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August 1996

Clarence Cannon Re-regulation Structure, Salt River, Missouri

Hydraulic Model Investigation

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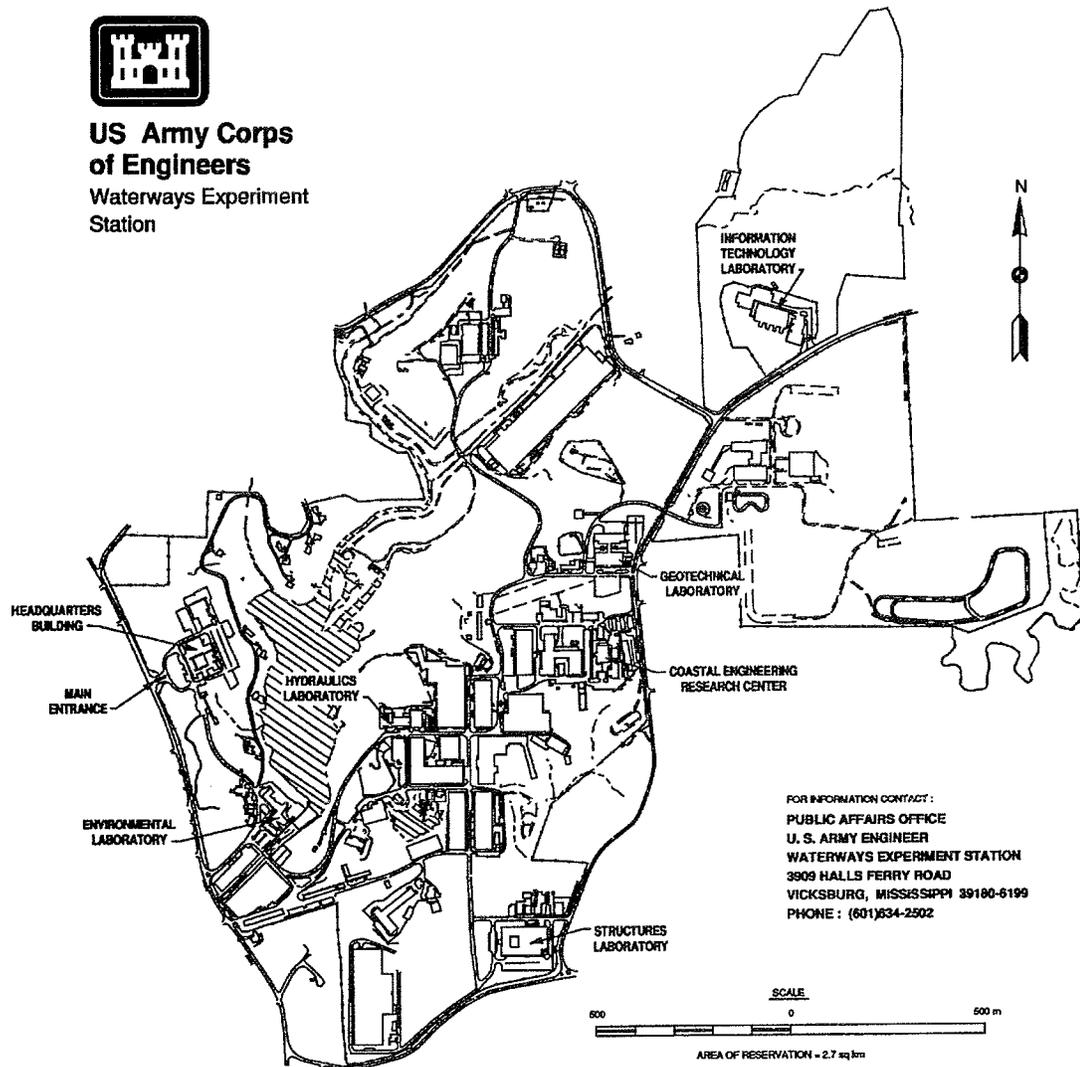
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Preface

The model investigation reported herein was authorized by Headquarters, U.S. Army Corps of Engineers, on 27 May 1993 at the request of the U.S. Army Engineer District, St. Louis (LMS), through the U.S. Army Engineer Division, Lower Mississippi Valley (LMVD).

The model investigation was conducted during the period January 1994 to January 1995 in the Hydraulics Laboratory (HL) of the U.S. Army Engineer Waterways Experiment Station (WES) under the general supervision of Messrs. F. A. Herrmann, Jr., Director, HL; R. A. Sager, Assistant Director, HL; G. A. Pickering, former Chief of the Hydraulic Structures Division (HSD), HL; and J. F. George, Acting Chief, HSD, and under the direct supervision of Messrs. N. R. Oswalt, former Chief of the Spillway and Channels Branch, (SCB), HSD, and B. P. Fletcher, Chief, SCB. The tests were conducted by Messrs. H. O. Turner, Jr., and E. L. Jefferson, both of SCB. This report was prepared by Mr. Turner.

Messrs. M. Dove of LMVD and P. Eydman, D. Fenske, J. Hankins, and L. Wernle and Mrs. C. Hsieh of LMS visited WES during the course of the model study to observe model operation and correlate results with design studies.

During the preparation and publication of this report, Dr. Robert W. Whalin was the Director of WES. COL Bruce K. Howard, EN, was Commander.

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1 Introduction

The Prototype

The Clarence Cannon Re-regulation Structure is located 15.3 km (9.5 miles) downstream of Clarence Cannon Dam (CCD) on the Salt River in the state of Missouri (Figure 1). The re-regulation structure maintains the level of Mark Twain Lake between el 528.0 and 521.0¹ for hydropower pumpback and regulation. The re-regulation structure is operated remotely at CCD to supply hydropower.

The re-regulation structure is a concrete navigation-type, low-head overflow spillway with crest el at 499.0 (Plate 1). Flow is controlled by two 9.14-m- (30-ft-) wide by 9.45-m- (31-ft-) high tainter gates separated by a 2.44-m- (8-ft-) wide center pier. Bulkhead slots are located upstream of the gates. Design of the stilling basin was based on previous work at the U.S. Army Engineer Waterways Experiment Station (WES) on the Arkansas River.²

Operation of the re-regulation structure is based on three flow conditions: flow regulation, pumpback, and passing. Whenever the main reservoir has sufficient inflow, the flow regulation condition passes the daily power releases downstream after dampening the power release surge. For pumpback conditions, the penstock releases are stored and pumped back using off-peak energy. The passing condition conveys the CCD penstock and main dam spillway flow releases.

Purpose of Model Investigation

A model study of the project was conducted to investigate modifications to the existing re-regulation stilling basin and design a replacement stilling basin

¹ All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD). To convert elevations to meters, multiply by 0.3048.

² J. L. Grace, Jr. (1964). "Spillway for typical low-head navigation dam, Arkansas River, Arkansas; Hydraulic model investigation," Technical Report 2-655, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

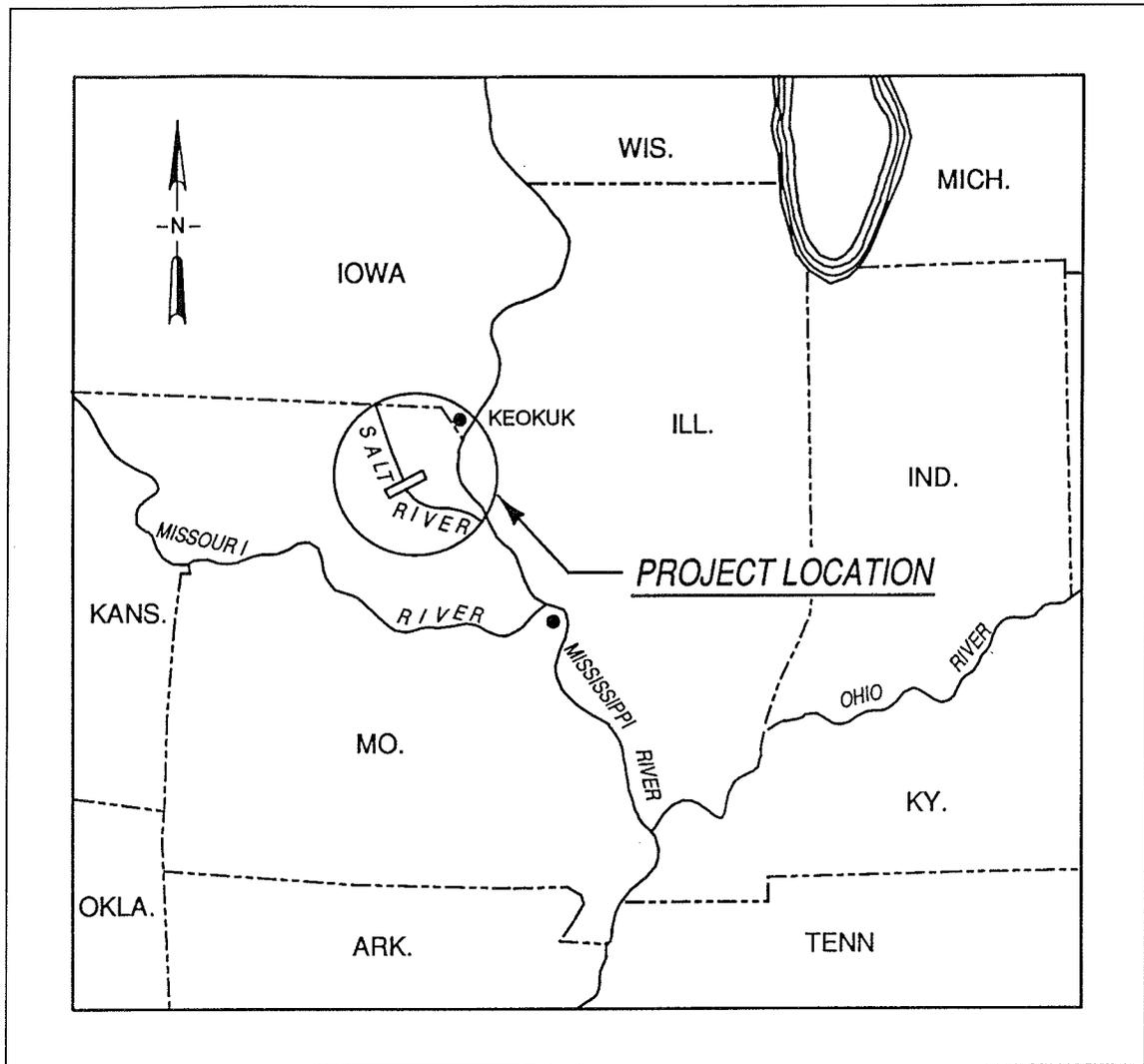


Figure 1. Vicinity and location map

if considered necessary to minimize downstream scour. The main objectives of the model study were to obtain quantitative information on energy dissipation, flow patterns, and flow distribution. Qualitative information on downstream scour potential was also obtained.

Scope

The scope of the model investigation involved studying the hydraulic problems created by the existing stilling basin and designing a suitable replacement basin. The problem was further complicated by construction requirements that would prevent deepening the stilling basin. Since this structure must remain operative at all times, the recommended modifications must be installed during potential partial operation.

2 The Model

Description

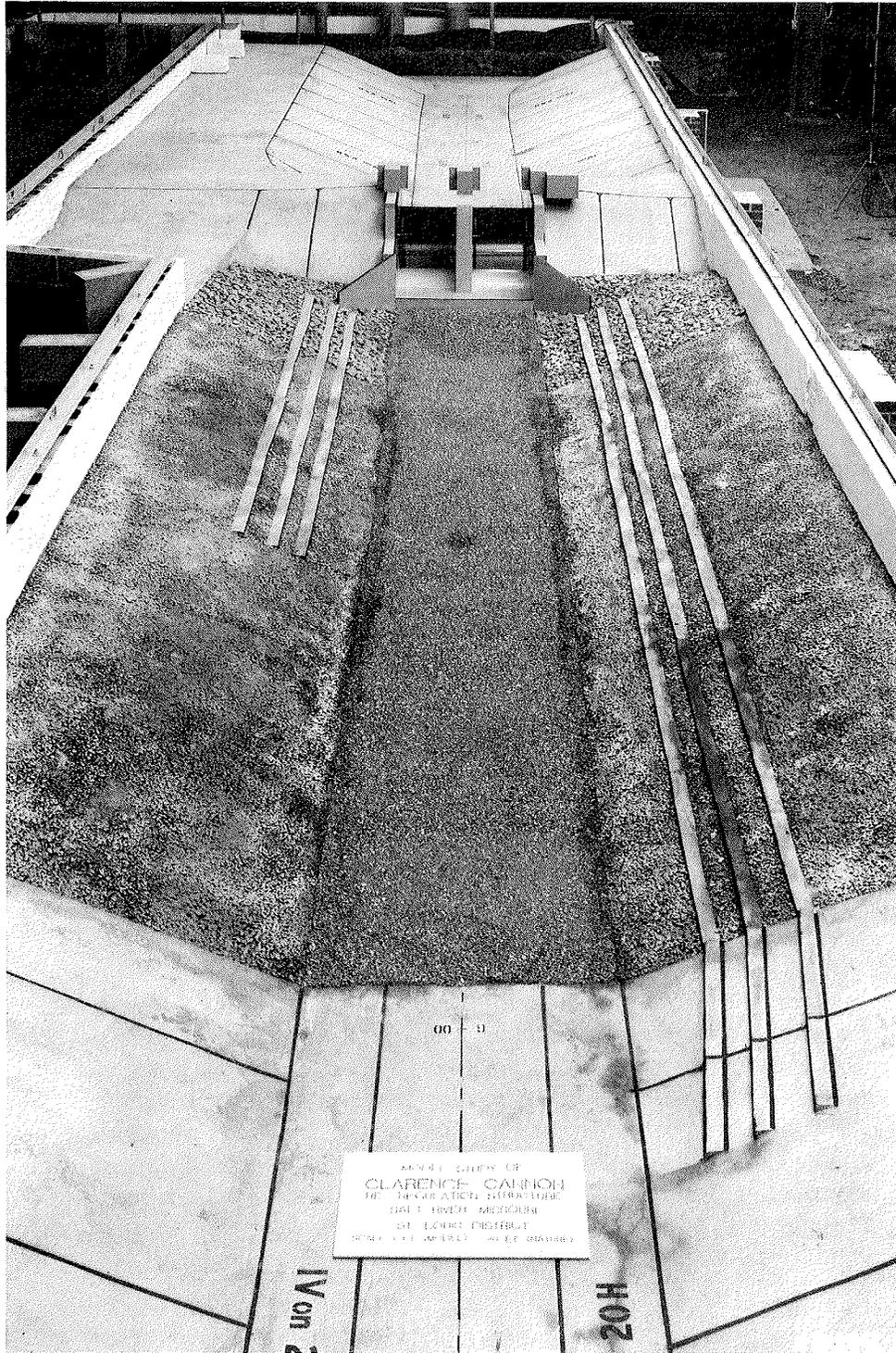
The investigation was conducted using a 1:20-scale physical model (Figure 2). The model reproduced approximately 472 m (1,550 ft) of trapezoidal channel from sta 5+50 upstream (US) to sta 10+00 downstream (DS) including the re-regulation structure. Station 0+00 is shown in Plate 1. The approach channel was molded in cement mortar to sheet metal templates. Immediately downstream of the structure to sta 5+80, the side slopes were constructed of crushed stone, mixed according to prototype gradations to accurately simulate the prototype riprap. Pea-size gravel was used in this area to provide an erodible material. Equivalent prototype sizes of this type gravel would be approximately 0.17- to 0.25-m- (7- to 10-in.-) diameter rounded stone. The downstream exit channel from sta 5+80 to sta 10+00 was also molded in cement mortar to sheet metal templates.

Model Appurtenances

Water used in the operation of the model was supplied by a recirculating system. Discharges were measured with venturi meters. Steel rails graded to specific elevations were placed along both sides of the model to serve as supports for measuring devices and to provide a convenient means of establishing stations and elevations in the model. Velocities were measured with an electronic velocity meter. Tailwater elevations were regulated by an adjustable gate at the end of the flume. Water-surface elevations were measured with point gages and sonic water-surface detectors. Various designs along with different flow conditions were recorded photographically.

Scale Relations

The 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 transferring model data to prototype equivalents are as follows:



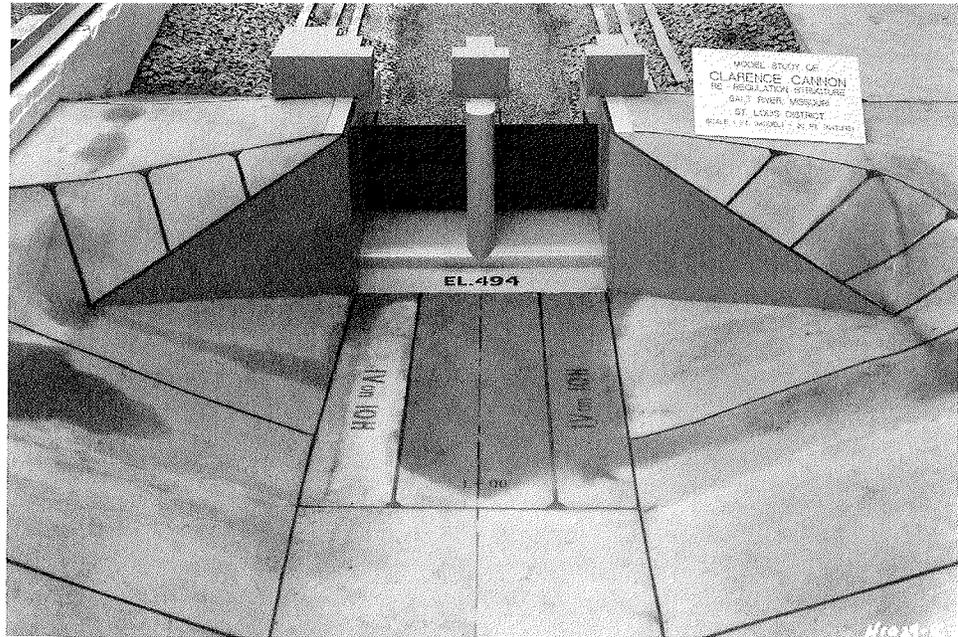
a. View from downstream channel looking upstream

Figure 2. 1:20-scale physical model (Continued)

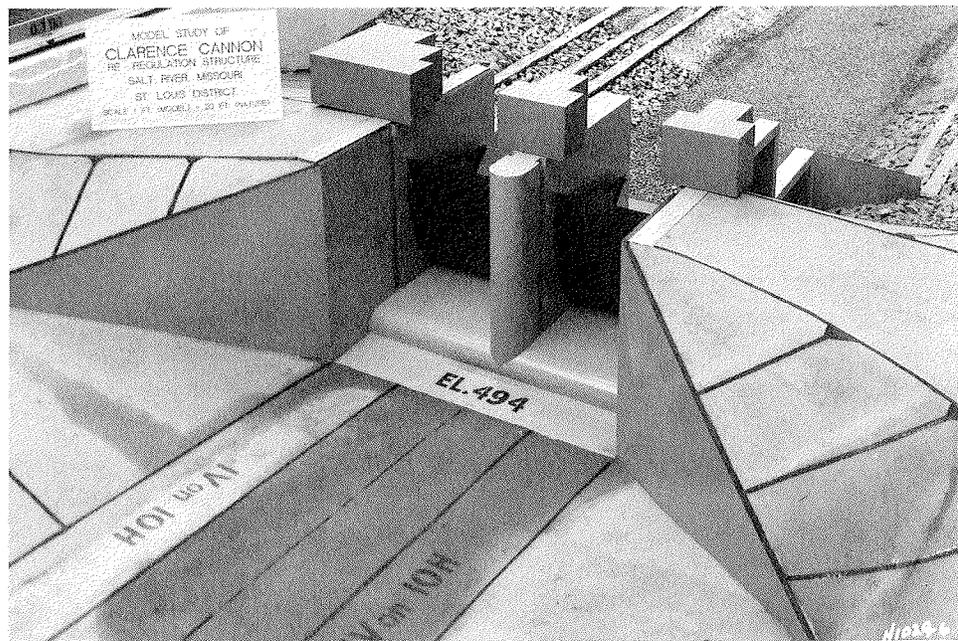


b. View from upstream channel looking downstream

Figure 2. (Continued)

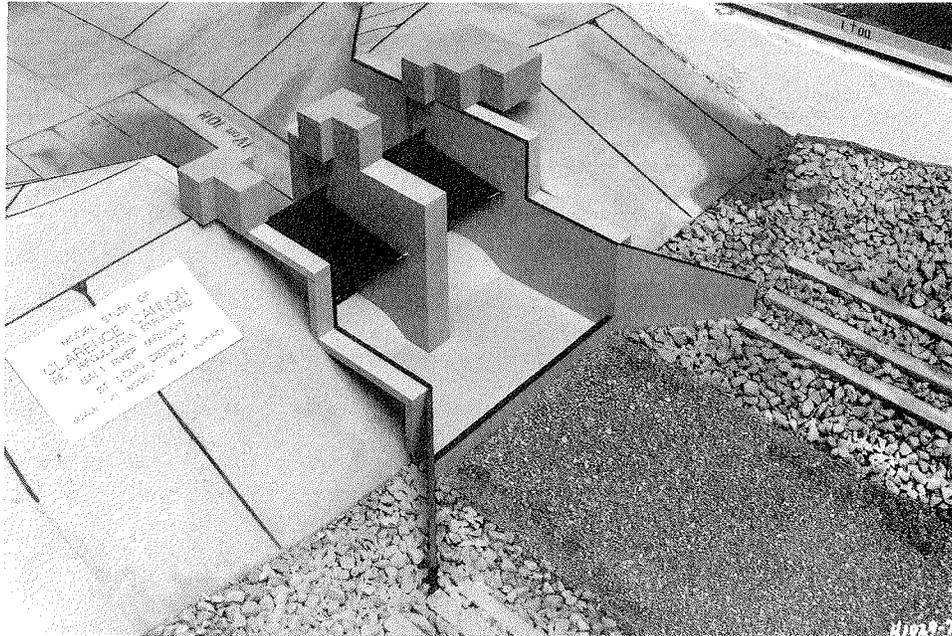


c. Upstream approach to the structure

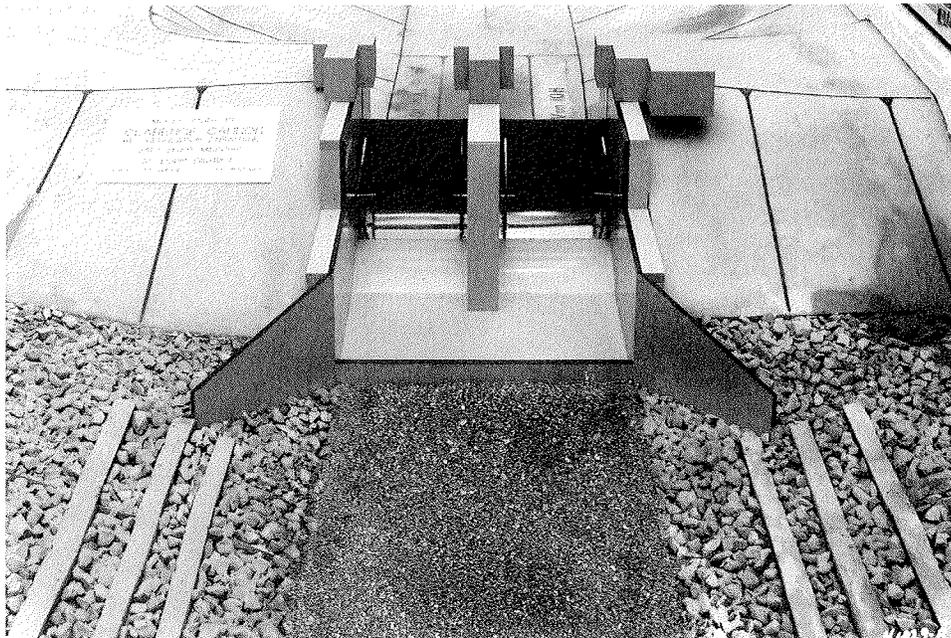


d. Upstream view showing structure detail

Figure 2. (Continued)



e. Downstream view showing structure detail



f. Downstream view of structure

Figure 2. (Concluded)

Characteristic	Dimension ¹	Model:Prototype Scale Relations
Length	L_r	1:20
Area	$A_r = L_r^2$	1:400
Velocity	$V_r = L_r^{1/2}$	1:4.4721
Discharge	$Q_r = L_r^{5/2}$	1:1,789
Time	$T_r = L_r^{1/2}$	1:4.4721
¹ Dimensions are in terms of length.		

3 Experiments and Results

Initial experiments were conducted to observe general flow conditions for single and dual gate operation and to determine the adequacy of various modifications to the stilling basin. Normally, the structure operates with both gates; however, during the repair process, single gate operation will be required. The maximum discharge was 170 cu m/sec (6,000 cfs) for single gate operation and 340 cu m/sec (12,000 cfs) for dual gate operation. Water-surface elevations, velocities, and photographs of the model were obtained to document hydraulic performance. Velocity magnitudes for various designs are included in Tables 1-5.

For dual gate analysis, design flow conditions of 340 cu m/sec (12,000 cfs), both gates open 2.44 m (8 ft), and tailwater el 512.8 were used throughout the model investigation. For single gate analysis, a discharge of 170 cu m/sec (6,000 cfs), one gate open 2.44 m (8 ft), and a tailwater el 509.2 were used.

Type 1 (Original) Design

The type 1 design is shown in Figure 2 and Plate 1. Flow through the structure is controlled by two 9.14-m- (30-ft-) wide tainter gates as shown in Figure 2d. The crest begins at sta 0+02 DS at el 494 and rises to el 499. The crest remains at el 499 until sta 34.35 DS where the $x^2 = 40y$ trajectory begins. The toe of the crest ends at sta 0+48.5 DS at el 494. The stilling basin apron is 12.19 m (40 ft) long at el 494. An end sill 1.22 m (4 ft) high is located at the end of the stilling basin.

The gate design flow condition shown in Photo 1 revealed that the high end sill caused a critical depth control and created a secondary hydraulic jump downstream of the end sill. Minimal energy dissipation occurred in the stilling basin. The secondary hydraulic jump dissipated some of the flow energy downstream of the stilling basin. Unfortunately, severe scour occurred downstream due to the secondary jump and the high end sill as shown in Photo 2.

Operation of a single gate, shown in Photo 3, also created a secondary

hydraulic jump downstream of the open gate. This unbalanced flow condition created a downstream eddy condition that began at sta 2+50 DS and returned flow upstream to the stilling basin. Severe scour occurred during single gate operation because of the poor energy dissipation and turbulence induced by return flow.

Type 2 Design

The type 2 design (Figure 3 and Plate 2) consisted of the existing stilling basin with two rows of baffle blocks and an end sill reduced in height from 1.22 m (4.0 ft) to 0.84 m (2.75 ft). The baffle height was determined according to the initial depth (d_1) before the hydraulic jump in the stilling basin. The initial depth of 1.68 m (5.5 ft) was measured at the design flow conditions. According to previous work conducted at WES¹, the stilling basin should have two rows of baffles 1.68 m (5.5 ft) high and an end sill 0.84 m (2.75 ft) high.



Figure 3. Type 3 design, modifications to existing basin

¹ John F. George, Glenn A. Pickering, Herman O. Turner, Jr. (1994). "General design for replacement of or modifications to the Lower Santa Ana River drop structures, Orange County, California; Hydraulic model investigation," Technical Report HL-94-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Stilling basin performance of the type 2 design is shown in Photo 4. Although downstream water-surface waves were created in the stilling basin, the type 2 design eliminated the secondary jump present in the type 1 design (Photo 1).

The resulting scour shown in Photo 5 indicates that the basin length should be increased. Although this basin was too short, the resulting scour was much less than the scour that occurred in the type 1 design (Photo 2).

Type 3 Design

In the type 3 design (Figure 4 and Plate 3), the original stilling basin length of 40 ft was increased to 60 ft and parallel sidewalls were extended along each side of the additional stilling basin length. The first row of baffles was placed 30 ft downstream from the toe of the spillway crest.

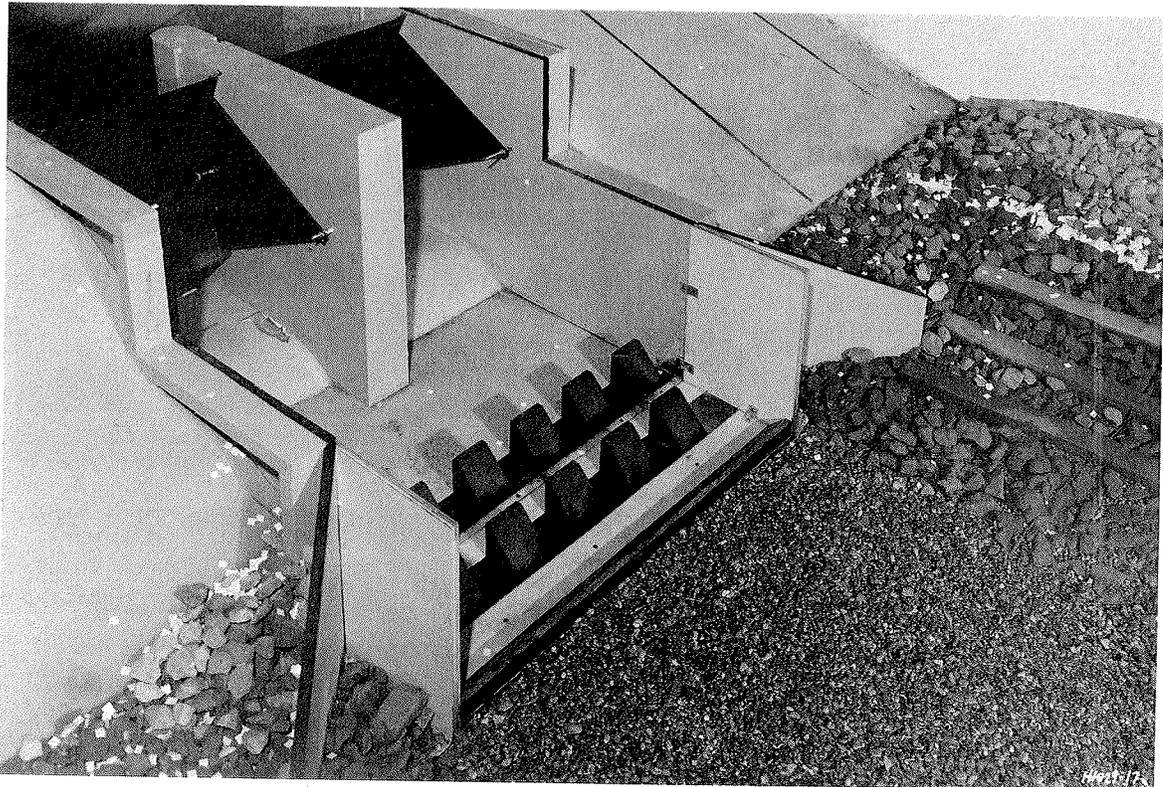


Figure 4. Type 3 design, stilling basin and sidewalls extended 6 m (20 ft)

Flow conditions with two gates operating (Photo 6) show that the abrupt expansion into the downstream channel (no wing walls) resulted in the formation of eddies as shown in Photo 6b. The scour results (Photo 7) were not improved from the type 2 design (Photo 5).

Type 4 Design

The stilling basin sidewall extensions were removed in the type 4 design (Figure 5 and Plate 4) to allow the existing wing walls to spread the flow downstream. As shown in Figure 5, riprap was used to fill between the extended basin and the original wing walls.

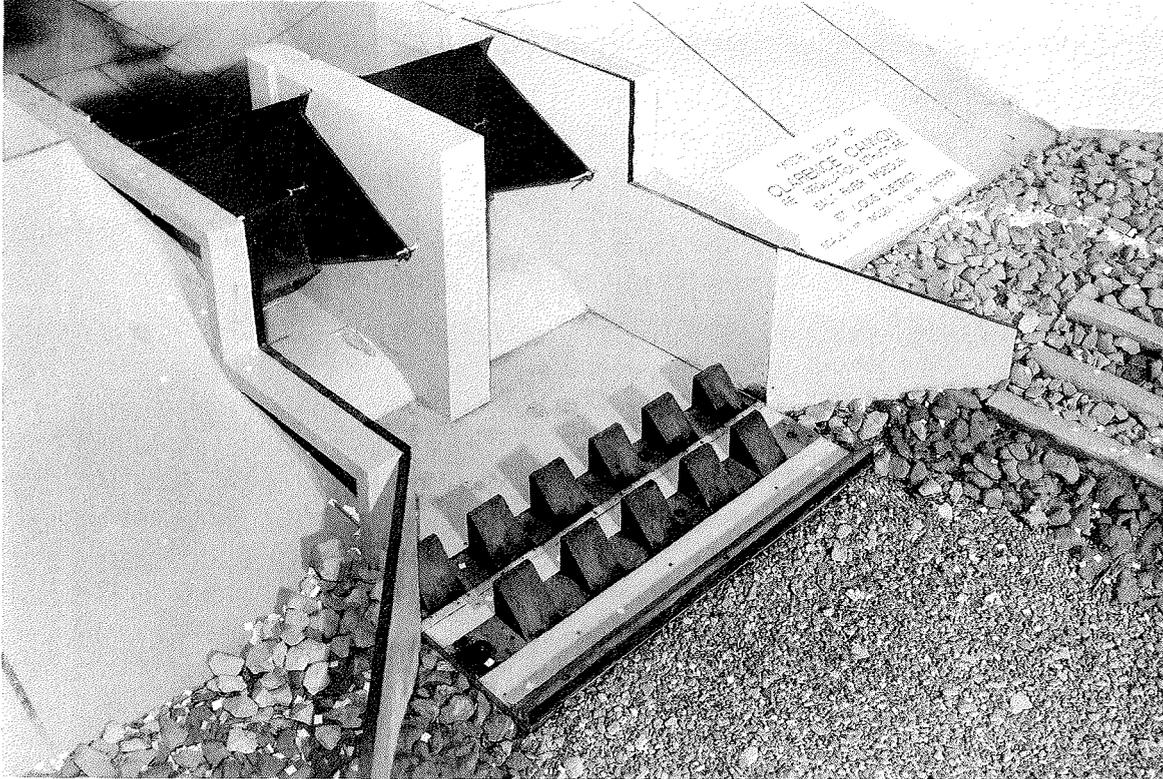


Figure 5. Type 4 design, stilling basin length extended 6 m (20 ft) (sidewall extensions removed)

Allowing the flow to expand downstream with the existing wing walls created better downstream flow conditions as shown in Photo 8. Using the existing wing walls prevented the eddy formation present in the type 3 design. Scour results (Photo 9) were much improved because of the extended basin length and the existing wing walls. The scour pattern appears to have been caused by turbulence from the extended parallel stilling basin walls.

Type 5 Design

The type 5 design (Figure 6 and Plate 5) extended the basin an additional 1.83 m (6 ft) to the tips of the wing walls for a total length of 20.1 m (66 ft). Two extra baffles were placed on the second row to dissipate the flow energy passing the first baffle row along the basin walls. The results of these



Figure 6. Type 5 design, stilling basin length extended to end of wing walls (8 m (26 ft))

refinements are shown in Photo 10. Only a slight amount of downstream material was moved along the left side.

Flow conditions, as shown in Photo 11, indicate the flow gradually expands into the downstream channel. Eddy formations are not indicated near the wing walls.

Type 6 Design

In the type 6 design (Figure 7 and Plate 6), the two rows of baffles were placed on the extended basin. The first row of baffles was moved 30.5 m (10 ft) downstream to the beginning of the extended basin. This modification was requested by the U.S. Army Engineer District, St. Louis, the project sponsor, for constructibility purposes. In the previous design, the first row of baffles was located in the existing basin, which would require structural modification to install.

Flow conditions (Photo 12) appear to be consistent with the previous designs which permitted the existing wing walls to expand the flow downstream. The scour results, shown in Photo 13, indicate only a slight amount of material was moved downstream. The amounts of displaced material for type 5 and type 6 are similar.

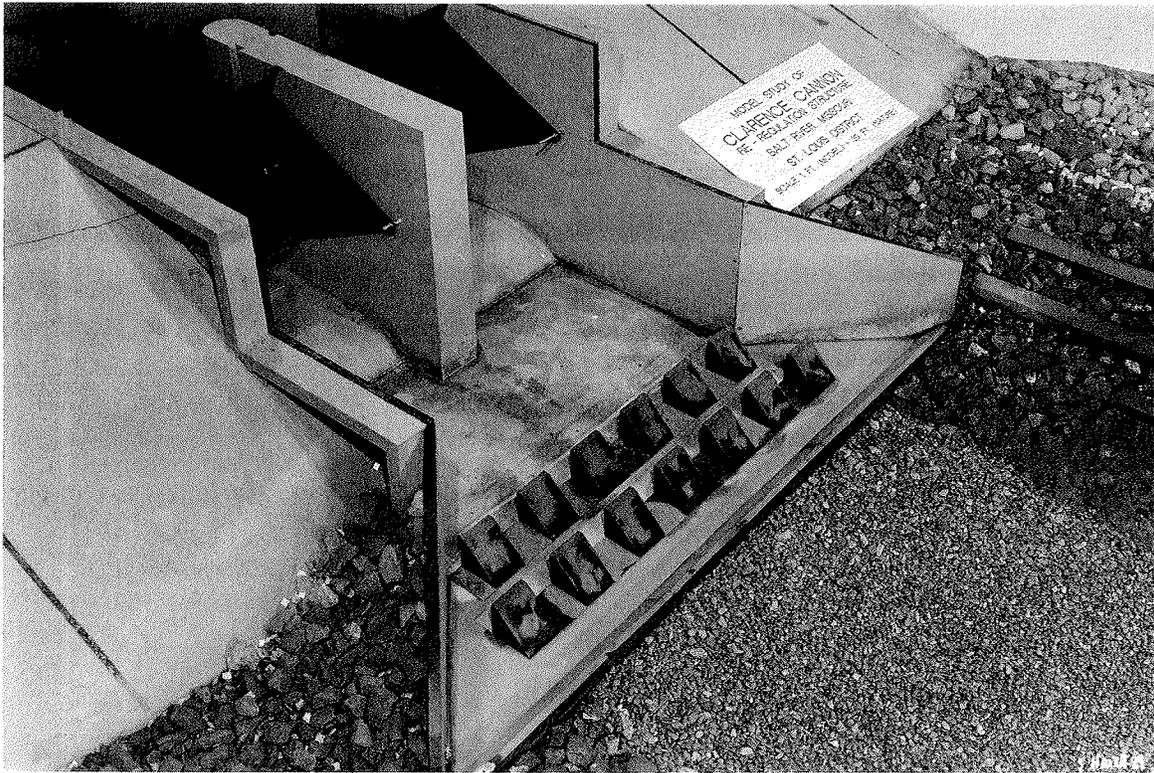


Figure 7. Type 6 design, two rows of baffle blocks located in extended basin

Type 7 Design

After the stilling basin in types 2-6 was modified to improve energy dissipation and minimize scour, the direction of the model study focused on modifying the center pier to provide for bulkhead slots. As an initial trial, the center pier was lengthened 6 m (20 ft) as shown in Figure 8 and Plate 7. Flow conditions, as shown in Photo 14, appear very similar to the previous design. Scour results (Photo 15) indicate that the addition of the center pier increased the movement of material downstream.

Type 8 Design

The type 8 design, Figure 9 and Plate 8, represents the recommended design for the extended basin, based on energy dissipation and scour potential. In the type 8 design, the extended pier used in the type 7 design was reduced to 1.8 m (6 ft) in length. This length was considered by the St. Louis District as the minimum to support bulkhead slots downstream of the gates. A concrete wedge was placed at each side of the extended stilling basin to avoid an abrupt transition with the channel side slopes. These concrete wedges were recommended by the St. Louis District.

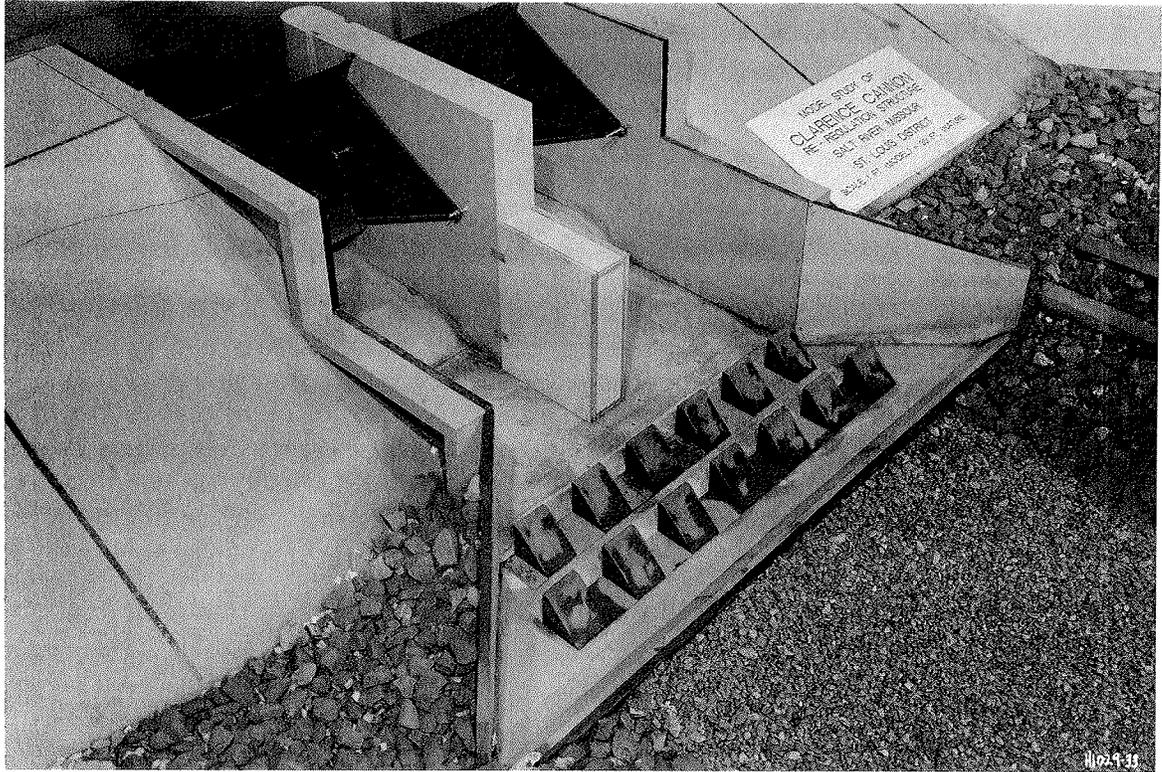


Figure 8. Type 7 design, pier extension (6 m (20 ft)) added to existing center pier

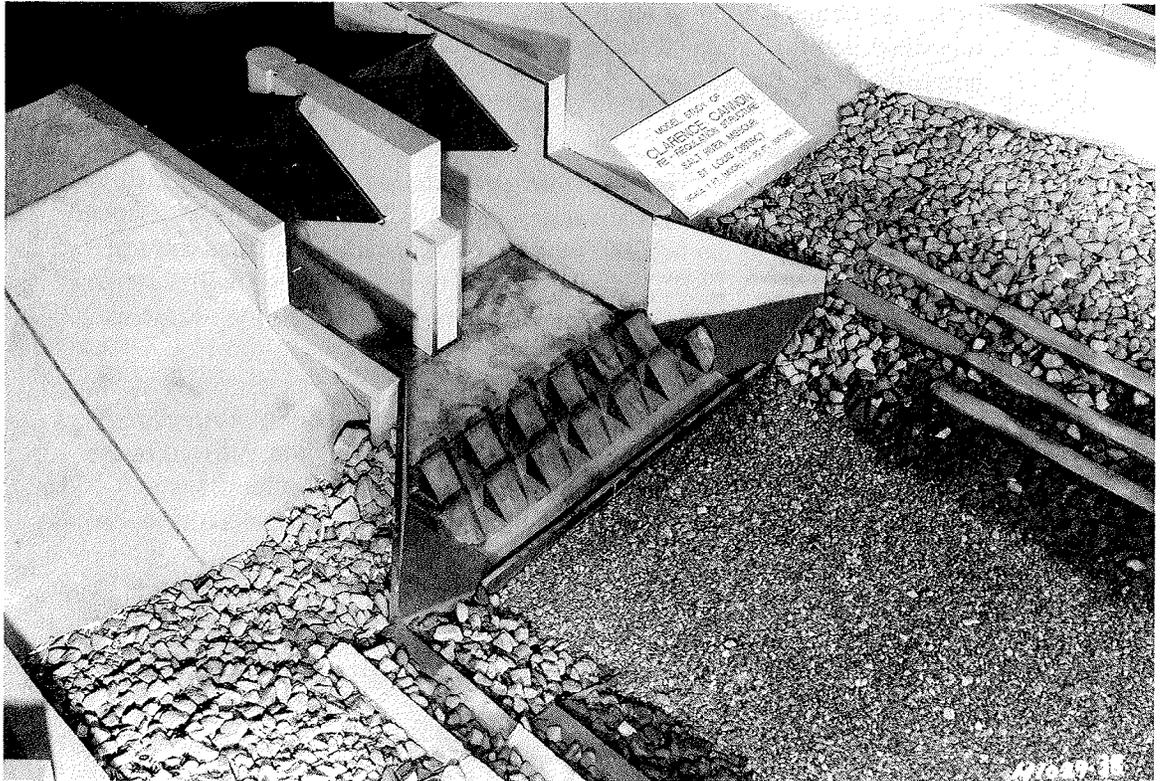


Figure 9. Type 8 design, two rows of baffle blocks located in extended basin

Design flow conditions shown in Photo 16 show that the hydraulic jump is contained in the basin and the water surface returns to tranquil flow by sta 2+00. Confetti streaks shown in Photo 16b reveal that the flow leaving the stilling basin is evenly distributed and free of eddy formations. The scour resulting from 4.5 hours of design flow conditions is shown in Photo 17. Very little scour occurred with this design at the design flow conditions.

Single-gate operations are shown in Photo 18. At the single-gate design flow of 170 cu m/sec (6,000 cfs), the stilling basin was not as effective as a balanced gate operation. As shown in Photo 18b, the unbalanced operation formed a circulation pattern that reduced the energy dissipation in the stilling basin. Standing waves formed downstream, which indicates reduced energy dissipation in the stilling basin and therefore increased scour. The circulation pattern shown in Photo 18b reveals the typical eddy formation resulting from an unbalanced gate operation.

Type 9 Design

St. Louis District personnel responsible for the Clarence Cannon modifications indicated that substantial construction cost savings could be achieved if excavation required for the stilling basin extension could be reduced or eliminated. Subgrade excavation required for the type 8 design would be in bedrock. As an alternative to the type 8 design, the St. Louis District personnel requested that the extended basin be raised 0.76 m (2.5 ft) in order to eliminate rock excavation.

The type 9 design (Figure 10 and Plate 9) shows the extended stilling basin raised 0.76 m (2.5 ft). The transition to the extended basin was formed from the existing end sill. Since the basin was raised 0.76 m (2.5 ft), corresponding modifications to the baffles and end sill were required. Two rows of baffle blocks 0.91 m (3 ft) high were used. The first row of baffles began at the start of the extended basin. An end sill 0.46 m (1.5 ft) high was used.

Design flow conditions are shown in Photo 19. A rougher water surface than that of the type 8 design is shown in Photo 19a. Confetti streaks in Photo 19b indicate that the downstream flow was more concentrated in the center of the channel and not as uniformly distributed as with the type 8. The scour results shown in Photo 20 also indicated that higher velocities occurred in the center of the channel.

Type 10 Design

In the type 10 design (Figure 11 and Plate 10), the first row of baffles was moved downstream 1.52 m (5 ft) and the second row of baffles was 2.74 m (9 ft) downstream from the face of the first row. Flow conditions, shown in Photo 21, and velocity data indicate higher velocities near the center of the

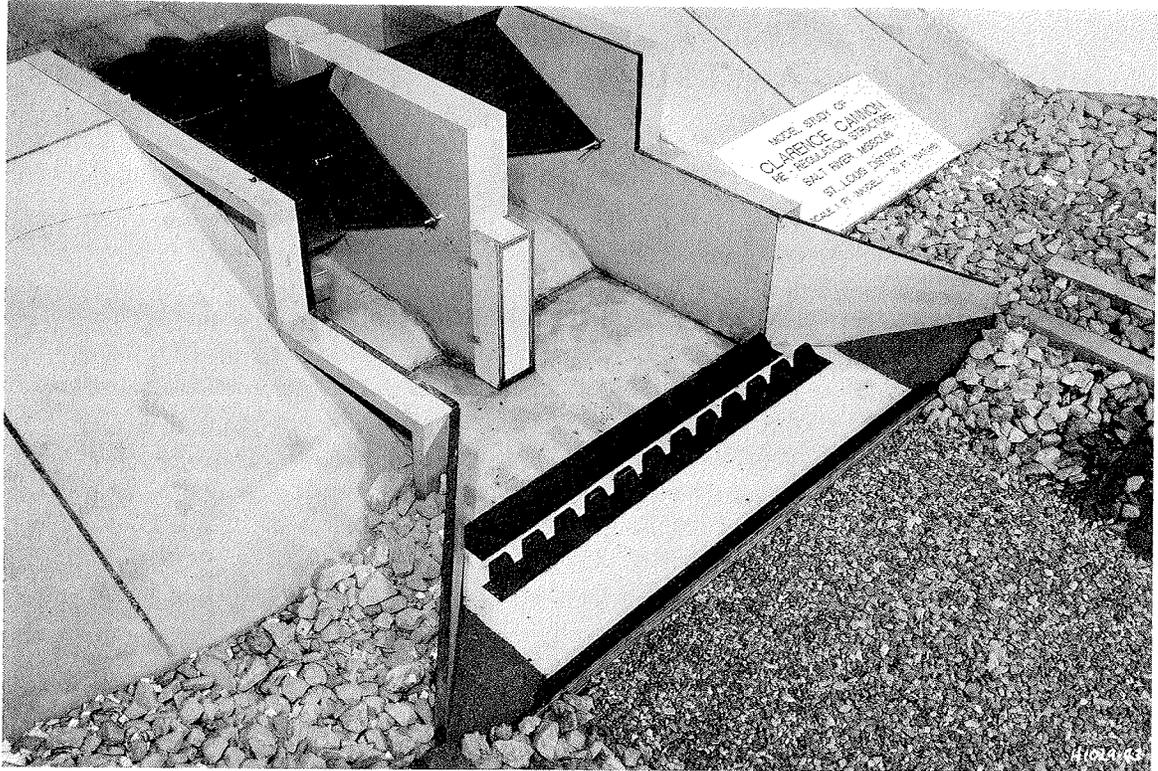


Figure 10. Type 9 design, two rows of baffle blocks located in raised extended basin

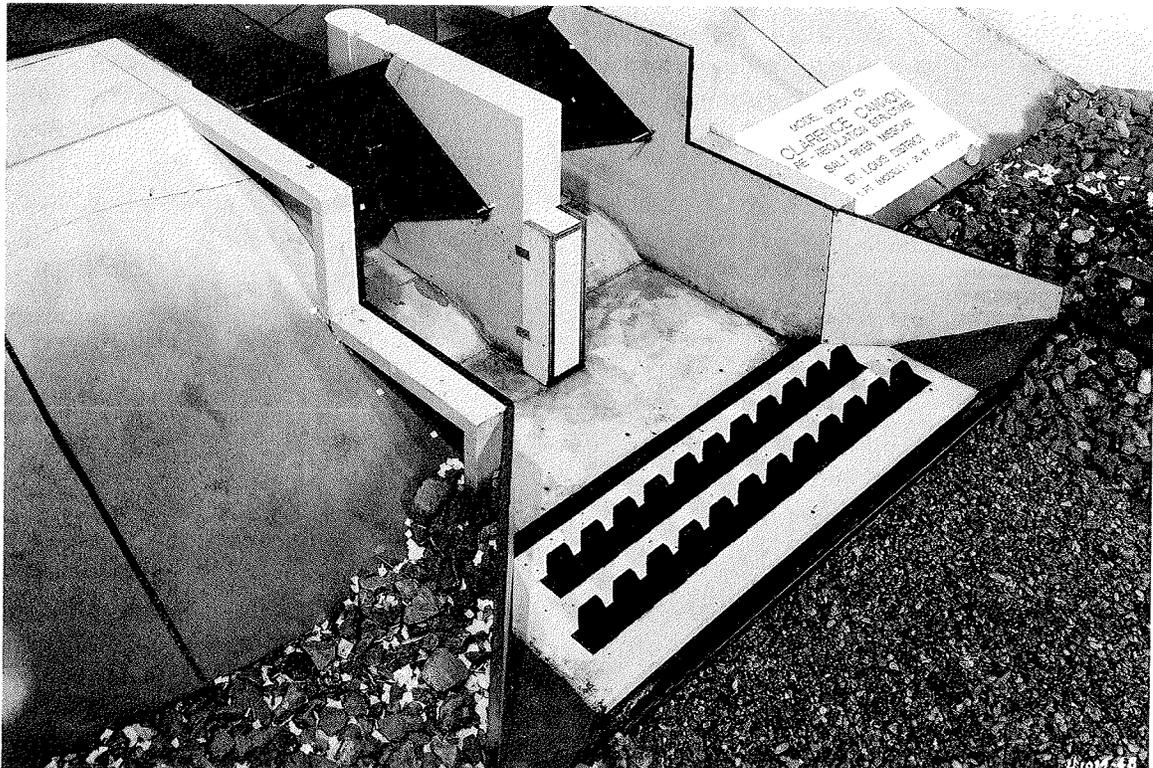


Figure 11. Type 10 design, two rows of baffle blocks moved downstream in raised extended basin

channel. Less downstream wave formation is shown in Photo 21(a) compared to the type 9 design (Photo 19a).

The downstream scour resulting from 4.5 hours at the design conditions is shown in Photo 22. As in the previous design, more scour is noted in the center of the channel. However, the type 10 design resulted in less scour than the type 9 design.

Single-gate flow tests on the type 10 design compare favorably with the type 8 design. Although a right side gate was used in the type 10 tests, the flow conditions shown in Photo 23 are similar to the type 8 flow conditions (Photo 18). Scour tests resulting from the single-gate operation at 170 cu m/sec (6,000 cfs) at 4.5 hours' duration are shown in Photo 24. Although the single-gate operation produced more scour than operation with both gates, the scour results were considered acceptable by both WES and St. Louis District engineers. The type 10 design provides satisfactory hydraulic performance and is considered acceptable for installation in the prototype.

4 Conclusions and Recommendations

Experiments were conducted on the Clarence Cannon Re-regulation Structure to determine modifications needed to improve energy dissipation and reduce erosion in the exit channel. Throughout the course of the model study, St. Louis District personnel provided important input regarding the final constructibility of the modifications. These recommendations helped direct the study from a hydraulic perspective. The first recommendations from the St. Louis District indicated that deepening the existing stilling basin could be cost prohibitive and other modifications should be examined. Therefore, the stilling basin would require additional length, baffle blocks, and a lower end sill.

Several modifications were made to the stilling basin. The type 2 design used the existing stilling basin length with two rows of baffle blocks and a shorter end sill. Although this basin was too short, the resulting scour test indicated less movement of downstream bed material. Gradually, the basin was lengthened until the basin length terminated at the ends of the existing downstream wing walls. Although a slightly shorter basin length would give similar performance, recommendations by the St. Louis District indicated that extending the basin to the tips of the wing walls would be easier to construct.

The type 5 design proved to be very close to the optimal design. This design placed the first row of baffles in the existing stilling basin. The scour test revealed minimum movement of downstream material. However, the St. Louis District preferred placing the first row of baffles on the extended basin for construction reasons. This change became the type 6 design. The type 6 scour test also revealed minimum movement of downstream material.

The type 7 design involved lengthening the center pier to provide for bulkhead slots. Initially, the pier tested was 6.1 m (20 ft) long. This modification proved to be too long and resulted in greater scour than the previous design. A minimum pier length extension of 1.83 m (6 ft) was recommended for bulkhead support. The center pier was shortened to 1.83 m (6 ft) and tested for hydraulic performance in the type 8 design. Concrete wedges on each side of the extended basin were added to remove the abrupt

transition to the channel side slopes. These modifications were beneficial and the scour experimental results were almost identical to the type 6 design.

At this point in the model study, the type 8 was the recommended design. Upon its recommendation, the St. Louis District indicated that excavation in bedrock would be required to construct the extended basin. As an alternative design, the extended stilling basin was raised 0.76 m (2.5 ft) and evaluated. The type 9 design raised the extended basin 0.76 m (2.5 ft). The original end sill was modified to form a sloped transition to the raised extended basin. Two rows of 0.91-m- (3-ft-) high baffles were tested with a 0.46-m- (1.5-ft-) high end sill. The first row of baffles was placed at the upstream end of the raised extended basin. Flow observations indicated that the raised basin caused the flow to concentrate in the center of the channel, preventing flow from being uniformly distributed as in the type 8 design. Slightly greater scour depths were observed in the type 9 design. These results indicated that moving the baffle blocks downstream would improve the flow conditions.

In the type 10 design, the first row of baffles was moved 1.52 m (5 ft) downstream from the upstream end of the raised basin and the second row 2.74 m (9 ft) downstream from the first row. This modification improved the flow conditions and reduced the amount of material moved in the scour test.

In conclusion, two recommendations for stilling basin modifications are made: type 8 (flat basin) or the type 10 (raised basin). Scour tests with the type 10 indicated that more material was moved than with the type 8 design. However, for enhanced constructibility and retaining favorable hydraulic performance, the type 10 basin is recommended. St. Louis District personnel indicated that the downstream bed is not easily eroded.

Table 1
Downstream Velocities, fps, Type 1, 340 cu m/sec (12,000 cfs), 2.4-m (8-ft)
Gate (Both)

12,000 CFS 8 FT GATE (BOTH)											
STA 1+00 DS											
	50	40	30	LEFT 20	10	CL 0	10	RIGHT 20	30	40	50
ELEV											
511.0		7.9	15.7	19.3	15.7	14.0	10.2	12.8	19.5	15.0	
503.0		3.2	3.7	4.1	5.9	13.5	13.7	3.7	2.9	10.7	
495.0		5.3	4.7	4.8	3.7	3.2	1.5	1.8	1.3	6.3	
STA 1+20 DS											
	50	40	30	LEFT 20	10	CL 0	10	RIGHT 20	30	40	50
ELEV											
511.0	4.1	8.3	8.1	10.8	10.0	10.6	17.7	11.6	8.5	11.8	3.6
503.0	4.3	3.2	3.5	3.4	7.3	8.0	10.5	4.0	3.6	4.5	3.4
495.0	3.3	3.4	3.0	4.3	3.1	4.9	3.4	5.3	3.7	4.3	2.9
STA 1+40 DS											
	50	40	30	LEFT 20	10	CL 0	10	RIGHT 20	30	40	50
ELEV											
511.0	3.0	2.2	7.1	11.6	13.8	15.5	13.3	11.6	8.6	4.1	2.5
503.0	4.3	2.1	8.9	7.6	4.5	13.7	8.3	6.3	7.5	3.3	3.3
495.0	4.7	2.5	4.9	3.7	2.9	7.8	3.3	3.1	3.6	2.5	2.7
STA 1+60 DS											
	50	40	30	LEFT 20	10	CL 0	10	RIGHT 20	30	40	50
ELEV											
511.0	2.1	2.3	8.1	5.0	13.5	14.5	12.0	10.4	9.6	5.2	2.0
503.0	2.4	2.2	4.8	5.1	8.7	12.4	6.9	5.4	5.8	3.8	1.7
495.0	2.3	2.2	2.5	3.7	7.5	7.9	4.9	2.7	3.8	2.9	1.9
STA 2+00 DS											
	50	40	30	LEFT 20	10	CL 0	10	RIGHT 20	30	40	50
ELEV											
511.0	5.0	6.5	7.3	8.0	9.6	12.3	11.9	9.6	9.3	7.4	6.1
503.0	3.3	5.3	4.7	5.7	6.8	9.6	10.0	6.6	6.1	6.1	4.0
495.0	2.3	1.3	2.0	2.3	4.5	5.6	5.1	5.3	4.0	1.9	2.2
STA 2+40 DS											
	50	40	30	LEFT 20	10	CL 0	10	RIGHT 20	30	40	50
ELEV											
511.0	5.8	6.8	8.0	9.4	10.7	11.6	10.7	9.5	8.2	6.6	5.9
503.0	4.7	5.0	5.6	5.1	7.7	6.5	5.7	5.2	5.9	5.0	4.8
495.0	3.2	2.3	2.9	1.5	1.4	1.7	1.7	1.8	2.6	2.4	3.7

Note: To convert velocities to meters per second, multiply by 0.3048.

Table 2
Downstream Velocities, fps, Type 4, 340 cu m/sec (12,000 cfs), 2.4-m (8-ft)
Gate (Both)

12,000 CFS
 8 FT GATE (BOTH)

STA 1+00 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0			5.9	13.6	15.1	9.8	13.5	15.0	13.6		
503.0			3.0	9.6	10.1	7.8	3.5	13.3	6.7		
495.0			2.5	5.5	6.1	2.2	3.1	6.8	3.0		

STA 1+20 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	7.4	13.3	8.9	16.3	14.9	13.0	8.1	17.5	12.1	3.3	1.6
503.0	2.6	2.7	8.5	7.5	7.5	10.4	7.9	9.2	2.6	2.0	1.6
495.0	3.0	2.4	1.9	1.4	1.8	2.3	1.8	1.7	2.1	1.7	1.4

STA 1+60 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.6	11.1	14.6	15.2	14.1	13.3	14.6	15.4	5.9	8.1	4.8
503.0	2.1	4.2	7.0	6.6	8.3	10.3	7.7	6.6	5.7	2.3	2.2
495.0	2.1	2.2	1.7	2.2	4.2	4.4	3.8	2.7	1.9	2.7	2.1

STA 1+80 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	10.8	11.0	13.0	12.5	12.3	12.5	13.0	13.1	10.5	6.4	3.5
503.0	4.0	3.7	5.0	5.4	9.0	10.2	6.8	6.4	4.6	1.8	2.6
495.0	1.8	1.5	1.7	2.4	4.3	4.8	2.9	1.8	1.7	1.8	1.5

STA 2+00 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.9	10.0	11.6	10.4	11.9	12.1	10.9	11.7	9.8	6.4	3.4
503.0	3.1	3.6	4.7	6.5	8.8	9.7	6.9	6.1	4.3	2.5	2.6
495.0	1.7	2.0	2.3	3.4	5.4	6.6	3.6	2.5	2.5	1.6	1.4

STA 2+20 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	8.5	9.4	9.0	9.8	11.8	11.8	11.2	9.7	8.6	6.7	4.0
503.0	3.6	4.7	5.1	5.4	8.5	8.7	6.4	5.0	4.3	2.8	2.2

(Continued)

Note: To convert velocities to meters per second, multiply by 0.3048.

Table 2 (Concluded)

STA 2+20 DS (Continued)

495.0 1.0 2.0 2.7 3.5 3.5 5.8 3.4 2.1 2.7 1.8 1.5

STA 2+40 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.9	8.4	8.9	9.1	10.5	11.0	9.3	9.4	8.8	6.5	4.9
503.0	2.6	4.8	5.3	5.4	8.1	9.4	6.7	4.7	4.2	3.5	2.0
495.0	1.3	1.6	1.8	3.0	4.7	4.8	4.9	2.7	2.6	2.1	1.3

STA 2+60 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.6	6.7	8.7	8.9	10.0	10.7	10.0	8.8	7.3	6.6	5.2
503.0	3.1	5.3	5.2	5.5	7.5	9.6	7.4	5.2	4.9	4.1	2.5
495.0	2.1	2.7	2.6	3.7	5.0	4.6	4.4	2.3	1.8	2.3	1.8

STA 2+80 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.6	6.7	7.3	8.2	9.7	10.3	9.1	8.1	7.4	6.1	4.5
503.0	3.3	4.3	4.7	5.7	6.9	8.8	8.1	4.8	4.9	3.6	3.8
495.0	2.9	3.3	3.4	3.0	5.0	5.2	4.4	3.4	2.4	2.3	2.6

STA 3+00 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.1	5.9	6.1	7.7	9.1	9.3	8.6	7.2	6.6	5.5	4.5
503.0	3.3	4.0	5.1	5.9	7.6	8.1	7.3	5.6	3.8	4.2	3.4
495.0	2.5	2.4	2.2	3.5	4.6	5.4	4.3	2.7	2.2	2.4	2.0

Table 3
Downstream Velocities, fps, Type 5, 340 cu m/sec (12,000 cfs), 2.4-m (8-ft)
Gate (Both)

12,000 CFS
 8 FT GATE (BOTH)

STA 1+20 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	6.2	3.4	14.9	8.7	14.3	13.3	14.3	10.8	14.2	7.4	4.5
503.0	1.7	3.1	5.9	10.2	9.0	10.3	8.6	11.8	8.1	3.1	2.1
495.0	2.5	1.7	1.9	1.7	2.1	1.6	1.5	1.8	1.8	1.7	1.7

STA 1+40 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	7.6	12.4	14.2	14.3	13.3	13.1	14.6	9.8	15.0	10.1	5.3
503.0	2.3	5.0	8.2	6.5	9.0	10.3	7.2	6.5	6.6	2.5	2.0
495.0	3.0	2.0	2.4	1.8	5.3	4.7	3.1	2.0	2.2	2.0	1.9

STA 1+60 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	6.8	12.4	15.2	14.5	13.4	12.5	13.8	14.6	14.3	9.9	2.4
503.0	3.4	4.5	6.6	6.1	8.9	10.3	7.4	7.0	7.3	2.5	1.7
495.0	2.2	2.5	3.6	3.1	7.0	7.8	4.0	2.3	4.4	1.9	1.8

STA 1+80 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	6.7	11.3	12.8	12.7	12.9	12.2	12.1	13.1	13.2	9.5	4.7
503.0	2.9	5.6	5.6	5.9	7.5	9.9	6.3	5.9	5.5	5.6	3.0
495.0	2.0	2.2	2.3	2.8	5.1	6.5	4.5	1.9	2.2	1.7	1.5

STA 2+00 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	6.7	10.1	10.6	10.3	11.5	11.6	11.2	10.4	10.9	9.0	5.1
503.0	2.7	4.4	5.2	5.5	7.7	9.5	6.4	4.0	5.5	3.8	2.7
495.0	2.1	1.9	2.1	3.4	6.0	6.8	5.4	1.9	1.9	1.7	1.3

STA 2+20 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	7.5	8.9	9.2	9.6	10.4	10.7	9.3	6.9	10.2	8.2	4.8
503.0	3.7	4.1	4.2	5.8	7.6	8.7	6.2	5.1	4.4	4.6	4.0

(Continued)

Note: To convert velocities to meters per second, multiply by 0.3048.

Table 3 (Concluded)

STA 2+20 DS (Continued)

495.0 2.6 2.3 3.2 4.0 5.9 7.0 4.8 2.1 2.8 3.2 2.2

STA 2+40 DS

	LEFT				CL	RIGHT					
	50	40	30	20	10	0	10	20	30	40	50
511.0	7.0	8.0	8.4	8.4	8.5	8.2	8.2	8.1	8.1	8.1	6.3
503.0	5.1	4.9	5.0	6.2	7.7	8.3	7.1	5.2	4.7	4.9	3.9
495.0	2.1	3.7	2.3	5.2	6.4	7.0	6.3	4.0	3.3	4.7	2.6

STA 2+60 DS

	LEFT				CL	RIGHT					
	50	40	30	20	10	0	10	20	30	40	50
511.0	6.7	6.9	7.4	8.2	8.5	8.5	8.1	7.5	7.9	6.8	6.7
503.0	4.4	5.2	5.3	6.2	7.1	7.9	6.9	6.0	5.3	5.0	5.3
495.0	3.6	4.5	4.0	5.2	6.6	7.2	6.0	5.1	4.2	4.2	3.6

STA 2+80 DS

	LEFT				CL	RIGHT					
	50	40	30	20	10	0	10	20	30	40	50
511.0	6.9	7.2	7.3	7.6	8.5	8.2	7.4	7.4	7.0	7.0	6.8
503.0	5.1	5.3	5.6	6.0	7.6	7.7	7.2	5.7	5.3	5.3	5.2
495.0	4.4	4.8	4.4	5.8	7.1	6.9	6.6	3.2	3.4	4.0	4.8

STA 3+00 DS

	LEFT				CL	RIGHT					
	50	40	30	20	10	0	10	20	30	40	50
511.0	7.8	7.7	8.2	8.1	8.6	8.9	8.5	7.4	7.6	7.7	7.1
503.0	6.9	6.2	5.8	6.7	8.0	8.2	7.0	6.6	7.0	6.9	5.8
495.0	5.9	4.6	4.5	6.3	7.4	7.4	7.0	6.8	5.8	5.1	5.0

Table 4
Downstream Velocities, fps, Type 6, 340 cu m/sec (12,000 cfs), 2.4-m (8-ft)
Gate (Both)

2,000 CFS
 8 FT GATE (BOTH)

STA 1+20 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.1	12.2	15.8	16.0	14.0	11.4	15.6	16.7	10.1	11.0	11.9
503.0											
495.0	1.3	1.6	2.9	2.9	4.6	6.1	4.5	4.9	2.3	1.9	1.6

STA 1+40 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	7.9	11.7	14.0	13.5	12.9	12.4	12.1	12.2	12.2	9.2	5.6
503.0	2.1	2.6	4.9	5.4	7.1	9.9	10.2	7.0	6.8	3.7	2.2
495.0	1.5	2.6	3.0	5.2	6.2	4.9	2.1	1.2	0.8	2.4	0.7

STA 1+60 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	6.3	10.1	10.6	11.0	11.4	12.7	12.4	11.5	11.5	10.1	7.0
503.0	2.0	2.9	4.0	4.7	7.6	10.2	7.2	5.0	4.1	2.5	3.0
495.0	1.6	1.7	1.6	1.6	4.0	7.4	5.1	2.6	2.7	1.9	1.5

STA 1+80 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	6.9	6.4	6.8	5.9	14.1	10.2	8.1	6.8	6.7	7.2	5.9
503.0	2.4	2.7	3.0	4.7	8.2	9.8	7.6	5.0	4.1	3.5	2.6
495.0	1.4	1.7	2.3	3.6	7.0	7.3	5.8	3.5	1.8	1.1	2.3

STA 2+20 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.8	5.8	6.6	6.6	7.0	7.0	8.0	9.8	7.8	6.7	5.2
503.0	3.1	2.8	3.0	4.0	5.0	7.0	6.2	4.1	3.4	3.4	3.3
495.0	2.3	2.2	2.1	3.0	5.2	6.4	5.9	3.3	2.1	2.6	2.2

STA 2+40 DS

				LEFT		CL	RIGHT				
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.0	5.0	6.0	6.4	8.4	9.5	9.3	7.0	6.9	5.7	5.0
503.0	3.3	3.0	3.1	4.1	6.2	8.7	6.6	4.6	3.6	3.8	3.8

(Continued)

Note: To convert velocities to meters per second, multiply by 0.3048.

Table 4 (Concluded)

STA 2+40 DS (Continued)

495.0	2.5	3.3	2.5	3.2	5.6	6.9	6.4	4.0	2.5	2.9	2.1
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STA 2+60 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.2	5.3	6.1	7.1	8.2	9.4	8.1	7.6	6.9	5.6	4.7
503.0	4.3	3.3	6.4	4.2	6.6	8.4	6.6	4.5	3.9	3.9	4.3
495.0	2.5	2.0	2.6	4.6	6.5	6.9	5.6	2.8	3.2	2.6	3.1

STA 3+00 DS

	LEFT			CL	RIGHT						
	50	40	30	20	10	0	10	20	30	40	50
511.0	5.0	5.1	7.3	6.8	8.9	5.9	5.9	5.6	5.2	5.3	4.3
503.0	4.3	4.2	4.3	6.6	7.8	7.0	5.1	4.9	3.4	4.0	4.3
495.0	2.8	2.9	3.4	4.7	6.7	7.0	6.2	5.3	3.4	2.9	3.3

Table 5
Downstream Velocities, fps, Type 10, 340 cu m/sec (12,000 cfs), 2.4-m (8-ft)
Gate (Both)

12,000 CFS
 8 FT GATE (BOTH)

STA 1+20 DS

			LEFT			CL	RIGHT					
50	40	30	20	10	0	10	20	30	40	50		
511.0	7.5	11.6	8.9	15.8	13.4	11.2	9.9	12.8	13.7	10.3	6.0	
503.0	2.1	2.4	5.8	7.7	8.5	9.5	7.5	5.3	3.1	2.8	3.0	
495.0	1.4	2.5	2.3	1.7	1.9	1.5	1.6	1.9	2.6	1.9	2.4	

STA 1+40 DS

			LEFT			CL	RIGHT					
50	40	30	20	10	0	10	20	30	40	50		
511.0	6.8	10.8	15.9	16.6	16.6	14.2	15.8	15.8	12.1	7.2	5.9	
503.0	2.6	2.7	4.5	6.4	9.5	9.0	6.5	4.5	3.2	2.0	2.8	
495.0	1.7	3.5	2.9	2.1	4.4	4.2	3.2	2.7	3.3	2.9	1.8	

STA 1+60 DS

			LEFT			CL	RIGHT					
50	40	30	20	10	0	10	20	30	40	50		
511.0	5.7	7.5	9.6	8.1	8.7	11.6	12.6	9.9	9.2	8.9	6.8	
503.0	2.6	3.2	5.1	6.3	8.0	10.0	8.5	5.4	4.0	3.4	1.9	
495.0	1.5	1.7	2.3	2.4	5.0	6.9	5.0	2.6	1.8	2.0	1.3	

STA 1+80 DS

			LEFT			CL	RIGHT					
50	40	30	20	10	0	10	20	30	40	50		
511.0	5.3	7.1	6.3	6.9	5.2	8.4	7.2	7.4	7.6	7.2	6.1	
503.0	3.5	3.3	4.5	5.6	7.7	8.6	7.2	5.4	4.4	3.2	3.5	
495.0	1.2	1.2	1.8	2.1	5.6	7.4	5.4	2.7	1.5	1.0	1.2	

STA 2+20 DS

			LEFT			CL	RIGHT					
50	40	30	20	10	0	10	20	30	40	50		
511.0	5.6	6.6	7.3	7.2	7.2	4.8	5.8	7.0	7.8	7.1	6.4	
503.0	3.8	3.3	4.5	6.9	8.7	8.9	7.8	6.5	4.6	4.7	5.1	
495.0	1.7	1.5	1.3	1.8	4.9	6.8	4.7	1.1	1.8	1.7	1.6	

STA 2+40 DS

			LEFT			CL	RIGHT					
50	40	30	20	10	0	10	20	30	40	50		
511.0	5.0	6.4	6.8	7.4	7.1	6.9	7.7	7.5	7.2	6.9	5.2	
503.0	3.6	4.0	5.0	5.6	7.9	8.0	7.9	7.2	5.5	4.3	4.5	

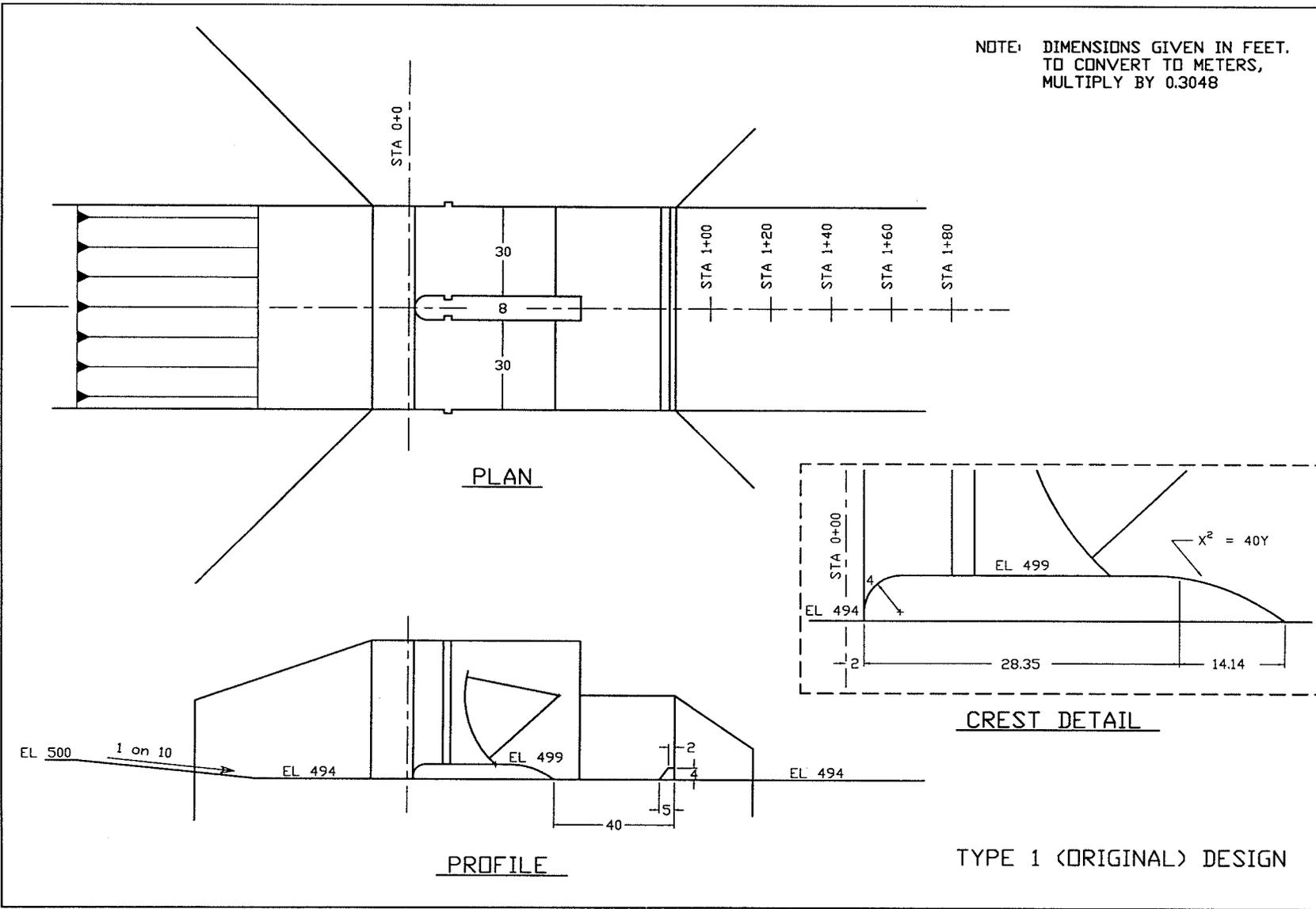
(Continued)

Note: To convert velocities to meters per second, multiply by 0.3048.

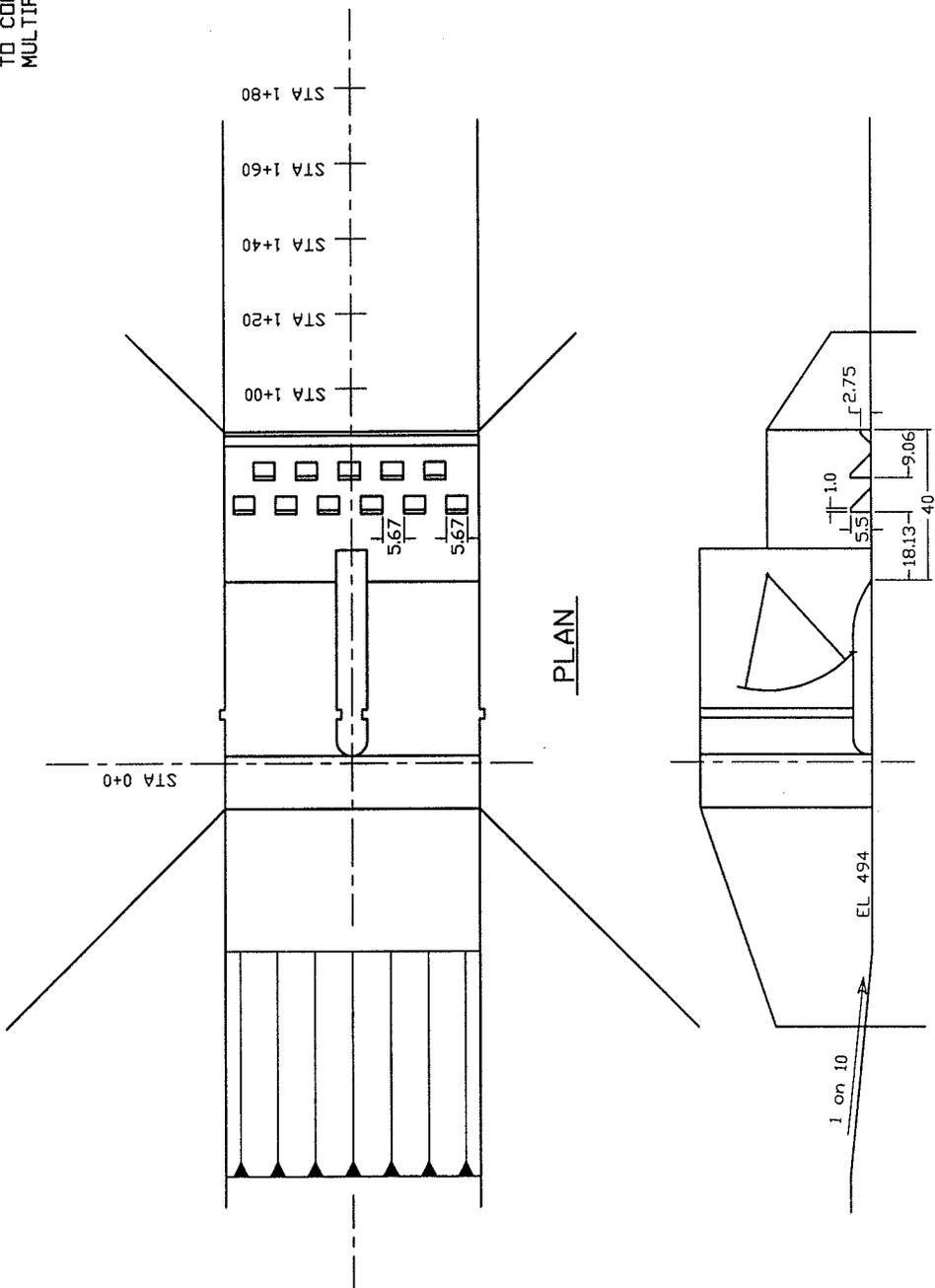
Table 5 (Concluded)

STA 2+40 DS (Continued)											
495.0	1.9	1.1	1.7	2.6	4.6	5.8	4.2	2.6	1.2	2.1	2.4
STA 2+60 DS											
	50	40	30	LEFT 20	10	CL 0	10	RIGHT 20	30	40	50
511.0	4.2	4.3	3.8	3.5	2.2	2.4	3.5	3.6	3.5	3.6	3.8
503.0	2.8	2.9	3.4	3.4	3.0	2.6	3.3	3.7	3.3	3.3	3.3
495.0	1.4	1.3	1.8	2.5	3.9	3.0	2.9	3.0	1.9	2.0	2.4
STA 3+00 DS											
	50	40	30	LEFT 20	10	CL 0	10	RIGHT 20	30	40	50
511.0	3.7	4.1	3.9	3.6	2.0	1.9	2.8	2.7	3.1	3.5	3.4
503.0	2.6	1.9	3.5	3.8	2.8	2.4	3.0	3.1	3.1	3.0	2.9
495.0	1.2	1.6	2.2	3.5	3.4	3.5	3.4	2.4	2.3	1.9	2.5

NOTE: DIMENSIONS GIVEN IN FEET.
TO CONVERT TO METERS,
MULTIPLY BY 0.3048

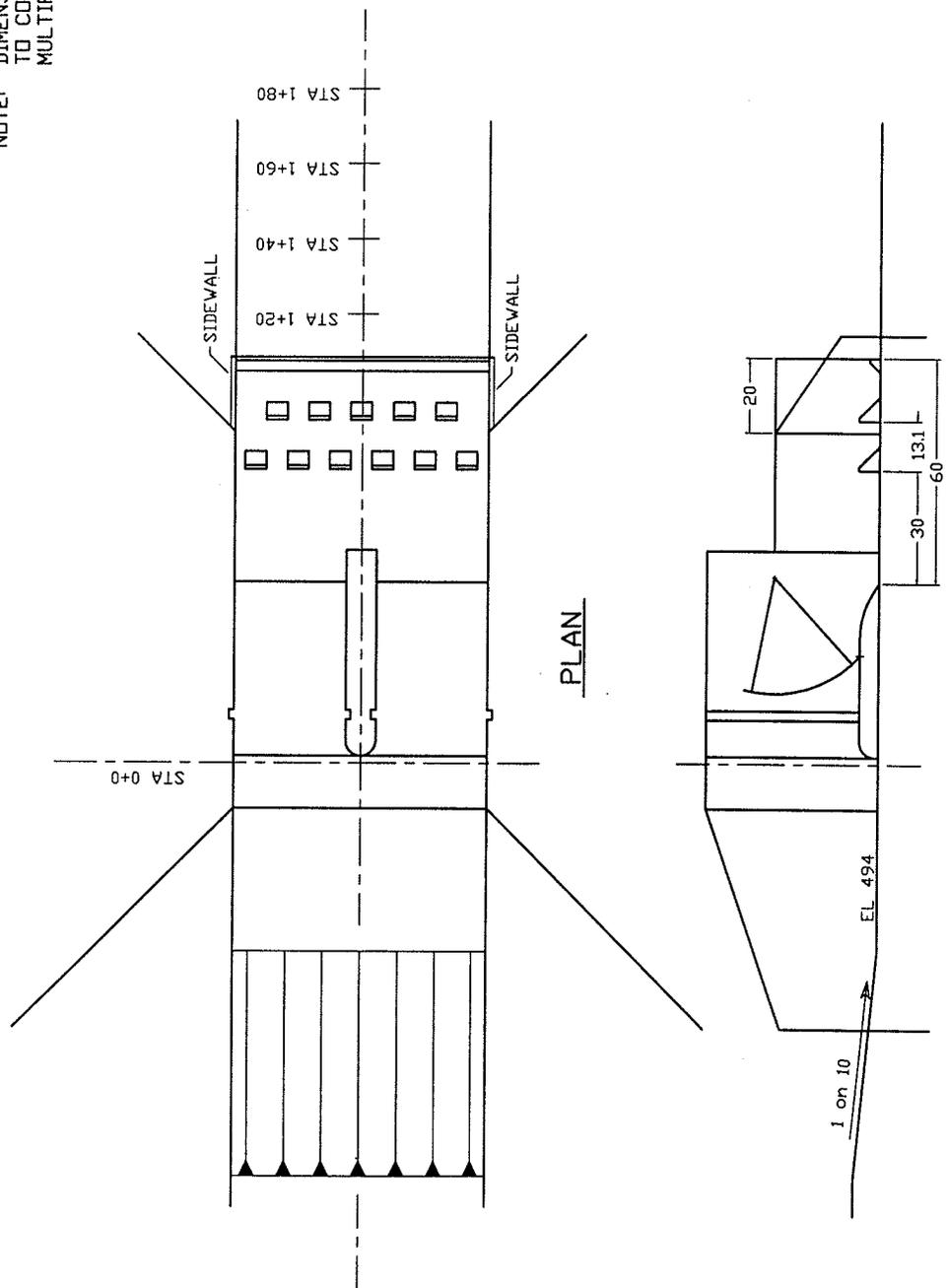


NOTE: DIMENSIONS GIVEN IN FEET.
TO CONVERT TO METERS,
MULTIPLY BY 0.3048



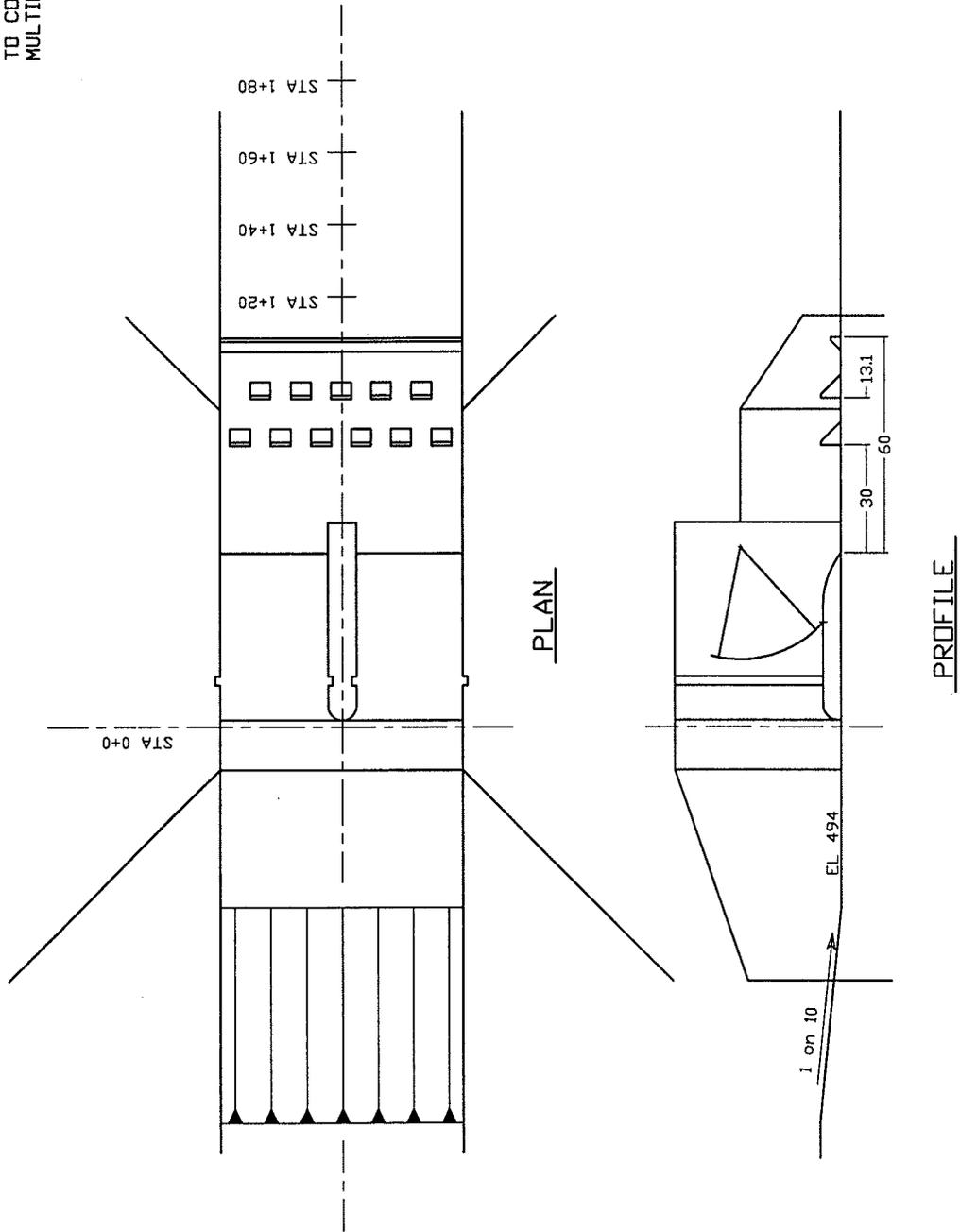
TYPE 2 DESIGN

NOTE: DIMENSIONS GIVEN IN FEET.
TO CONVERT TO METERS,
MULTIPLY BY 0.3048



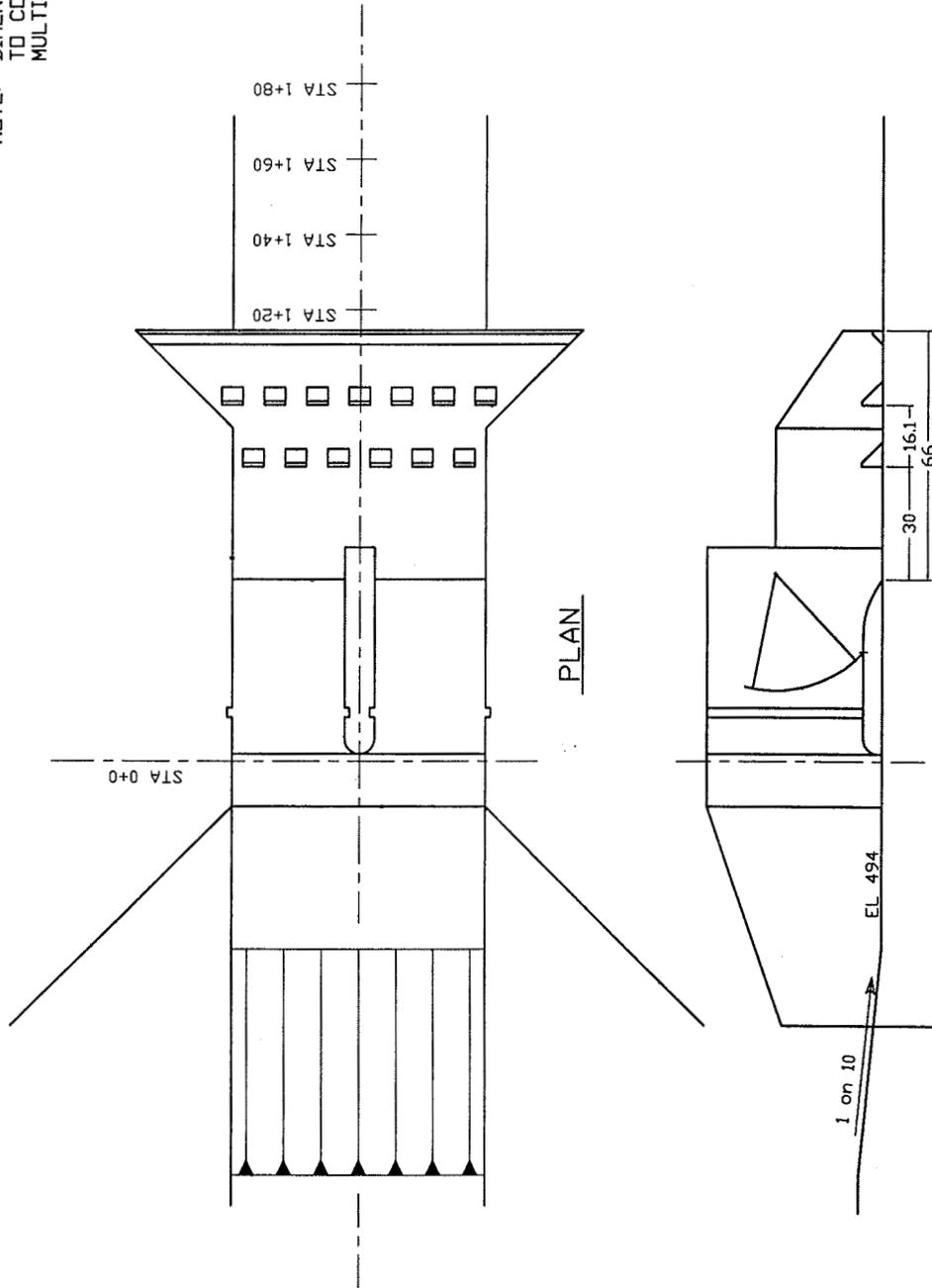
TYPE 3 DESIGN

NOTE: DIMENSIONS GIVEN IN FEET.
TO CONVERT TO METERS,
MULTIPLY BY 0.3048



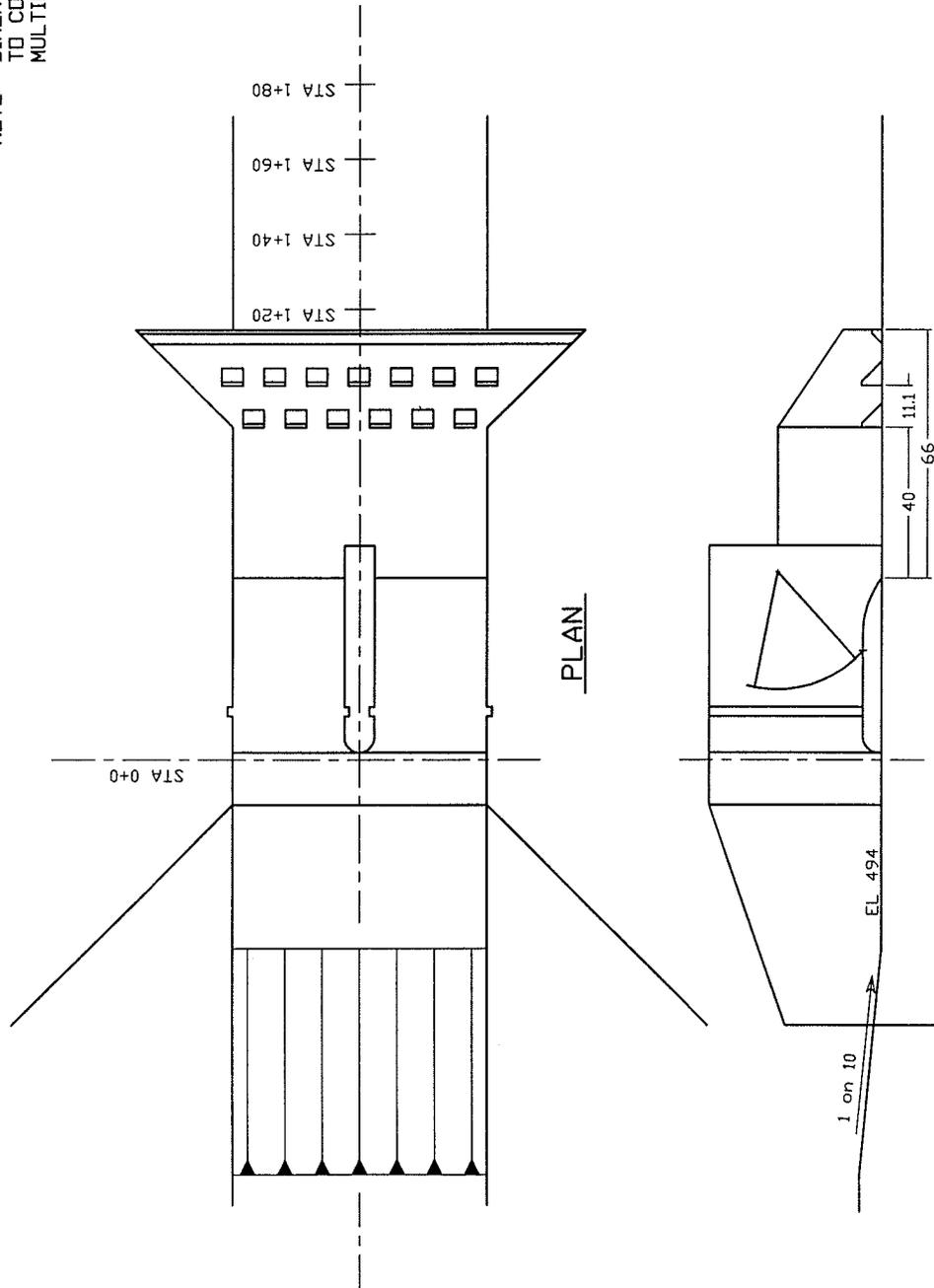
TYPE 4 DESIGN

NOTE: DIMENSIONS GIVEN IN FEET,
TO CONVERT TO METERS,
MULTIPLY BY 0.3048



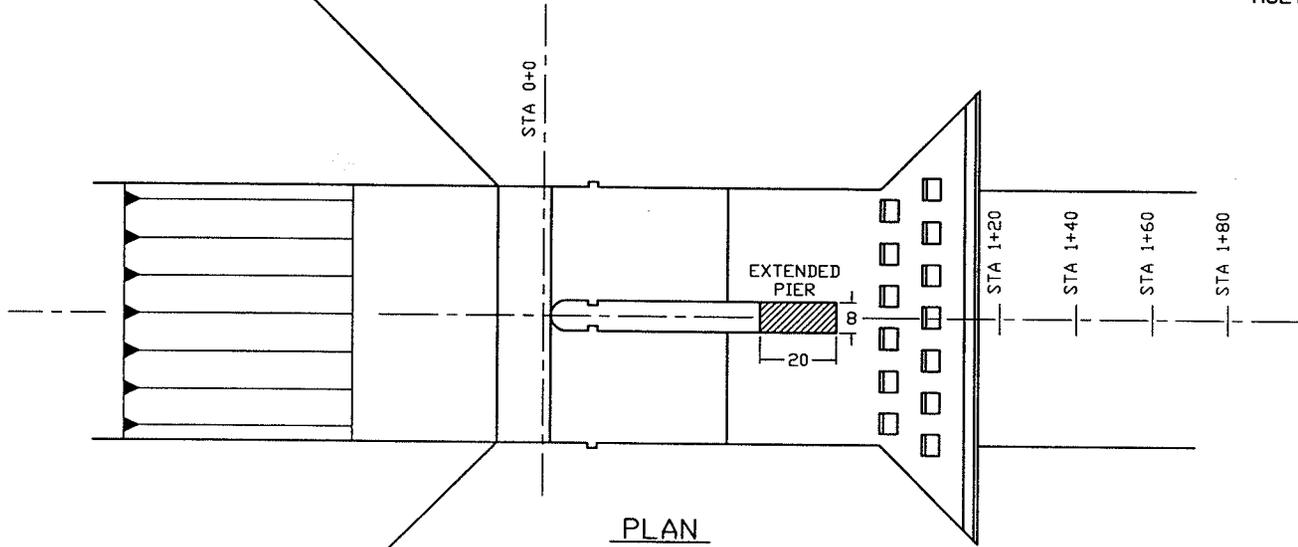
TYPE 5 DESIGN

NOTE: DIMENSIONS GIVEN IN FEET.
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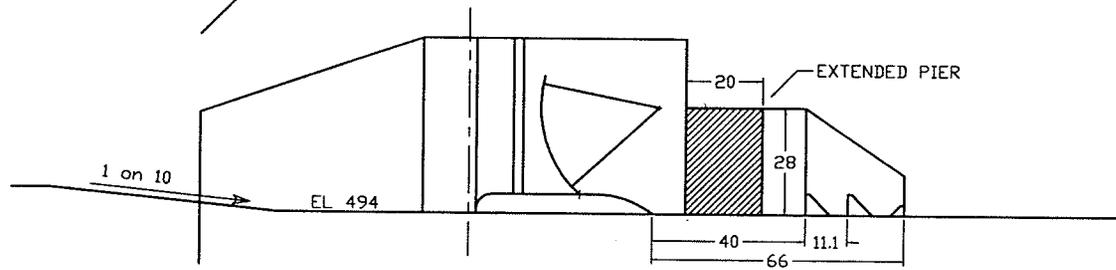


TYPE 6 DESIGN

NOTE: DIMENSIONS GIVEN IN FEET.
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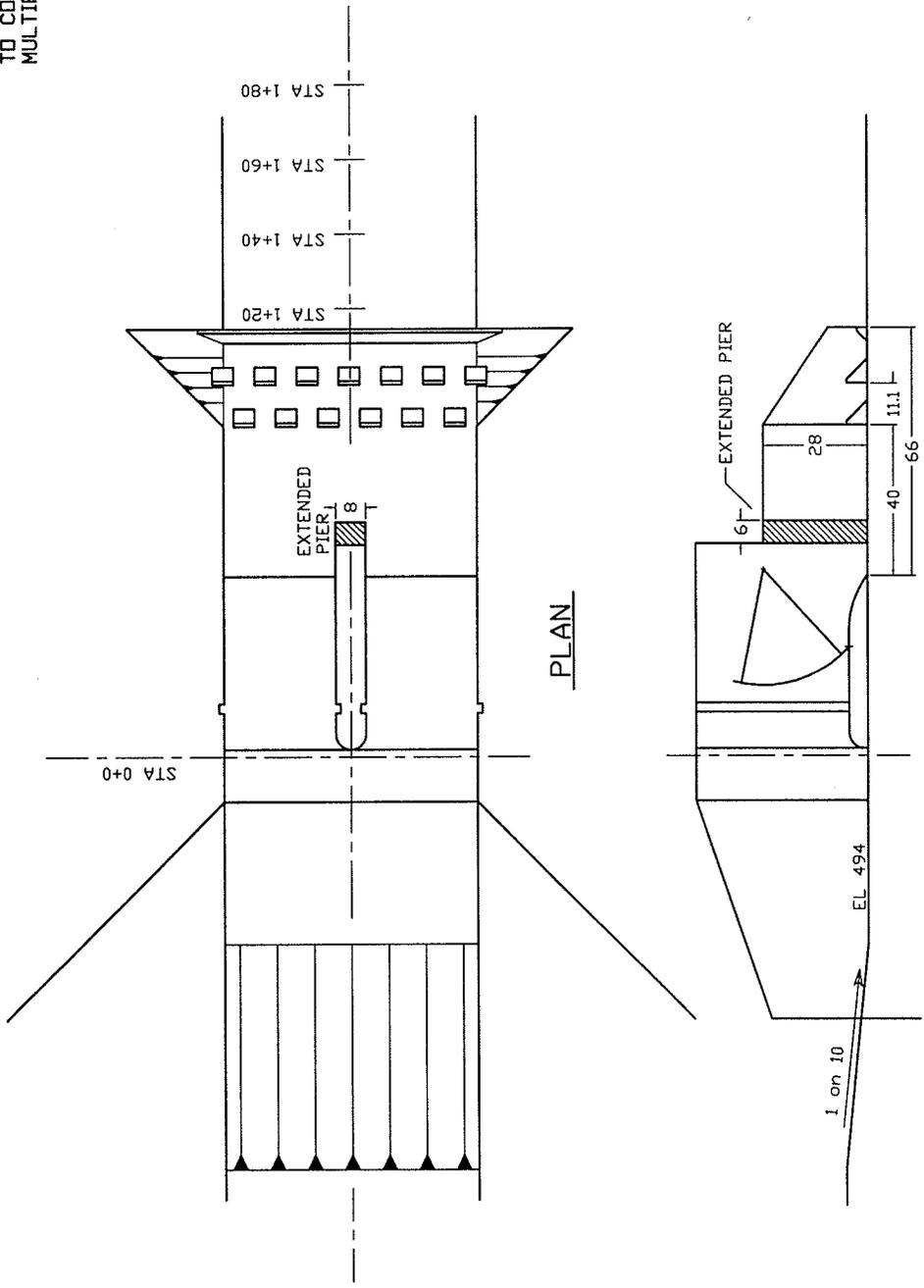
PLAN



PROFILE

TYPE 7 DESIGN

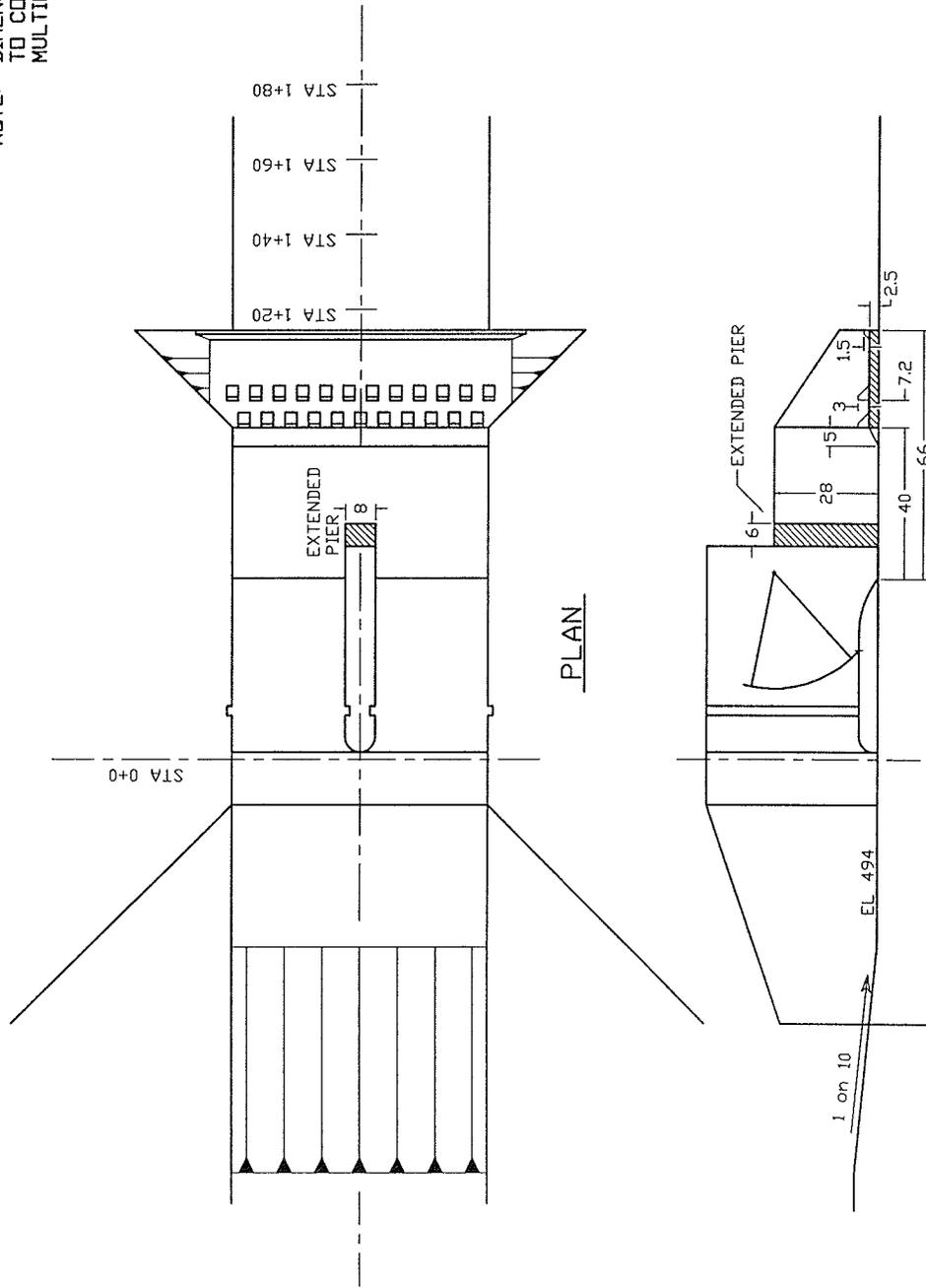
NOTE: DIMENSIONS GIVEN IN FEET.
TO CONVERT TO METERS,
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TYPE 8 DESIGN

Plate 8

NOTE: DIMENSIONS GIVEN IN FEET.
TO CONVERT TO METERS,
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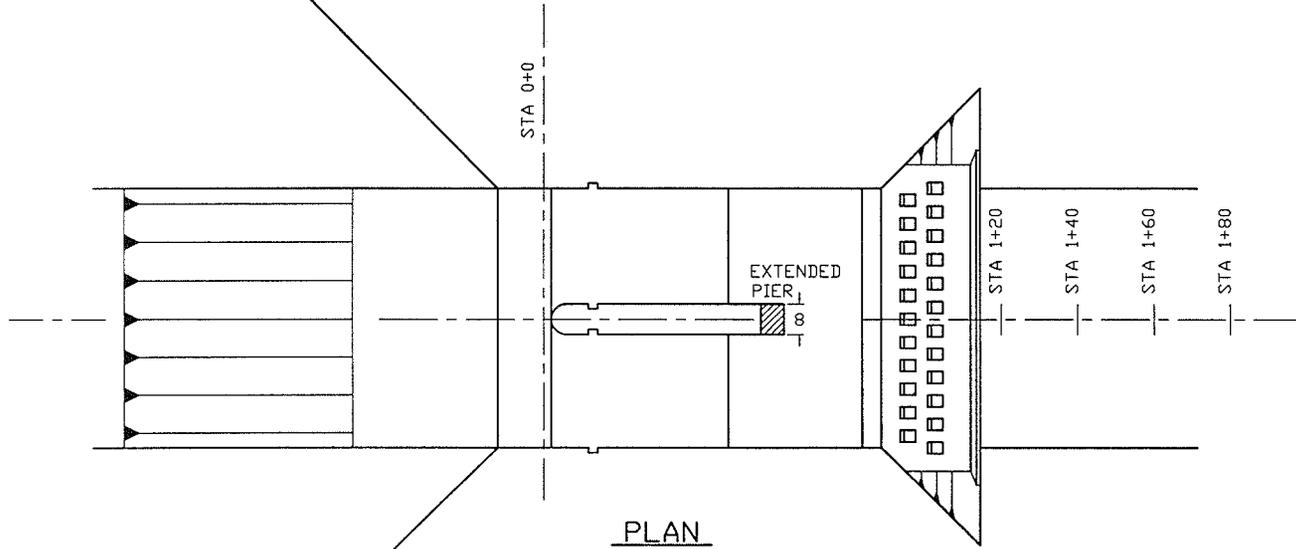


PLAN

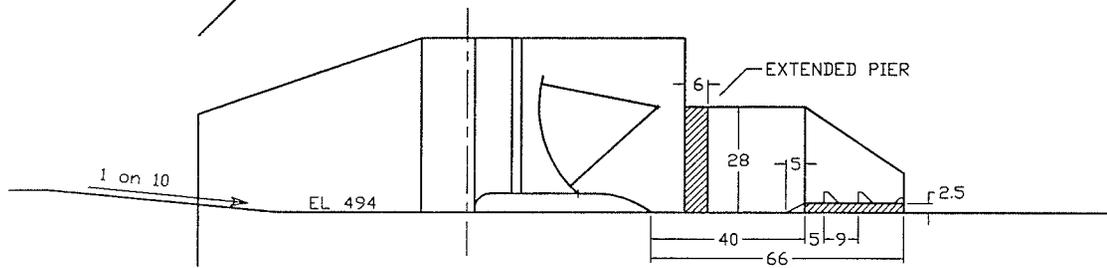
PROFILE

TYPE 9 DESIGN

NOTE: DIMENSIONS GIVEN IN FEET.
TO CONVERT TO METERS,
MULTIPLY BY 0.3048



PLAN



PROFILE

TYPE 10 DESIGN



Photo 1. Downstream flow conditions, type 1 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8

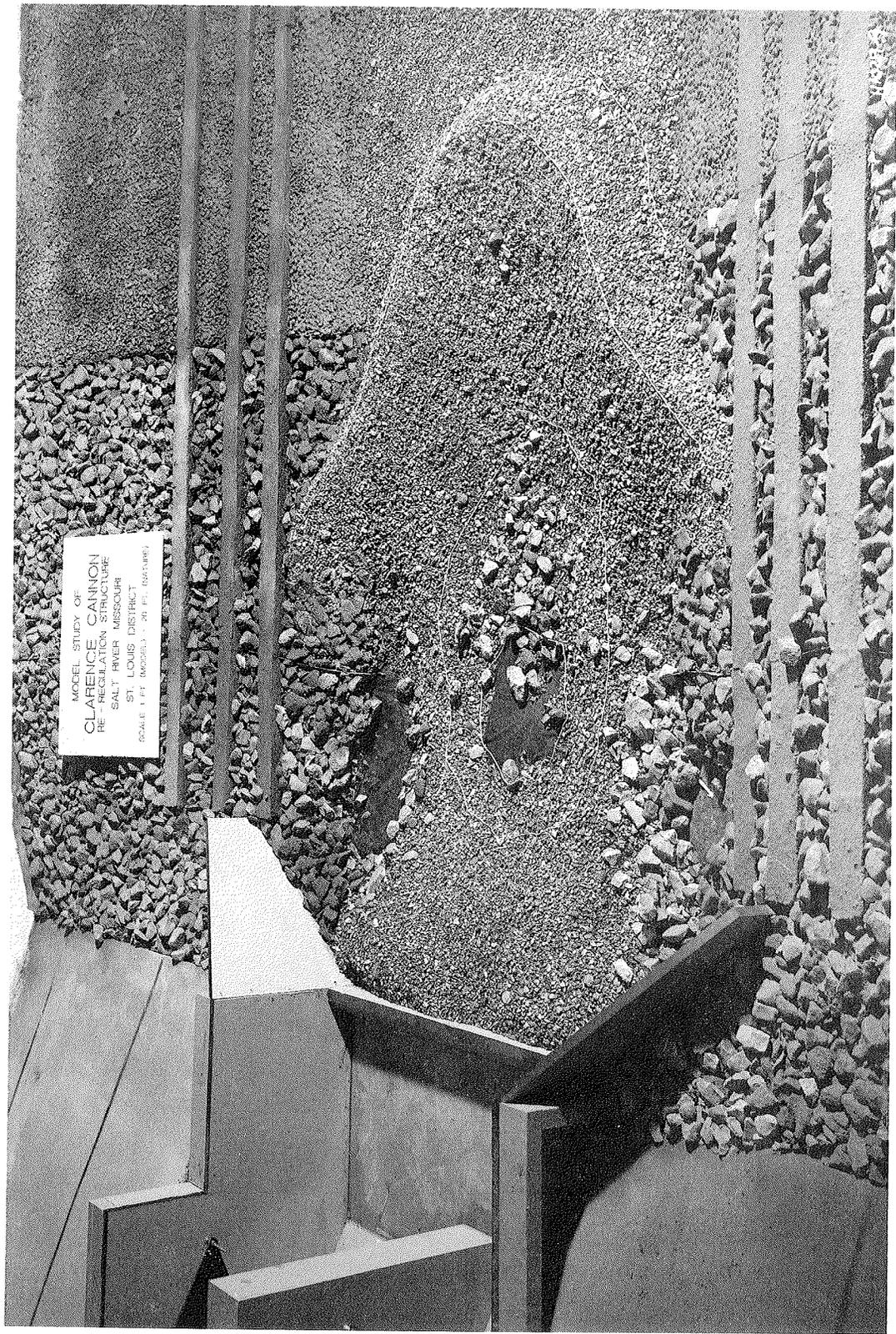
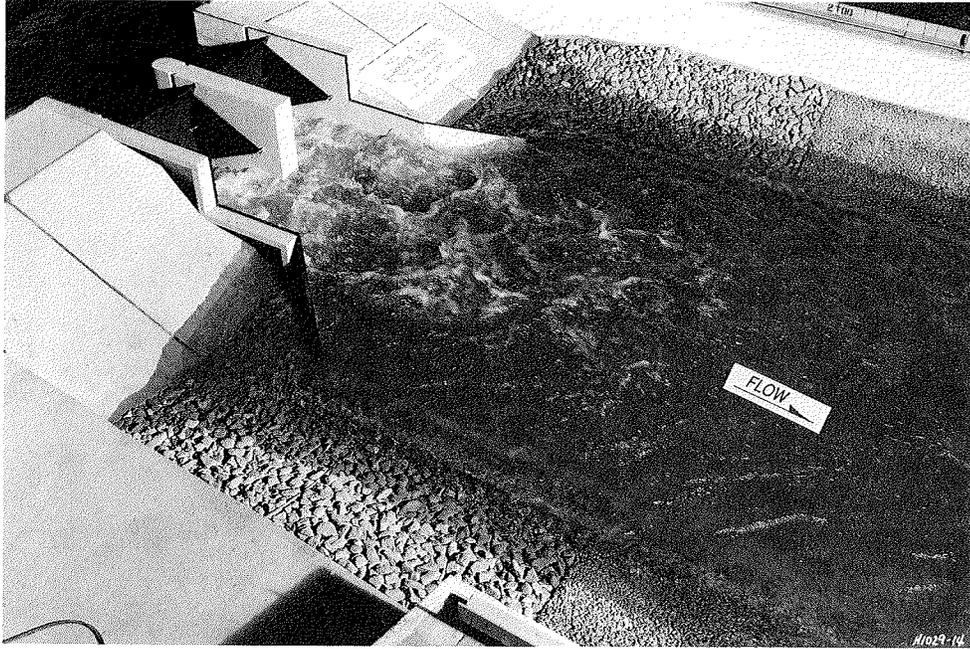


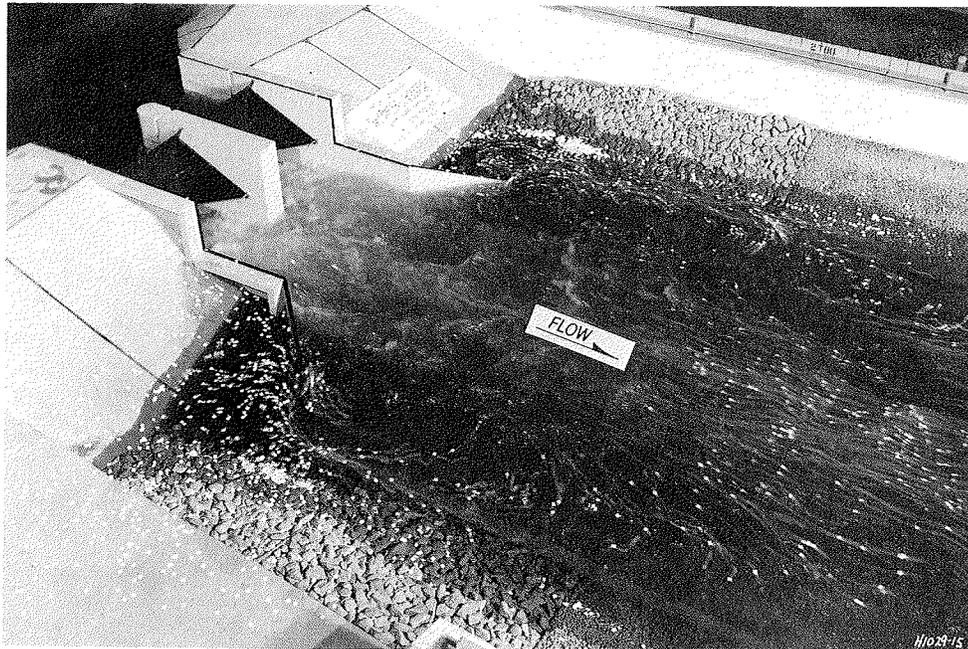
Photo 2. Downstream scour after 4.5 hours, type 1 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



Photo 3. Downstream flow conditions, type 1 design, 170 cu m/sec (6,000 cfs), one gate at 2.4 m (8 ft), tailwater el 509.2



a. Downstream flow conditions



b. Circulation patterns

Photo 4. Type 2 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8

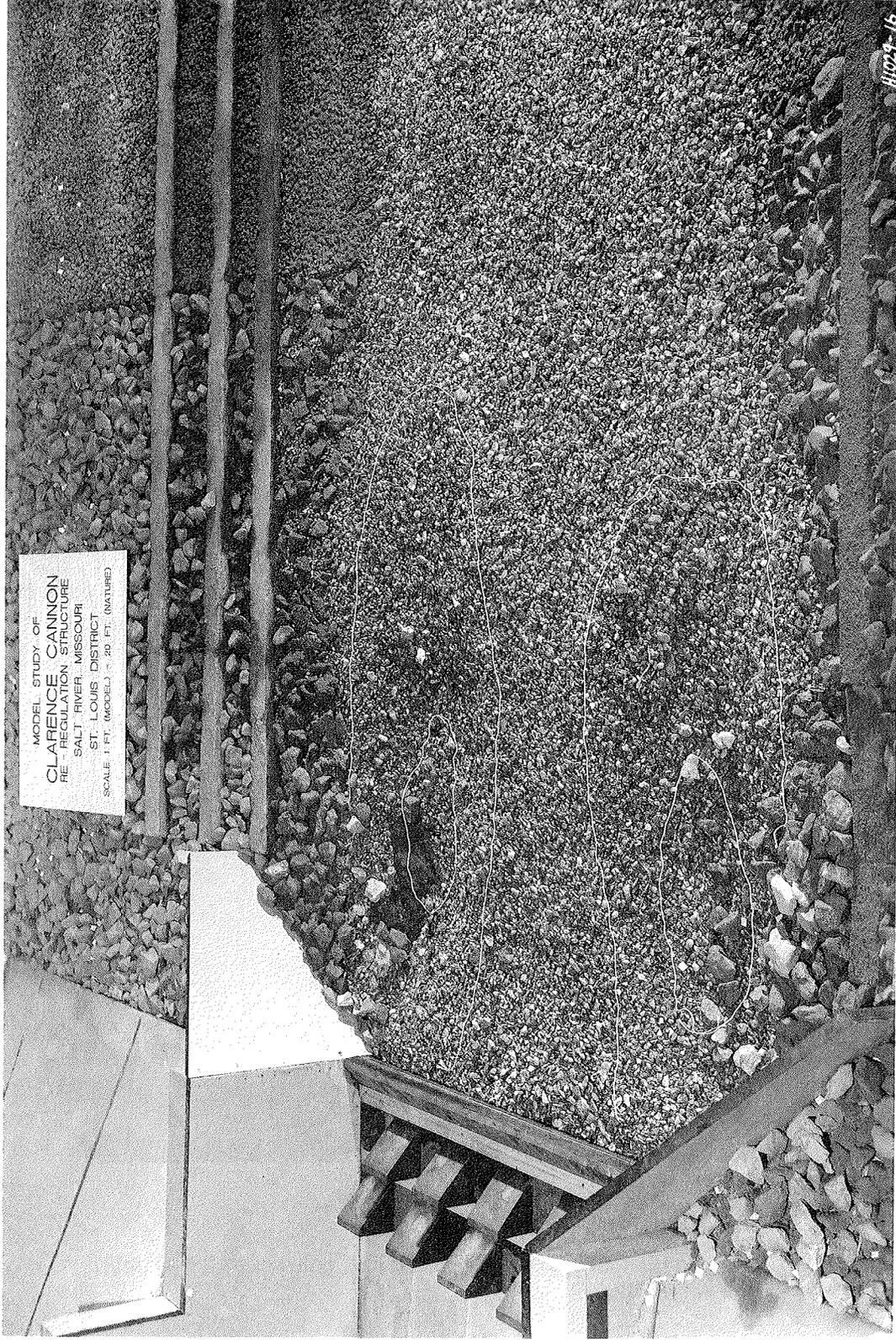
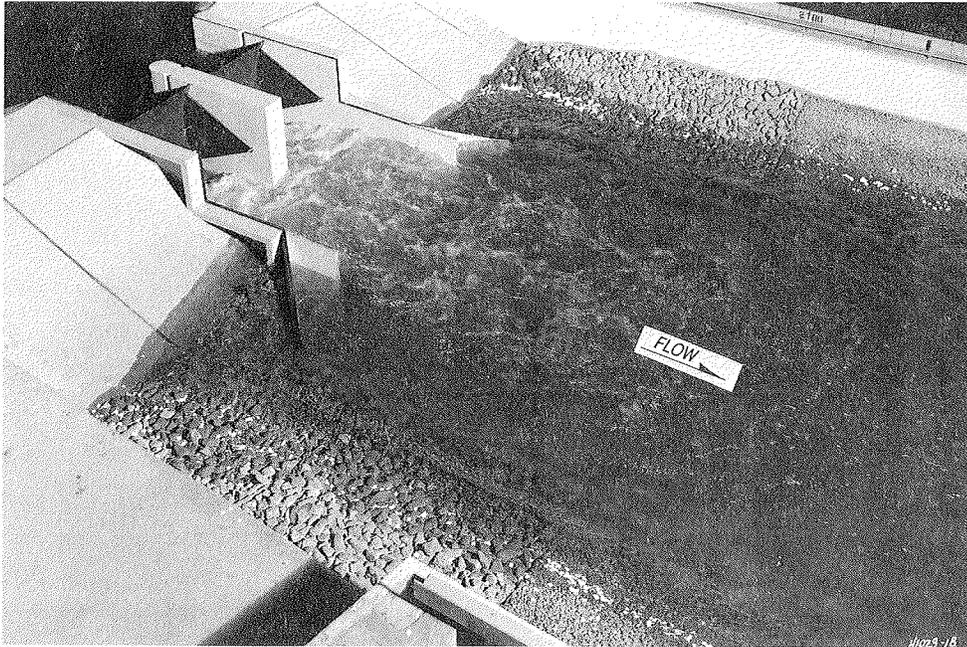
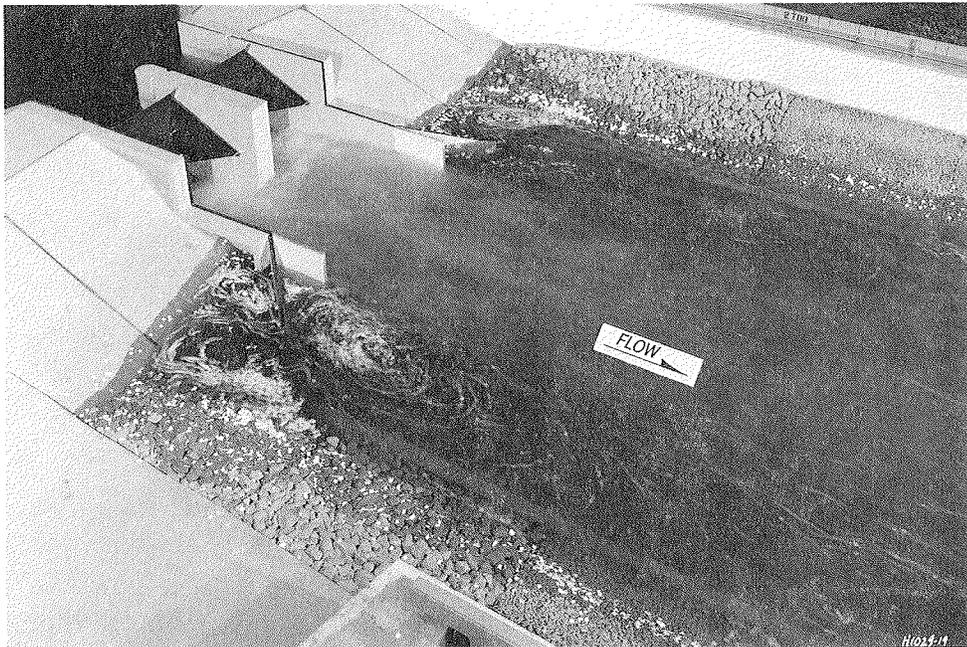


Photo 5. Downstream scour after 4.5 hours, type 2 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



a. Flow conditions

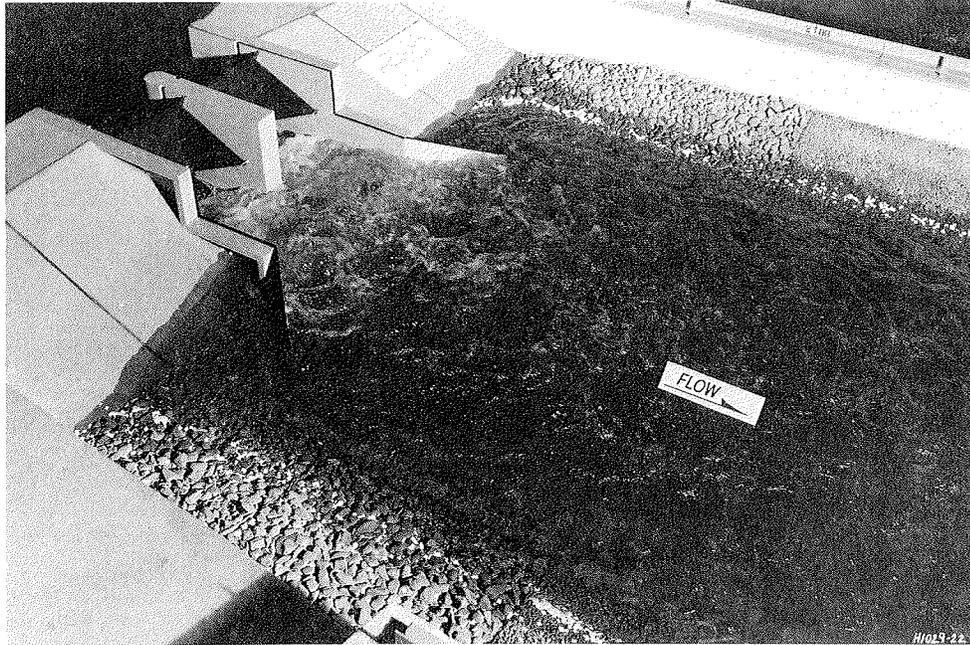


b. Circulation patterns

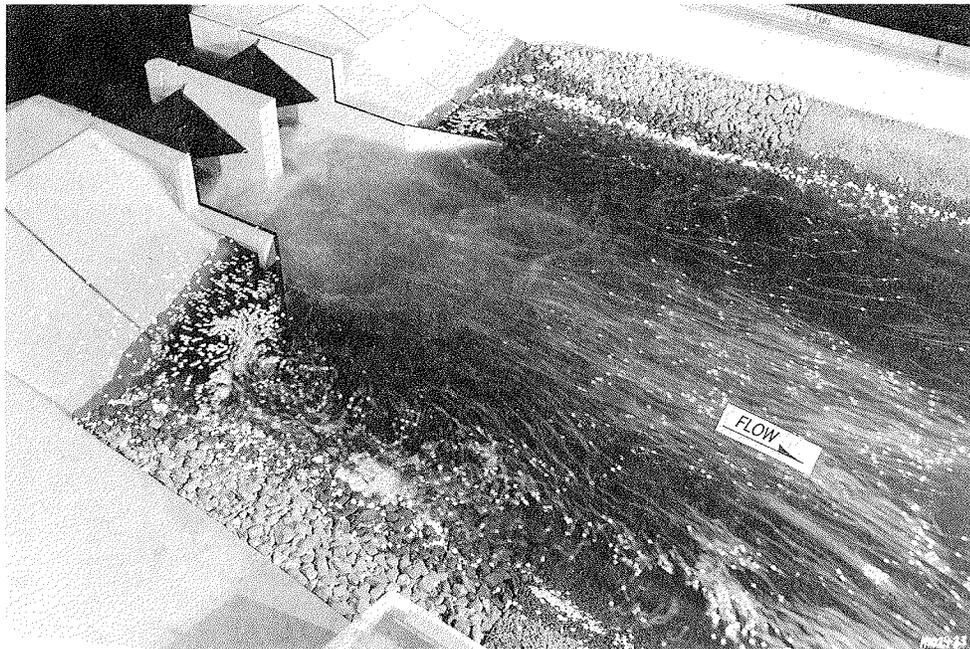
Photo 6. Type 3 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



Photo 7. Downstream scour after 4.5 hours, type 3 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



a. Flow conditions



b. Circulation patterns

Photo 8. Type 4 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8

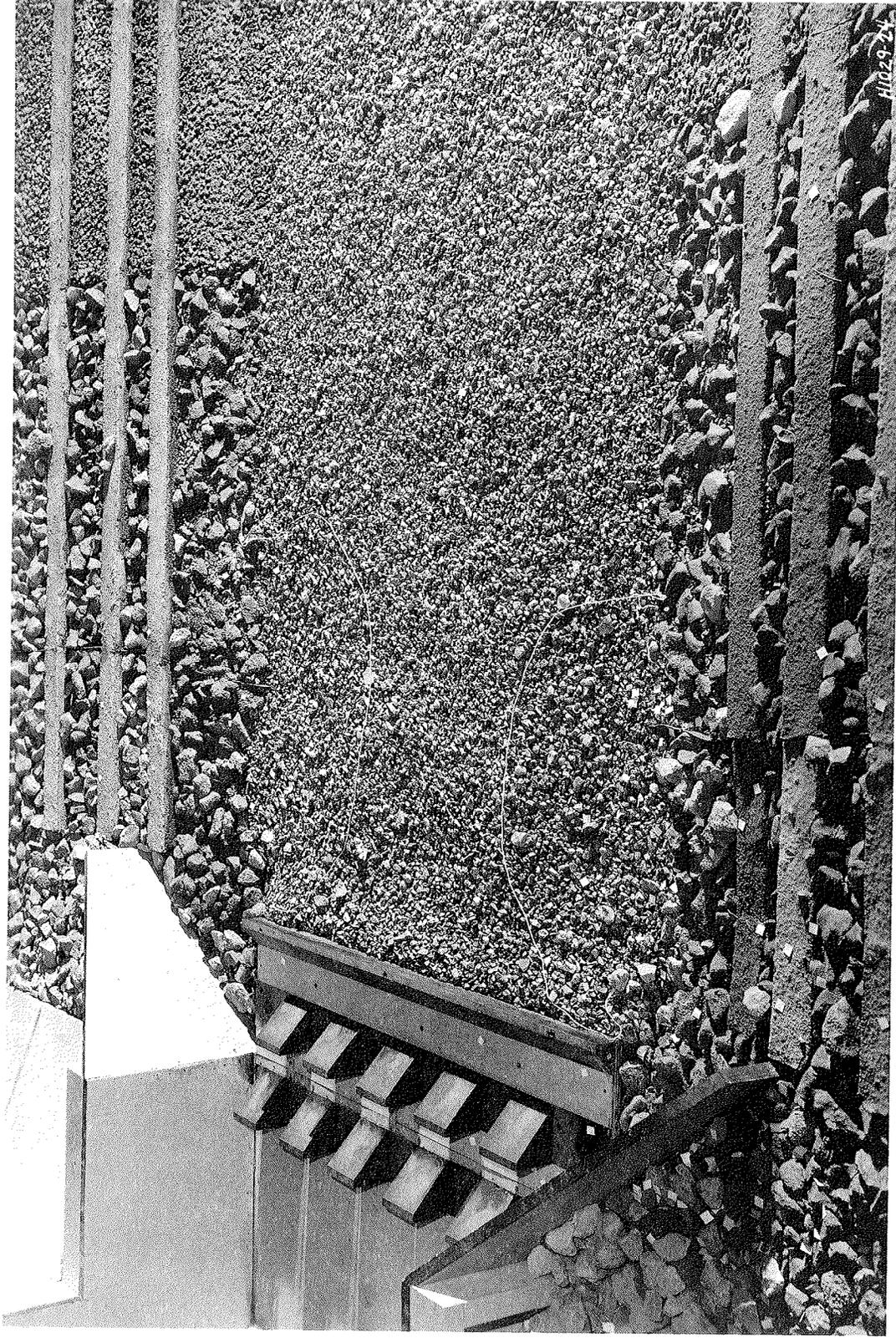


Photo 9. Downstream scour after 4.5 hours, type 4 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8

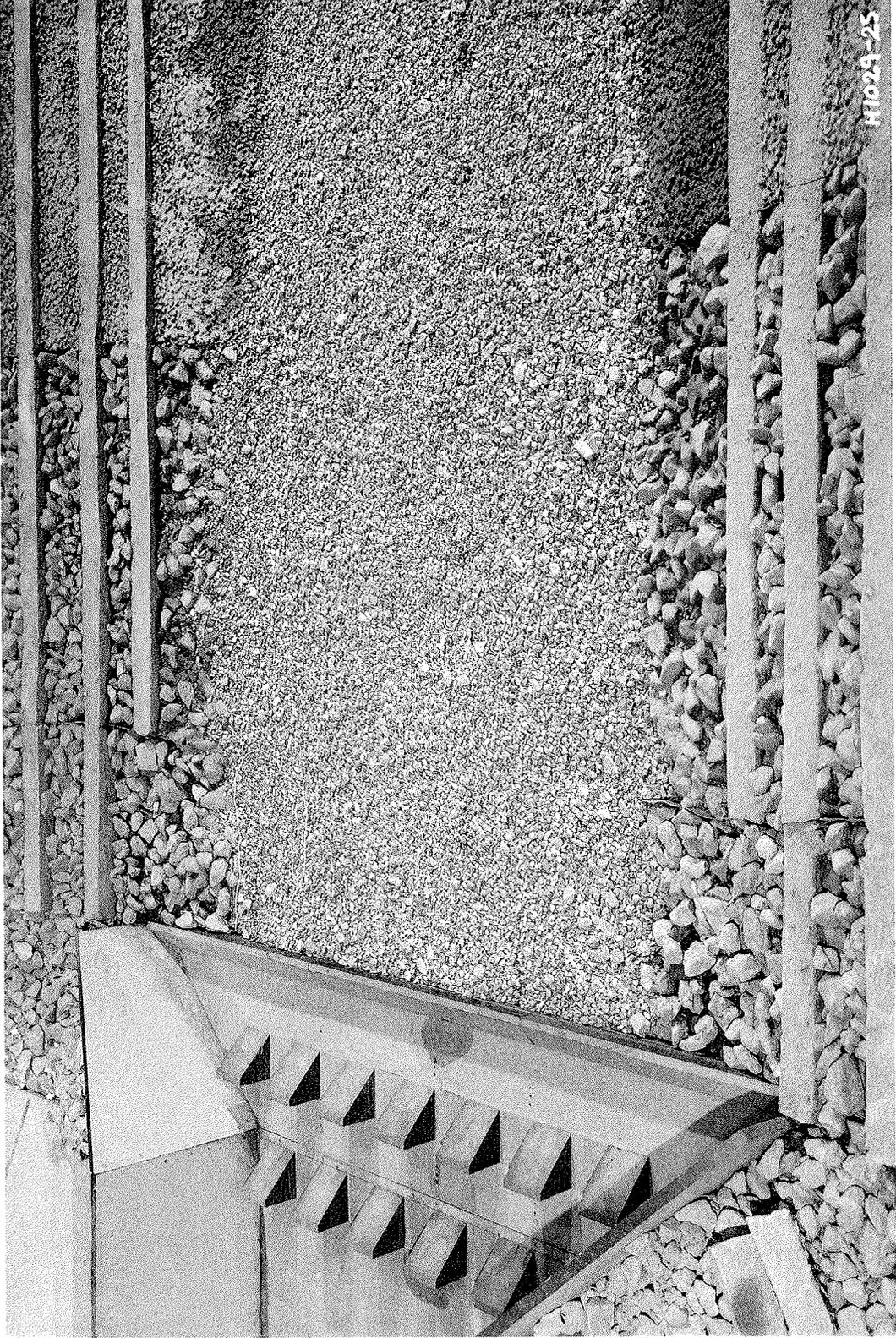
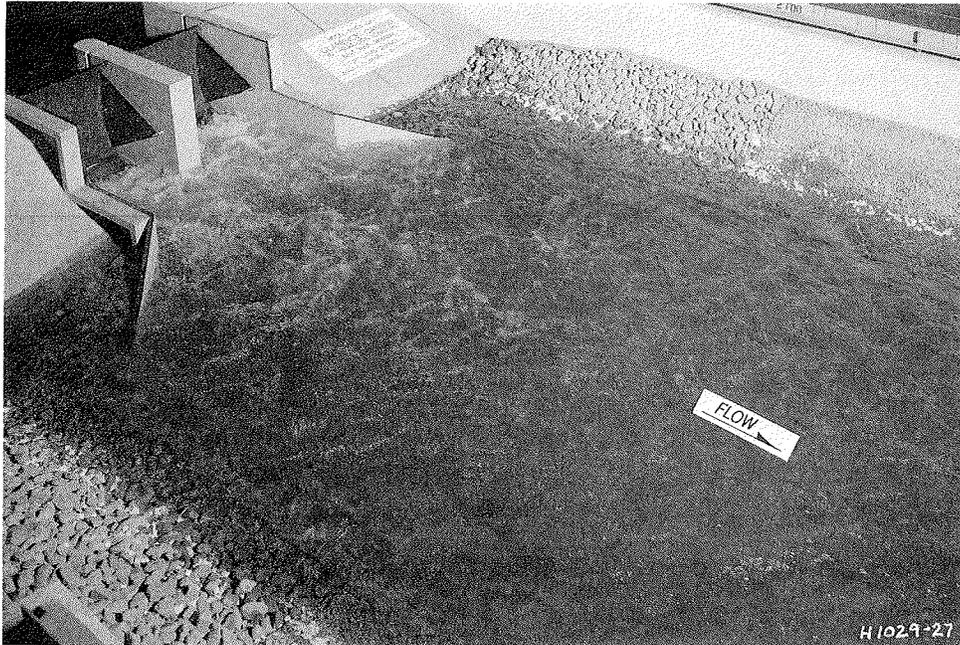
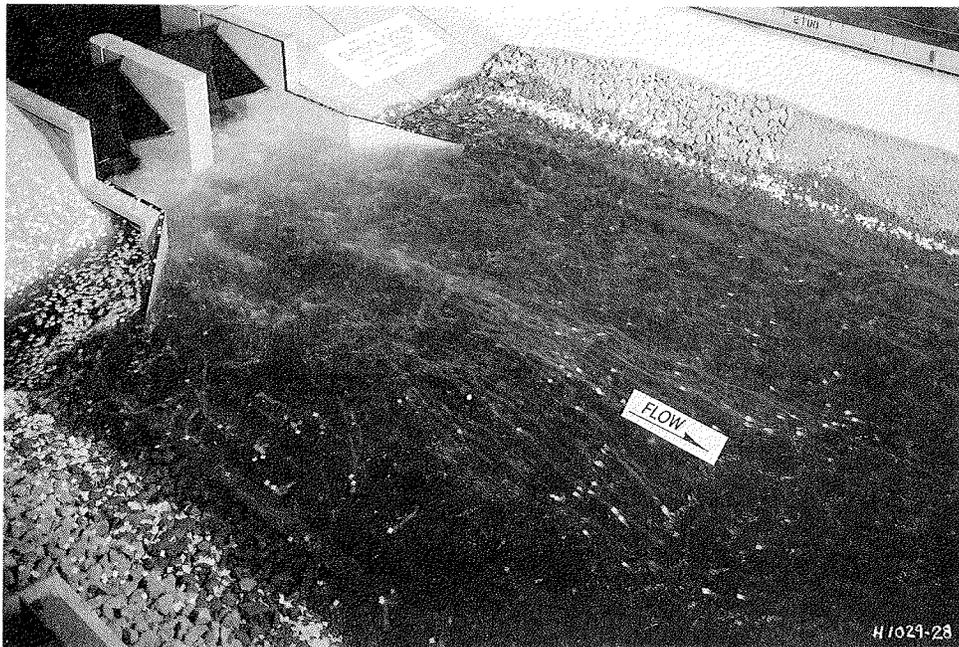


Photo 10. Downstream scour after 4.5 hours, type 5 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



a. Flow conditions

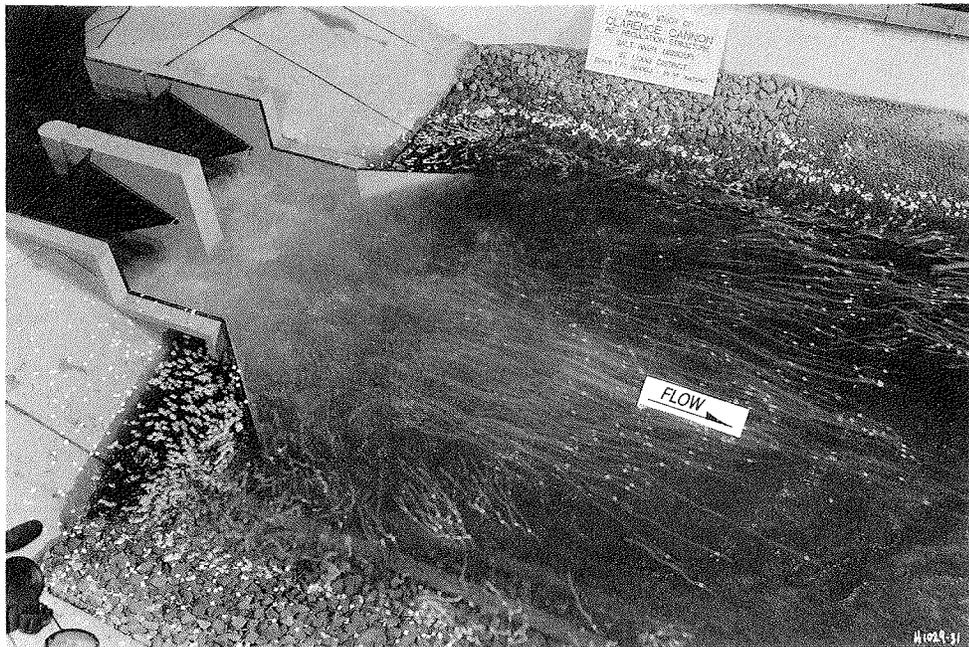


b. Circulation patterns

Photo 11. Type 5 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



a. Flow conditions



b. Circulation patterns

Photo 12. Type 6 design, 340 cu m/sec (12,000 cfs), gates at 2.4 m (8 ft), tailwater el 512.8

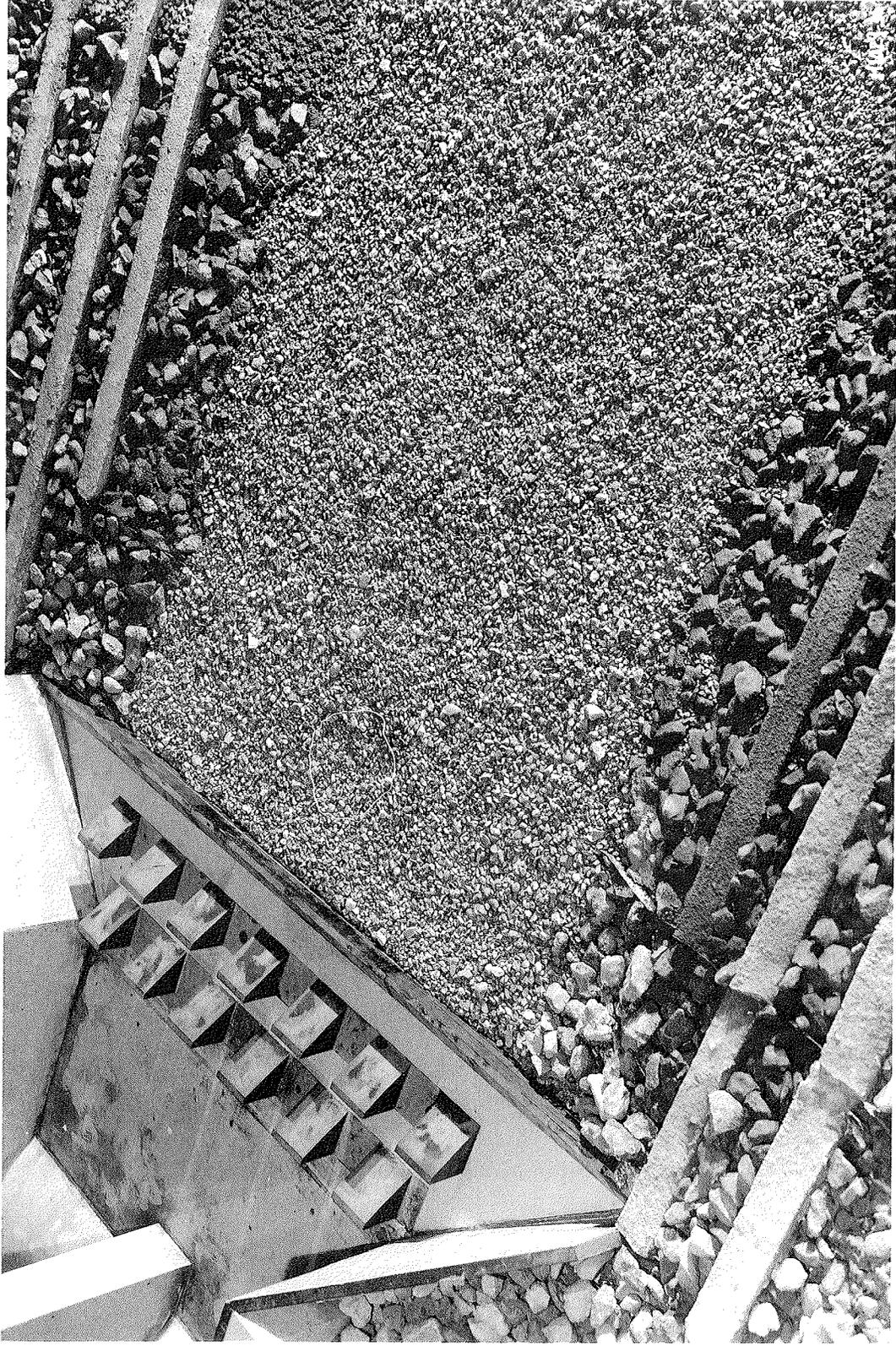


Photo 13. Downstream scour after 4.5 hours, type 6 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8

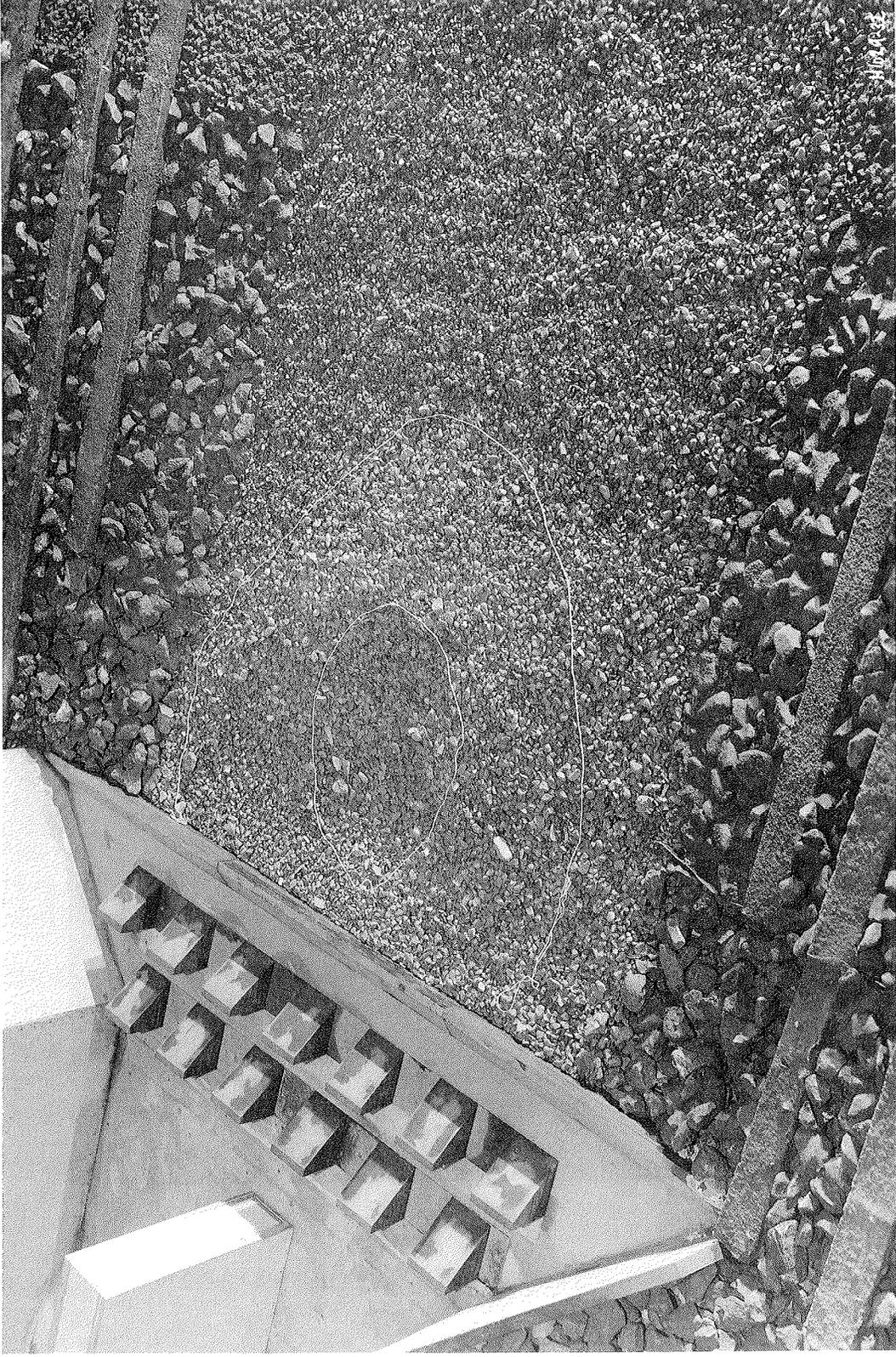
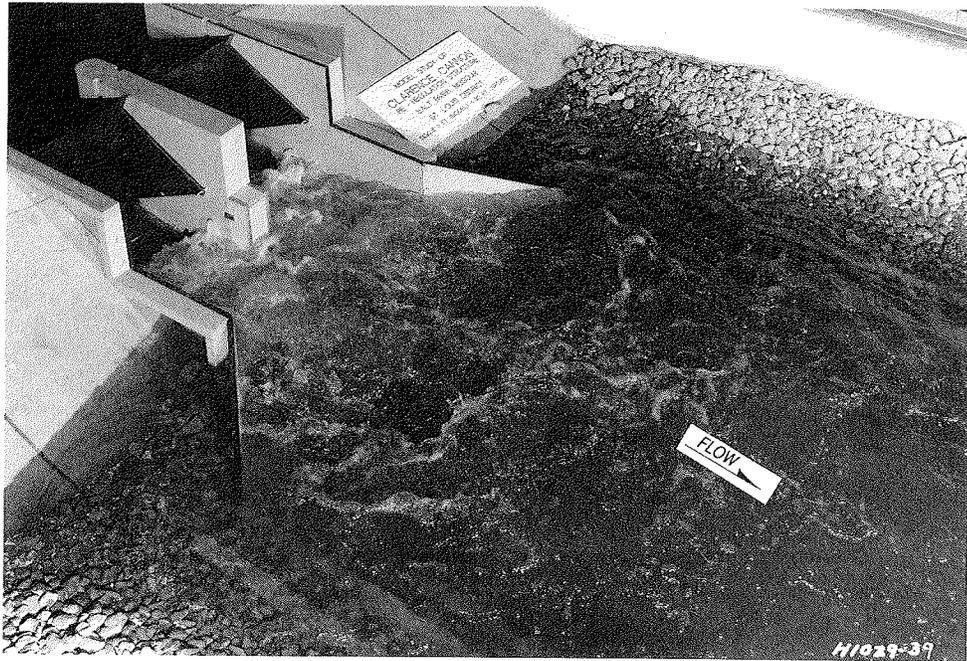
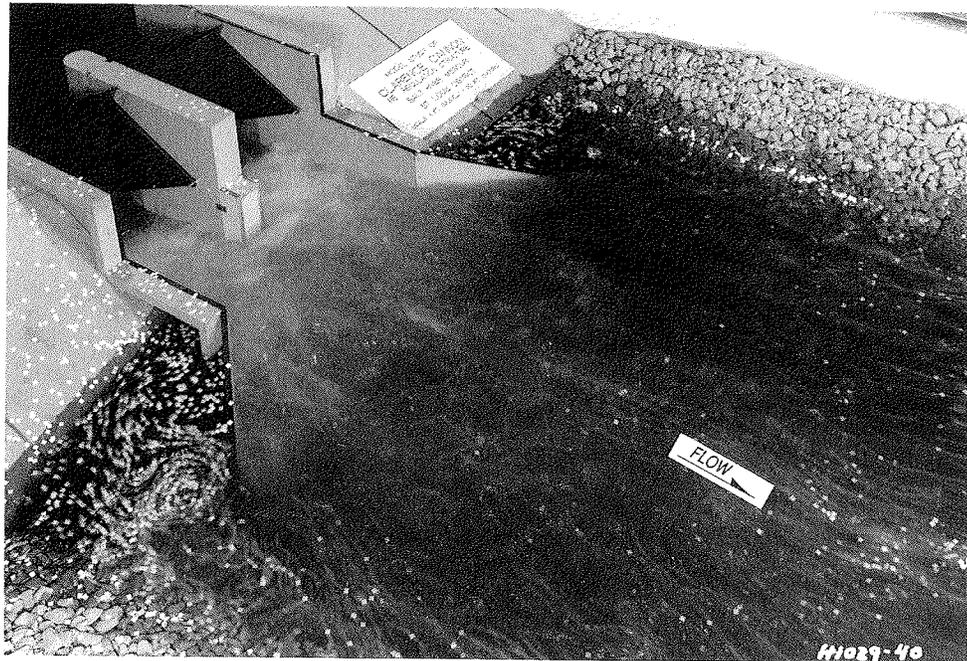


Photo 15. Downstream scour after 4.5 hours, type 7 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



a. Flow conditions

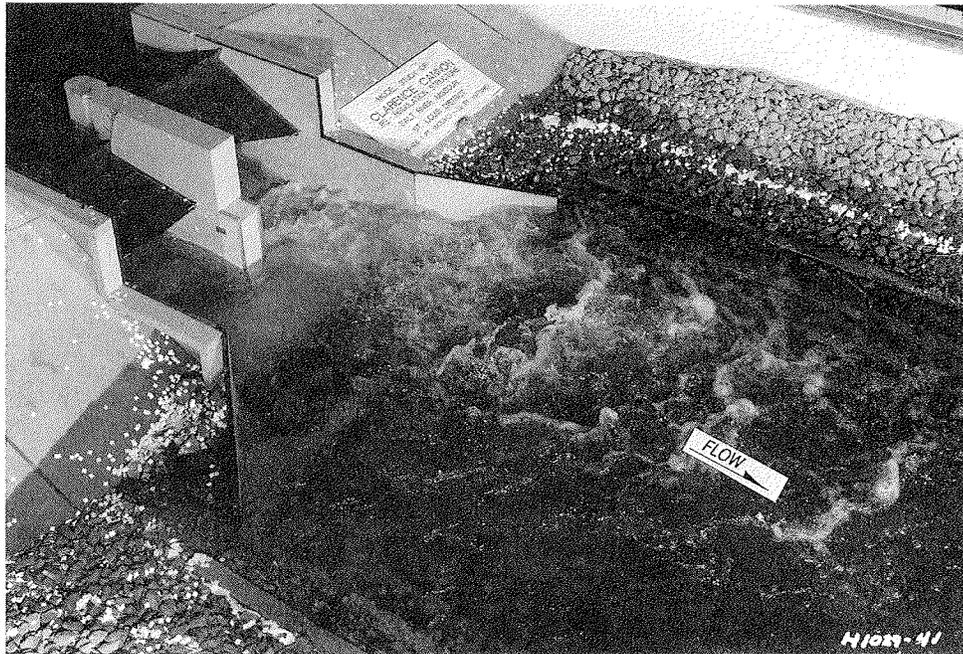


b. Circulation patterns

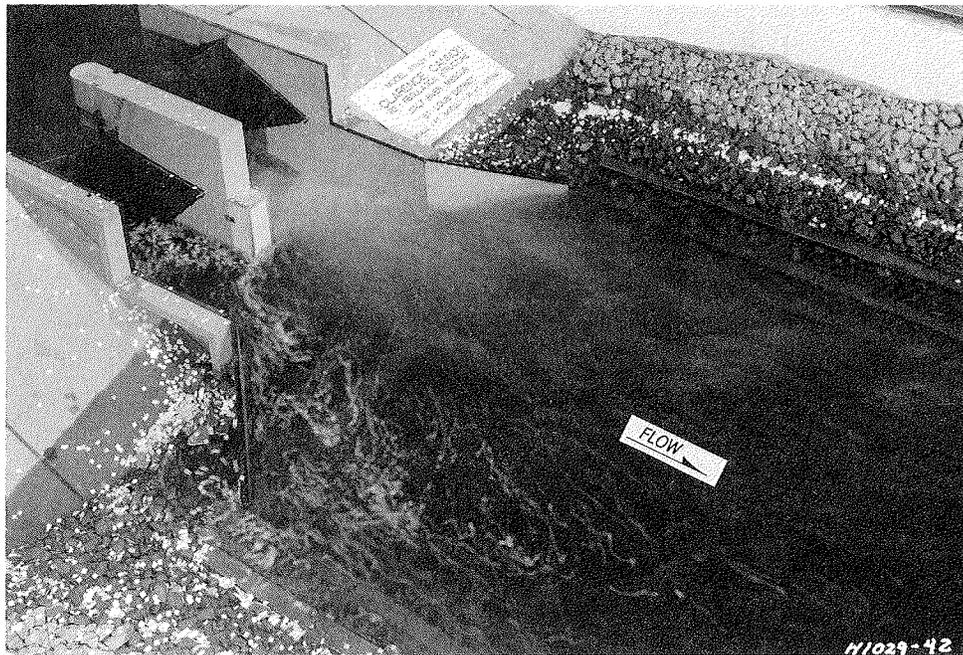
Photo 16. Type 8 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



Photo 17. Downstream scour after 4.5 hours, type 8 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



a. Downstream flow conditions



b. Circulation patterns

Photo 18. Type 8 design, 170 cu m/sec (6,000 cfs), one gate at 2.4 m (8 ft), tailwater el 509.2



a. Flow conditions



b. Circulation patterns

Photo 19. Type 9 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8

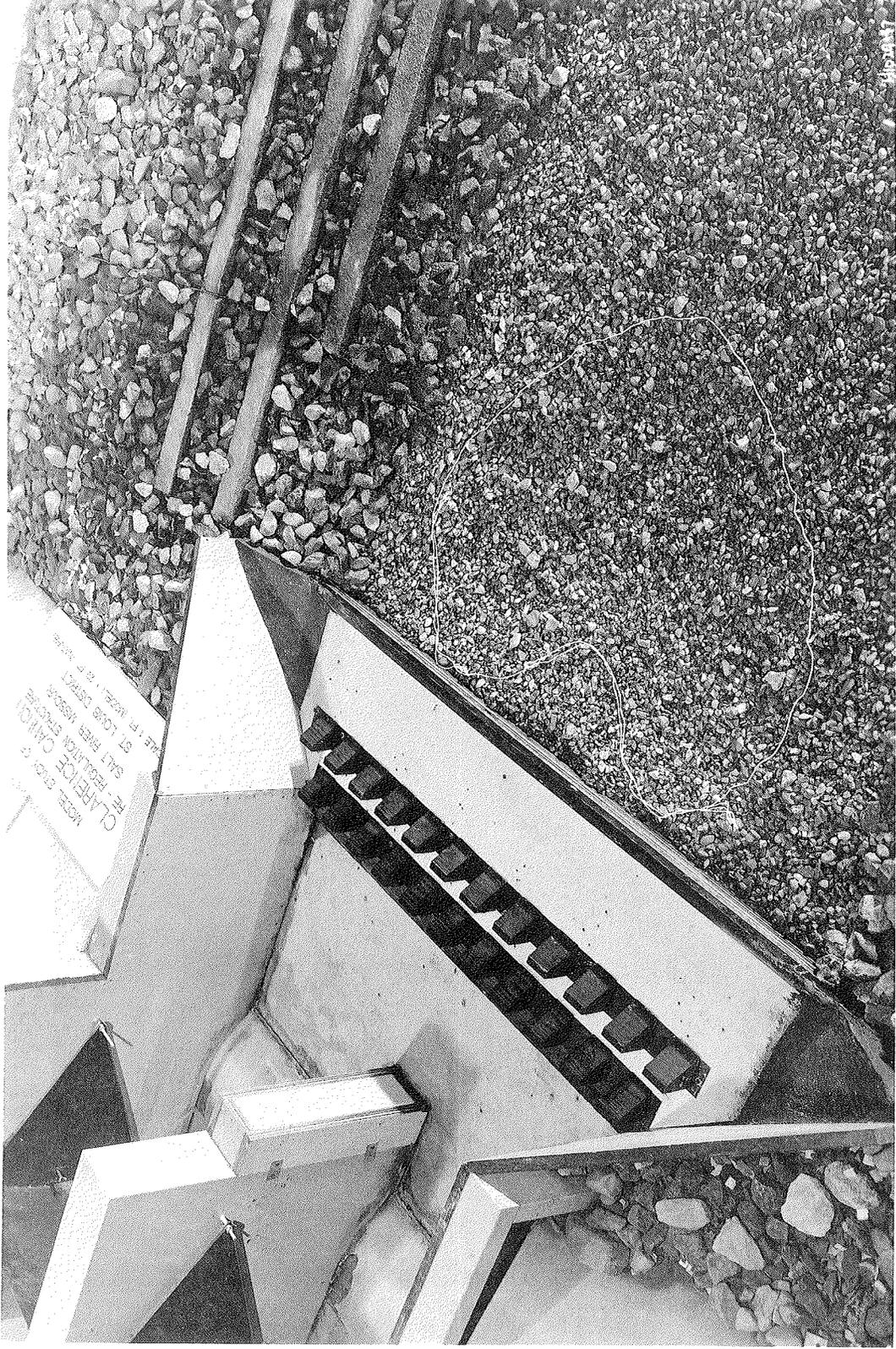
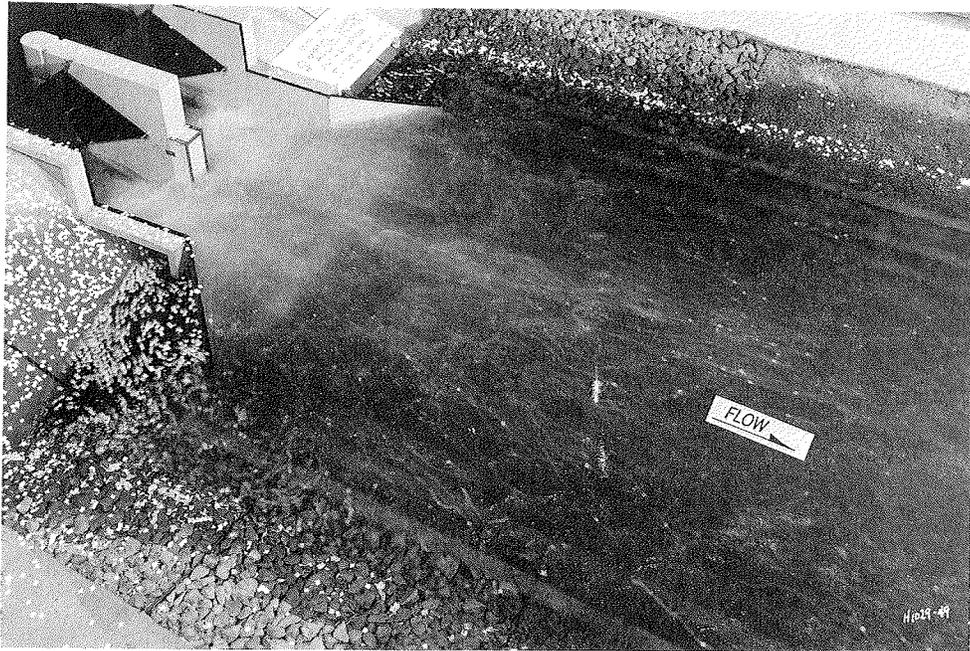


Photo 20. Downstream scour after 4.5 hours, type 9 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



a. Flow conditions



b. Circulation patterns

Photo 21. Type 10 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8

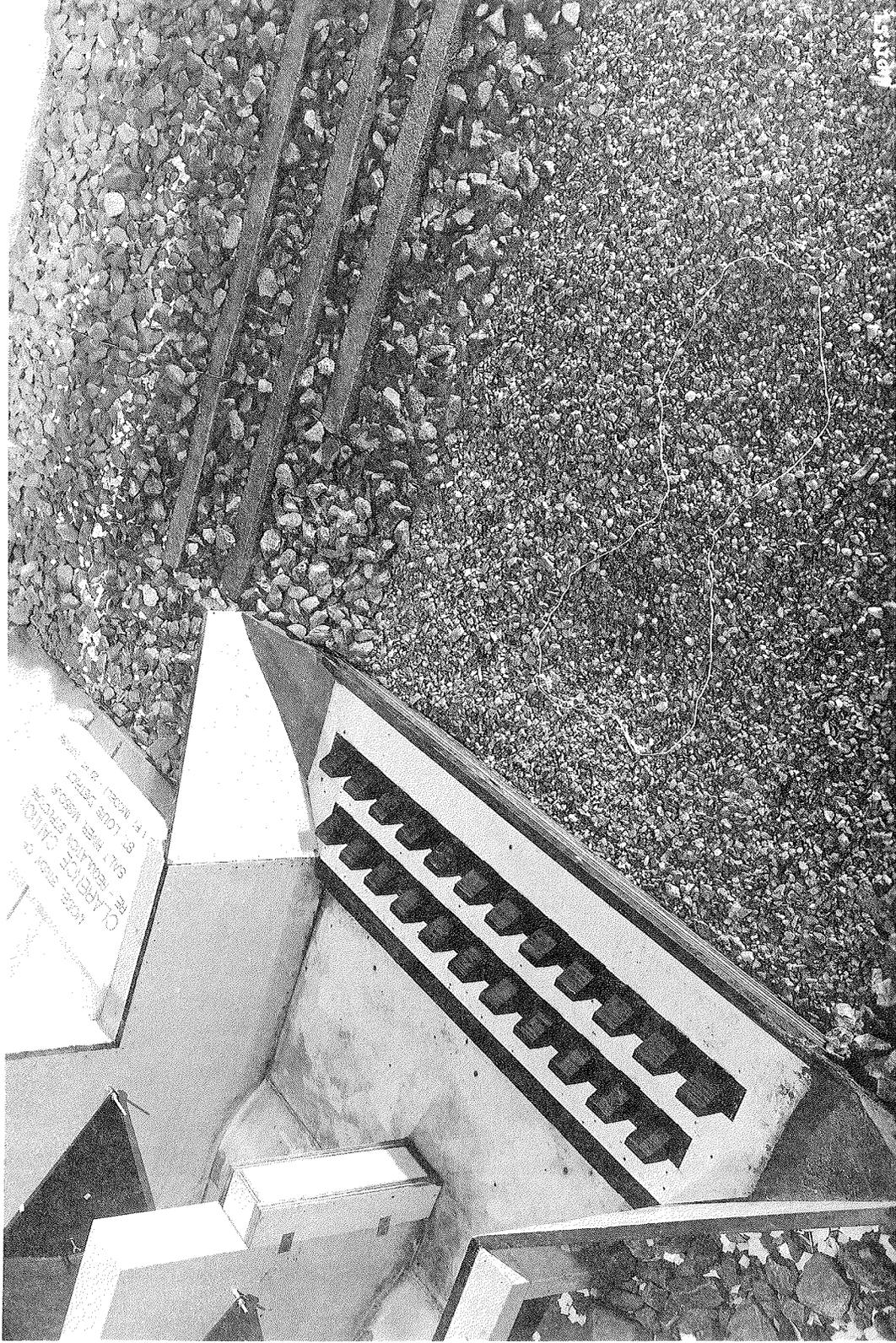


Photo 22. Downstream scour after 4.5 hours, type 10 design, 340 cu m/sec (12,000 cfs), gates open 2.4 m (8 ft), tailwater el 512.8



a. Flow conditions



b. Circulation patterns

Photo 23. Type 10 design, 170 cu m/sec (6,000 cfs), one gate at 2.4 m (8 ft), tailwater el 509.2

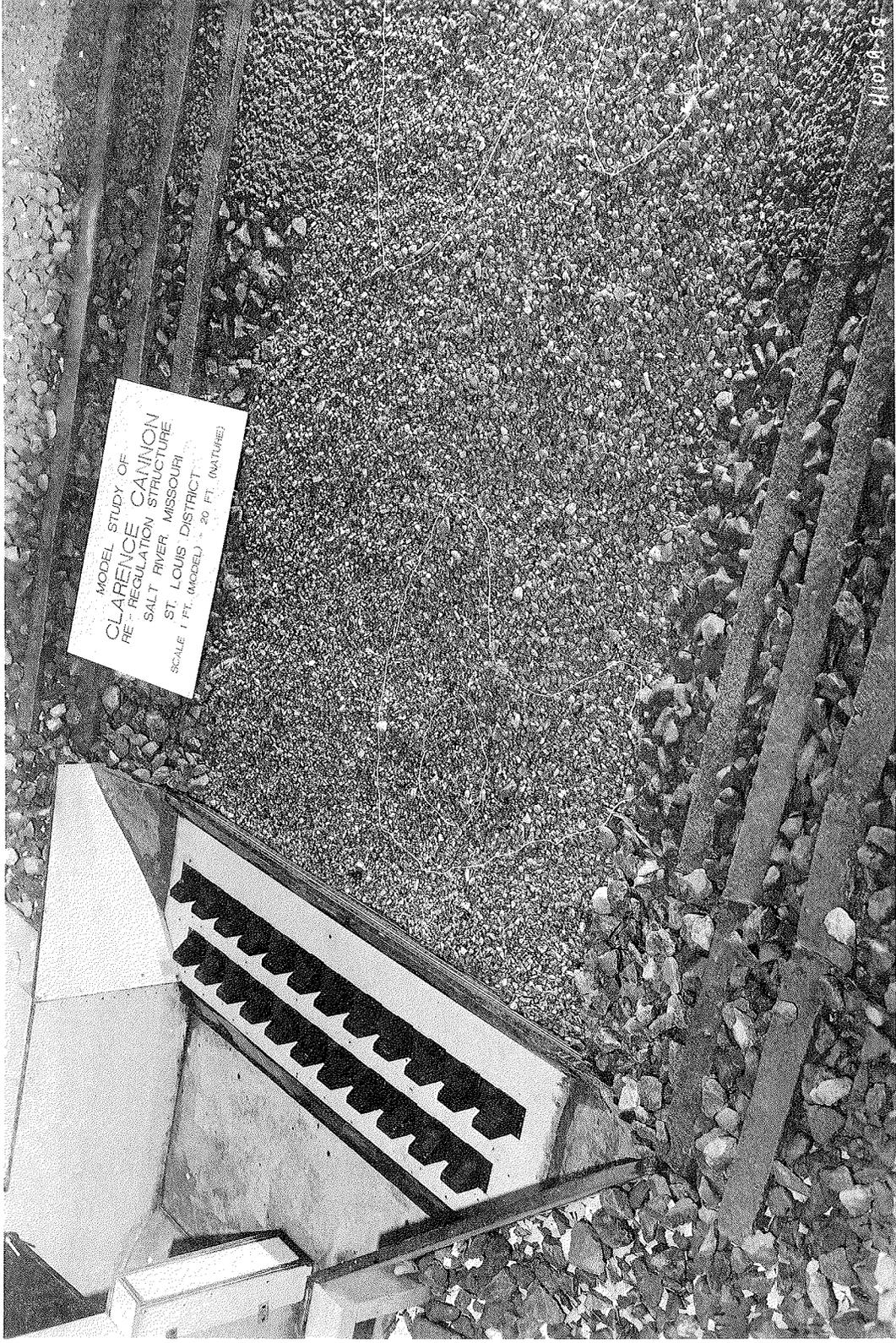


Photo 24. Downstream scour after 4.5 hours, type 10 design, 170 cu m/sec (6,000 cfs), one gate at 2.4 m (8 ft), tailwater el 509.2

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) <p>The Clarence Cannon Re-regulation Structure was reproduced in a 1:25-scale model to study ways of reducing scour downstream of the structure. The existing structure was designed according to criteria used for low-head navigation dams on the Arkansas River. This type of structure had a low ogee spillway and tainter gates. The model and testing conditions were reproduced according to prototype data received from the U.S. Army Engineer District, St. Louis.</p> <p>Experiments conducted on the existing structure showed that severe scour would occur at maximum discharge conditions. Baffle blocks and a shorter end sill placed on the existing stilling basin reduced the downstream scour. Additional stilling basin length, two rows of baffle blocks, and a shorter end sill almost eliminated the downstream scour.</p> <p>Due to downstream geologic conditions, the extended stilling basin was raised for constructibility purposes. The resulting design placed two rows of baffle blocks and the end sill on the raised extended stilling basin. Downstream scour levels with the raised basin design were also very low.</p>			
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