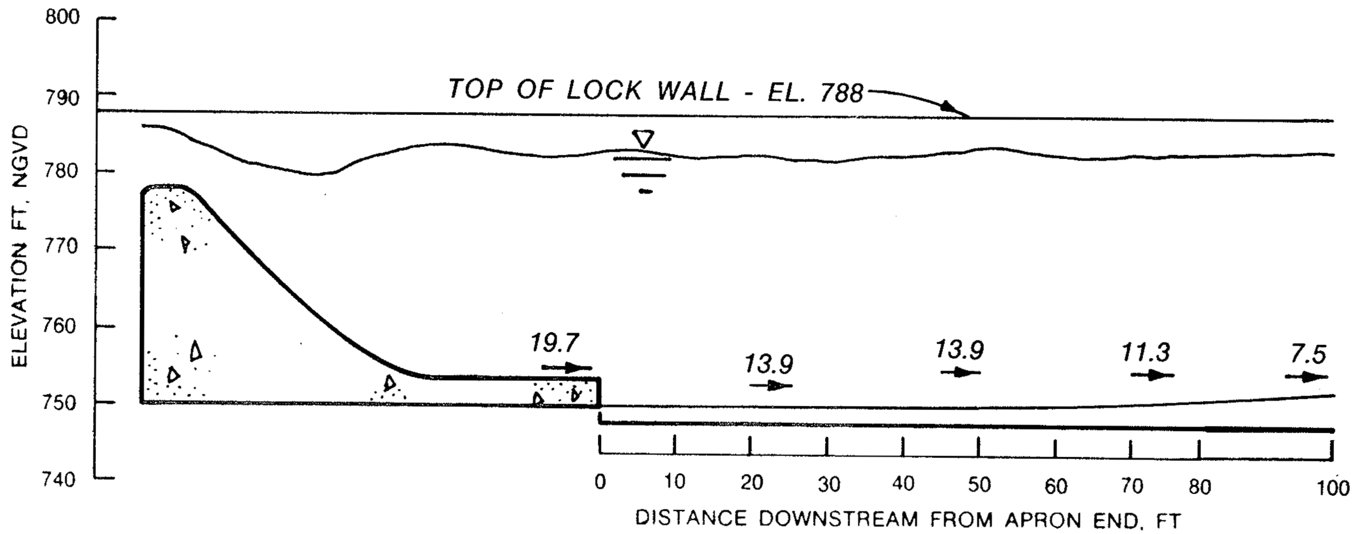
NOTE: VELOCITIES TAKEN 1 FT. OFF BOTTOM AND
1 FT. OUT FROM RIVER WALL OF LOCK

VELOCITIES ALONG RIVER WALL OF THE LOCK
DISCHARGE - 20,000 CFS
TW EL - 769.7



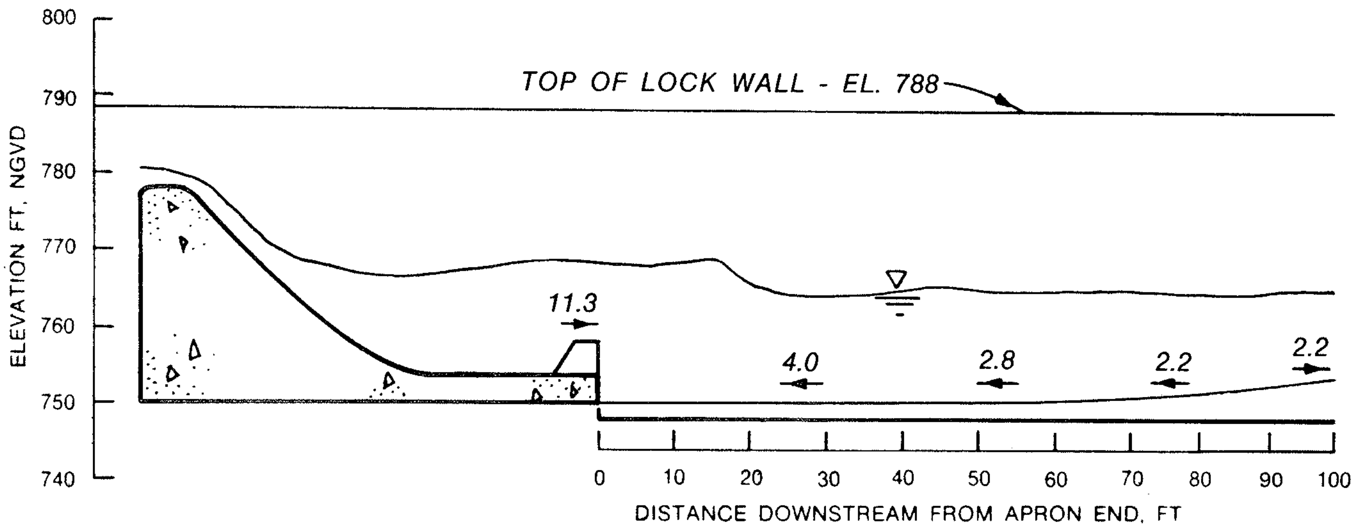
NOTE: VELOCITIES TAKEN 1 FT. OFF BOTTOM AND
1 FT. OUT FROM RIVER WALL OF LOCK

VELOCITIES ALONG RIVER WALL OF THE LOCK
DISCHARGE - 50,000 CFS
TW EL - 776.5



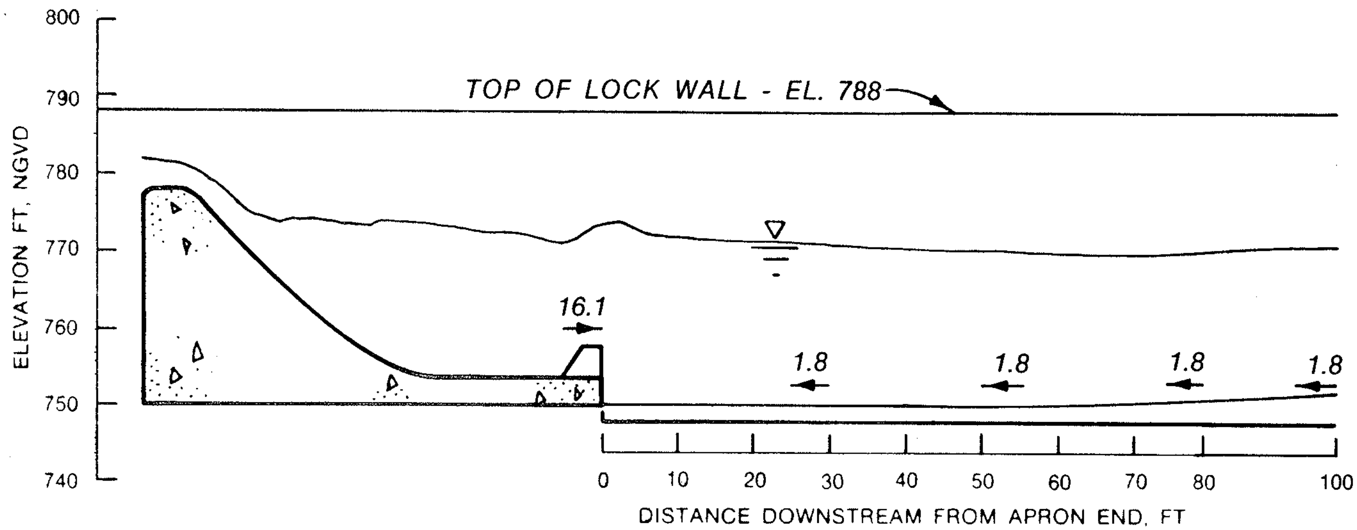
NOTE: VELOCITIES TAKEN 1 FT. OFF BOTTOM AND
1 FT. OUT FROM RIVER WALL OF LOCK

VELOCITIES ALONG RIVER WALL OF THE LOCK
DISCHARGE - 85,000 CFS
TW EL - 783.5



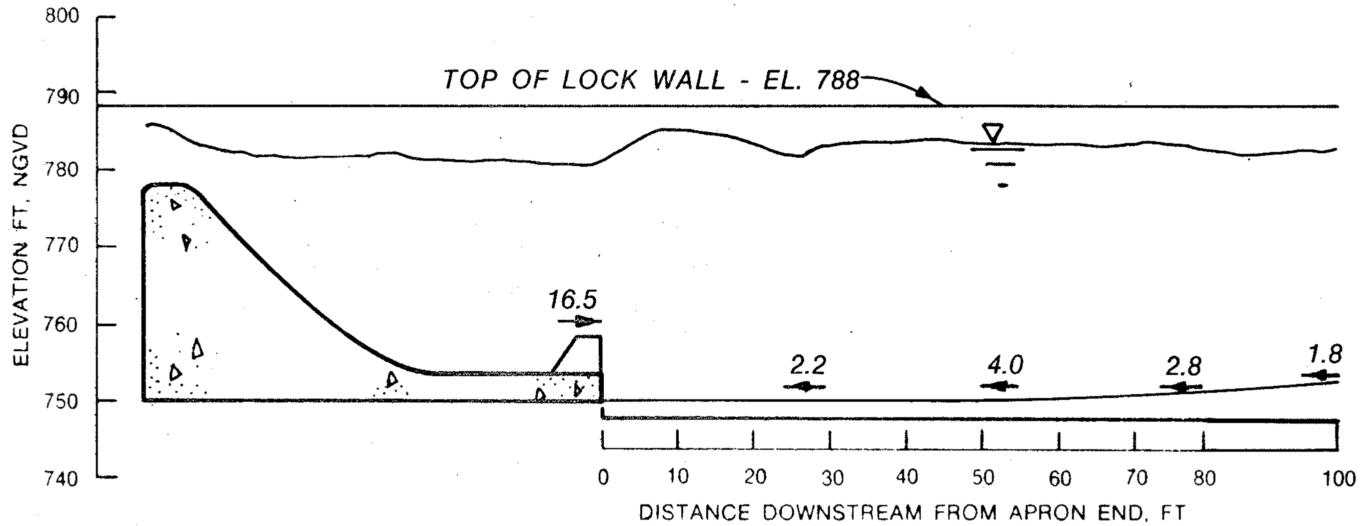
NOTE: VELOCITIES TAKEN 1 FT. OFF BOTTOM AND
1 FT. OUT FROM RIVER WALL OF LOCK

VELOCITIES ALONG RIVER WALL OF THE LOCK
3- FT- HIGH END SILL AT END OF APRON
DISCHARGE - 20,000 CFS
TW EL - 769.7



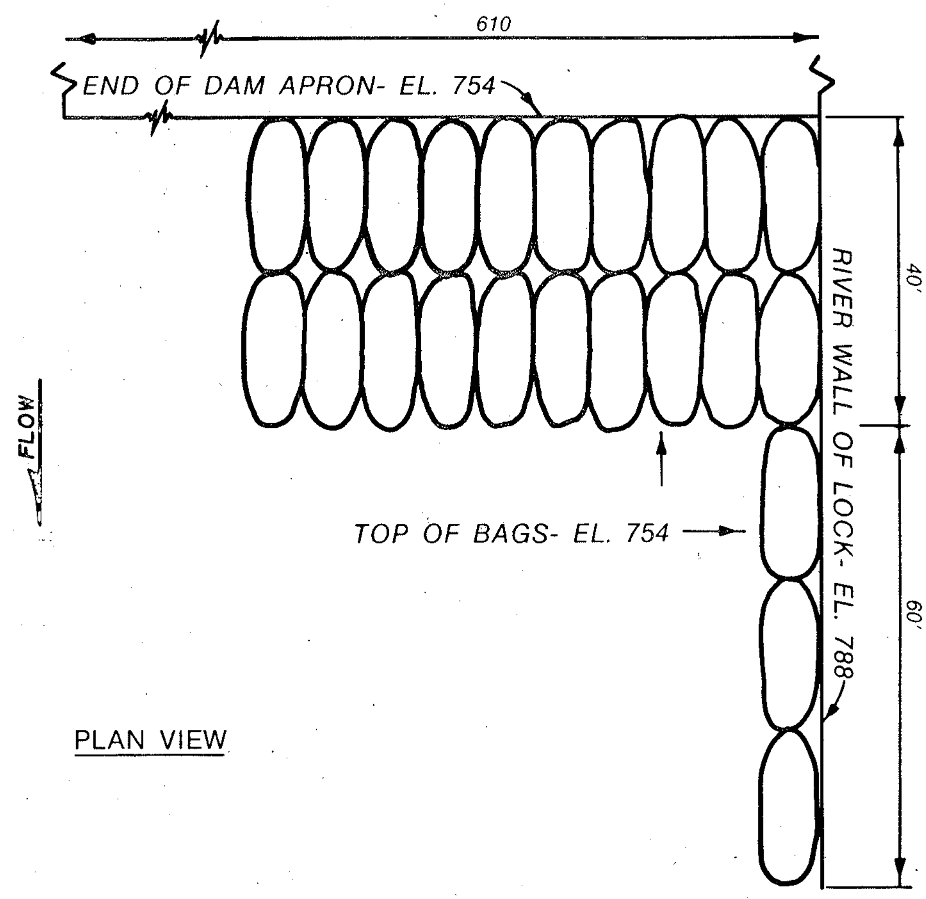
NOTE: VELOCITIES TAKEN 1 FT. OFF BOTTOM AND
1 FT. OUT FROM RIVER WALL OF LOCK

VELOCITIES ALONG RIVER WALL OF THE LOCK
3- FT- HIGH END SILL AT END OF APRON
DISCHARGE - 50,000 CFS
TW EL - 776.5



NOTE: VELOCITIES TAKEN 1 FT. OFF BOTTOM AND
1 FT. OUT FROM RIVER WALL OF LOCK

VELOCITIES ALONG RIVER WALL OF THE LOCK
3- FT- HIGH END SILL AT END OF APRON
DISCHARGE - 85,000 CFS
TW EL - 783.5



NOTE: 3- FT.- HIGH SLOPING END SILL
AT END OF DAM APRON

TYPE 14 SCOUR PROTECTION PLAN