TECHNICAL REPORT HL-79-9

VORTEX PROBLEM AT INTAKE LOWER ST. ANTHONY FALLS LOCK AND DAM MISSISSIPPI RIVER, MINNEAPOLIS, MINNESOTA

Hydraulic Model Investigation

by

Jackson H. Ables, Jr.

Hydraulics Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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Tests were conducted on a 1:25-scale model to develop the most feasible and permanent solution to a vortex problem at the Lower St. Anthony Falls Lock Intake on the Mississippi River at Minneapolis, Minnesota. On 10 March 1974, a lock employee in a small boat was accidentally drawn into the vortex and killed. Since that time a delayed valve-operating schedule has been used, which results in a fill time in excess of 14 min or about twice the design

(Continued)

20. ABSTRACT (Continued).

fill time; and although the vortex condition is reduced, the conditions are not considered satisfactory or safe. The lock is 56 ft wide, 400 ft long, and has a lift of 25 ft.

The recommended design (type 5) moved the intakes from the top of the upper gate sill and positioned a new intake in the upstream face of the sill, lowered the approach geometry in the approach to the intake ports, lengthened the bull-nose pier 28.75 ft between the existing lock and a possible future auxiliary lock and replaced the 7.5-ft-radius nose of the pier with an elliptical nose, added a vortex suppressor across the 56-ft-wide approach, and modified the culvert tainter control valve schedule from 2.07 min to 4.14 and 6.21 min. These modifications to the intake, geometry of the structure, and approach, together with the slower valve schedules, permited vortex-free operation of the lock. The lock filled in 7.9 min with a 4.14-min valve schedule. The lock can be filled in 8.9 min with a 6.21-min valve schedule. In order to obtain these satisfactory operating conditions and vortex-free operation, the type 5 design as described must be adopted and operated as recommended. Optimum conditions will not be obtained with adoption of only parts of the type 5 design.

PREFACE

The model investigation reported herein was authorized by the Office, Chief of Engineers (OCE), U. S. Army, on 3 April 1975, at the request of the U. S. Army Engineer District, St. Paul (NCS).

The study was conducted in the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) during the period May 1976 to September 1977 under the general supervision of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, and J. L. Grace, Jr., Chief of the Hydraulic Structures Division, and under the direct supervision of Mr. G. A. Pickering, Chief of the Locks and Conduits Branch. The engineer in immediate charge of the model was Mr. J. H. Ables, Jr., assisted by Messrs. D. B. Murray and C. L. Dent. This report was prepared by Mr. Ables.

During the course of the study, Messrs. S. B. Powell and J. Robertson of OCE, Mr. J. F. Ordenez of the North Central Division, Messrs. R. B. Fletcher, Joe Schultz, Jr., Grant Westall, S. V. Dobberpuhl, Richard Pomerleau, and Chuck Spitzack of NCS visited WES to discuss test results and correlate these results with design work being accomplished concurrently.

Directors of WES during the conduct of the studies and the preparation and publication of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.856	square metres
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	25.4	millimetres
miles (U. S. statute)	1.609344	kilometres
square miles (U. S. statute)	2.589988	square kilometres

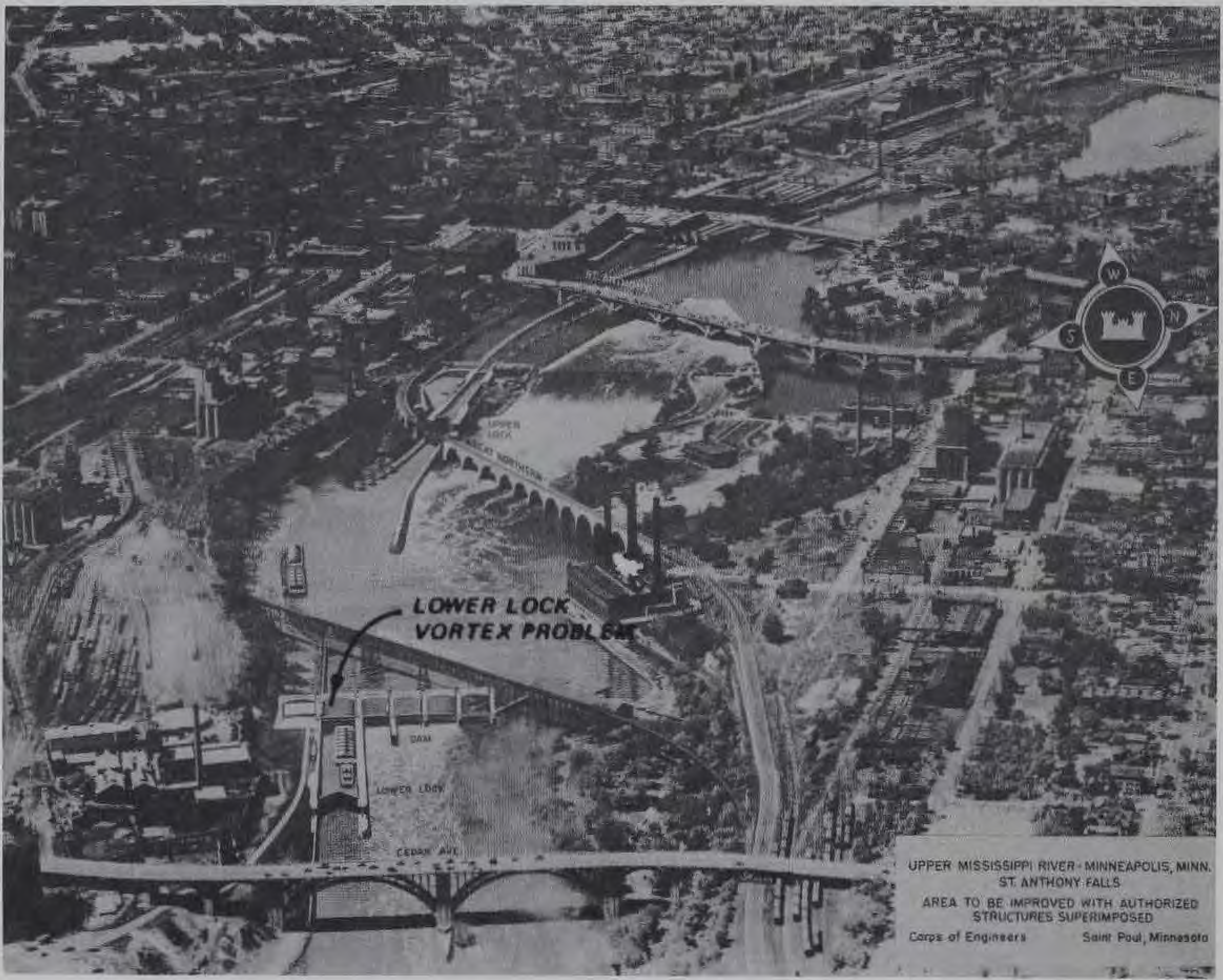

Figure 1. Aerial view of St. Anthony Falls project

VORTEX PROBLEM AT INTAKE, LOWER ST. ANTHONY FALLS LOCK AND DAM, MISSISSIPPI RIVER MINNEAPOLIS, MINNESOTA

Hydraulic Model Investigation

PART I: INTRODUCTION

The Prototype

1. The Lower St. Anthony Falls Lock and Dam is located on the Upper Mississippi River near Minneapolis, Minnesota (Figure 1 and Plate 1). It is part of a project designed to extend a 9-ft* navigation channel 4.6 miles upstream by ascending St. Anthony Falls in two steps and was completed in 1956.

2. The lock (Plate 2) is a gravity-type structure, placed on bedrock on the right bank of the river, below the original, fixed-crest lower dam that has been removed. The main lock chamber is 56 ft by 400 ft and with project pool and tailwater el 750.0 and 725.1,** respectively, provides the normal lift of 24.9 ft. The upper gate of an auxiliary lock has been provided so that a second lock may be added in the future if the traffic volume should require such an addition.

3. The lower gate in the main lock is a miter gate, and the upper gates in both the main and auxiliary lock chambers are tainter gates that can be used when needed to aid in discharging high flows in addition to being used in locking operations. For the passage of navigation, the upper gate in the open position is submerged. The tainter gates are 56 ft in length and have a damming height of 15.2 ft (top of sill, el 736.3; to top of sealed tainter gate, el 751.5). The filling and emptying system was designed to perform either function in 7.5 min.

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

** All elevations (el) cited herein are in feet referred to mean sea level.

4. The dam has a gravity-type, movable gate section that adjoins the auxiliary lock and consists of three 56-ft-long tainter gates that with a damming height of 20.5 ft (top of sill, el 731.0, to the top of sealed tainter gate, el 751.5). A steel plate girder service bridge spans the movable dam section, lock chambers, and storage yard and provides for the operation of the electric locomotive crane. To provide closure for the dam, a section of a gravity-type, nonoverflow structure, placed on bedrock, was constructed between the end of the movable gate section and the dam power station. See Table 1 and Plate 2 for additional Lower Lock and Dam data.

Operation data

5. The project pool, besides providing sufficient depth for navigation, must store water to generate electricity. Whenever the tainter gates are used to aid in maintaining project pool elevation, the following method of operation (from the Reservoir Regulation Manual*) has been adopted:

a. Whenever the flow is greater than hydroplant capacity, gate 1 (the most northerly gate, see Plate 2) is raised as required, up to a maximum opening of 1.5 ft.

b. For greater flows, after gate 1 has been opened 1.5 ft, gate 2 is raised, as required, up to a maximum opening of 1.5 ft.

c. For greater flows, after gates 1 and 2 have each been opened 1.5 ft, gate 3 is raised, as required, up to a maximum opening of 1.5 ft.

d. For greater flows, after gates 1, 2, and 3 have each been opened 1.5 ft, all additional gate openings are divided equally among these three gates, until a total discharge of 24,000 cfs (8,000 cfs per gate) is reached.

e. For flows greater than 24,000 cfs, the auxiliary lock gate is raised as necessary until a total discharge of 32,000 cfs (8,000 cfs per gate) is reached.

f. For flows greater than 32,000 cfs, all additional gate openings are divided equally among gates 1, 2, 3, and the

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* U. S. Army Engineer District, St. Paul, CE, "Reservoir Regulation Manual Appendix SAF, St. Anthony Falls Upper and Lower Lock and Dam," Minneapolis, Minnesota, Aug 1975.

auxiliary lock gate until a total discharge of 40,000 cfs (10,000 cfs per gate) is reached.

g. For flows greater than 40,000 cfs, all navigation is halted and the main lock gate is raised as necessary until a total discharge of 50,000 cfs (10,000 cfs per gate) is reached.

h. For flows greater than 50,000 cfs, all additional gate openings are divided equally among the five gates until the operating head becomes less than 1.0 ft. At this head all tainter gates are raised out of the water to their highest elevation, open river conditions are in effect in the Intermediate Pool, and the St. Anthony Falls Project is out of control.

6. Because of its small storage capacity, the pool is quickly affected by lockages and changes in power demand, and maintaining project pool, el 750.0, requires frequent tainter gate changes. Discharge curves obtained from United States Geological Survey gate calibrations for the tainter gates open in the normal and submerged positions are plotted in Plates 3 and 4, respectively. The tailwater rating curve is plotted in Plate 5.

Vortex problem

7. Plate 2 and Figure 2 show details of the lock and existing intake manifold. During the filling cycle of the lock, an intense vortex forms over the intake. Figure 3a shows how the vortex is generated from strong flow separation around the bullnose of the intermediate lock wall; Figure 3b is a photograph of the vortex at its approximate peak intensity. The vortex usually forms over port 1, as shown in Figure 3b, but has been observed over other ports as well. Figure 4 is a schematic presentation of the existing intake geometry in the prototype approach.

8. On 10 March 1974, a lock employee in a small boat was accidentally drawn into the vortex and killed. The vortex that forms during normal filling operations is considered extremely hazardous to pleasure craft. It was found that by restricting the filling valve movement and lengthening valve time and filling time, the vortices could be reduced to sizes that offer less hazard to pleasure craft. The original

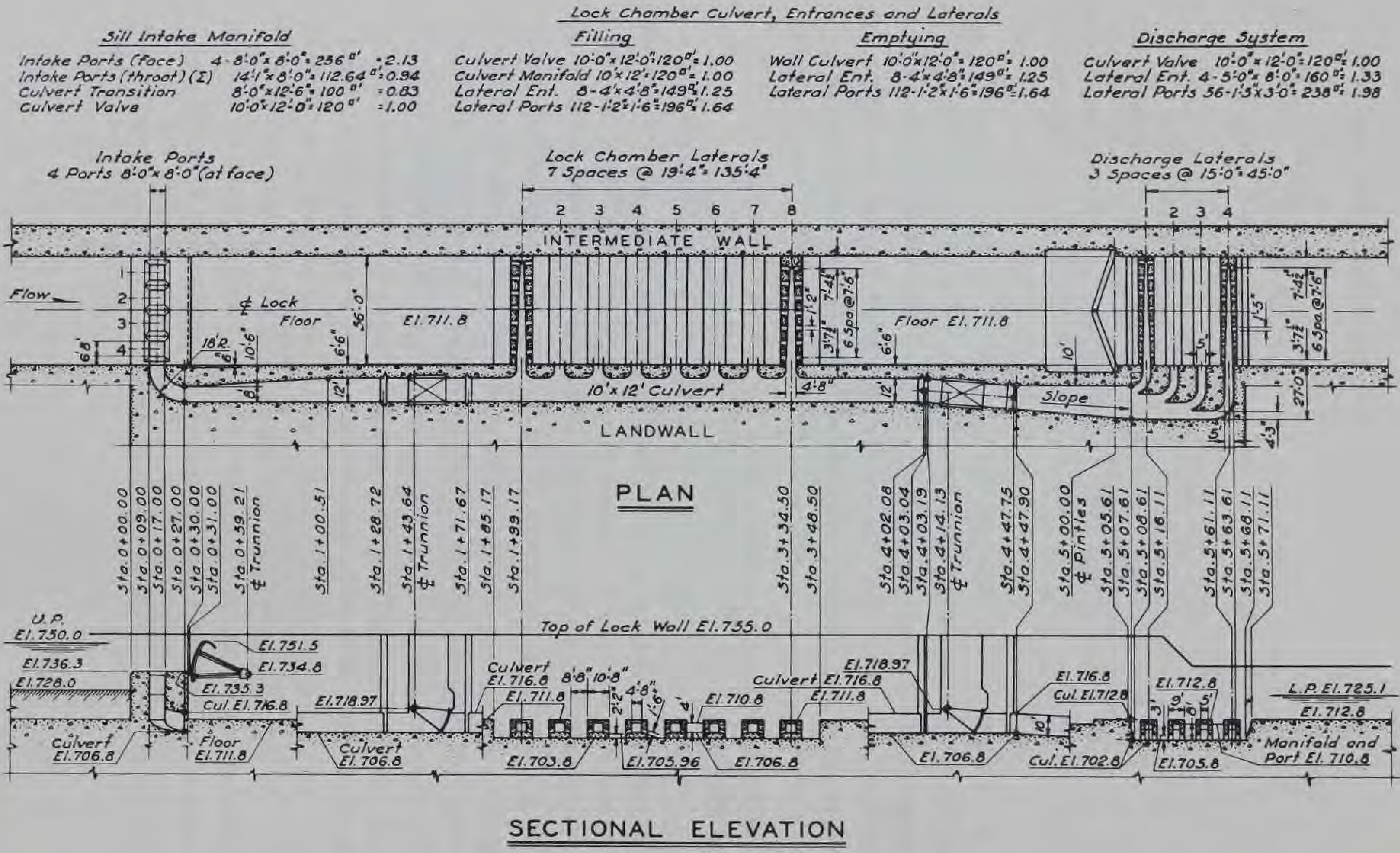


Figure 2. Lower lock filling and emptying system

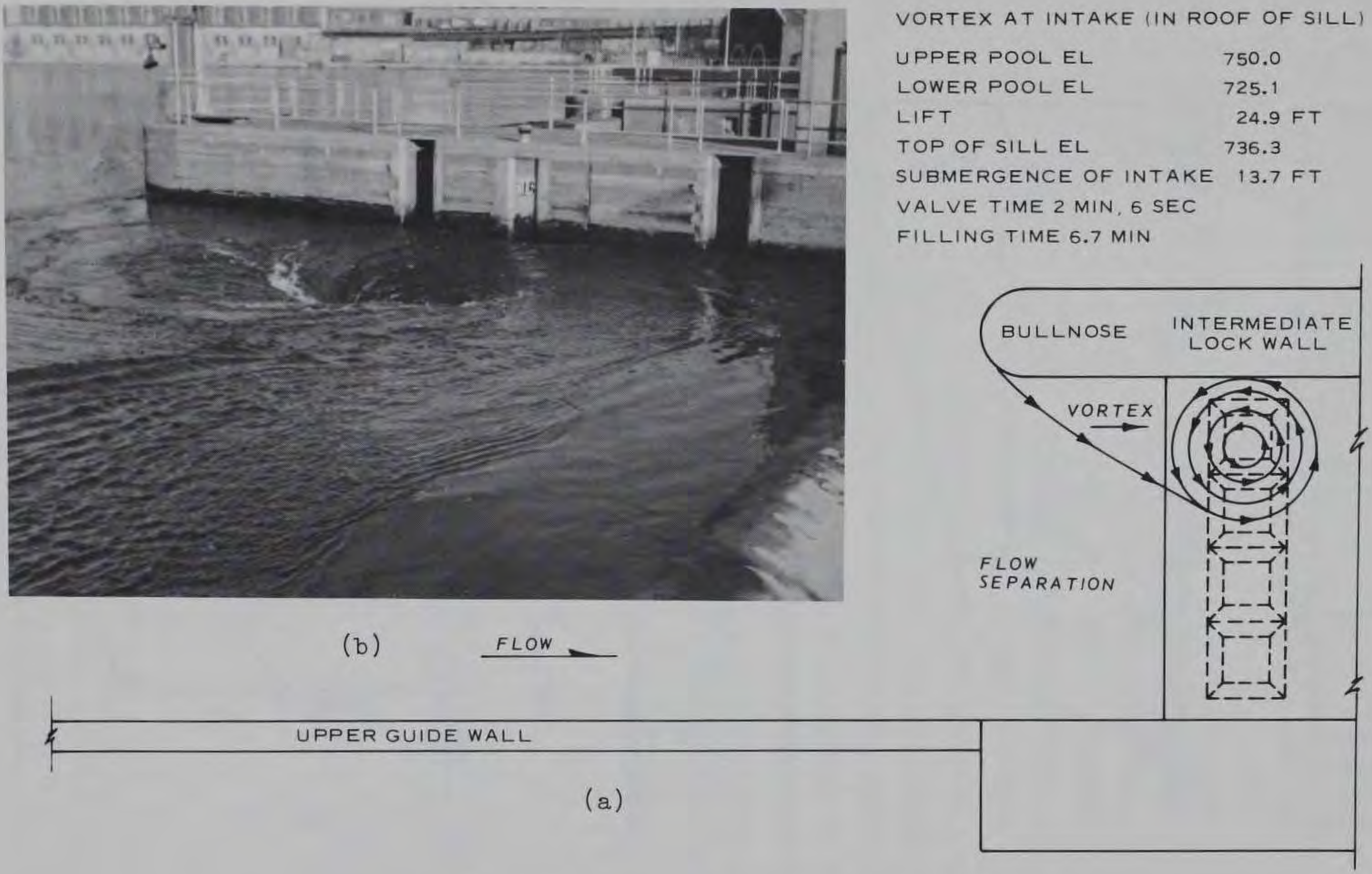
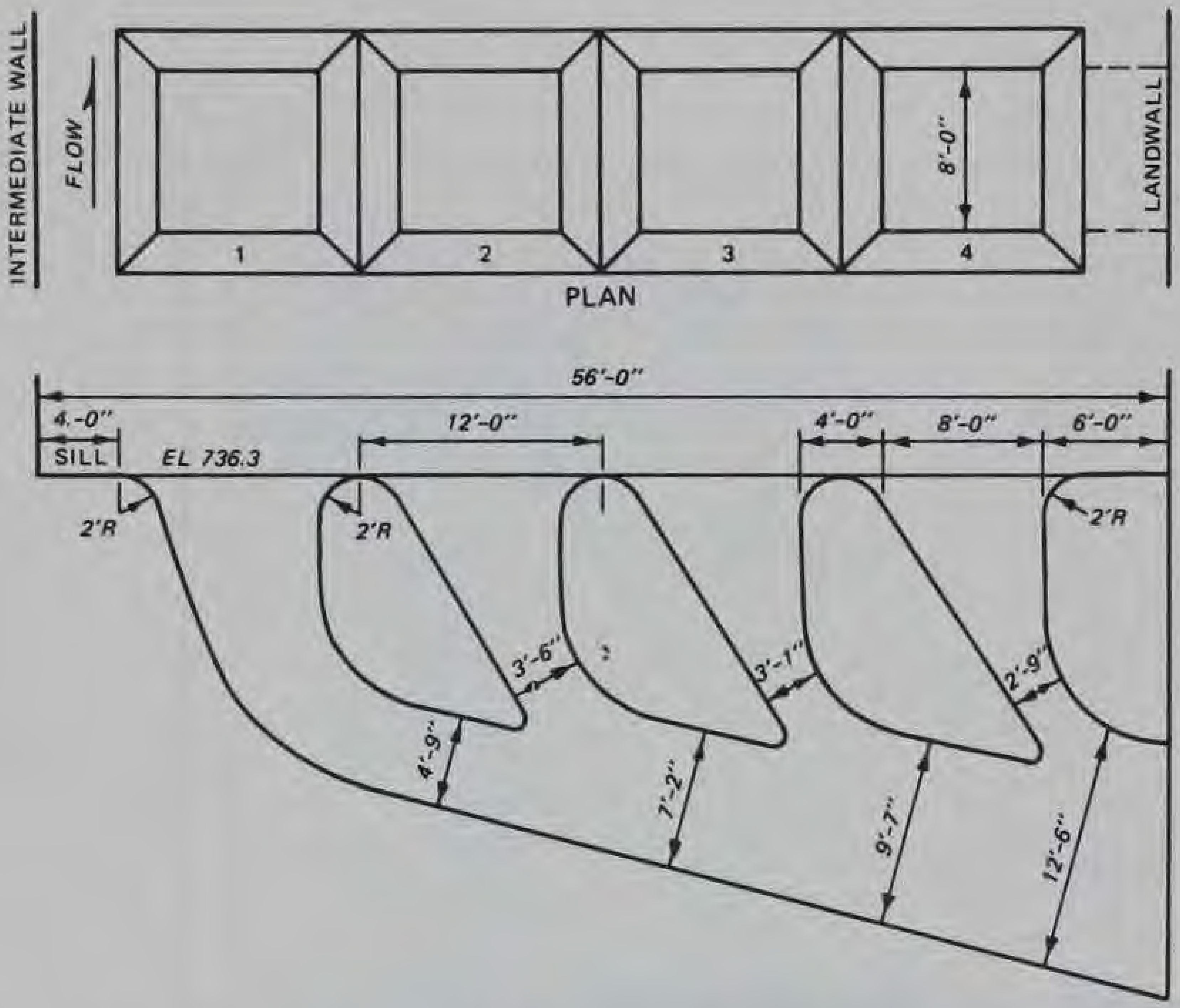
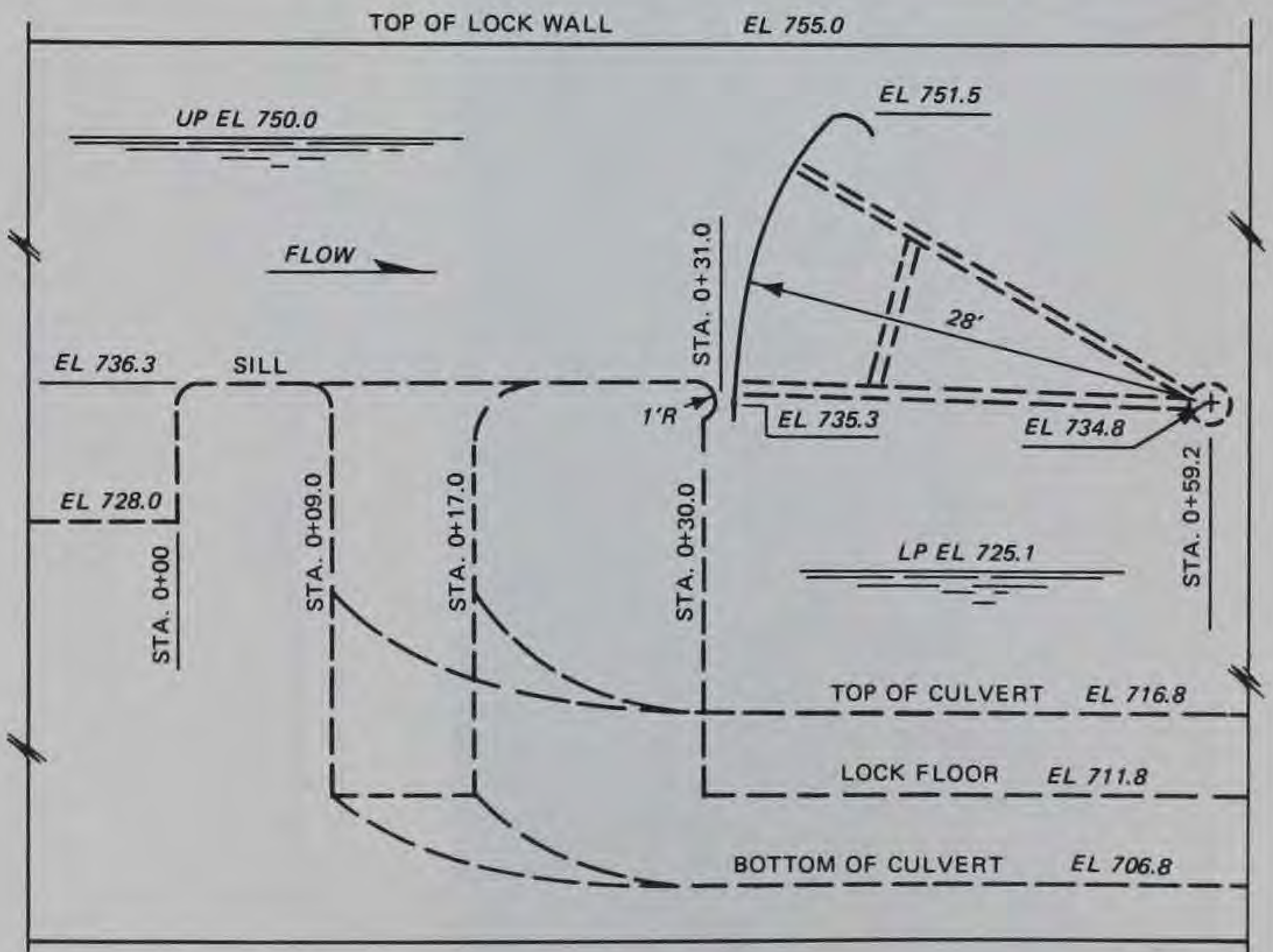


Figure 3. Schematic and view of vortex



a. Cross section, sill intake manifold, Lower Lock



b. Cross section, upstream to downstream, Lower Lock

Figure 4. Details of existing intakes

prototype and the St. Anthony Falls Hydraulic Laboratory* (SAFHL) model culvert valve schedule opened the valve in 2.05 and 2.08 min, respectively, and filled the lock in about 6.9 and 6.7 min, respectively (see Plate 6). The modified valve opening adopted after the accident is as follows:

Time Increment					
Min	Sec	to	Min	Sec	Modified Valve Schedule
0	00		0	37	Opens to 1/4 open position
0	37		3	56	Remains in 1/4 open position
3	56		4	25	Opens to 1/3 open position
4	25		11	58	Remains in 1/3 open position
11	58		12	58	Opens to full open position

This modified valve schedule increases the total lock filling time to more than 14 min or double that of the unrestricted valve operation. It is therefore highly desirable to operate the valve according to design and to develop modifications for preventing the vortex from reaching a hazardous intensity. Although the above delayed prototype operational schedule improves conditions, it does not result in completely satisfactory, safe, or vortex-free conditions.

Purpose of the Model Study

9. Because of the vortex problem discussed above, a model study was needed to determine the most feasible method for eliminating the vortex.

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* Saul Fidelman and James J. Hartigan, "Filling and Emptying Systems for St. Anthony Falls Locks, Mississippi River, Minnesota; Hydraulic Model Investigation," Hydraulic Laboratory Report No. 76, Dec 1964, U. S. Army Engineer District, St. Paul, Minnesota.

PART II: THE MODEL

Description

10. The 1:25-scale model reproduced approximately 600 ft of existing topography upstream of the lock intake and submergible tainter gate sill, the right bank topography and guide wall, 500 ft of topography north of the intermediate lock wall with bullnose pier, the auxiliary lock approach with tainter gate, and three gated spillway bays (capable of passing up to 32,000 cfs). The model included the lower lock intake, culvert, and culvert tainter valve control with the capability to reproduce the filling time and filling curve in a schematic chamber with appropriate upper and lower pools. Plate 7 indicates limits of prototype features included in the model test facilities. The upstream approach and guide wall were molded in concrete and the piers, intake sill, gated spillway, and bridge across the project were reproduced in sheet metal (Figure 5). The lock culvert was reproduced in sheet metal and plastic with a sheet-metal tainter control gate, and the schematic lock chamber was reproduced in brick with an adjustable control gate at the downstream end.

Appurtenances and Instrumentation

11. Water was supplied to the model through a circulating system. The headbay of the model contained a skimming weir that maintained essentially constant upper pool during filling operations. The lower pool below the lock and dam was controlled by a tailgate. The vertical control gate in the downstream end of the chamber permitted control of the lock chamber water surface for reproducing actual filling operations or steady-state peak discharge conditions. Dye and confetti were used to study subsurface and surface current directions in the approach and particularly in the vicinity of the problem area near the intake. Steel rails set to grade along both sides of the model provided a reference plane for measuring devices. Velocities were measured with a pitot tube;

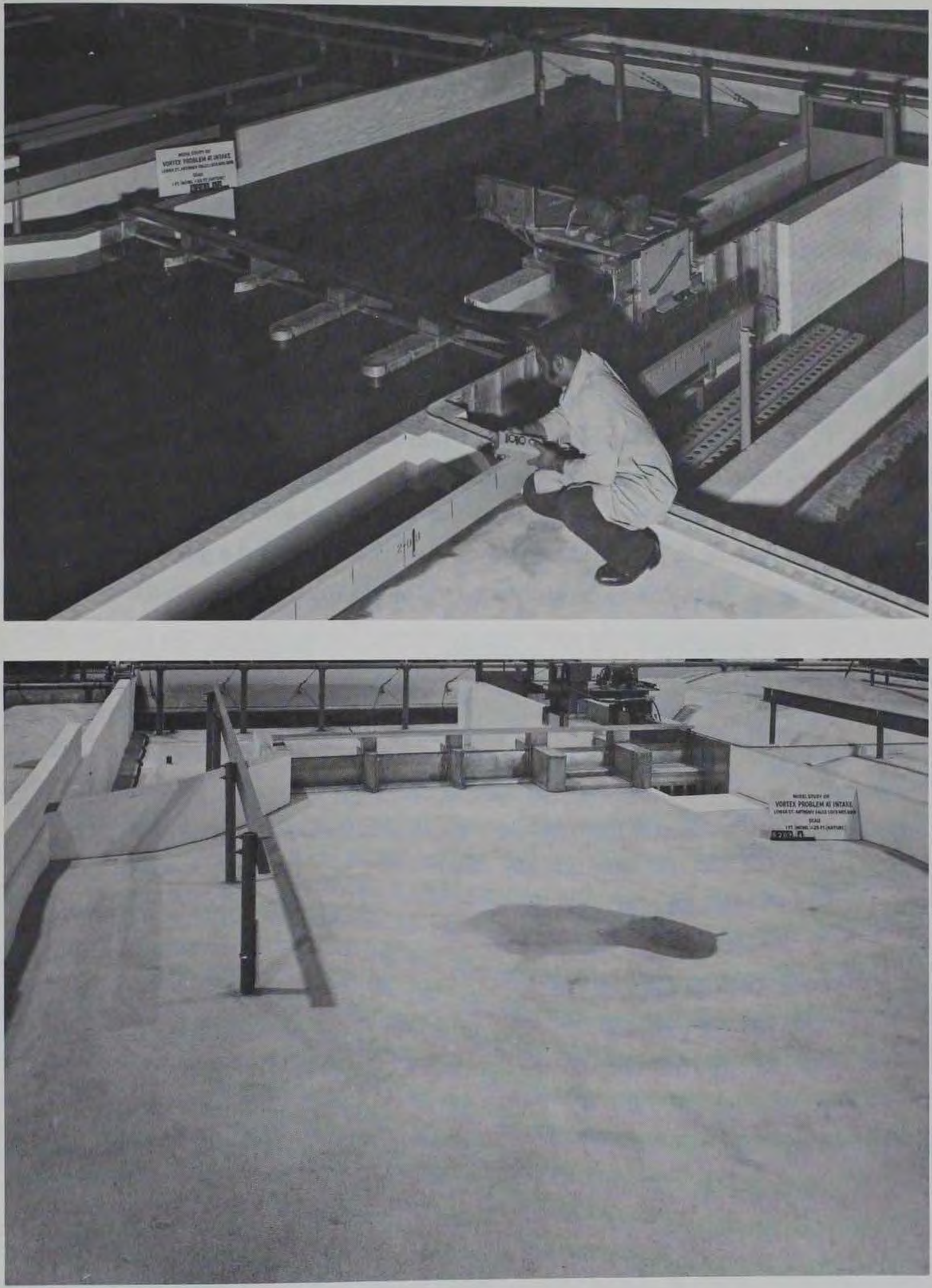

Figure 5. General views of upstream approach to Lower St. Anthony Falls Lock and Dam

water-surface elevations were measured with point gages; intake manifold and culvert pressures were measured in manometers connected by tubes to piezometers in the structure. Discharges through the lock and dam were controlled by means of venturi meters. Certain flow conditions in the models were recorded photographically. An exposure time of 1 sec in the model is equivalent to 5 sec in the prototype; this is most important in the interpretation of the photographic data.

Interpretation of Test Results

12. The accepted equations of hydraulic similitude, based on Froudian relations, were used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General relations for transference of the model data to prototype equivalent, or vice versa, are presented in the following tabulation:

Dimensions	Ratio	Scale Relations
Length	$L_r = L$	1:25
Area	$A_r = L^2$	1:625
Time	$T_r = L^{1/2}$	1:5
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3125

PART III: MODEL TEST AND RESULTS

Previous Model Investigation

13. The existing prototype intake in the top of the sill was previously model-tested at the SAFHL (see footnote on page 11) in an available facility that did not permit reproduction of the prototype approach topography with multiple riverflow conditions. Modeling of this area with riverflow capabilities would have identified the severity of the vortex problem and permitted the development of an improved design.

Type 1 Design

14. No purpose, other than verification of the severity of the vortex problem, could be served by building the existing structure and reproducing the intake with ports in the top of the sill (see Plate 2 and Figures 2-4). For this reason the sponsor submitted the type 1 intake design with four ports in the upstream face of the sill, as shown in Plate 8, for initial testing. During filling tests, valve operation and filling time were in agreement with the schedules shown in Plate 6. For both steady-flow and filling observations, water-surface elevations within the lock chamber were set from the filling curves shown in Plate 6. Approach topography in the immediate vicinity of the intake is shown in Plate 9.

15. Steady-flow data showing velocities and flow distribution in the intake ports and average pressures in the intake are shown in Plate 10 and Table 2. Piezometer locations are shown in Plate 8. Velocity measurements were recorded at 15 locations on the wall face of each port. From these data the percentage of total flow carried by each port was computed and plotted. Maximum velocities varied from 3 to 5 fps, with the highest velocity developing at port 1. The flow distribution in the intake ports reflected a balance in ports 2-4 with port 1 carrying between 4 and 5 percent greater flow.

16. The bullnose pier at sta 0+54 (Plates 8 and 9) was identified

as a trigger device stimulating vortex action over the intake ports. Navigation through the lock continues until river discharge exceeds 40,000 cfs. Thus, with a range of discharges between 5,000 and 40,000 cfs there are multiple flow conditions that can occur around the bullnose and in the vicinity of the lock intake. Sequence photographs showing surface currents in the upstream approach in the immediate vicinity of the type 1 intake during a filling operation with a 2.07-min valve schedule are shown in Photo 1. The lock filled in 6.9 min. Photo 2 shows peak steady-flow discharge conditions that occurred with the culvert valve fully opened, the lock chamber at el 732.0, and the upper pool at el 750.0. An air-entraining vortex 5 to 10 ft to the right and downstream of the tangent of the bullnose pier around sta 0+43 occurred during the period 2 to 5 min after the valve began to open. The bullnose pier stimulated this vortex action, even though the invert of the immediate approach area had been lowered 16.2 ft from el 728.0 (existing conditions) to el 711.8 (type 1 design) in front of the bullnose pier and the existing and future auxiliary lock to sta 1+25A.

17. Tests were conducted with various modifications to the approach area, including different lengths of bullnose pier, ports through the piers, hoods over the intake, and thin vertical walls or vanes on the approach floor. None of these modifications eliminated vortex tendencies. Movement of the bullnose upstream and the use of hoods over the intake moved the vortex position farther upstream by the length of hood added. The bullnose could be extended far enough (80 ft to sta 1+34) to greatly reduce the vortex, but the practicality of such a modification was questionable.

Type 2 Design

18. The throat of intake port 1 of the type 1 intake manifold was modified in order to improve flow distribution at the intake. This design was designated type 2 and is shown in Plate 11. Velocities, flow distribution, and average pressures for the steady-flow condition are shown in Plate 12 and Table 2. A comparison of flow distribution

in the existing type 1 and type 2 intakes is shown in the following tabulation:

Port No.	Flow Distribution in Percent Total Flow		
	Existing Intake*	Type 1	Type 2
1	25.0	28.4	25.1
2	22.0	24.8	25.5
3	23.2	23.6	24.7
4	29.8	23.6	24.7

* From Figure 6, Hydraulic Laboratory Report No. 76, December 1964 (see footnote, page 11).

Flow distribution obtained with the type 2 intake was considered excellent, but vortex conditions similar to those observed with the type 1 intake persisted.

Type 3 Design

19. With the type 2 intake manifold installed, attention was directed to the geometry of the approach and the bullnose pier. The approach invert length immediately upstream of the intake was reduced from 12.89 to 5 ft at el 711.8, and the 1V-on-2.5H slope then extended to sta 0+79.11. Vortex problems remained evident, but increasing the length of the bullnose pier 28.75 ft from sta 0+54 to 0+82.75 and changing the pier nose shape from circular to elliptical on the lock side resulted in less abrupt flow around the pier nose as riverflows increased. A 56-ft-wide by 5-ft-high deflector wall was installed at sta 0+81.61A and improved flow conditions, particularly for the lower flows. These changes are detailed in Plate 13 and were designated the type 3 design.

20. Surface currents in the immediate vicinity of the type 3 design during a filling operation with no flow through the spillway or auxiliary lock gates are shown in Photo 3. Photo 4 shows flow conditions with a steady-flow (peak) discharge condition. The effect of passing about 15,000-cfs riverflow through spillway gates 1, 2, and 3

can be seen by comparing Photos 4 and 5. Note that there is an air-entraining vortex in Photo 5, but some improvement has occurred at lesser riverflows.

21. The type 3 design was also tested with a single deflector beam, or multiple beams across the 56-ft width of the lock approach immediately upstream of the intake sill and below el 736.3 (crest of the sill); but this was ineffective in reducing vortex tendencies.

Type 4 Design

22. Since no trashrack had been investigated with previous designs, a design that used a vortex suppressor as a trashrack was developed during a conference at the U. S. Army Engineer Waterways Experiment Station (WES) with representatives of the St. Paul District, North Central Division, and WES. Further, it was agreed at this conference that slower valve schedules should be considered as a means of reducing the vortex tendencies, particularly for riverflow conditions. The St. Paul District furnished a flow duration curve for the Mississippi River at Anoka, Minnesota, river mile 871.3 (Plate 14) to be used as a guide in evaluating the flows over the dam and through the auxiliary lock in solving the vortex problem. These data cover a period from 1932-1968, and the following conditions were selected for developing the final design:

River Discharge cfs	Percent of Time Discharge Exceeded
0	100.0
2,500	80.0
5,000	47.0
7,500	28.0
14,000	11.0
24,000	4.0
32,000	1.2
40,000	Navigation ceases

23. Details of the type 4 design are shown in Plate 15. The 56-ft-wide by 5-ft-high deflector wall at sta 0+81.61, an element of the type 3 design, was eliminated in the type 4 design. The wall had appeared to improve flow conditions at lower flows but was less effective at higher flows. The intake from the type 2 design and the bullnose and invert geometry from the type 3 design were incorporated into the type 4 design. Installation of the 56-ft-wide vortex suppressor detailed in Plate 15 was a most significant addition. The optimum position of the vortex suppressor as shown was selected after many adjustments and observations. The open flow area of this suppressor was such that any energy loss at the rack did not result in increased filling times relative to tests made without a suppressor installed. The vortex suppressor modification significantly reduced vortex tendencies at the intake and within the approach area.

24. Tests were conducted with the type 4 design and the culvert valve opening times increased from 2.07 min to 4.14 and 6.21 min to determine the effect of valve time on vortex tendencies. Plates 16 and 17 are plots of filling curves and filling time versus valve time that result with the three valve times. All valve times were in accordance with the schedule in Plate 6.

25. Riverflows were varied from 0 to 40,000 cfs with the type 4 design, and observations were recorded for peak discharge (steady state), as well as filling operations with two or three valve times. Valve times recommended for optimum conditions with various riverflows are listed in the column on the right in Table 3. With increased river discharges, the lower pool in the prototype would be significantly raised above el 725.0 and head differentials would be reduced. However, all tests were made with a 25-ft design head condition so that approach conditions would be less severe in the prototype than those obtained in the model. Thus, it is very probable that valve times slightly less than those shown in Table 3 would provide satisfactory performance in the prototype.

Type 5 (Recommended) Design

26. Several modifications were model-tested prior to recommending a final design. These included raising the approach invert immediately upstream of the intake ports 2 ft from el 711.8 to 713.8, the invert of the culvert intake. Also, tests were conducted with the elliptical bullnose shortened in steps from the type 4 position at sta 0+82.75 to the existing position at sta 0+54. Shortening the elliptical pier resulted in the stimulation of vortex tendencies as river discharges increased.

27. Details of the type 5 (recommended) design and approach are shown in Plate 18 and Figure 6. The type 5 design was identical with the type 4 design, except that the approach invert immediately upstream of the intake ports was raised from el 711.8 to 713.8.

28. Photographic documentation of flow conditions with the type 5

Figure 6. Type 5 (recommended) design of intake, bullnose pier, vortex suppressor, and approach

design was obtained for selected conditions (Photos 6-19) based on the flow duration curve of the Mississippi River at Anoka, Minnesota, for the period 1932-1968. The following tabulation indicates river discharge, percent of time riverflow is above indicated discharge, recommended valve time for the operation, and photograph numbers for steady-state peak discharge and sequence photographs during the filling operation:

			Photograph Numbers for Flow Conditions in Lock Approach	
River Discharge cfs	Percent of Time Discharge Exceeded	Recommended Valve Time min	Steady-State Peak Discharge	Sequence During Filling Operation
0	100.0	4	6	13
2,500	80.0	4	7	14
5,000	47.0	4	8	15
7,500	28.0	4	9	16
14,000	11.0	6	10	17
24,000	4.0	6	11	18
32,000	1.2	6	12	19
40,000	Navigation ceases			

At no time during these tests did a vortex occur. Swirls and large mild eddies did occur in the model, but there should be no air-entraining vortex problem in the prototype if the type 5 (recommended) design is adopted, constructed, and operated in accordance with the recommended valve time schedules shown above. It should be noted that partial adoption of the design elements cannot be expected to result in optimum conditions in the prototype.

29. During the final conference on the subject model, the sponsor requested that WES make visual observations with various amounts of the lower portion of the 56-ft-wide trashrack and vortex suppressor immediately upstream of the intake covered to simulate debris collection and blockage. Results of observations made with the lower 7.5-, 10-, 15-, and 20-ft portion of the rack blocked over the full 56-ft width for peak discharge steady-flow conditions are presented in Table 4 and those

with normal filling operations and both 4.14- and 6.21-min valve schedules are presented in Table 5. These observations indicate that debris collection can be tolerated to about a 10-ft depth without any difficulty and possibly to 15 ft, but should not be allowed to go higher. It should be noted that lock filling times did not increase even with debris cover 20 ft high. However, it should be expected that there will be some collection of debris, and a submerged tree or other object of unusual geometry could trigger vortex activity. For this reason, daily inspection by the lockmaster of approach flow conditions during filling is recommended. Thus, as debris collects over much longer periods of time - which will normally be the case - he will recognize changes in approach flow condition and anticipate the necessity to clean the upstream face of the trashrack as required.

PART IV: DISCUSSION AND RECOMMENDATIONS

30. 1:25-scale model tests were conducted to assist engineers in selecting the most feasible permanent solution to the vortex problem at the Lower St. Anthony Falls lock intakes. The problem has existed since the prototype structure was completed in 1956, and on 10 March 1974 a lock employee was accidentally drawn into the vortex and killed. The vortex forms during normal filling operations and is considered extremely hazardous to pleasure craft. Since the accident in 1974 a delayed schedule of culvert valve operation has been implemented, which increases lock filling time from the design filling time of 6.9 min to approximately 14 min; and even with this slower filling time the upper lock approach conditions are not considered satisfactory or safe and continue to sustain air-entraining vortices.

31. As a result of very thorough model investigations, a design that eliminated the vortex was developed. The existing intake is in the top of the gate sill with the portals at el 736.3, while the recommended intake portals are in the upstream face of the sill with intake port invert at el 713.8. The shape of the existing bullnose pier at sta 0+54 was changed from round (7.5-ft radius) to elliptical and extended upstream 28.75 ft to sta 0+82.75. With the intakes positioned in the face of the sill to provide deeper submergence and to reduce approach velocities and strong surface and subsurface currents, a certain amount of excavation was necessary below the upstream topography, which was at el 728± in the immediate approach vicinity. The excavation shown in Plate 18 was the optimum amount required. The vortex suppressor, as detailed in Plate 18, completed the structural and geometry recommendations. Each element is important and collectively the type 5 design will function satisfactorily. In addition, changing from the 2.07-min existing valve time to provisions that will permit valve times of 4.14 and 6.21 min will further improve flow conditions in the lock approach. Whereas the existing 2.07-min valve time fills the lock in about 6.9 min, the 4.14-min valve will fill the lock in 7.9 min and the 6.21-min valve will fill the lock in 8.9 min. These valve times are required

for variations in river discharges. For river discharges from 0 to 7,500 cfs, a 4.14-min valve time is recommended, and for discharges from 7,500 cfs to 40,000 cfs when all navigation ceases, it is recommended that a 6.21-min valve time be adopted. The opening schedule should agree with the opening time ratio in Plate 6.

32. Adoption of the type 5 design together with the valve schedules recommended will result in a lock approach free of vortex problems and also in improved navigation conditions in the intake approach area of the lock. Each element of the type 5 design plays an important role in the overall performance, and partial adoption will not result in optimum or safe conditions.

33. Operation of the model spillway gates and future auxiliary lock control gate was in accordance with the "Reservoir Regulation Manual Appendix SAF.* This method of operating the spillway gates and auxiliary lock gate was found to be most satisfactory with the recommended type 5 design and culvert valve times for the lower lock.

34. A number of post-World War II navigation locks were designed with intake ports in the top of miter gate and tainter control gate sills, and history has proved these intakes to be vortex-prone and hazardous to pleasure craft. It is suggested that positioning intakes in the top of the upper gate sill be avoided in future lock design.

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* See footnote on page 6.

Table 1

General Data, Lower Lock and Dam

Project Intermediate Pool	el 750.0
Project Lower Pool (with 2 ft of flashboards atop Dam 1)	725.1
Lift	24.9 ft
River miles above Ohio River	853.4
Drainage area	19,680 square miles
Pool area at project pool elevation	50 acres
Maximum stages of record (17 April 1965):	
Intermediate Pool	el 751.42
Lower Pool	739.02
Discharge	91,000 cfs

Lower Lock*

Width (main and auxiliary locks)	56 ft
Length (main lock)	400 ft
Length (auxiliary lock)	upper gate only
Top of walls	el 755.0
Top of upper sill (tainter gate)	el 736.3
Top of lower sill (miter gate)	el 712.8
Floor	el 711.8

Upper gate (tainter gate) 56 ft × 15.2 ft damming height
Lower gate (miter gate) 2 leaves, each 32'2" × 39'8" damming height
Lock closed to navigation when discharge = 40,000 cfs
Number of emergency bulkheads (3'0" × 6'0" × 59'9-1/2") 13

Dam

Movable dam sections: 3 tainter gates, each 56-ft × 20.5-ft damming height

Top of sill	el 731.0
Apron, length	65.5 ft
Apron, top	el 710.0
Service bridge, base of rail	el 786.85

Electric locomotive crane, 25-ton capacity, 50-ft boom
Number of emergency bulkhead storage trucks (5'7-1/8" × 8'4") 8

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* All bulkheads for both Lower Lock and Dam and Upper Lock are stored at Lower Lock.

Table 2

Pressures Under Steady-Flow Conditions in Type 1 and 2 Intakes*

Piezometer No.	Zero	Type 1 Intake Reading	Type 1 Intake Pressure	Type 2 Intake Reading	Type 2 Intake Pressure
1	713.8	744.2	30.4	743.0	29.2
2	713.8	743.0	29.2	743.3	29.5
3	713.8	742.9	29.1	742.6	28.8
4	713.8	741.1	27.3	740.6	26.8
5	713.8	743.9	30.1	744.0	30.2
6	713.8	741.9	28.1	742.0	28.2
7	713.8	738.7	24.4	737.0	23.6
8	710.3	739.2	28.9	739.0	28.7
9	715.3	742.7	27.4	742.5	27.2
10	720.3	739.0	18.7	739.0	18.7
11	715.3	731.1	15.8	730.7	15.4

* Elevations in feet are referred to mean sea level. Pressures are in prototype feet of water. Culvert valve opened full (downstream miter gate partially open to maintain 18-ft head). Upper pool el 750.0, lower pool el 732.0. Piezometer locations are shown in Plates 8 and 11.

Table 3

Type 4 Design Observations, 25-ft Head (Upper Pool el 750.0, Lower Pool el 725.0); Steady-Flow Peak Discharge and Filling Operations Based on 2.07- and 4.14-min Valve Time

Total	Dam Gates			Auxiliary	Valve	Observations		Valve Schedule
Q, cfs	No. 1 Q, cfs	No. 2 Q, cfs	No. 3 Q, cfs	Lock Gate Q, cfs	Time min	Steady State (Max Q)	Filling	Recommended
0	0	0	0	0	2.07	Swirl at bullnose bulkhead slot	Swirl at bullnose bulkhead slot	
					4.14	Same	No swirls	4.14-min valve
1,375	0	0	0	1,375 1.0 ft open	2.07	Swirl at bullnose wall	No swirls	
					4.14	Infrequent swirl at bullnose wall	No swirls	4.14-min valve
2,500	2,500 1.5 ft open	0	0	0	2.07	Swirl at bullnose wall	No swirls	
					4.14	Swirl at bullnose wall	No swirls, smooth, random movement	4.14-min valve
3,875	2,500 1.5 ft open	0	0	1,375 1.0 ft open	2.07	Smooth large mild eddy over area	No swirls, smooth	
					4.14	Same	No swirls, smooth	4.14-min valve
5,000	2,500 1.5 ft open	2,500	0	0	2.07	Large mild eddy motion with occasional swirls	No swirls, smooth, some eddy motions	
					4.14	Swirls come and go with some eddy action at bullnose wall	No swirls, no eddy motion	4.14-min valve
6,375	2,500 1.5 ft open	2,500	0	1,375 1.0 ft open	2.07	Small swirl at bullnose wall near sill face	No swirls or eddy action	
					4.14	No swirls, mild eddy over approach area	No swirls or eddy action	4.14-min valve
7,500	2,500 1.5 ft open	2,500	2,500	0	2.07	Slow motion around bullnose and dead over sill area	Slow random movement	
					4.14	Same but slower around bullnose	Slow random movement	4.14-min valve
14,580	4,860 3.0 ft open	4,860	4,860	0	2.07	Smooth with random movement	Swirl attempts to form; right side is kicked upstream and dissipates	
					4.14	Slight swirl at trashrack break	Swirl starts but dies after maximum flow or full valve open reached	4.14-min valve
24,000	8,000 5.1 ft open	8,000	8,000	0	2.07	Mild eddy over approach area, swirls develop near center trashrack and sill, move toward right wall in upstream direction and dissipate	Mild eddy develops over approach, swirls appear as in steady-state but move upstream and dissipate	
					4.14	Slower version of 2.07-min condition but much improved	Swirl develops, moves upstream at slower rate	
					6.21	Very similar to 4.14-min conditions but further improvement	Almost swirl-free, swirls very insignificant	6.21-min valve
32,000	8,000 5.1 ft open	8,000	8,000	8,000 7.7 ft open	2.07	Eddy over approach area with increase in upstream movement at right wall upstream of trashrack, small swirl	Swirls will develop and move upstream along right wall	
					4.14	Slower eddy over approach, very little swirling	Some swirls but dissipate quickly	
					6.21	Mild eddy with minor circulation at right wall upstream of trashrack	Light swirl off right wall at maximum flow	6.21-min valve
40,000	10,000 6.6 ft open (Navigation ceases)	10,000	10,000	10,000 11 ft open	2.07	Strong eddy over lock approach area with strong swirls along right wall moving upstream, might vortex in prototype but no problem	Eddy on right side 15 to 20 ft along right wall upstream of sill	
					4.14	Large eddy with flow upstream along bullnose pier and right wall in lock approach area, might vortex in prototype but no problem	Mild eddy over approach area with small swirls upstream over right wall	
					6.21	Swirls develop 5 to 10 ft off right wall between 15 to 30 ft from sill. Strong but not persistent, might vortex in prototype but no problem	No eddy over approach but small swirls	6.21-min valve

Table 4

Observations of the Effect of Simulated Debris Covering Trashrack Vortex Depressor on Vortex Tendencies

With Steady-State Peak Discharge Through Lock, Type 5 (Recommended) Design

25-ft Head (Upper Pool el 750.0, Lower Pool el 725.0)

River Total Q cfs	Division River Discharge: Dam Gates No. 1 cfs	Dam Gates No. 2 cfs	Dam Gates No. 3 cfs	Auxiliary Lock Gate cfs	Valve Time Min	Fill Time Min	Visual Observations of Vortex Tendencies at Intake With Steady-Flow Peak Lock Discharge Through Intake with 56 ft Wide Trashrack, Vortex Depressor Covered*: 7.5 ft High	10 ft High	15 ft High	20 ft High
0	0	0	0	0	4.14	7.9	Swirls at bullnose bulkhead slot	Swirls at bullnose bulkhead slot	Swirls at bullnose bulkhead slot over open rack	Swirls at bullnose bulkhead slot over open rack
2,500	2,500 1.5 ft open	0	0	0	4.14	7.9	Occasional swirl at bullnose wall	Occasional swirl at bullnose wall	Occasional swirl off bullnose pier over open rack	Occasional swirl off bullnose pier over open rack
5,000	2,500 1.5 ft open	2,500	0	0	4.14	7.9	Occasional swirls	Occasional swirls	Occasional swirl off bullnose pier and on left wall at break in trashrack	Persistent swirl at left wall over open rack
7,500	2,500 1.5 ft open	2,500	2,500	0	4.14	7.9	Occasional swirls	Same as 7.5-ft-high observation	Occasional swirl off bullnose above open area and occasionally 6-12 ft off left wall above open area	Persistent swirl at left wall over open rack area
14,580	4,860 3.0 ft open	4,860	4,860	0	6.21	8.9	Occasional swirl 5-10 ft upstream toe of rack and 7 ft off right wall	Constant swirl 10-ft off right wall moves upstream of rack	Steady swirl 3-5 ft off right wall moves upstream of rack. Occasional swirl 12 ft off wall on ℄ above roof moves upstream	At 3 to 6 min strong vortex at upstream edge of sill 15 ft off right wall (potential for air-entraining in prototype)
24,000	8,000 5.1 ft open	8,000	8,000	0	6.21	8.9	Occasional swirls near center trashrack area	Occasional swirls near center trashrack area	Steady swirls near center trashrack area	Persistent swirls and occasional vortex at upstream edge ℄ of sill (potential problem for air-entraining plot)
32,000	8,000 5.1 ft open	8,000	8,000	8,000 7.7 ft open	6.21	8.9	Mild eddy with minor circulation at right wall upstream of intake	Same as 7.5-ft-high observation	Mild eddy continues with swirls near open trashrack area	Persistent swirls and occasional vortex at upstream edge sill (potential problem for air-entraining in prototype)
40,000	10,000 6.6 ft open	10,000	10,000	10,000 11 ft open	6.21	8.9	Navigation ceases, strong but not persistent swirls (potential for vortex in prototype)	Navigation ceases, strong but not persistent swirls (potential for vortex in prototype)	Navigation ceases, persistent swirls, occasional vortex over open trashrack (potential vortex problem in prototype)	Navigation ceases, persistent vortex at open area (potential vortex problem and air-entraining vortex in prototype)

* Terminology used in describing vortex tendencies:

(a) Swirl: A vortex with only a slight concave depression in water surface and without an air cavity or tail below the water surface.
(b) Vortex: A vortex with an air cavity or tail extending below the water surface.
(c) Air-Entraining Vortex: A vortex with a tail extending into the culvert intake.

Table 5

Observations of the Effect of Simulated Debris Covering Trashrack Vortex Depressor on Vortex Tendencies

During Normal Filling Operations, Type 5 (Recommended) Design

25-ft Head (Upper Pool el 750.0, Lower Pool el 725.0)

River Total Q cfs	Division River Discharge: Dam Gates No. 1 cfs	No. 2 cfs	No. 3 cfs	Auxiliary Lock Gate cfs	Valve Time Min	Fill Time Min	Visual Observation of Vortex Tendencies During Filling Operations with 56 ft Wide Trashrack, Vortex Depressor Covered*: 7.5 ft High	10 ft High	15 ft High	20 ft High
0	0	0	0	0	4.14	7.9	No swirls	Slight swirl at bullnose bulkhead slot at 5 min	Slight swirl at 2.75 to 5 min about 2 ft off bullnose wall above upstream edge rack	Strong swirls 3 to 5 min at about 5 to 10 ft off left wall above open rack
2,500	2,500 1.5 ft open	0	0	0	4.14	7.9	No swirls	Occasional swirls	Occasional swirl over open rack	Strong swirls at left wall over open rack
5,000	2,500 1.5 ft open	2,500	0	0	4.14	7.9	No swirls	Occasional swirls	Occasional swirl over open rack	Strong swirls above open rack area
7,500	2,500 1.5 ft open	2,500	2,500	0	4.14	7.9	Random movement, no swirls	Occasional swirls	Swirl over open rack	Persistent swirls at left wall over open rack
14,580	4,860 3.0 ft open	4,860	4,860	0	6.21	8.9	Swirl above toe trashrack at left wall moves upstream and dissipates	Same as 7.5-ft-high observation	Swirl 3.5 to 5 min at 12 ft off sill and over upstream edge trashrack	Strong vortex 3.5 to 6 min over upstream edge rack 15 to 5 ft off left wall (potential for air-entraining prototype)
24,000	8,000 5.1 ft open	8,000	8,000	0	6.21	8.9	Insignificant swirls	Same as 7.5-ft-high observation	Swirl over open rack center area	Persistent swirls and occasional vortex 3-6 min (potential for prototype vortex problem)
32,000	8,000 5.1 ft open	8,000	8,000	8,000 7.7 ft open	6.21	8.9	Slight swirl at right wall around peak flow	Swirl at right wall above toe of rack at peak flow	Swirls over open rack area dissipate quickly	Persistent swirls and occasional vortex (potential for prototype vortex problem)
40,000	10,000 6.6 ft open	10,000	10,000	10,000 11 ft open	6.21	8.9	Navigation ceases. Swirls of no significance	Navigation ceases. Swirls same as 7.5-ft-high observation	Navigation ceases, swirls strengthen, occasionally a vortex (potential for prototype vortex)	Navigation ceases (potential for prototype vortex problem)

* Terminology used in describing vortex tendencies:

(a) Swirl: A vortex with only a slight concave depression in water surface and without an air cavity or tail below the water surface.
(b) Vortex: A vortex with an air cavity or tail extending below the water surface.
(c) Air-Entraining Vortex: A vortex with a tail extending into the culvert intake.

a. Before filling started

b. 2.0 min after filling started

c. 3.5 min after filling started

Photo 1. Surface currents during filling operation, type 1 (original) intake, time exposure 5 sec; upper pool el 750.0, lower pool el 725.0, 2.07-min valve time (sheet 1 of 2)

d. 5.0 min after filling started

e. 7.0 min after filling started

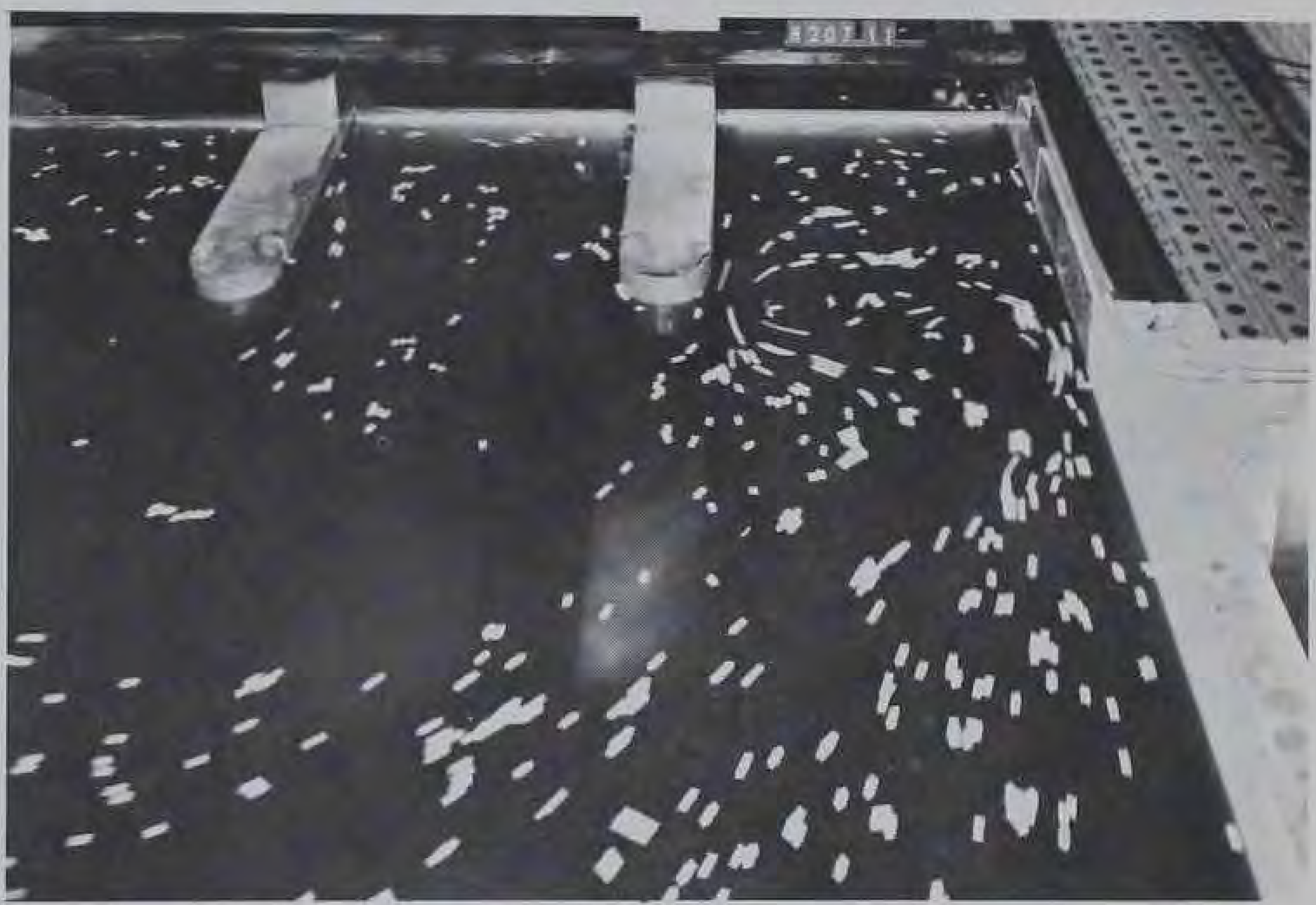
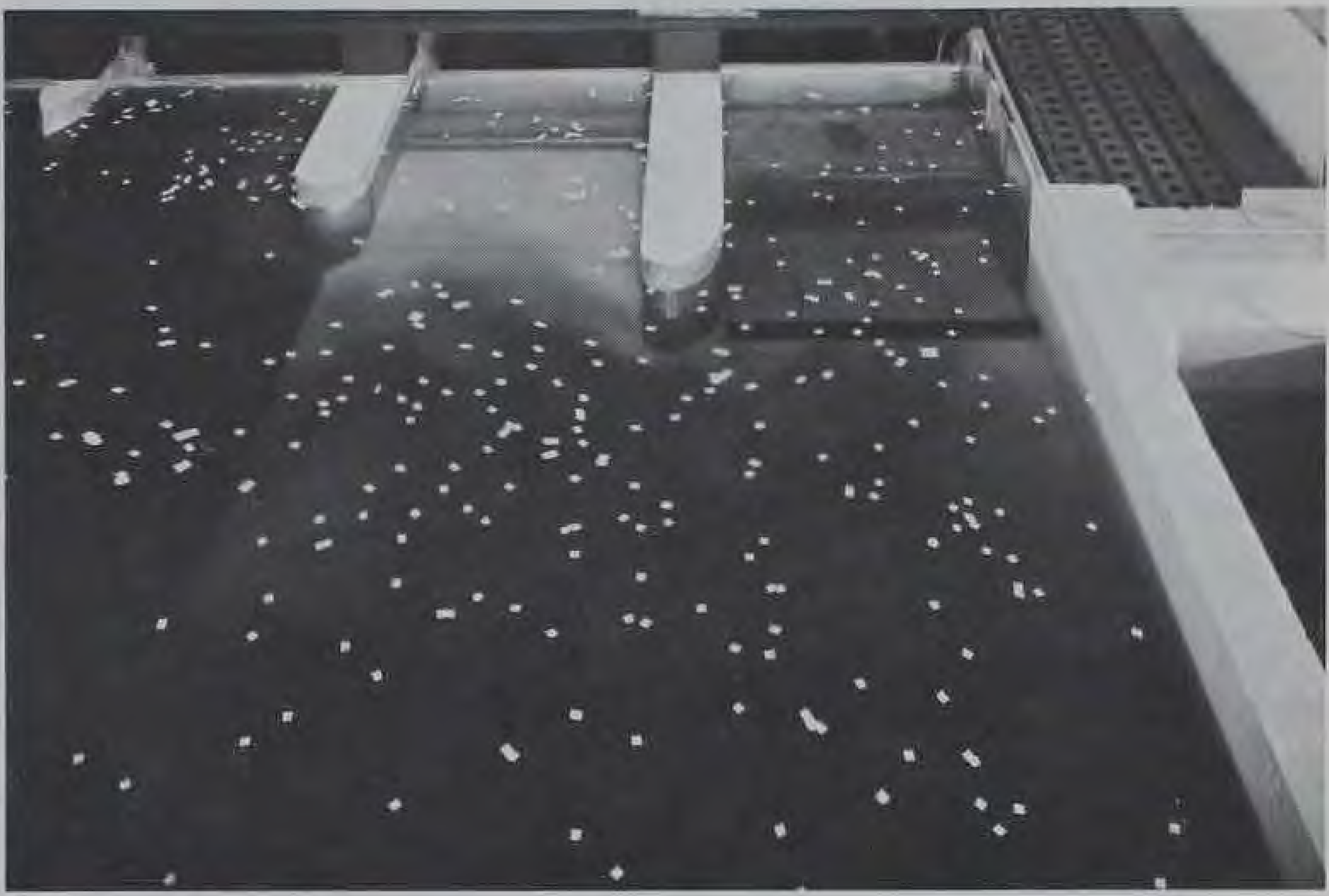
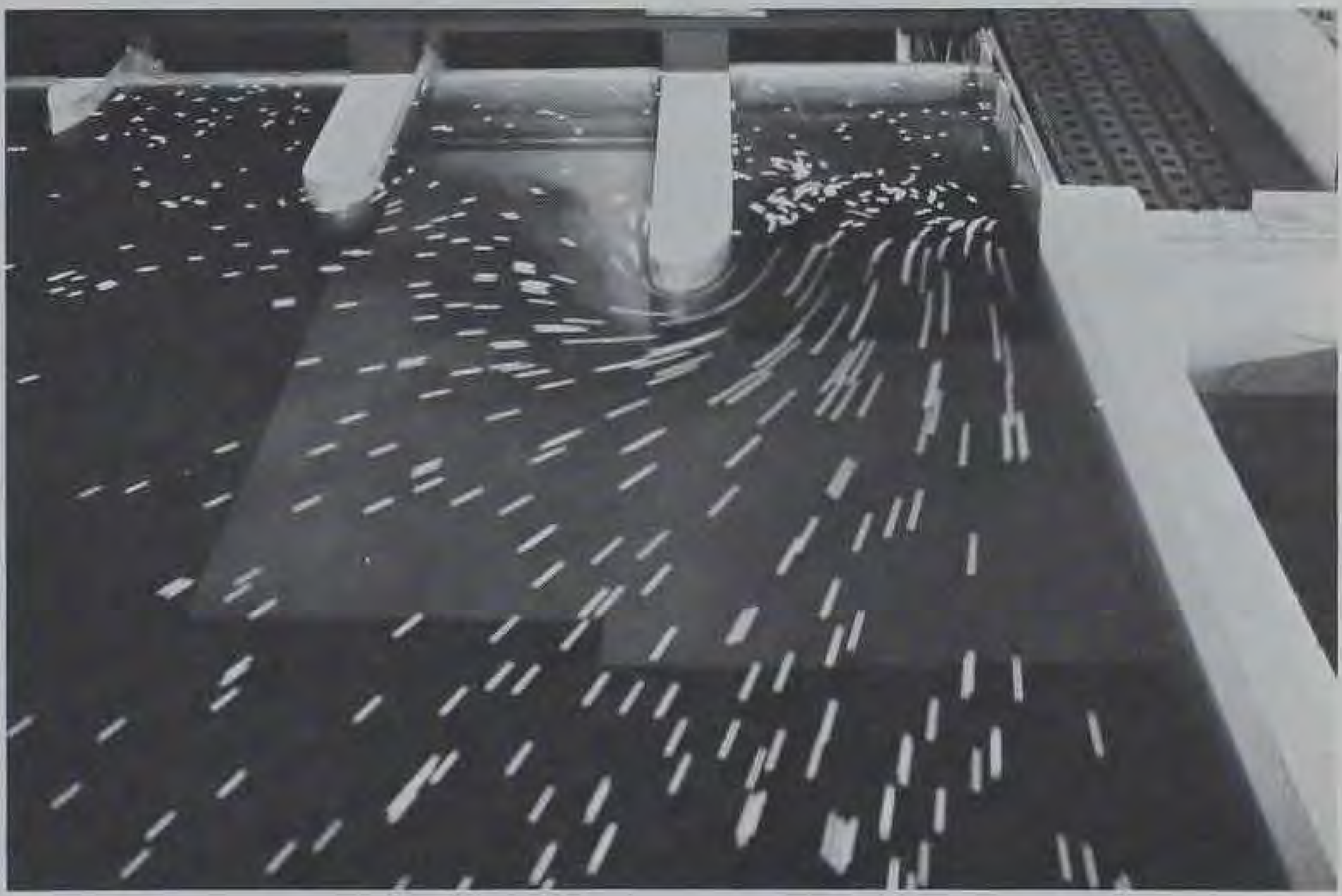


Photo 1 (sheet 2 of 2)

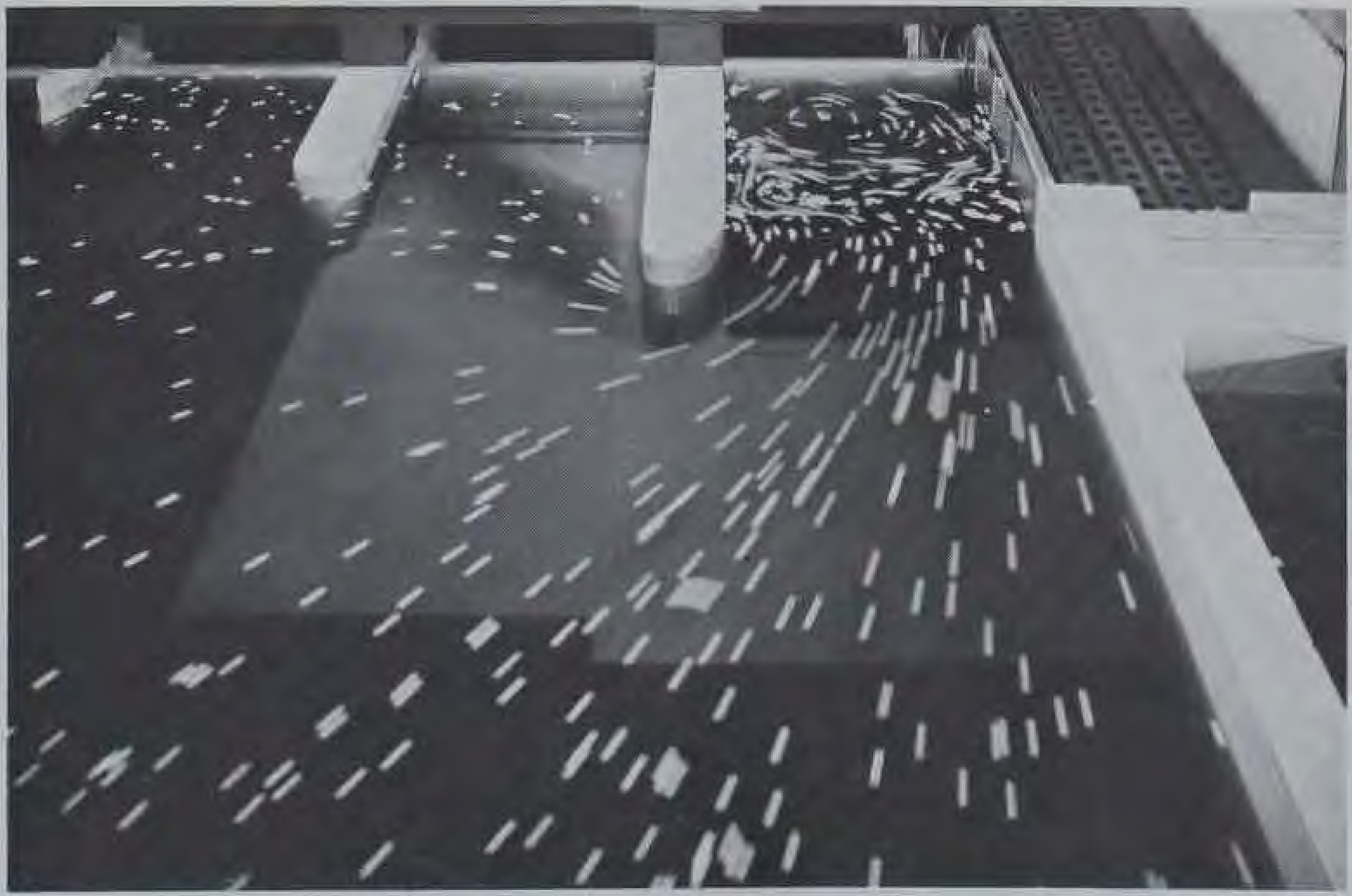
Photo 2. Surface currents during steady-flow peak discharge conditions at type 1 (original) intake, time exposure 5 sec, culvert valve fully open; upper pool el 750.0, lock chamber el 732.0



a. Before filling started



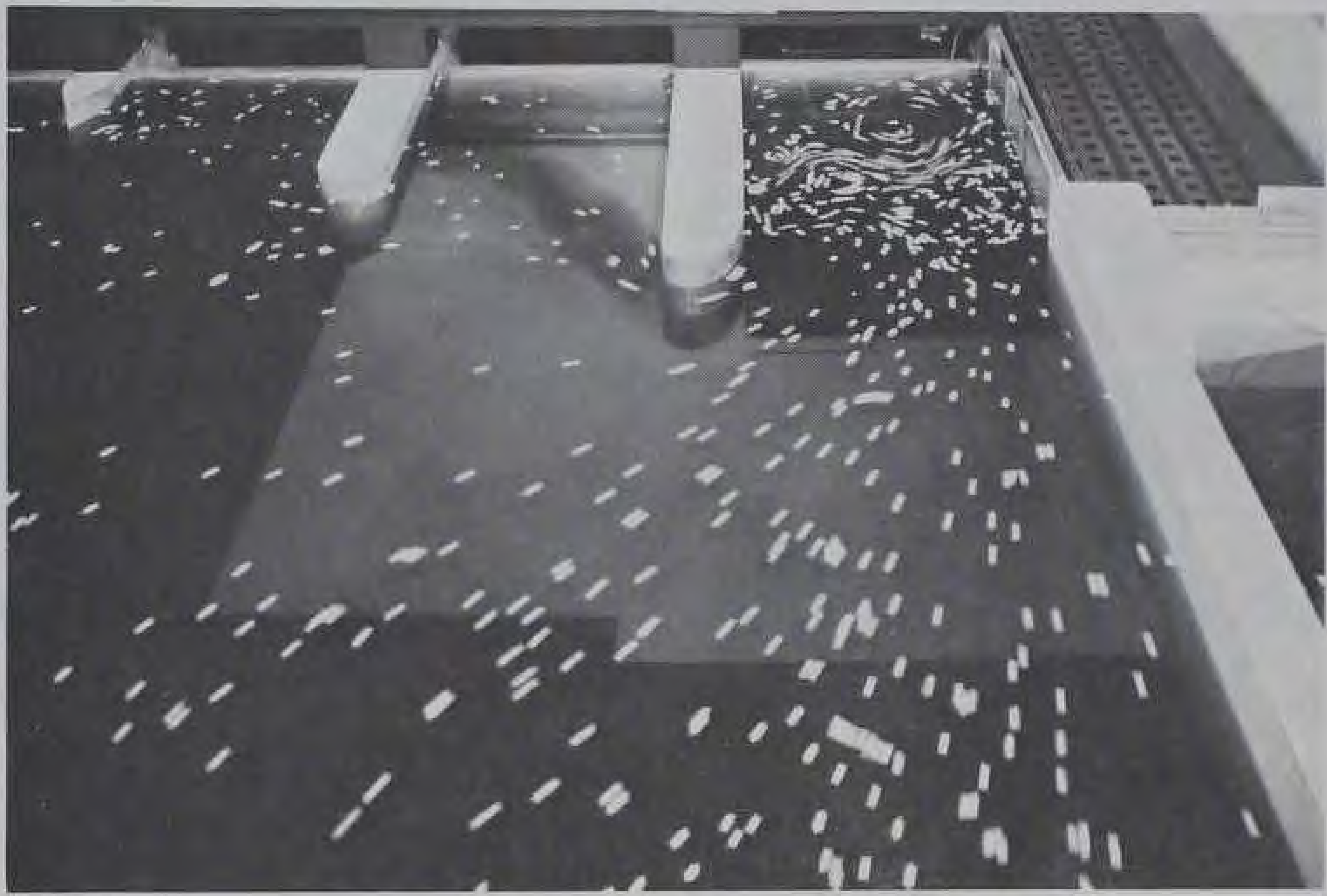
b. 2.0 min after filling started



c. 3.5 min after filling started

Photo 3. Surface currents during filling operation, type 3 design, time exposure 5 sec; upper pool el 750.0, lower pool el 725.0, 2.07-min valve time (sheet 1 of 2)

d. 5.0 min after filling started



e. 7.0 min after filling started

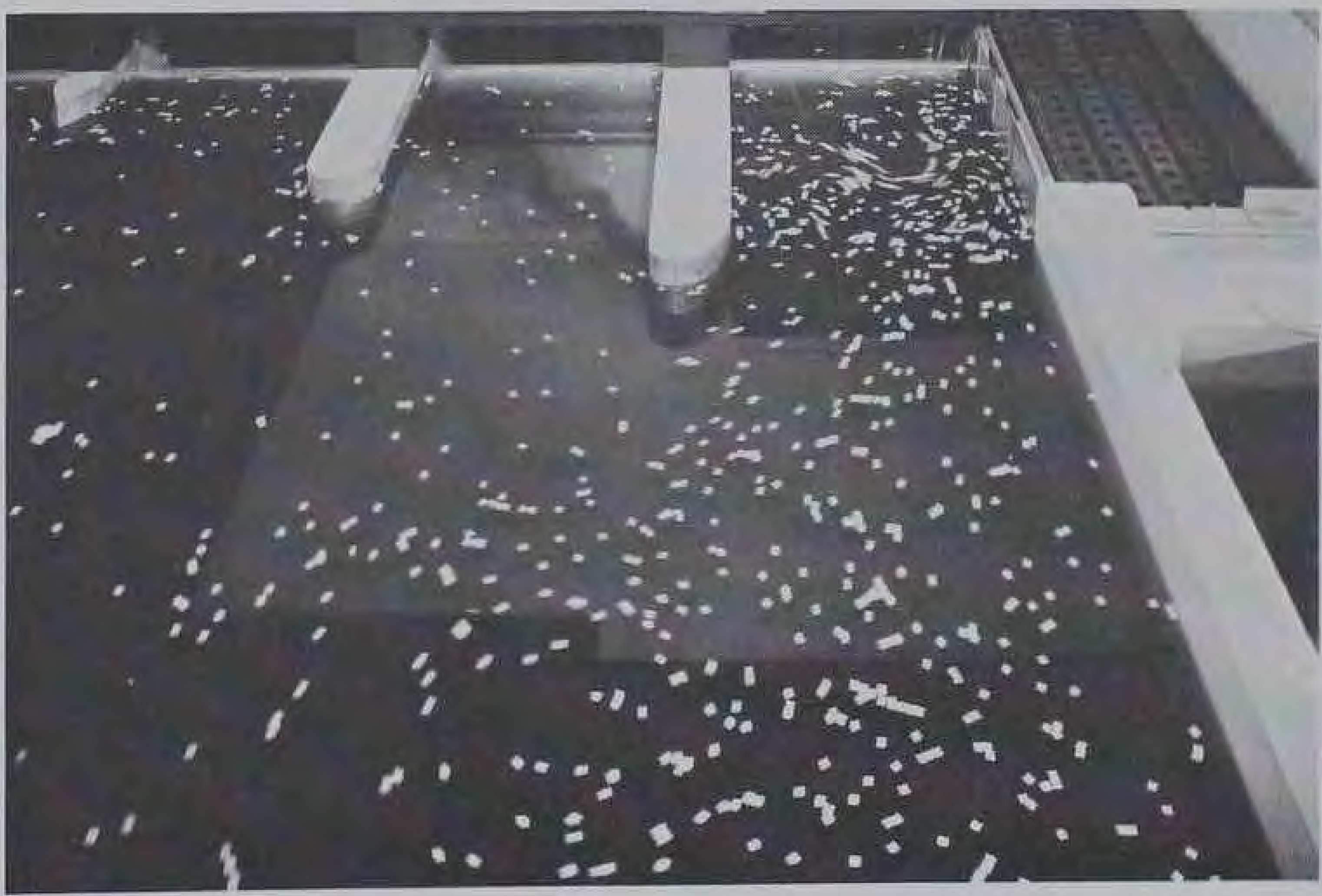


Photo 3 (sheet 2 of 2)

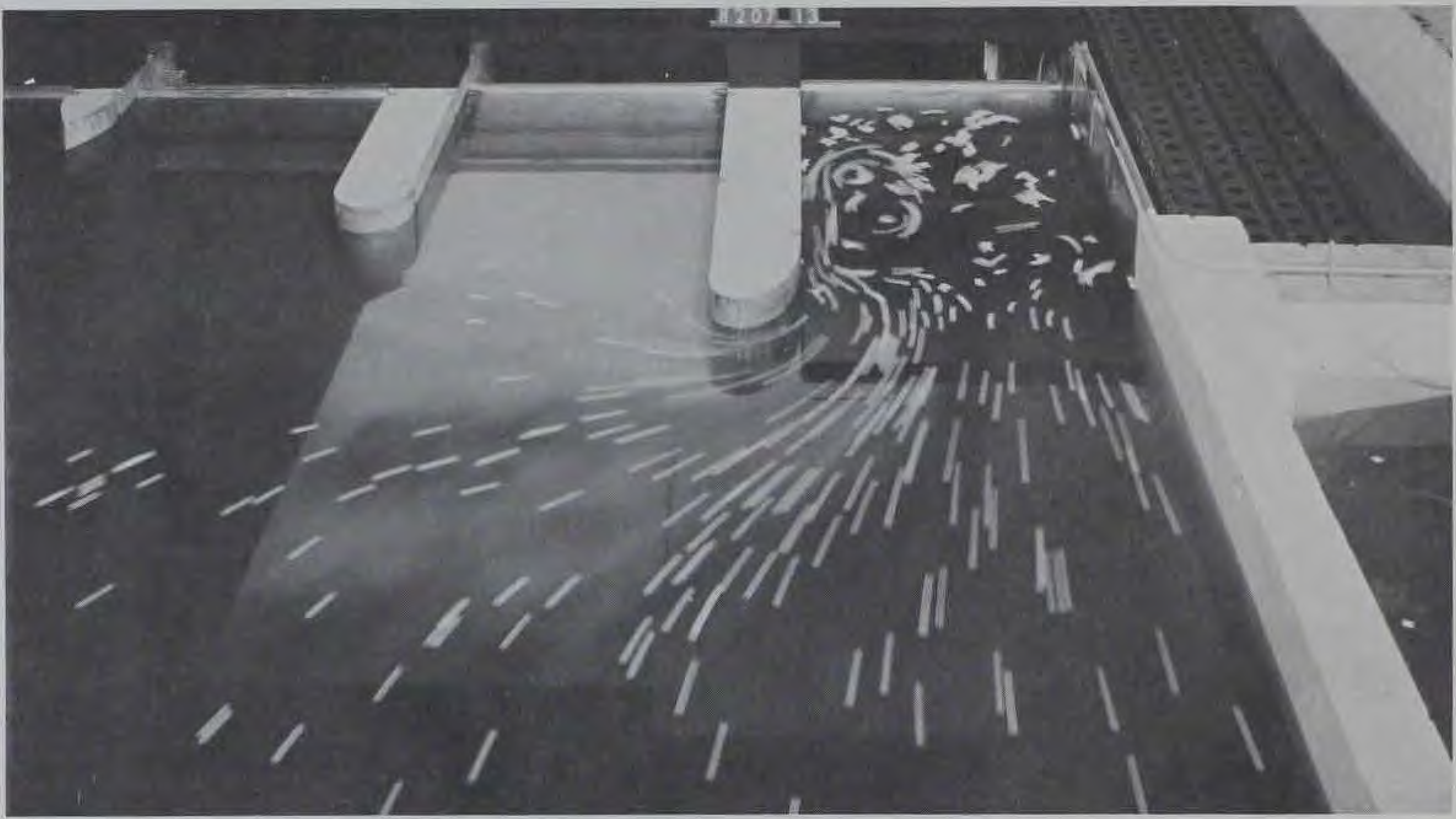


Photo 4. Surface currents during steady-flow peak discharge conditions, type 3 design, time exposure 5 sec; upper pool el 750.0, lock chamber el 732.0, culvert valve fully open

Photo 5. Surface currents during steady-flow peak discharge conditions through intake, type 3 design, culvert valve fully open; upper pool el 750.0, lock chamber el 732.0, auxiliary lock gate closed. Dam gates 1 and 2 open 3 ft, each gate passing 4,920-cfs discharge; dam gate 3 open 3.2 ft, passing 5,230-cfs discharge. Tailgate downstream of dam el 727.0; total discharge through dam approximately 15,070 cfs

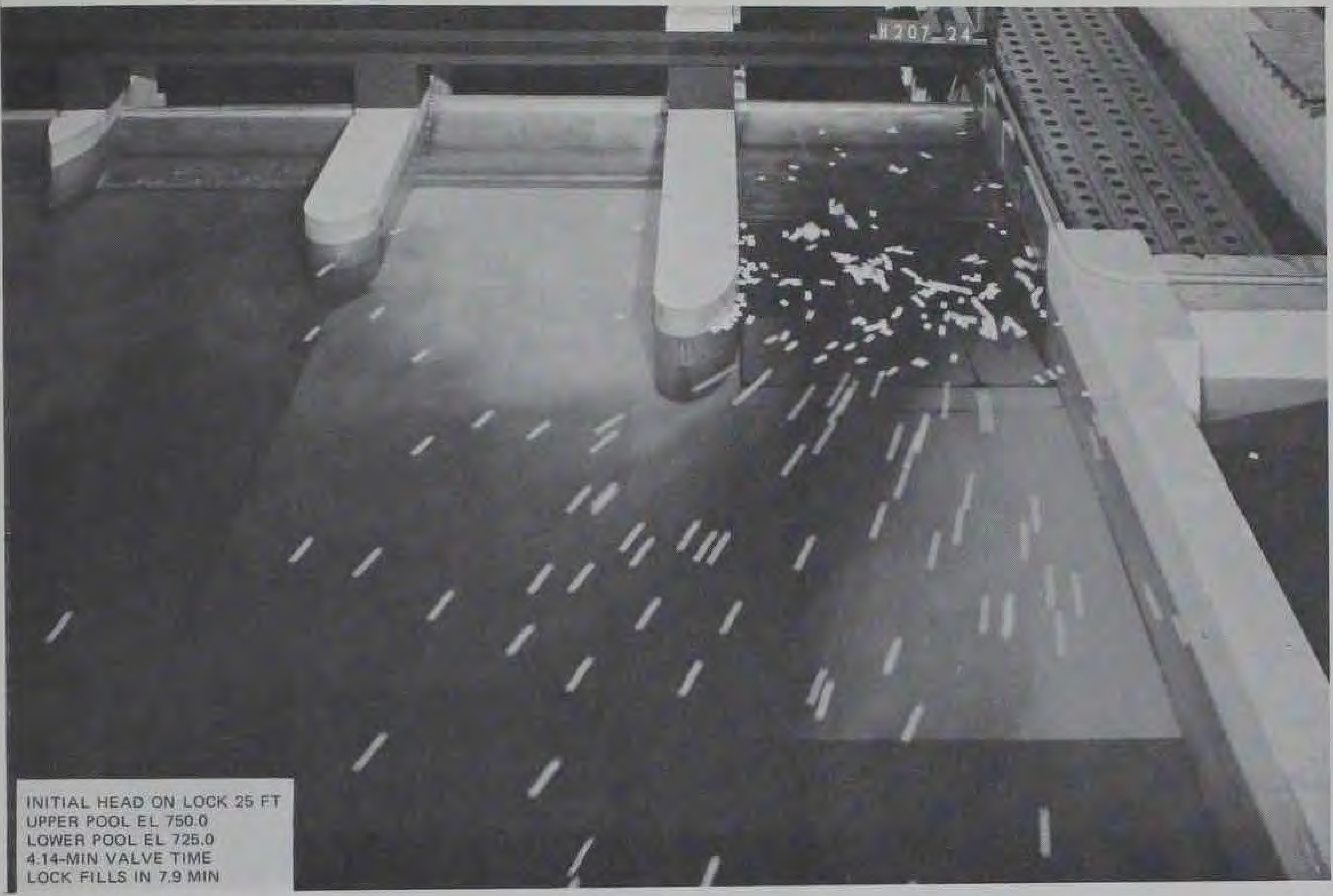


Photo 6. Type 5 (recommended) design, steady-flow peak discharge conditions through intake, time exposure 5 sec, culvert valve fully open; river discharge 0 cfs, discharge exceeded 100 percent of time

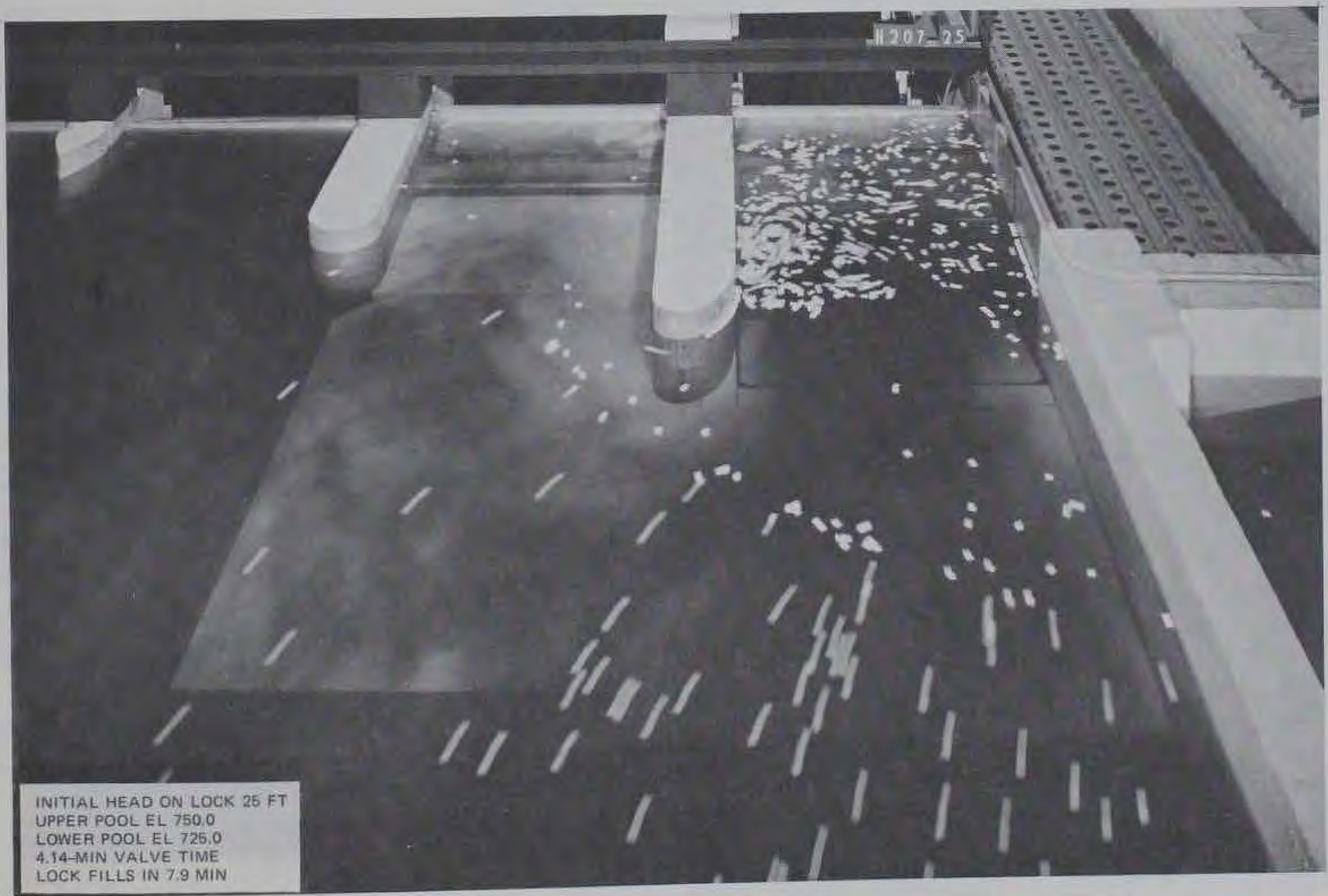


Photo 7. Type 5 (recommended) design, steady-flow peak discharge conditions through intake, time exposure 5 sec, culvert valve fully open; river discharge 2,500 cfs, discharge exceeded 80 percent of time; dam gate 1 opened 1.5 ft, auxiliary lock gate closed

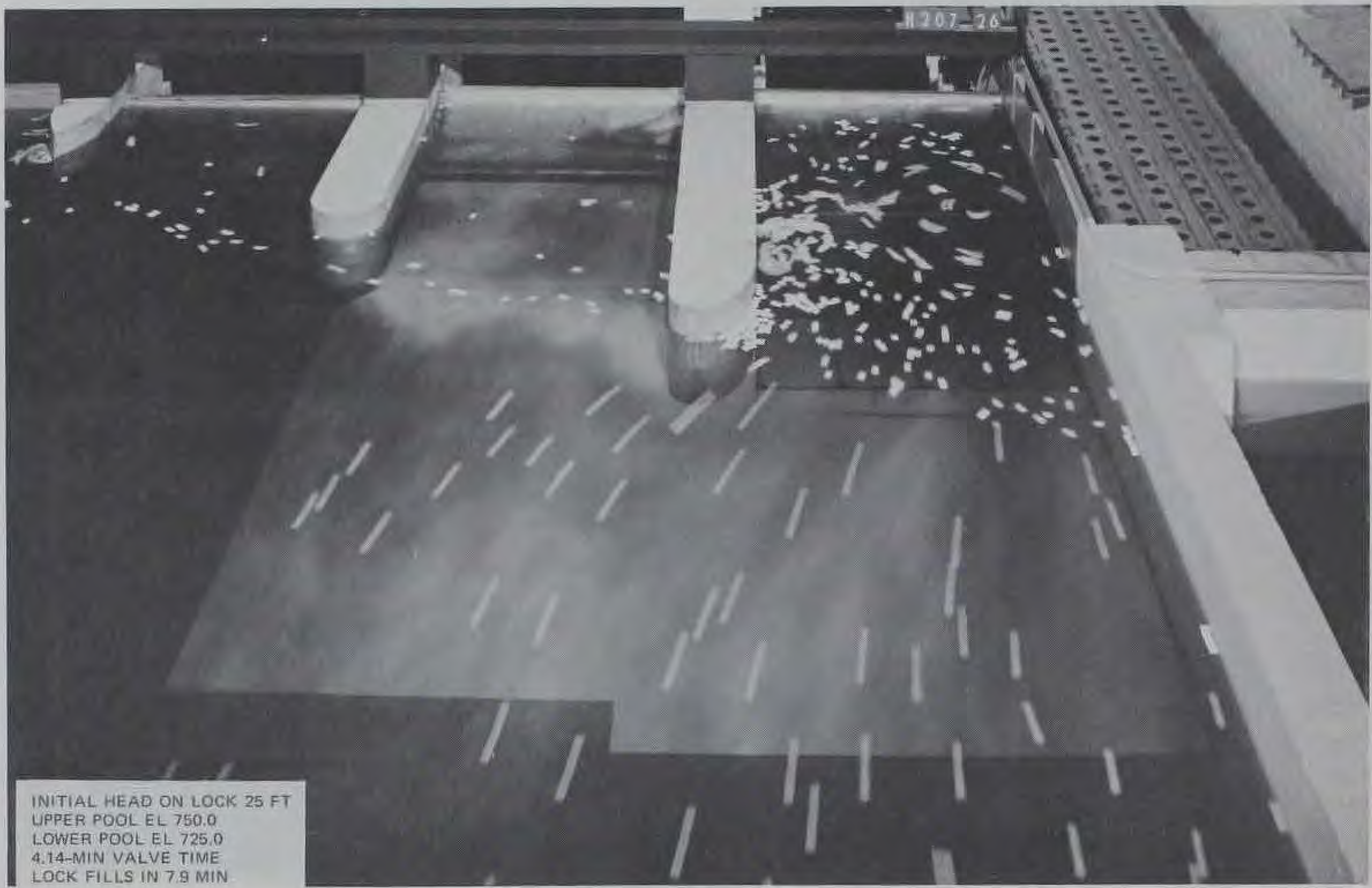


Photo 8. Type 5 (recommended) design, steady-flow peak discharge conditions through intake, time exposure 5 sec, culvert valve fully open; river discharge 5,000 cfs, discharge exceeded 47 percent of time; dam gates 1 and 2 open 1.5 ft, auxiliary lock gate closed

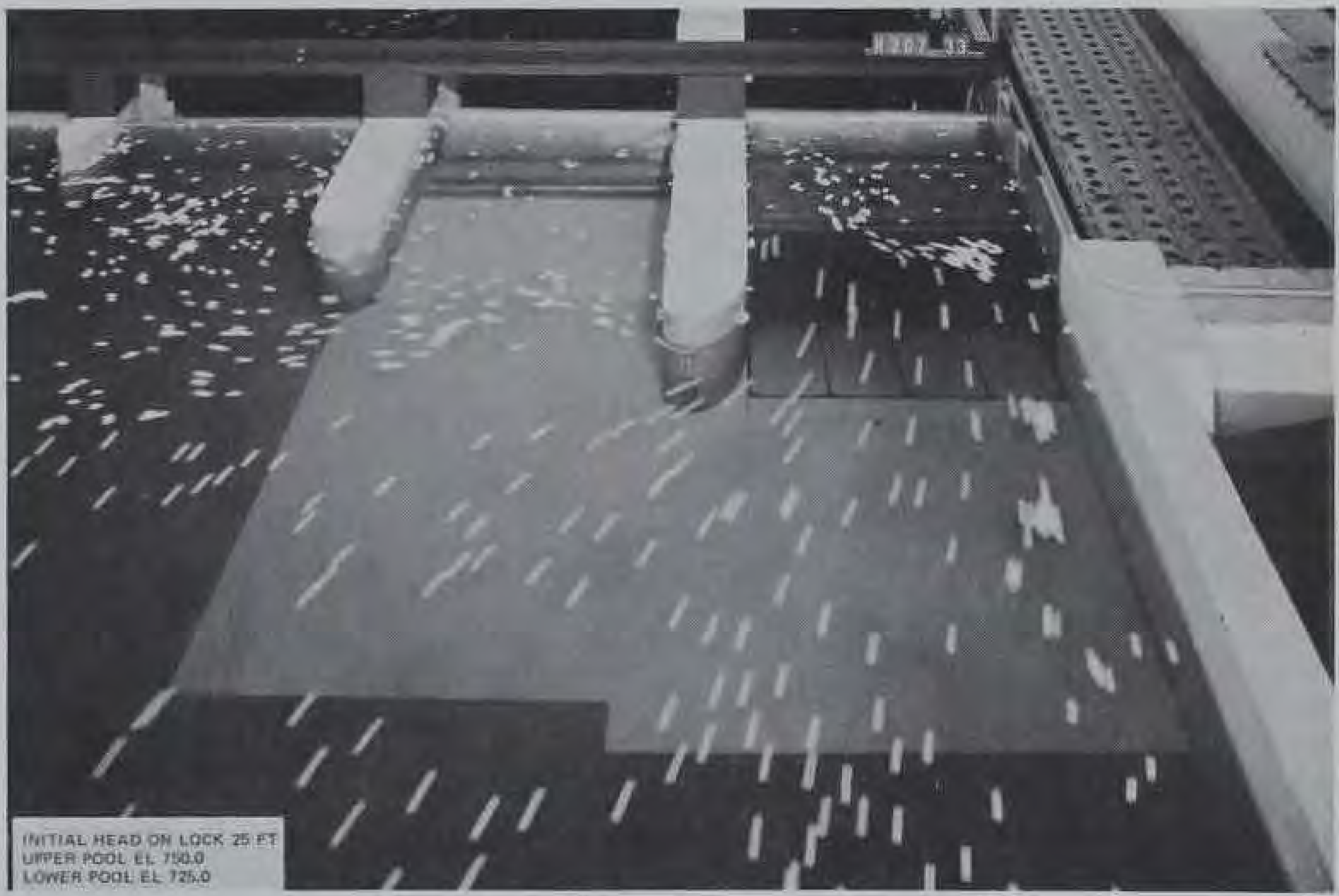
Photo 9. Type 5 (recommended) design, steady-flow peak discharge conditions through intake, time exposure 5 sec, culvert valve fully open; river discharge 7,500 cfs, discharge exceeded 28 percent of time; dam gates 1, 2, and 3 open 1.5 ft, auxiliary lock gate closed

Photo 10. Type 5 (recommended) design, steady-flow peak discharge conditions through intake, time exposure 5 sec, culvert valve fully open; river discharge 14,000 cfs, discharge exceeded 11 percent of time; dam gates 1, 2, and 3 open 3.0 ft, auxiliary lock gate closed

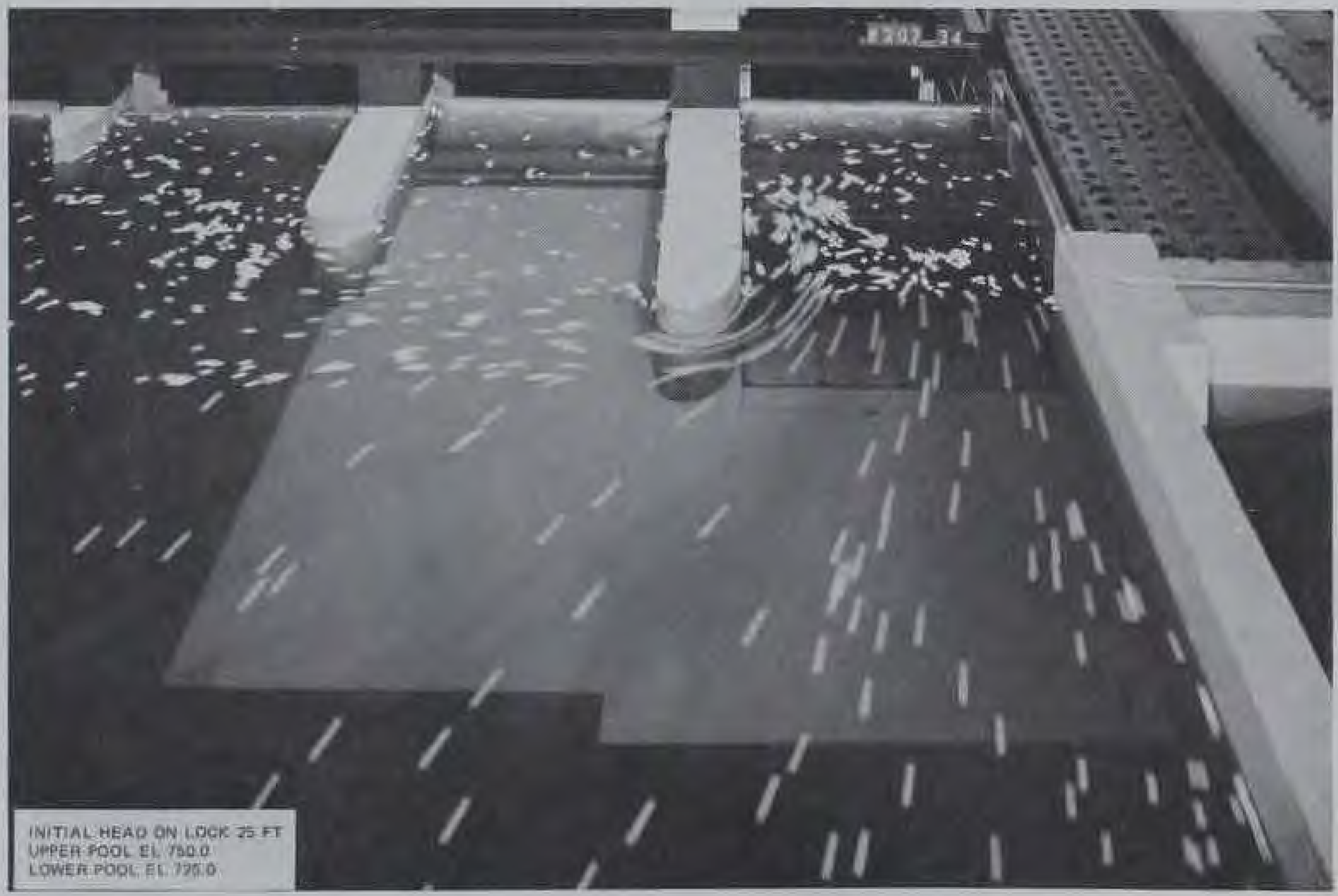
Photo 11. Type 5 (recommended) design, steady-flow peak discharge conditions through intake, time exposure 5 sec, culvert valve fully open; river discharge 24,000 cfs, discharge exceeded 4 percent of time; dam gates 1, 2, and 3 open 5.1 ft, auxiliary lock gate closed

Photo 12. Type 5 (recommended) design, steady-flow peak discharge conditions through intake, time exposure 5 sec, culvert valve fully open; river discharge 32,000 cfs, discharge exceeded 1.2 percent of time; date gates 1, 2, and 3 open 5.1 ft, auxiliary lock gate open 7.7 ft

a. Before filling started



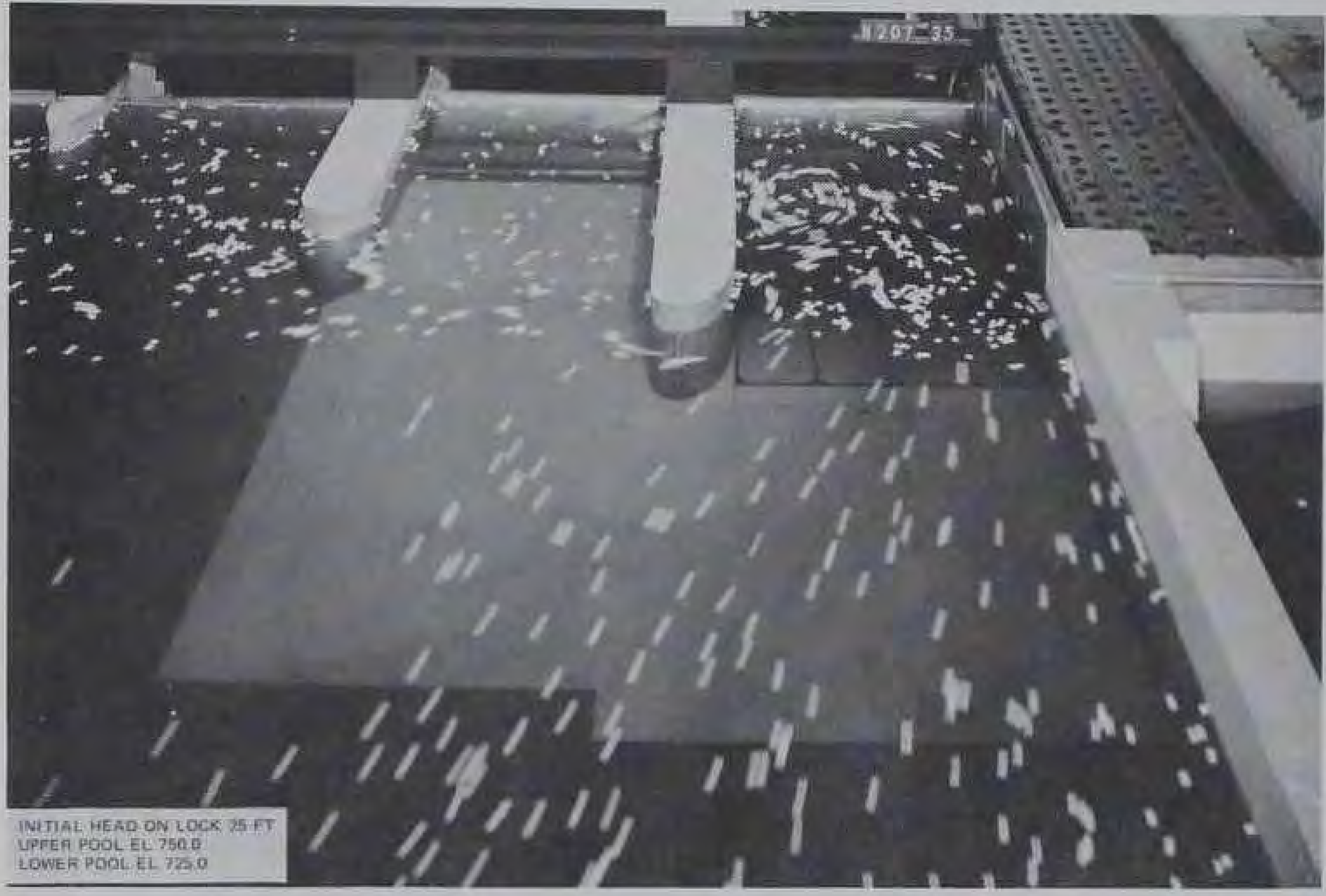
b. 2.0 min after filling started



c. 4.0 min after filling started

Photo 13. Surface currents during filling operation, type 5 (recommended) design, time exposure 5 sec; river discharge 0 cfs, discharge exceeded 100 percent of time, 4.14-min valve time (sheet 1 of 2)

d. 6.0 min after filling started



e. 8.0 min after filling started

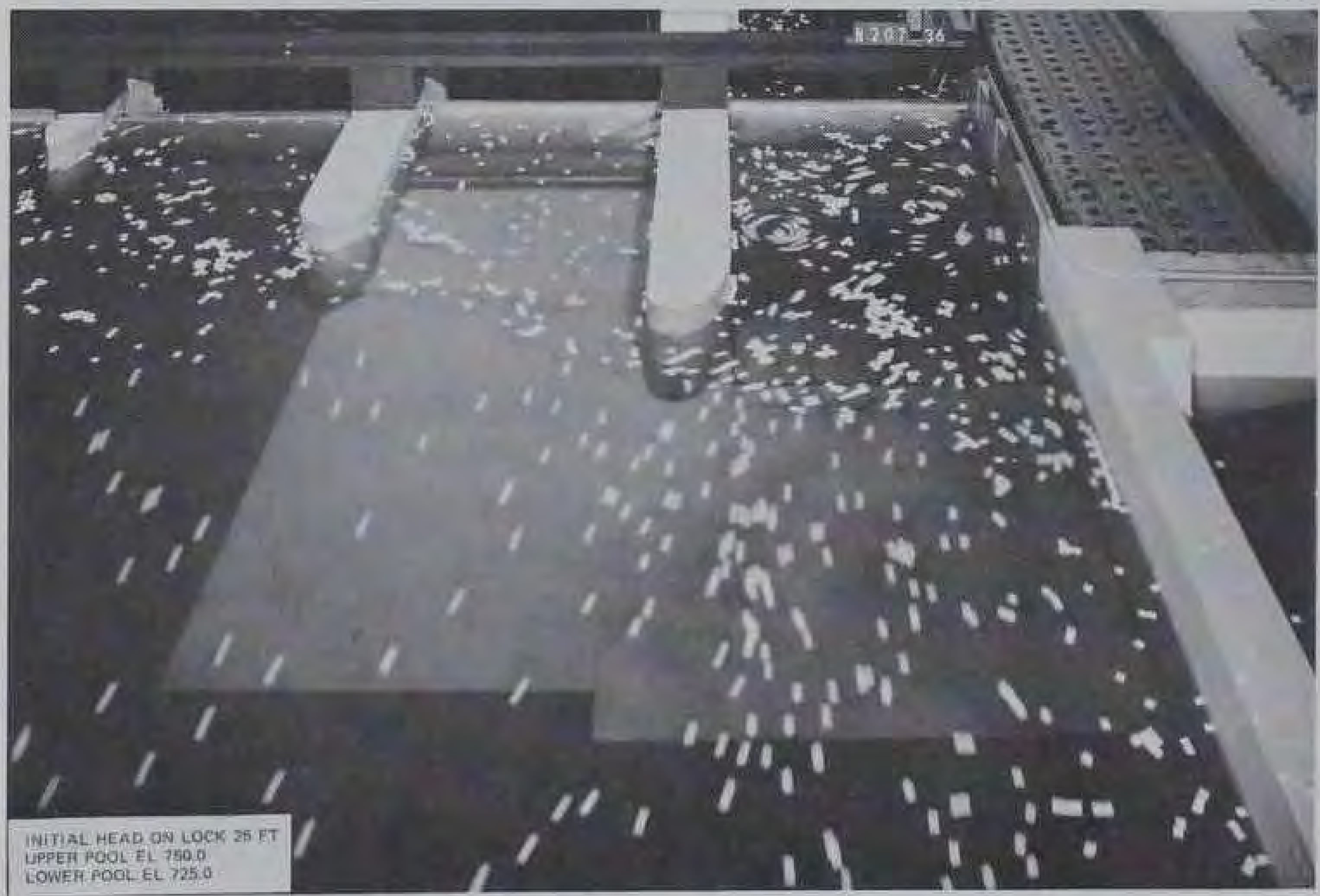
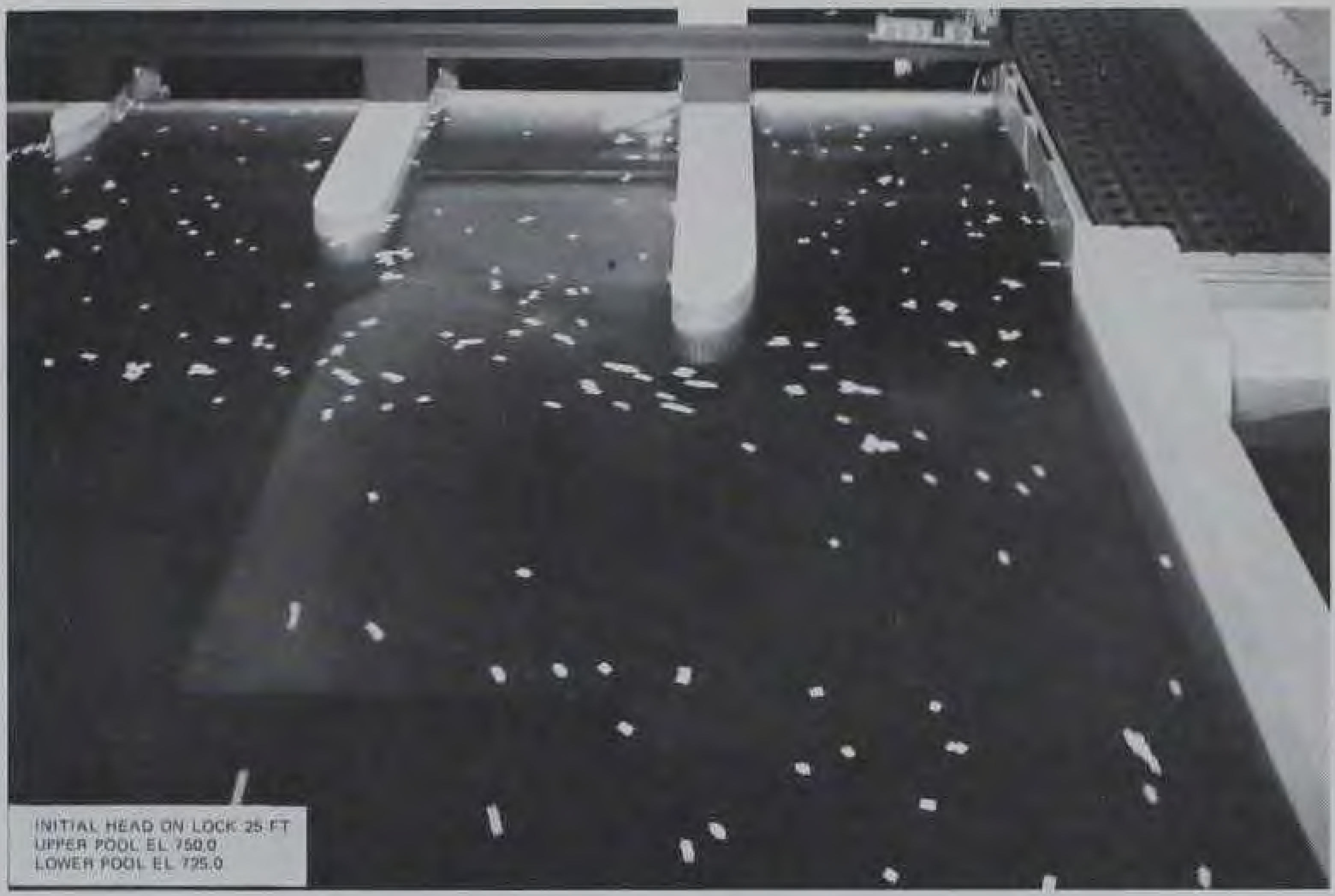
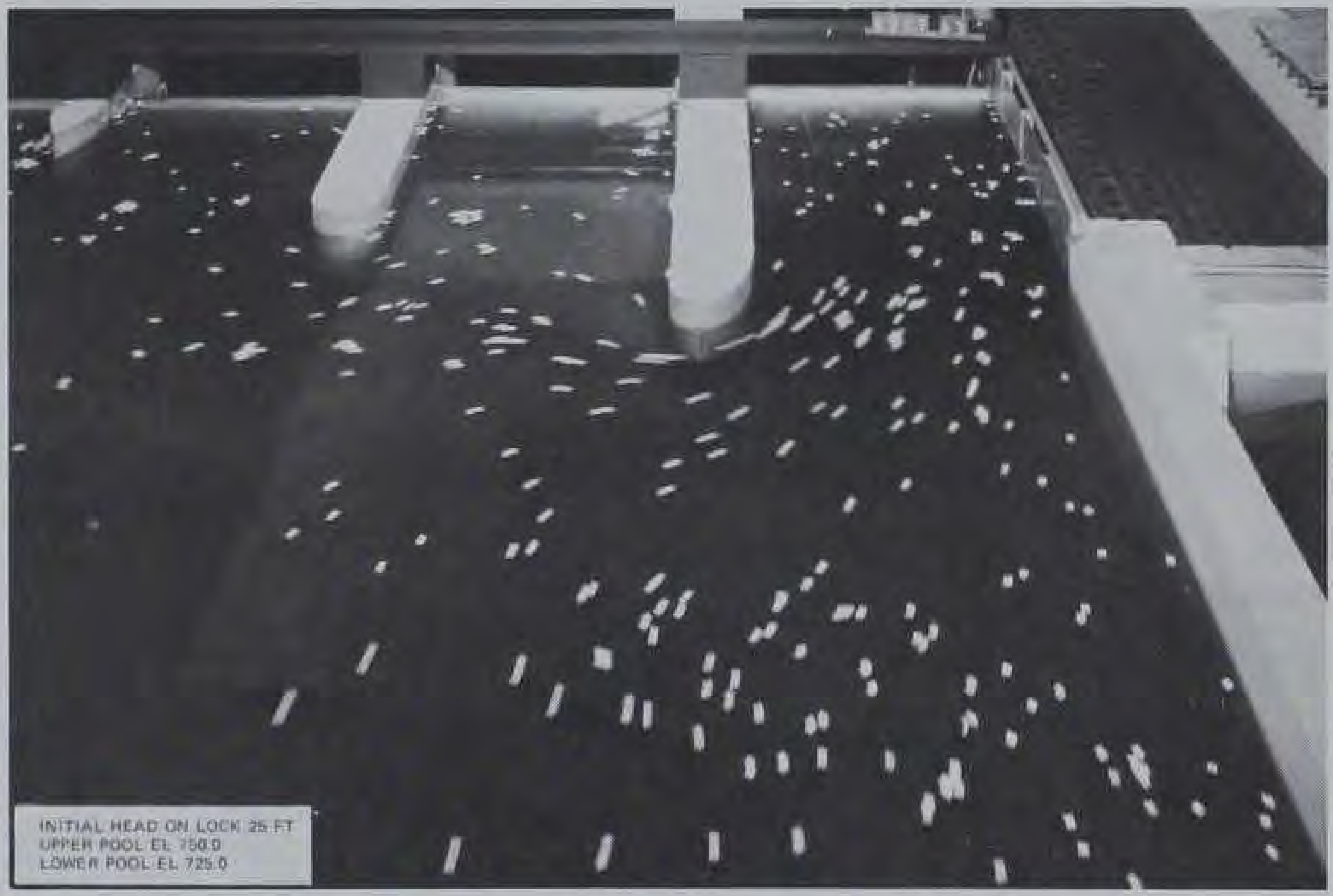


Photo 13 (sheet 2 of 2)



a. Before filling started

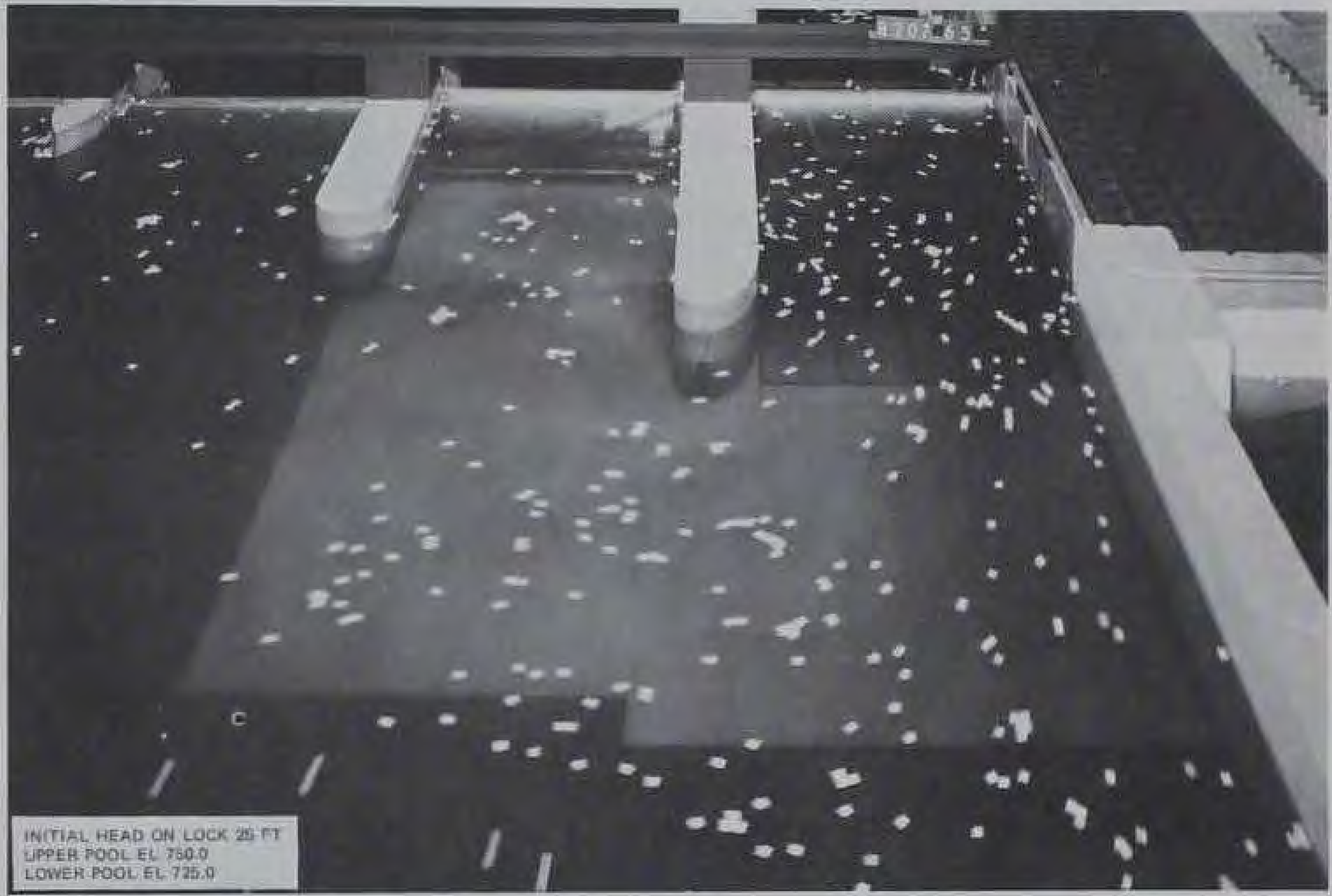


b. 2.0 min after filling started

c. 4.0 min after filling started

Photo 14. Surface currents during filling operation, type 5 (recommended) design, time exposure 5 sec; river discharge 2,500 cfs, discharge exceeded 80 percent of time, 4.14-min valve time; dam gate 1 open 1.5 ft, auxiliary lock gate closed (sheet 1 of 2)

d. 6.0 min after filling started



e. 8.0 min after filling started

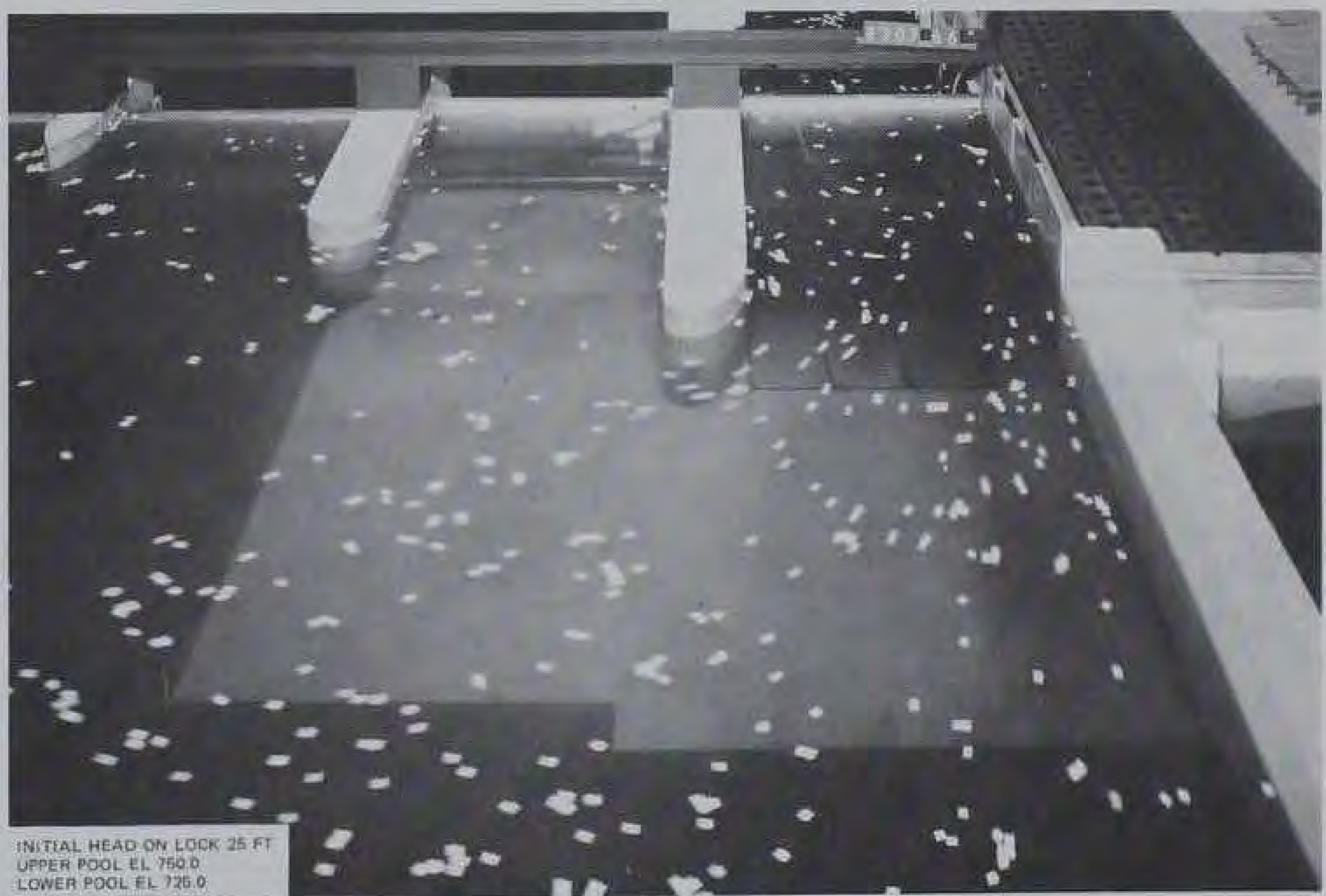
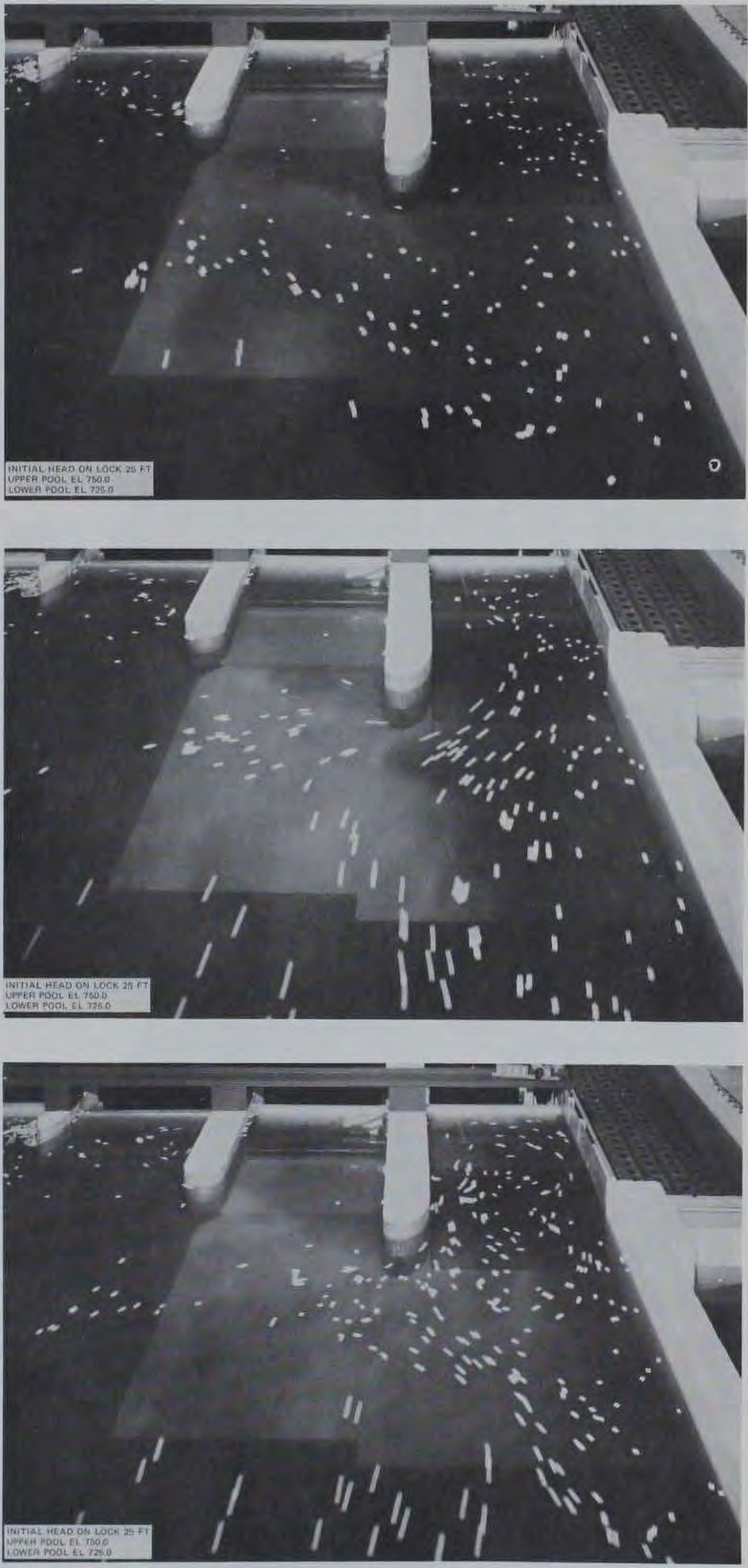


Photo 14 (sheet 2 of 2)



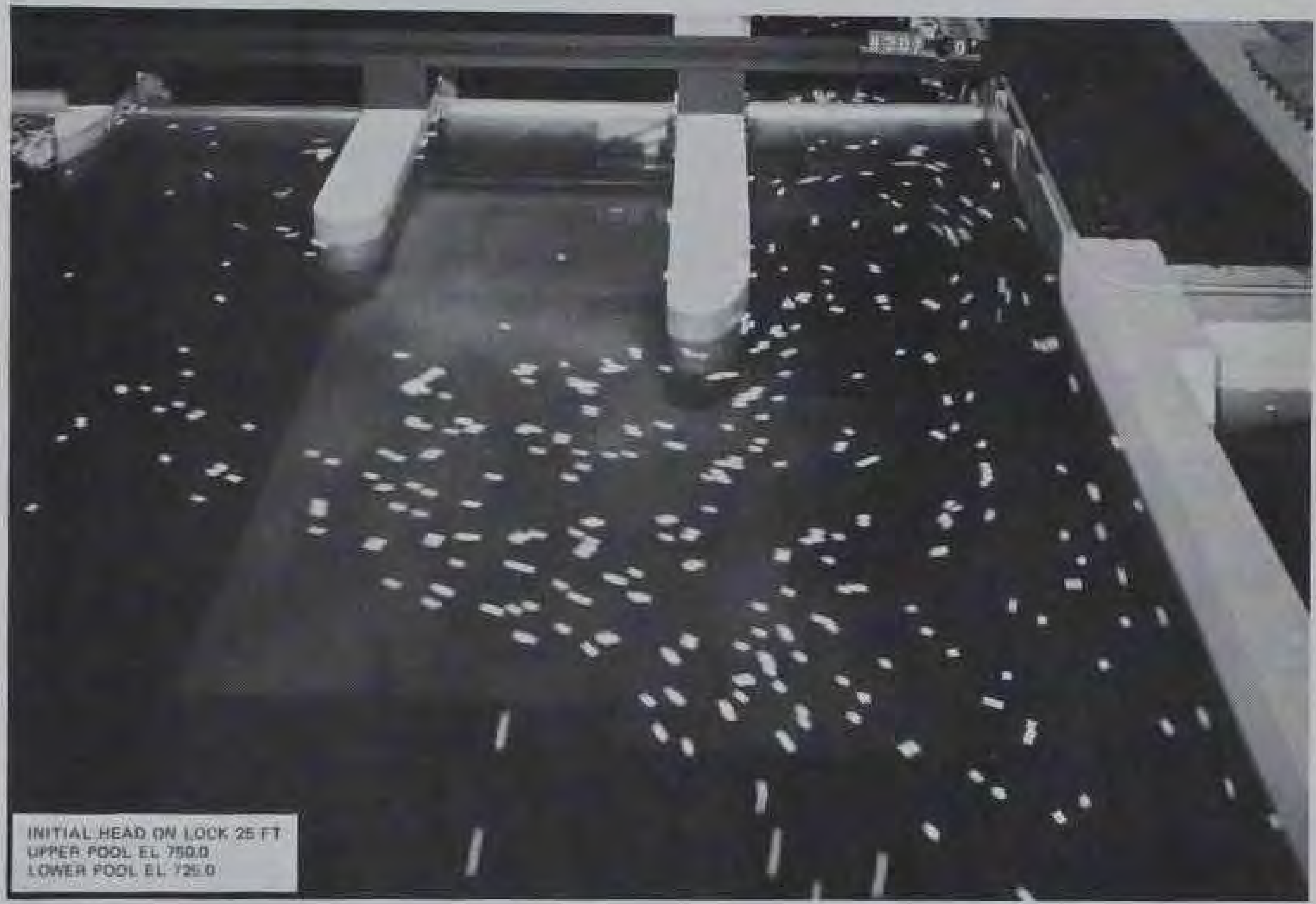
a. Before filling started

b. 2.0 min after filling started

c. 4.0 min after filling started

Photo 15. Surface currents during filling operation, type 5 (recommended) design, time exposure 5 sec; river discharge 5,000 cfs, discharge exceeded 47 percent of time, 4.14-min valve time; dam gates 1 and 2 open 1.5 ft, auxiliary lock gate closed (sheet 1 of 2)

d. 6.0 min after
filling started



e. 8.0 min after
filling started

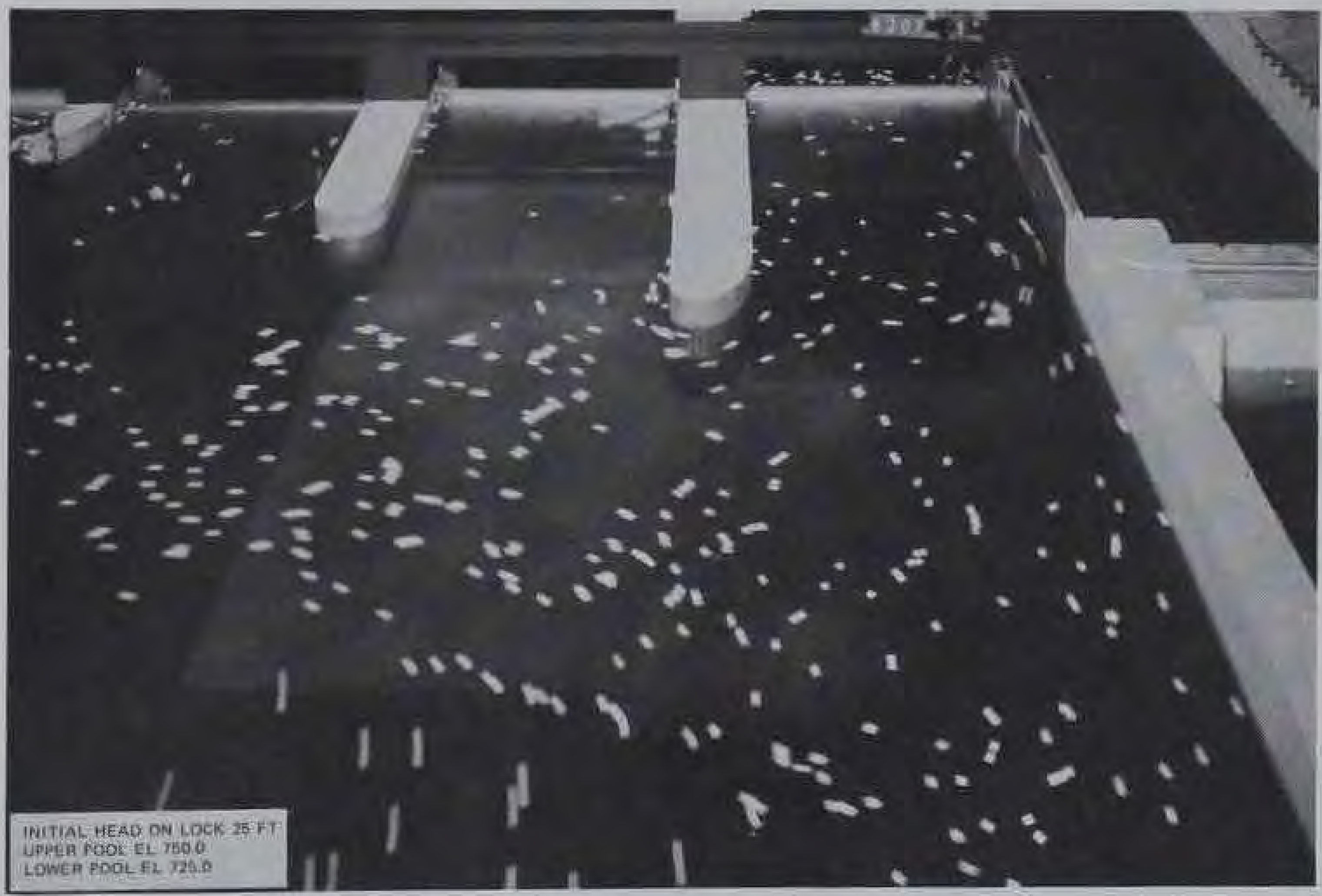
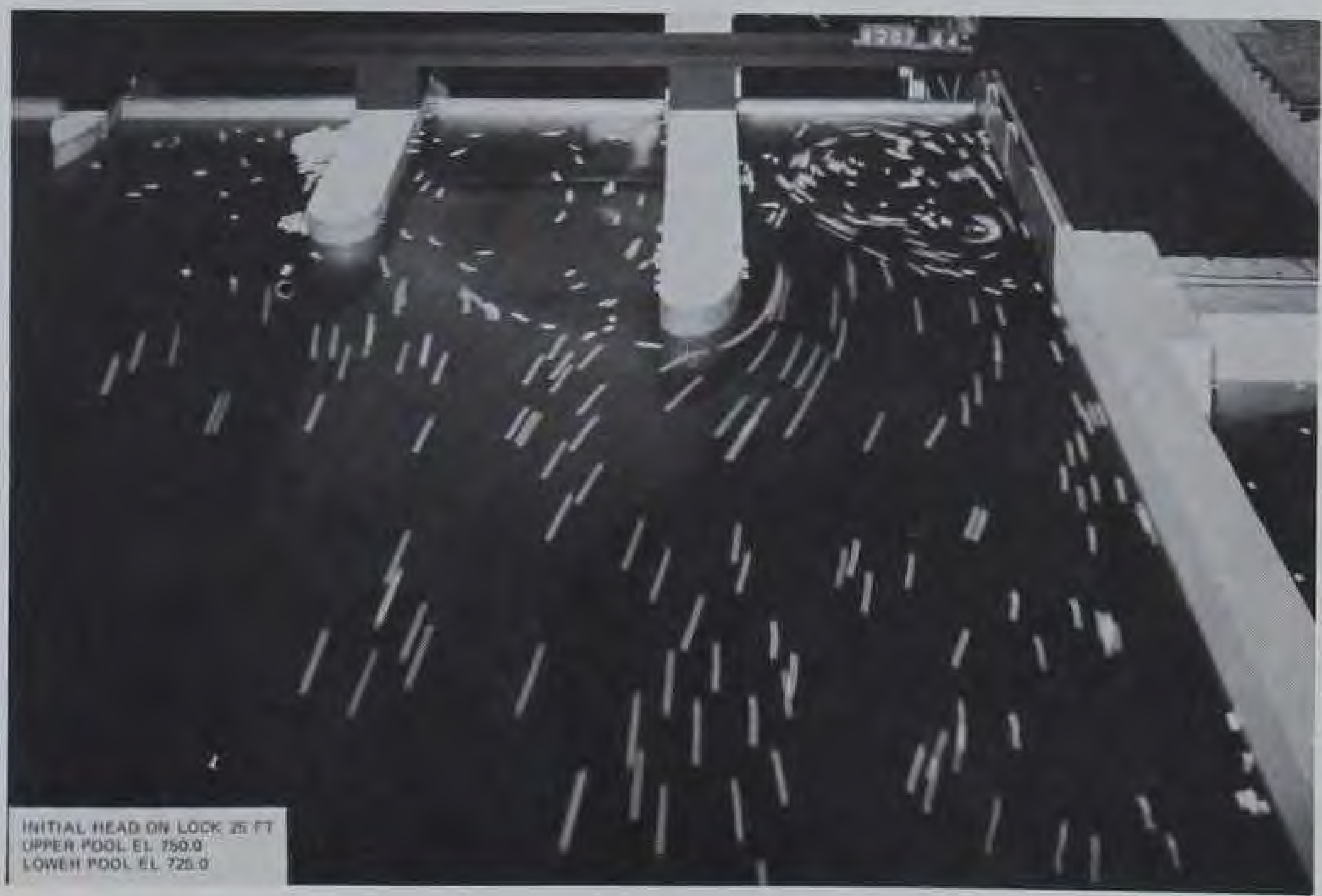


Photo 15 (sheet 2 of 2)

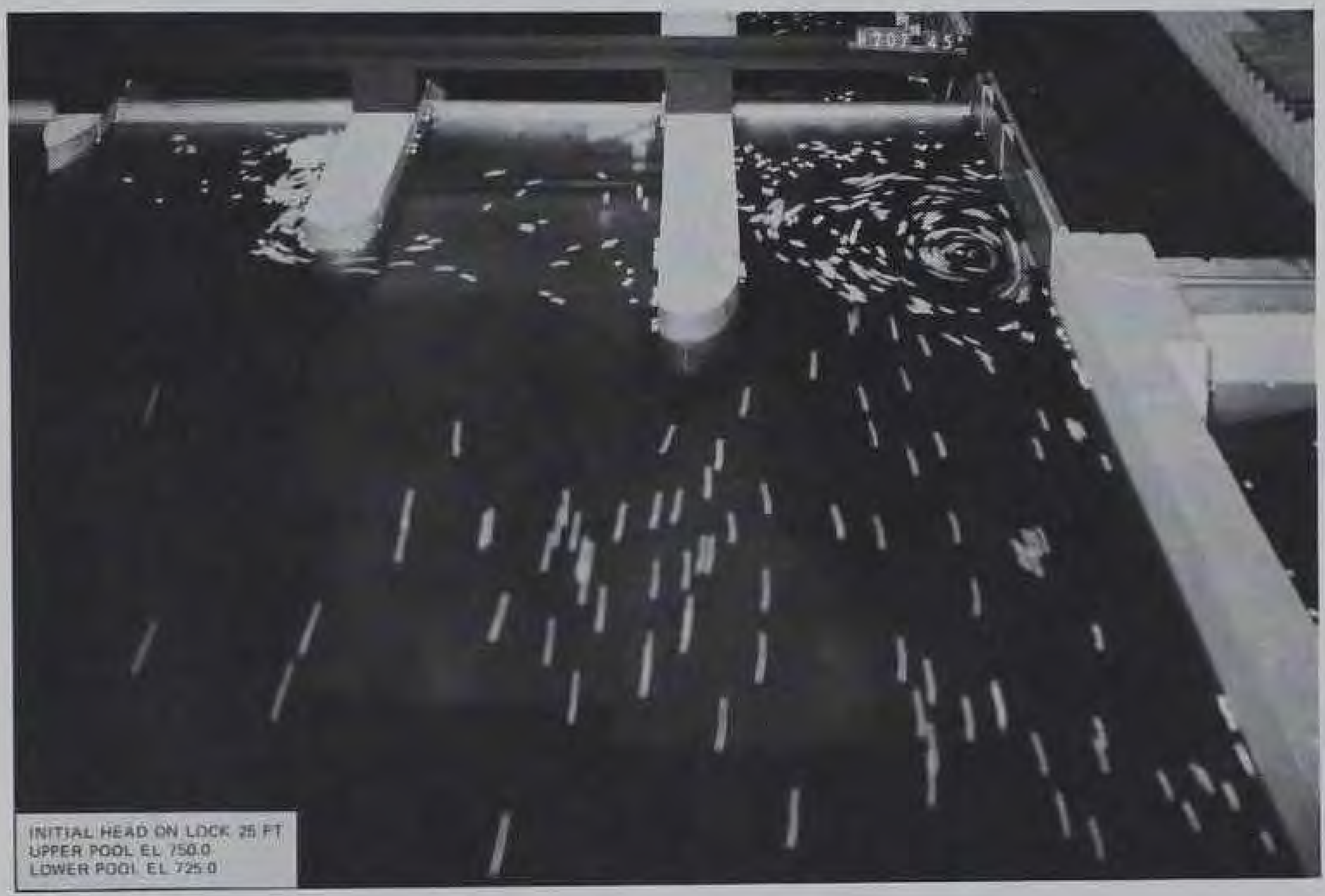
a. Before filling started

b. 2.0 min after filling started



c. 4.0 min after filling started

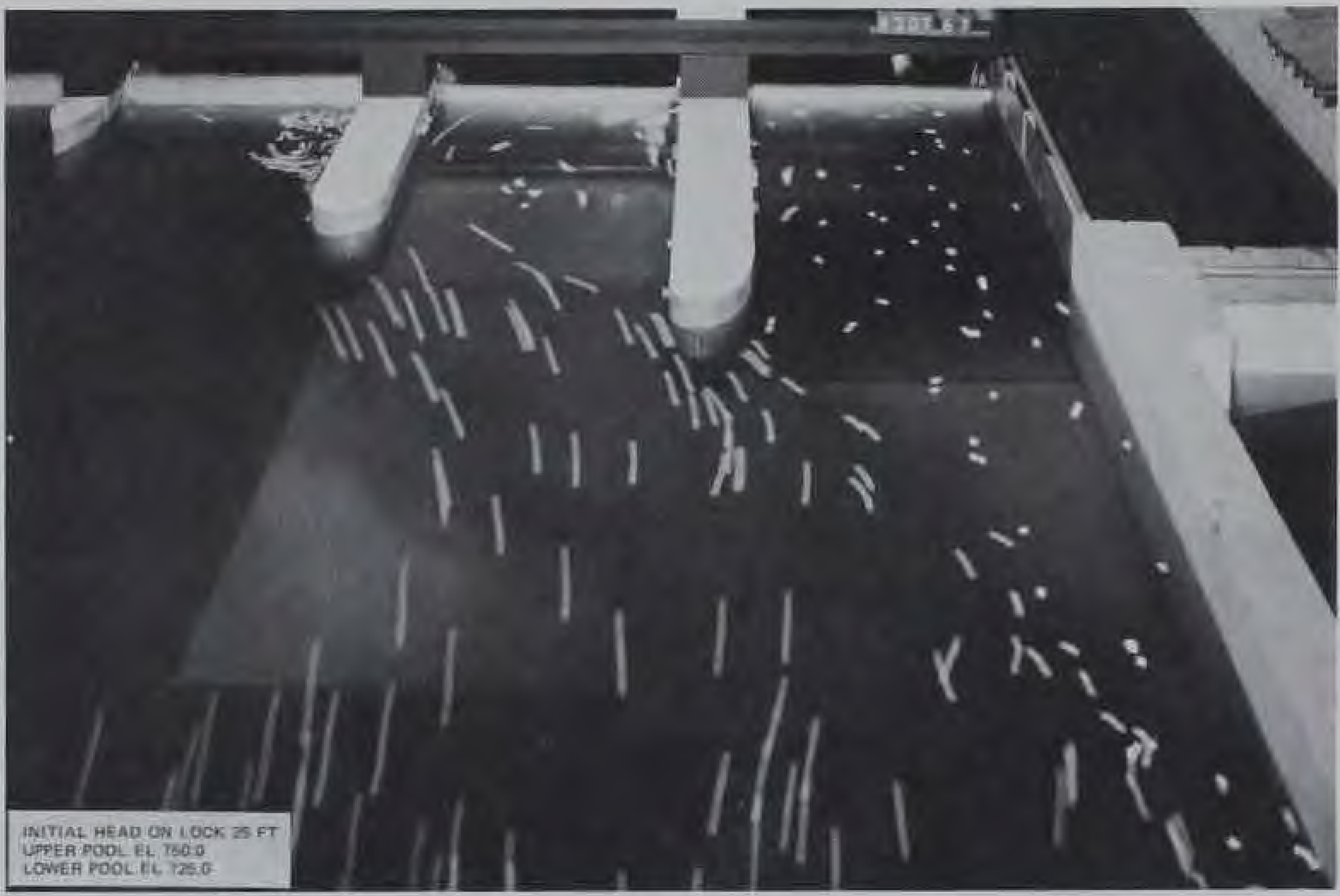
Photo 16. Surface currents during filling operation, type 5 (recommended) design, time exposure 5 sec; river discharge 7,500 cfs, discharge exceeded 28 percent of time, 4.14-min valve time; dam gates 1, 2, and 3 open 1.5 ft, auxiliary lock gate closed (sheet 1 of 2)



d. 6.0 min after filling started

e. 8.0 min after filling started

Photo 16 (sheet 2 of 2)



a. Before filling started

b. 2.0 min after filling started

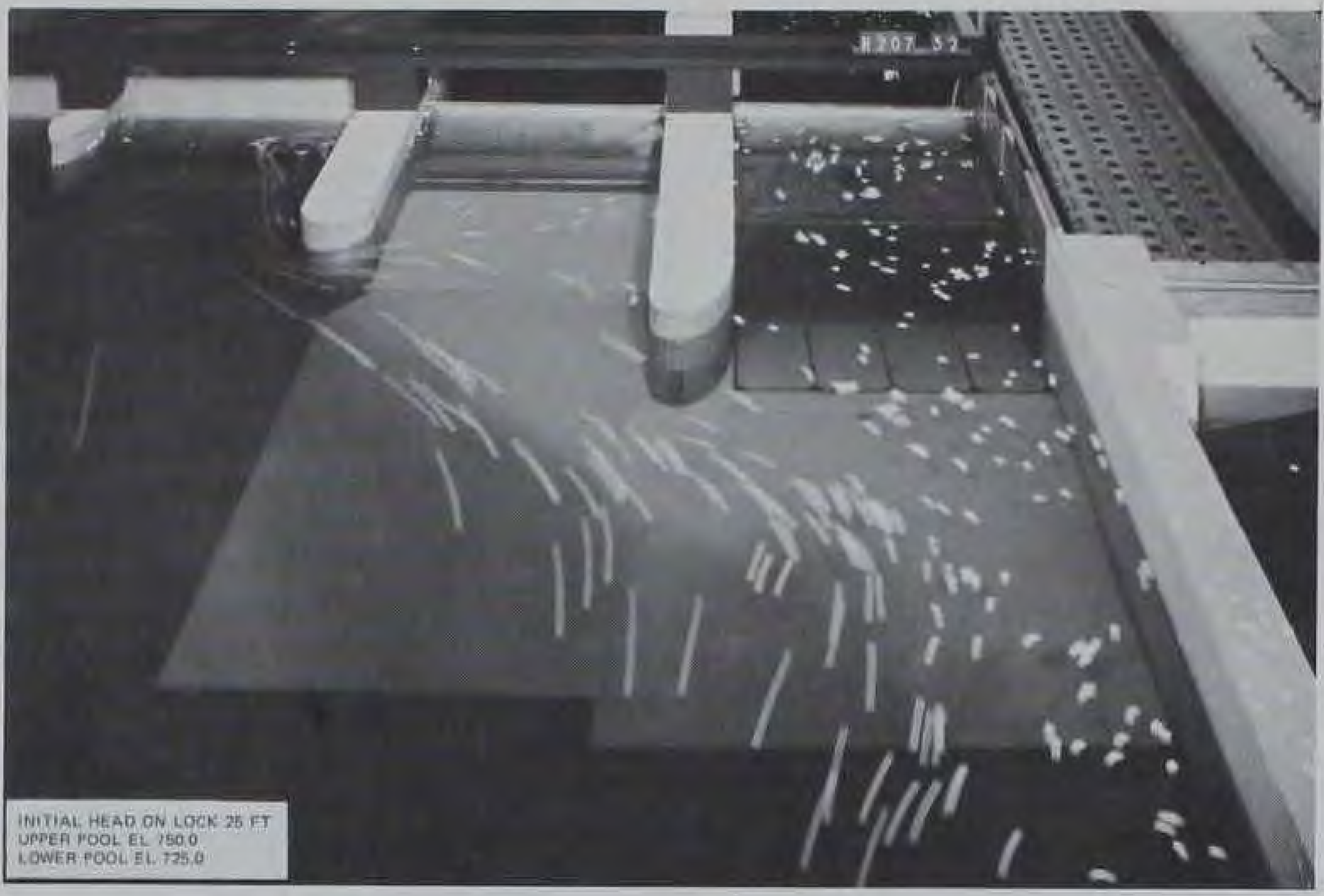
c. 4.0 min after filling started

Photo 17. Surface currents during filling operation, type 5 (recommended) design, time exposure 5 sec; river discharge 14,000 cfs, discharge exceeded 11 percent of time, 6.21-min valve time; dam gates 1, 2, and 3 open 3.0 ft, auxiliary lock gate closed (sheet 1 of 2)

d. 6.0 min after filling started

e. 9.0 min after filling started

Photo 17 (sheet 2 of 2)



a. Before filling started

b. 2.0 min after filling started

c. 4.0 min after filling started

Photo 18. Surface currents during filling operation, type 5 (recommended) design, time exposure 5 sec; river discharge 24,000 cfs, discharge exceeded 4 percent of time, 6.21-min valve time; dam gates 1, 2, and 3 open 5.1 ft, auxiliary lock gate closed (sheet 1 of 2)

d. 6.0 min after filling started

e. 9.0 min after filling started

Photo 18 (sheet 2 of 2)

a. Before filling started

b. 2.0 min after filling started

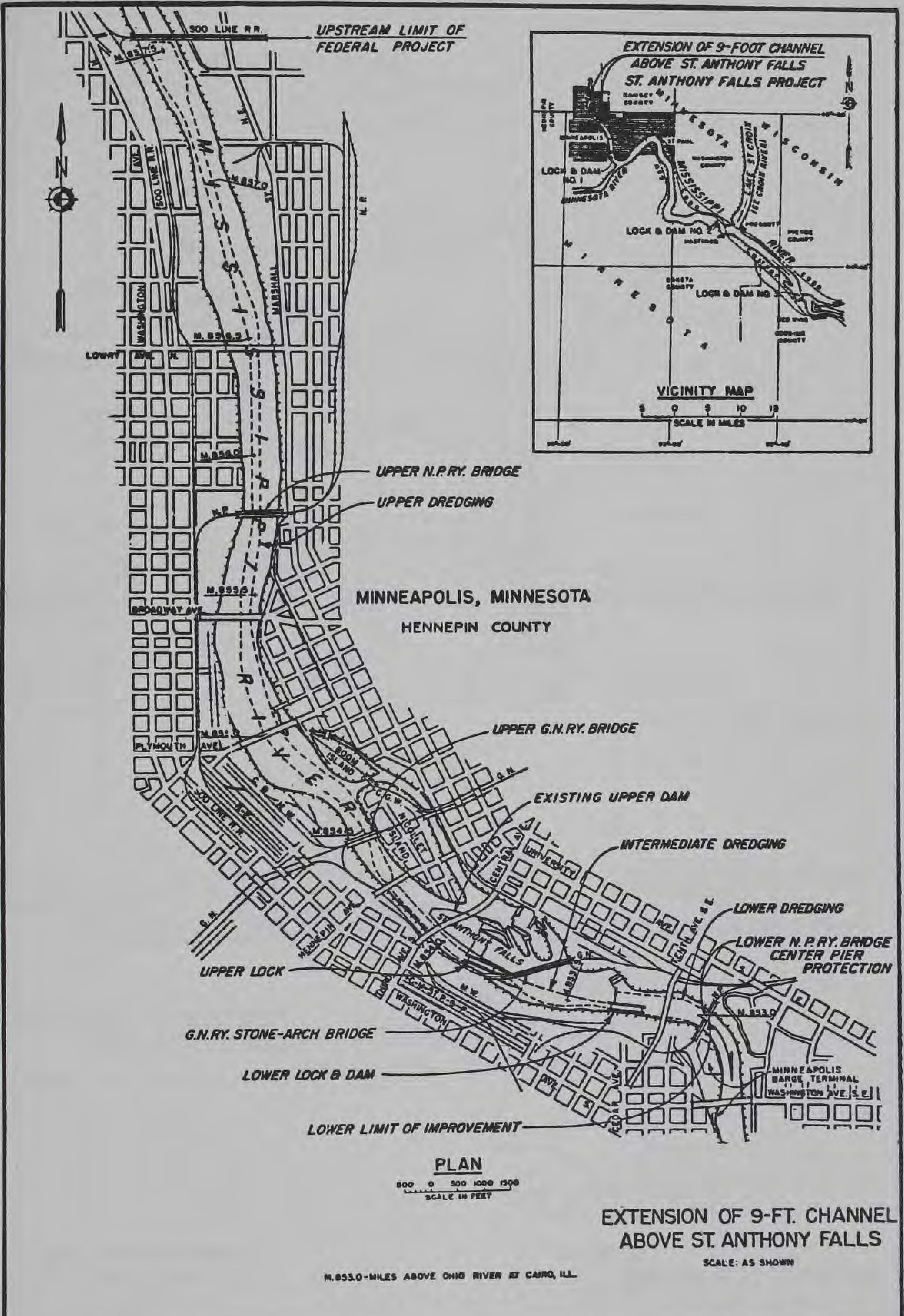
c. 4.0 min after filling started

Photo 19. Surface currents during filling operation, type 5 (recommended) design, time exposure 5 sec; river discharge 32,000 cfs, discharge exceeded 1.2 percent of time, 6.21-min valve time; dam gates 1, 2, and 3 open 5.1 ft, auxiliary lock gate open 7.7 ft (sheet 1 of 2)

d. 6.0 min after filling started

e. 9.0 min after filling started

Photo 19 (sheet 2 of 2)



EXTENSION OF 9-FT. CHANNEL ABOVE ST. ANTHONY FALLS

SCALE: AS SHOWN

PLATE 1

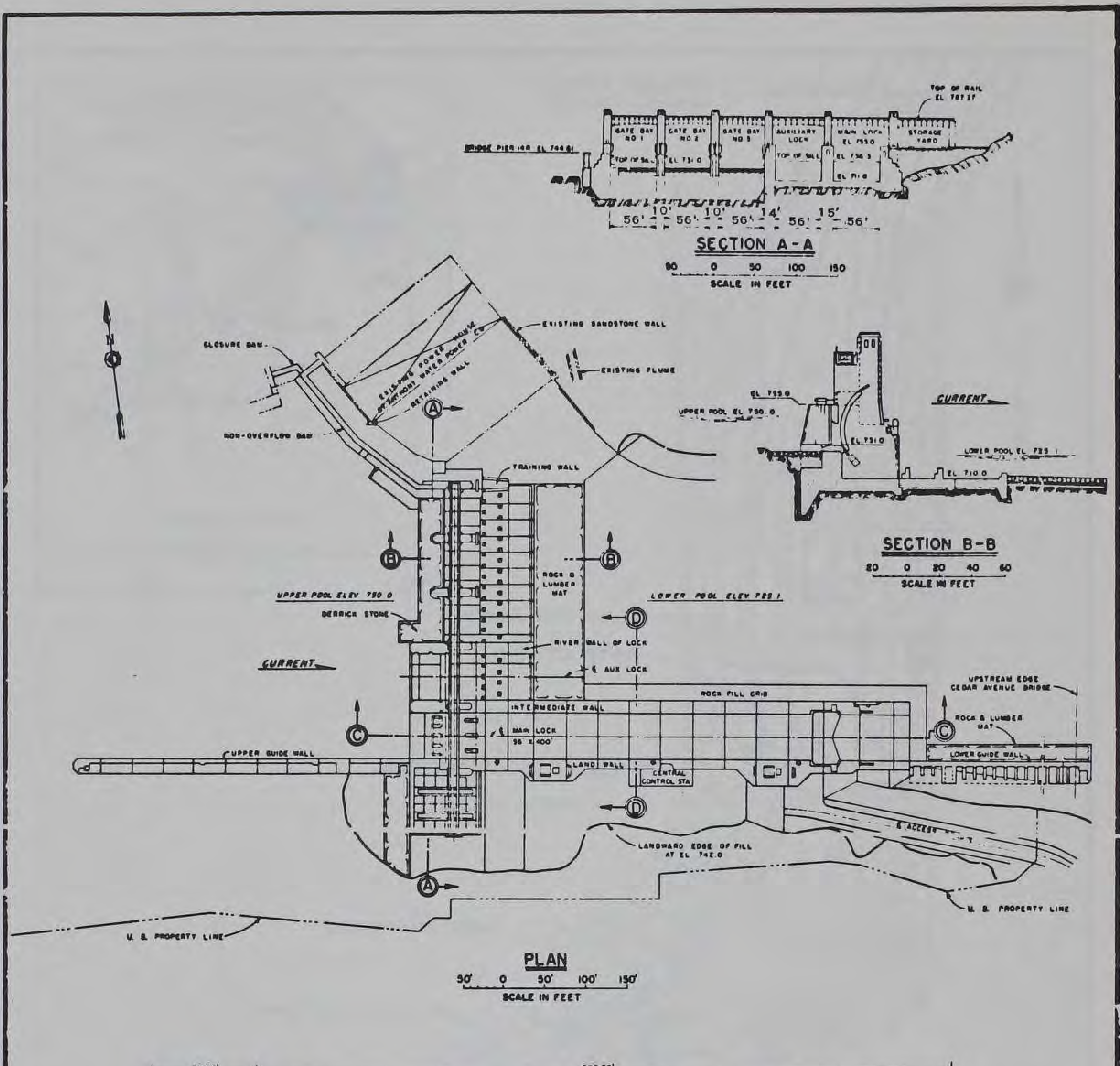
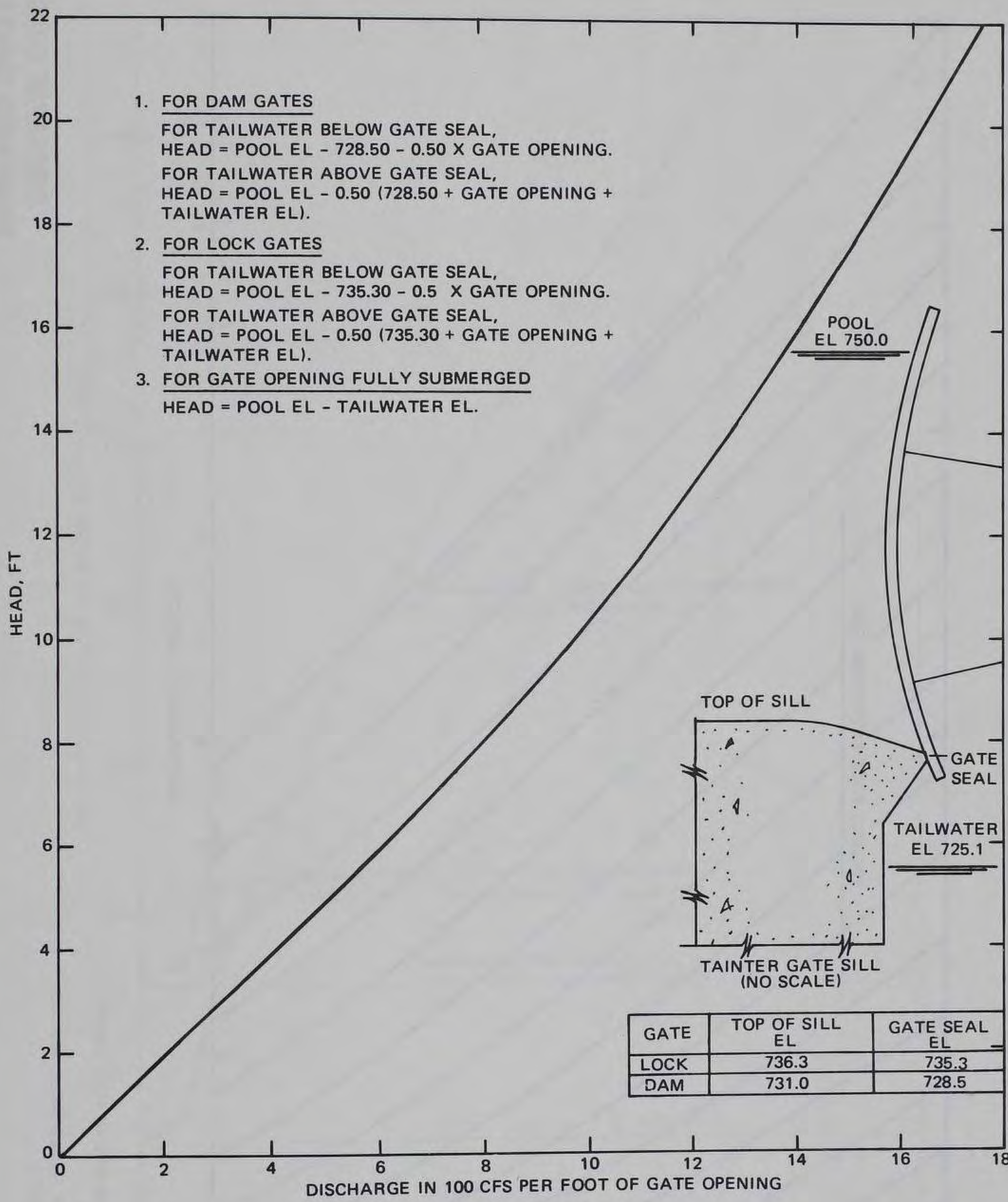
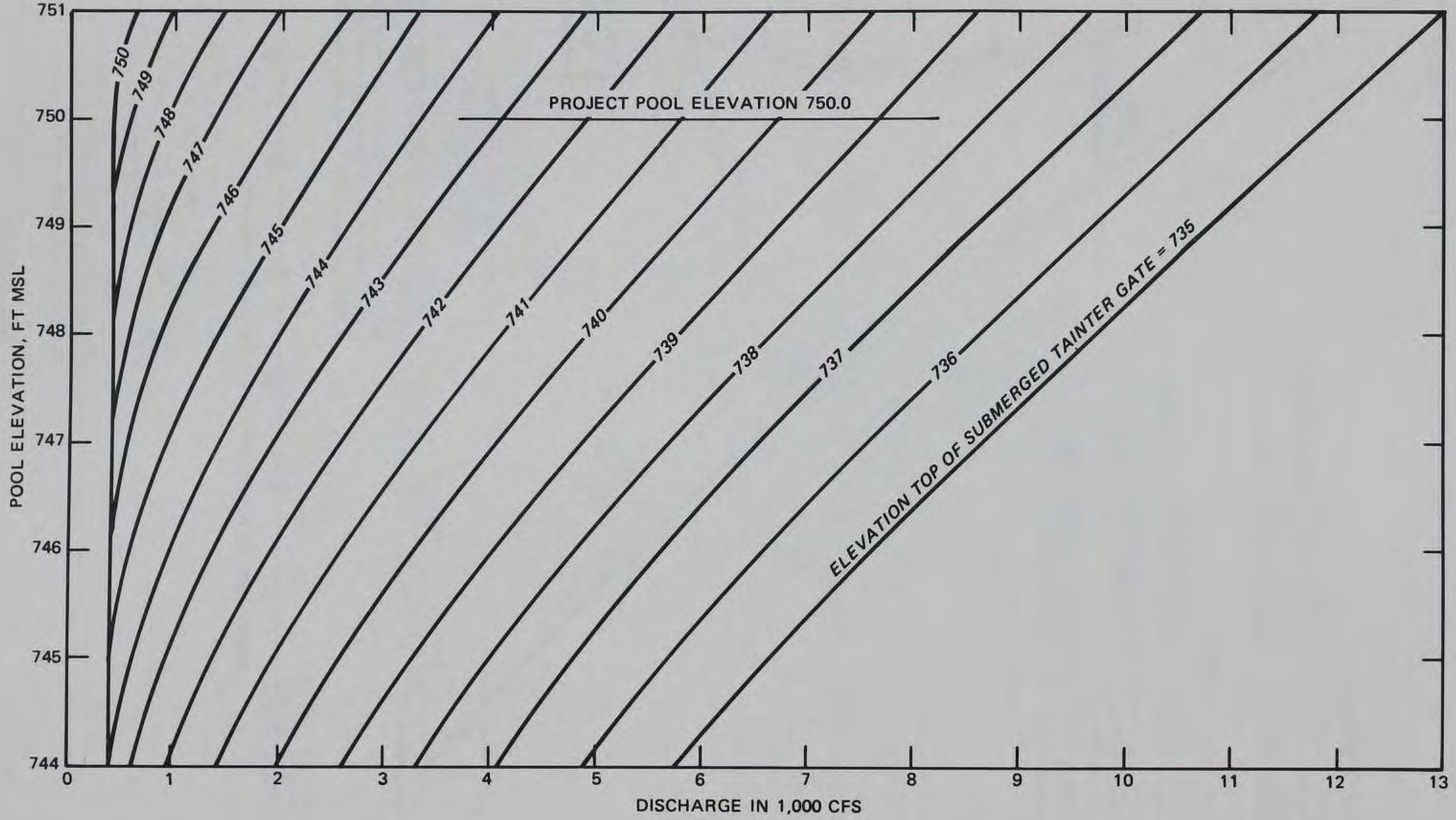

SECTION A-A
SCALE IN FEET
SECTION B-B
SCALE IN FEET
CURRENT
PLAN
SCALE IN FEET
EXISTING SANDSTONE WALL
EXISTING FLUME
CLOSURE DAM
NON-OVERFLOW DAM
TRAINING WALL
UPPER POOL ELEV 750.0
LOWER POOL ELEV 725.1
DERRICK STONE
RIVER WALL OF LOCK
ROCK FILL CRIB
INTERMEDIATE WALL
UPPER GUIDE WALL
LOWER GUIDE WALL
LAND WALL
CENTRAL CONTROL STA
UPSTREAM EDGE CEDAR AVENUE BRIDGE
LANDWARD EDGE OF FILL AT EL 742.0
U. S. PROPERTY LINE
SECTION C-C
SCALE IN FEET
TAINTER GATE
PORTS FOR FILLING AND EMPTYING
LOWER POOL EL 725.1
DEPTH ON UPPER GATE SILL 13.70 (U.P. EL. 750.00)
DEPTH ON LOWER GATE SILL 12.30 (L.P. EL. 725.10)
ELEVATION UPPER GATE SILL 736.30
ELEVATION LOWER GATE SILL 712.80
ELEVATIONS ARE REFERRED TO M.S.L. (1912 ADJ.)
SECTION D-D
SCALE IN FEET
LOWER LOCK AND DAM
SCALE: AS SHOWN

PLATE 2



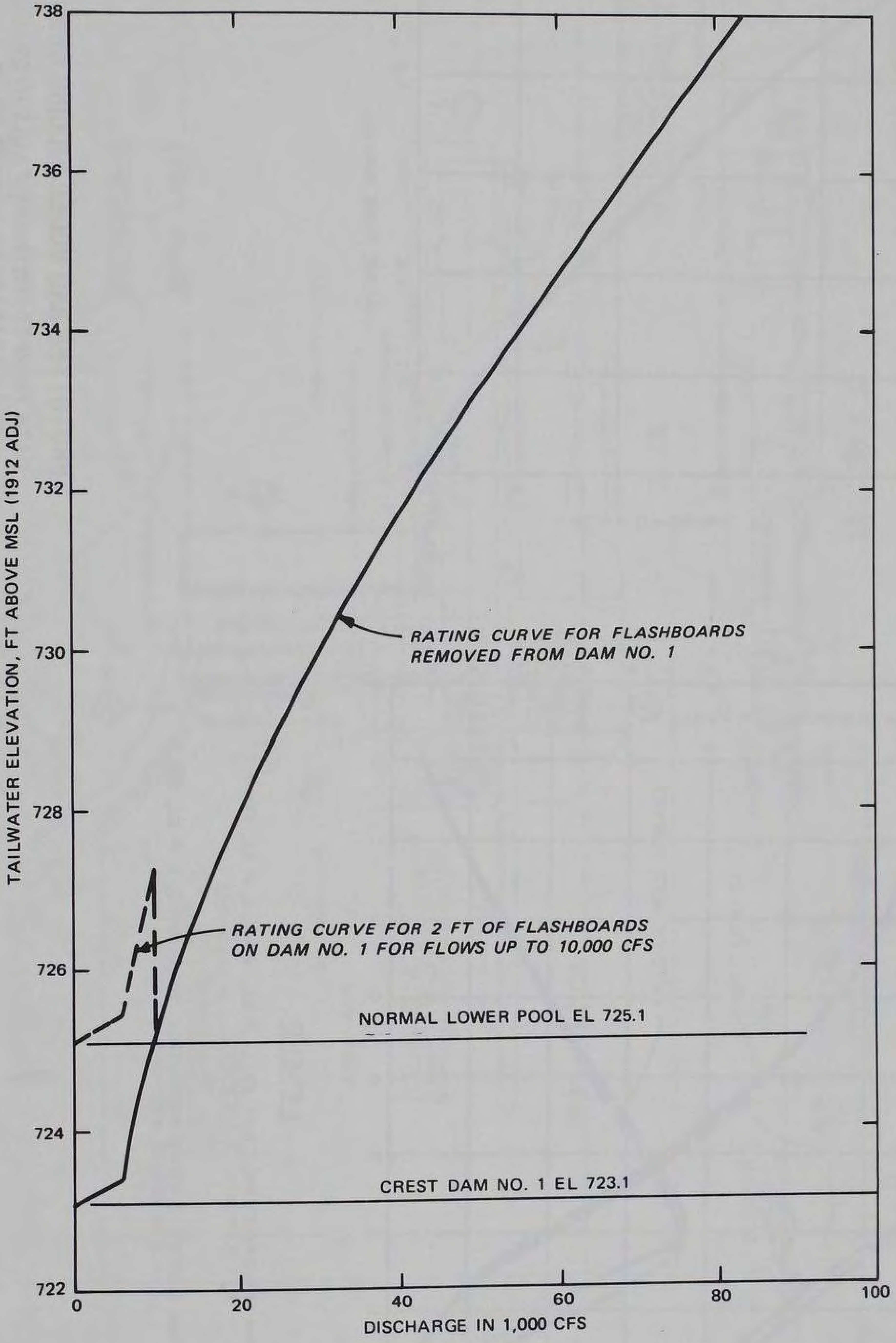
GATE	TOP OF SILL EL	GATE SEAL EL
LOCK	736.3	735.3
DAM	731.0	728.5

TAINTER GATE DISCHARGE RATING CURVE

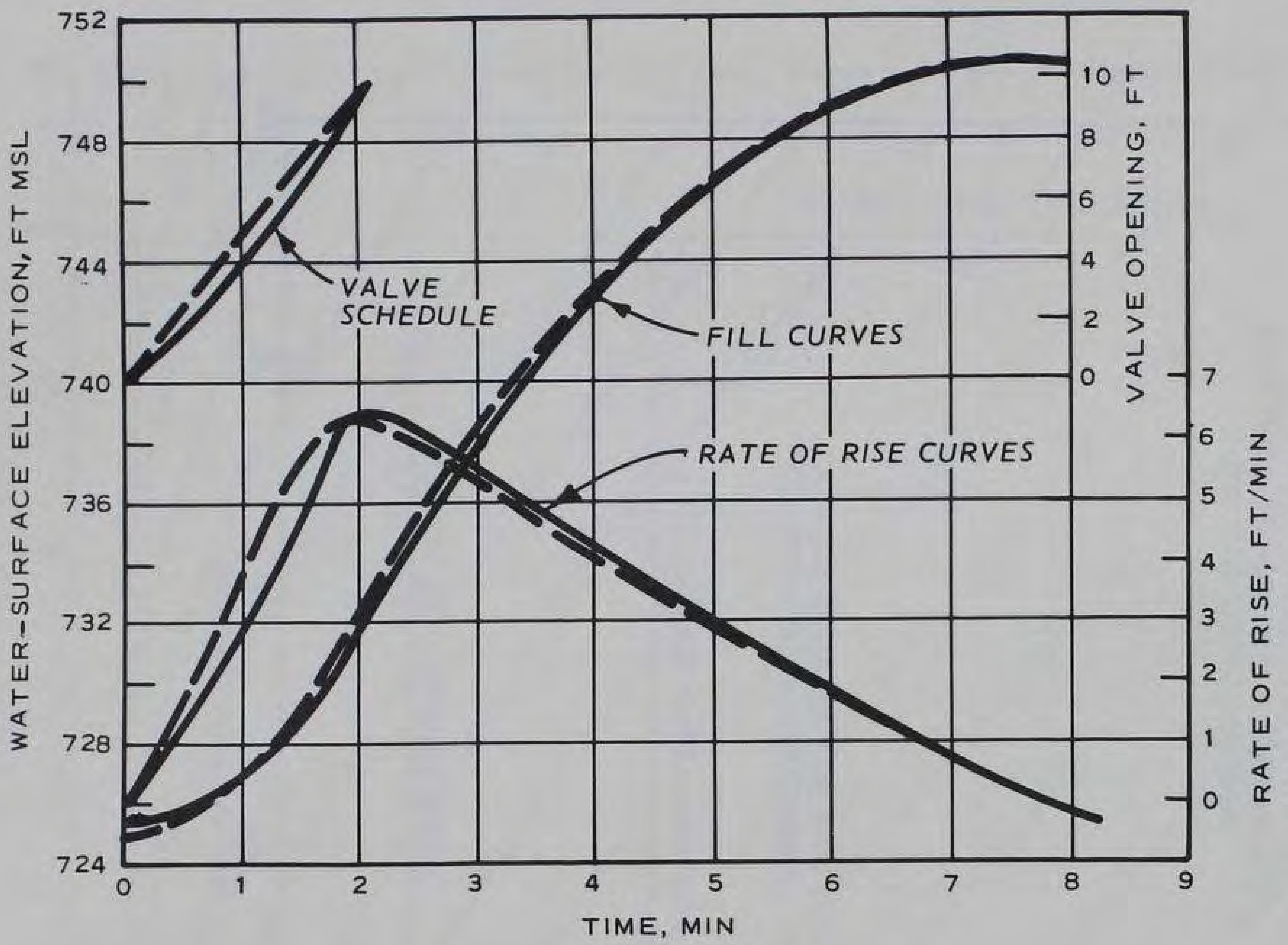


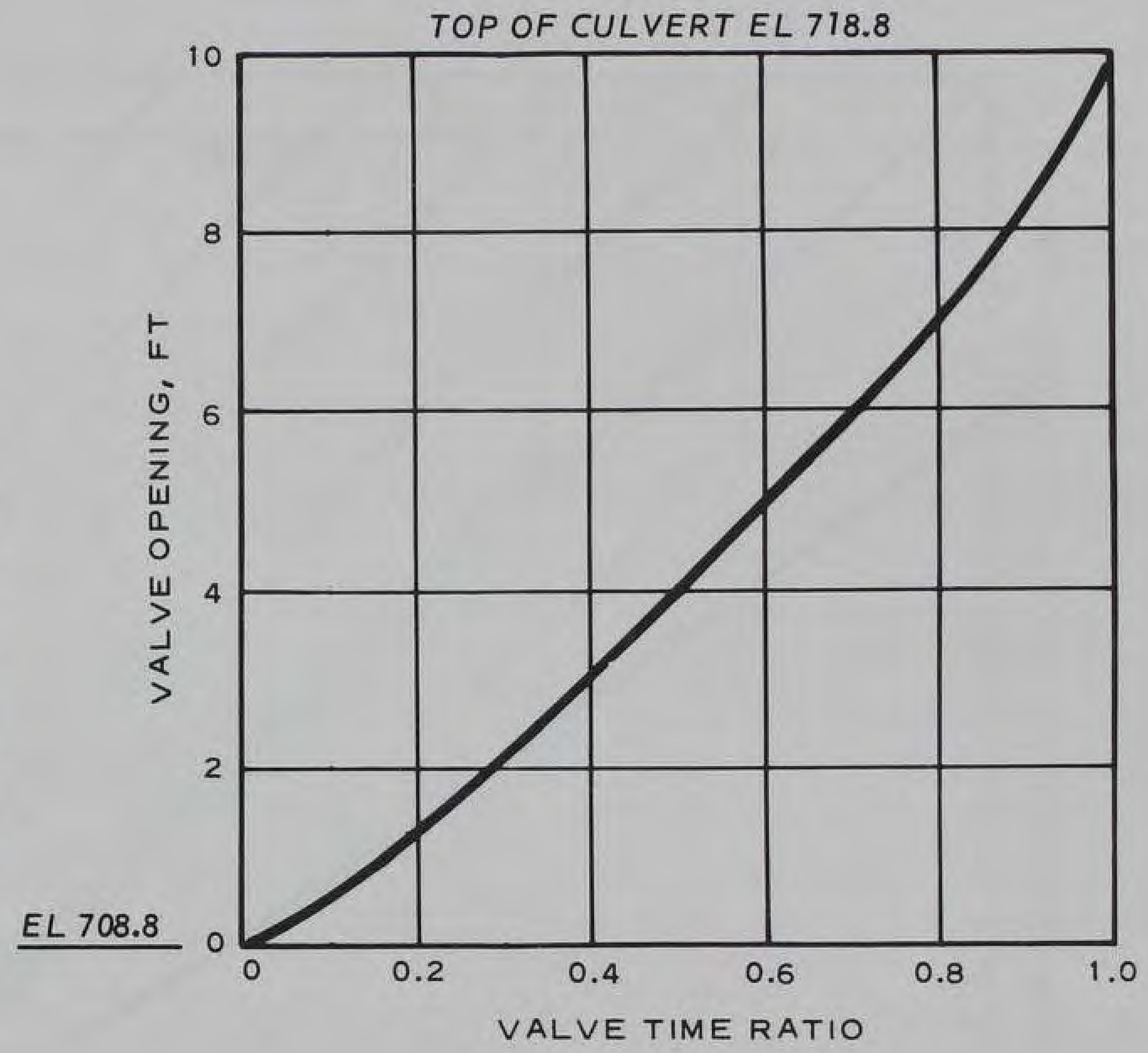
NOTE: ALL ELEVATIONS ARE IN FEET ABOVE MSL (1912 ADJ.)
TOP OF TAINTER GATES WHEN SEALED IS ELEVATION 751.5

DISCHARGE OVER ONE SUBMERGED TAINTER GATE



TAILWATER RATING CURVE





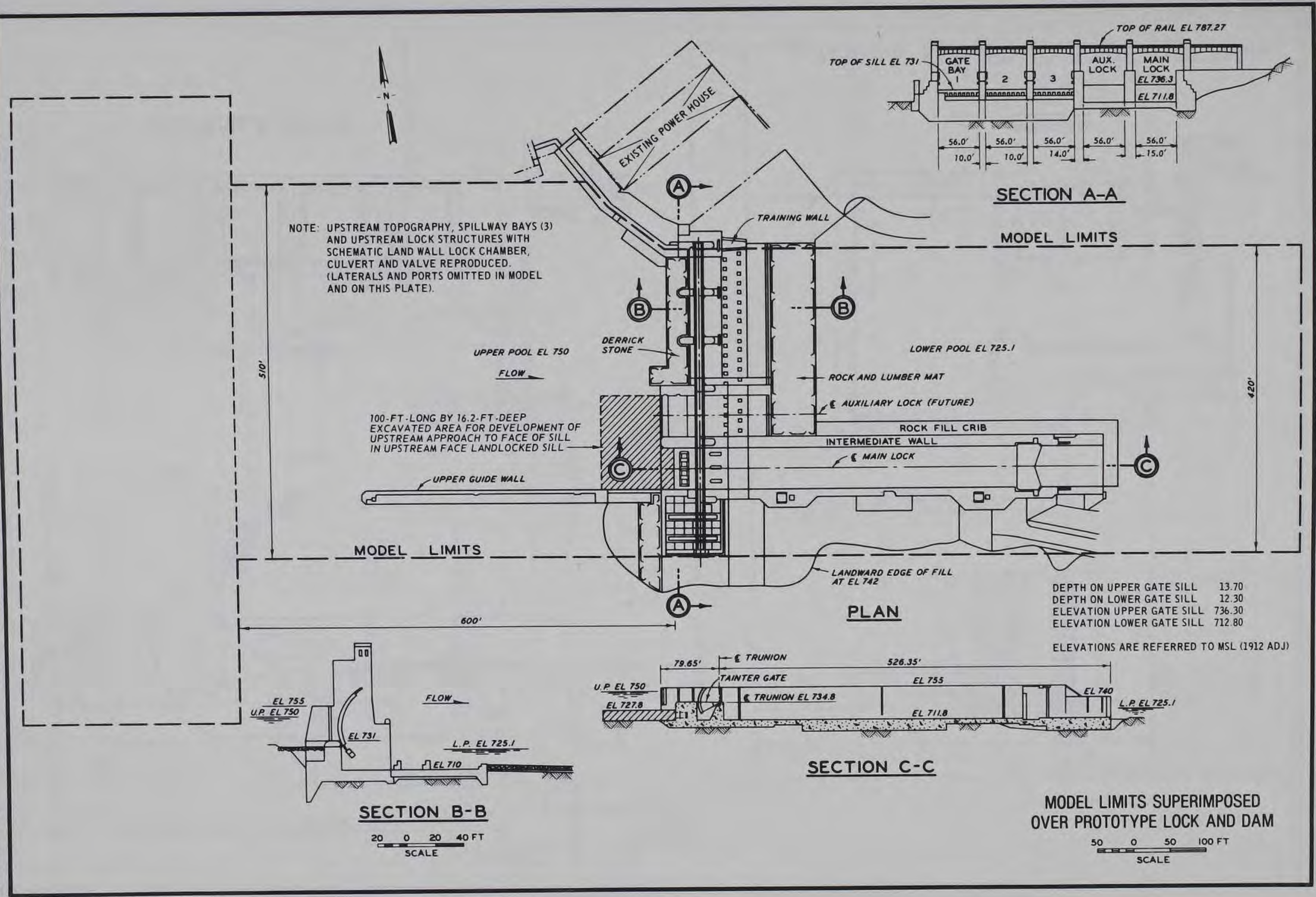
LEGEND

PROTOTYPE TEST 57, U P EL 750.1, L P EL 725.5
t_v = 2.05 MIN; T = 6.9 MIN

MODEL 5 CE-F TEST 12, U P EL 750.0, L P EL 725.1
t_v = 2.08 MIN; T = 6.7 MIN

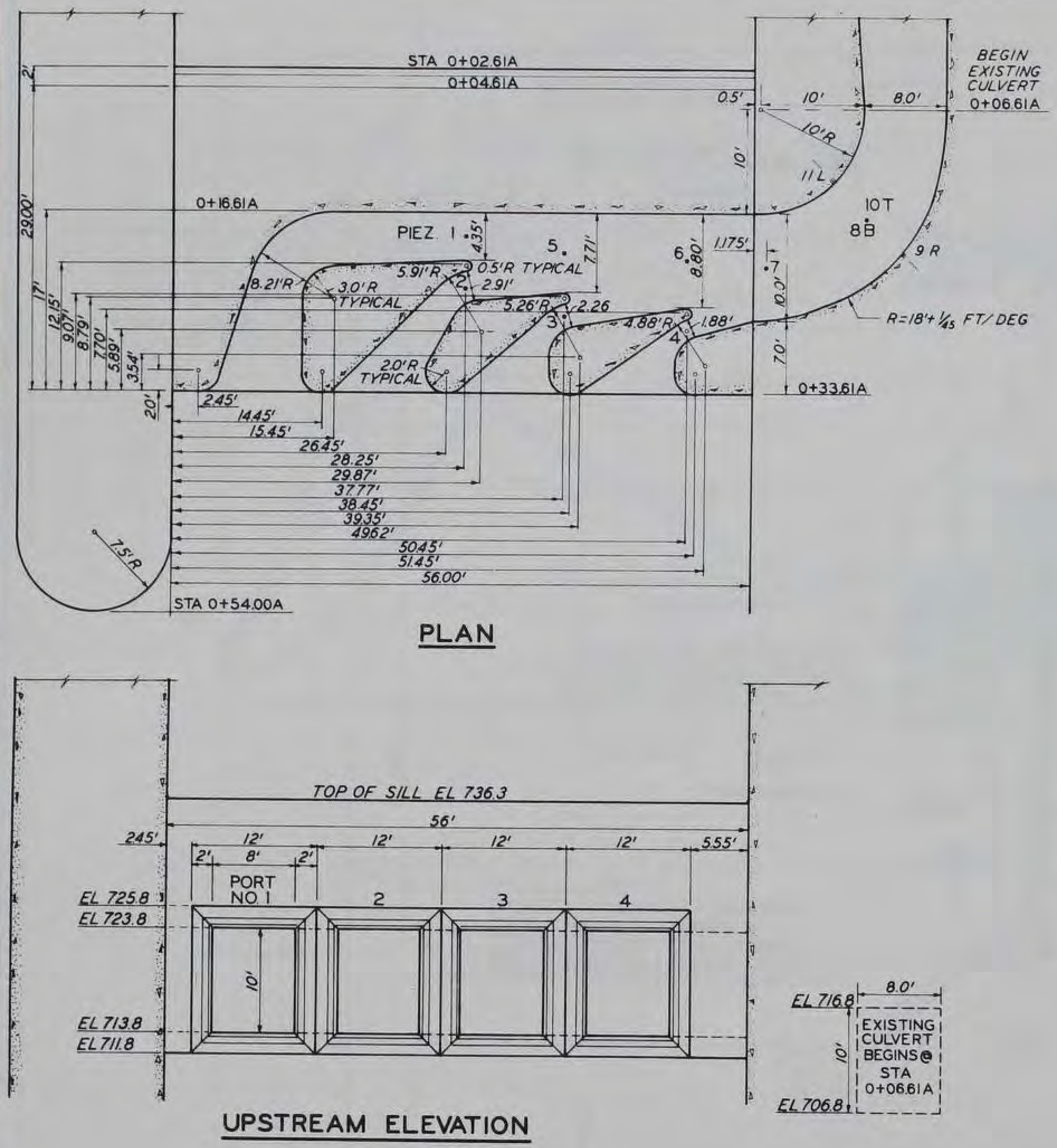
PROTOTYPE AND MODEL FILLING CURVES

DATA FROM ST. ANTHONY FALLS HYDRAULIC LABORATORY REPORT NO. 76
DECEMBER 1964

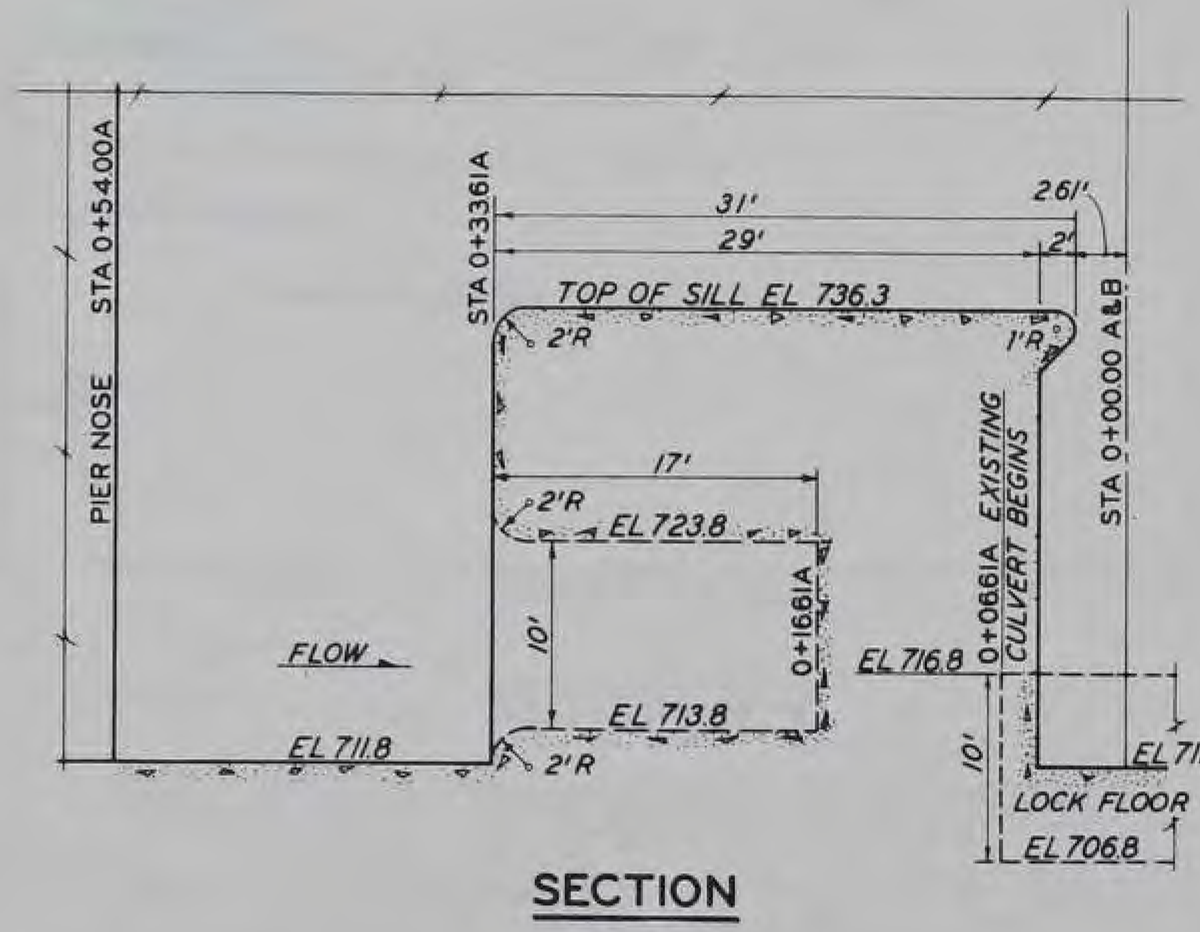


MODEL LIMITS SUPERIMPOSED OVER PROTOTYPE LOCK AND DAM

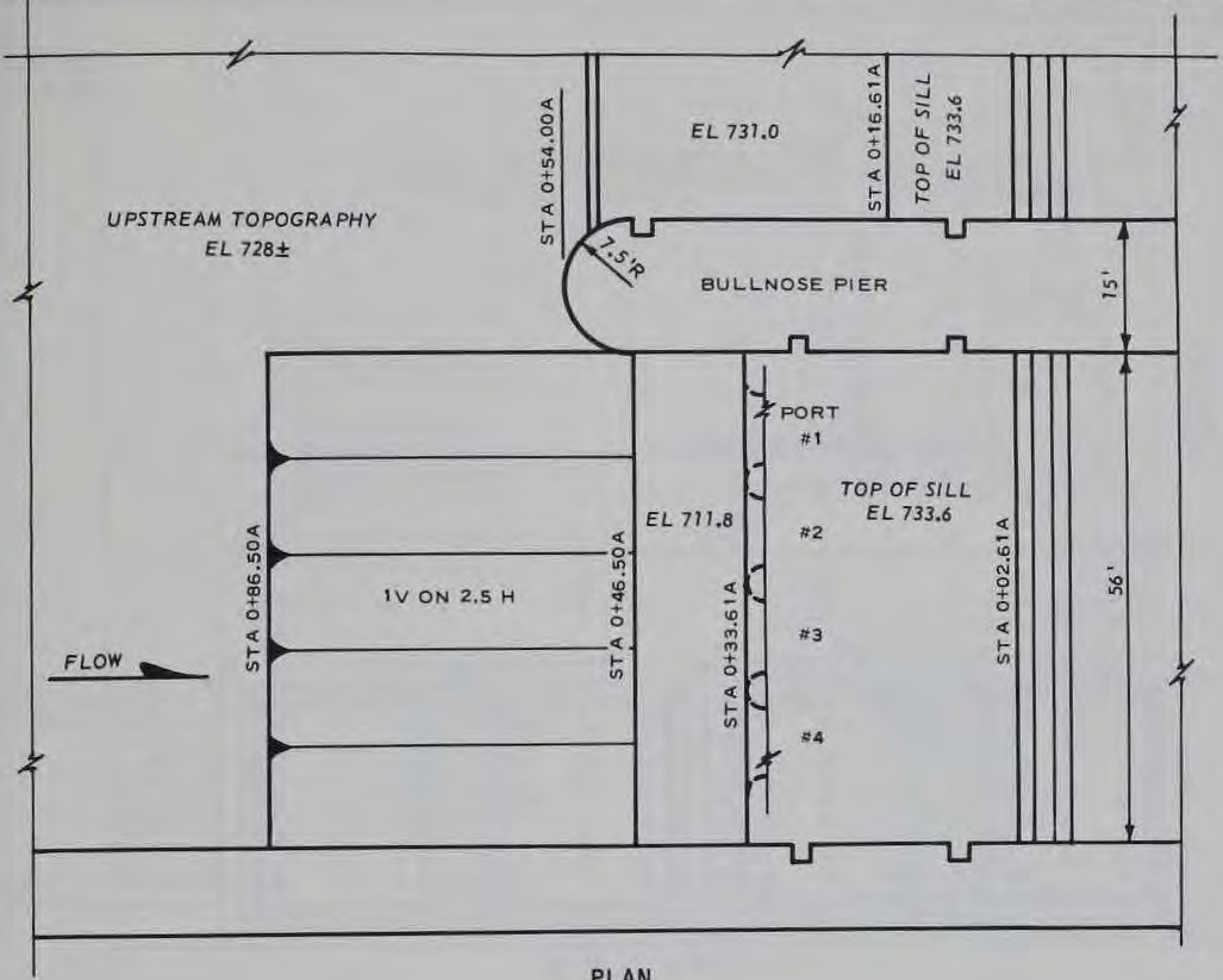
PLATE 7



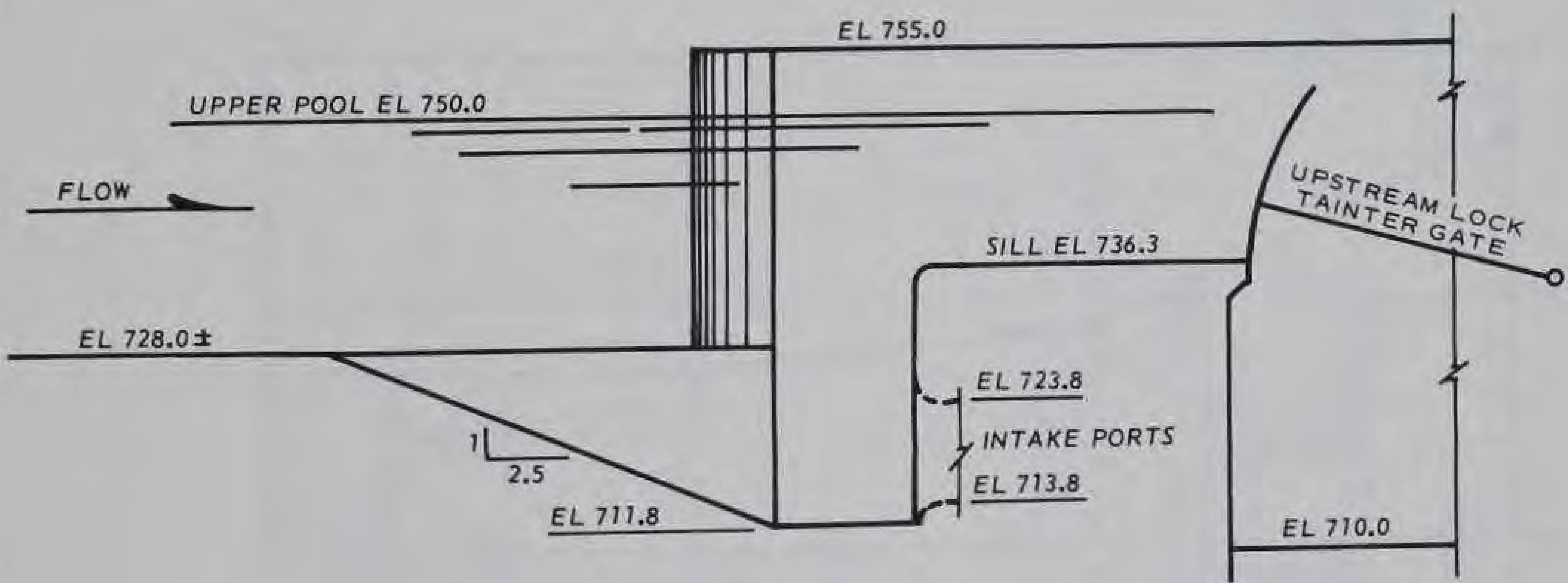
PIEZOMETER LOCATIONS		
NO	STATION	ELEVATION
1	0+18.78A	713.8
2	0+23.61 A	713.8
3	0+26.16 A	713.8
4	0+27.51 A	713.8
5	0+20.46A	713.8
6	0+21.00A	713.8
7	0+21.16A	713.42
8	0+16.86A	710.3
9	0+20.04A	715.3
10	0+16.86A	720.3
11	0+13.68A	715.3



INTAKE MANIFOLD TYPE 1 DESIGN

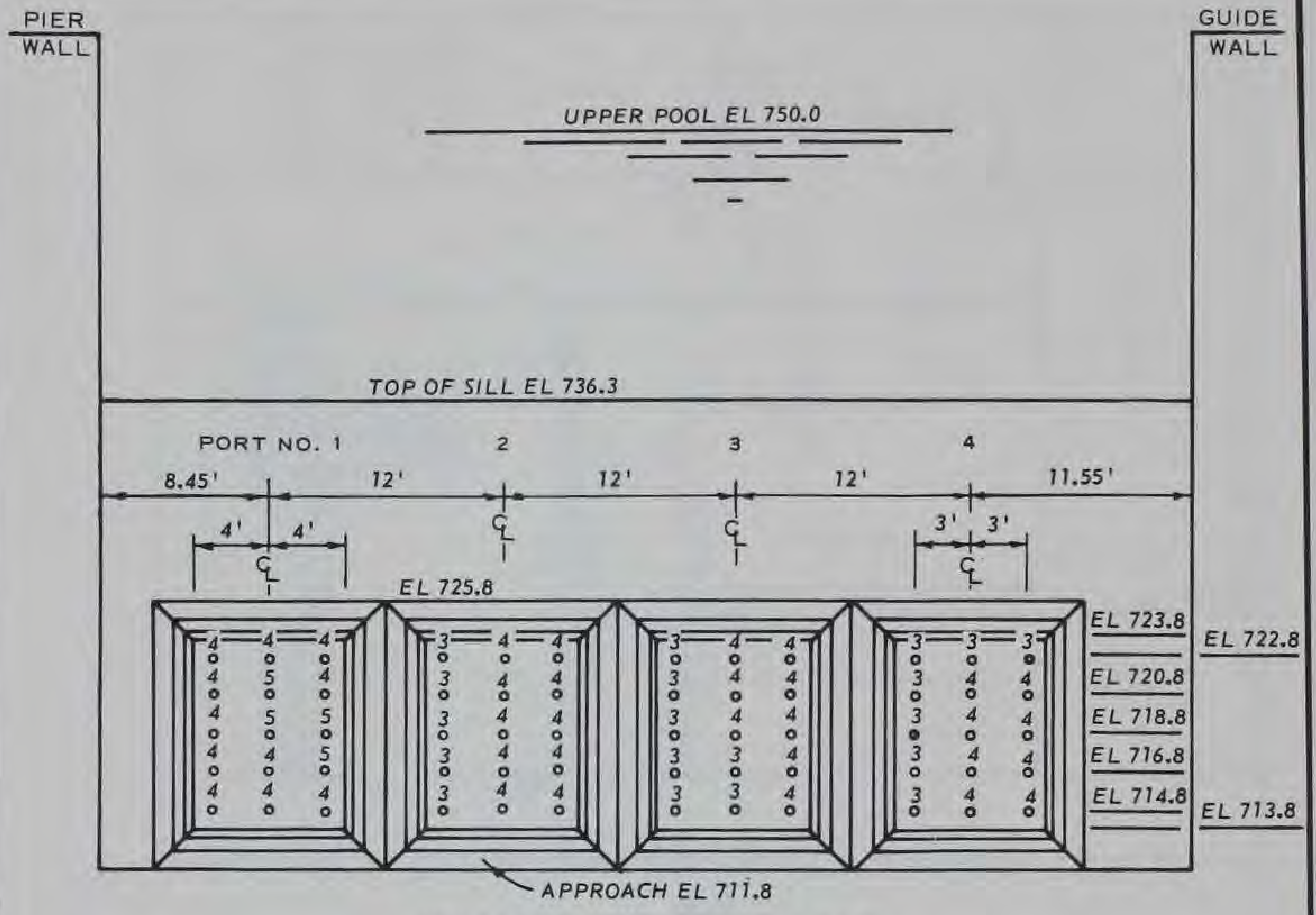


PLAN

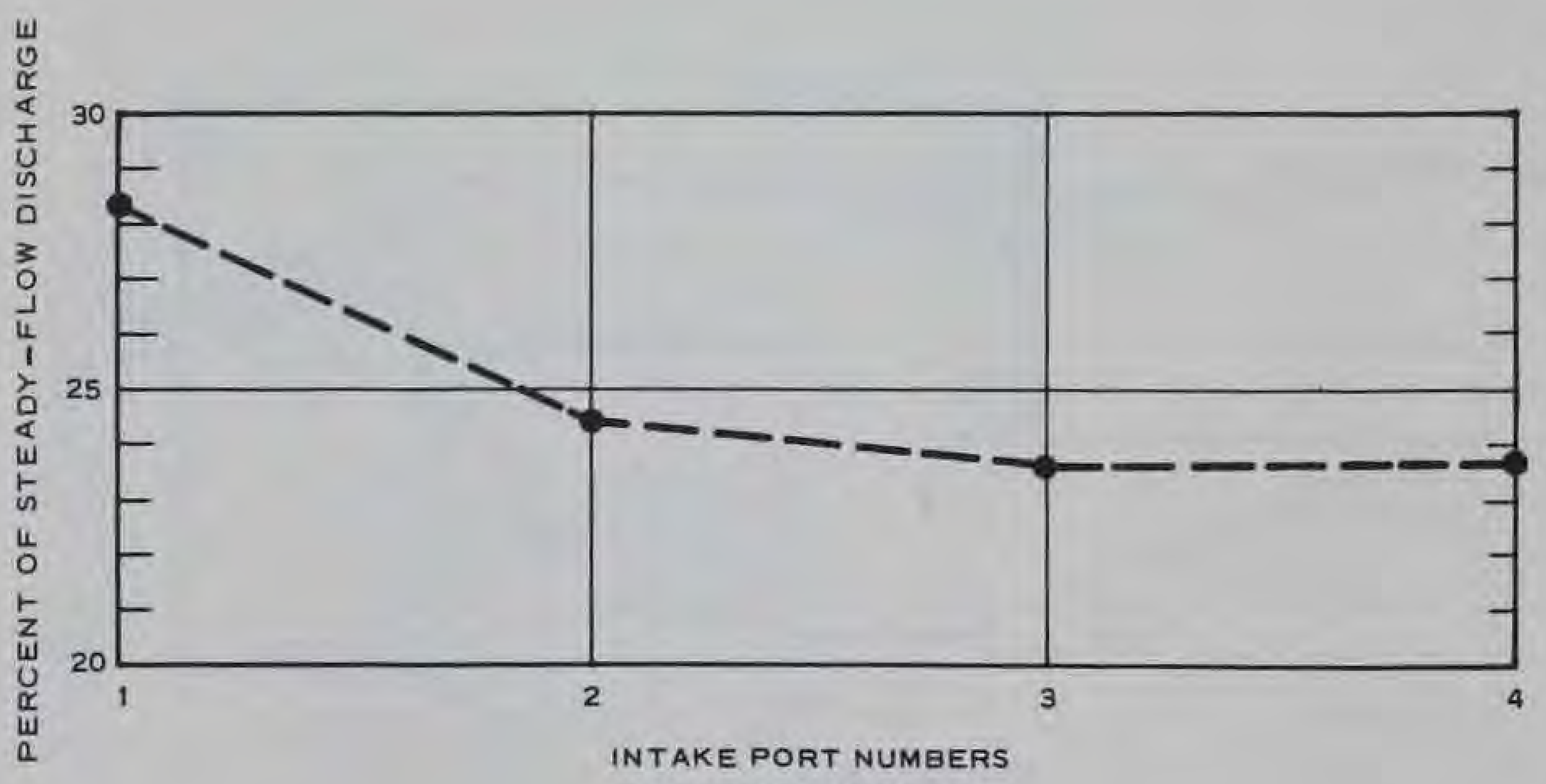


ELEVATION

UPSTREAM APPROACH IN VICINITY
TYPE 1 INTAKE
WITH BULLNOSE PIER IN PROTOTYPE POSITION



VELOCITIES AT INTAKE PORT FACE



FLOW DISTRIBUTION

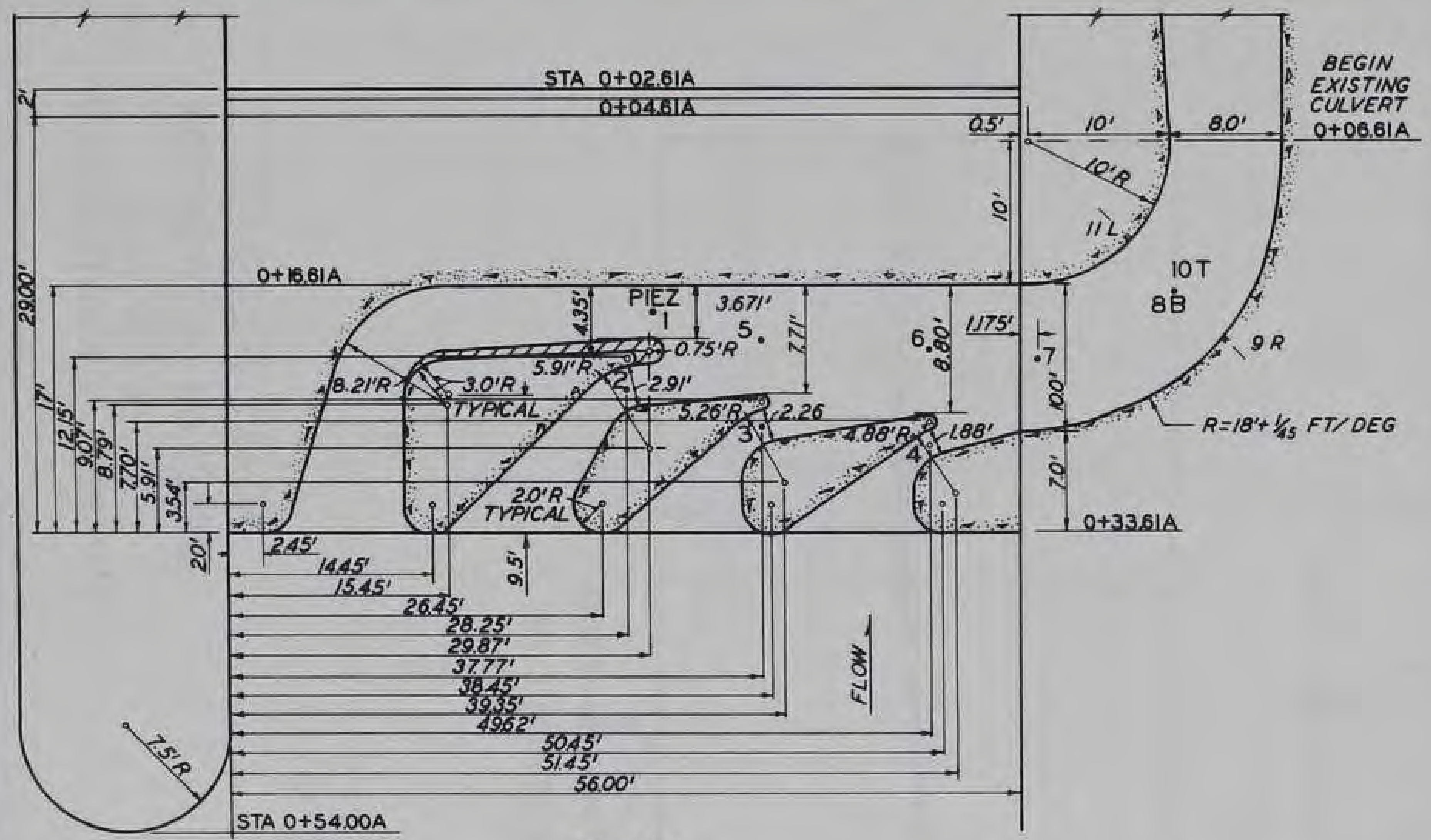
TEST CONDITIONS

UPPER POOL EL 750.0
LOCK CHAMBER EL 732.0
FILL VALVE OPEN FULL
DOWNSTREAM MITER GATE OPEN TO MAINTAIN POOLS

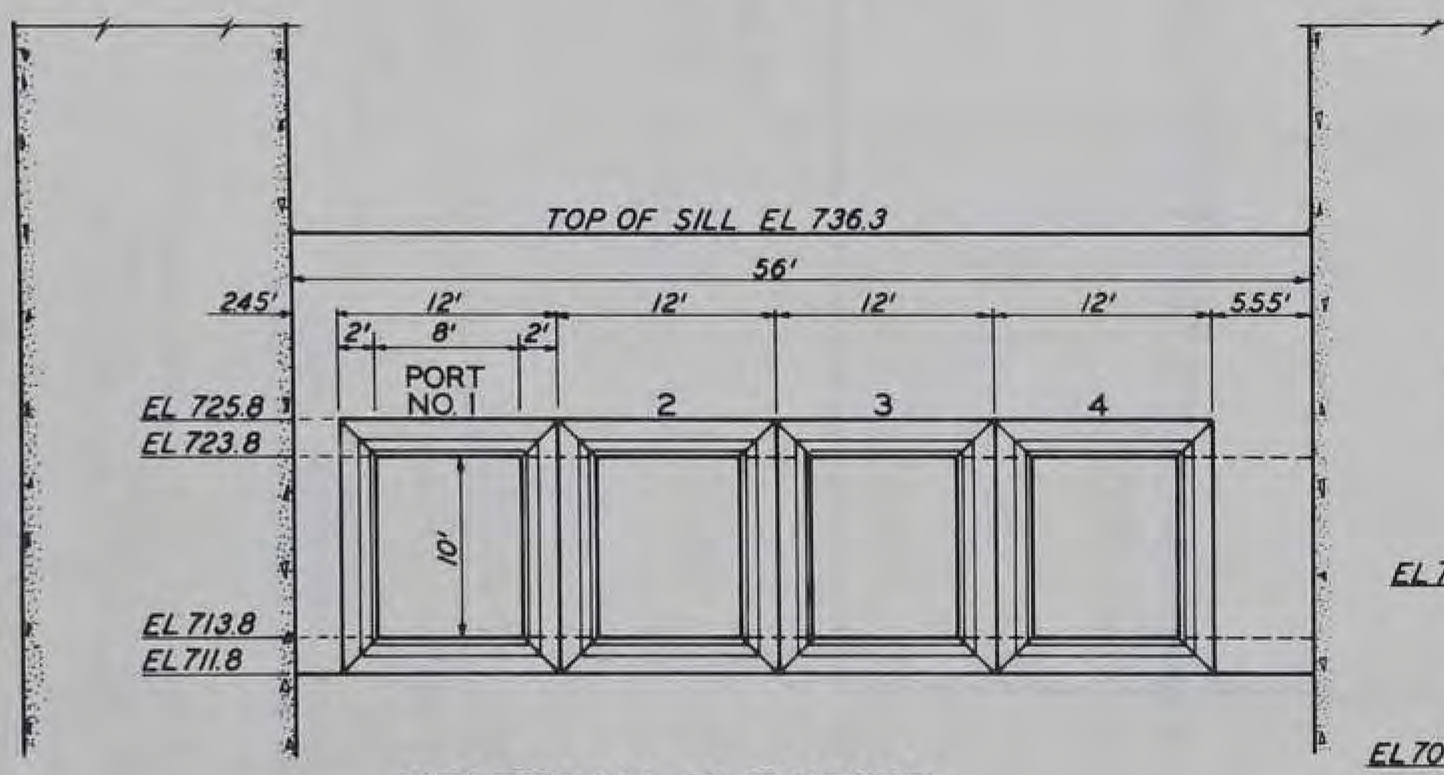
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND ARE MEASURED AT WALL FACE OF INTAKE.

INTAKE VELOCITIES AND FLOW DISTRIBUTION

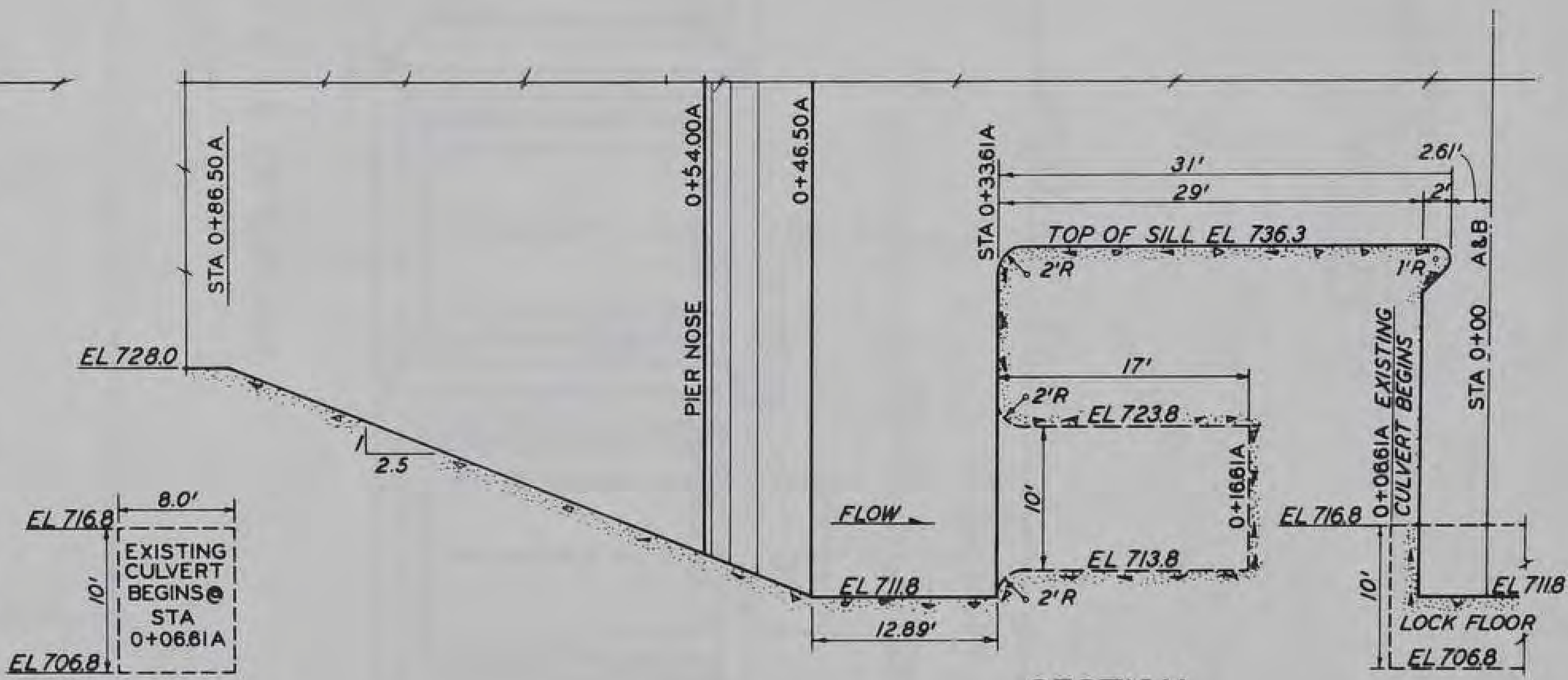
TYPE 1 DESIGN
STEADY-FLOW DISTRIBUTION



PLAN



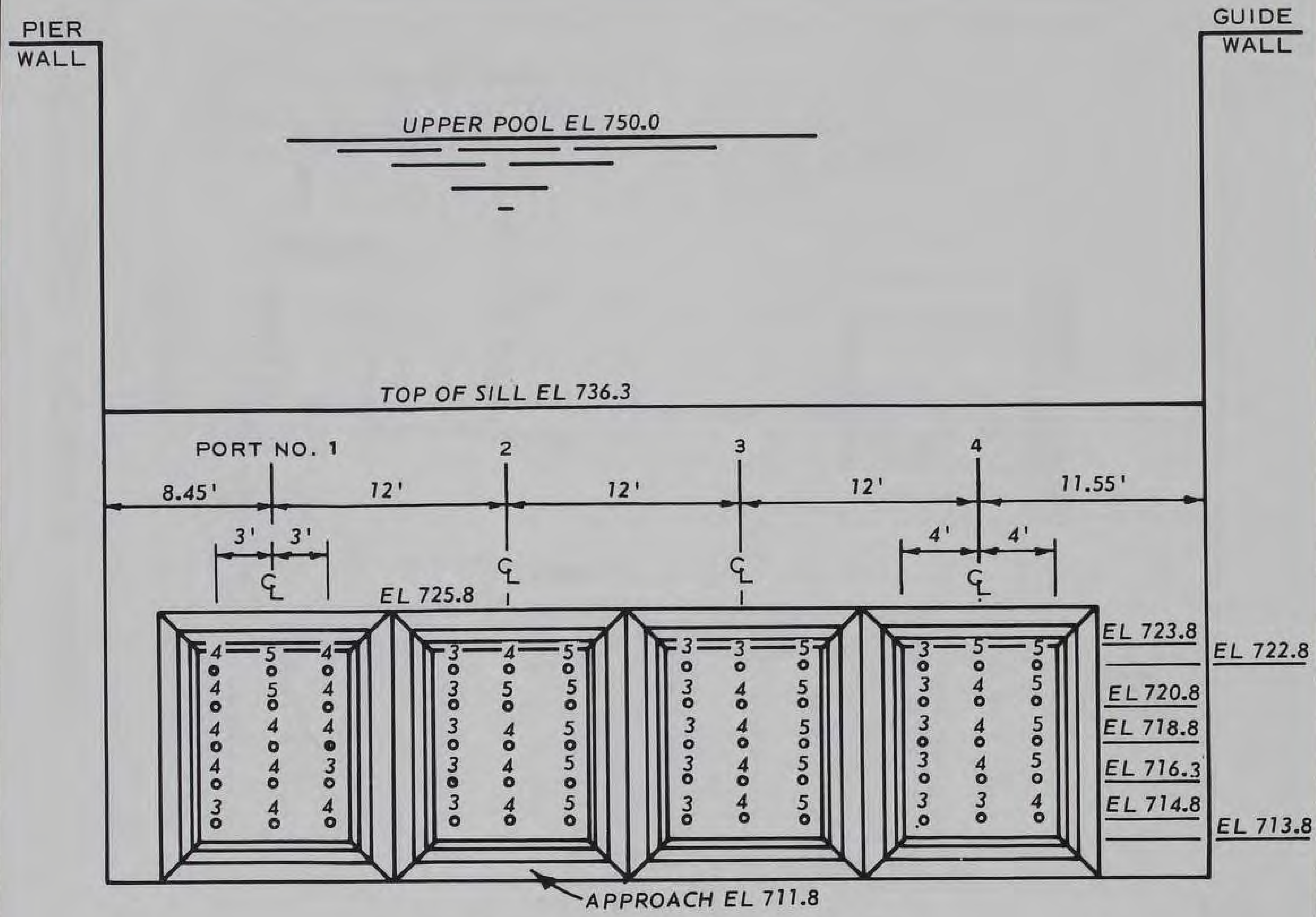
UPSTREAM ELEVATION



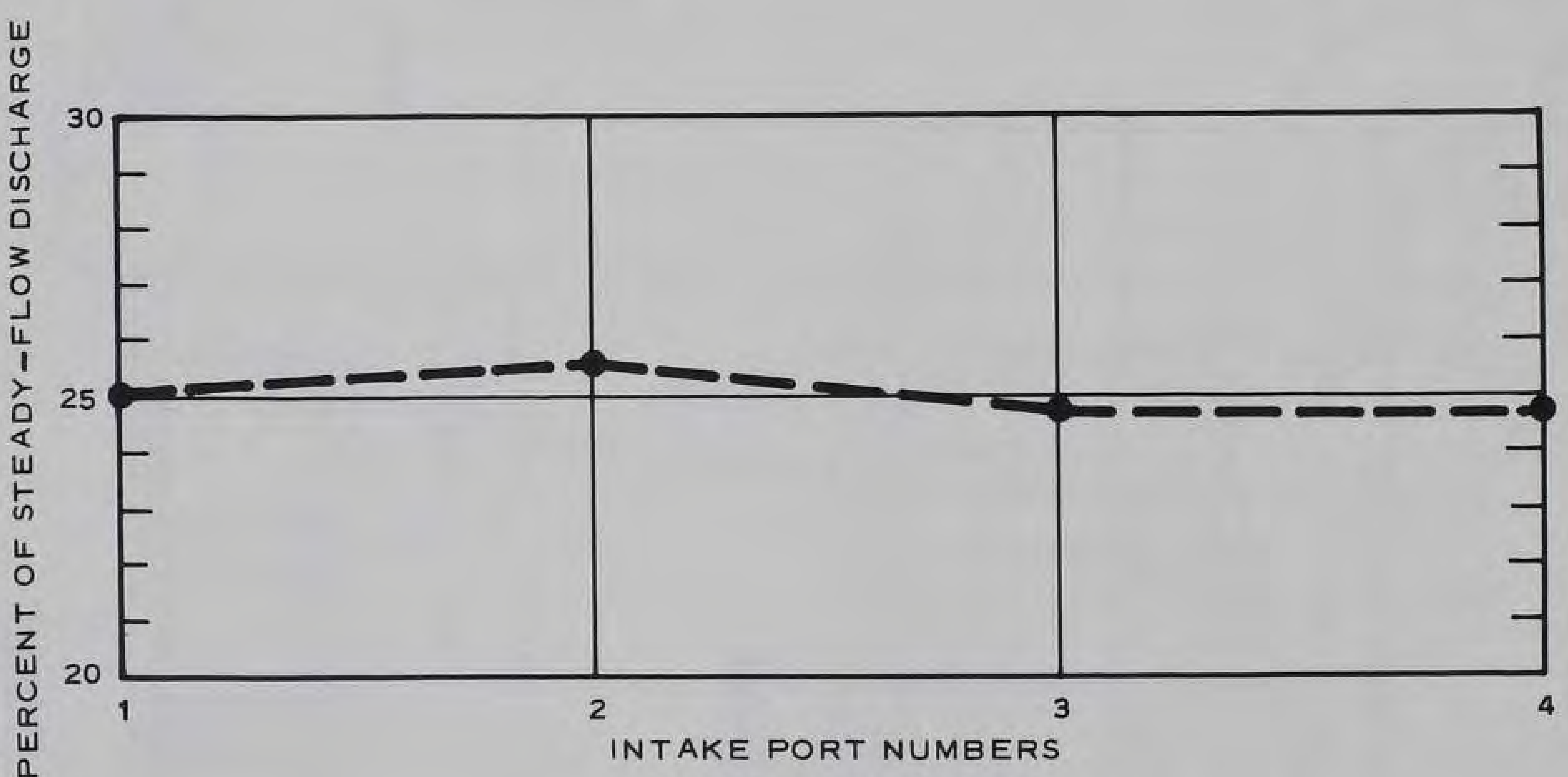
SECTION

PIEZOMETER LOCATIONS		
NO	STATION	ELEVATION
1	0+18.45A	713.8
2	0+23.61 A	713.8
3	0+26.16 A	713.8
4	0+27.51 A	713.8
5	0+20.46A	713.8
6	0+21.00A	713.8
7	0+21.16A	713.42
8	0+16.86A	710.3
9	0+20.04A	715.3
10	0+16.86A	720.3
11	0+13.68A	715.3

INTAKE MANIFOLD TYPE 2 DESIGN



VELOCITIES AT INTAKE PORT FACE



FLOW DISTRIBUTION

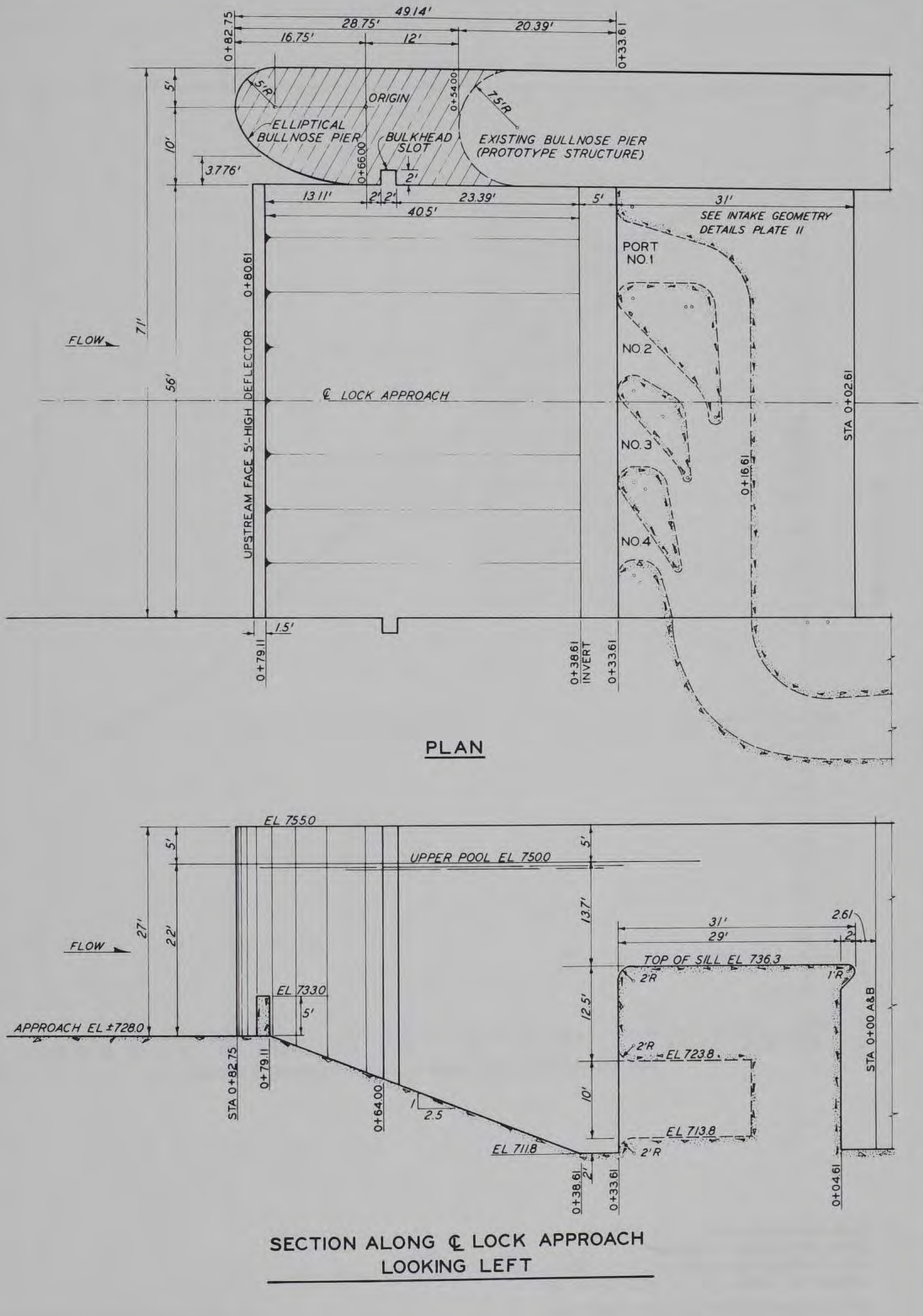
TEST CONDITIONS

UPPER POOL EL 750.0
LOCK CHAMBER EL 732.0
FILL VALVE OPEN FULL
DOWNSTREAM MITER GATE OPEN TO MAINTAIN POOLS

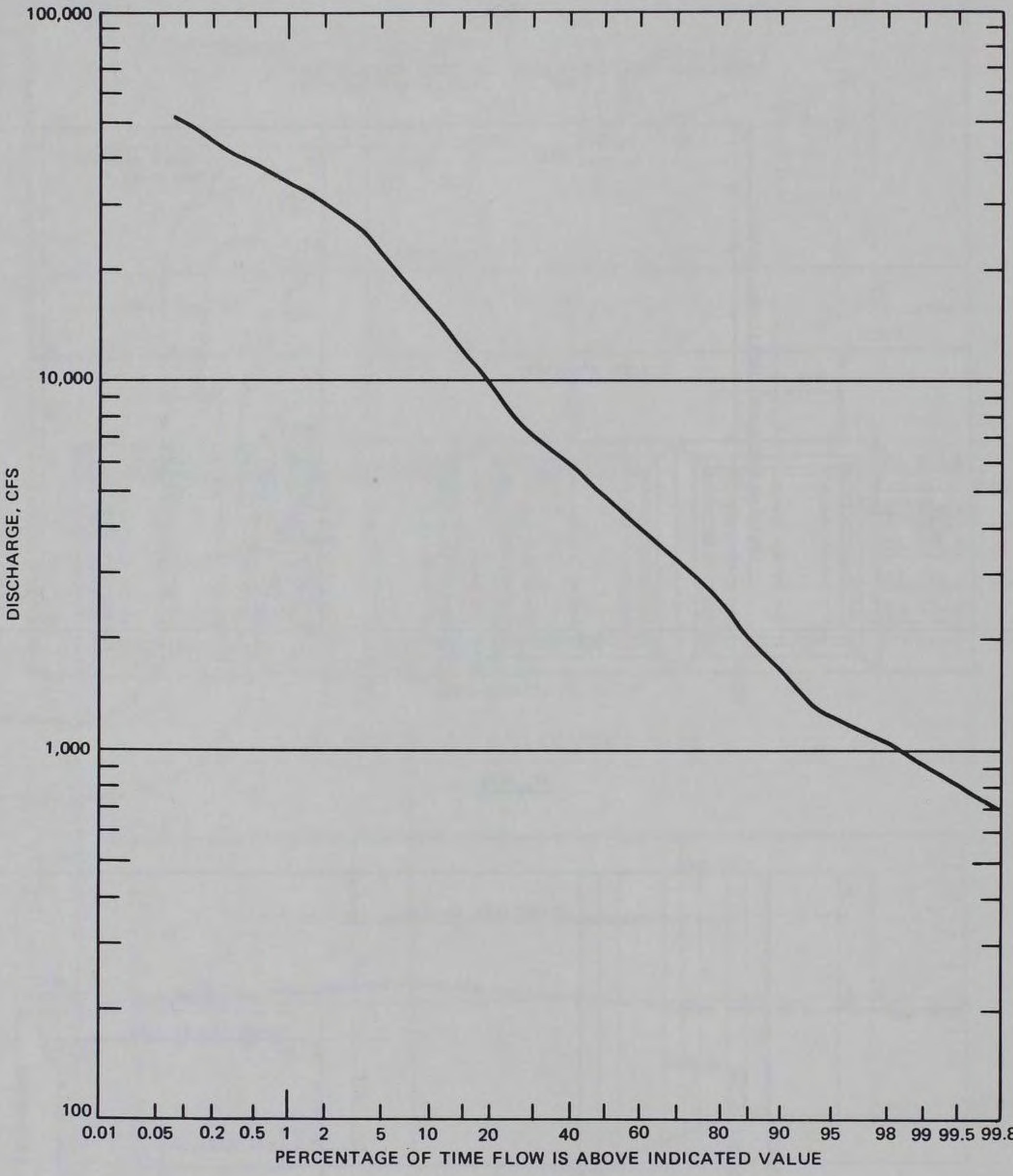
NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND AND ARE MEASURED AT WALL FACE OF INTAKE.

INTAKE VELOCITIES AND FLOW DISTRIBUTION

TYPE 2 INTAKE
STEADY-FLOW DISTRIBUTION



TYPE 3 DESIGN



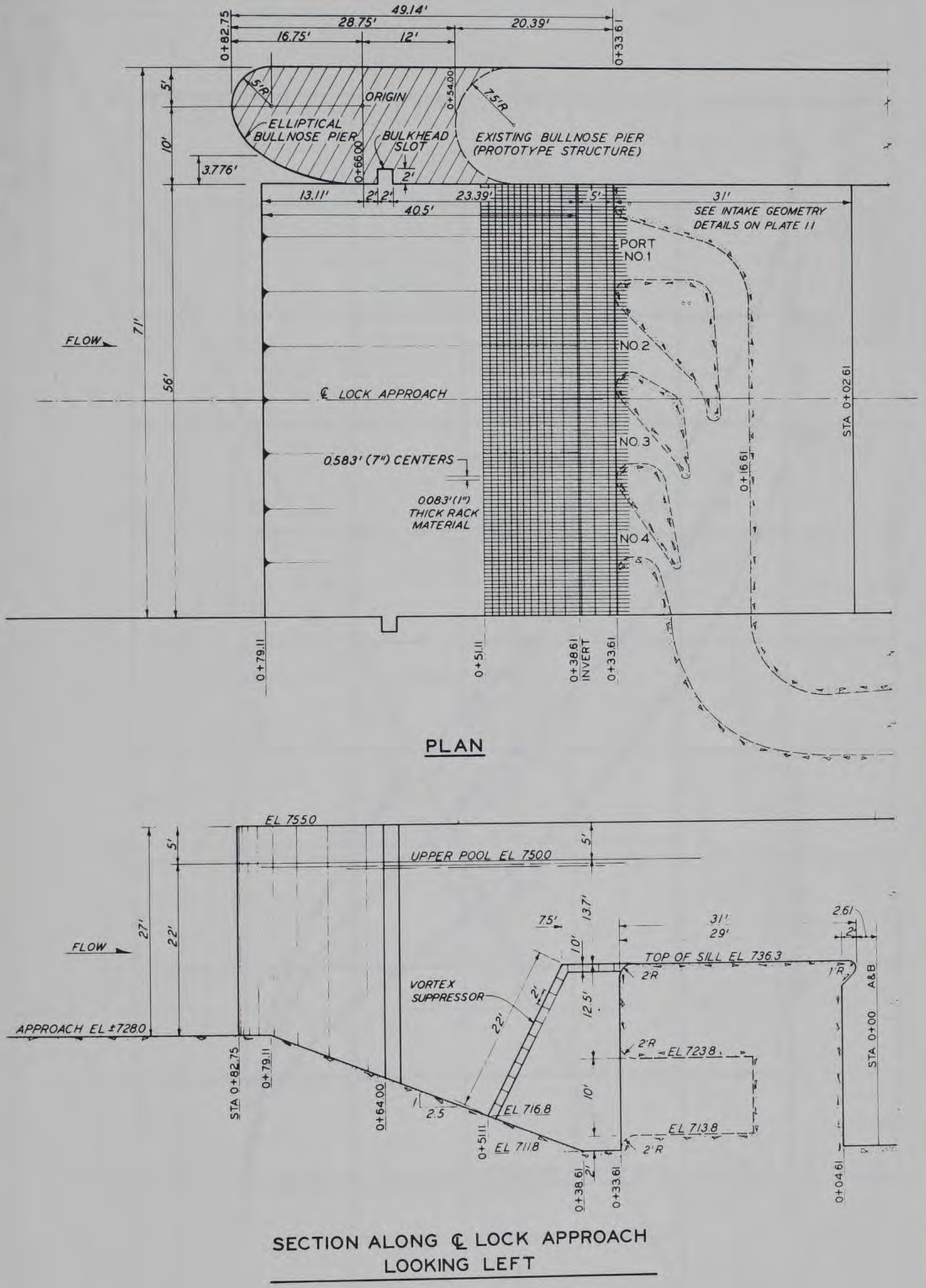
BASED ON USGS DATA FOR GAGING
STATION NUMBER 05288500
FOR A PERIOD OF RECORD FROM 1932 to 1968
DRAINAGE AREA = 17,100 SQUARE MILES

RIVER MILE 871.3 UPSTREAM FROM THE
CONFLUENCE WITH THE OHIO RIVER

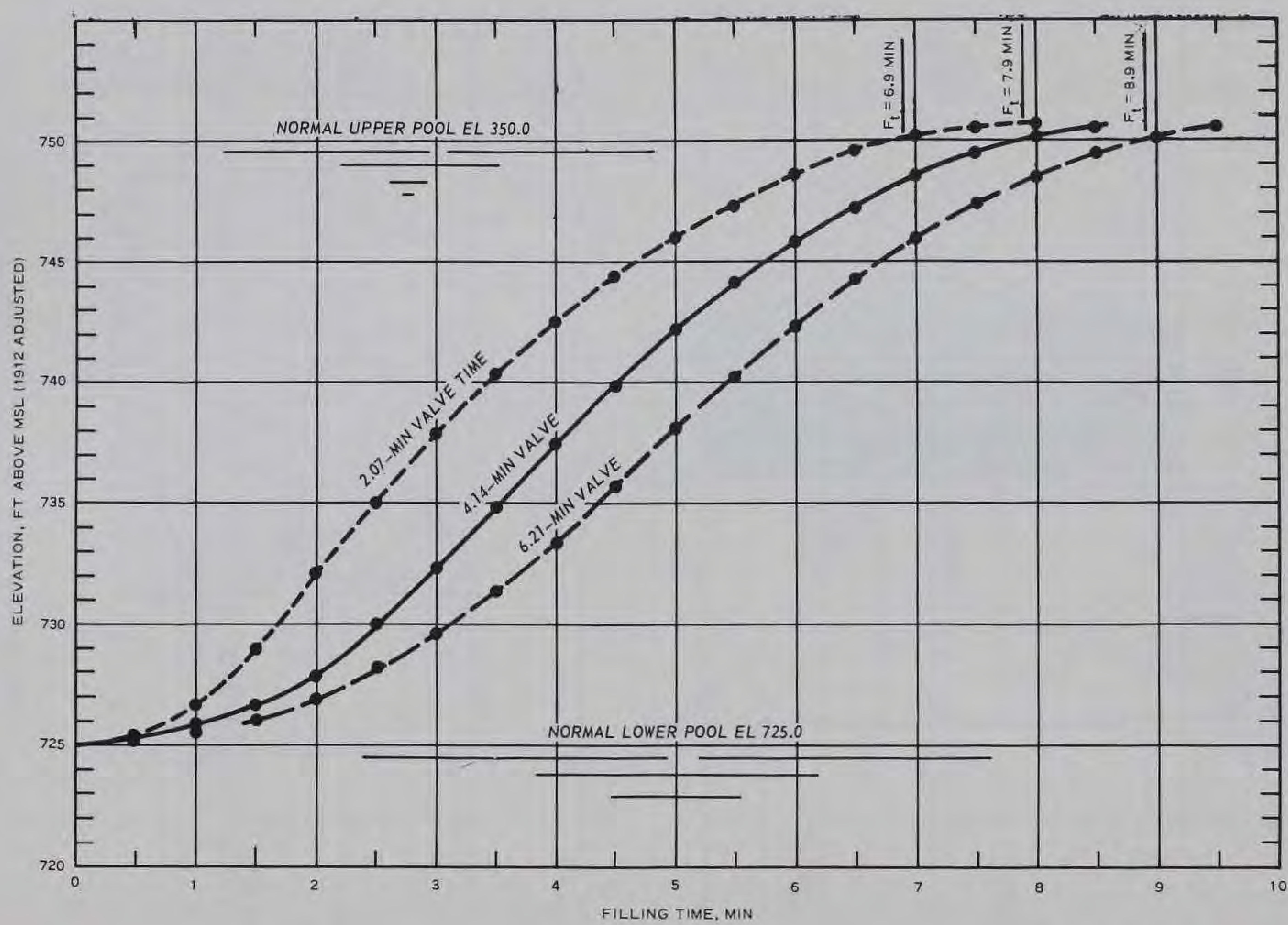
FLOW-DURATION CURVE

MISSISSIPPI RIVER AT ANOKA, MN

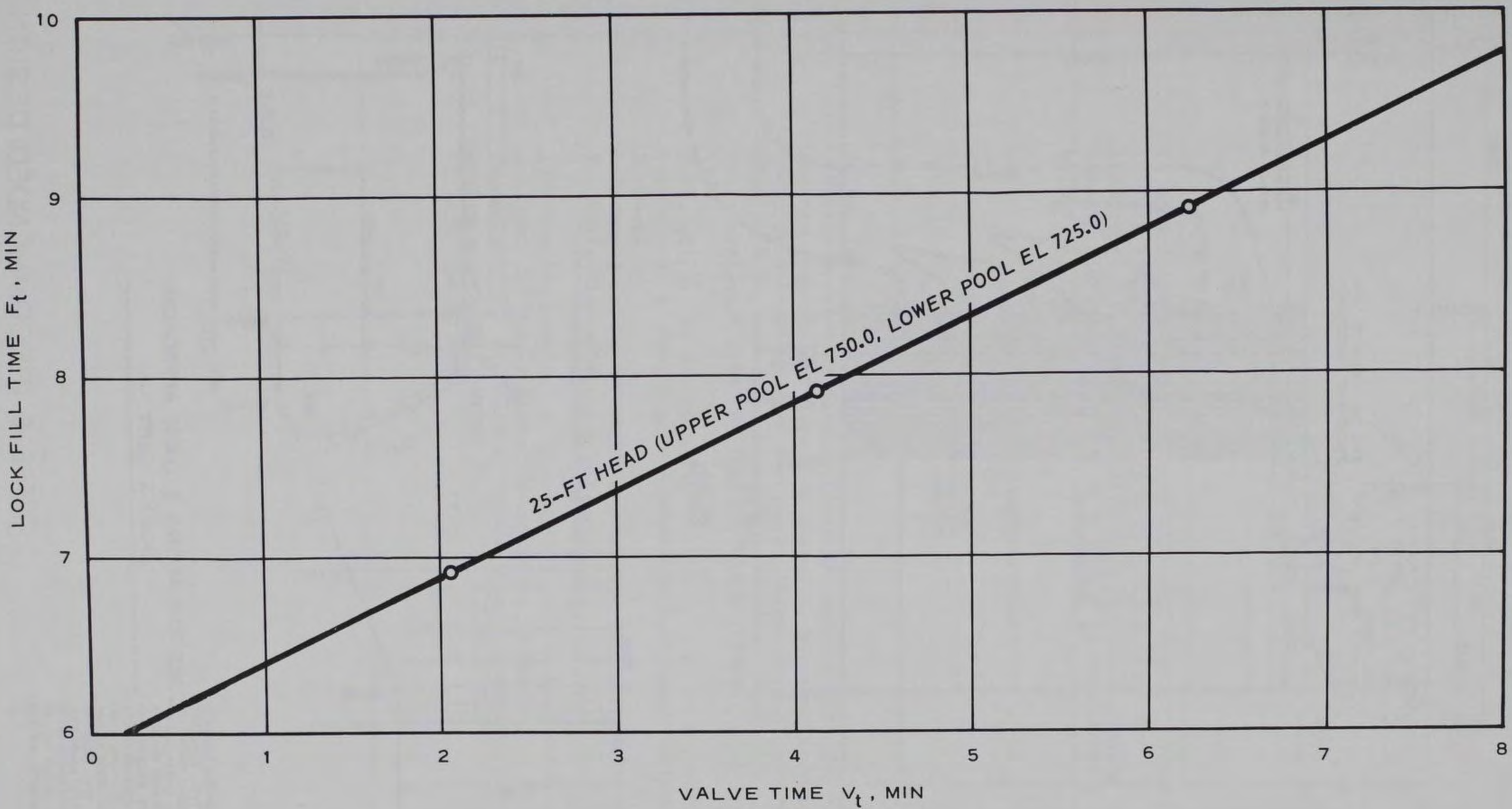
ST. PAUL DISTRICT USCE
MAY 1977 RTP



TYPE 4 DESIGN

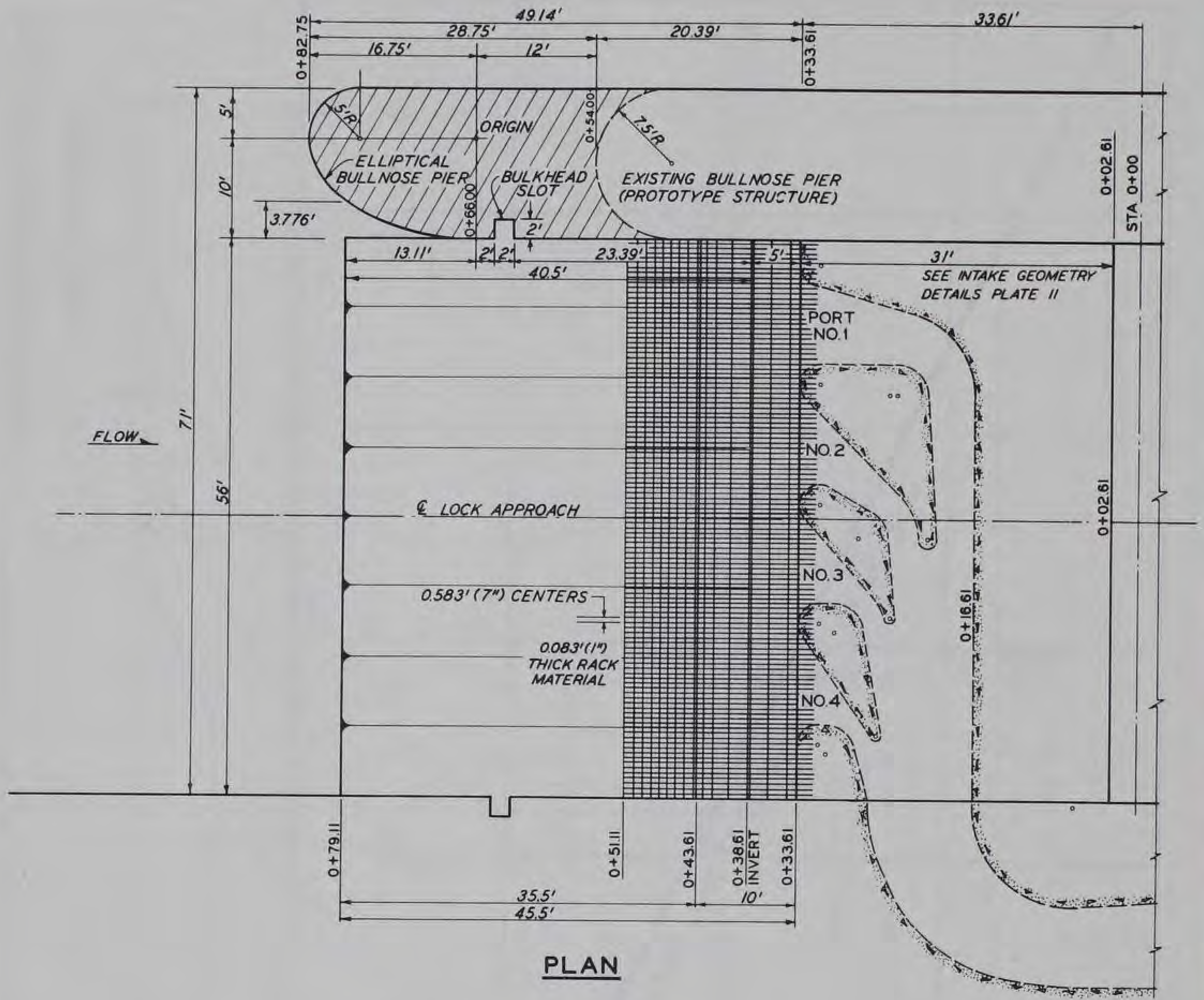


LOCK FILLING CURVES
VALVE TIMES VARIES
TYPE 4 DESIGN

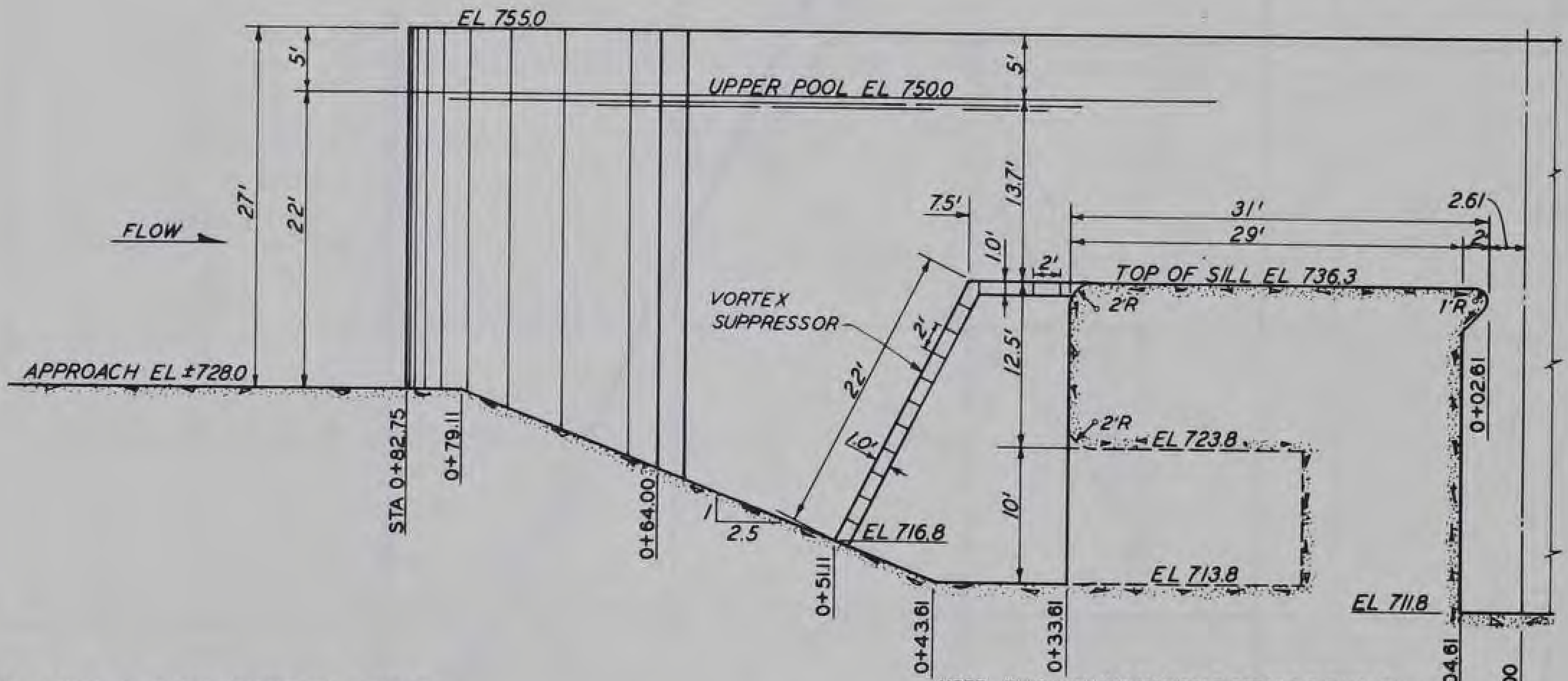


TYPE 4 DESIGN

FILLING TIME VS VALVE TIME



PLAN



NOTE: TYPE 2 INTAKE MANIFOLD DETAILS FURNISHED IN PLATE 11.

NOTE: TYPE 5 (RECOMMENDED) DESIGN CONSISTS OF THE TYPE 2 INTAKE MANIFOLD, A 10-FT-LONG INVERT AT EL 713.8 IMMEDIATELY UPSTREAM OF THE INTAKE TO STA 0+43.61 WHERE A 1(V) ON 2.5(H) SLOPE BEGINS AND CONTINUES TO UPSTREAM APPROACH CHANNEL EL 727.0 AT STA 0+79.11. AN ELLIPTICAL SHAPE BULLNOSE AT STA 0+82.75 REPLACES THE EXISTING CIRCULAR FACE PIER AT STA 0+54. A 56-FT-WIDE TRASH RACK EXTENDS FROM THE UPSTREAM FACE OF THE SILL AT STA 0+33.61 TO UPSTREAM SLOPE STA 0+51.11, AS SHOWN.

SECTION ALONG ℄ LOCK APPROACH
LOOKING LEFT

TYPE 5 (RECOMMENDED) DESIGN