Technical Report HL-94-4
April 1994

US Army Corps of Engineers
Waterways Experiment Station

General Design for Replacement of or Modifications to the Lower Santa Ana River Drop Structures, Orange County, California

Hydraulic Model Investigation

by John F. George, Glenn A. Pickering, Herman O. Turner, Jr.

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Prepared for U.S. Army Engineer District, Los Angeles

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Final report

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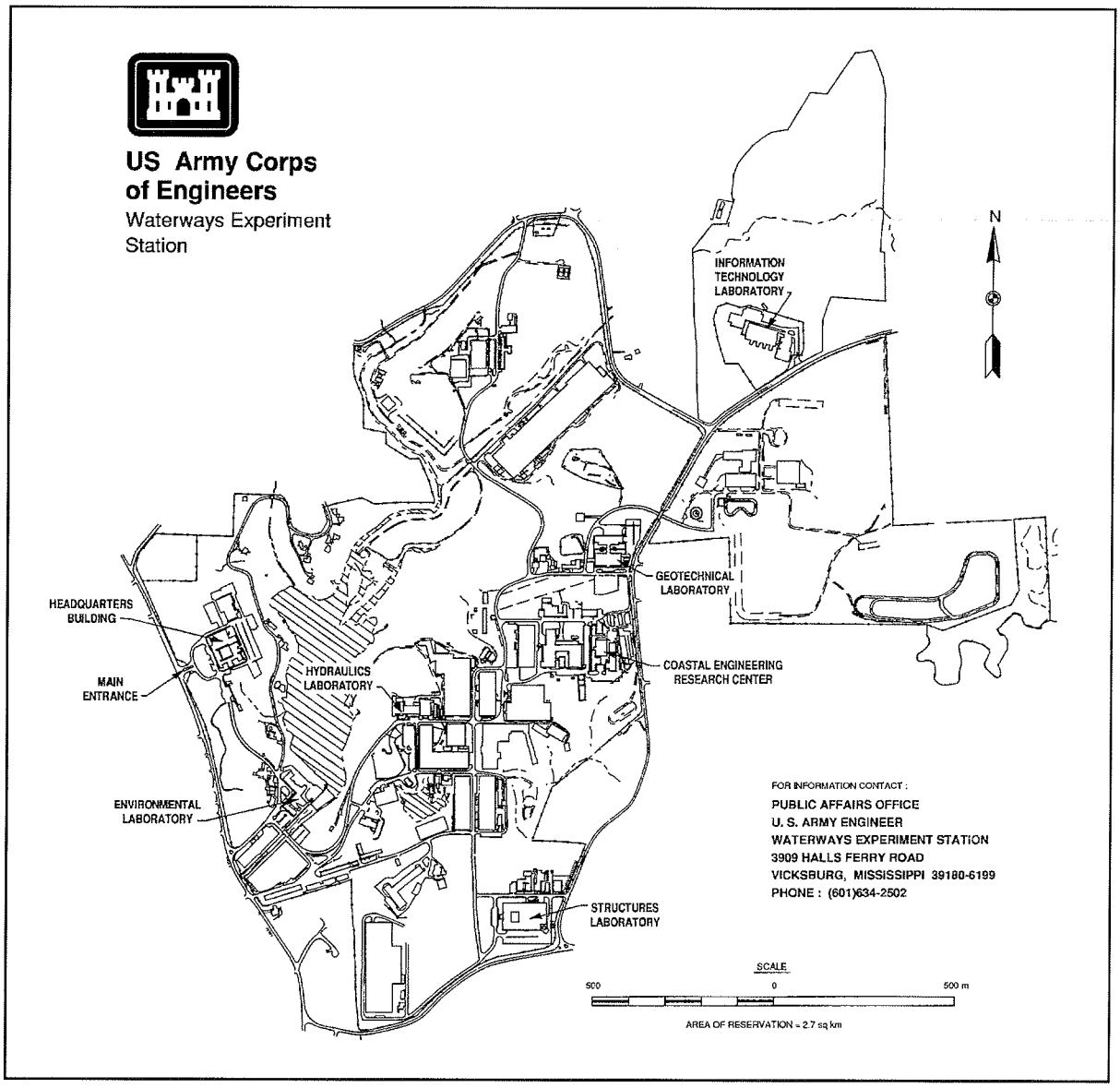
Los Angeles, CA 90053-2325



Waterways Experiment Station Cataloging-in-Publication Data

George, John F.

General design for replacement of or modifications to the lower Santa Ana River drop structures, Orange County, California : hydraulic model investigation / by John F. George, Glenn A. Pickering, Herman O. Turner, Jr. ; prepared for U.S. Army Engineer District, Los Angeles.

306 p. : ill. ; 28 cm. — (Technical report ; HL-94-4)

Includes bibliographic references.

1. Stream channelization — California — Orange County. 2. Hydraulic structures — California — Santa Ana River. 3. Santa Ana River (Calif.) — Channelization. 4. Hydraulic models. I. Pickering, Glenn A. II. Turner, Herman O. III. United States. Army. Corps of Engineers. Los Angeles District. IV. U.S. Army Engineer Waterways Experiment Station. V. Title. VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; HL-94-4.

TA7 W34 no.HL-94-4

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Preface

The model investigations reported herein were authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), on 27 May 1983 (replacement study) and 2 May 1986 (modification study) at the request of the U.S. Army Engineer District, Los Angeles (SPL), through the U.S. Army Engineer Division, South Pacific (SPD). The model tests were accomplished during the period August 1983 to September 1985 (replacement study) and June 1986 to June 1987 (modification study) in the Hydraulics Laboratory of the U.S. Army Engineer Waterways Experiment Station (WES) under the general supervision of Messrs. F. A. Herrmann, Jr., Director of the Hydraulics Laboratory; R. A. Sager, Assistant Director of the Hydraulics Laboratory; and J. L. Grace, Jr., former Chief of the Hydraulic Structures Division, Hydraulics Laboratory; and under the direct supervision of Mr. G. A. Pickering, Chief of the Hydraulic Structures Division; and Mr. J. F. George, Chief of the Locks and Conduits Branch, Hydraulic Structures Division. The tests were conducted by Messrs. H. O. Turner, Jr., and J. E. Myrick, Locks and Conduits Branch. Ms. S. K. Martin, Locks and Conduits Branch, conducted the modification tests on the structure located at sta 836+50. This report was prepared by Messrs. Pickering, Turner, and George.

Messrs. Tom Muncey, HQUSACE; Dick DiBuono, SPD; Joe Evelyn, Eddie Chew, Mike Mulvihill, Rene Vermeeren, Andy Sienkiewich, and Christopher Tu, SPL; and Dick Runge and Jerry Sterling of Orange County Environmental Management Agency visited WES during the course of the model study to observe model operation and correlate results with design studies.

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

Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
acres	4,046.873	square meters
feet	0.3048	meters
cubic feet	0.02831685	cubic meters
cubic feet per second per foot	0.0929029	cubic meters per second per meter
miles (U.S. statute)	1.609347	kilometers
square miles	2.589998	square kilometers
pounds (mass)	0.4535924	kilograms

1 Introduction

The Prototype

The Santa Ana River (Figure 1), which drains an area of approximately 2,500 square miles,[1] is roughly 75 miles long and flows through San Bernardino, Riverside, and Orange counties. It discharges to the Pacific Ocean about 30 miles south of Los Angeles, CA. Prado Dam, the principal flood control structure in the basin, is located 31.2 miles upstream from the ocean. The river below Prado Dam flows through a natural canyon for about 9 miles and then opens onto a coastal floodplain, which is essentially a large alluvial fan. Historically, the river has entrenched itself in different locations across the fan in a pendulum fashion with the apex at the canyon mouth, about 23 miles upstream of the ocean. Recent channelization has fixed the river alignment near the east edge of the fan.

Rugged mountains rising to elevations[2] over 10,000 ft form the headwaters of the Santa Ana River. The river is partly ephemeral in response to the Southern California semiarid climate. Runoff develops rapidly from the steep mountain slopes and the urbanized valley floor. Periodic north Pacific winter storms produce floods lasting from 1 to 3 days. A severe flood threat exists within Orange County downstream of Prado Dam. During the past 45 years the downstream area has become densely populated. A major flood could endanger and disrupt the lives of over 2 million people and cause damages in excess of $11 billion. The existing lower basin channel is inadequate to convey the flood flows from events exceeding the estimated 70-year event safely to the ocean.

Prado Dam was built in 1941 to control what was then calculated to be a 200-year flood event. However, recent hydrologic projections based on more complete data have shown that Prado Dam actually provides protection for only a 70-year flood event. Existing flood control channel improvements have reduced damages from small floods. However, these improvements fail to

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page viii.

[2] All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

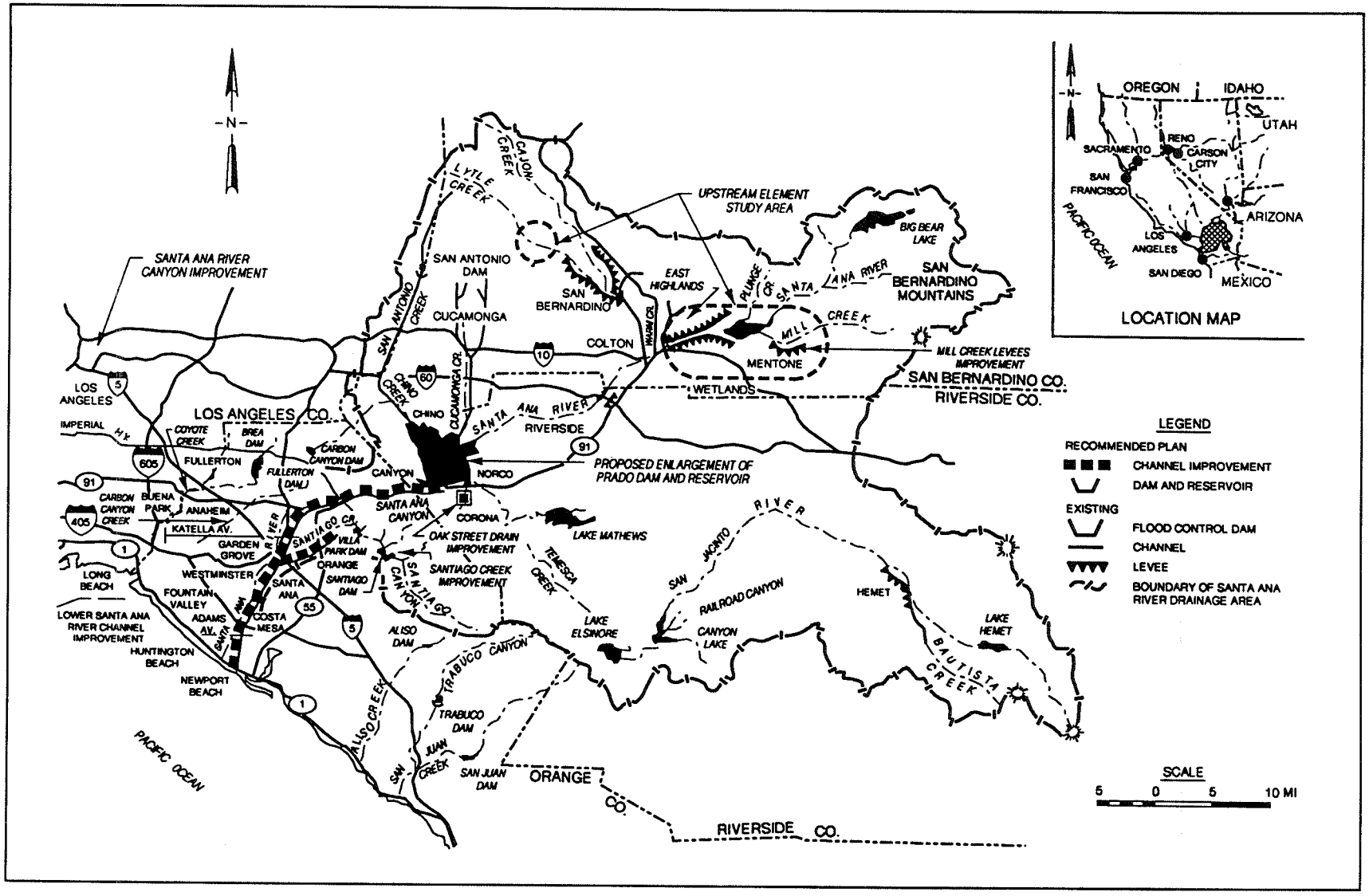

Figure 1. Vicinity map

provide adequate protection for the highly urbanized lower Santa Ana floodplain.

The Santa Ana River plan of improvement was authorized for construction by the Water Resources Development Act of 1986. The recommended plan provides flood protection to major parts of a three-county area, with greatest effect on the heavily urbanized Lower Santa Ana River Basin (Orange County). The recommended plan consists of the following elements on the Santa Ana River main stem: (a) construction of Seven Oaks Dam in the upper Santa Ana Canyon to control a 350-year flood event at the damsite, (b) delineation of the 100-year floodway and floodway fringe for the 35-mile reach between Seven Oaks Dam and Prado Dam, with local authorities managing this area in accordance with guidelines established by the Federal Emergency Management Agency, (c) modifications to the existing Federal flood control levees at Mill Creek to restore their original Standard Project Flood level of protection, (d) construction of a 100-year level of protection channel on the Oak Street Drain in the City of Corona, (e) modifications to the existing Prado Dam to provide a 190-year level of protection, (f) channel improvements to provide a 100-year level of flood protection along Santiago Creek in Orange County, (g) construction of the Lower Santa Ana River channel to provide a 190-year level of flood protection, and (h) enhancement of 84 acres of marshland at the mouth of the Santa Ana River for endangered species plus restoration of 8 acres of marshland for mitigation of wildlife habitat.

Proposed channel improvements downstream from Prado Dam are constrained by existing channel widths, drop structures, bridge deck levels, utilities along the river, existing rights-of-way, and urban development adjacent to the channel. The proposed improvements from Weir Canyon Road to just downstream of Santiago Creek, a distance of 12.8 miles, consist of an earth-bottom trapezoidal channel with riprap and grouted stone side slopes. Portions of this sandy-bottom reach are used for groundwater recharge. Eleven drop structures exist in this reach.

Purpose of Model Investigation

The existing lower basin channel is inadequate to convey the project design flows safely to the ocean. Existing flood control improvements built by local interests have reduced damages from small floods. However, these improvements fail to provide sufficient protection for the highly urbanized lower Santa Ana floodplain. About 2 million people live and work in this floodplain. Additional channel right-of-way is not available because of the urbanization.

According to Santa Ana River studies conducted by the U.S. Army Engineer District, Los Angeles, increased channel capacity can be achieved by additional depth of flow without additional right-of-way. The increased channel flow will require drop structures designed for higher unit discharges. An improved channel design will require the replacement or modification of existing drop structures to implement a new drop structure configuration. Project

design flows for the drop structure reach vary from 37,000 to 42,000 cfs. Adequate guidance is not available to address all aspects of the design. Therefore, physical model studies were deemed necessary to address the various issues.

The design objectives of the model testing program were to ensure that the drop structures would provide good energy dissipation within the basin, minimize downstream scour, and provide for good performance for a range of discharges and tailwaters. In addition to meeting these objectives, a general design method was developed from the model test results.

Scope

The model study discussed in this report was conducted in two parts. The first part, the purpose of which was to investigate the possibility of designing new vertical drop structures and sloping grouted stone drop structures to replace the existing structures, used 1:25-scale section models of drop structures. Initial tests on the preliminary designs showed that an oscillating hydraulic jump would form at discharges expected during a flood event. Various modifications were tested on these preliminary designs without success. The drop structures were then redesigned to incorporate elements based on the sequent depths of the hydraulic jump. Modifications tested included a parabolic drop, one row and two rows of baffle blocks, and a sloping end sill. Sloping drop structures constructed of grouted stone were also tested using a 1:25-scale section model and a 1:40-scale full-width model.

Building new structures would have been very costly. Therefore, the second part of the study investigated the possibility of using the existing drop structures. This part used several 1:25-scale section models of selected drop structures and a 1:25-scale full-width model to determine if the existing structures were adequate, and if not, then what modifications to the structures would be needed. A general design was developed from these tests for the other existing drop structures on the Santa Ana that were not model tested.

Initial tests on the existing drop structures showed that an oscillating hydraulic jump would form at discharges expected during a flood event. A sequent depth analysis using the results from a study by Basco (1969) was performed on each drop structure tested. From these sequent depths, dimensions of the modifications were sized. Modifications tested included a parabolic-shaped drop downstream from the crest, one row and two rows of baffle blocks, and a sloping end sill.

2 The Model

Description

In the first part of the study, involving replacement of the existing drop structures, 1:25-scale section models of vertical and parabolic drop structures were installed in an existing 2.5-ft-wide glass-sided flume. Since the drop structure tests were general in nature, arbitrary stations and reference elevations were selected. The crest of each drop was placed at sta 0+00 and el 100.0. All other dimensions were referenced from this point. A 1:40-scale sloping grouted stone drop structure was installed in the downstream channel of an existing model and 800 ft of approach and 1,200 ft of exit channel from the structure were reproduced.

The second part of the study, involving modifications to the existing drop structures, required the use of both section models and a full-width model. All models were constructed at a scale of 1:25. The 1:25-scale section models were installed in existing 2.0- and 2.5-ft-wide glass-sided flumes. Plastic-coated plywood was used to form the channel invert elevations and drop structures. Scour tests were performed by removing the plywood downstream of the drop structures and installing masonry sand to the appropriate elevations. Parabolic crests used were formed of sheet metal.

The full-width model reproduced 600 ft of approach channel, the 310-ft-wide drop structure located at sta 1022+98.55 (Figure 2), and 750 ft of channel downstream from the structure. The channel was molded in cement mortar to sheet metal templates. Portions of the channel immediately downstream of the drop structure were molded in sand with scaled riprap placed on filter cloth on the side slopes. A scaled mixture of crushed stone, mixed according to prototype gradations, was placed in the appropriate areas to accurately simulate the prototype riprap. In the areas requiring grouted stone, cement dust was sprinkled over the crushed stone, moistened, and allowed to harden.

Model Appurtenances

Water used in the operation of the model was supplied by a circulating system. Discharges for the main channel were measured with venturi meters.

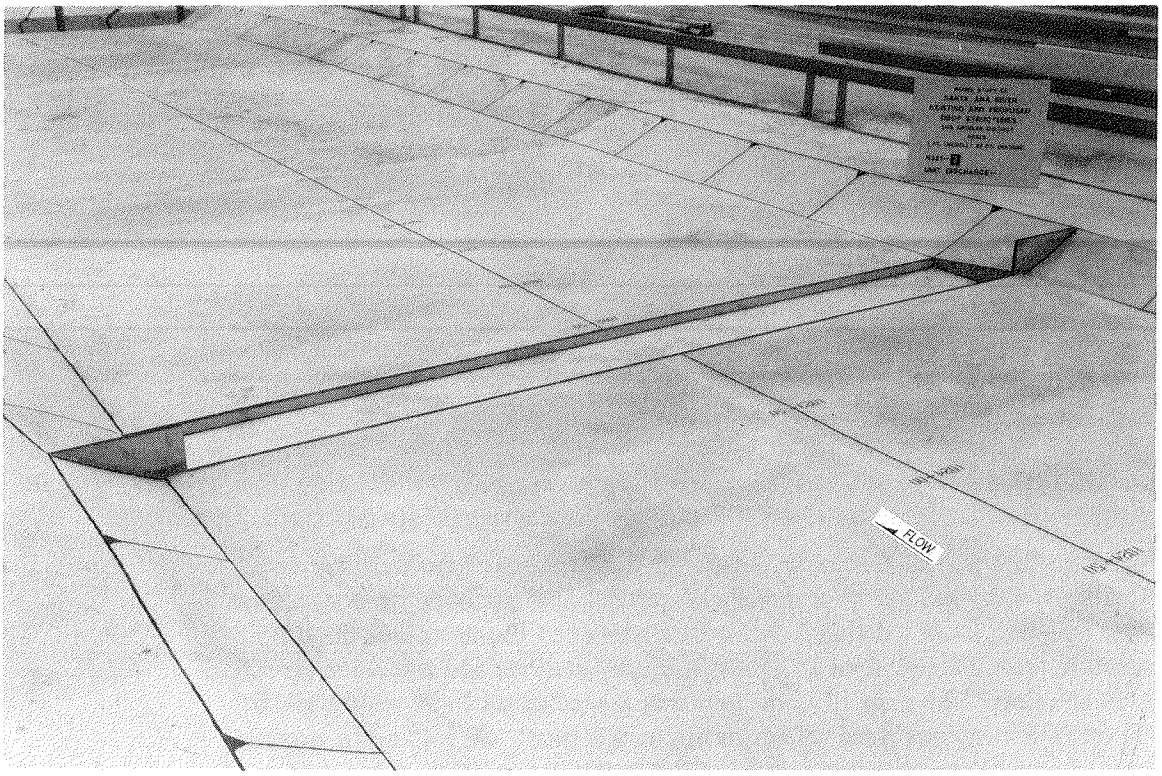

Figure 2. Type 1 design drop structure, sta 1022+98.55

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 either a pitot tube or 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. Various designs along with different flow conditions were photographed and video-taped.

Scale Relations

As is the case with most hydraulic structures, it was determined that the flow phenomena would be governed primarily by gravitational forces; therefore, the Froude model law would have to be satisfied. 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 presented in the following tabulation. Because of the nature of the phenomena involved, certain model data can be accepted quantitatively, while other data are reliable only in a qualitative sense. Measurements in the model of discharges, water-surface elevations, velocities, and resistance to displacement of riprap material can be transferred quantitatively from model to prototype by means of these scale relations. Evidence of scour of the model sand

Characteristic	Dimension[1]	Scale Relations Model:Prototype	
Length	L_r	1:25	1:40
Area	L_r^2	1:625	1:1,600
Velocity	$L_r^{1/2}$	1:5.0	1:6.32
Discharge	$L_r^{5/2}$	1:3,125	1:10,119
Time	$L_r^{1/2}$	1:5.0	1:6.32
Volume	L_r^3	1:15,625	1:64,000
Weight	L_r^3	1:15,625	1:64,000

[1] Dimensions are in terms of length.

bed, however, is to be considered only as qualitatively reliable since the resistance to erosion of fine-grained prototype bed material cannot be reproduced quantitatively in a model yet. Data on scour tendencies provided a basis for determination of the relative effectiveness of the different designs and indicated the areas most subject to attack.

3 Replacement Study Tests and Results

The testing program for the replacement study involved making observations and evaluations of vertical and parabolic drop structures and sloping grouted rock drop structures with unit discharges up to a maximum of 250 cfs and 209.3 cfs, respectively. Tailwater elevations furnished by the Los Angeles District were reproduced with the maximum unit discharge for the various designs tested. Vertical drop structure designs with changes in channel invert elevations of 10, 12, and 8 ft are discussed first followed by a discussion of tests conducted with sloping grouted rock drop structures.

10-ft Drop Structure

Type 1 (original) design

The initial drop structure design (Figure 3) was furnished by the Los Angeles District and was based on criteria developed at Saint Anthony Falls (SAF) Hydraulic Laboratory (Donnelly and Blaisdell 1954) and printed in Hydraulic Design Criteria (HDC) Chart 624 (Figure 4) (U.S. Army Corps of Engineers). This vertical drop (designated type 1) had a stilling basin length of 76 ft with one row of 10-ft-high baffle blocks located 54 ft downstream of the crest of the drop. These dimensions (Plate 1) were obtained from the design guidance shown in Figure 4.

Flow conditions for the type 1 design (Photo 1) were observed at a unit discharge of 250 cfs/ft with three tailwater elevations furnished by the Los Angeles District. The hydraulic jump action observed was unstable, which resulted in the development of standing waves immediately downstream of the structure, as shown in Photo 2. These downstream waves would create the need for greater levee heights and protection. Due to the unstable hydraulic jump and resulting downstream waves, the type 1 design was deemed unacceptable.

Even though the type 1 design was considered unacceptable, additional tests were conducted to serve as a basis of comparison for later designs.

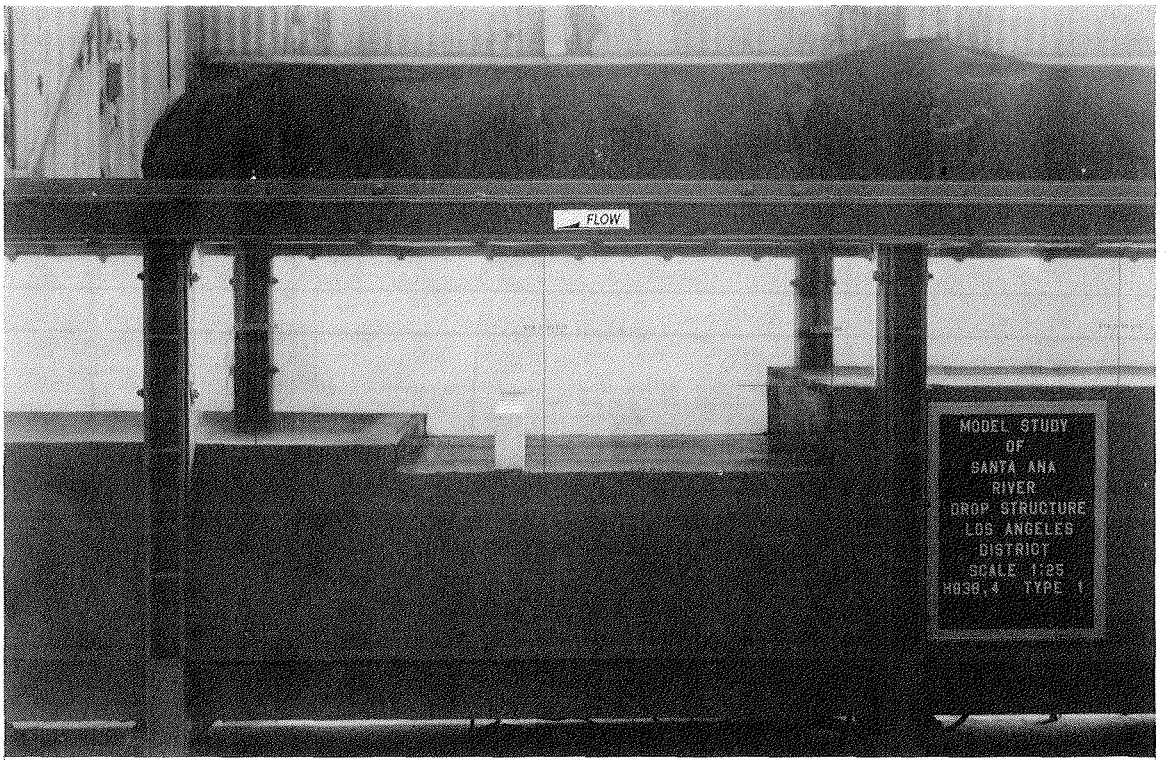

Figure 3. Type 1 design drop structure (10-ft drop)

Water-surface profiles were recorded with the three tailwater elevations furnished and are shown in Plate 2.

Scour tests were also conducted with the type 1 design drop structure. The results of these tests give a qualitative indication of the stilling basin scour potential. The resulting scour elevations are given in prototype units. However, these elevations cannot be considered equivalent to the scour that might occur in the prototype as the model durations and discharges used are not representative of the design event and because the model bed material does not accurately represent the prototype bed material. In the model, the bed material was locally available masonry sand. At the model scale of 1:25, this model sand would be equivalent to small pebbles. An accurate reproduction of the prototype bed material could probably be sized for model use. However, the resulting small size of model material would not reproduce a noncohesive granular prototype material, but would result in a cohesive material in the model. Therefore, a direct relationship of model scour to prototype scour is not possible.

For the scour tests conducted with the type 1 design drop structure, the riprap gradation given in the following tabulation was placed in the riverbed immediately downstream from the stilling basin. These scour tests were conducted by setting the discharge to 250 cfs/ft and maintaining the desired tailwater elevation for 1 hr in the model (5 hr prototype). Plate 3 shows the resulting scour for a riprap slope of 1V on 2H. Plate 4 shows the resulting

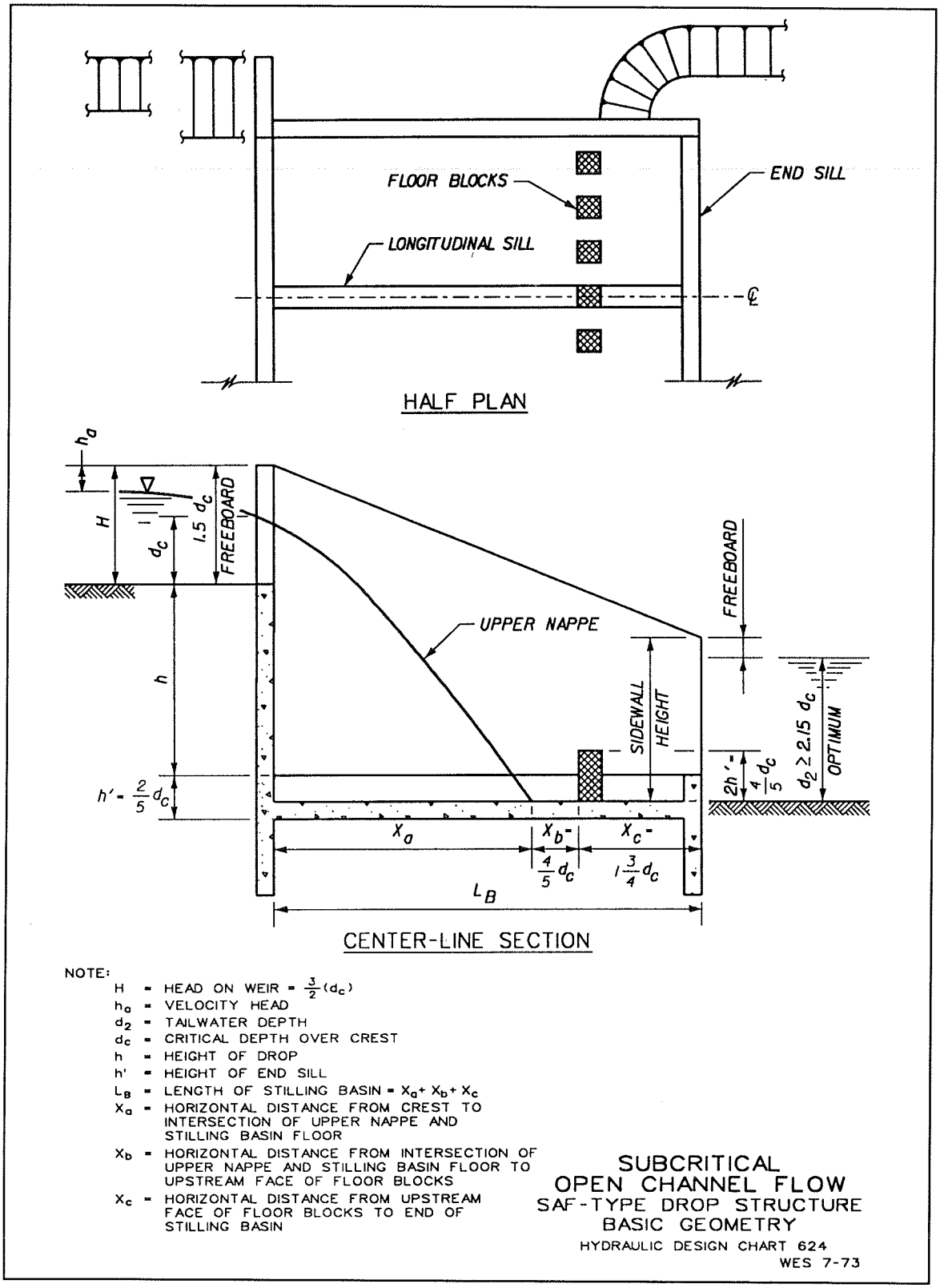

Figure 4. SAF-type drop structure

scour for a riprap slope of 1V on 3H. The riprap remained stable during these tests.

Percent Smaller by Weight	Prototype Riprap Weight, lb	Model Riprap Weight Prototype lb
100	9,000	6,250
65-100	6,500	6,250
50-70	5,000	–
15-50	4,000	–
0-15	3,000	2,637

Type 2 design

In the type 2 design, the baffle blocks were moved upstream 10 ft to sta 0+44. This modification did not improve the drop structure energy dissipation and performance was worse than with the type 1 design. Dimensions and elevations of the type 2 design are shown in Plate 5. Flow conditions at design discharge for the type 2 design are shown in Photo 3. No additional data were recorded with this design.

Type 3 design

A parabolic curve trajectory, based on the equation $X^2 = 40Y$, was installed in the type 1 design drop structure. This was designated the type 3 design drop structure (Photo 4, Plate 5). The maximum design head H was calculated to be 18.7 ft (1.5 times the critical depth of 12.47 ft) for the design unit discharge (250 cfs/ft). The equation $X^2 = 40Y$ was used for the curve of the trajectory because previous model tests of low-head navigation dams (Grace 1964) had shown this curve to produce satisfactory flow conditions with heads in this range. The addition of the curved trajectory greatly improved the energy dissipation in the stilling basin and downstream water-surface conditions. Flow conditions in Photo 4 show a stable hydraulic jump and calm downstream water-surface conditions.

A movable bed was installed downstream of the stilling basin and scour tests were conducted with the type 3 design drop structure. Photo 5a shows the molded downstream bed before the scour tests. The design discharge tested was 250 cfs/ft for 5 hr (prototype). As with the type 1 design, two riprap slopes were tested: 1V on 2H and 1V on 3H. Test results from the scour tests are shown in Photo 5b and Plate 6 for the 1V on 2H slope and Plate 7 for the 1V on 3H slope. No significant difference was observed in scour test results between the type 1 and 3 design drop structures.

Type 4 design

The type 4 basin used the same elements as the type 3 basin except the baffle blocks were moved 10 ft upstream to sta 0+44. Dimensions and elevations of the type 4 design are shown in Plate 8. Observations of flow conditions indicated that the hydraulic performance was essentially the same as was observed with the type 3 design drop structure.

Type 5 design

In the type 5 basin, a parabolic curve trajectory based on the equation $X^2 = 30Y$ was installed to evaluate the hydraulic performance of the drop structure with a shorter trajectory. Details of the type 5 design drop structure are shown in Plate 8. Flow conditions at the design discharge of 250 cfs/ft are shown in Photo 6 for the minimum, normal, and maximum tailwater conditions. The downstream water-surface conditions for the normal tailwater elevation are shown in Photo 7. The shorter curve did not increase downstream water-surface roughness with normal tailwater conditions; however, water-surface conditions were considerably rougher with minimum tailwater conditions as compared to the type 3 design drop structure (compare Photos 4 and 6). Maximum water-surface elevations with normal tailwater conditions are plotted in Plate 9. Scour tests using a 1V on 2H riprap slope were conducted with the type 5 design with results provided in Plate 10. The resulting scour with the type 5 design drop structure showed no improvement over previous designs tested.

Type 6 design

The type 6 basin was formed by moving the baffle blocks 10 ft upstream to sta 0+44 and retaining the short trajectory that was tested in the type 5 design. Test results indicated the hydraulic performance of the drop structure was unsatisfactory with minimum tailwater conditions.

Type 7 design

In an attempt to develop a more effective drop structure design, guidance was used from a previous study by Basco (1969). The type 7 basin was designed according to this design guidance shown in Plate 11. All dimensions are based on the hydraulic jump parameters d_1 and d_2 (the depth immediately before and after a hydraulic jump). These parameters were measured and calculated at the design discharge of 250 cfs/ft and found to be 6.4 ft and 21.45 ft, respectively. A Froude number (Froude number in this report always refers to flow entering the stilling basin) of 2.72 was calculated for a height of 15 ft from crest to stilling basin floor. Basco's guidance specifies using a parabolic drop; however, in the type 7 design, no parabolic curve was used. Dimensions of the stilling basin length were increased by the nappe length,

which was determined to be approximately 30 ft at the design discharge. Plate 12 shows the dimensions of the type 7 basin designed according to this guidance. The basin length was set at the minimum dimension of $2.5d_2$ downstream from the point where the nappe intersects the basin floor. The first row of baffle blocks was placed $1.5d_2$ downstream from the nappe. The second row of baffles was placed $0.5d_2$ downstream from the first row. A sloping end sill 5 ft high was used. The baffle blocks were 6 ft in height.

Flow conditions observed with the type 7 drop structure with design conditions (Photo 8) were worse than with drop structure designs with parabolic curve trajectories installed. A water-surface profile recorded with design discharge and the normal tailwater elevation of 106.5 is shown in Plate 12.

Type 8 and 9 designs

In the type 8 and 9 designs, baffle blocks were moved further upstream than in type 7 tests in an effort to further improve the performance of the drop structure. Flow conditions observed indicated the hydraulic performance of the drop structure decreased; therefore, additional tests were not conducted.

Type 10 design

A parabolic curve based on the equation $X^2 = 30Y$ was installed in the type 9 basin to form the type 10 design (Photo 9, Plate 13). The $X^2 = 30Y$ curve was selected over the $X^2 = 40Y$ curve based upon economics and earlier tests involving the type 3 and 5 design drop structures, which showed little change in performance at design conditions.

The installation of the trajectory curve significantly improved flow conditions in the stilling basin as shown in Photo 9. Water-surface elevations with design conditions are shown in Plate 14.

Type 11 and 12 designs

In the type 11 and 12 designs (Plate 13), the baffle blocks were moved downstream 28.8 ft and 40.9 ft, respectively, from the toe of the trajectory ($X^2 = 30Y$) to evaluate the effects on the performance of the stilling basin. It was determined from flow conditions observed and water-surface profiles recorded (Plate 14) that there was not much difference in stilling basin performance between the type 10, 11, and 12 design drop structures.

Type 13, 14, and 15 designs

Baffle blocks 4 ft high (approximately equal to $d_2/6$) were installed to determine the stilling basin performance using smaller baffle blocks without the curved trajectory. Dimensions and elevations for type 13, 14, and 15

designs are shown in Plate 15. Flow conditions at the design conditions are shown in Photo 10. Water-surface profiles for these designs were recorded and are shown in Plate 16.

Test results indicated that even though the baffle blocks were designed according to $d_2/6$, which has application in higher Froude number structures, no improvement in hydraulic performance was observed when compared to basin designs with the larger baffle blocks, such as the type 10 design.

Type 16, 17, and 18 designs

The $X^2 = 30Y$ curve trajectory was added to the type 13, 14, and 15 design stilling basins (Plate 17) to evaluate the effect of the smaller $d_2/6$ blocks with a parabolic drop.

Flow conditions observed in these designs showed no significant improvement compared to the type 10 design drop structure. Design flow conditions are shown in Photo 11. Water-surface elevations with design flow conditions are shown in Plate 18.

Type 19-27 designs

The length of the stilling basin was extended to 105 ft. This dimension was the combined distances of $3.5d_2$ and approximately 30 ft created by the nappe. These stilling basin designs were tested with baffle blocks whose heights approximately equaled d_1 and $d_2/6$ and were moved to various locations in the stilling basin. The baffle block locations were tested with and without the $X^2 = 30Y$ curve trajectory. Flow conditions observed with the various modifications installed indicated little improvement in the hydraulic performance of the drop structures compared to previous designs tested.

Type 28 design

The stilling basin floor was lowered from el 85 to el 80 (Photo 12, Plate 19) in an effort to improve the performance of the drop structure. The channel invert drop of 10 ft (el 100 to el 90) was not changed. Lowering the basin floor an additional 5 ft created a d_1 of 5.92 ft, d_2 of 22.65 ft, and a Froude number F of 3.06. The downstream water-surface profile did not improve with this modification. At design flow conditions, the 10-ft-high end sill acted to constrict the flow and caused standing waves to form in the downstream area (Photo 12). Water-surface elevations were not recorded due to the unsatisfactory downstream conditions observed.

Type 29 and 30 designs

In the type 29 and 30 designs, a 3-ft-high end sill, approximately $0.5d_1$, was installed according to the design criteria shown in Plate 11. A 1V on 10H adverse slope provided the transition from the top of the end sill (el 83) to the downstream bed elevation (el 90). Plate 19 provides the dimensions and elevations for type 29 (curved trajectory) and type 30 (no curve) designs.

In the type 29 design, satisfactory water-surface conditions were observed due to the smaller end sill. However, flow conditions observed in the type 30 design showed that removal of the parabolic curve causes the water-surface roughness to increase in and downstream of the drop structure.

Type 44 design

Additional modifications were made to the drop structure that involved adjusting the length to 90 ft and 119.5 ft, varying the apron elevation from 80 to 85 ft, and looking at different locations of baffle blocks with and without a parabolic curved trajectory ($X^2 = 30Y$). Test results indicated that the type 44 design drop structure (Figure 5) provided the best hydraulic performance over all other designs previously tested, and is therefore recommended for the prototype. The type 44 design had a d_1 of 5.92 ft, d_2 of 22.65 ft, and a Froude number of 3.06. With an adverse slope of 1V on 7H transitioning from the end sill elevation to the downstream channel invert, smooth water-surface conditions were present downstream of the structure. Water-surface profiles and flow conditions with this design are shown in Plate 20 and Photo 13, respectively. The riprap protection proposed was determined to provide adequate protection. Table 1 contains the pertinent data for each of the designs tested.

12-ft Drop Structure (Type 50 Design)

Tests were conducted to determine if the drop structure designed for a 10-ft drop in channel elevation (type 41 design, Table 1) would perform satisfactorily with the exit channel lowered 2 ft, which would represent a 12-ft drop. This was designated the type 50 design drop structure (Figure 6, Photo 14a). Since the exit channel was 2 ft lower relative to the basin floor elevation, tailwater elevations were 2 ft lower. As shown in Photo 14b, the performance of this structure was satisfactory and very similar to the type 41 design (10-ft drop). Water-surface elevations with the type 50 design structure are shown in Plate 21. Table 2 contains the pertinent data for the design tested.

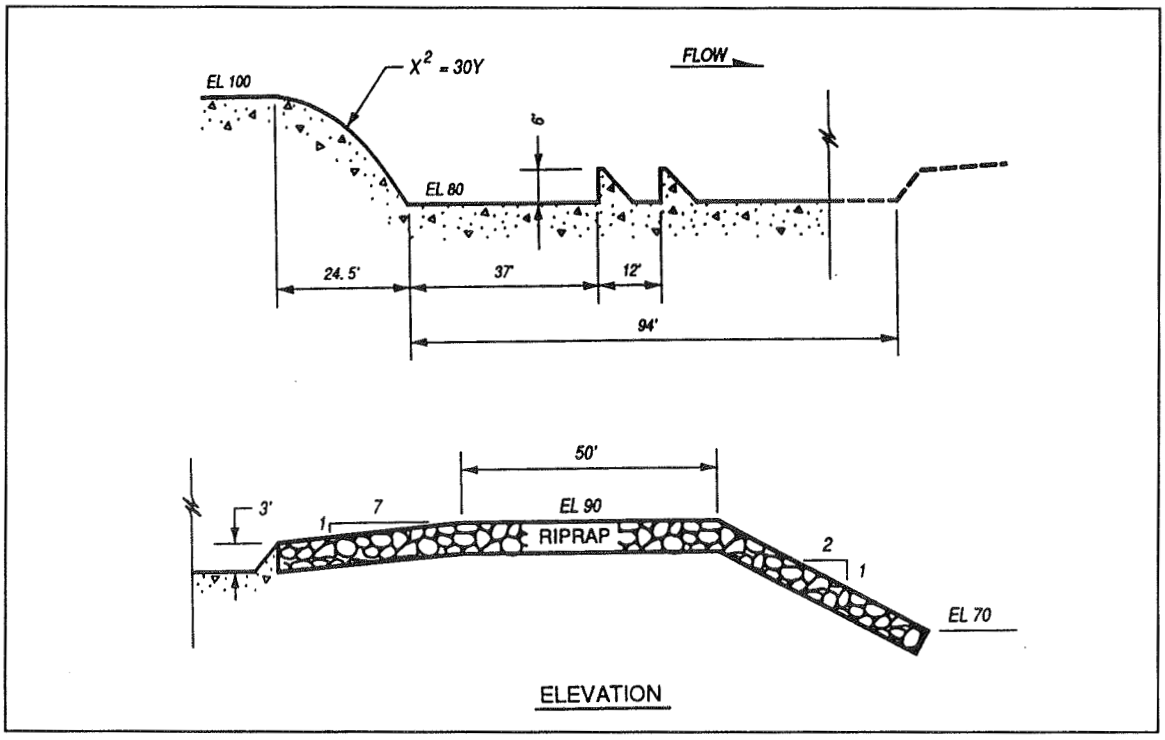

Figure 5. Type 44 design, recommended design 10-ft drop structure

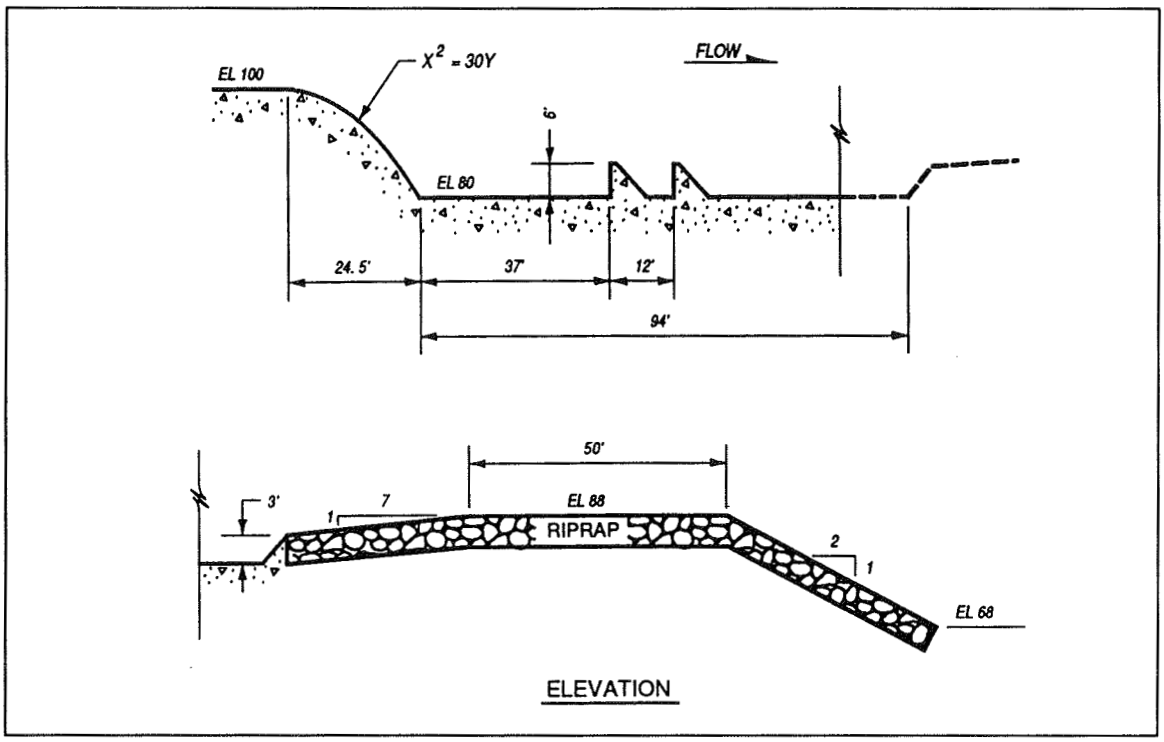

Figure 6. Type 50 design, recommended design 12-ft drop structure

8-ft Drop Structure

Type 75 design

The type 41 design drop structure (Table 1) was used with the exit channel elevation raised to el 92 to represent a drop of 8 ft (type 75 design structure). This resulted in tailwater elevations that were 2 ft higher than those observed with the 10-ft drop. Details of the type 75 design are shown in Plate 22. The hydraulic jump in the basin was near submerged conditions with normal tailwater as shown in Photo 15. Energy dissipation was not as good as was observed with the 10-ft drop. A water-surface profile with the design discharge and normal tailwater is shown in Plate 22.

Type 81 design

The stilling basin length was gradually shortened until a basin length of 59 ft or $2.60d_2$ was tested. This was designated the type 81 design drop structure (Plate 23). This represents the shortest basin length tested in this series of tests on the 8-ft drop structures.

Due to the high tailwater depth and associated submergence, changes in basin length had little effect on the 8-ft drop structure's performance. Results obtained with a basin length of $2.6d_2$ were as good as any of the longer basins tested. Due to the high degree of submergence experienced by the 8-ft drop structure, energy dissipation was not as effective as was observed with the 10- and 12-ft drop structures. Therefore, an 8-ft drop structure was not recommended for these design conditions. Design flow conditions are shown in Photo 16. Maximum water-surface elevations were recorded with design flow conditions and are shown in Plate 23.

The riprap blanket was extended 175 and 200 ft downstream of the crest. These modifications had no effect on the flow conditions due to the already submerged drop structure. The riprap blanket remained intact and stable under all tests.

Type 82 design

At the sponsor's request, the stilling basin floor was raised 2 ft to create an 18-ft drop from the crest to the basin floor. The downstream riprap was extended downstream past the stilling basin to sta 2+00. Dimensions and elevations of the type 82 design are shown in Plate 24. Design flow conditions are shown in Photo 17. Maximum water-surface elevations were recorded at the design flow conditions and are shown in Plate 24.

Flow conditions were not improved by raising the basin floor 2 ft. This modification had little or no effect on the flow conditions and energy dissipation due to the near-submerged flow conditions in the stilling basin. Due to these flow conditions, an 8-ft drop structure with the associated high tailwater

elevation is not recommended. Table 3 contains the pertinent data for each of the designs tested.

Grouted Stone Drop Structures

Several grouted stone drop structure designs were evaluated with a total change in elevation of 10 ft. These designs were investigated to determine if grouted stones could be used as an alternative construction material for drop structures. These drop structures were constructed of loose stones and grouted together with concrete. As requested by the sponsor, a revised maximum unit discharge of 209.3 cfs/ft was used for these grouted stone drop structures.

Type 100 design

The type 100 design (Photo 18a) was the initial design tested. A 1V on 10H was selected for the crest slope and the basin floor was 15 ft lower than the top of the crest. Dimensions and elevations of the type 100 design are shown in Plate 25. This design proved to be unacceptable because a hydraulic jump would not form on the 1V on 10H slope at any tailwater elevation. Flow conditions are shown in Photos 18b-f. Maximum water-surface elevations were recorded at the design flow conditions and are shown in Plate 25.

Type 101 design

The slope of the drop structure was changed to 1V on 5H (type 101 design) in an effort to allow the hydraulic jump to form in the basin. Dimensions and elevations of the type 101 design are shown in Plate 26. This design proved to be unacceptable because a hydraulic jump would not form on the 1V on 5H slope at any tailwater elevation. Design flow conditions are shown in Photo 19. Maximum water-surface elevations were not recorded at the design flow conditions due to the poor hydraulic conditions observed in this drop structure.

Type 102 design

In the type 102 design (Plate 26), the slope was changed to 1V on 3H. This modification proved partially successful in that a hydraulic jump would form only at or near the maximum discharge condition of 209.3 cfs/ft and tailwater elevation of 106.5 ft. At conditions less than maximum, a hydraulic jump would not form. Test results indicated that a steeper slope or a deeper basin was needed. Design flow conditions are shown in Photo 20.

Type 103 design

The basin floor was lowered an additional 5 ft to el 80.0 (Plate 26) in an attempt to improve the hydraulic performance of the drop structure. This modification proved to be unsuccessful because a hydraulic jump would not form at any discharge. Design flow conditions are shown in Photo 21.

Type 104 design

The crest slope was changed to 1V on 2H and the basin floor raised to el 85.0 (Photo 22a) in another attempt to improve the hydraulic performance of the drop structure. The change in crest slope proved to be successful because a satisfactory hydraulic jump formed at all discharges observed. Dimensions and elevations of the type 104 design are shown in Plate 27. Flow conditions are shown in Photo 22b-f. Maximum water-surface elevations were recorded at the design flow conditions and are shown in Plate 27.

Based upon the results of these tests, the grouted stone drop structure slope should be 1V on 2H to form a hydraulic jump for all discharges.

Type 105 design drop structure: full-width tests

The type 105 design (Figure 7) was tested as a full-width model at a scale of 1:40 to evaluate the grouted stone drop structure in a three-dimensional environment. Section models provide only a two-dimensional analysis and do not always reveal adverse circulation patterns normally associated with flow transitions. A crest slope of 1V on 2H was used; however, the basin length was reduced to 80 ft or $3.73d_2$, as the previous section model tests indicated that a shorter basin would still be effective.

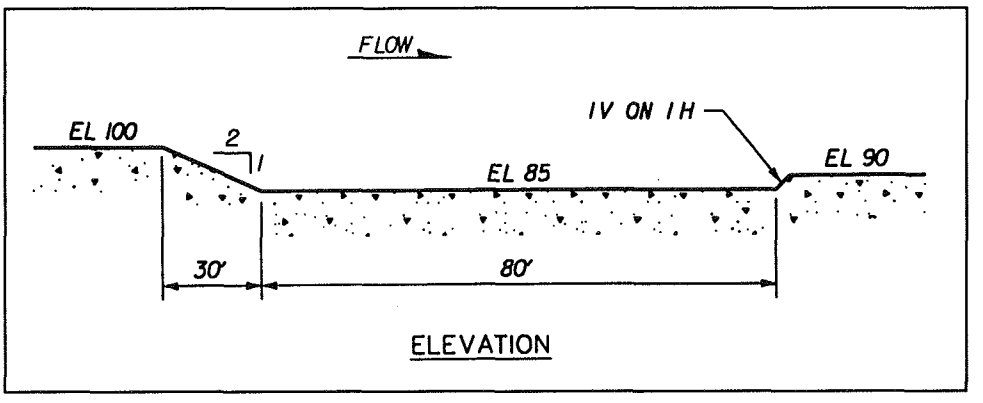

Figure 7. Type 105 design, recommended design grouted stone drop structure

This design proved to be acceptable because a satisfactory hydraulic jump formed in the drop structure for all flow conditions observed; therefore, this design is recommended for the prototype. Flow conditions are shown in Photo 23. Dye patterns in the full-width model indicated no circulation problems at either side of the grouted stone drop structure. The shorter basin length ($3.73d_2$) did not produce any adverse flow or scour conditions. Basin lengths of less than $3.73d_2$ were not tested as longer riprap protection would be required. Table 4 contains the pertinent data for each of the designs tested.

4 Modification of Existing Structures Tests and Results

In redesigning the drop structure reach of the lower Santa Ana River for higher discharges, an attempt was made to maintain the existing drop structure crest and end sill elevations. By adding three additional drop structures, it will be feasible to maintain these elevations. However, there was uncertainty that the existing drop structures would effectively dissipate the energy associated with higher flow rates. In order to resolve this question, a model testing program of modification of existing structures was undertaken at the U.S. Army Engineer Waterways Experiment Station (WES).

The design objectives of the modification testing program were to maximize the utilization of the existing drop structure configuration and to minimize the cost of modifications while ensuring that the drop structures would provide good energy dissipation within the basin, minimize downstream scour, and provide for good performance for a range of discharges and tailwaters.

It was necessary that the drop structures adequately dissipate energy not only for the channel design discharge but also for the freeboard design discharge. The freeboard design discharge is used to ensure that the levees downstream from the drop structures are designed to stay intact for floods greater than the design flood. The flow exceeding the channel design discharge overtops the levees at designated "least hazardous" overbank areas. Thus, by providing for overtopping in designing the drop structures and levees, catastrophic failure in highly urbanized areas will be prevented. In the course of conducting the model studies, when the existing drop structures did not perform satisfactorily, then modifications to ensure satisfactory performance were made.

The existing structures consist of two types. The first is the California Institute of Technology (CIT) type (Figure 8) with no baffles in the basin (HDC Chart 623). The second is the SAF type (Figure 4) with one row of baffle blocks in the basin. Information for the design of the SAF and CIT drop structures is given in *Hydraulic Design Criteria* (U.S. Army Corps of Engineers).

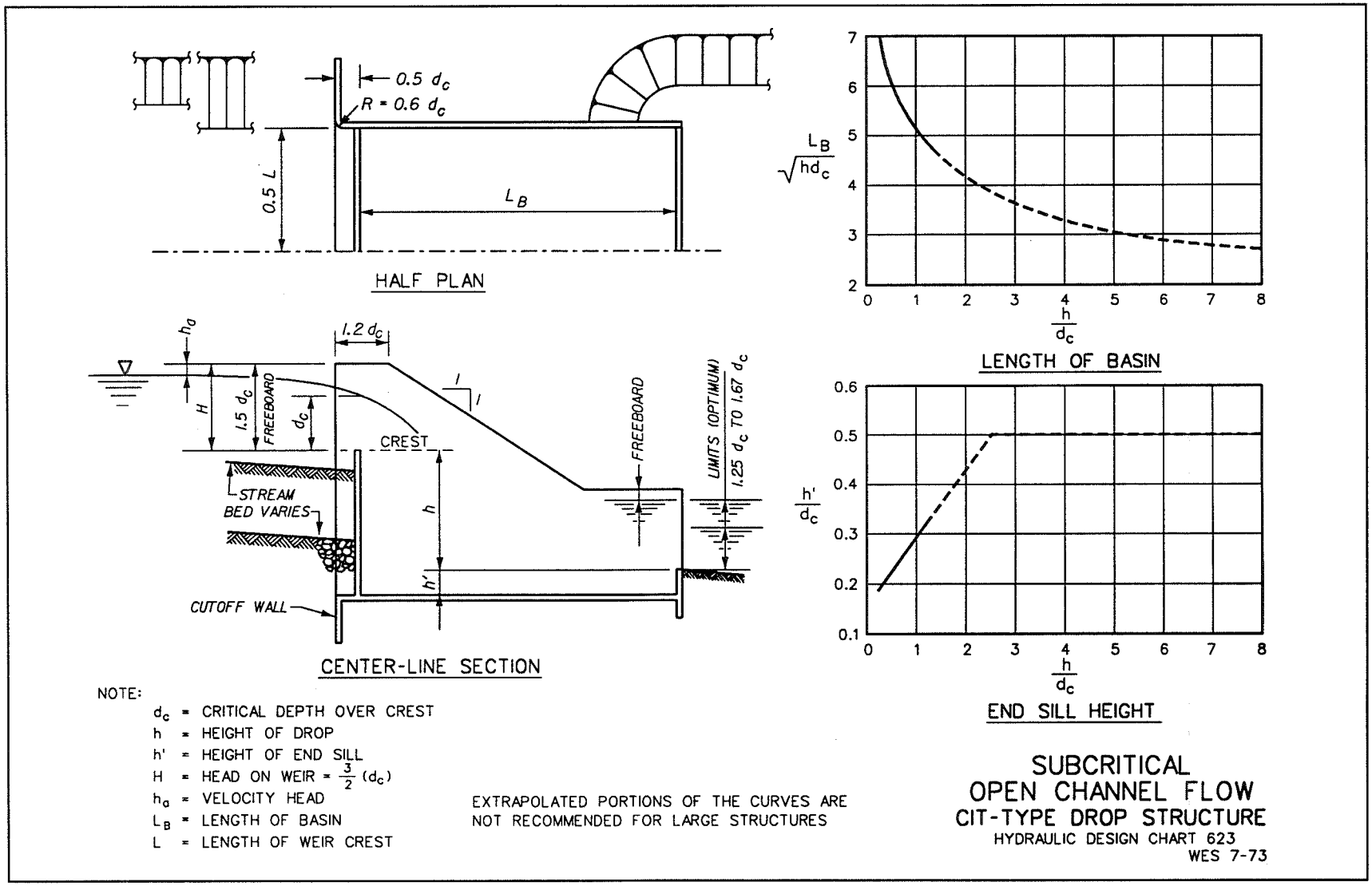

Figure 8. CIT-type drop structure

In this portion of the testing program, 5 of the 11 existing lower Santa Ana River drop structures were model tested. All five were tested as 1:25-scale section models, and the structure located at sta 1022+98.55 was additionally tested as a 1:25-scale full-width model. The range of drop heights was sufficient to formulate a general design that would apply to the untested drop structures. The maximum drop height (the distance from the drop structure crest to the stilling basin floor) tested was 14.0 ft, and the minimum was 6.79 ft, both at sta 1198+08. At the request of the Los Angeles District, tailwater operating conditions associated with channel Manning's n of 0.02 and 0.03 were used.

Restrictions were placed by the Los Angeles District on what modifications could be made to the existing structures. The elevations of the existing stilling basin floors and crests of the drops could not be changed. The only possible modifications would be the addition of a parabolic-shaped drop downstream from the crest, baffle blocks, a sloping end sill, and additional basin length. These modifications usually required installation of the first row of baffle blocks on the existing slab and additional basin length for the second baffle row and end sill. A 1V on 5H adverse slope provided the transition from the top of the end sill to the channel invert.

Various methods were used to determine the adequacy of the designs. These included visual observations, photographs and video of flow conditions in the stilling basin, waves on the water surface downstream from the basin, scour downstream from the structure, and velocity measurements. Scour measurements and velocities were obtained only for selected designs since such a large number of modifications were tested for some of the structures. In many of the designs, velocities were very similar so other parameters were used to judge whether one design was superior to another.

Sta 1022+98.55 Drop Structure

Type 1 (existing) design

The type 1 design drop structure (Photo 24a), which has a vertical drop of 9 ft to the stilling basin floor, was initially tested in a 2.5-ft-wide flume as a section model. The model reproduced a 62.5-ft-wide section of the drop structure (Plate 28) with 300 ft of upstream and downstream channel. Discharges reproducing prototype unit discharges ranging from a minimum of 50 cfs/ft to a maximum of 165 cfs/ft were observed. The design unit discharge was 125 cfs/ft. Operating conditions showing unit discharge and corresponding tailwater operating conditions associated with Manning's n values of 0.02 and 0.03 in the channel are provided in the following tabulation:

Unit Discharge cfs/ft	Tailwater El	
	n = 0.02	n = 0.03
50	263.9	265.3
100	266.5	268.5
125 (design)	267.5	269.9
150	268.5	271.2
165 (maximum)	269.1	271.9

Flow conditions with the type 1 design drop structure and tailwater elevations resulting from a Manning's n of 0.03 are shown in Photos 24b-f. For all discharges, rough downstream water-surface conditions were created (Photos 24c and 24d). An unsteady hydraulic jump was observed at discharges greater than the design discharge, as shown in Photos 24e and 24f. Oscillation was due to the Froude number associated with the d_1 (supercritical depth) on the basin floor being in the transitory range of less than 4.5. The unsteady nature of the hydraulic jump indicated a greater potential for scour due to poor energy dissipation.

Velocity cross sections were recorded at the end sill and 50 ft downstream of the stilling basin and are shown in Plate 29. The velocity magnitude near the channel bed indicated the potential for scour to occur. Due to the oscillation of the hydraulic jump, these velocity magnitudes presented are average values.

Scour tests were performed using only sand (Photo 25a) and with a riprap plan installed (Photo 25b). The riprap gradation used is listed in the tabulation in the section "10-ft Drop Structure." The resulting scour elevations, plotted in Plate 30, served as a basis of comparison for different designs tested. Scour tests were conducted with the design unit discharge and n = 0.02 tailwater elevation for a period of 1 hr in the model (5 hr prototype).

Type 2 design

The type 2 design (Photo 26a, Plate 31) was based on the sequent depths (d_1 and d_2) of a free hydraulic jump with the design discharge. These depths were determined to be 4.13 ft (d_1) and 12.16 ft (d_2). The drop structure incorporated a parabolic-shaped drop downstream from the crest, a basin length of $2.5d_2$, two rows of baffles, and a sloping end sill. The shape of the parabolic curve was based on the trajectory of a free jet with the head resulting from the design discharge. The first row of baffles was placed $1.5d_2$ downstream from the toe of the trajectory and the second row $0.5d_2$ downstream from the first row of baffles.

Different flow conditions observed indicated that the hydraulic jump was stable and no longer oscillated as it did with the type 1 design. The water surface was somewhat rough downstream with the stilling basin providing some energy dissipation, but the overall performance of this design was significantly better than that observed with the type 1 design drop structure. Observations of the flow conditions indicated that the second row of baffles was too close to the first row and did not provide maximum energy dissipation. Tailwater elevations corresponding to n values of 0.02 and 0.03 were tested. Flow conditions with the design discharge are shown in Photo 26b and c. Velocity cross sections recorded at the end sill and 50 ft downstream of the stilling basin are shown in Plate 32.

Type 3 design

The parabolic drop downstream from the crest used in the type 2 design was removed to form the type 3 design drop structure (Photo 27a, Plate 31). This was done to determine if the parabolic drop was needed to obtain satisfactory results in the performance of the drop structure.

Test results showed that removing the curved drop was detrimental to the energy dissipation and downstream water surface of the drop structure. Oscillation of the hydraulic jump occurred at the higher discharges as was observed in the type 1 design. Therefore, it was determined that a curved drop was required to avoid an oscillating hydraulic jump. Flow conditions corresponding to Manning's n of 0.02 and 0.03 tailwater elevations are shown in Photos 27b and c, respectively.

Type 4 design

The Los Angeles District indicated to WES that installing baffle blocks on the existing slab would be difficult and create added expense. Therefore, the drop structure was modified by placing a single row of baffle blocks approximately where the existing end sill was located. This was designated the type 4 design drop structure (Photo 28, Plate 33).

A stable hydraulic jump was observed in the stilling basin due to the parabolic drop, which resulted in smooth downstream water surfaces. However, velocity cross sections recorded at the end sill and 50 ft downstream from the end sill (Plate 34) indicated that the type 4 design had a greater potential for scour to occur immediately downstream of the structure than the type 2 design drop structure.

Type 5 design

An additional row of baffle blocks and corresponding basin length were added to the type 4 design to create the type 5 design drop structure

(Photo 29a, Plate 33). This second row of blocks was placed $0.75d_2$ (9.12 ft) downstream from the upstream face of the first row of blocks. The end sill was placed $0.75d_2$ downstream from the upstream face of the second row of blocks.

Satisfactory flow conditions existed for the full range of discharges observed. Flow conditions with the design unit discharge of 125 cfs/ft are shown in Photos 29b and c. A reduction in average velocities along the channel invert just downstream of the structure was also indicated, as shown in Plate 35.

Type 6 design

Additional tests were conducted to determine if the existing end sill could be incorporated in the drop structure modifications. Both rows of baffle blocks were removed from the type 5 design and the existing end sill reinstalled in its original location. This was designated the type 6 design drop structure. Details are shown in Photo 30a and Plate 36.

Flow conditions indicated that using the existing end sill as a solid barrier caused the flow to ride over the barrier resulting in little dissipation and a rough water surface downstream. Therefore, using the existing end sill in place of baffle blocks is not recommended. Flow conditions that resulted from tailwater elevations set according to Manning's values of 0.02 and 0.03 are shown in Photos 30b and c, respectively.

Type 7 design

The type 7 design (Photo 31) had the same features of the type 6 design except that the solid end sill was slotted to form individual baffle blocks. Dimensions and elevations of the type 7 design are shown in Plate 36.

The spaces created by slotting the solid end sill resulted in better energy dissipation and flow conditions than with the type 6 design. However, velocity cross sections (Plate 37) recorded downstream of the stilling basin indicated that the type 7 design drop structure was not as effective in reducing velocities as other designs previously tested.

Type 8 design

Since attempts to incorporate the existing end sill or portions of the end sill into the drop structure modifications showed little improvement and even reduced the effectiveness of the drop structure, efforts were redirected toward extending the length of the drop structure and using baffle blocks with a height of d_1.

The existing drop structure was modified to incorporate a parabolic drop, a basin length of $2.5d_2$ and one row of baffles placed $1.5d_2$ from the toe of the trajectory (Photo 32a, Plate 38). This was designated the type 8 design drop structure.

Flow conditions observed indicated that a satisfactory hydraulic jump occurred in the basin for the full range of discharges observed, including the design unit discharge shown in Photos 32b and c. Scour tests also indicated a significant improvement with this design compared to that observed with the type 1 design drop structure (Photo 33). Velocities measured downstream of the structure are also provided in Plate 39.

Type 9 design

To evaluate the effectiveness of a longer basin and a second row of baffles, the basin length was extended to $3d_2$ and a second row of baffle blocks placed 8.3 ft downstream from the first row of baffle blocks. This was designated the type 9 design drop structure and is shown in Photo 34a and Plate 40. An earlier design (type 2 design drop structure) also used two rows of baffle blocks, but they were placed $0.5d_2$ apart.

Test results indicated the type 9 design drop structure performed satisfactorily for all discharges observed. Scour tests also showed an improvement when compared to previous results of other designs tested (Plate 30). Flow conditions and velocities recorded with this design are provided in Photo 34b and c and Plate 41, respectively.

Type 10 design

Since noted improvement was observed in the hydraulic performance of the drop structure design that incorporated a longer basin floor, the basin length was extended to $3.5d_2$ (type 10 design drop structure, Photo 35). The first row of baffles was placed $1.5d_2$ from the toe of the trajectory, which was the same location tested in the type 9 design. However, the second row of baffles was moved downstream from 8.3 ft (type 9 design) to 9.12 ft ($0.75d_2$) from the upstream face of the first row of baffles. Details of this design are shown in Plate 42.

Flow conditions were satisfactory for the full range of discharges observed. Scour tests indicated only a slight improvement over test results observed with the type 9 design drop structure, as shown in Plate 30. Flow conditions corresponding to tailwater elevations for Manning's n of 0.02 and 0.03 are shown in Photos 36 and 37, respectively. Velocities recorded downstream of the type 10 design drop structure are shown in Plate 43.

Full-Width Model Tests, Sta 1022+98.55

To evaluate the effectiveness of the section model results, a full-width model of the drop structure located at sta 1022+98.55 was constructed (Figure 2). Designs tested in the full-width model were the type 1 (existing) and type 8 through 10 designs developed in the section model.

Type 1 design

In the type 1 design drop structure (Photo 38), the crest elevation sloped downward from the left bank to the right bank (looking downstream) a total vertical distance of 1 ft over the width of the structure. This was incorporated into the existing design to direct the low flows to one side of the stilling basin. Test results indicated that the uneven crest elevation had little effect on the hydraulic performance of the drop structure. It was noted that an uneven distribution of flow did occur with the higher discharges (Photos 38c-e). This was due to the overall design of the drop structure and not the slope in the crest. Oscillation also occurred in the stilling basin for the same discharges observed in the section model. The performance of the drop structure was unsatisfactory due to poor energy dissipation in the stilling basin and wave action in the downstream channel. A general view of flow conditions at the drop structure is shown in Photo 39.

Scour tests were conducted using a simulated stepped hydrograph with the expected peak flow conditions at sta 1022+98.55 (Plate 44). Failure of the riprap occurred at several locations, as shown in Photo 40. Details of the type 1 design riprap protection plan and gradation are shown in Plate 45 and discussed in the section "10-ft Drop Structure," respectively.

Type 8 design

With the type 8 design drop structure (Photo 41a) installed in the full-width model, a stable hydraulic jump was observed for low to intermediate discharges. With the higher range of discharges, the hydraulic jump was very rough in the stilling basin with significant wave action occurring downstream (Photo 41b and c). Scour tests conducted using the simulated hydrograph also resulted in failure in the type 1 design riprap in several areas (Photo 42).

Type 9 design

Due to the unsatisfactory performance of the type 8 design drop structure, the model was modified to reproduce the type 9 design drop structure (Photo 43a). Flow conditions observed indicated an improvement in the stability of the hydraulic jump and a reduction in the wave action in the downstream channel for the full range of discharges (Photo 43b and c). Scour tests

conducted using the simulated hydrograph indicated an improvement in the hydraulic performance of the drop structure with no significant failure occurring in the riprap protection plan (Photo 44).

Type 10 design

Although satisfactory results were obtained with the type 9 design drop structure, the type 10 design drop structure (Photo 45) was installed in the model to examine the effects of a longer basin length. Satisfactory flow conditions were observed in the stilling basin and in the downstream channel for the full range of discharges for both sets of tailwater elevations resulting from Manning's roughness values of 0.02 and 0.03 (Photos 46 and 47, respectively). Scour tests conducted also indicated a slight improvement in the energy dissipation resulting from this design, with no failure observed in the type 1 design riprap protection plan (Photo 48).

Recommended design structure

Because the type 10 design indicated only a slight improvement over the type 9 design, the type 9 design drop structure is recommended for the prototype. This design is shown in Figure 9. The type 9 design drop structure provided satisfactory results and is more economical to construct since the structure is 6.1 ft shorter than the type 10 design drop structure. Table 5 contains the pertinent data for each of the designs tested.

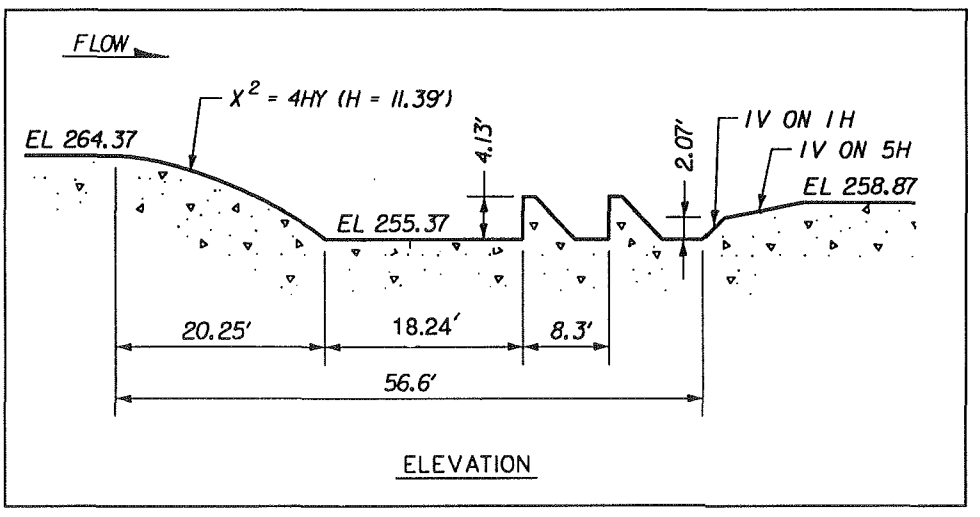

Figure 9. Type 9 design, recommended design drop structure at sta 1022+98.55

Sta 836+50 Drop Structure

Type 1 (existing) design

The existing drop structure located at sta 836+50 (Photo 49) was designed according to SAF criteria with a vertical drop to the stilling basin floor ranging from 11.75 to 12.75 ft (the crest slopes 1 ft across prototype structure). Dimensions and elevations of the type 1 design are shown in Plate 46. Unit discharges ranging from a minimum of 50 cfs/ft to a maximum of 175 cfs/ft were tested. The design unit discharge is 130 cfs/ft. Operating conditions showing unit discharge and tailwater operating conditions created by Manning's n values of 0.02 and 0.03 in the channel are provided in the following tabulation.

Unit Discharge cfs/ft	Tailwater El, ft	
	n = 0.02	n = 0.03
50	198.7	200.1
100	201.2	203.2
130 (design)	202.5	204.9
150	203.2	205.8
175 (maximum)	204.1	207.0
180 (revised design)	204.5	207.6

At the higher discharge conditions, the type 1 design drop structure performed unsatisfactorily. An oscillating hydraulic jump was present at unit discharges above 100 cfs/ft and the hydraulic jump was submerged at a unit discharge of 175 cfs/ft. Operation of the basin in this range of discharges would create increased downstream scour and fluctuating water-surface conditions. Flow conditions for the various discharges with tailwater elevations resulting from Manning's roughness values of 0.02 and 0.03 are shown in Photos 50 and 51, respectively. Flow in the photographs for the structure at sta 836+50 is from left to right because this model was tested in a different flume.

Type 2 design

In the type 2 design (Photo 52a, Plate 46), a parabolic-shaped drop was installed downstream from the crest. The trajectory of this curve was necessarily made steeper than the trajectory that would result from the design discharge because of the location of the existing baffle blocks. Previous studies at WES (Grace 1964) indicated that a curve this steep would provide satisfactory flow conditions without creating uplift negative pressures along the curve. Test results indicated that the parabolic-curved drop improved the

performance of the basin by increasing the range of discharges where good energy dissipation occurred. Flow conditions with the design unit discharge are shown in Photos 52b and c. As shown in these photographs, flow conditions with the design discharge were greatly improved. However, flow conditions were very rough downstream of the structure and oscillation of the hydraulic jump was observed at the maximum discharge of 175 cfs/ft as shown in Photo 52d.

Type 3 design

Chute blocks were placed on the crest near the toe in an attempt to stabilize the hydraulic jump in the drop structure. This was labeled the type 3 design drop structure and is shown in Photo 53a and Plate 47.

Test results showed that the addition of the chute blocks had little impact in improving energy dissipation in the drop structure, as shown in Photos 53b and c.

Type 4 design

In the type 4 design drop structure (Photo 54), the existing end sill was removed and replaced with a sloping end sill. A 1V on 5H adverse slope provided the transition from the top of the end sill to the channel invert. Dimensions and elevations of the type 4 design are shown in Plate 47.

Flow conditions indicated that the sloping end sill modification did not improve the performance of the stilling basin. The existing baffle blocks created a high water-surface elevation in the basin, which resulted in rough downstream water surfaces.

Type 5 design

In the type 5 design drop structure (Photo 55), the existing baffle blocks were shortened to a height of d_1 (3.8 ft). A second row of baffles was added at the existing end sill location, additional basin length was added, and the chute blocks were removed. Dimensions and elevations of the type 5 design are shown in Plate 48.

Flow conditions in the stilling basin were unsatisfactory for the higher unit discharges with the hydraulic jump becoming unstable in some cases. At the maximum unit discharge of 175 cfs/ft, an oscillating hydraulic jump was present, which created very rough downstream water-surface conditions.

Type 6 design

The type 6 design shown in Photo 56 and Plate 48 was the same as type 5 except the existing first row of baffles was raised to its original height of 6.5 ft. This modification was made to stabilize the hydraulic jump for the full range of unit discharges and reduce the roughness in the water surface immediately downstream.

Test results did indicate a small improvement at lower discharges over previous designs tested, but flow conditions were not satisfactory for the higher unit discharges.

Type 7 design

Since modifications incorporating the use of the existing baffle blocks were unsuccessful, efforts were redirected toward modifying the existing drop structure using the sequent depths as design parameters, as was used on the drop structure at sta 1022+98.55. The design unit discharge of 130 cfs/ft was used to measure the hydraulic jump parameters d_1 and d_2. A single row of baffle blocks with a height of d_1 was placed at the existing end sill location. The parabolic drop downstream from the crest was sized so that the toe was $1.5d_2$ upstream of the baffle blocks and the stilling basin length was $2.5d_2$, as shown in Photo 57a and Plate 49.

Even though the stilling basin was designed for a unit discharge of 130 cfs/ft, acceptable performance was obtained for unit discharges ranging up to 165 cfs/ft. Flow conditions with this design are shown in Photos 57b-d. At the revised maximum discharge of 180 cfs/ft, the hydraulic jump was very close to spraying out at the tailwater elevation resulting from an n value of 0.02 (Photo 57d). Velocities measured above the end sill are shown in Plate 49 with a unit discharge of 130 cfs/ft.

Type 8 design

The drop structure was redesigned for a unit discharge of 180 cfs/ft (type 8 design drop structure, Photo 58a, and Plate 50) as requested by the sponsor. Satisfactory flow conditions were observed in the stilling basin for the full range of discharges. The hydraulic jump was stable with no indication of spraying with the higher unit discharges. Due to the higher baffles in this design, a small boil of the water surface was noticed at lower flows. However, this did not cause objectionable downstream water-surface fluctuations. Flow conditions with the design unit discharge are shown in Photos 58b and c and velocities recorded in Plate 50.

Type 9 design

The basin length was extended to $3d_2$ and a second row of baffle blocks was installed in an effort to further improve the stilling basin performance. This was called the type 9 design drop structure (Photo 59).

Flow conditions observed with this design were also satisfactory with a stable hydraulic jump present for the full range of discharges. Velocities measured at the top of the end sill showed a significant reduction, but higher velocities were present along the surface compared to previous designs tested (Plate 51).

Type 10 design

The basin length was increased from $3.0d_2$ to $3.5d_2$ (type 10 design drop structure, Photo 60) in another attempt to further reduce the velocities and wave action in the downstream channel. The locations of the baffle blocks were the same as were tested in the type 9 design. Details are shown in Plate 52.

Test results indicated an additional reduction in the velocities measured at the end sill (Plate 52) compared to those recorded with the type 9 design drop structure (Plate 51). Flow conditions were satisfactory in the stilling basin and in the downstream channel (Photos 61 and 62). Wave action downstream of the structure was minimized from previous designs tested, further indicating that this design performed more effectively for the full range of discharges than other designs tested.

Recommended design structure

Although the type 10 design drop structure produced slightly better flow conditions in the basin and velocities were slightly less at the end sill, the type 9 design drop structure was recommended for sta 836+50 because it was shorter and thus more economical. The type 9 structure should perform satisfactorily for all expected discharges and tailwater elevations. This design is shown in Figure 10. Table 6 contains the pertinent data for each of the designs tested.

Sta 884+00 Drop Structure

Type 1 (existing) design

The drop structure, which consists of a simple straight drop of 7.5 ft, was based on the CIT design. The existing design was installed in a 2.5-ft-wide

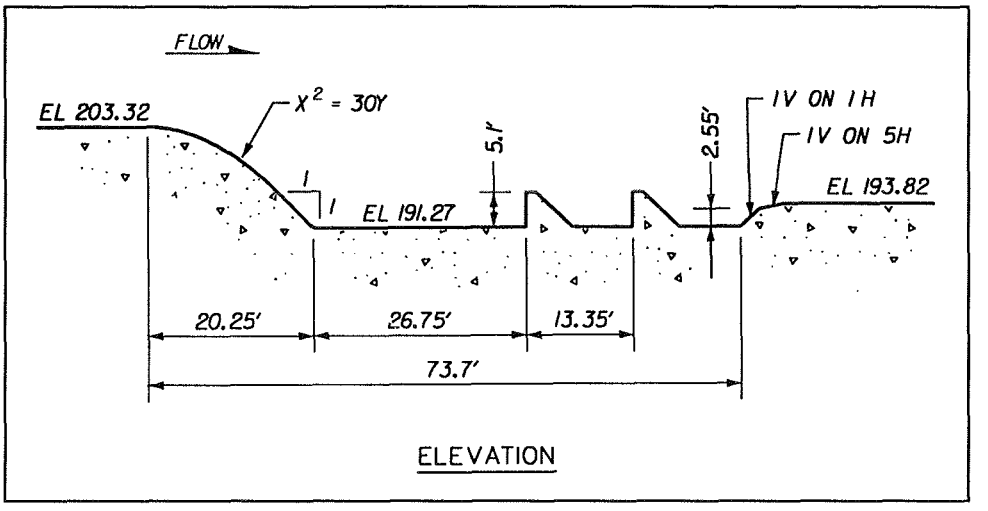

Figure 10. Type 9 design, recommended design drop structure at sta 836+50

glass-sided flume as a section model. Dimensions and elevations of the type 1 design are shown in Plate 53. Unit discharges ranging from a minimum of 50 cfs/ft to a maximum of 165 cfs/ft were observed with the design unit discharge being 125 cfs/ft. Operating conditions showing unit discharge and tailwater operating conditions created by Manning's n values of 0.02 and 0.03 in the channel are provided in the following tabulation:

Unit Discharge cfs/ft	Tailwater El, ft	
	n = 0.02	n = 0.03
50	218.1	219.4
100	220.6	222.6
125 (design)	221.6	223.9
150	222.6	225.1
165 (maximum)	223.1	225.8

Unsatisfactory flow conditions due to downstream water-surface fluctuations were observed in the drop structure with an unstable hydraulic jump present at the higher discharges. This produced poor energy dissipation and rough downstream water-surface conditions (Photos 63 and 64). Velocities measured at the end sill (Plate 53) indicated high velocities at the channel invert, which greatly increases the potential for scour just downstream of the structure. Based on flow conditions observed and data obtained, the hydraulic performance of the drop structure was unsatisfactory.

Type 2 design

A sequent depth analysis was performed with the type 1 design drop structure to help determine the modifications required for the higher unit discharges. With the design discharge of 125 cfs/ft, values of d_1 and d_2 were measured to be 4.45 ft and 12.24 ft, respectively. Resulting modifications to the type 1 design drop structure consisted of increasing the basin length to $2.5d_2$ and adding a single row of baffle blocks. The height of the baffle blocks was equal to d_1 or 4.45 ft. The baffle blocks were placed at the existing end sill location and the parabolic drop profile was adjusted so that a space of $1.5d_2$ was between the toe of the curve and the first row of baffles. This was designated the type 2 design drop structure, shown in Photo 65. Dimensions and elevations of the type 2 design drop structure are shown in Plate 54.

A notable improvement in the hydraulic performance of the drop structure was observed for various discharges. A fairly stable hydraulic jump was present throughout the range of discharges observed and a reduction in velocities was measured at the end sill and 50 ft downstream from the end sill (Plate 55).

Type 3 design

The type 2 design drop structure was modified in an effort to improve the stability and efficiency of the hydraulic jump present in the stilling basin. The only modification involved shortening the parabolic curve length by 9.48 ft. All other elements that were tested in the type 2 design drop structure remained the same. This was called the type 3 design drop structure (Photo 66, Plate 56).

Observed flow conditions at the higher discharges indicated that the shorter curve length used in the type 3 design drop structure was not as effective as was the longer length in the type 2 design. Velocities measured above the end sill (Plate 56) also show a slight increase compared to those recorded in the type 2 design drop structure.

Type 4 design

Since the shorter parabolic curve did not improve the performance of the drop structure, the longer parabolic crest was reinstalled. The length of the basin was also increased from $2.5d_2$ to $3.0d_2$ so that a second row of baffles could be installed in the stilling basin. This was called the type 4 design drop structure (Photo 67).

Flow conditions observed indicated that the hydraulic jump was more stable at the higher discharges than for previous designs due to the longer parabolic

curve length (Photos 68 and 69). The velocities measured at the end sill and 50 ft downstream of the end sill are shown in Plate 57.

Type 5 design

In the type 5 design drop structure (Photo 70), the basin length was increased to $3.5d_2$ in an attempt to lower scour-producing velocities at the end sill and smooth water surfaces downstream of the structure. The parabolic curve and size and location of the baffle blocks were the same as was tested in the type 4 design drop structure. Details are shown in Plate 58.

Satisfactory flow conditions were observed with this design for the full range of discharges. The hydraulic jump was stable for the discharges observed. The velocities measured at the end sill (Plate 58) indicate only a slight improvement over the type 4 design. Wave action downstream was also slightly less than the type 4 design. The type 5 design indicated that only minimal improvements would be created by the longer basin length.

Type 6 design

In an effort to reduce the length of the drop structure, modifications were made that incorporated the shorter parabolic curve used in the type 3 design drop structure and two rows of baffle blocks (type 6 design drop structure, Photo 71a). Details of this design are shown in Plate 59.

The overall performance of this design was unsatisfactory. An unstable hydraulic jump was present in the stilling basin and the water surface was very rough downstream of the structure with the higher unit discharges. Flow conditions with the design unit discharge are shown in Photos 71b and c. Velocities measured at the end sill are shown in Plate 59.

Recommended design structure

Test results indicated that the longer parabolic crest and corresponding basin length of the type 4 design were needed for effective energy dissipation and smooth downstream water surfaces. The type 5 design, with a longer basin length than the type 4 design, recorded only slightly better performance than the type 4 design. Since satisfactory flow conditions were observed with the type 4 design drop structure, it is the recommended design for sta 884+00. This design is shown in Figure 11. Table 7 contains the pertinent data for each of the designs tested.

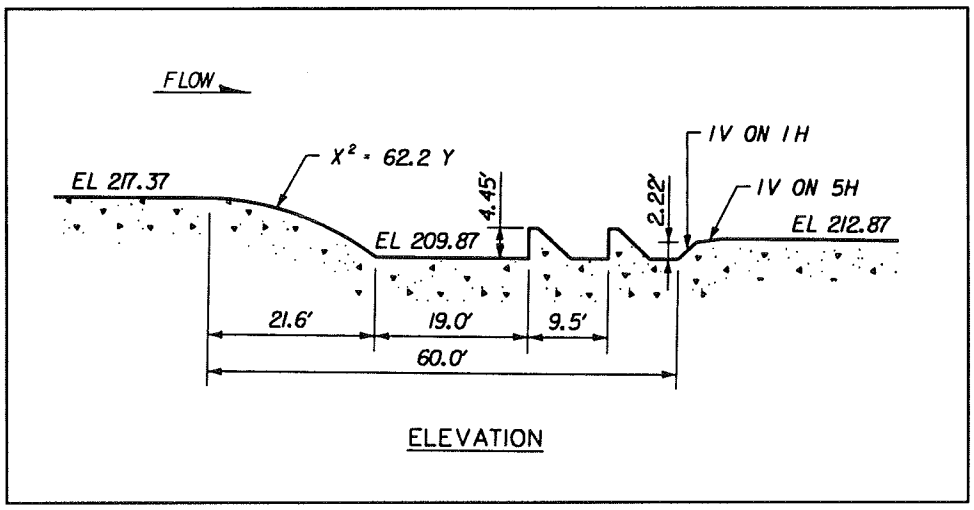

Figure 11. Type 4 design, recommended design drop structure at sta 884+00

Sta 593+35 Drop Structure

Type 1 (existing) design

The existing drop structure located at sta 593+35 was designed according to the SAF criteria, having a vertical drop of 10 ft. Dimensions and elevations of the type 1 design are shown in Plate 60. Unit discharges ranging from a minimum of 50 cfs/ft to a maximum of 215 cfs/ft were tested with the design unit discharge being 125 cfs/ft. Discharge and tailwater operating conditions resulting from Manning's n values of 0.02 and 0.03 in the channel are provided in the following tabulation:

Unit Discharge cfs/ft	Tailwater El, ft	
	n = 0.02	n = 0.03
50	111.0	112.2
100	113.3	115.2
125 (design)	114.3	116.5
165	115.7	118.3
215	117.3	120.3

With the existing design, rough downstream water-surface conditions were encountered. An unstable hydraulic jump present at the higher discharges produced poor energy dissipation and rough downstream water-surface conditions. Observations of these flow conditions indicated that severe scour would probably occur downstream of the stilling basin. Based upon model results obtained with a similar type drop structure located at sta 836+50, maximum

energy dissipation and smooth downstream water-surface conditions would not be obtained using the existing baffle blocks and basin dimensions. Flow conditions in the existing type 1 design drop structure are shown in Photos 72 and 73.

Type 2 design

The type 2 design drop structure (Photo 74) incorporated design features that were determined from previous model tests. Modifications to the type 1 design drop structure consisted of extending the basin length to $3.0d_2$ and adding a parabolic drop downstream from the crest, two rows of baffle blocks, and a sloping end sill.

Because previous tests conducted with an 8-ft drop structure (page 17) resulted in near-submerged conditions when the model was operated at a unit discharge of 250 cfs/ft, it was not recommended for the prototype. However, in the type 2 design, observed flow conditions indicated that the modifications produced a stable hydraulic jump in the stilling basin for unit discharges up to 215 cfs/ft. The water surface was smooth downstream of the basin with the design unit discharge of 125 cfs/ft. The water surface did become rougher as the unit discharge increased, but it still remained satisfactory. Flow conditions in the type 2 design drop structure are shown in Photos 75 and 76.

Recommended design structure

Since the type 2 design produced satisfactory results for the full range of discharges observed, it is recommended for sta 593+35. Figure 12 shows the

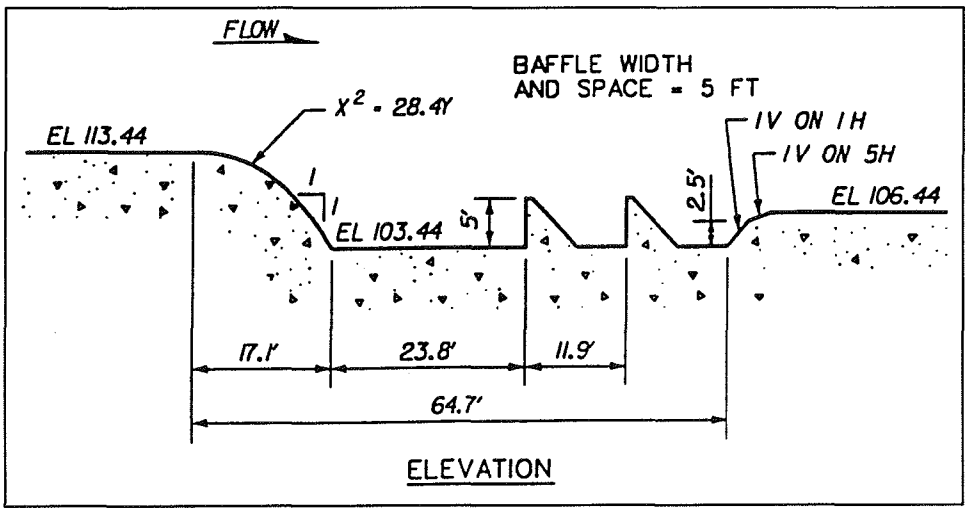

Figure 12. Type 2 design, recommended design drop structure at sta 593+35

dimensions of this design. Table 8 contains the pertinent data for each of the designs tested.

Sta 1198+08 Drop Structure

Type 1 (existing) design

The existing drop structure located at sta 1198+08 (Photo 77, Plate 61) has the lowest drop height (6.79 ft) of all the structures tested. Unit discharges ranging from a minimum of 50 cfs/ft to a maximum of 165 cfs/ft were observed with the design unit discharge being 125 cfs/ft. Operating conditions showing unit discharge and tailwater operating conditions created by Manning's n values of 0.02 and 0.03 in the channel are provided in the following tabulation:

Unit Discharge cfs/ft	Tailwater El, ft			
	Downstream Channel Invert el = 309.21		Downstream Channel Invert el 303.2	
	n = 0.02	n = 0.03	n = 0.02	n = 0.03
50	314.4	315.9	308.4	309.9
100	317.1	319.3	–	–
125 (design)	318.2	320.7	312.2	314.7
150	319.3	322.0	–	–
165 (maximum)	319.9	322.9	313.9	316.8
200	–	324.3	–	318.2
250	–	326.4	–	320.4
290 (revised maximum)	–	327.7	–	321.7

General observations of the performance of the type 1 design drop structure indicated that the existing design was not adequate for the unit discharges expected. An unstable hydraulic jump was present throughout the range of discharges, which resulted in rough water surfaces and a high probability of scour occurring immediately downstream of the structure. Flow conditions for the various discharges and Manning's 0.02 and 0.03 tailwater elevations are shown in Photos 78 and 79.

Type 2 design

The type 2 design drop structure (Photo 80, Plate 61) was based on previous test results obtained in this study. Due to the existing basin length of

$3d_2$, the parabolic drop profile was shortened so that two rows of baffle blocks and an end sill could be placed on the existing basin floor.

Satisfactory performance was obtained with the type 2 design although the curved drop was shorter than most of the previous designs. With unit discharges higher than 125 cfs/ft (design) the hydraulic jump approached a submerged state due to the low drop height and tailwater effects. However, flow conditions in and downstream of the structure were satisfactory up to a unit discharge of 165 cfs/ft. Flow conditions with this design are shown in Photo 81.

During the course of this study, the maximum unit discharge of 165 cfs/ft was raised to 290 cfs/ft by the Los Angeles District. At these higher unit discharges, the drop structure became submerged due to the higher flow, the low drop height, and increased tailwater elevations. The type 2 design was based on a design unit discharge of 125 cfs/ft; therefore, satisfactory performance was not expected with the significantly higher design unit discharge. Flow conditions with unit discharges of 200 and 250 cfs/ft are shown in Photo 82.

Type 3 design

To adequately convey a maximum unit discharge of 290 cfs/ft, substantial modifications were made. The type 3 design drop structure (Photo 83a, Plate 62) was based on a sequent depth analysis of a design unit discharge of 250 cfs/ft.

Tests indicated that the type 3 design did not improve flow conditions and energy dissipation of the drop structure. The drop structure was submerged with the maximum unit discharge, as shown in Photo 83b.

Type 4 design

The sequent depth design method was reexamined due to the unsatisfactory results of the type 3 design drop structure. A variable not considered in previous designs was the Froude number entering the basin. The Froude number at structure 1198+08 and a drop height of 6.74 ft at the various unit discharges was calculated using a method developed by Rand (1955) and is presented in the accompanying tabulation. In the previous structures tested in this study, the Froude number for design conditions ranged from 2.37 to 2.78, as listed in the next tabulation. Satisfactory performance was always obtained when the Froude number was 2.5 or greater.

Unit Discharge, cfs/ft	Froude Number Entering Basin
50	3.05
100	2.52
125	2.37
150	2.26
165	2.20
290	1.88

Structure	Drop Height, ft	Design Unit Discharge cfs/ft	Froude Number Entering Basin
1022+98.55	9.00	125	2.67
836+50	12.75	180	2.78
884+00	7.50	125	2.47
593+35	10.00	125	2.78
1198+08	6.79	125	2.37
1198+08	14.0	290	2.54

The type 4 design drop structure (Photo 84a) was based on a Froude number of 2.5. Thus, the stilling basin floor was lowered to el 299.50 to obtain a Froude number of 2.54. A 1V on 5H adverse slope was used to provide a transition from the top of the end sill to the channel invert (el 309.21). Dimensions and elevations of the type 4 design are shown in Plate 63.

Unsatisfactory performance was still observed in the type 4 design drop structure due to the existing high tailwater elevations, which caused the drop structure to become submerged. With unit discharges greater than 150 cfs/ft, the drop structure was submerged with little, if any, energy dissipation occurring. Flow conditions with the design unit discharge are shown in Photo 84b.

Type 5 design

The channel invert was lowered to the top of the end sill so that the relative tailwater depths over the end sill (el 303.20) could be maintained (Plate 63). This was designated the type 5 design drop structure.

With lower tailwater elevations resulting from the lower downstream channel invert, a stable hydraulic jump with good energy dissipation was present for the full range of discharges observed. The water surface downstream was also smooth for these conditions. This design produced satisfactory results up to the maximum unit discharge of 290 cfs/ft. Flow conditions for the various discharges with tailwater elevations resulting from Manning's n of 0.02 are shown in Photo 85. Flow conditions for the various discharges with tailwater elevations resulting from a Manning's n of 0.03 are shown in Photo 86.

Although the lower channel cannot be used in the prototype because it is not practical to lower the invert of the downstream channel to obtain the desired tailwater depths, these test results do indicate what modifications are necessary to adequately convey a unit discharge of 290 cfs/ft. These modifications are provided in Figure 13. In addition, the general design method developed in this study was further refined due to work on this structure.

Recommended design structure

For a design unit discharge of 125 cfs/ft, the type 2 design is recommended. Additional downstream protection will be required for the revised maximum unit discharge of 290 cfs/ft because structural modifications are not planned. Figure 13 shows the dimensions of this design. Table 9 contains the pertinent data for each of the designs tested.

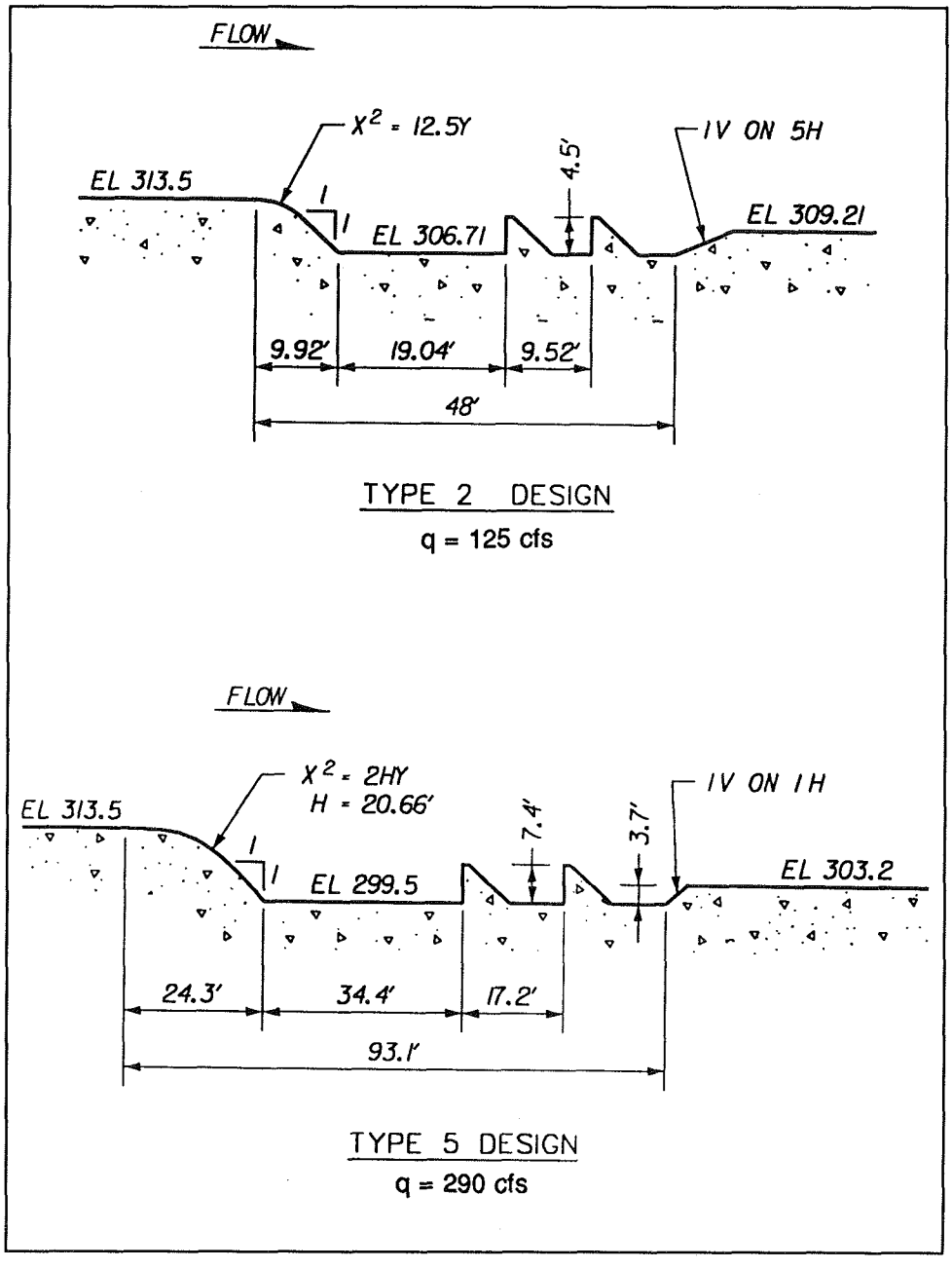

Figure 13. Recommended design drop structures at sta 1198+08 for two different unit discharges

5 Design Procedure

Based on test results from model investigations discussed in this report, this chapter presents a general design procedure for parabolic drop structures.

First, a design unit discharge q, tailwater elevation, and desired drop in channel elevation must be known. The unit discharge is used to calculate the parabolic drop profile and the basin dimensions. Critical depth d_c for the unit discharge is calculated by the equation:

$$d_c = \left[\frac{q^2}{g}\right]^{1/3} \tag{1}$$

where g is the acceleration due to gravity. Since in a rectangular channel the velocity head for critical depth $v_c^2/2g$ is always 0.5 times the critical depth, the design head H is 1.5 times the critical depth ($H = y_c + v_c^2/2g$). Once the design head is known, the parabolic drop profile may be calculated using the equation:

$$X^2 = KHY \tag{2}$$

where the coefficient K can vary from 2 to 4. Although coefficient values of less than 2 were tested in the model studies, a coefficient value of 2 proved to be a safe recommended minimum value for low-head structures. The drop profile follows the parabola until the slope of the equation is equal to 1. At this point the drop profile becomes a 1H on 1V slope until the basin floor is reached.

The next series of steps involves designing the stilling basin. This is a trial and error procedure. An estimate of the distance from the crest to the stilling basin floor h is made. The sequent depths d_1 and d_2 are computed from a method developed by Rand (1955) for straight drop spillways. Rand's method is also published in Chow (1959). The pertinent equations are shown here for convenience.

a. Equation 15-9 (Chow 1959):

$$D = q^2/gh^3 \tag{3}$$

b. Equation 15-12 (Chow 1959):

$$d_1/h = 0.54\ D^{0.425} \tag{4}$$

c. Equation 15-13 (Chow 1959):

$$d_2/h = 1.66\ D^{0.27} \tag{5}$$

Although these equations were developed for a straight drop spillway (no curved drop trajectory), they consistently computed depths of flow entering the stilling basin similar to those measured in this study. After computing d_2 from Equation 15-13 with the assumed value of h, a comparison is made between d_2 and the depth of tailwater available (tailwater elevation - basin floor elevation). If these numbers are different, a new value of h is assumed and the procedure repeated until a favorable comparison is made. This will usually require three or four iterations. The values of d_1 and d_2, computed with the correct h, are then used to determine the length of basin and size of basin elements from the typical drop structure stilling basin shown in Figure 14. The height of the baffle blocks should be equal to d_1. Spaces between the blocks should be 1.0 times the height while the width should be from 0.75 to 1.0 times the height. The stilling basin length is defined as the distance from the toe of the parabolic drop to the toe of the end sill. The stilling basin length should be 3.0 times d_2. The first row of baffles should start $1.5d_2$ downstream from the toe of the parabolic drop. The second row of baffles is located $0.75d_2$ downstream of the first row. The end sill is located at the end of the basin and has a height of 0.5 d_1. An end sill slope of 1V on 1H is recommended for self-cleaning of trapped debris. If the top of the end sill is lower than the channel invert, then a 1V on 5H adverse slope should be used.

An energy dissipator designed according to these criteria should provide adequate energy dissipation with tailwater elevations equal to or greater than d_2 . However, if the tailwater elevation becomes too high, the jet entering the basin will not follow the curved trajectory into the basin, and as the tailwater increases, will eventually ride the surface. When this occurs, a hydraulic jump

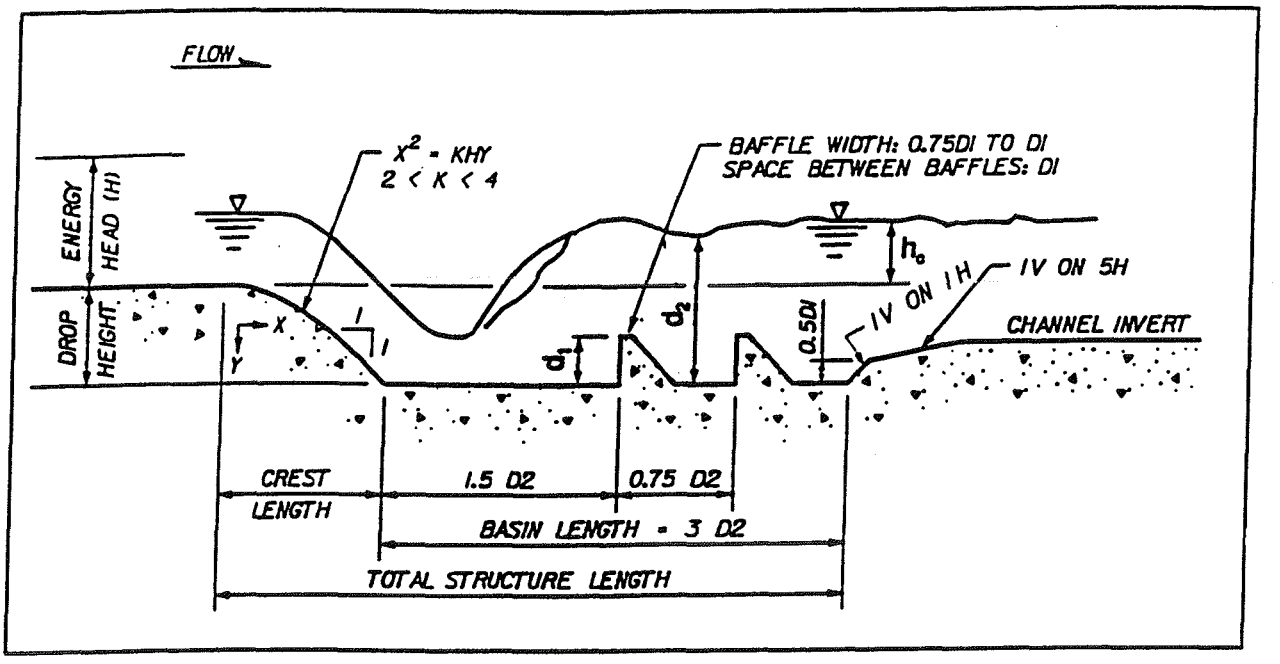

Figure 14. Drop structure general design

will not form and unsatisfactory flow conditions with large surface waves will occur. The point when the tailwater becomes too high is difficult to determine. This problem was not specifically addressed during this study since most of the research addressed specific structures on the Santa Ana River with specific tailwater elevations. However, the results of these studies were analyzed in an effort to obtain some generalized guidance. A plot of q and tailwater submergence (depth of tailwater above crest h_c divided by d_c) was made for the various designs tested (Plate 64). Notations were made as to whether flow conditions were satisfactory or not. The Froude number entering the basin $F_1 = V_1^2/(gd_1)^{0.5}$ where V_1 is the velocity at d_1 was also plotted against submergence, since F_1 is influenced by both q and h. This plot with satisfactory and unsatisfactory flow notated is shown in Plate 65. Plates 64 and 65 can be used to make judgments as to the effectiveness of energy dissipation with the design being considered. However, it is obvious that data are sparse in several areas. Additional research is needed to better define the exact submergence at which this type of structure will and will not be effective. A systematic series of tests with a number of designs and design conditions would be required to obtain these data.

Example design problems are shown in Tables 10 and 11 for clarification of the design procedure.

6 Discussion of Results and Recommendations

Replacement Study

Several modifications to the initial replacement drop structure design were required to adequately convey the anticipated increased discharges and dissipate the energy. These modifications included a parabolic drop downstream from the crest, baffle blocks, a sloping end sill, and additional basin length.

Although effective at lower unit discharges of less than 100 cfs/ft, the Saint Anthony Falls (SAF) design drop structure proved unsuitable for unit discharges of 250 cfs/ft. An unstable hydraulic jump, rough downstream water-surface conditions, and excessive scour rendered this design unsuitable.

A parabolic drop based on the equation $X^2 = KHY$ installed downstream from the crest significantly improved flow conditions in the basin and downstream water-surface conditions. Two curve profiles were tested (K = 1.6 and 2.14). The K = 1.6 curve performed satisfactorily; however, for general design, a K value of 2.0 should be used. This will provide a flatter trajectory that will ensure positive pressure under the nappe.

Several basins were tested with and without the parabolic drop. Basins with parabolic drops performed better in terms of energy dissipation, less scour, and smoother downstream water-surface conditions. Therefore, a parabolic drop was recommended.

Additional improvements were made by designing the basin according to the initial and sequent depths of a hydraulic jump (d_1 and d_2). Baffle block heights sized according to d_1 and $d_2/6$ were tested. Better results were obtained with the d_1-sized blocks. The d_1-high blocks provided greater blockage, which is needed for these low Froude number basins. An end sill height of $d_1/2$ should be used. If required, an adverse slope of 1V on 7H can be used to transition from the top of the end sill to the channel bed. Additional refinements to this basic design were made in the Santa Ana existing and proposed model study conducted later.

A drop structure constructed of grouted stone may be used as an alternative structure. These structures should have a slope of 1V on 2H to form a hydraulic jump in the basin. A basin length as short as $3.7d_2$ may be used.

Modification of Existing Structures

Substantial modifications were required to the existing Santa Ana River drop structures to adequately convey the anticipated increased discharges and dissipate the energy. These modifications include a parabolic drop downstream from the crest, one or two rows of baffle blocks on the basin floor, a sloping end sill, and additional basin length. Basin lengths of $2.5d_2$, $3.0d_2$, and $3.5d_2$ were tested. Scour tests conducted with the drop structure at sta 1022+98.55 indicated that basin lengths of $3.0d_2$ and $3.5d_2$ had the lowest scour potential. Attempts to use the existing basin length were not successful. The existing baffle blocks used in the SAF designs should be replaced with redesigned baffle blocks placed according to the model test results.

These modifications can be made without jeopardizing the structural integrity of the existing structures. During the course of the model investigation, a recommendation was made that the first row of baffles be placed at the location of the present end sill, if possible, due to construction and cost considerations. Several basins were designed accordingly and tested. Usually, only minor modifications to the crest profile were necessary to meet this requirement. Later in the model study, this requirement was lifted and baffles could be placed on the existing basin floor. A final decision on this issue should be made, considering the existing basin length and a construction cost analysis. Placing the baffles on the existing slab usually resulted in a shorter overall basin.

Tests were conducted with the first row of baffles placed $1.5d_2$ downstream of the toe of the drop. A second row of baffle blocks for basin lengths of $3.0d_2$ and $3.5d_2$ was originally placed $0.5d_2$ downstream from the first row. This distance between the baffle blocks proved to be too close and additional length was needed for better energy dissipation. Therefore, the space between baffle rows was changed to $0.75d_2$. The sloping end sill was placed at the end of the stilling basin. Since the sloping end sill was lower than the channel invert, a 1V on 5H adverse slope was used as a transition from the end sill to the channel invert.

The problems encountered throughout this study were due to hydraulic conditions operating in a Froude number range of 1.9 to 3.1. Hydraulic jumps occurring in this range of Froude numbers naturally produce an oscillating hydraulic jump, which is difficult to dampen. Previous designs for this range of Froude numbers include wave suppressors, impact-type structures, and deeper and longer drop structures. As this model study has produced a significant alternative to these previous designs, a general design procedure was

developed from the model test results (Chapter 5). This procedure will eventually be incorporated into EM 1110-2-1601, "Hydraulic Design of Flood Control Channels" (Headquarters, U.S. Army Corps of Engineers 1991).

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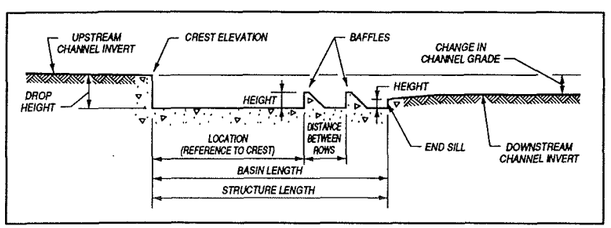
Table 1
Summary of Model Test Results
Replacement Structures (10-ft Drop Structure)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
1	10	100	15	—	—	1	—	54	10	76.0	5	V	—	76	100	102.5	1	SAF design	P1	8
																106.5	3			
																108.5	3			
															150	102.5	1			
																106.5	3			
																108.5	3			
															200	102.5	1			
																106.5	1			
																108.5	3			
															250	102.5	2			
																106.5	2			
																108.5	3			
2	10	100	15	—	—	1	—	44	10	76.0	5	V	—	76	250	102.5	3	SAF design	P5	11
																106.5	3			
																108.5	3			

(Sheet 1 of 4)

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable



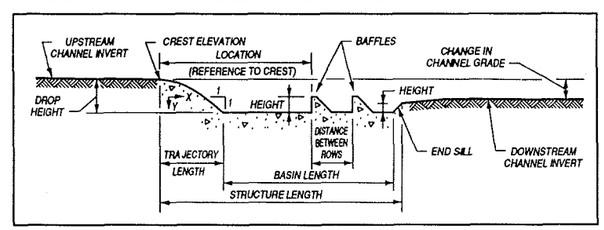


Table 1 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
3	10	100	15	x^2=40y	24.5	1	—	54.0	10	51.5	5	V	—	76.0	250	102.5	2	—	P5	11
																106.5	1			
																108.5	1			
4	10	100	15	x^2=40y	24.5	1	—	44.0	10	51.5	5	V	—	76.0	250	102.5	2	—	P8	12
																106.5	1			
																108.5	1			
5	10	100	15	x^2=30y	21.2	1	—	54.0	10	54.8	5	V	—	76.0	250	102.5	3	—	P8	12
																106.5	2			
																108.5	1			
6	10	100	15	x^2=30y	21.2	1	—	44.0	10	54.8	5	V	—	76.0	250	102.5	3	—	—	12
																106.5	2			
																108.5	2			
7	10	100	15	—	—	2	10.7	62.1	6	83.5	5	—	1V on 1H	88.5	250	106.5	2	—	P12	12
8	10	100	15	—	—	2	10.7	50.0	6	83.5	5	—	1V on 1H	88.5	250	106.5	3	—	—	13
9	10	100	15	—	—	2	10.7	35.0	6	83.5	5	—	1V on 1H	88.5	250	106.5	3	—	—	13
10	10	100	15	x^2=30y	21.2	2	10.7	35.0	6	62.3	5	—	1V on 1H	88.5	250	106.5	2	—	P13	13
11	10	100	15	x^2=30y	21.2	2	10.7	50.0	6	62.3	5	—	1V on 1H	88.5	250	106.5	3	—	P13	13
12	10	100	15	x^2=30y	21.2	2	10.7	62.1	6	62.3	5	—	1V on 1H	88.5	250	106.5	2	—	P13	13
13	10	100	15	—	—	2	10.7	62.1	4	83.5	5	—	1V on 1H	88.5	250	106.5	1	—	P15	13
14	10	100	15	—	—	2	10.7	50.0	4	83.5	5	—	1V on 1H	88.5	250	106.5	2	—	P15	13
15	10	100	15	—	—	2	10.7	35.0	4	83.5	5	—	1V on 1H	88.5	250	106.5	2	—	P15	13
16	10	100	15	x^2=30y	21.2	2	10.7	35.0	4	62.3	5	—	1V on 1H	88.5	250	106.5	1	—	P17	14
17	10	100	15	x^2=30y	21.2	2	10.7	50.0	4	62.3	5	—	1V on 1H	88.5	250	106.5	2	—	P17	14
18	10	100	15	x^2=30y	21.2	2	10.7	62.1	4	62.3	5	—	1V on 1H	88.5	250	106.5	1	—	P17	14
19	10	100	15	—	—	2	10.7	70.0	6	105.0	5	—	1V on 1H	110.0	250	106.5	2	—	—	14
20	10	100	15	x^2=30y	21.2	2	10.7	70.0	6	83.8	5	—	1V on 1H	110.0	250	106.5	1	—	—	14

(Sheet 2 of 4)

[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 1 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
21	10	100	15	x^2=30y	21.20	2	10.7	50.0	6	83.80	5	—	1V on 1H	110.0	250	106.5	2	—	—	14
22	10	100	15	x^2=30y	21.20	2	10.7	50.0	4	83.80	5	—	1V on 1H	110.0	250	106.5	1	—	—	14
23	10	100	15	—	—	2	10.7	50.0	4	105.00	5	—	1V on 1H	110.0	250	106.5	3	—	—	14
24	10	100	15	—	—	2	10.7	70.0	4	105.00	5	—	1V on 1H	110.0	250	106.5	2	—	—	14
25	10	100	15	x^2=30y	21.20	2	10.7	70.0	4	83.80	5	—	1V on 1H	110.0	250	106.5	2	—	—	14
26	10	100	15	—	—	2	10.7	30.0	4	105.00	5	—	1V on 1H	110.0	250	106.5	3	—	—	14
27	10	100	15	x^2=30y	21.20	2	10.7	30.0	4	83.80	5	—	1V on 1H	110.0	250	106.5	2	—	—	14
28	10	100	20	x^2=30y	24.50	2	12.0	61.5	6	85.00	10	—	1V on 1H	119.5	250	106.5	3	—	P19	14
29	10	100	20	x^2=30y	24.50	2	12.0	61.5	6	85.00	3	—	1V on 1H	112.5	250	106.5	2	—	P19	15
30	10	100	20	—	—	2	12.0	61.5	6	109.50	3	—	1V on 1H	112.5	250	106.5	2	—	P19	15
31	10	100	20	x^2=30y	24.50	2	12.0	61.5	6	65.50	3	—	1V on 1H	93.0	250	106.5	1	—	—	—
32	10	100	20	—	—	2	12.0	61.5	6	90.00	3	—	1V on 1H	93.0	250	106.5	2	—	—	—
33	10	100	18	x^2=30y	23.24	2	12.0	61.5	6	66.76	3	—	1V on 1H	93.0	250	106.5	1	1V on 10H riprap slope	—	—
34	10	100	18	—	—	2	12.0	61.5	6	90.00	3	—	1V on 1H	93.0	250	106.5	2	1V on 10H riprap slope	—	—
35	10	100	18	X^2=30y	23.24	2	12.0	61.5	6	66.76	3	—	1V on 1H	93.0	250	106.5	2	1V on 4H riprap slope	—	—
36	10	100	18	—	—	2	12.0	61.5	6	90.00	3	—	1V on 1H	93.0	250	106.5	2	1V on 4H riprap slope	—	—
37	10	100	18	X^2=30y	23.24	2	12.0	61.5	6	96.26	3	—	1V on 1H	122.5	250	106.5	2	—	—	—
38	10	100	18	—	—	2	12.0	61.5	6	119.50	3	—	1V on 1H	121.5	250	106.5	2	—	—	—
39	10	100	15	—	—	2	12.0	61.5	6	119.50	3	—	1V on 1H	121.5	250	106.5	3	—	—	—
40	10	100	15	x^2=30y	21.21	2	12.0	61.5	6	98.29	3	—	1V on 1H	122.5	250	106.5	3	—	—	—
41	10	100	20	x^2=30y	24.50	2	12.0	61.5	6	94.00	3	—	1V on 1H	121.5	150	102.5	1	1V on 10H riprap slope	—	—
															250	106.5	1	—	—	—
42	10	100	20	x^2=30y	24.50	2	12.0	61.5	6	94.00	3	—	1V on 1H	121.5	150	102.5	1	1V on 4H riprap slope	—	—
															250	106.5	2	—		
43	10	100	20	x^2=30y	24.50	2	12.0	61.5	6	94.00	3	—	1V on 1H	121.5	150	102.5	1	1V on 7H riprap slope	—	—
															250	106.5	2	—		

(Sheet 3 of 4)

[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 1 (Concluded)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajec-tory Length ft	Baffles				Basin Length ft	End Sill Height	End Sill Shape		Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation ft	Hydraulic Perform-ance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
						Rows	Distance Between Rows ft	Location (Reference to Crest) ft	Height ft			Ver-tical (V)	Sloped V on H							
44	10	100	20	$x^2=30y$	24.5	2	12	61.5	6	94	3	—	1V on 1H	121.5	150	102.5	1	**Recommended design - 1V on 7H riprap slope and 50-ft-horizontal riprap blanket**	F5	15
															250	106.5	1	—		

(Sheet 4 of 4)

[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 2
Summary of Model Test Results
Replacement Structures (12-ft Drop Structure)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
50	12	100	20	$x^2 \approx 30y$	24.5	2	12	61.5	6	94	3	—	1V on 1H	121.5	150	100.3	1	**Recommended design**	F6	15
															250	104.6	1			

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] 1 = Acceptable
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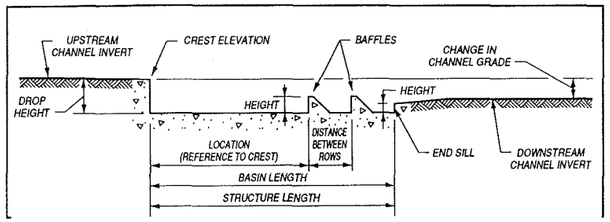
3 = Unacceptable



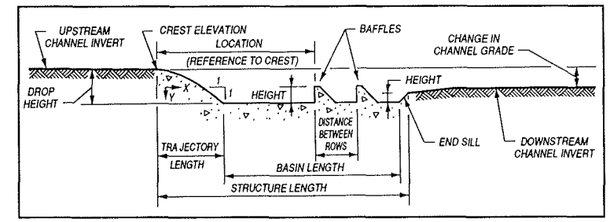
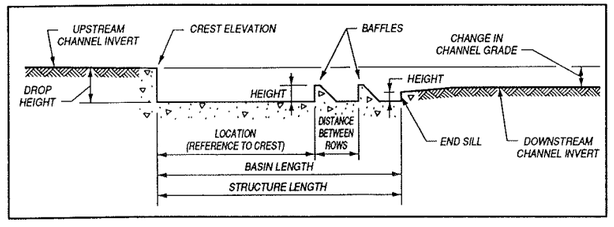


Table 3
Summary of Model Test Results
Replacement Structures (8-ft Drop Structure)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajec-tory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Ver-tical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation ft	Hydraulic Perform-ance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
75	8	100	20	x^2=30y	24.5	2	12	61.5	6	94	3	—	1V on 1H	121.5	150	104.3	1	—	P22	17
															250	108.6	3			
76	8	100	20	x^2=30y	24.5	2	12	61.5	6	89	3	—	1V on 1H	116.5	150	104.3	1	—	—	—
															250	108.6	3			
77	8	100	20	x^2=30y	24.5	2	12	61.5	6	84	3	—	1V on 1H	111.5	150	104.3	1	—	—	—
															250	108.6	3			
78	8	100	20	x^2=30y	24.5	2	12	61.5	6	79	3	—	1V on 1H	106.5	150	104.3	1	—	—	—
															250	108.6	3			
79	8	100	20	x^2=30y	24.5	2	12	61.5	6	74	3	—	1V on 1H	101.5	150	104.3	1	—	—	—
															250	108.6	3			
80	8	100	20	x^2=30y	24.5	2	12	61.5	6	69	3	—	1V on 1H	96.5	150	104.3	1	—	—	—
															250	108.6	3			
81	8	100	20	x^2=30y & IV on 1H	27.5	2	12	64.5	6	59	3	—	1V on 1H	89.5	150	104.3	1	—	P23	17
															250	108.6	3			
82	8	100	18	x^2=30y & IV on 1H	25.5	2	12	62.5	6	59	3	—	1V on 1H	87.5	150	104.3	1	—	P24	17
															250	108.6	3			

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable



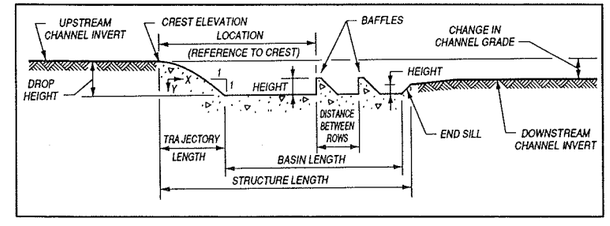
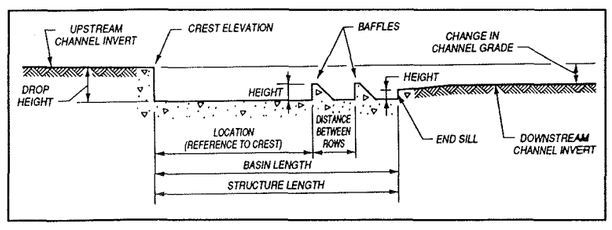


Table 4
Summary of Model Test Results
Replacement Structures (Grouted Stone Drop Structures)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation[1]	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation ft	Hydraulic Performance[2]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
100	10	100	15	1V on 10H	150	—	—	—	—	120	5	—	1V on 1H	275	50	97.0	1	—	P25	18
															100	100.5	2			
															150	103.5	3			
															200	106.5	3			
															250	108.4	3			
101	10	100	15	1V on 5H	75	—	—	—	—	120	5	—	1V on 1H	200	150	103.5	3	—	P26	18
															200	106.5	3			
102	10	100	15	1V on 3H	45	—	—	—	—	120	5	—	1V on 1H	170	50	97.0	2	—	P26	18
															100	100.5	3			
															150	103.5	3			
															200	106.5	1			
															250	108.4	1			
103	10	100	20	1V on 3H	60	—	—	—	—	120	10	—	1V on 1H	190	150	103.5	3	—	P26	19
															200	106.5	3			

(Continued)

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] Sloped Trajectory (V on H)
[2] 1 = Acceptable
2 = Marginal
3 = Unacceptable



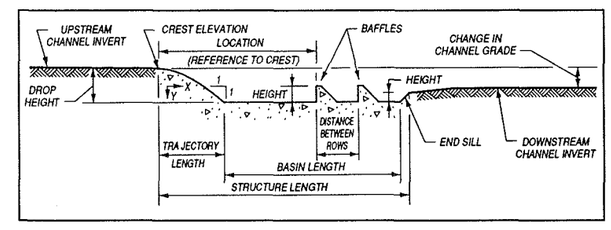


Table 4 (Concluded)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation[1]	Trajectory Length ft	Baffles				Basin Length ft	End Sill Height	End Sill Shape		Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation ft	Hydraulic Performance[2]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
						Rows	Distance Between Rows ft	Location (Reference to Crest) ft	Height ft			Vertical (V)	Sloped V on H							
104	10	100	15	1V on 2H	30	—	—	—	—	120	5	—	1V on 1H	155	50	97.0	1	—	P27	19
															100	100.5	1			
															150	103.5	1			
															200	106.5	1			
															250	108.4	1			
105	10	100	15	1V on 2H	30	—	—	—	—	80	5	—	1V on 1H	115	50	97.0	1	**Recommended design**	F7	19
															100	100.5	1			
															150	103.5	1			
															200	106.5	1			
															250	108.4	1			

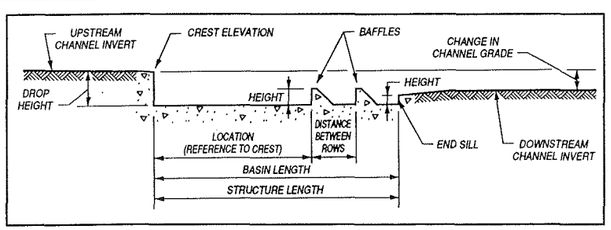
[1] Sloped Trajectory (V on H)
[2] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 5
Summary of Model Test Results
Modifications to Existing Structures (Sta 1022+98.55)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
1	5.5	264.37	9	—	—	—	—	—	—	40.00	3.50	V	—	40.00	50	—	265.27	1	—	P28	23
															100	—	268.47	3			
															125	—	269.87	3			
															150	—	271.17	3			
															165	—	271.87	3			
2	5.5	264.37	9	x^2=45.56y	20.25	2	6.08	38.49	4.13	30.25	2.07	—	1V on 1H	52.57	50	263.87	—	1	—	P31	24
																—	265.27	1			
															100	266.47	—	3			
																—	268.47	1			
															125	267.47	—	3			
																—	269.87	2			
															150	268.47	—	3			
																—	271.17	2			
															165	269.07	—	3			
																—	271.87	3			

(Sheet 1 of 5)

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable



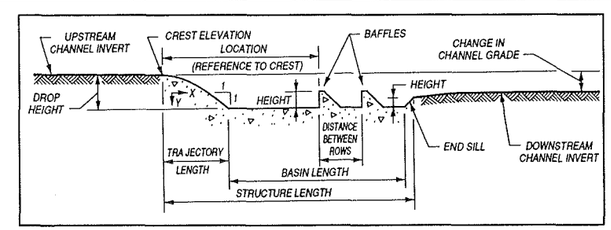


Table 5 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
3	5.5	264.37	9	x^2=45.56y	20.25	2	6.08	38.49	4.13	50.50	2.07	—	1V on 1H	52.57	50	263.87	—	2	—	P31	25
																—	265.27	1			
															100	266.47	—	3			
																—	268.47	2			
															125	267.47	—	3			
																—	269.87	3			
															150	268.47	—	3			
																—	271.17	3			
															165	269.07	—	3			
																—	271.87	3			
4	5.5	264.37	9	x^2=45.56y	20.25	1	—	38.49	4.13	30.25	2.07	—	1V on 1H	52.57	50	263.87	—	1	—	P33	25
																—	265.27	1			
															100	266.47	—	1			
																—	268.47	1			
															125	267.47	—	3			
																—	269.87	1			
															150	268.47	—	3			
																—	271.17	2			
															165	269.07	—	3			
																—	271.87	3			
5	5.5	264.37	9	x^2=45.56y	20.25	2	9.12	32.41	4.13	30.25	2.07	—	1V on 1H	52.57	50	263.87	—	1	—	P33	25
																—	265.27	1			
															100	266.47	—	1			
																—	268.47	1			
															125	267.47	—	2			

(Sheet 2 of 5)

[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 5 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
5 (Cont)	5.5	264.37	9	x^2=45.56y	20.25	2	9.12	32.41	4.13	30.25	2.07	—	1V on 1H	52.57	125	—	269.87	1	—	P33	25
															150	268.47	—	3			
																—	271.17	1			
															165	269.07	—	3			
																—	271.87	1			
6	5.5	264.37	9	x^2=45.56y	20.25	1	—	40.00	3.50	30.25	2.07	—	1V on 1H	52.57	50	263.87	—	3	Used existing end sill for baffle	P36	26
																—	265.27	3			
															100	266.47	—	3			
																—	268.47	3			
															125	267.47	—	3			
																—	269.87	3			
															150	268.47	—	3			
																—	271.17	3			
															165	269.07	—	3			
																—	271.87	3			
7	5.5	264.37	9	x^2=45.56y	20.25	1	—	40.00	3.50	30.25	2.07	—	1V on 1H	52.57	50	263.87	—	1	Slotted existing end sill for baffle	P36	26
																—	265.27	1			
															100	266.47	—	3			
																—	268.47	2			
															125	267.47	—	3			
																—	269.87	1			
															150	268.47	—	3			
																—	271.17	1			
															165	269.07	—	3			
																—	271.87	1			

(Sheet 3 of 5)

[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 5 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
8	5.5	264.37	9	x^2=45.56y	20.25	1	—	38.49	4.13	30.25	2.07	—	1V on 1H	52.57	50	263.87	—	1	—	P38	26
																—	265.27	1			
															100	266.47	—	1			
																—	268.47	1			
															125	267.47	—	2			
																—	269.87	1			
															150	268.47	—	1			
																—	271.17	1			
															165	269.07	—	2			
																—	271.87	1			
9	5.5	264.37	9	x^2=45.56y	20.25	2	8.30	38.49	4.13	36.35	2.07	—	1V on 1H	58.67	50	263.87	—	1	**Recommended design**	P40/F9	27
																—	265.27	1			
															100	266.47	—	1			
																—	268.47	1			
															125	267.47	—	1			
																—	269.87	1			
															150	268.47	—	1			
																—	271.17	1			
															165	269.07	—	1			
																—	271.87	1			
10	5.5	264.37	9	x^2=45.56y	20.25	2	9.12	38.49	4.13	42.45	2.07	—	1V on 1H	64.77	50	263.87	—	1	—	P42	27
																—	265.27	1			
															100	266.47	—	1			
																—	268.47	1			
															125	267.47	—	1			
																—	269.87	1			

(Sheet 4 of 5)

[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 5 (Concluded)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles				Basin Length ft	End Sill Height	End Sill Shape		Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation		Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
						Rows	Distance Between Rows ft	Location (Reference to Crest) ft	Height ft			Vertical (V)	Sloped V on H			n=0.02 ft	n=0.03 ft				
10 (Cont)	5.5	264.37	9	x^2=45.56y	20.25	2	9.12	38.49	4.13	42.45	2.07	—	1V on 1H	64.77	150	268.47	—	1	—	P42	27
																—	271.17	1			
															165	269.07	—	1			
																—	271.87	1			

(Sheet 5 of 5)

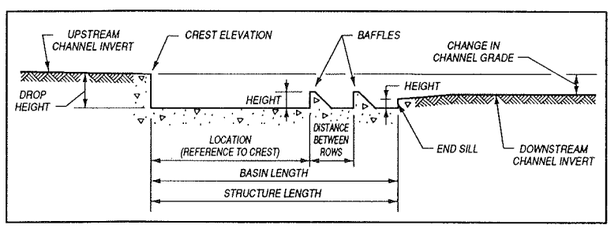
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 6
Summary of Model Test Results
Modifications to Existing Structures (Sta 836+50)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
1	9.5	203.32	12.75	—	—	1	—	32.5	6.5	47.00	3.25	V	—	47	50	198.72	—	2	—	P46	30
																—	200.12	1			
															100	201.22	—	3			
																—	203.22	3			
															130	202.52	—	3			
																—	204.92	3			
															150	203.22	—	3			
																—	205.82	3			
															175	204.12	—	3			
																—	207.02	3			
2	9.5	203.32	12.75	x^2=10y & 1V on 1H	15.25	1	—	32.5	6.5	31.75	3.25	V	—	47	50	198.72	—	2	—	P46	30
																—	200.12	1			
															100	201.22	—	3			
																—	203.22	3			

(Sheet 1 of 5)

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable



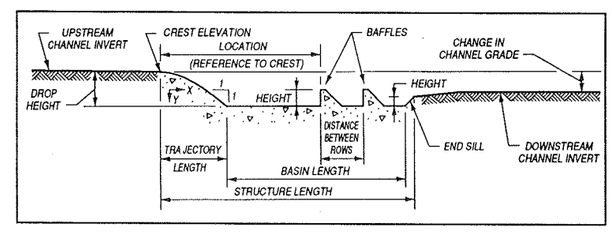


Table 6 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
2 (Cont)	9.5	203.32	12.75	x^2=10y & 1V on 1H	15.25	1	—	32.5	6.5	31.75	3.25	V	—	47.0	130	202.52	203.22	3	—	P46	30
																—	204.92	3			
															150	203.22	—	3			
																—	205.82	3			
															175	204.12	—	3			
																—	207.02	3			
3	9.5	203.32	12.75	x^2=10y & 1V on 1H	15.25	1	—	32.5	6.5	31.75	3.25	V	—	47.0	50	198.72	—	1	Chute blocks on trajectory	P47	31
																—	200.12	2			
															100	201.22	—	3			
																—	203.22	2			
															130	202.52	—	3			
																—	204.92	3			
															150	203.22	—	3			
																—	205.82	3			
															175	204.12	—	3			
																—	207.02	3			
4	9.5	203.32	12.75	x^2=10y & 1V on 1H	15.25	1	—	32.5	6.5	31.75	1.90		1V on 1H	48.9	50	198.72	—	1	—	P47	31
																—	200.12	1			
															100	201.22	—	2			
																—	203.22	1			
															130	202.52	—	3			
																—	204.92	2			

(Sheet 2 of 5)

[1] 1 = Acceptable
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3 = Unacceptable

Table 6 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
4 (Cont)	9.5	203.32	12.75	x^2=10y & 1V on 1H	15.25	1	—	32.5	6.5	31.75	1.9	—	1V on 1H	48.90	150	203.22	—	3	—	P47	31
																—	205.82	3			
															175	204.12	—	3			
																—	207.02	3			
5	9.5	203.32	12.75	x^2=10y & 1V on 1H	15.25	2	14.5	32.5	3.8	43.80	1.9	—	1V on 1H	60.95	50	198.72	—	2	—	P48	31
																—	200.12	2			
															100	201.22	—	3			
																—	203.22	2			
															130	202.52	—	3			
																—	204.92	2			
															150	203.22	—	3			
																—	205.82	3			
															175	204.12	—	3			
																—	207.02	3			
6	9.5	203.32	12.75	x^2=10y & 1V on 1H	15.25	2	14.5	32.5	6.5/3.8	43.80	1.9	—	1V on 1H	60.95	50	198.72	—	2	—	P48	32
																—	200.12	1			
															100	201.22	—	2			
																—	203.22	2			
															130	202.52	—	3			
																—	204.92	3			
															150	203.22	—	3			
																—	205.82	3			
															175	204.12	—	3			
																—	207.02	3			

(Sheet 3 of 5)

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Table 6 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
7	9.5	203.32	12.75	x^2=47y	24.50	1	—	47	3.9	37.50	1.95	—	1V on 1H	63.95	50	198.72	—	1	—	P49	32
																—	200.12	1			
															100	201.22	—	1			
																—	203.22	1			
															130	202.52	—	1			
																—	204.92	1			
															150	203.22	—	2			
																—	205.82	2			
															180	204.50	—	3			
																—	207.60	2			
8	9.5	203.32	12.05	x^2=30y & 1V on 1H	20.25	1	—	47	5.1	44.50	2.55	—	1V on 1H	67.30	50	198.72	—	1	—	P50	32
																—	200.12	1			
															100	201.22	—	1			
																—	203.22	1			
															130	202.52	—	1			
																—	204.92	1			
															150	203.22	—	2			
																—	205.82	1			
															180	204.50	—	2			
																—	207.60	1			
9	9.5	203.32	12.05	x^2=30y & 1V on 1H	20.25	2	13.35	47	5.1	53.45	2.55	—	1V on 1H	76.25	50	198.72	—	1	**Recommended design**	F10	33
																—	200.12	1			
															100	201.22	—	1			
																—	203.22	1			

(Sheet 4 of 5)

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3 = Unacceptable

Table 6 (Concluded)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
9 (Cont)	9.5	203.32	12.05	x^2=30y & 1V on 1H	20.25	2	13.35	47	5.1	53.45	2.55	—	1V on 1H	76.25	130	202.52	—	1	—	F10	33
																—	204.92	1			
															150	203.22	—	1			
																—	205.80	1			
															180	204.50	—	1			
																—	207.60	1			
10	9.5	203.32	12.05	x^2=30y & 1V on 1H	20.25	2	13.35	47	5.1	62.30	2.55	—	1V on 1H	85.10	50	198.72	—	1	—	P52	33
																—	200.12	1			
															100	201.22	—	1			
																—	203.22	1			
															130	202.52	—	1			
																—	204.92	1			
															150	203.22	—	1			
																—	205.80	1			
															180	204.50	—	1			
																—	207.60	1			

(Sheet 5 of 5)

[1] 1 = Acceptable
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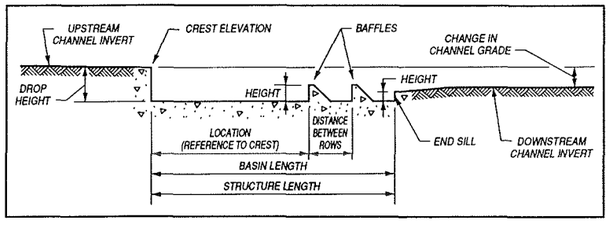
Table 7
Summary of Model Test Results
Modifications to Existing Structures (Sta 884+00)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
1	4.5	217.37	7.5	—	—	—	—	—	—	40.58	3.00	V	—	40.58	50	218.08	—	1	CIT design	P53	33
																—	219.38	1			
															100	220.58	—	1			
																—	222.58	3			
															125	221.58	—	2			
																—	223.88	3			
															150	222.58	—	3			
																—	225.08	3			
															165	223.08	—	3			
																—	225.78	3			
2	4.5	217.37	7.5	$x^2=62.20y$	21.6	1	—	40.6	4.45	30.65	2.22	—	1V on 1H	54.47	50	218.08	—	1	—	P54	35
																—	219.38	1			
															100	220.58	—	1			
																—	222.58	1			
															125	221.58	—	1			
																—	223.88	1			

(Sheet 1 of 3)

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable



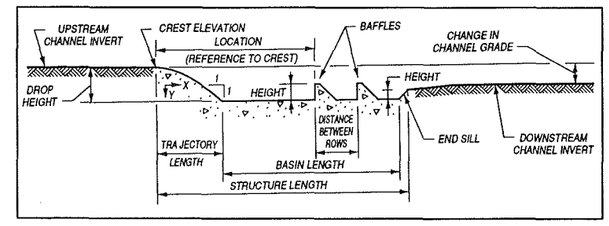


Table 7 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
2 (Cont)	4.5	217.37	7.5	x^2=62.20y	21.60	1	—	40.6	4.45	30.65	2.22	—	1V on 1H	54.47	150	222.58	—	2	—	P54	35
																—	225.08	1			
															165	223.08	—	2			
																—	225.78	1			
3	4.5	217.37	7.5	x^2=19.58y	12.12	1	—	40.6	4.45	40.13	2.22	—	1V on 1H	54.47	50	218.08	—	1	—	P56	35
																—	219.38	1			
															100	220.58	—	1			
																—	222.58	1			
															125	221.58	—	2			
																—	223.88	3			
															150	222.58	—	2			
																—	225.08	2			
															165	223.08	—	2			
																—	225.78	3			
4	4.5	217.37	7.5	x^2=62.20y	21.60	2	9.5	40.6	4.45	38.40	2.22	—	1V on 1H	62.22	50	218.08	—	1	**Recommended design**	F11	35
																—	219.38	1			
															100	220.58	—	1			
																—	222.58	1			
															125	221.58	—	1			
																—	223.88	1			
															150	222.58	—	1			
																—	225.08	1			
															165	223.08	—	1			
																—	225.78	1			

(Sheet 2 of 3)

[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 7 (Concluded)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
5	4.5	217.37	7.5	x^2=62.20y	21.6	2	9.5	40.6	4.45	44.3	2.22	—	1V on 1H	68.12	50	218.08	—	1	—	P58	36
																—	219.38	1			
															100	220.58	—	1			
																—	222.58	1			
															125	221.58	—	1			
																—	223.88	1			
															150	222.58	—	1			
																—	225.08	1			
															165	223.08	—	1			
																—	225.78	1			
6	4.5	217.37	7.5	x^2=23.60y	13.3	2	9.5	32.3	4.45	38.0	2.22	—	1V on 1H	53.52	50	218.08	—	1	—	P59	36
																—	219.38	1			
															100	220.58	—	2			
																—	222.58	2			
															125	221.58	—	2			
																—	223.88	3			
															150	222.58	—	3			
																—	225.08	3			
															165	223.08	—	3			
																—	225.78	3			

(Sheet 3 of 3)

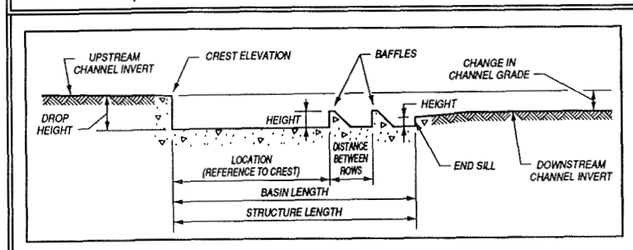
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 8
Summary of Model Test Results
Modifications to Existing Structures (Sta 593+35)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
1	7	113.44	10	—	—	1	—	38.17	6.67	49.5	3.0	V	—	49.5	50	111.04	—	1	—	P60	37
																—	112.24	1			
															100	113.34	—	2			
																—	115.24	3			
															125	114.34	—	2			
																—	116.54	3			
															165	115.74	—	3			
																—	118.34	3			
															215	117.34	—	3			
																—	120.34	3			
2	7	113.44	10	x^2=28.40y & 1V on 1H	17.1	2	11.9	40.90	5.00	47.6	2.5	—	1V on 1H	67.2	50	111.04	—	1	**Recommended design**	F12	38
																—	112.24	1			
															100	113.34	—	1			
																—	115.24	1			

(Continued)

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable



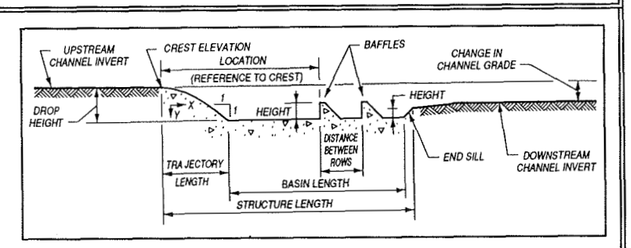


Table 8 (Concluded)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles				Basin Length ft	End Sill Height	End Sill Shape		Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation		Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
						Rows	Distance Between Rows ft	Location (Reference to Crest) ft	Height ft			Vertical (V)	Sloped V on H			n=0.02 ft	n=0.03 ft				
2 (Cont)	7	113.44	10	x^2=28.40y & 1V on 1H	17.1	2	11.9	40.9	5	47.6	2.5	—	1V on 1H	67.2	125	114.34	—	1	Recommended design	F12	38
																—	116.54	1			
															165	115.74	—	1			
																—	118.34	1			
															215	117.34	—	1			
																—	120.34	2			

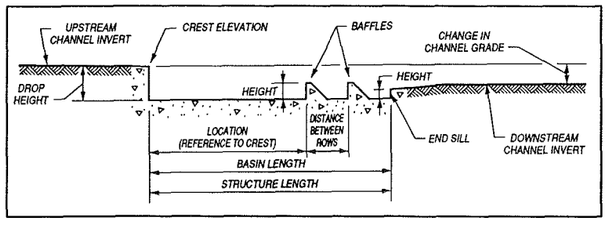
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable

Table 9
Summary of Model Test Results
Modifications to Existing Structures (Sta 1198+08)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
1	4.29	313.5	6.79	—	—	—	—	—	—	48.00	2.5	V	—	48.0	50	314.41	—	1	—	P61	39
																—	315.91	3			
															100	317.11	—	2			
																—	319.31	3			
															125	318.21	—	3			
																—	320.71	3			
															150	319.31	—	3			
																—	322.01	3			
															165	319.91	—	3			
																—	322.88	3			
2	4.29	313.5	6.79	x^2=12.50y & 1V on 1H	9.92	2	9.52	28.96	4.5	38.08	2.5	—	1V on 5H	60.5	50	314.41	—	1	**Recommended design for unit discharge up to 125 cfs/ft**	P61, F13	39
																—	315.91	1			
															100	317.11	—	1			
																—	319.31	1			

(Sheet 1 of 3)

Note: Recommended design was based on observations, velocity measurements, and economics.
[1] 1 = Acceptable
2 = Marginal
3 = Unacceptable



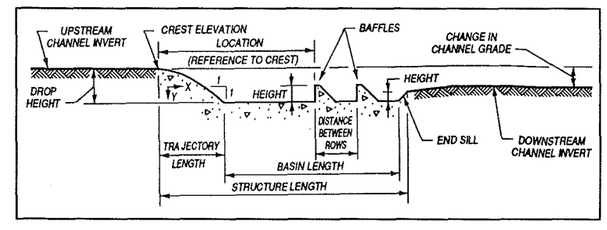


Table 9 (Continued)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles: Rows	Baffles: Distance Between Rows ft	Baffles: Location (Reference to Crest) ft	Baffles: Height ft	Basin Length ft	End Sill Height	End Sill Shape: Vertical (V)	End Sill Shape: Sloped V on H	Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation: n=0.02 ft	Tailwater Elevation: n=0.03 ft	Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
2 (Cont)	4.29	313.5	6.79	x^2=12.50y & 1V on 1H	9.92	2	9.52	28.96	4.5	38.08	2.5	—	1V on 5H	60.5	125	318.21	—	1	**Recommended design for unit discharge up to 125 cfs/ft**	P61, F13	39
																—	320.71	1			
															150	319.31	—	1			
																—	322.01	2			
															165	319.91	—	2			
																—	322.88	2			
															200	—	324.26	3			
															250	—	326.36	3			
3	4.29	313.5	6.79	x^2=37.40y	15.94	2	13.90	43.70	8.0	55.56	2.5	—	1V on 5H	84.0	50	314.41	—	1	—	P62	40
															125	318.21	—	1			
															165	319.91	—	3			
															250	—	326.36	3			
															290	—	327.70	3			
4	4.29	313.5	14.00	x^2=41.32y & 1V on 1H	24.30	2	17.20	58.70	7.4	68.80	3.7	—	1V on 1H	96.8	100	—	319.31	3	Downstream invert channel el 309.21	P63	40
															150	—	322.01	3			
															200	—	324.26	3			
															250	—	326.36	3			
															290	—	327.70	3			
5	10.30	313.5	14.00	x^2=41.32y & 1V on 1H	24.30	2	17.20	58.70	7.4	68.80	3.7	—	1V on 1H	96.8	50	308.40	—	1	**Recommended design for unit discharge up to 290 cfs/ft; Downstream invert channel el 303.2**	P63, F13	41
																—	309.90	1			
															125	312.20	—	1			
																—	314.70	1			
															165	313.90	—	1			
																—	316.80	1			

(Sheet 2 of 3)

[1] 1 = Acceptable
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Table 9 (Concluded)

Type	Change in Channel Grade ft	Crest El, ft	Drop Height ft	Trajectory Equation	Trajectory Length ft	Baffles				Basin Length ft	End Sill Height	End Sill Shape		Structure Length ft	Unit Discharge cfs/ft	Tailwater Elevation		Hydraulic Performance[1]	Additional Information	Plate (P) or Figure (F) Reference	Page No.
						Rows	Distance Between Rows ft	Location (Reference to Crest) ft	Height ft			Vertical (V)	Sloped V on H			n=0.02 ft	n=0.03 ft				
5 (Cont)	10.30	313.5	14.0	x^2=41.32y & IV on 1H	24.3	2	17.2	58.7	7.4	68.8	3.7	—	1V on 1H	96.8	200	—	318.23	1	Recommended design for unit discharge up to 290 cfs/ft; downstream invert channel el 303.2	P63, F13	41
															250	—	320.4	1			
															290	—	321.7	1			

(Sheet 3 of 3)

[1] 1 = Acceptable
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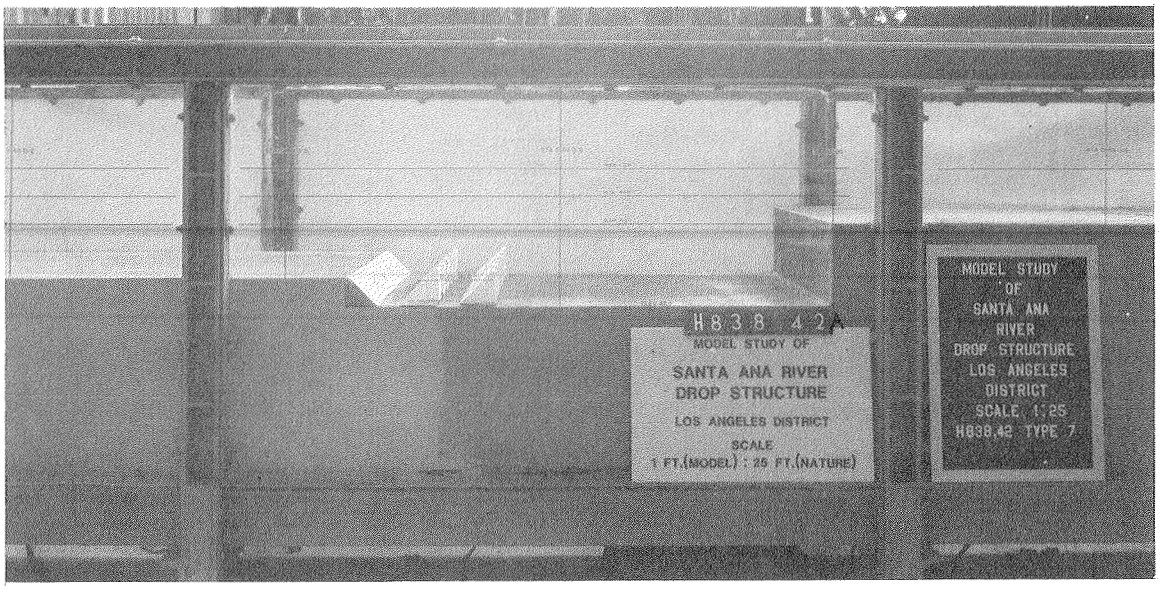
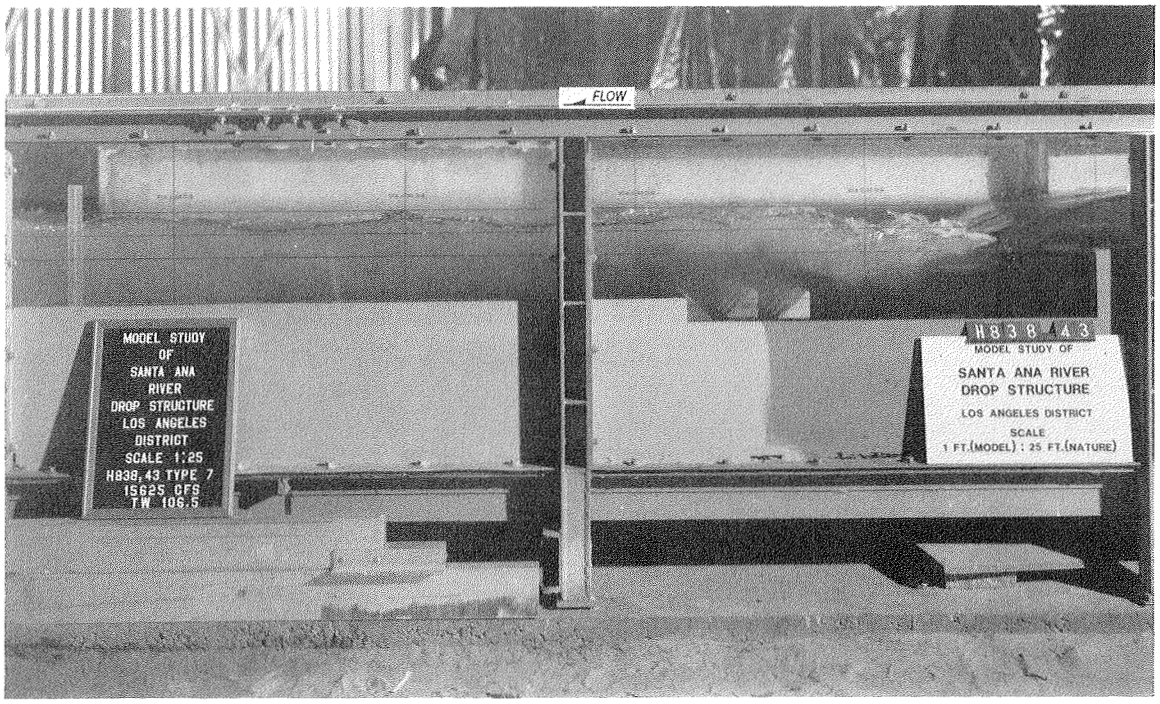
3 = Unacceptable



a. Dry bed



b. Unit discharge 250 cfs/ft, tailwater el 106.5

Photo 8. Type 7 design drop structure

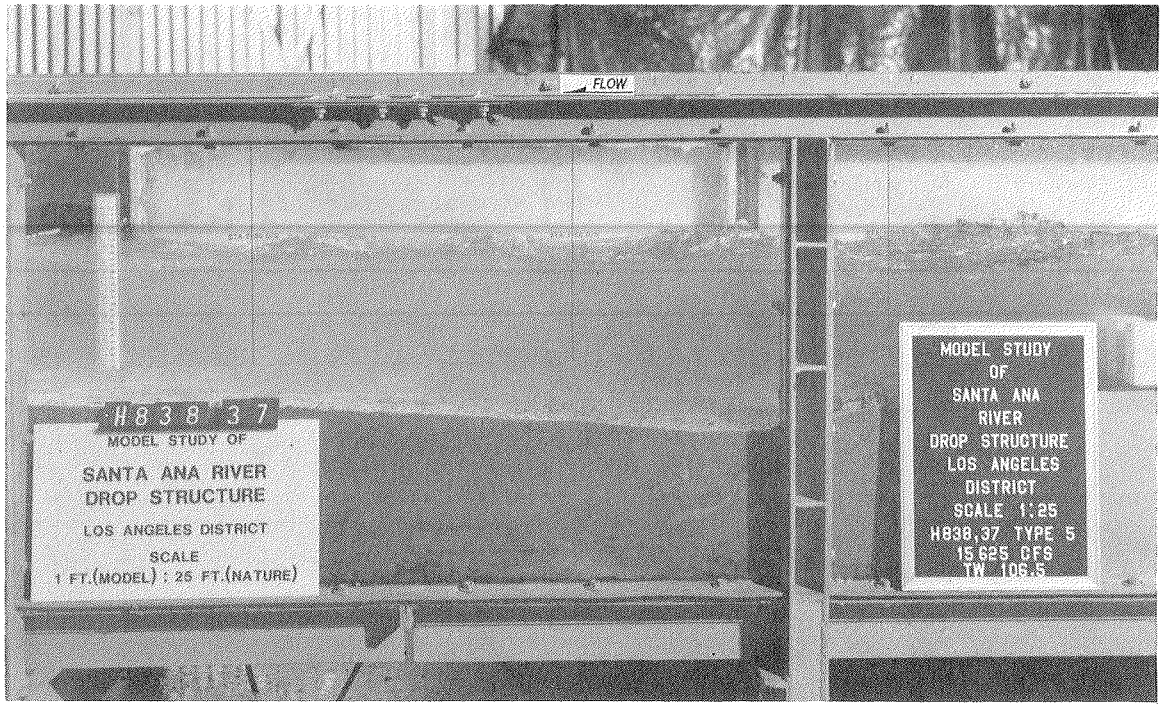
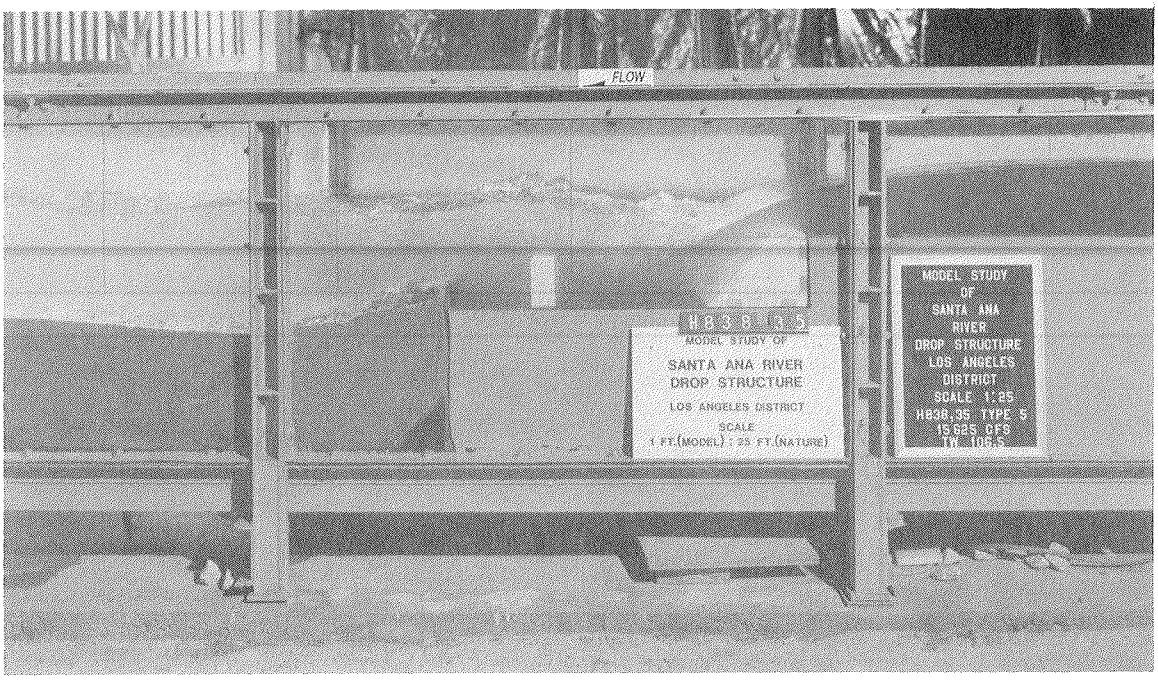


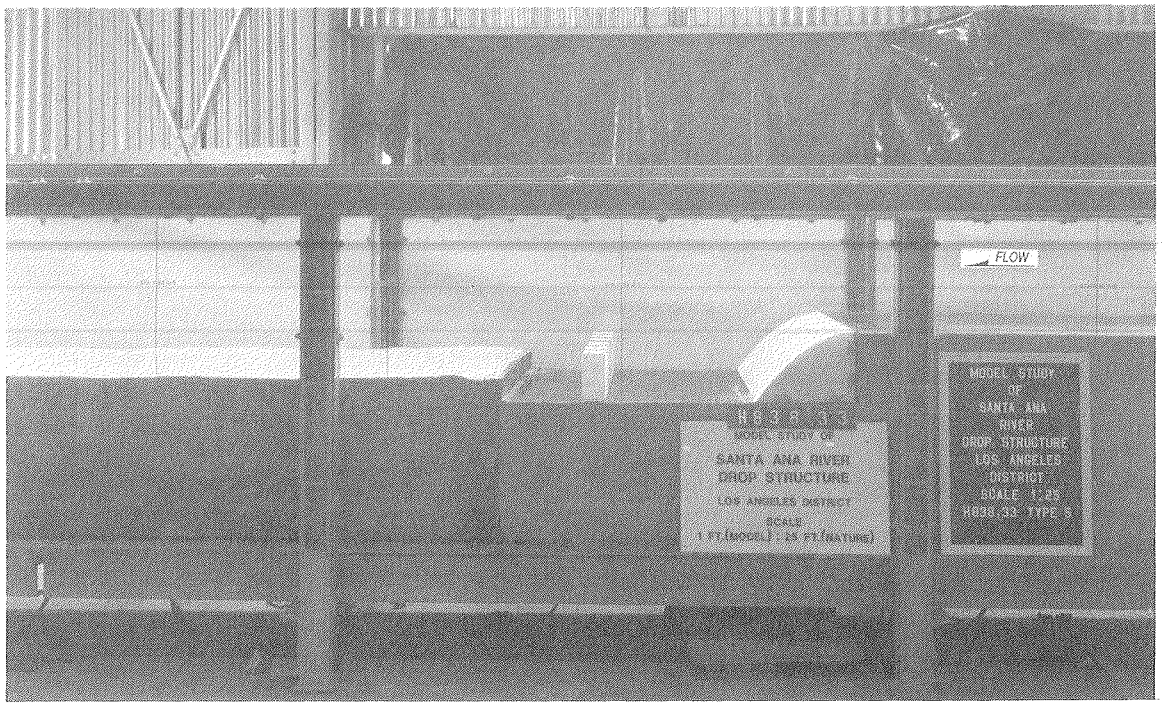
Photo 7. Type 5 design drop structure; unit discharge 250 cfs/ft, tailwater el 106.5



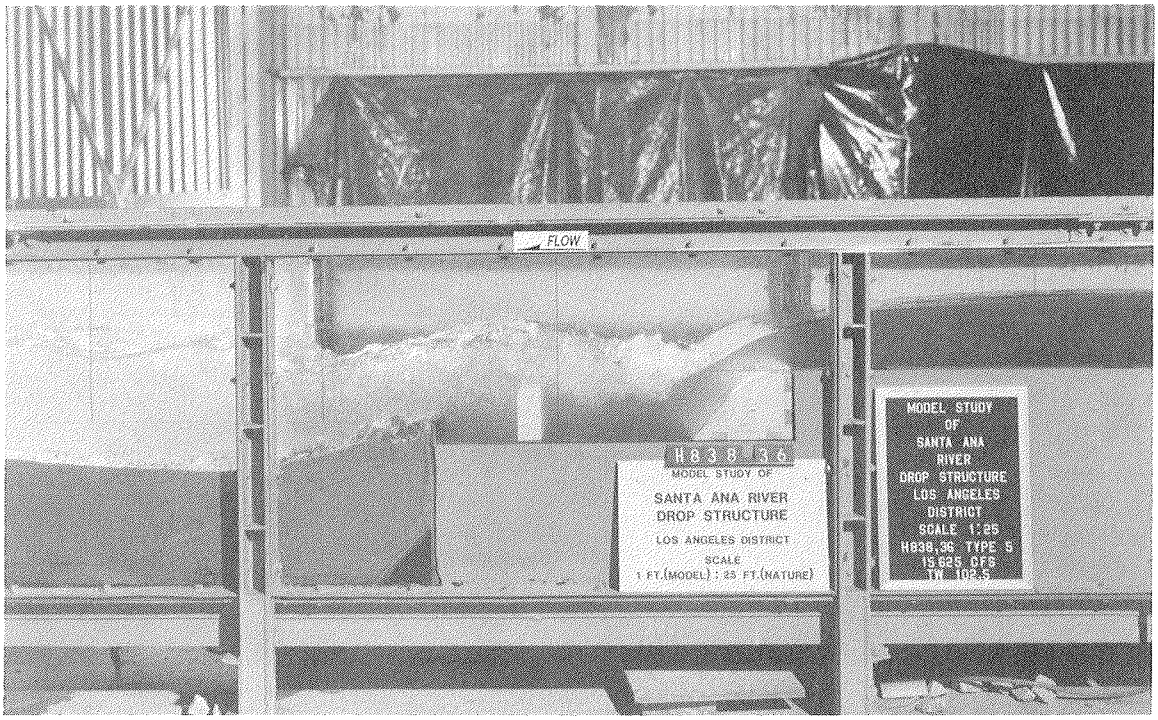
c. Tailwater el 106.5 (normal)

d. Tailwater el 108.35 (maximum)

Photo 6. (Concluded)

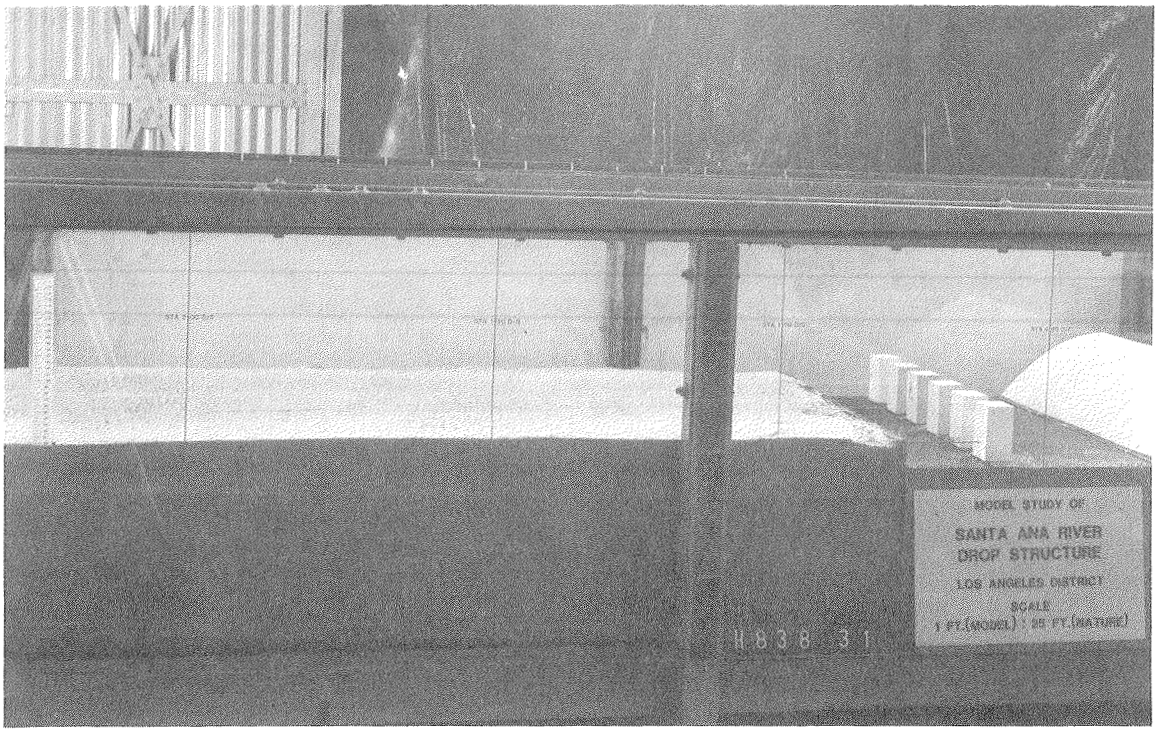


a. Dry bed

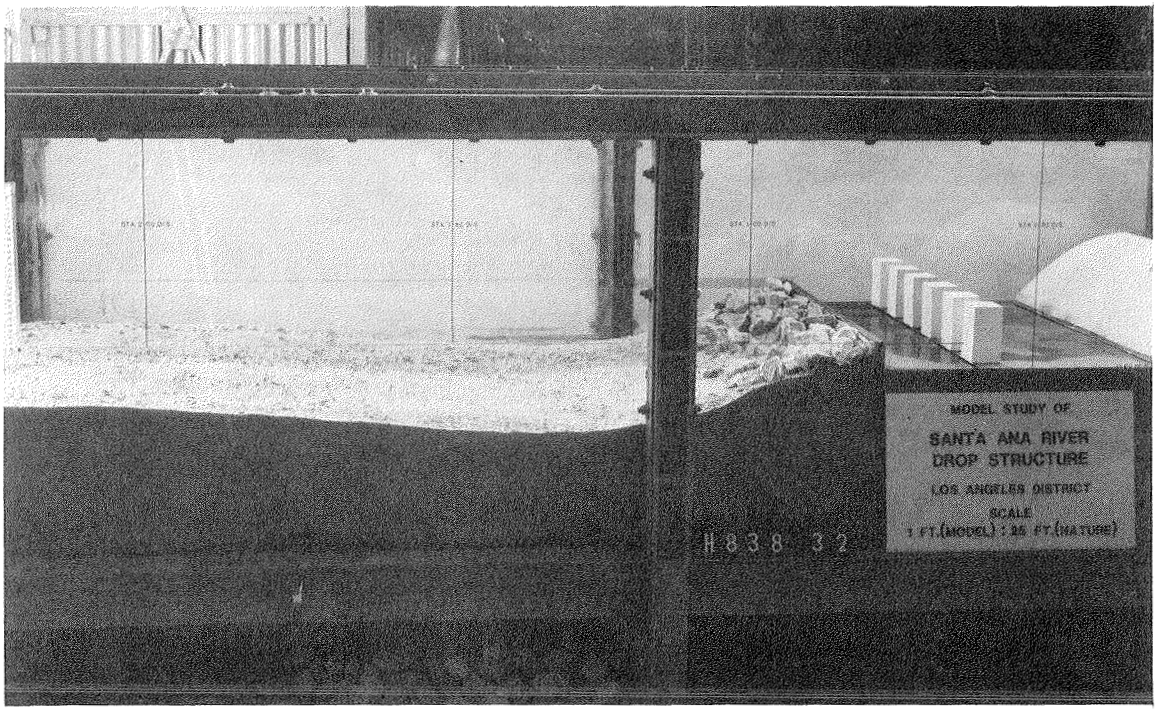


b. Tailwater el 102.5 (minimum)

Photo 6. Flow conditions in the type 5 design drop structure (10-ft drop) with unit discharge 250 cfs/ft (Continued)

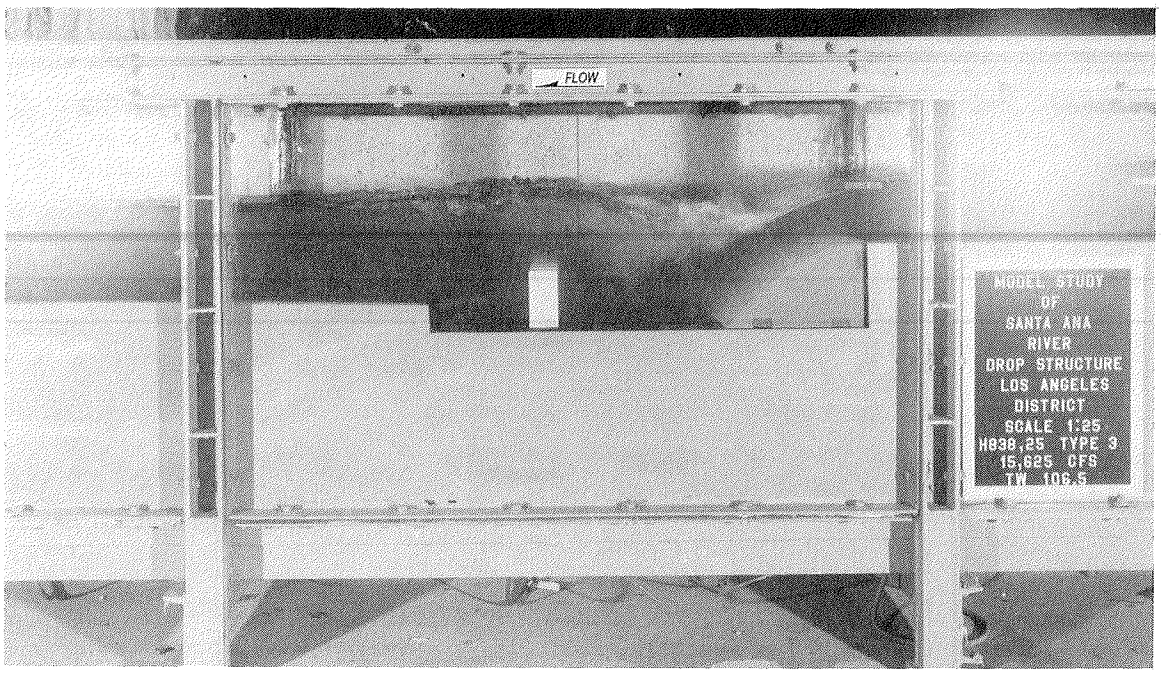


a. Dry bed

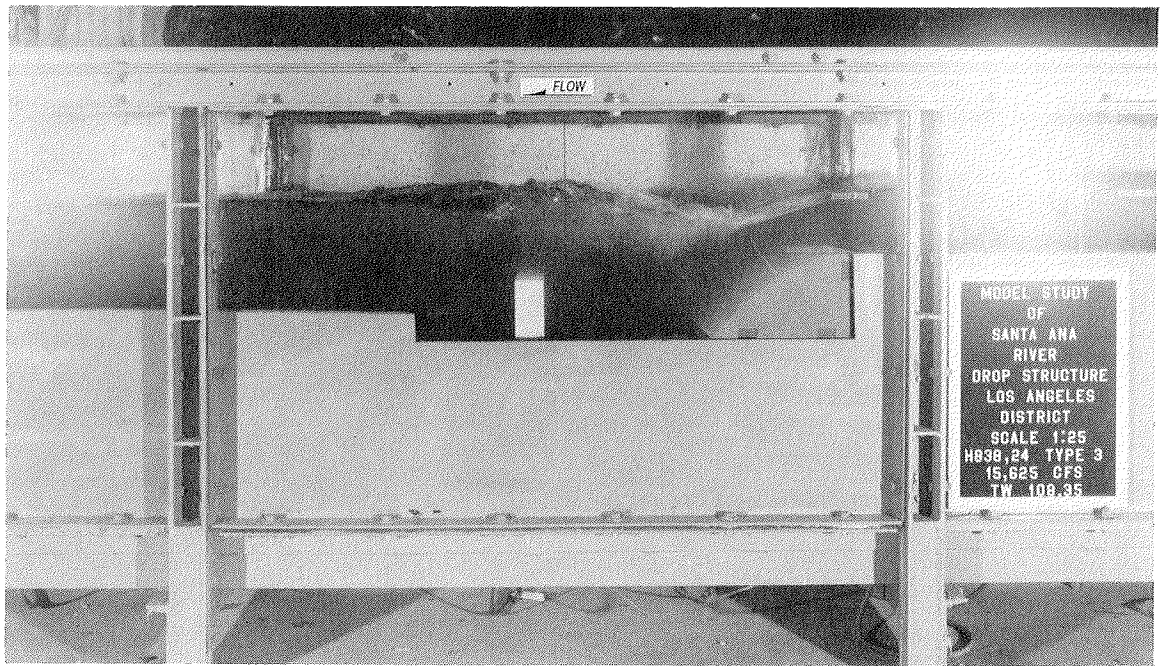


b. Scour test results

Photo 5. Type 3 design drop structure and scour test results

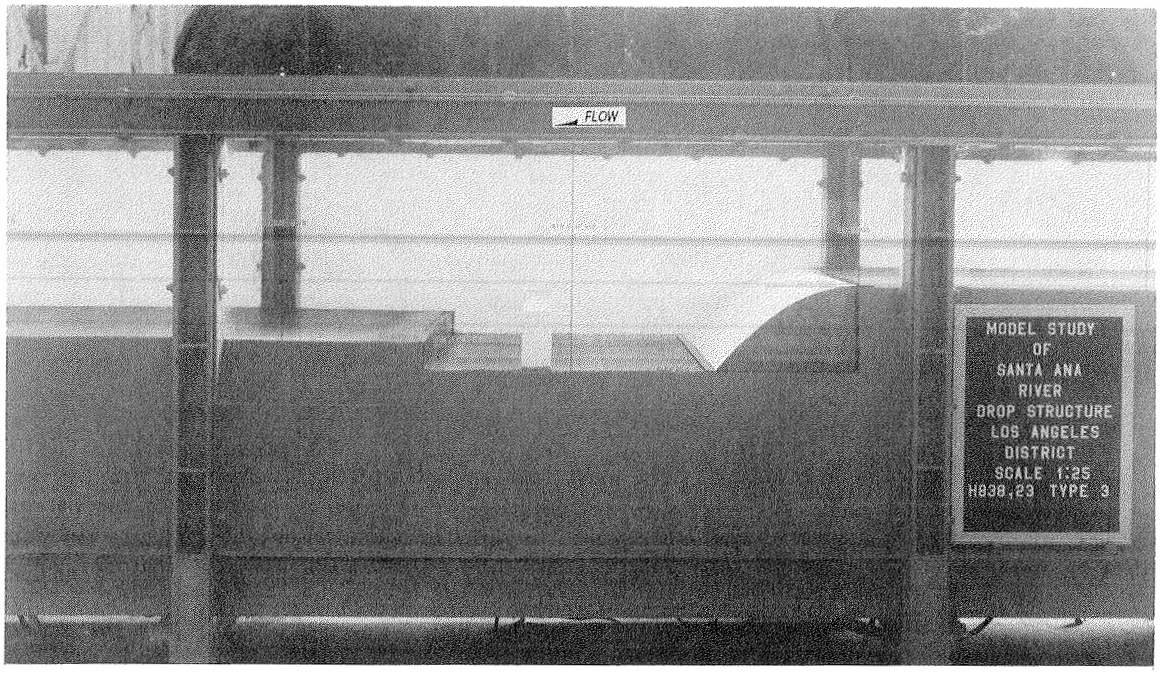


c. Tailwater el 106.5 (normal)

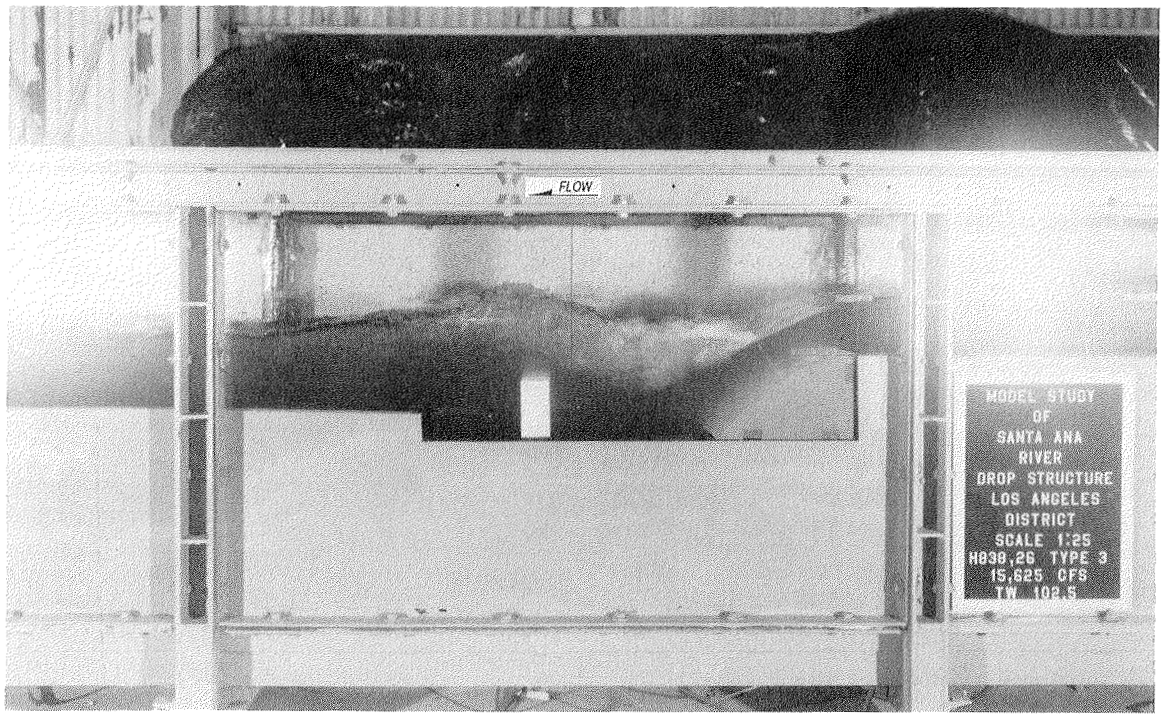


d. Tailwater el 108.35 (maximum)

Photo 4. (Concluded)

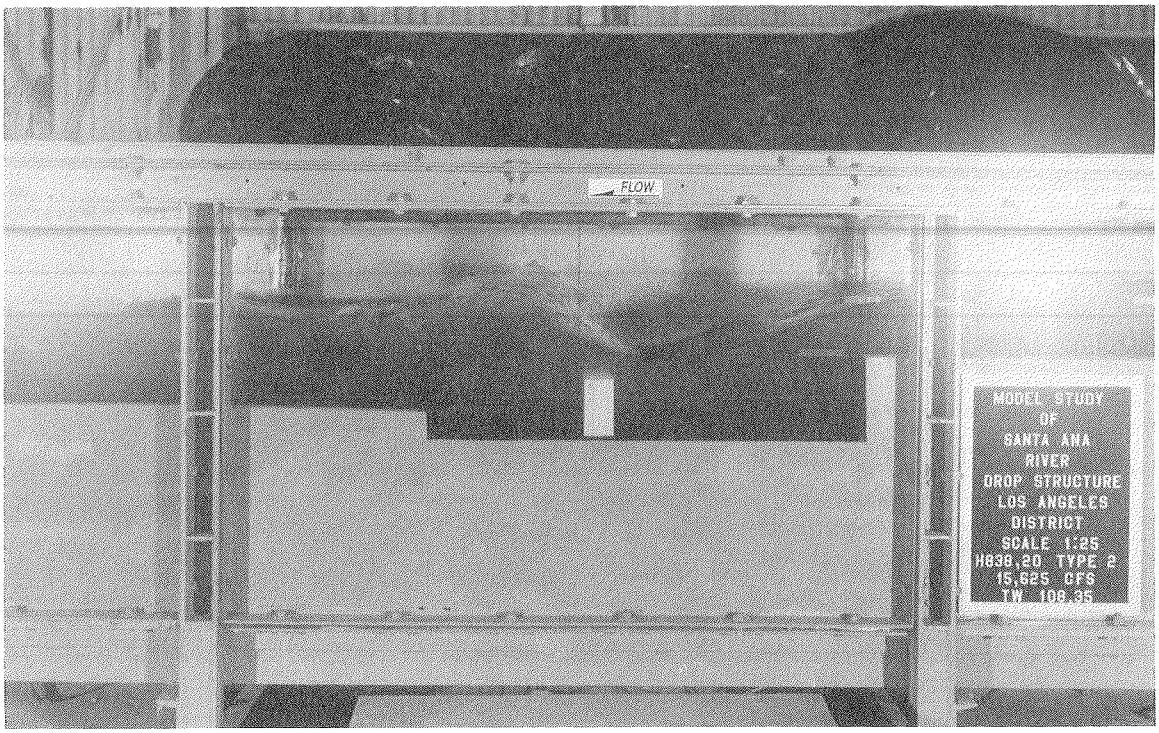


a. Dry bed



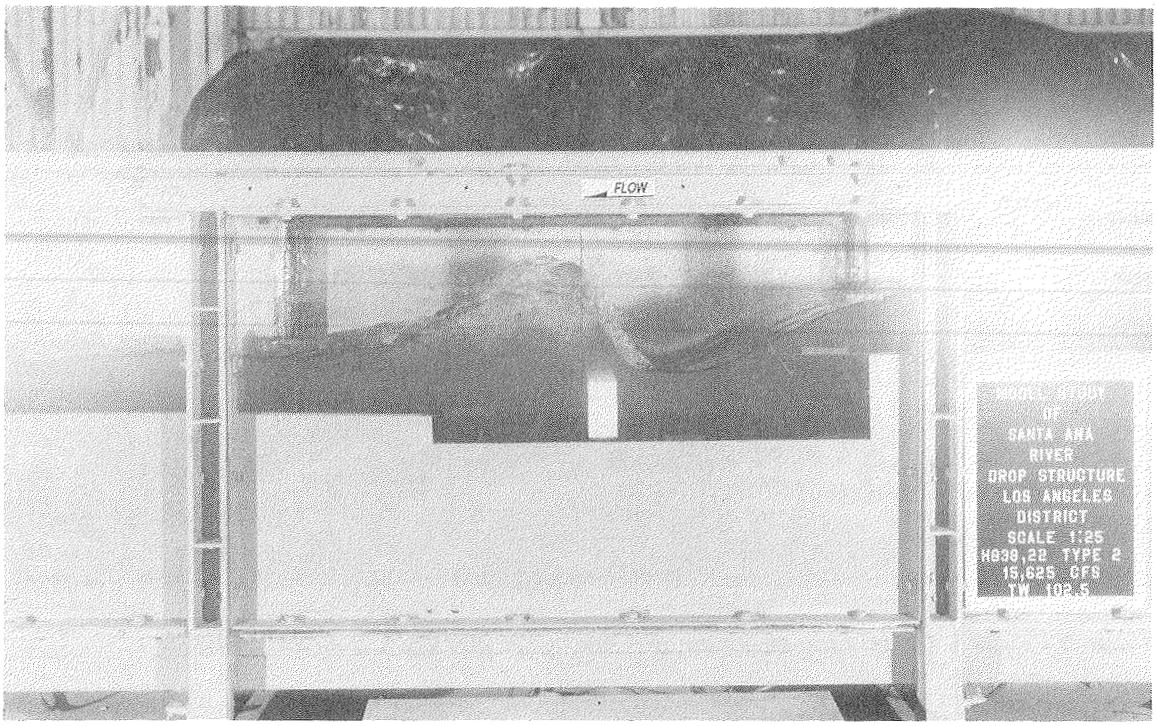
b. Tailwater el 102.5 (minimum)

Photo 4. Flow conditions in the type 3 design drop structure (10-ft drop) with unit discharge 250 cfs/ft (Continued)

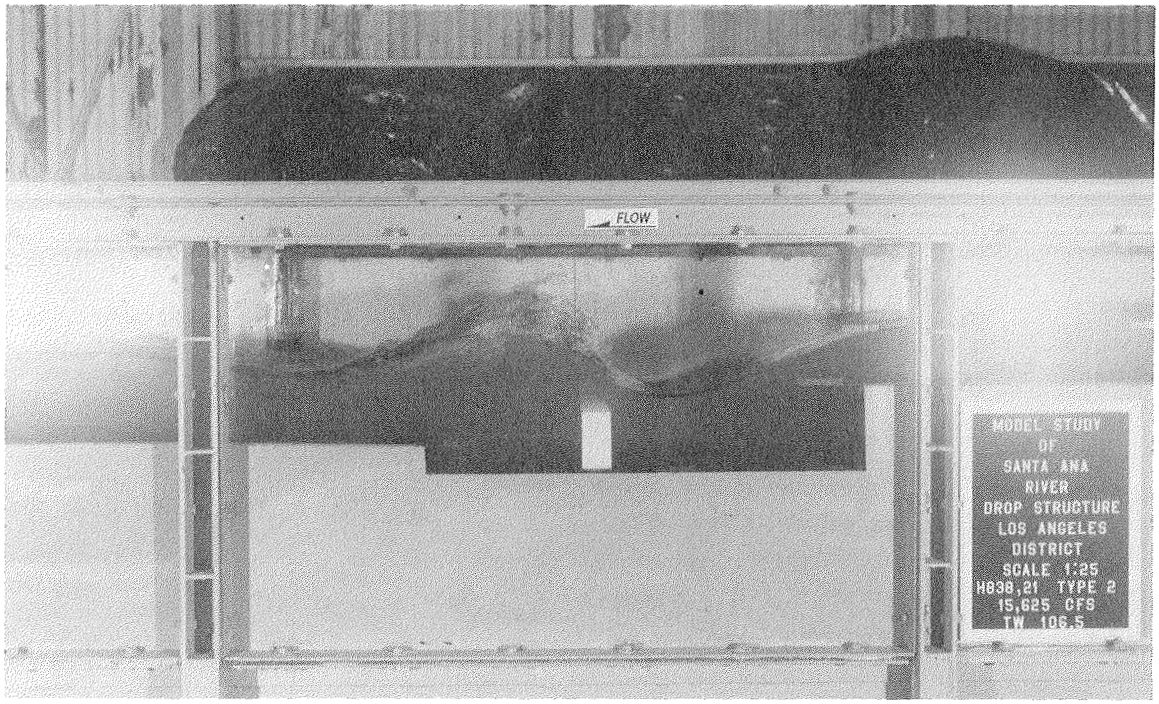


c. Tailwater el 108.35 (maximum)

Photo 3. (Concluded)



a. Tailwater el 102.5 (minimum)



b. Tailwater el 106.5 (normal)

Photo 3. Flow conditions in the type 2 design drop structure with unit discharge 250 cfs/ft (Continued)

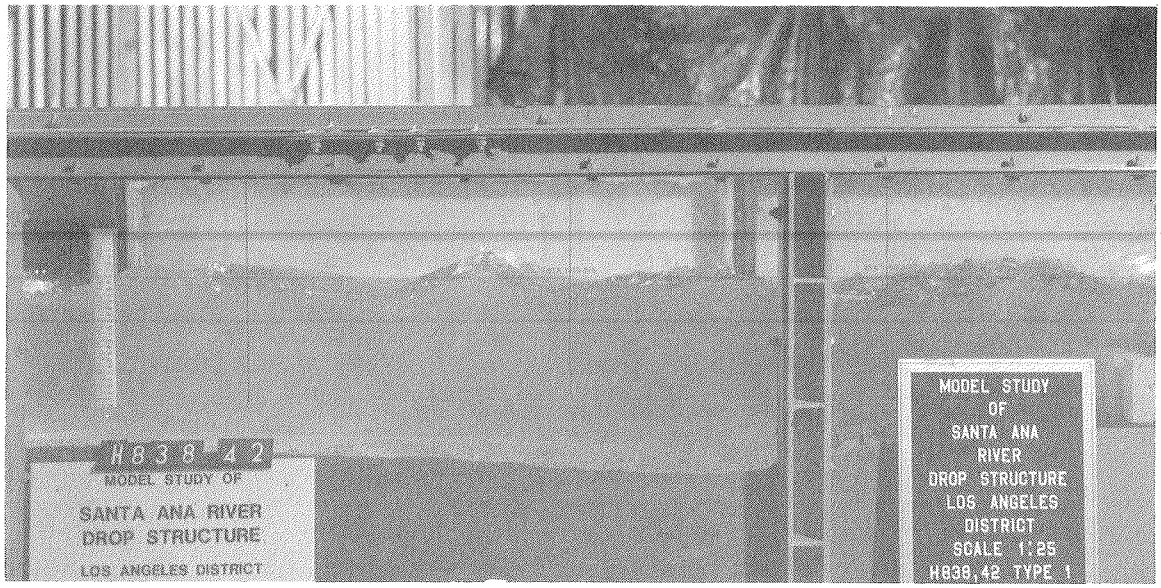
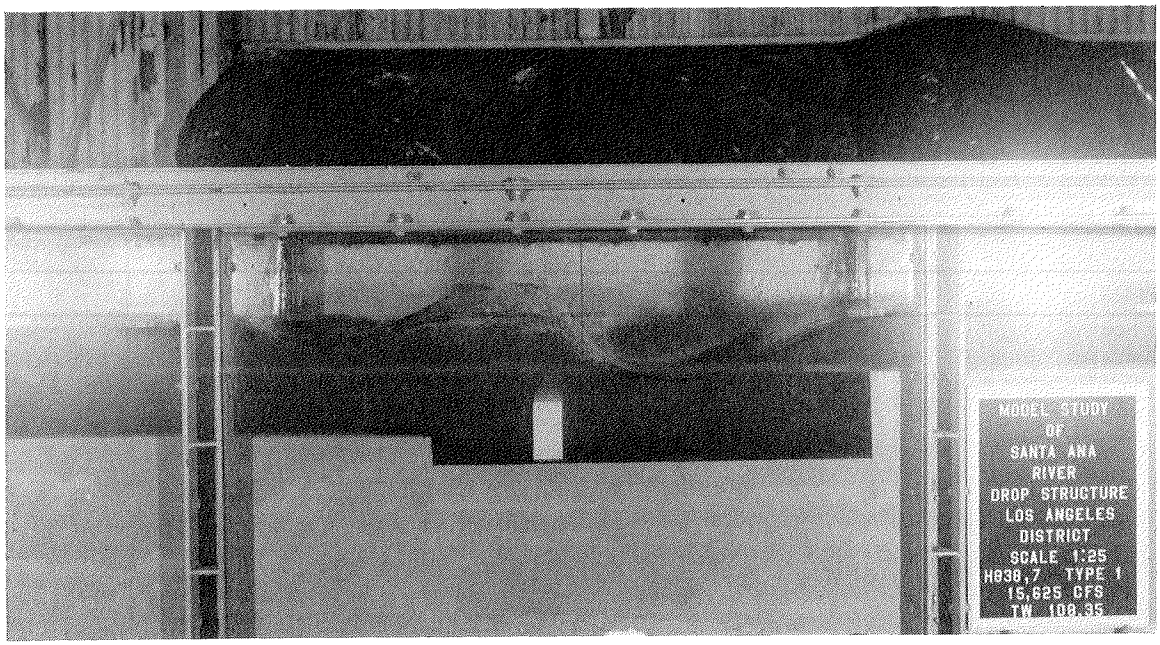
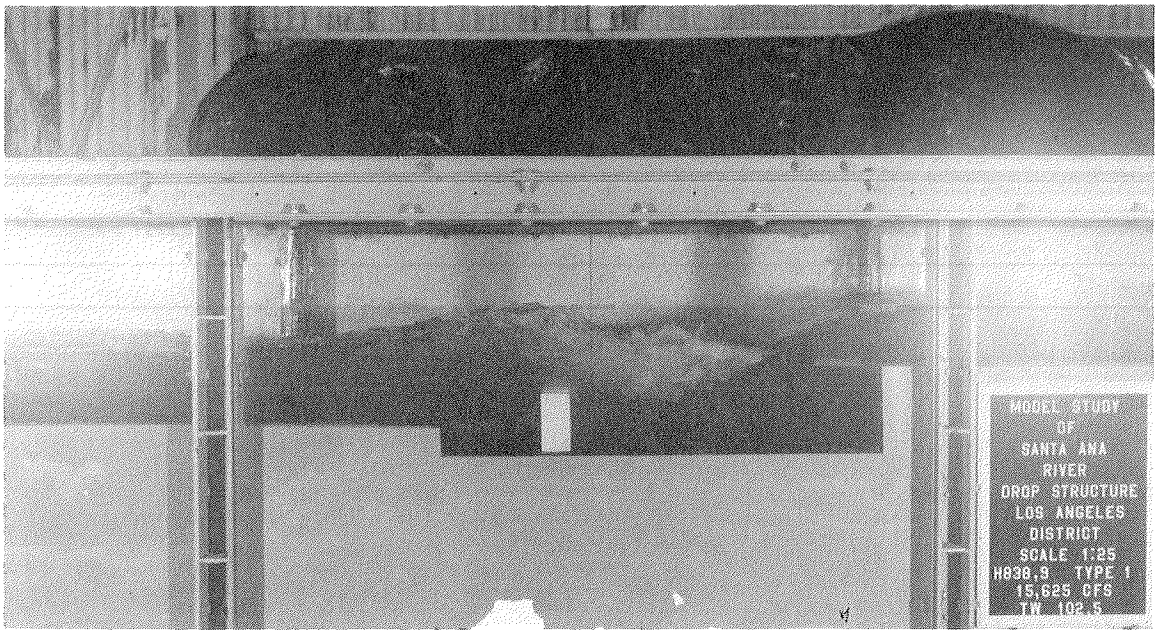


Photo 2. Type 1 design drop structure; unit discharge 250 cfs/ft, tailwater el 106.5

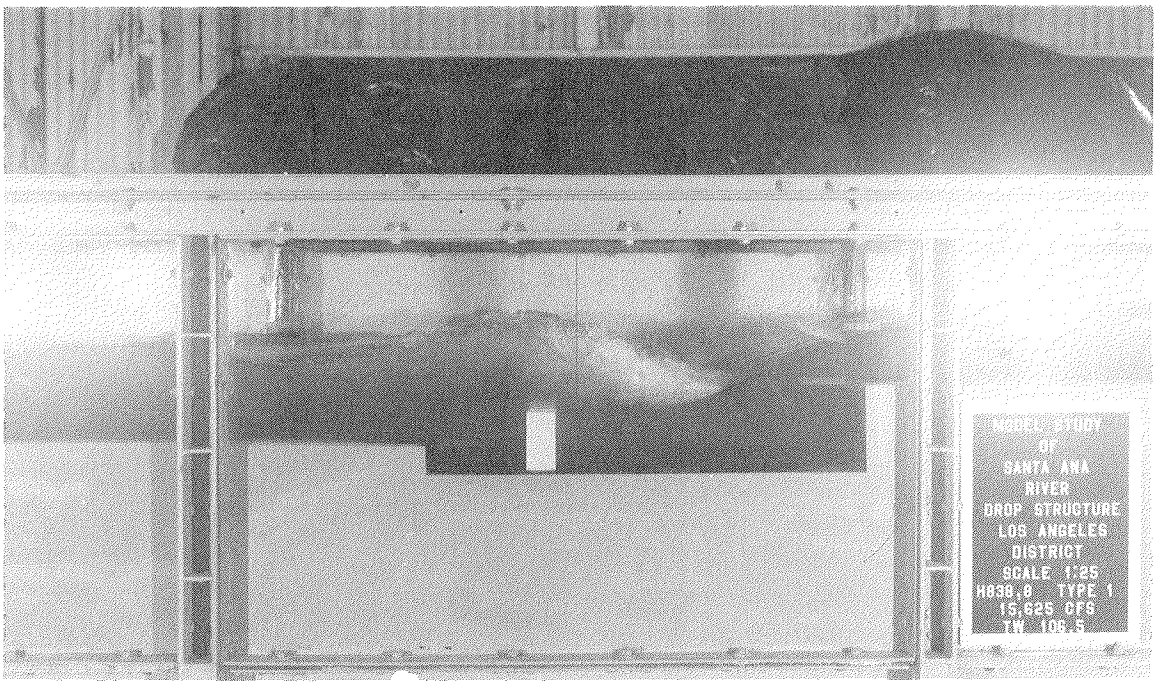


c. Tailwater el 108.35 (maximum)

Photo 1. (Concluded)



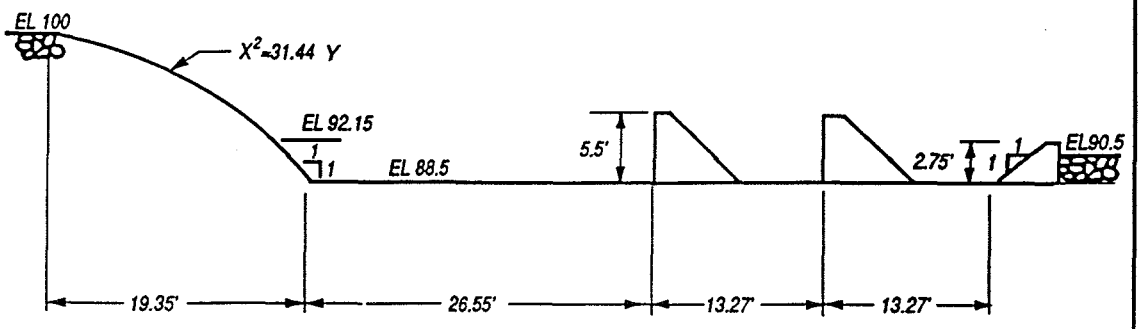
a. Tailwater el 102.5 (minimum)



b. Tailwater el 106.5 (normal)

Photo 1. Flow conditions in the type 1 design drop structure with unit discharge 250 cfs/ft (Continued)

Table 11 (Concluded)



DROP STRUCTURE FOR EXAMPLE PROBLEM NUMBER 2

Submergence:

h_c = tailwater elevation - crest elevation = 106.2 - 100 = 6.2 ft
h_c/d_c = 6.2/10.46 = <u>0.59</u>

Froude number entering basin:

$V_1 = q/d_1$ = 192/5.5 = 34.91 ft/sec
$F_1 = V_1/(gd_1)^{0.50}$ = 34.91/(32.2 × 5.5)$^{.50}$ = <u>2.62</u>

From Plates 64 and 65 it appears that good energy dissipation could be expected with this design.

Table 11
Example Design Problem 2

Design Conditions

Change in channel grade = 9.5 ft
Elevation of upstream channel (crest) = 100
Tailwater elevation = 106.2
Unit discharge = 192 cfs/ft

Design Computations

Critical depth: $d_c = (q^2/g)^{1/3} = [(192)^2/32.2]^{1/3} = \underline{10.46 \text{ ft}}$
Design head: $H = 1.5\ d_c = \underline{15.7 \text{ ft}}$
Parabolic crest profile: $X^2 = KHY = 2(15.7)Y$
$X^2 = \underline{31.4Y}$

Drop height: Assume a value of h

Assume h = 10 ft

Floor elevation = 100 - 10 = 90

$$D = q^2/gh^3 = 1.145$$
$$d_2/h = 1.66\ (D)^{0.27} = 1.66(1.145)^{0.27} = 1.722$$
$$d_2 = 10 \times 1.722 = \underline{17.22 \text{ ft}}$$

Depth of tailwater over floor = 106.2 - 90.0 = 16.2 ft
Since available tailwater (16.2 ft) is less than d_2 (17.22 ft), basin floor is too high

Assume h = 11.5 ft

Floor elevation = 100 - 11.5 = 88.5

$$D = q^2/gh^3 = (192)^2/32.2(11.5)^3 = 0.753$$
$$d_2/h = 1.66(0.753)^{0.27} = 1.54$$
$$d_2 = 11.5 \times 1.54 = 17.68$$

Depth of tailwater over floor = 106.2 - 88.5 = 17.7 ft
Since 17.7 ft ≈ 17.7 ft, use floor elevation 88.5
Basin design: with h = 11.5 ft and d_2 = 17.68 ft

$$d_1/h = 0.54(D)^{0.425} = 0.54\ (0.753)^{0.425} = 0.479$$
$$d_1 = 0.479 \times 11.5 = 5.50 \text{ ft}$$

Baffle block height = d_1 = 5.50 ft
End sill height = $0.5d_1$ = 2.75 ft
Basin length = $3d_2$ = 53.1 ft; use 53 ft
Parabolic curve shape: $X^2 = 31.4Y$
From example problem No. 1 (Table 10) curve shape reaches 1V on 1H when X = 15.7 and Y = 7.85
Since h = 11.5, the distance of 1V on 1H slope is 11.5 - 7.85 = 3.65 ft
Length of drop curve = 15.7 + 3.65 = 19.35 ft
Details of this design are shown in the following sketch.

(Continued)

Table 10 (Concluded)

From Figure 14:

Baffle block height = d_1 = 6.2 ft

End sill height = 0.5 d_1 = 3.1 ft

Basin length = $3d_2$ = 3 × 16.3 = 48.9 ft

Parabolic curve shape: $X^2 = 31.4\,Y$

To determine where curve reaches 1V on 1H slope, take first derivative of equation and make $dY/dX = 1/1 = 1.0$

$$X^2 = 31.4Y$$

$$2X\,dX = 31.4\,dY$$

$$dy/dX = \frac{2X}{31.4} = 0.0637X = 1$$

$X = 15.7$ (this is the value of X when curve reaches 1 on 1)

with $X = 15.7$ in parabolic curve

$$(15.7)^2 = 31.4\,Y$$

$$Y = 7.85$$

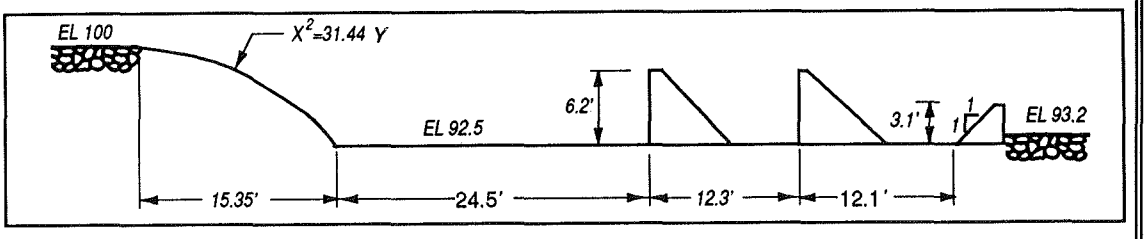
Since $h = 7.5$, which is less than 7.85, the parabolic curve will not reach 1V on 1H slope before it intersects the basin floor.

Length of curve is X value when $Y = h = 7.5$

$$X^2 = 31.4(7.5) = 235.5$$

$$X = \underline{15.35\text{ ft}}$$

Details of this design are shown in the following sketch:



Submergence: Depth of tailwater above crest h_c/critical depth d_c

h_c = 108.9 - 100 = 8.9 ft

d_c = 10.46 ft

h_c/d_c = 8.9/10.46 = 0.85

Froude number entering basin: $V_1/(gd_1)^{0.5}$

$V_1 = q/d_1$ = 192/6.2 = 30.97 ft/sec

$F_1 = 30.97/(32.2 \times 6.2)^{0.5}$ = 2.19

From Plates 64 and 65 with q = 192 cfs/ft, F_1 = 2.19, and h_c/d_c = 0.85, it appears that this structure would be borderline with respect to satisfactory energy dissipation. Additional research would be needed.

Table 10
Example Design Problem 1

Design Conditions

Change in channel grade = 6.8 ft
Elevation of upstream channel (crest) = 100
Tailwater elevation = 108.9
Unit discharge q = 192 cfs/ft

Design Computations

Critical depth: $d_c = (q^2/g)^{1/3} = [(192)^2/32.2]^{1/3} = \underline{10.46 \text{ ft}}$
Design head: $H = 1.5d_c = 1.5(10.46) = \underline{15.7 \text{ ft}}$
Parabolic drop profile: $X^2 = KHY$ (K = 2, Equation 2)
$X^2 = 2HY$ (H = 15.70 above)
$\underline{X^2} = 2(15.7)Y = \underline{31.4Y}$

Drop height: Assume a value of h

Assume h = 10 ft

Basin floor elevation: crest elevation - h = 100 - 10 = 90
$D = q^2/gh^3$ (Equation 15-9, Chow 1959)
$D = (192)^2/32.2(10)^3 = 1.145$
$d_2/h = 1.66(D)^{0.27}$ (Equation 15-13, Chow 1959)
$d_2/10 = 1.66(1.145)^{0.27} = 1.722$
$d_2 = \underline{17.22 \text{ ft}}$

Depth of tailwater above floor:
Tailwater elevation - floor elevation = 108.9 - 90 = 18.9 ft
Since available tailwater depth (18.9 ft) is greater than d_2 (17.22 ft), basin will probably be satisfactory. However, floor can be raised for more economical design.

Assume h = 7 ft

Basin floor elevation: crest elevation - h = 100 - 7 = 93

$D = q^2/gh^3 = (192)^2/32.2(7)^3 = 3.338$
$d_2/h = 1.66\ (3.338)^{0.27} = 2.298$
$d_2 = \underline{16.09 \text{ ft}}$

Depth tailwater above floor: 108.9 - 93 = 15.9 ft

Since available tailwater (15.9 ft) is less than d_2 (16.09 ft), basin floor is too high.

Assume h = 7.5 ft

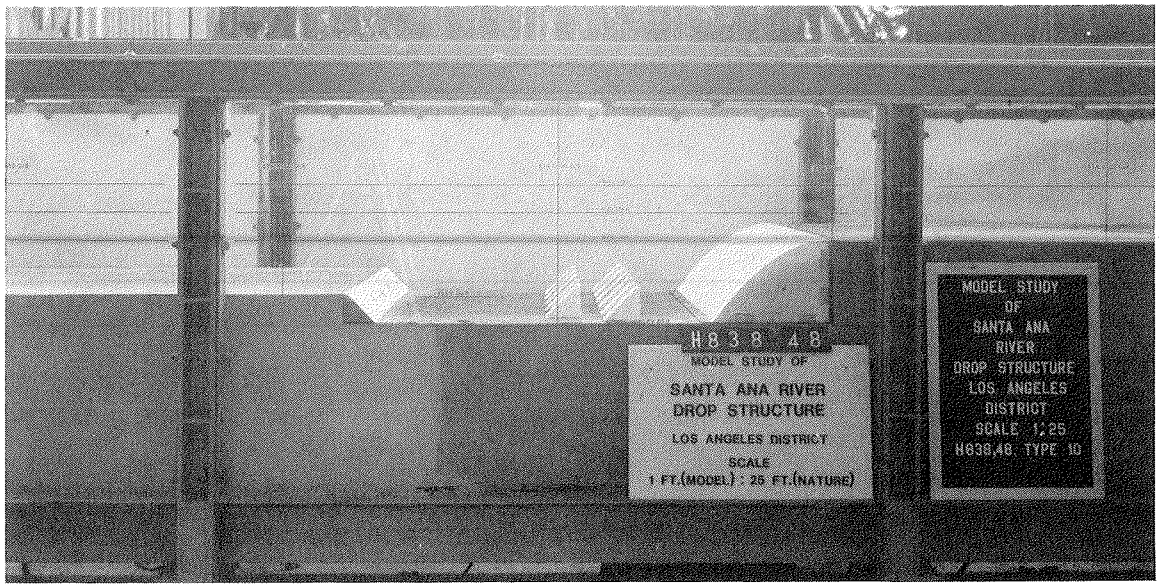
Basin floor elevation: 100 - 7.5 = 92.5
$D = q^2/gh^3 = (192)^2/32.2(7.5)^3 = 2.714$
$d_2/h = 1.66\ (2.714)^{0.27} = 2.174$
$d_2 = \underline{16.3 \text{ ft}}$

Depth tailwater above floor: 108.9 - 92.5 = 16.4 ft
Since 16.4 ≈ 16.3 use h = 7.5 ft

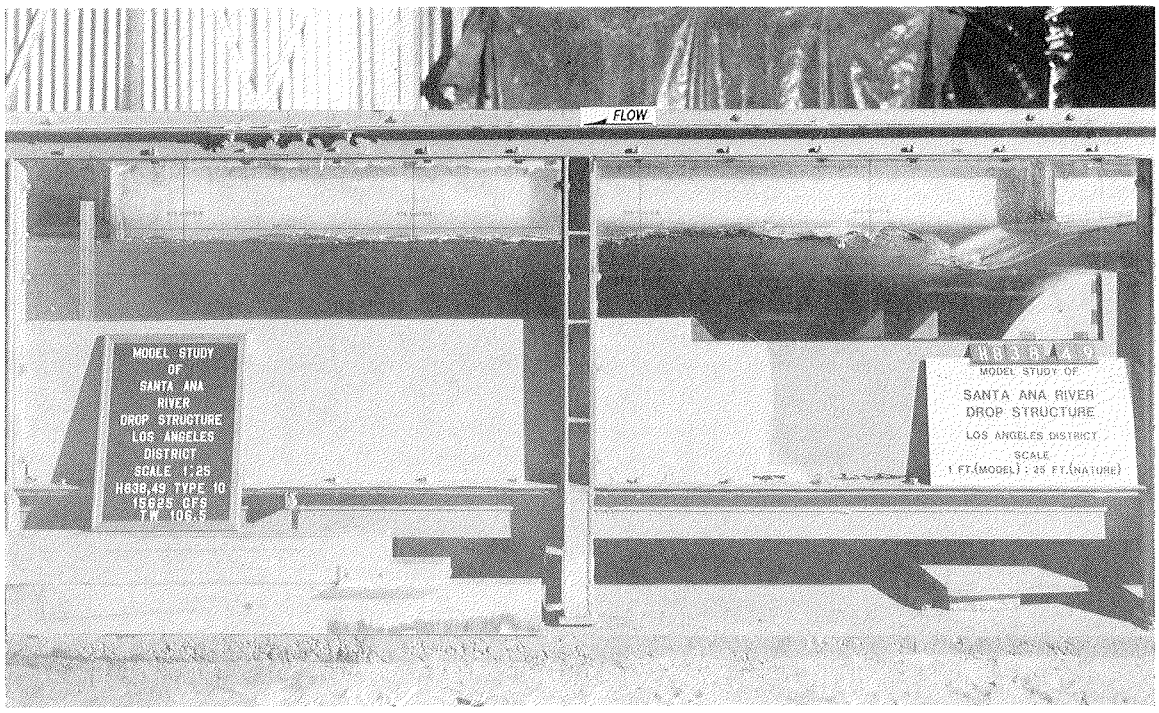
Basin design: with h = 7.5 ft and d_2 = 16.3 ft

$d_1/h = 0.54(D)^{0.425}$ (Equation 15-12, Chow 1959)
$d_1/7.5 = 0.54(2.714)^{0.425}$
$d_1 = \underline{6.2 \text{ ft}}$

(Continued)

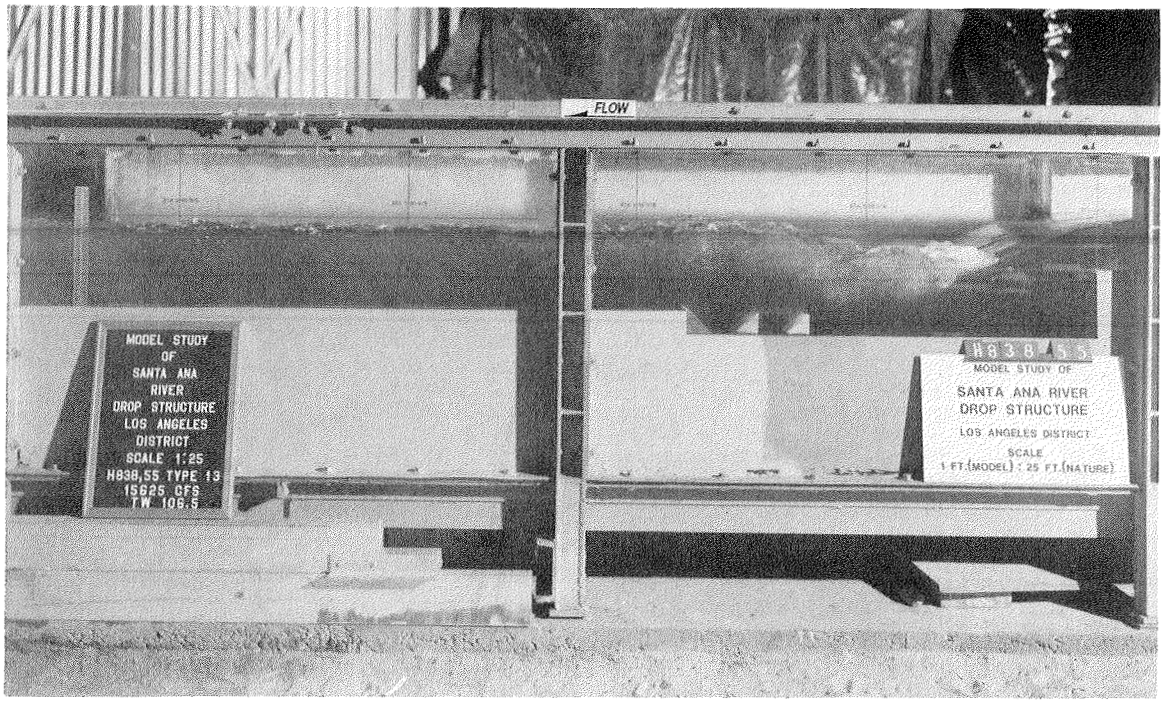


a. Dry bed

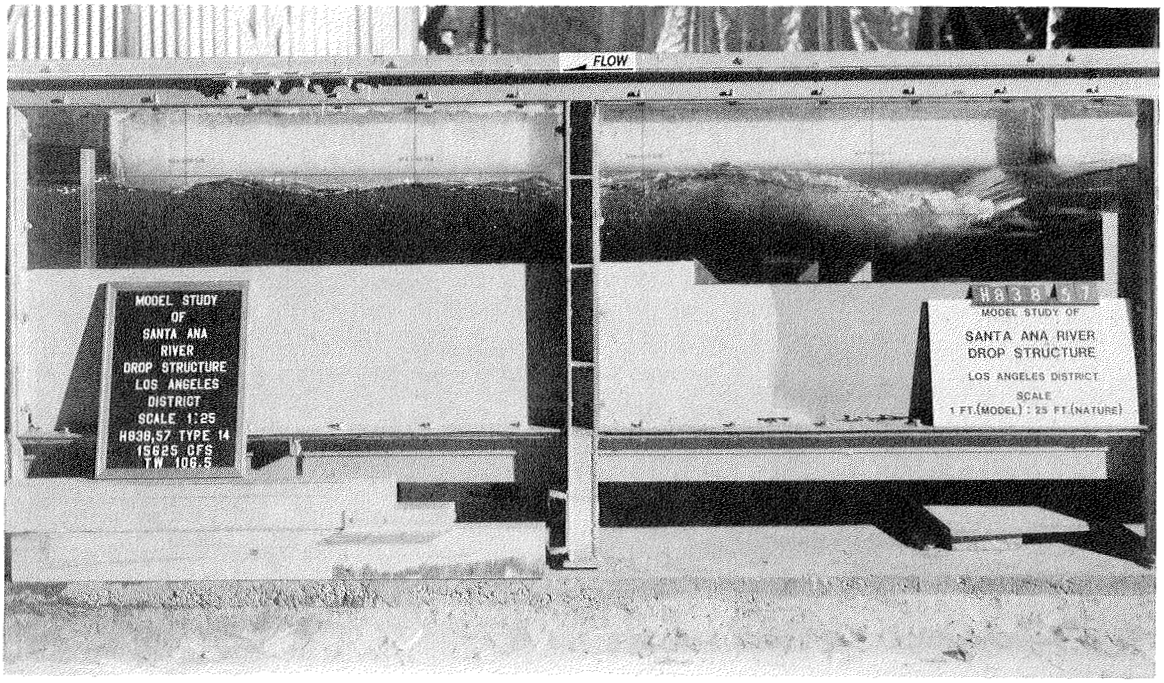


b. Unit discharge 250 cfs/ft, tailwater el 106.5

Photo 9. Type 10 design drop structure

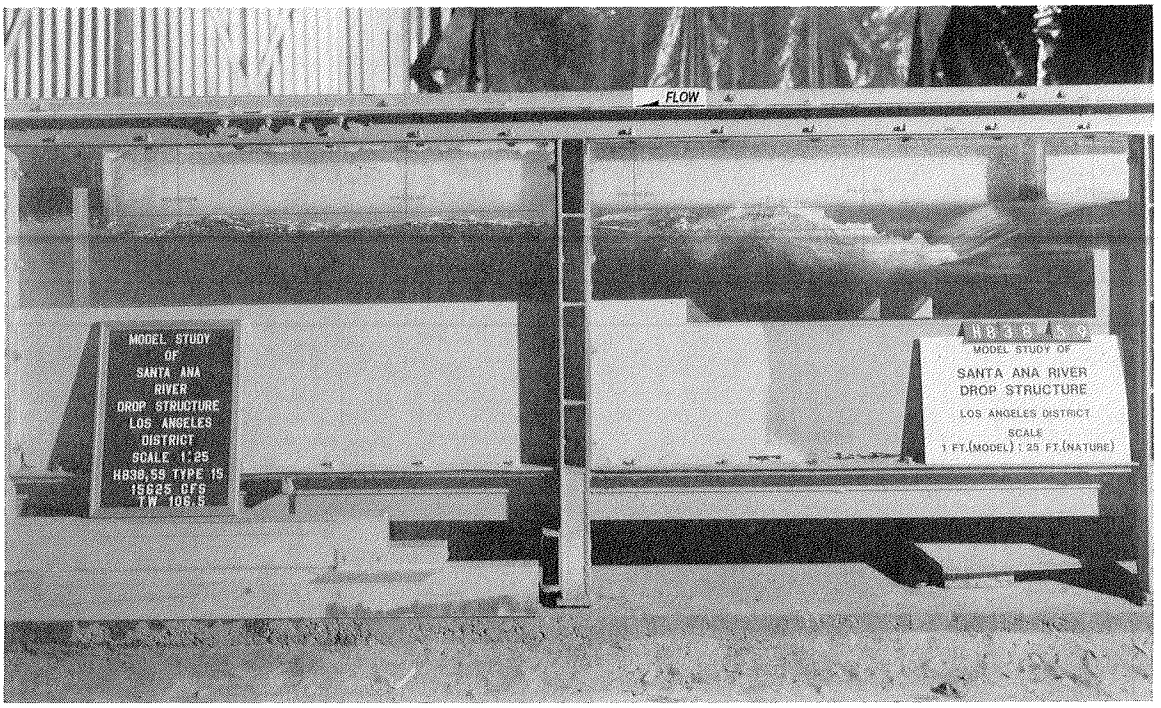


a. Type 13 design drop structure



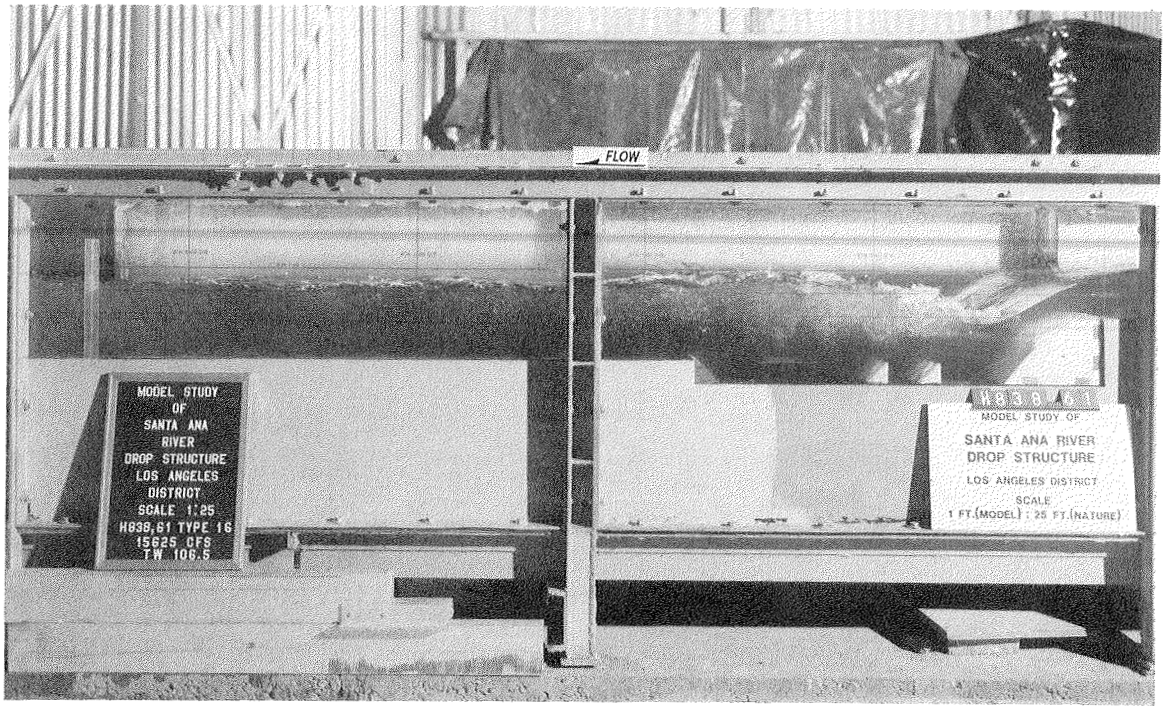
b. Type 14 design drop structure

Photo 10. Flow conditions in the type 13, 14, and 15 design drop structures; unit discharge 250 cfs/ft, tailwater el 106.5 (Continued)

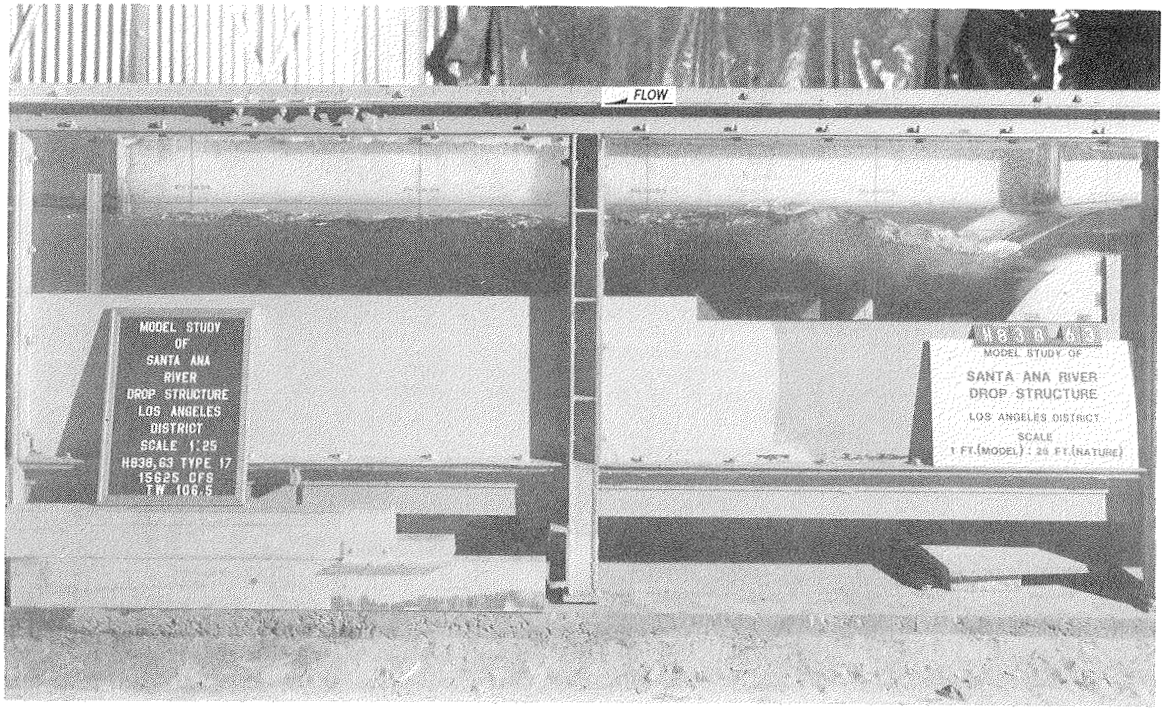


c. Type 15 design drop structure

Photo 10. (Concluded)

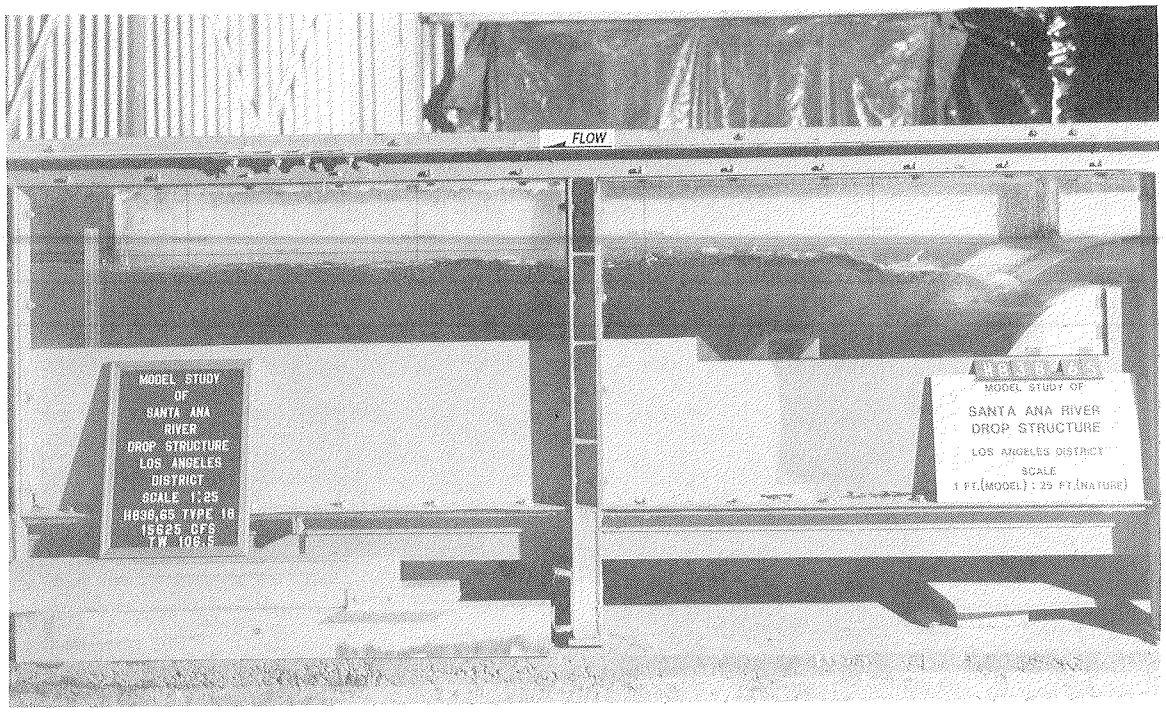


a. Type 16 design drop structure



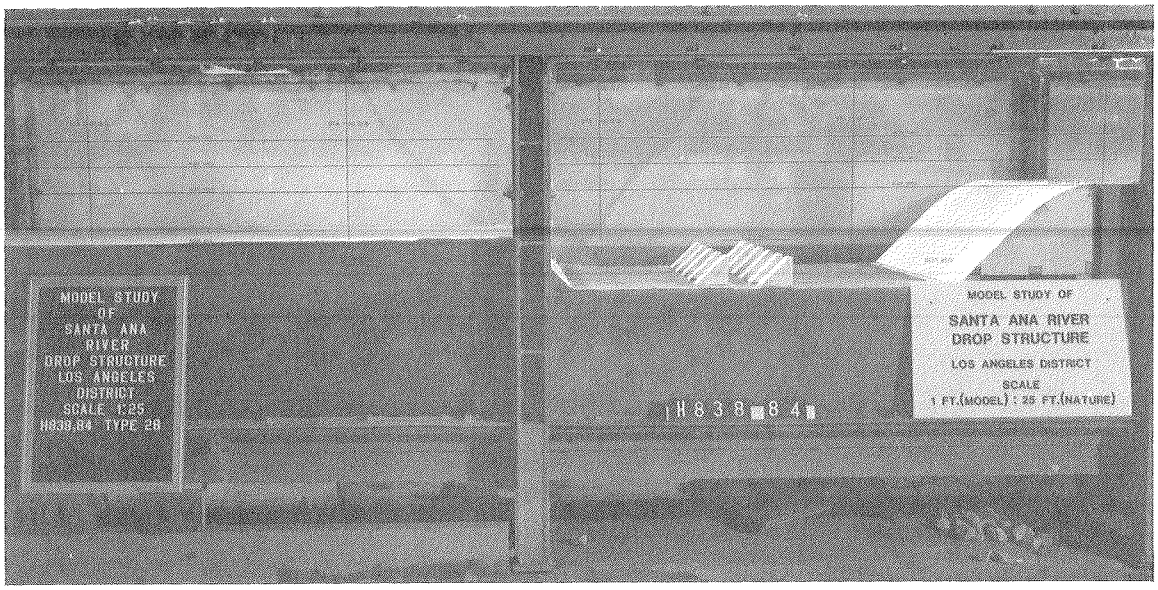
b. Type 17 design drop structure

Photo 11. Flow conditions in the type 16, 17, and 18 design drop structures; unit discharge 250 cfs/ft, tailwater el 106.5 (Continued)

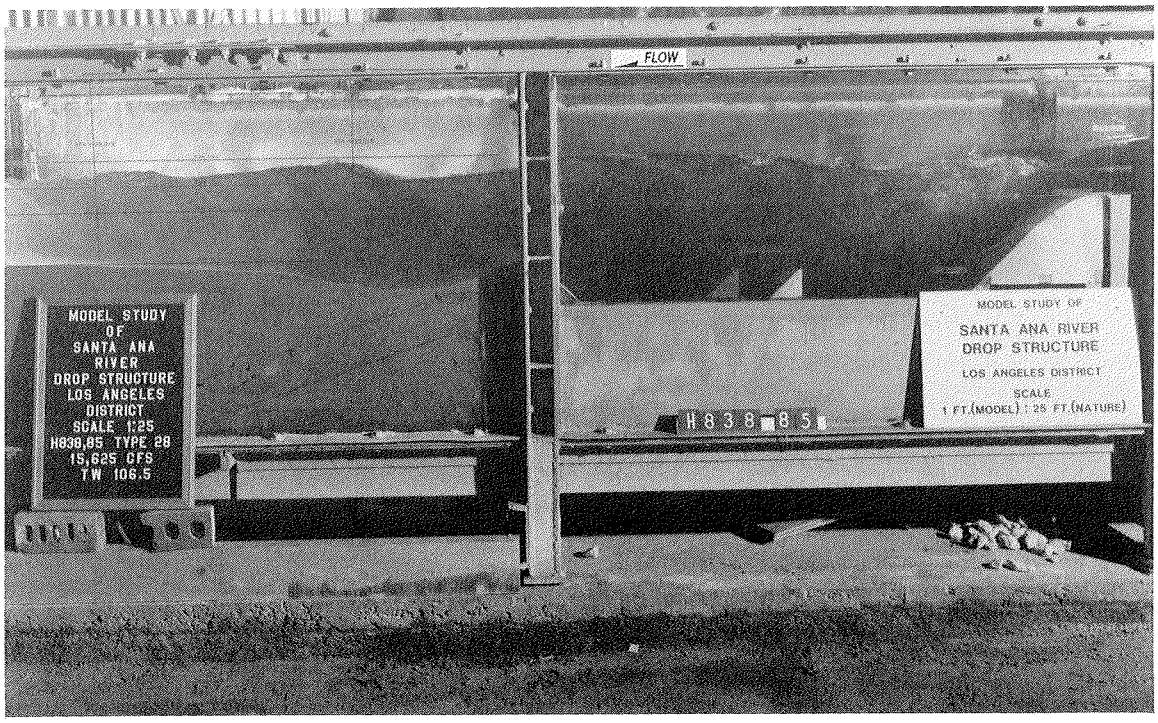


c. Type 18 design drop structure

Photo 11. (Concluded)

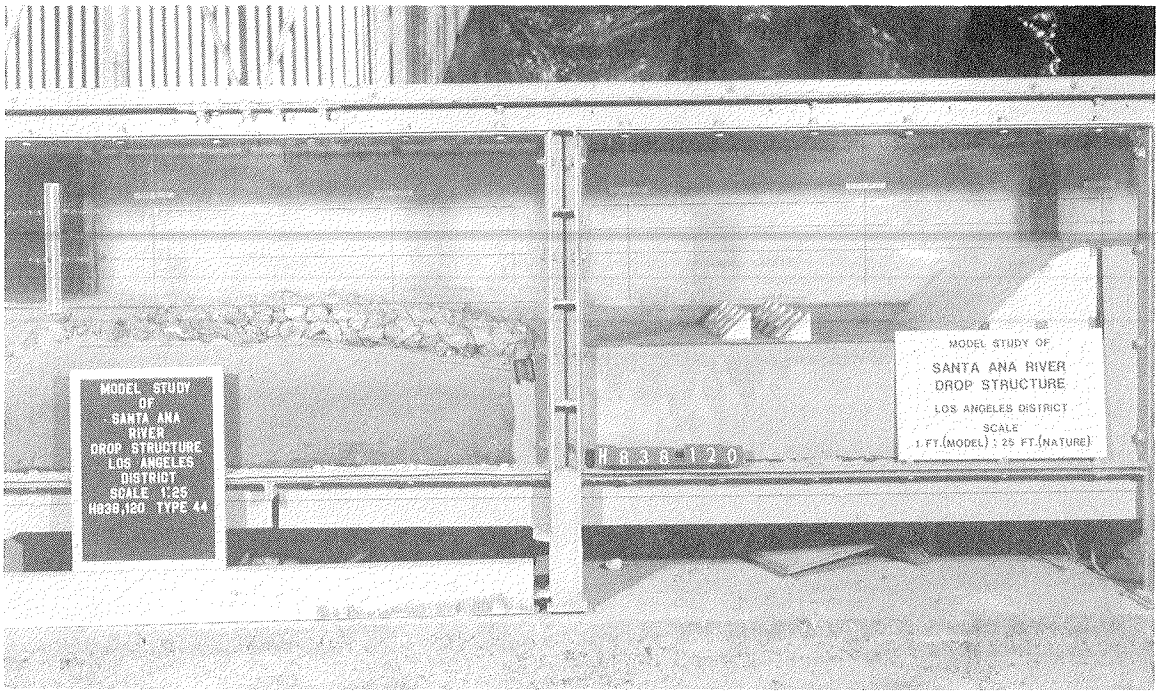


a. Dry bed

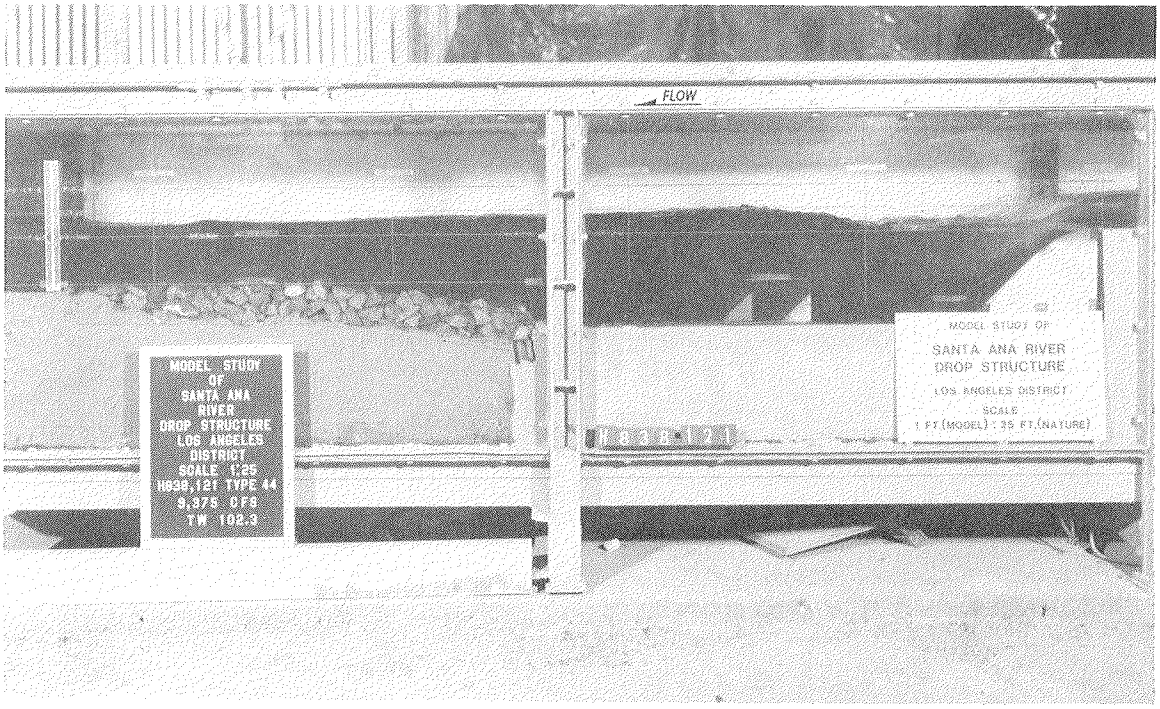


b. Unit discharge 250 cfs/ft, tailwater el 106.5

Photo 12. Type 28 design drop structure

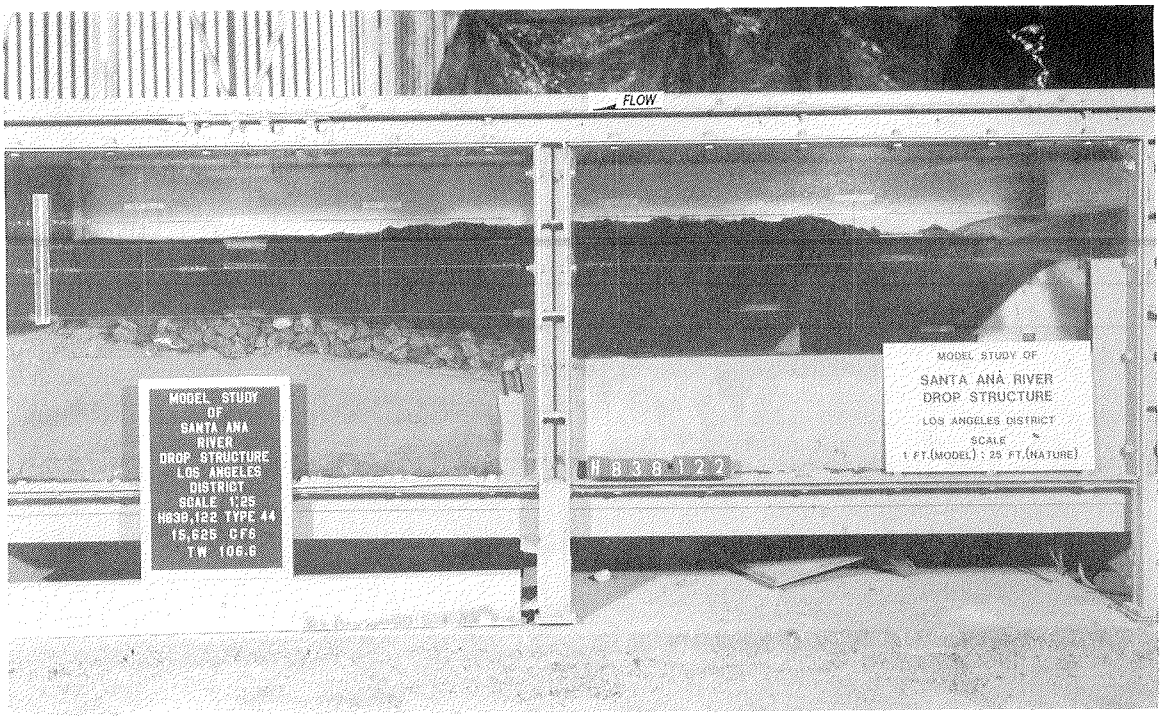


a. Dry bed



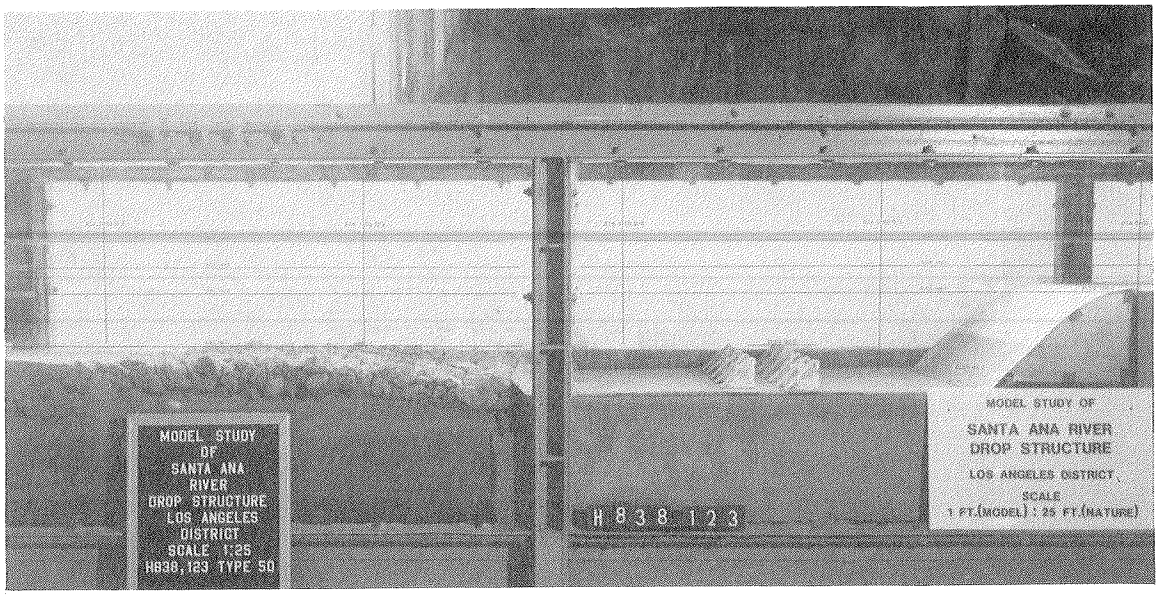
b. Unit discharge 150 cfs/ft, tailwater el 102.3

Photo 13. Type 44 design drop structure (10-ft drop) (Continued)

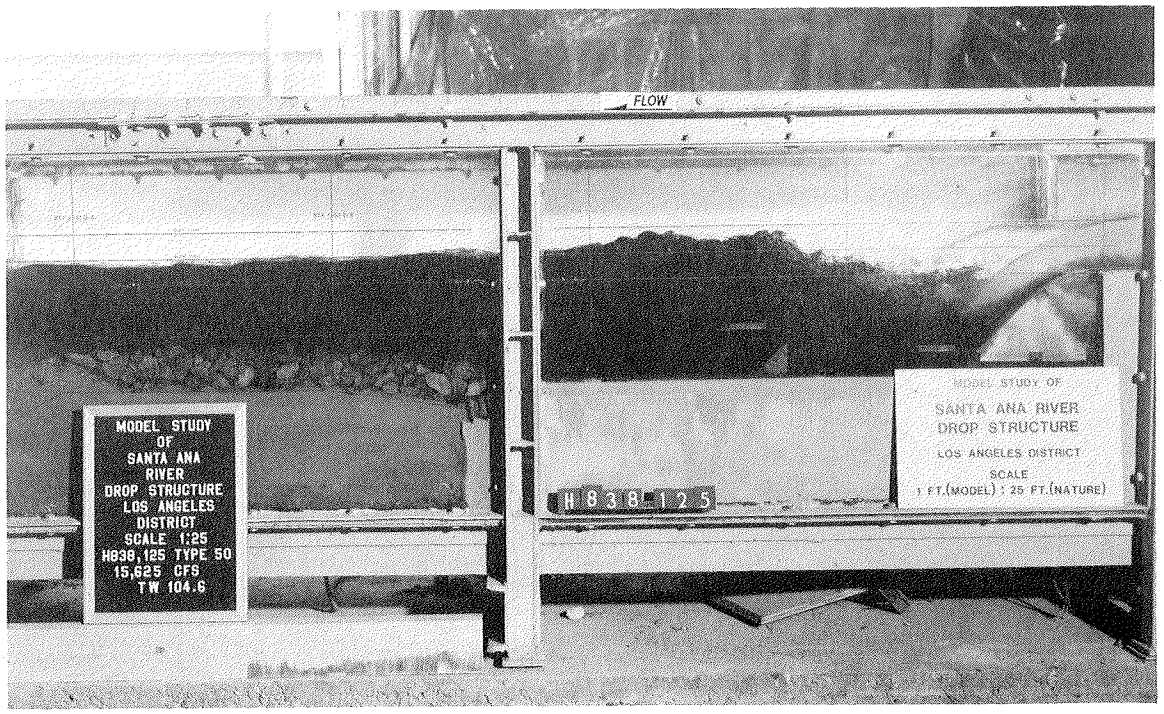


c. Unit discharge 250 cfs/ft, tailwater el 106.5

Photo 13. (Concluded)

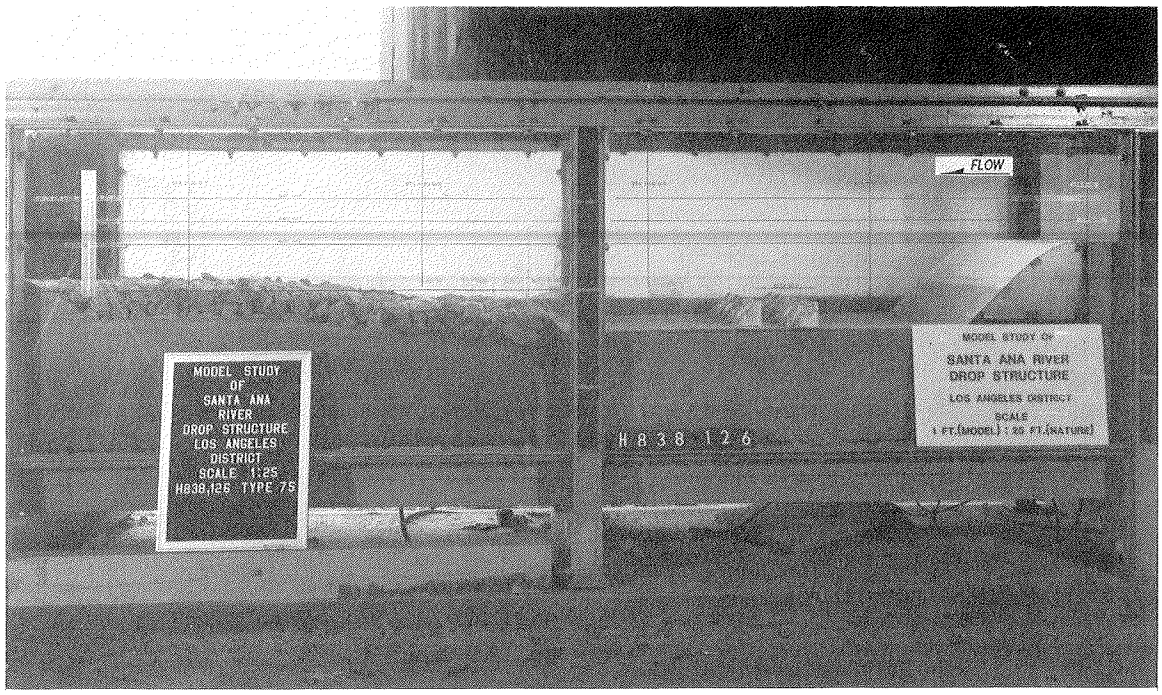


a. Dry bed

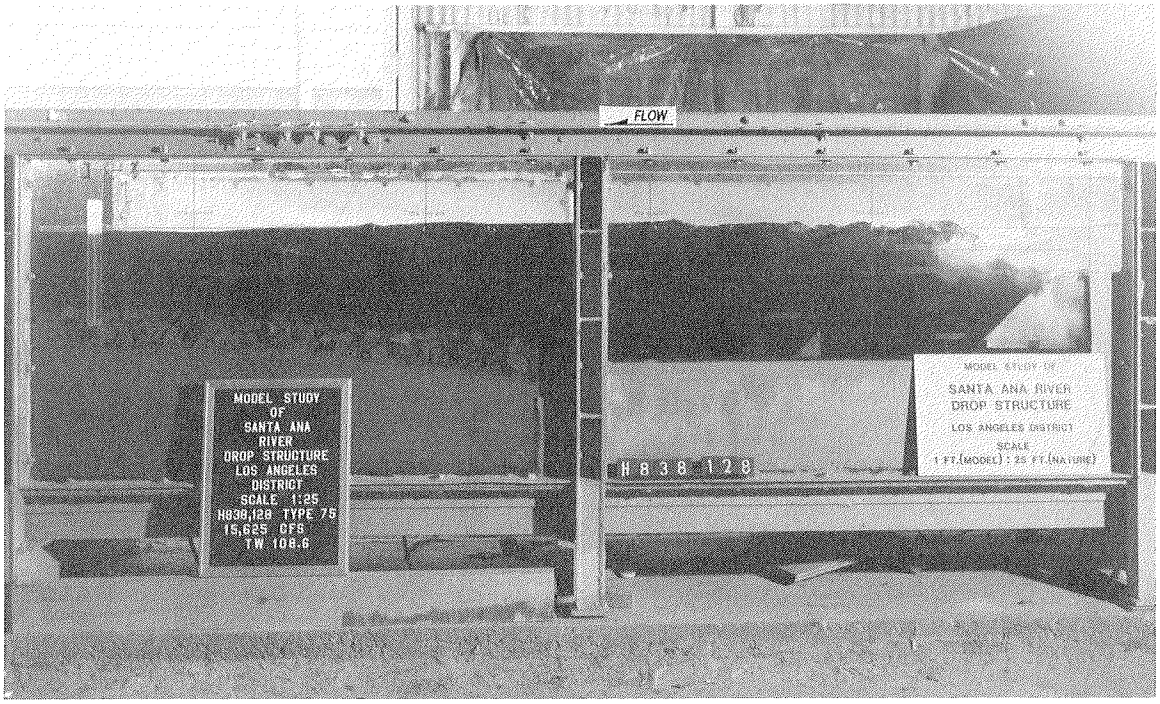


b. Unit discharge 250 cfs/ft, tailwater el 104.6

Photo 14. Type 50 design drop structure (12-ft drop)

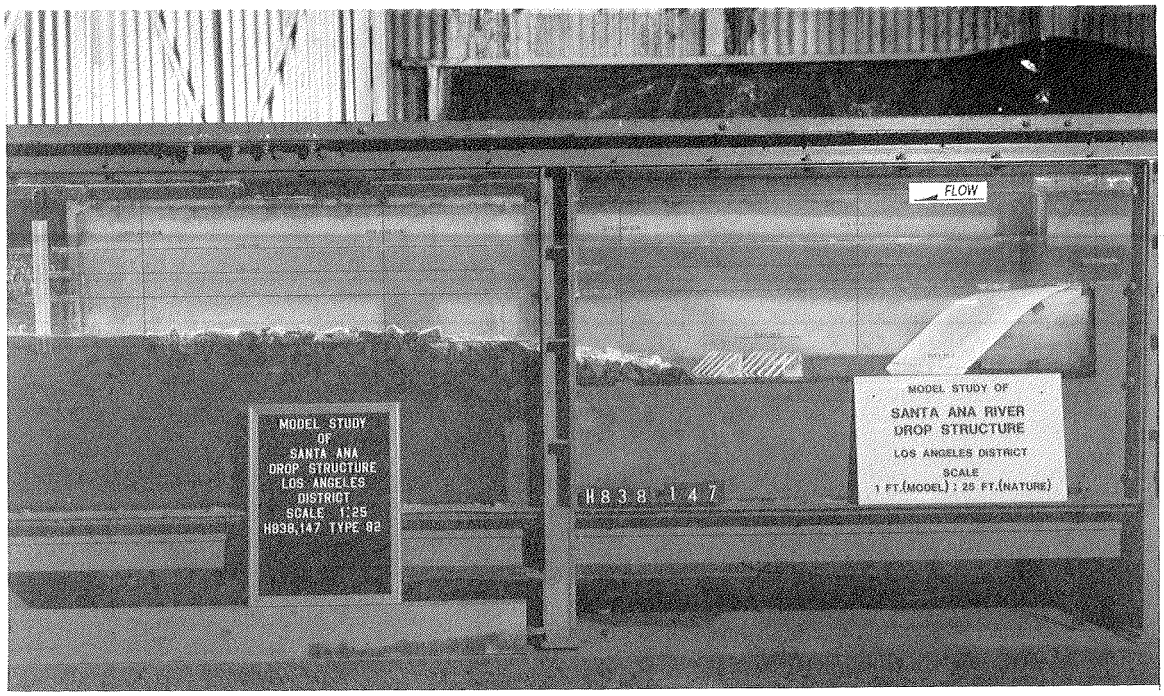


a. Dry bed

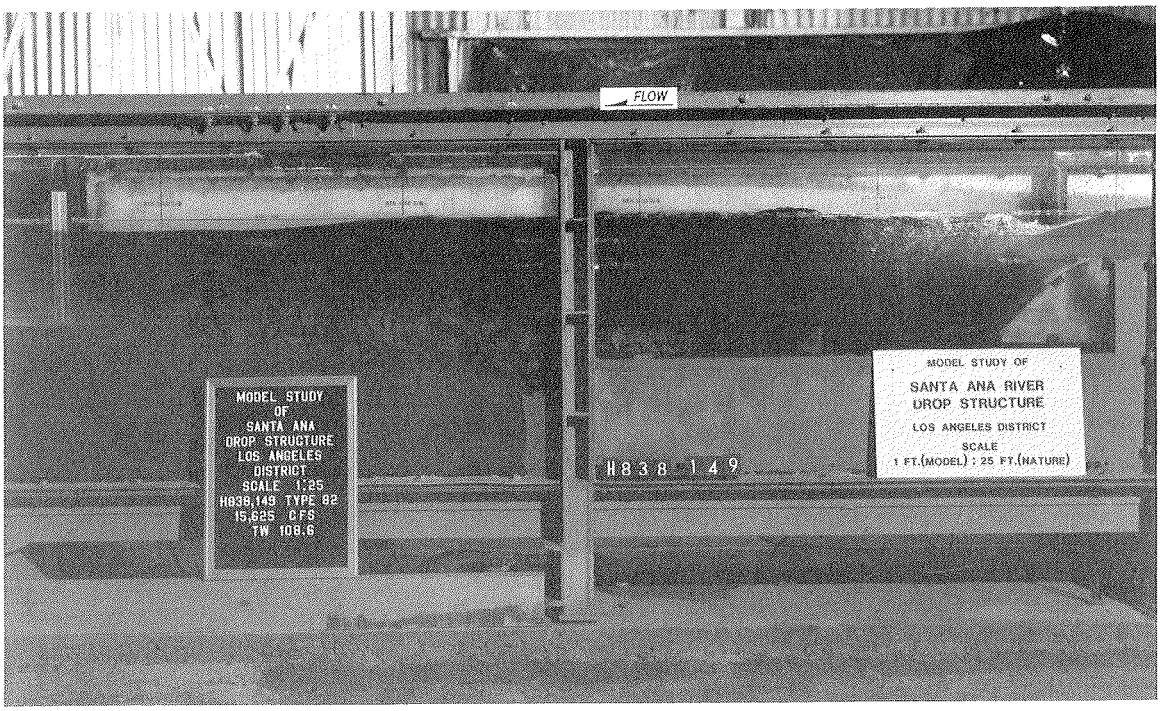


b. Unit discharge 250 cfs/ft, tailwater el 108.6

Photo 15. Type 75 design drop structure (8-ft drop)



a. Dry bed



b. Unit discharge 250 cfs/ft, tailwater el 108.6

Photo 16. Type 82 design drop structure (8-ft drop)

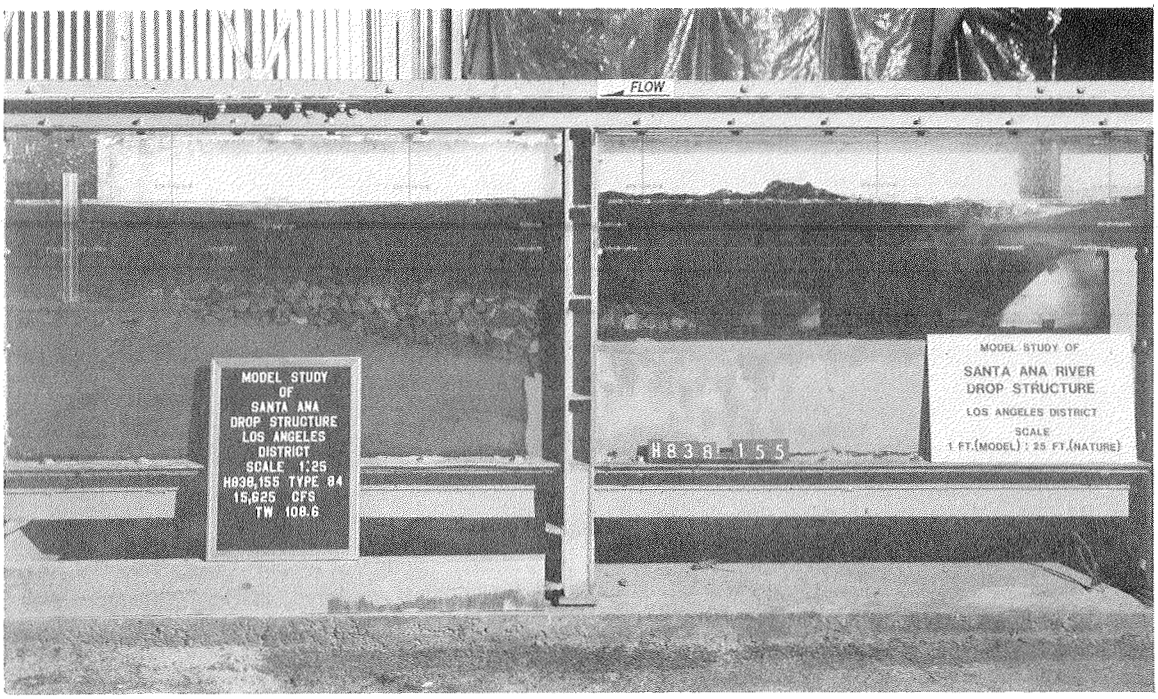
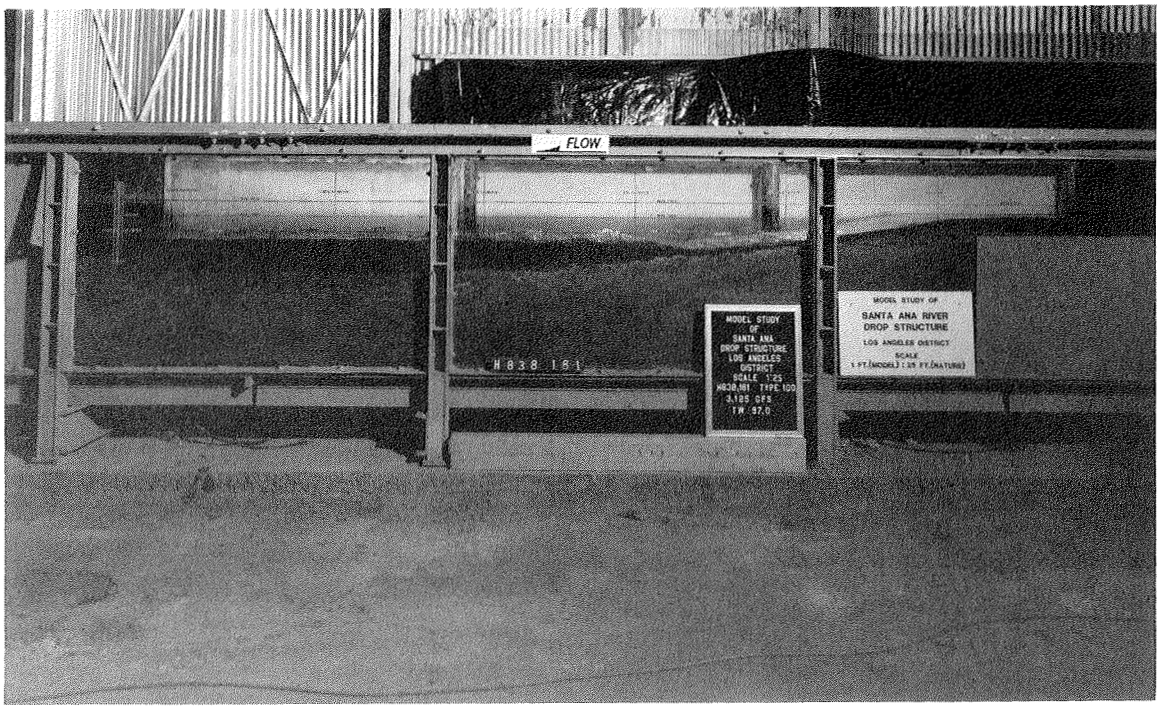


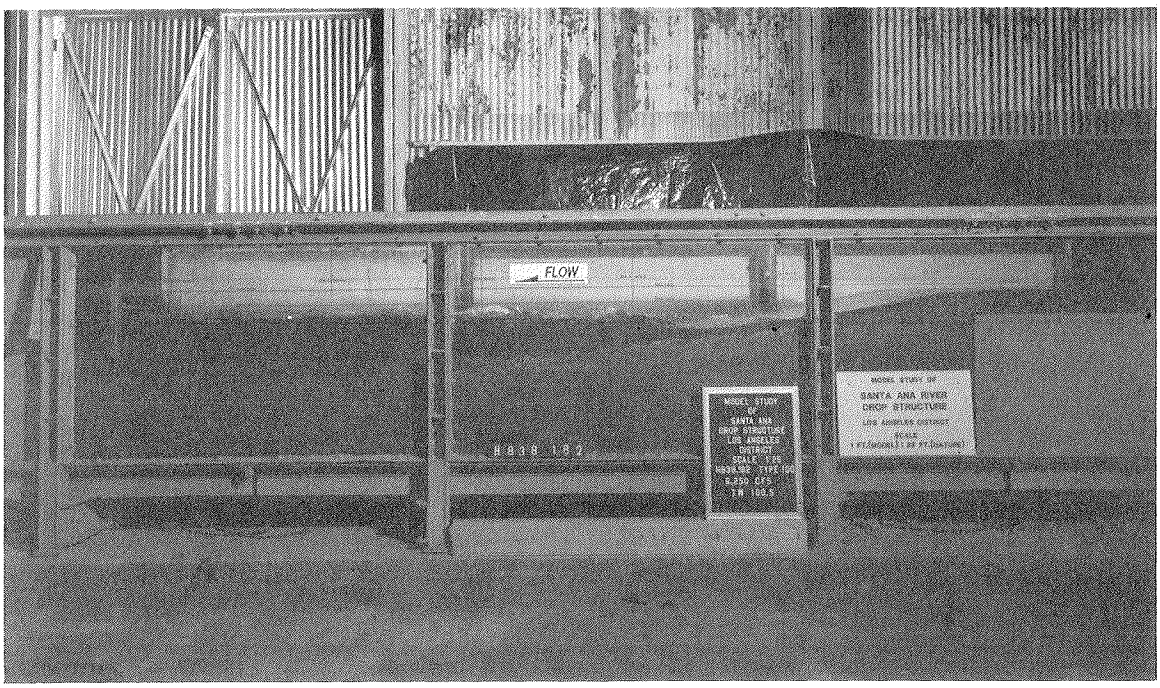
Photo 17. Type 84 design drop structure; unit discharge 250 cfs/ft, tailwater el 108.6

a. Dry bed

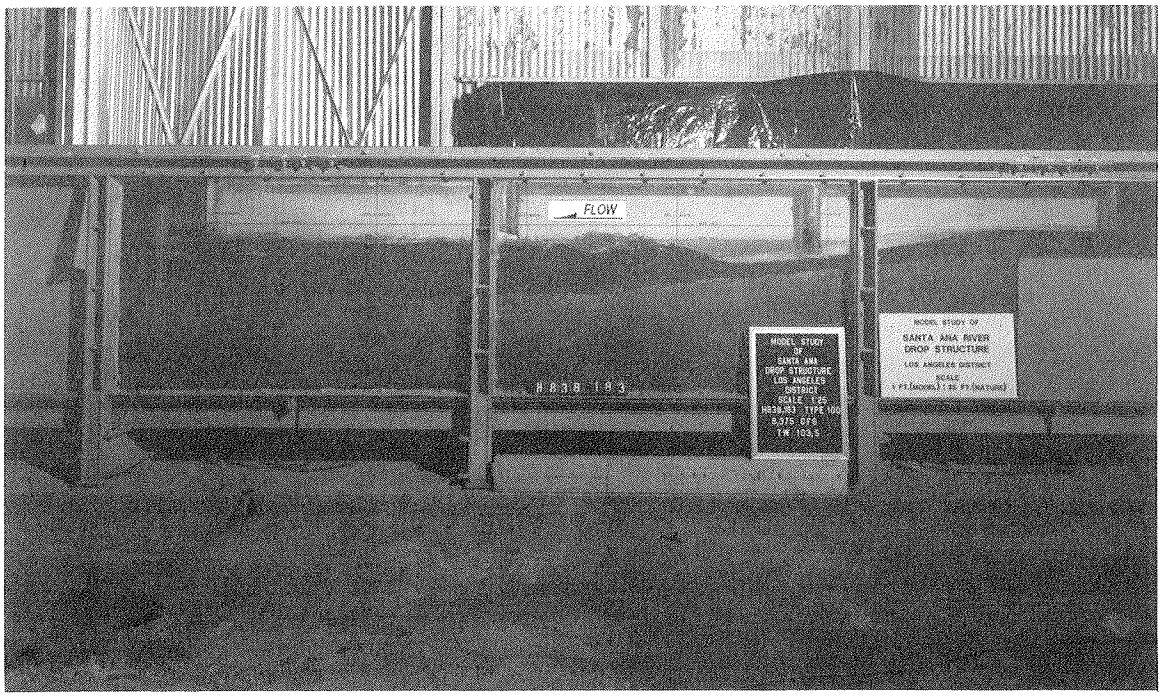


b. Unit discharge 50 cfs/ft, tailwater el 97.0

Photo 18. Type 100 design grouted stone drop structure (Sheet 1 of 3)

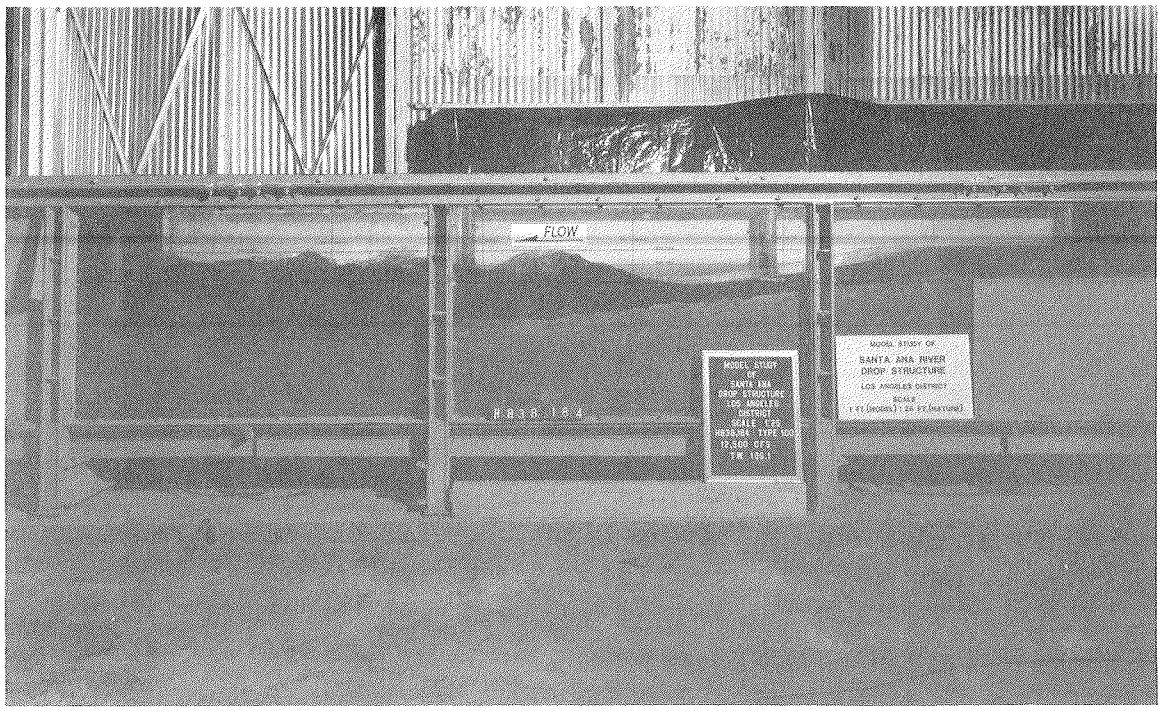


c. Unit discharge 100 cfs/ft, tailwater el 100.5

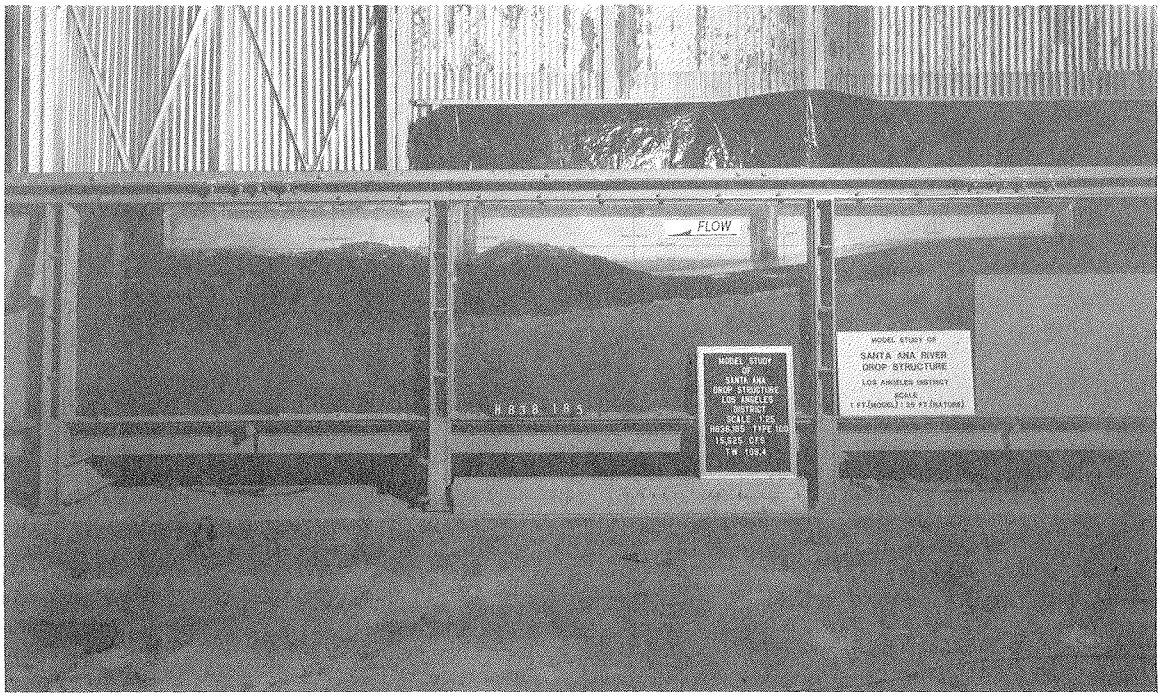


d. Unit discharge 150 cfs/ft, tailwater el 103.5

Photo 18. (Sheet 2 of 3)



e. Unit discharge 200 cfs/ft, tailwater el 106.1



f. Unit discharge 250 cfs/ft, tailwater el 108.4

Photo 18. (Sheet 3 of 3)

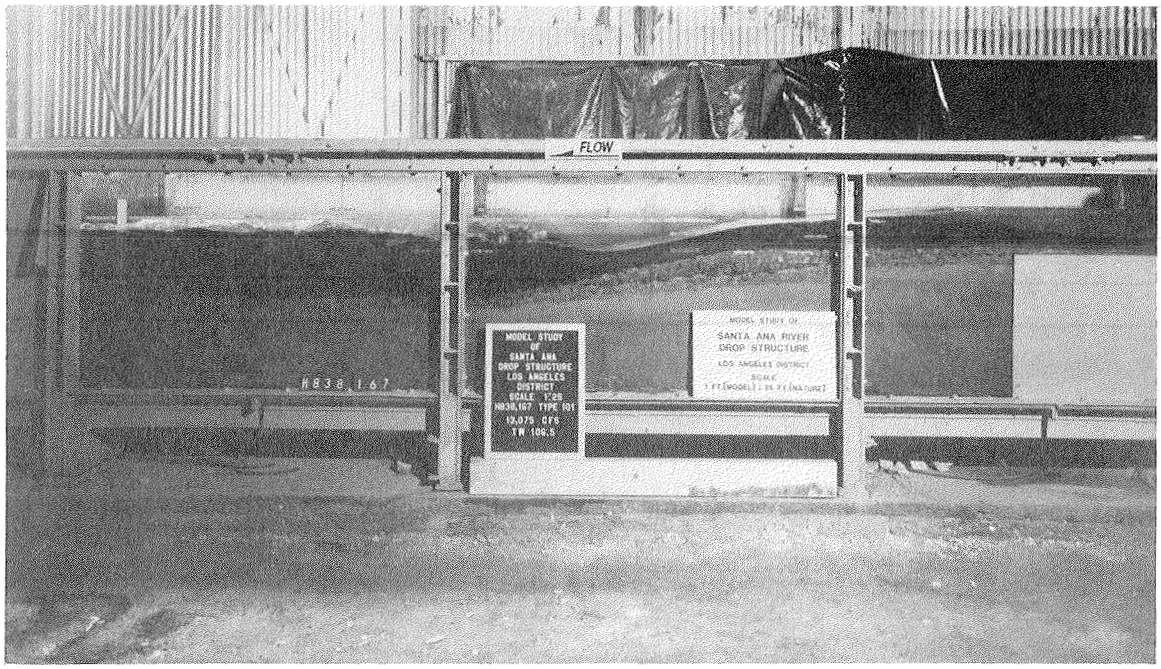


Photo 19. Type 101 grouted stone drop structure; unit discharge 209.3 cfs/ft, tailwater 106.5

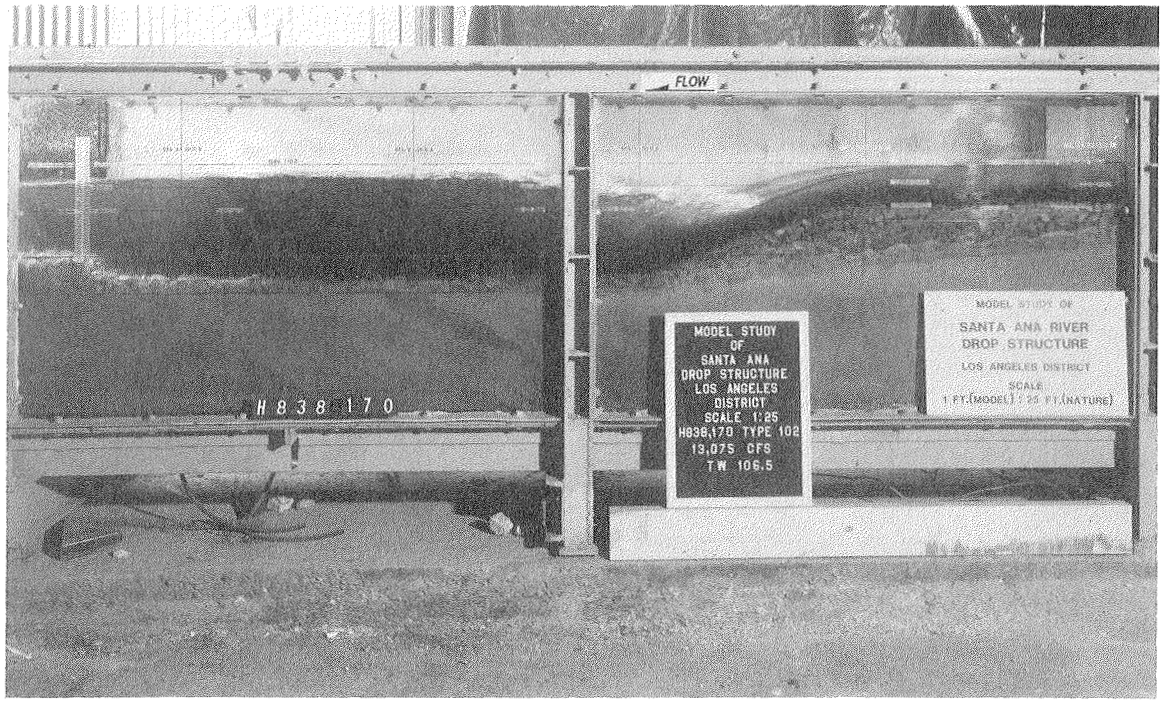


Photo 20. Type 102 grouted stone drop structure; unit discharge 209.3 cfs/ft, tailwater el 106.5

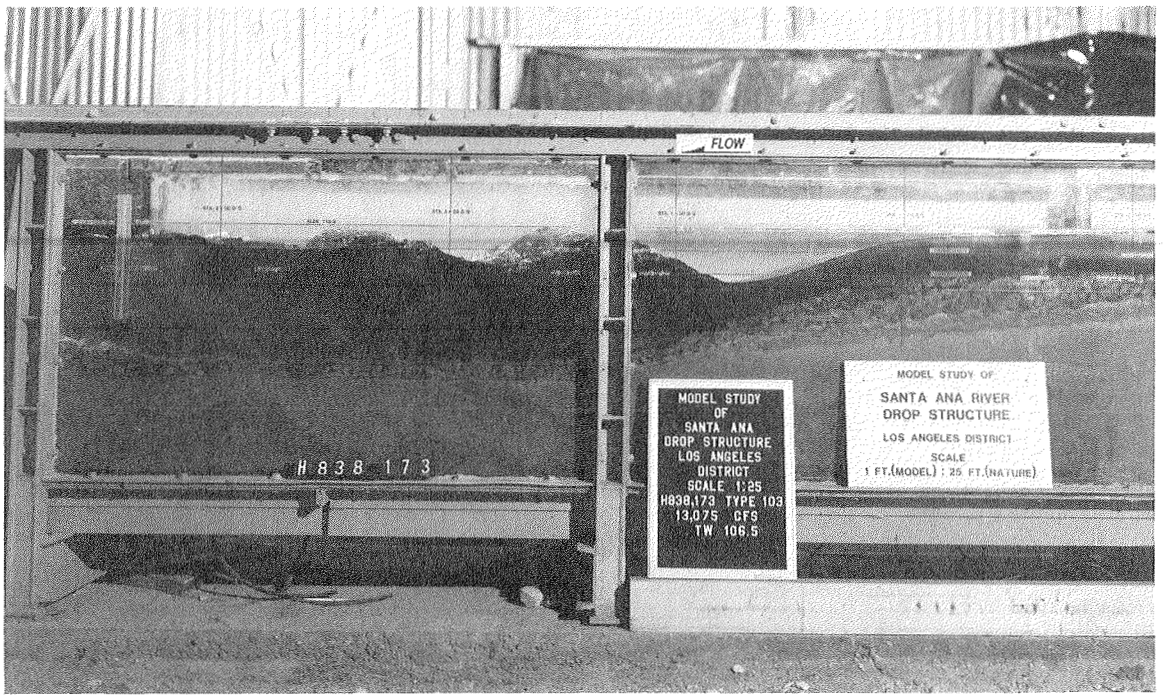
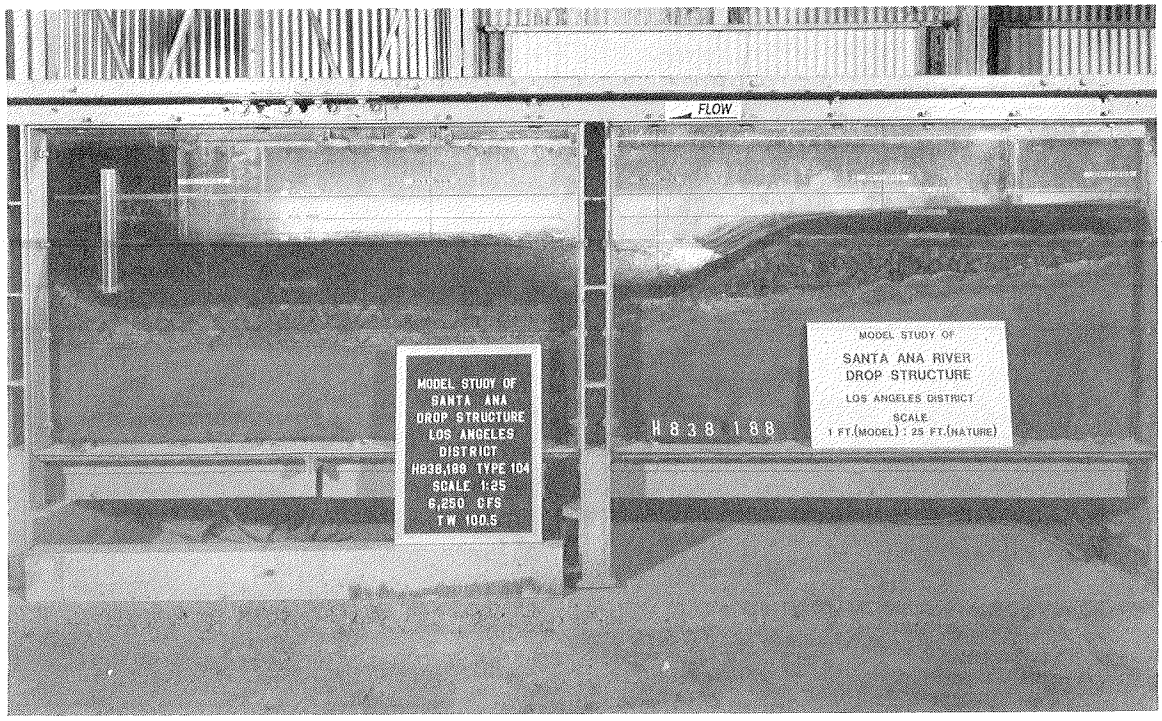


Photo 21. Type 103 grouted stone drop structure; unit discharge 209.3 cfs/ft, tailwater el 106.5

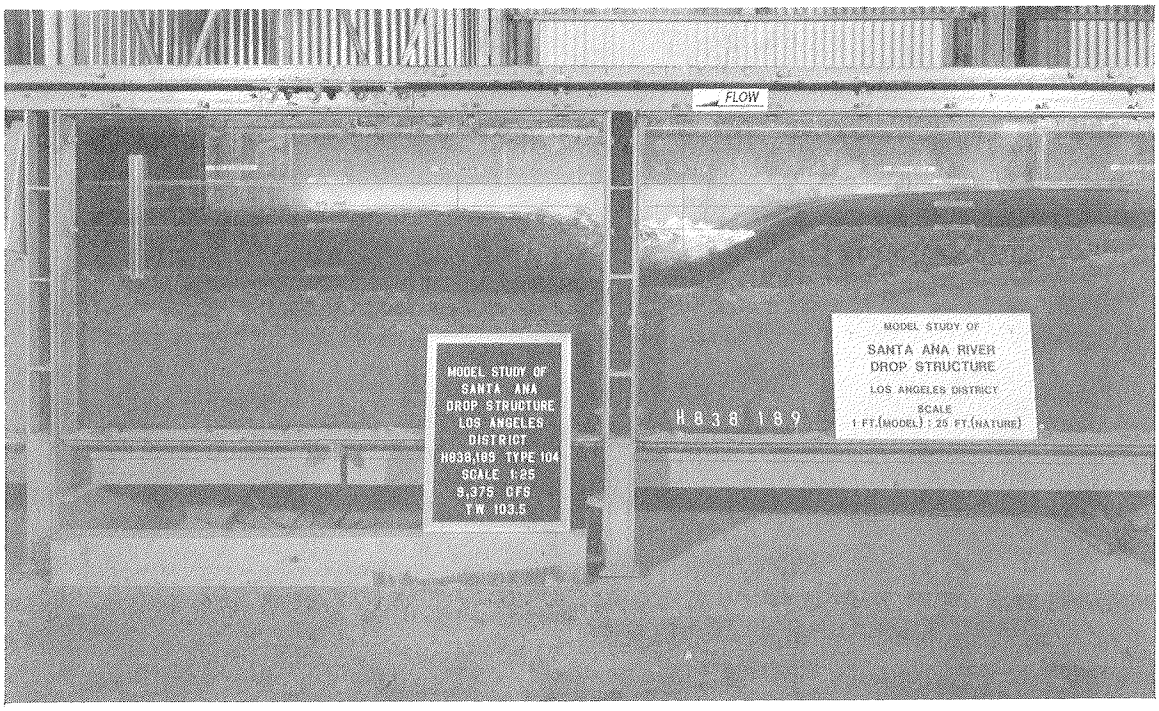
a. Dry bed

b. Unit discharge 50 cfs/ft, tailwater el 97.0

Photo 22. Type 104 design grouted stone drop structure (Sheet 1 of 3)

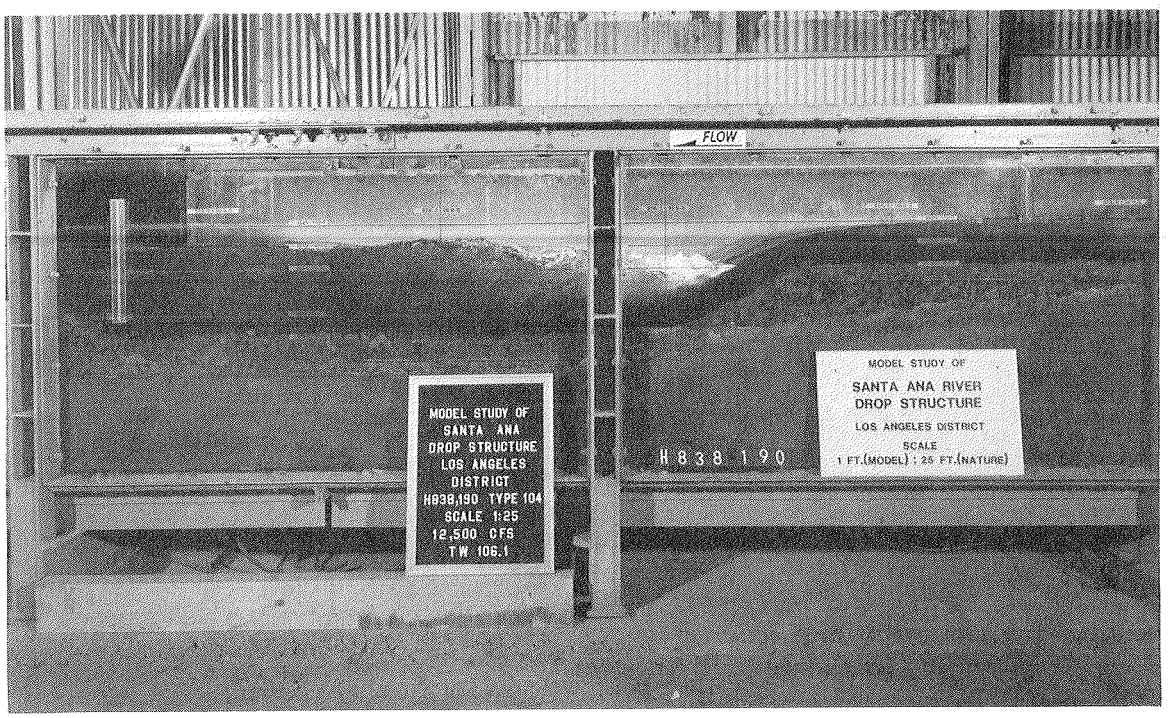


c. Unit discharge 100 cfs/ft, tailwater el 100.5

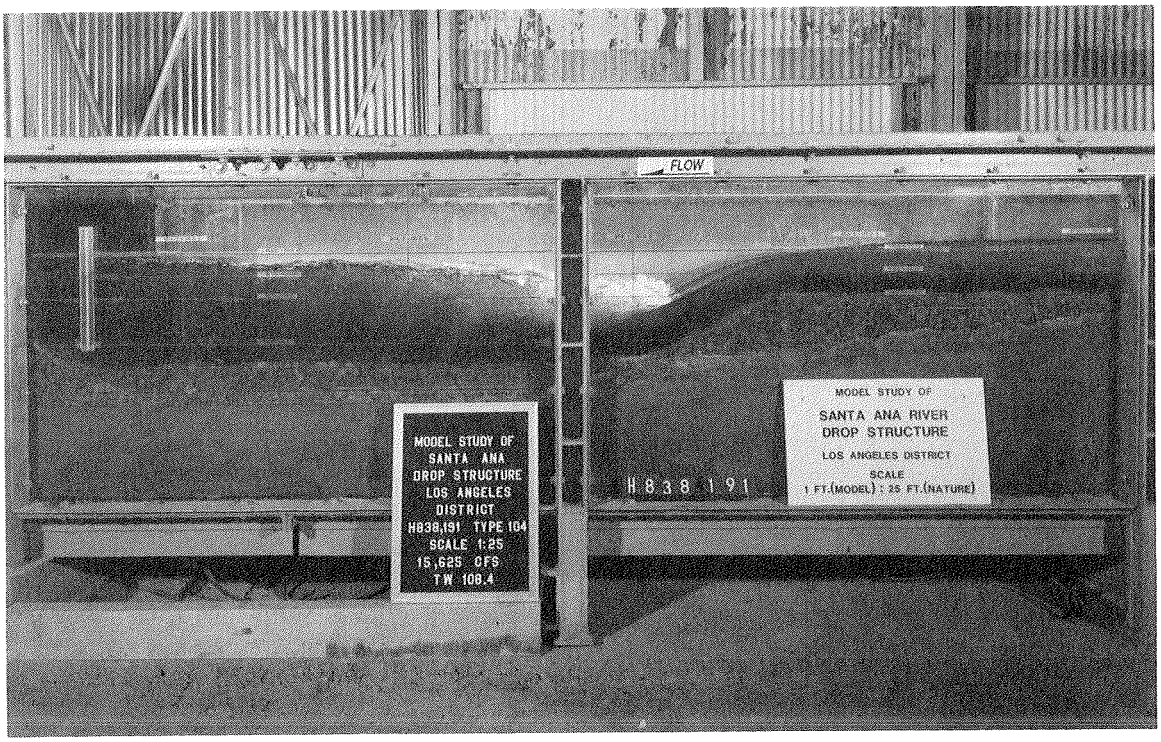


d. Unit discharge 150 cfs/ft, tailwater el 103.5

Photo 22. (Sheet 2 of 3)

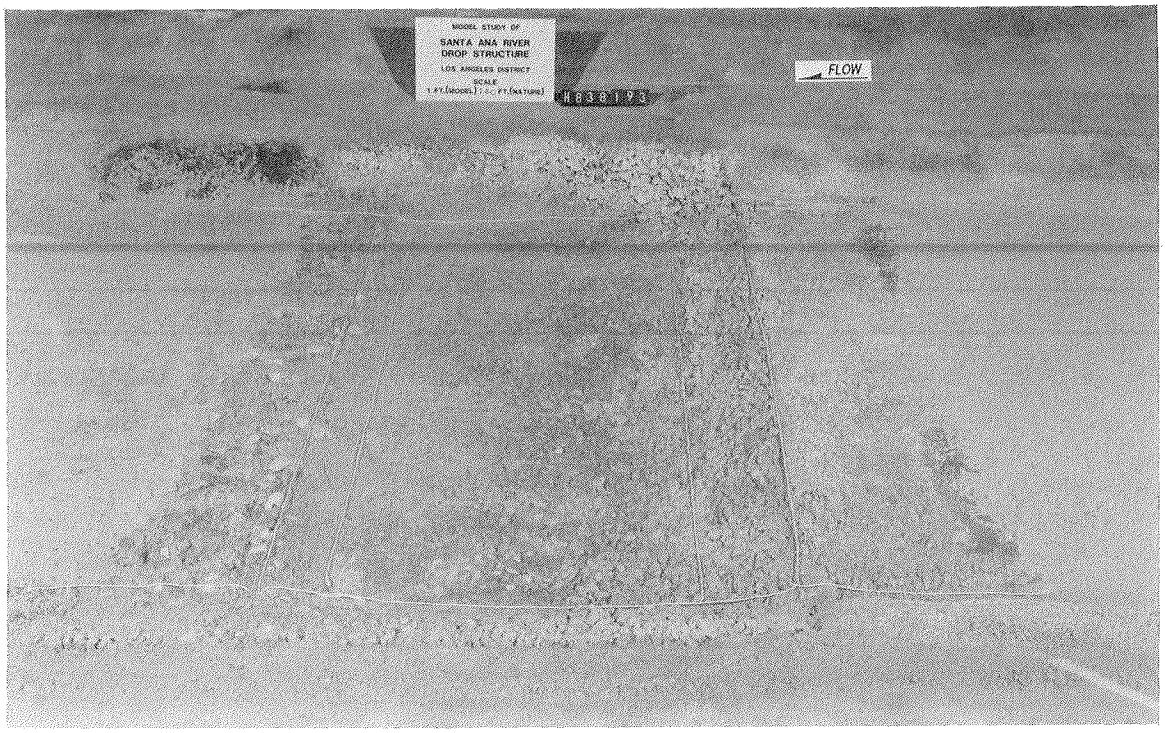


e. Unit discharge 200 cfs/ft, tailwater el 106.1

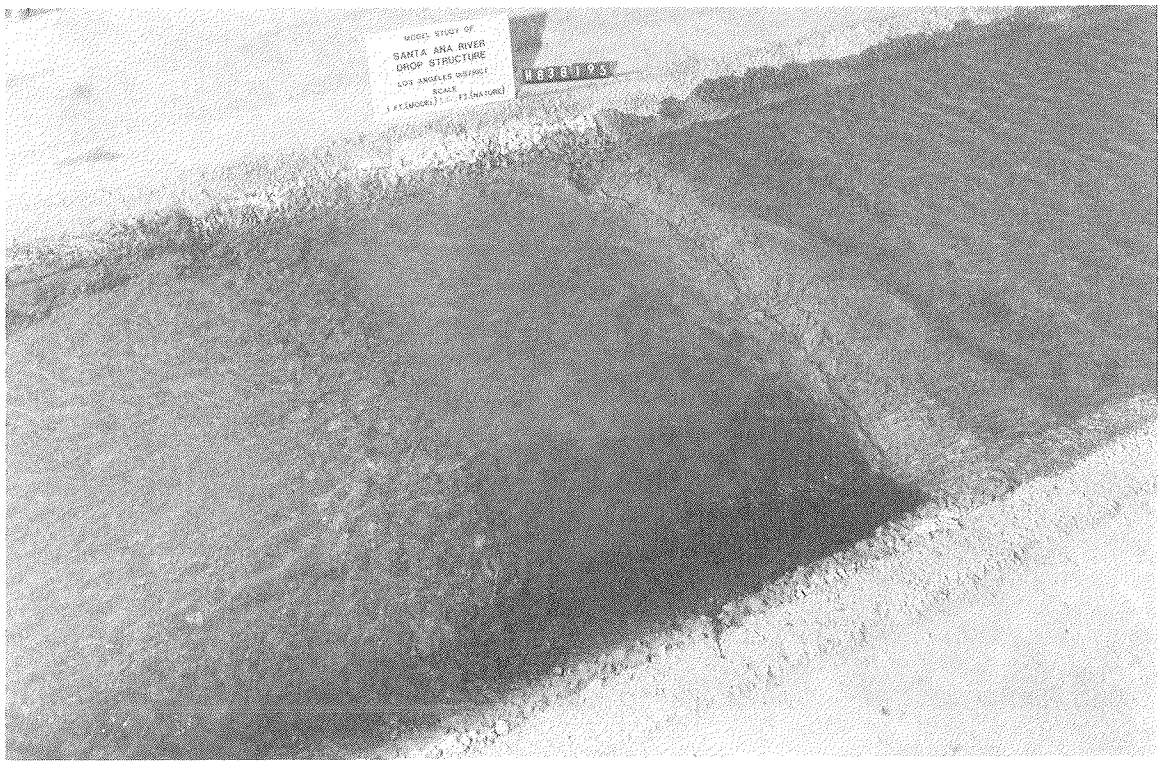


f. Unit discharge 250 cfs/ft, tailwater el 108.4

Photo 22. (Sheet 3 of 3)

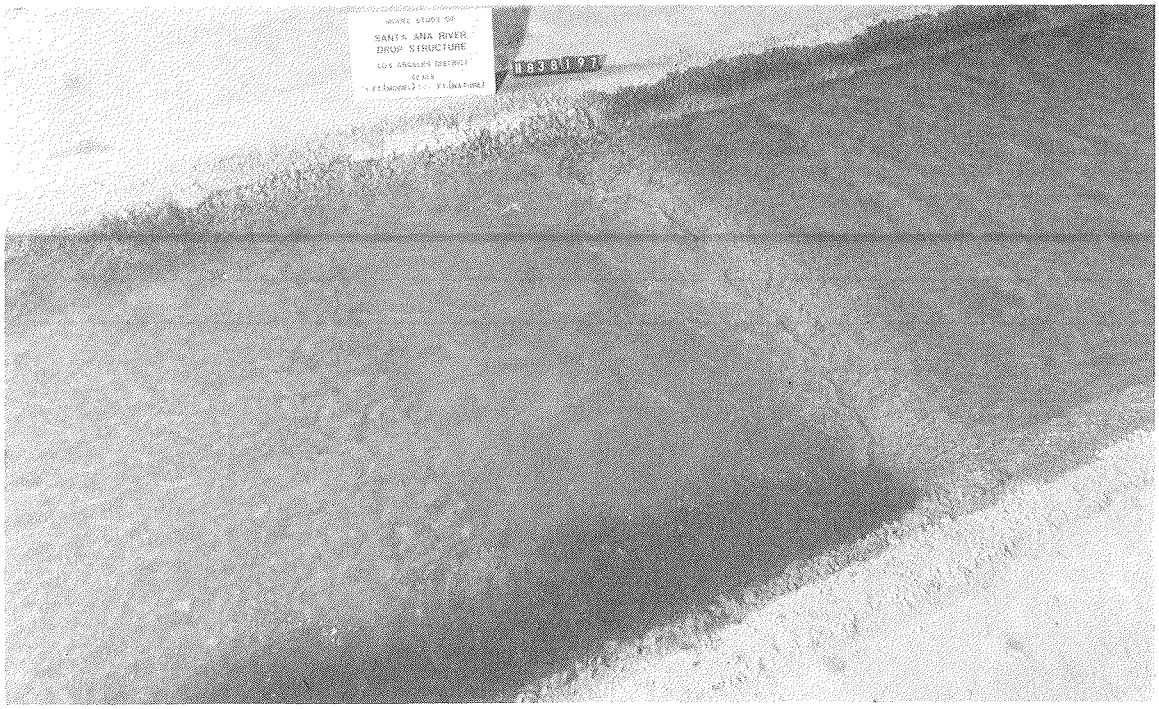


a. Dry bed

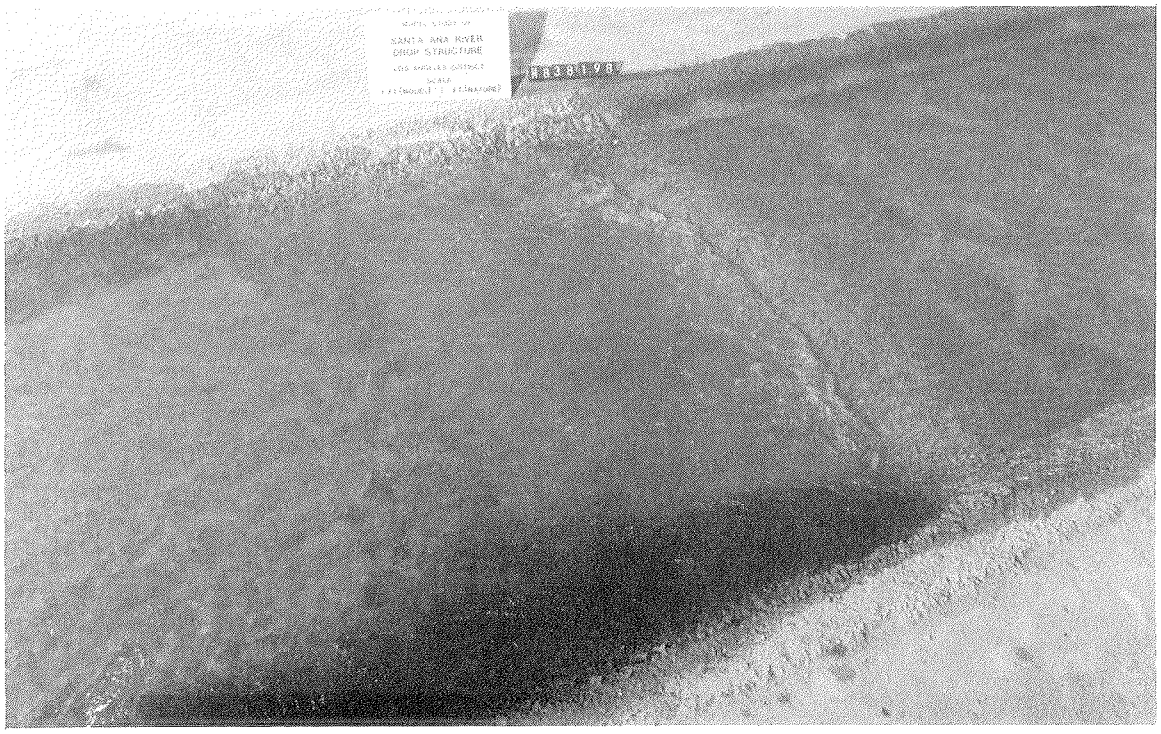


b. Unit discharge 50 cfs/ft, tailwater el 97.0

Photo 23. Type 105 design grouted stone drop structure (Sheet 1 of 3)

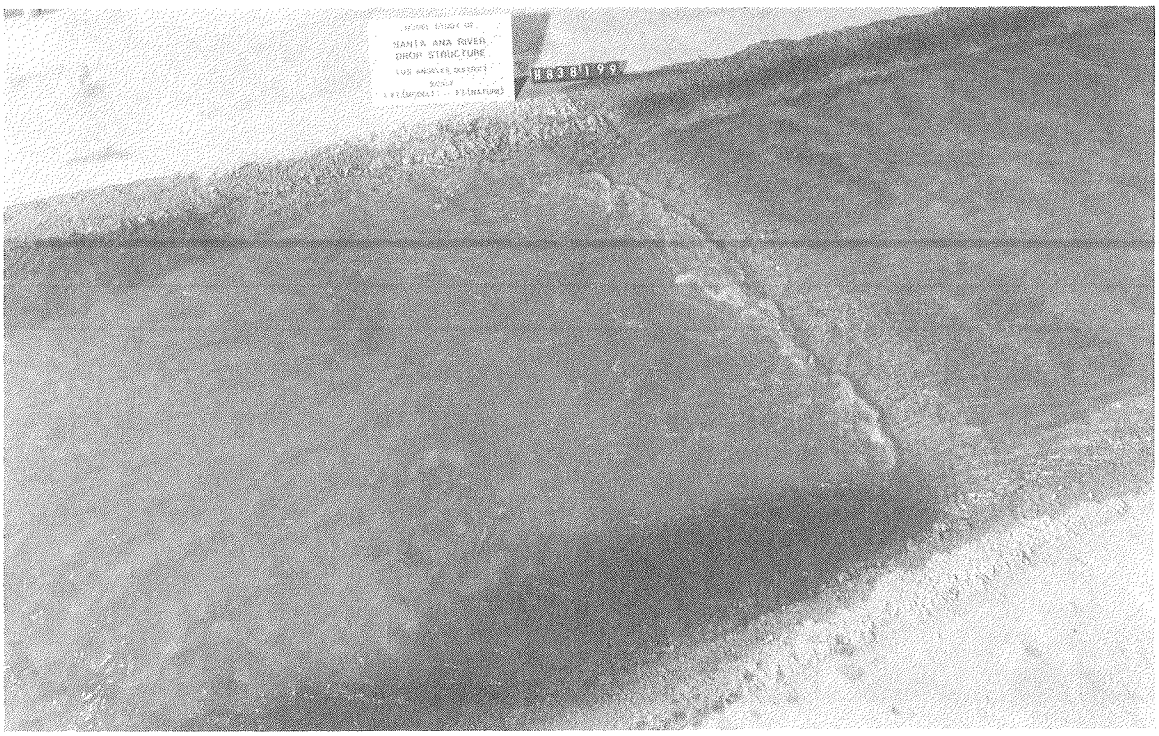


c. Unit discharge 150 cfs/ft, tailwater el 103.5



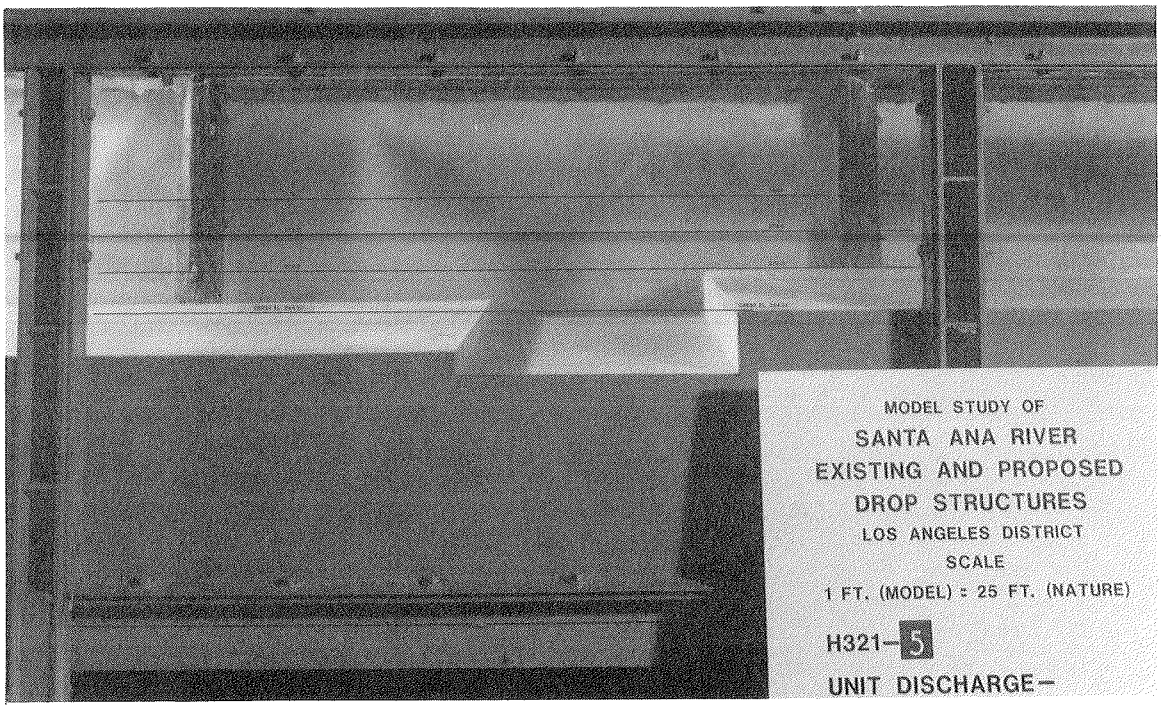
d. Unit discharge 200 cfs/ft, tailwater el 106.5

Photo 23. (Sheet 2 of 3)

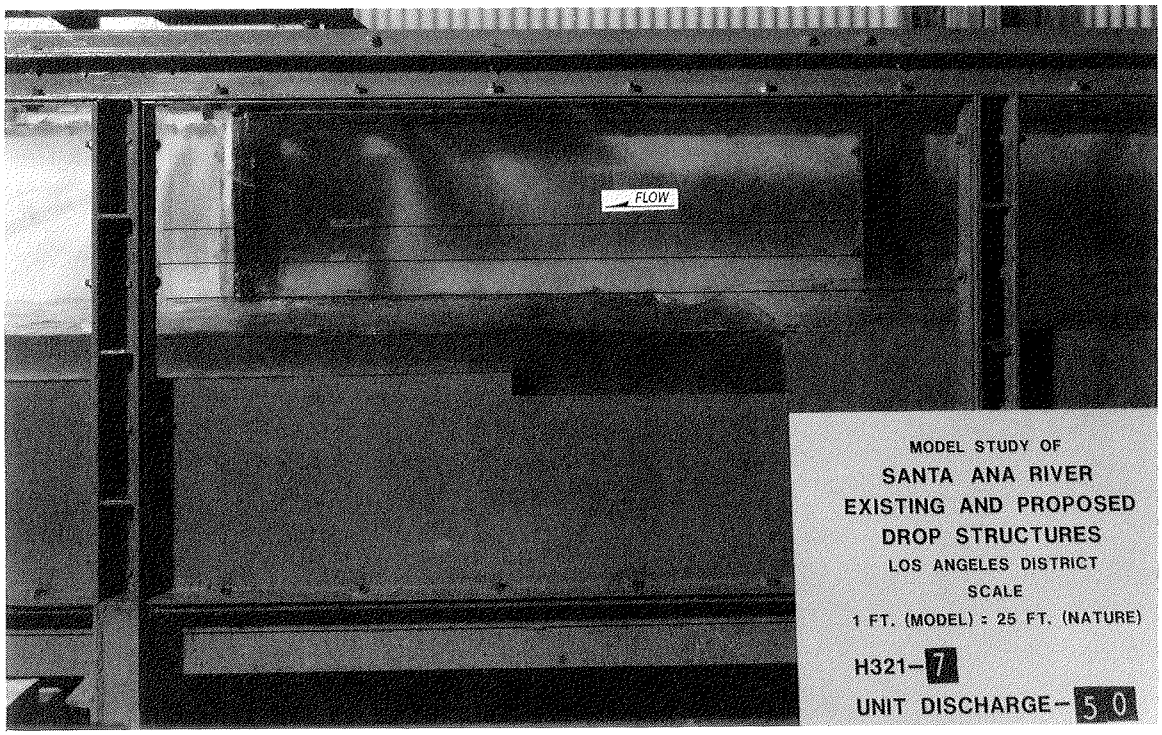


e. Unit discharge 250 cfs/ft, tailwater el 108.4

Photo 23. (Sheet 3 of 3)

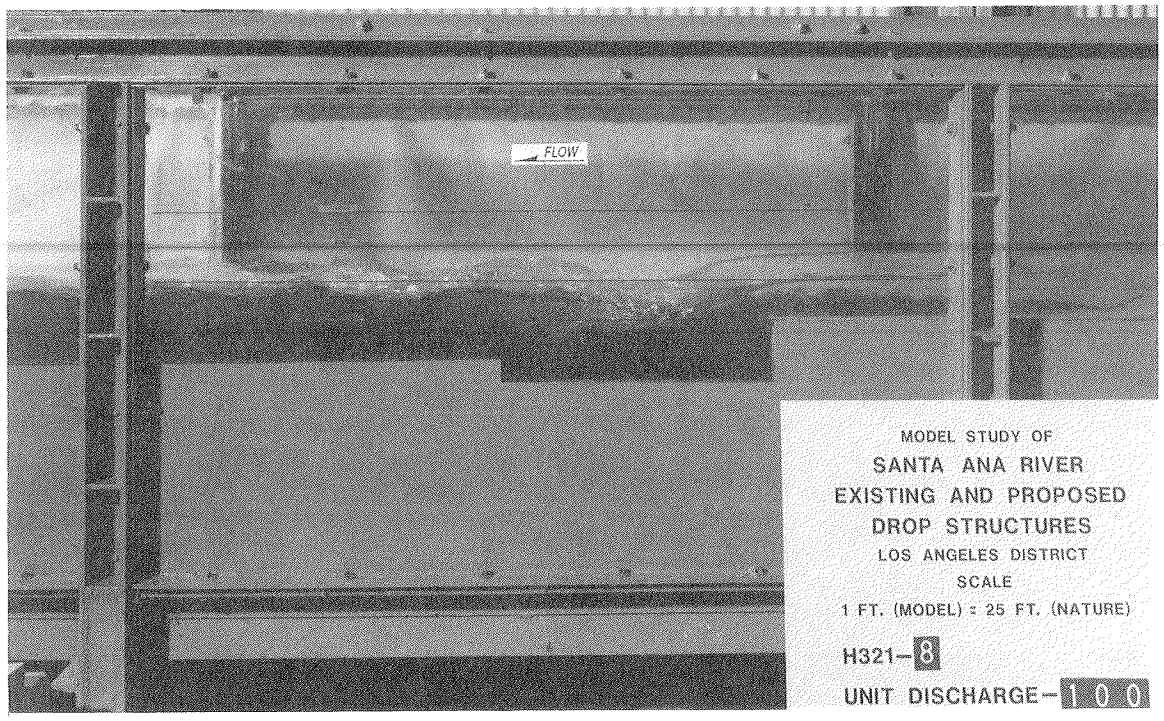


a. Dry bed

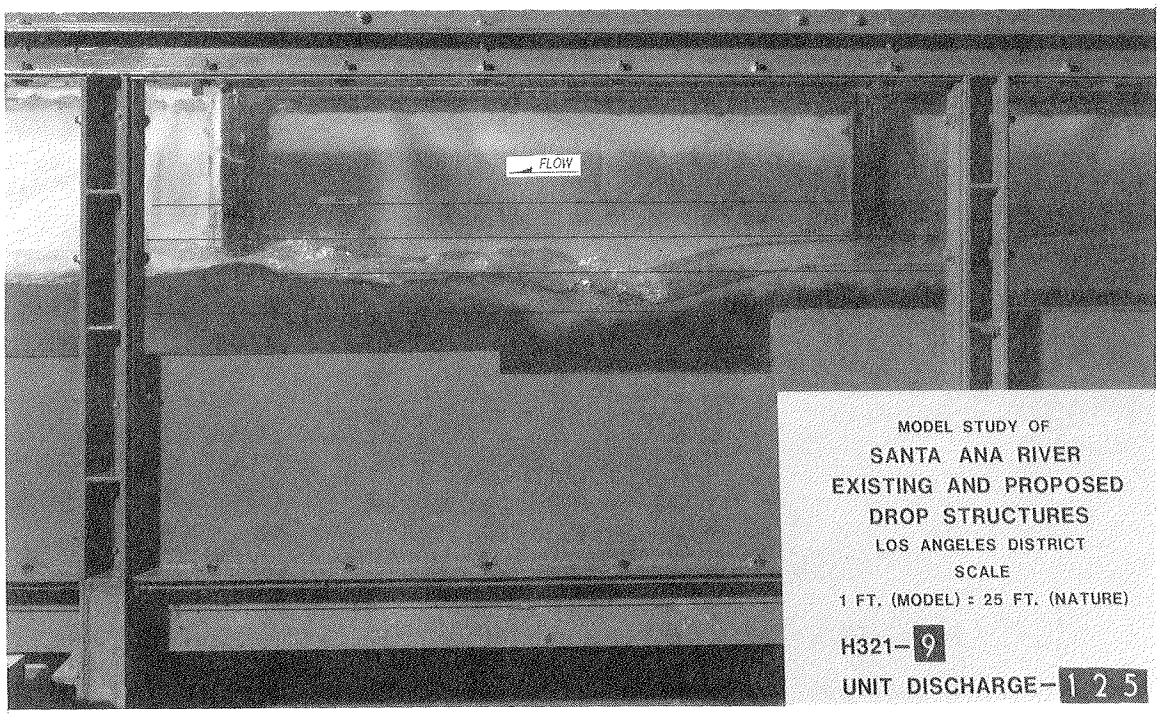


b. Unit discharge 50 cfs/ft, tailwater el 265.27

Photo 24. Flow conditions in the type 1 design drop structure at sta 1022+98.55 and n of 0.03 (Sheet 1 of 3)

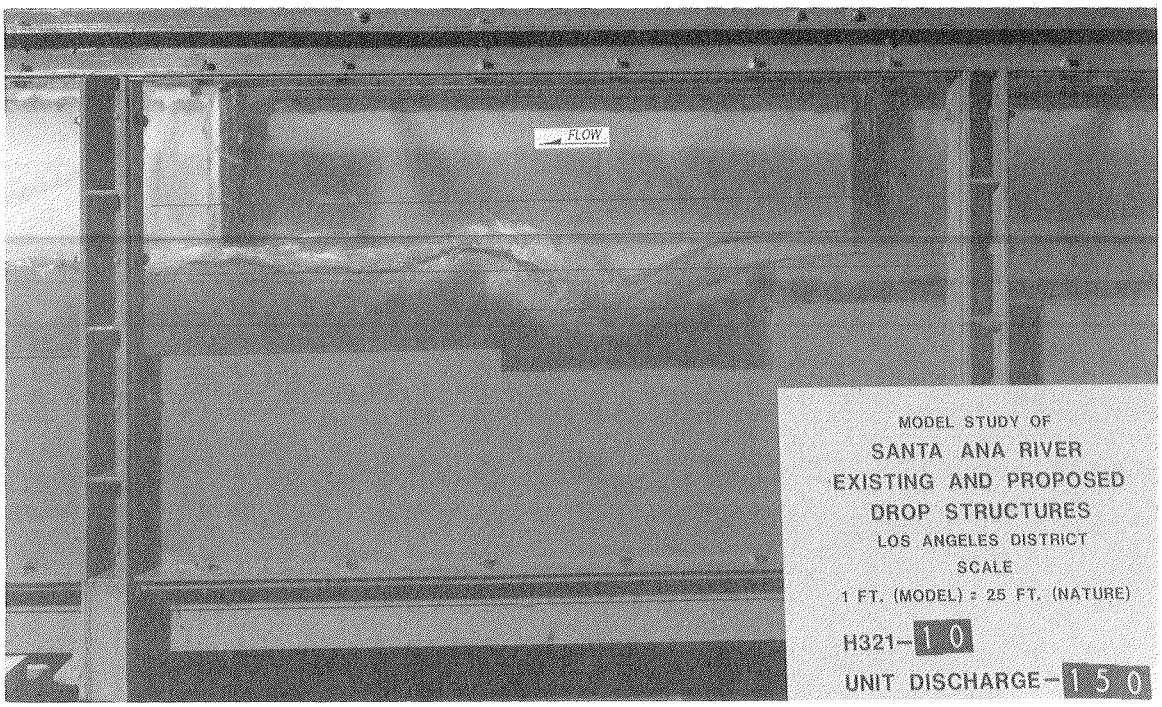


c. Unit discharge 100 cfs/ft, tailwater el 268.47

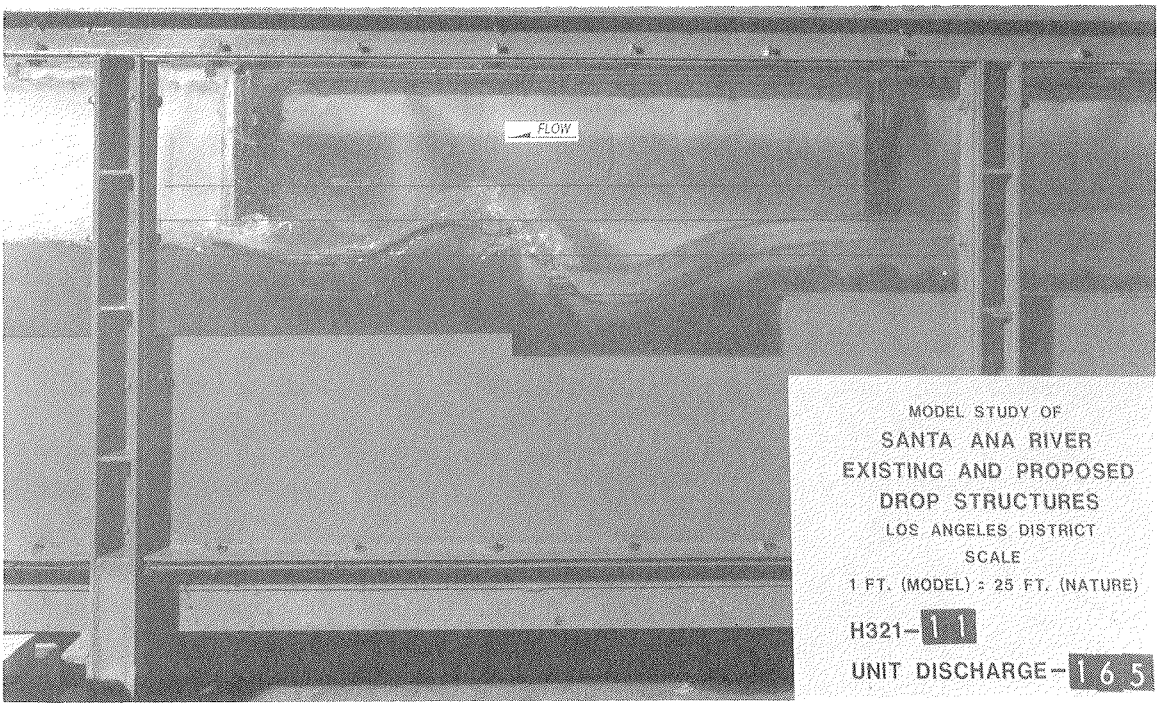


d. Unit discharge 125 cfs/ft, tailwater el 269.87

Photo 24. (Sheet 2 of 3)

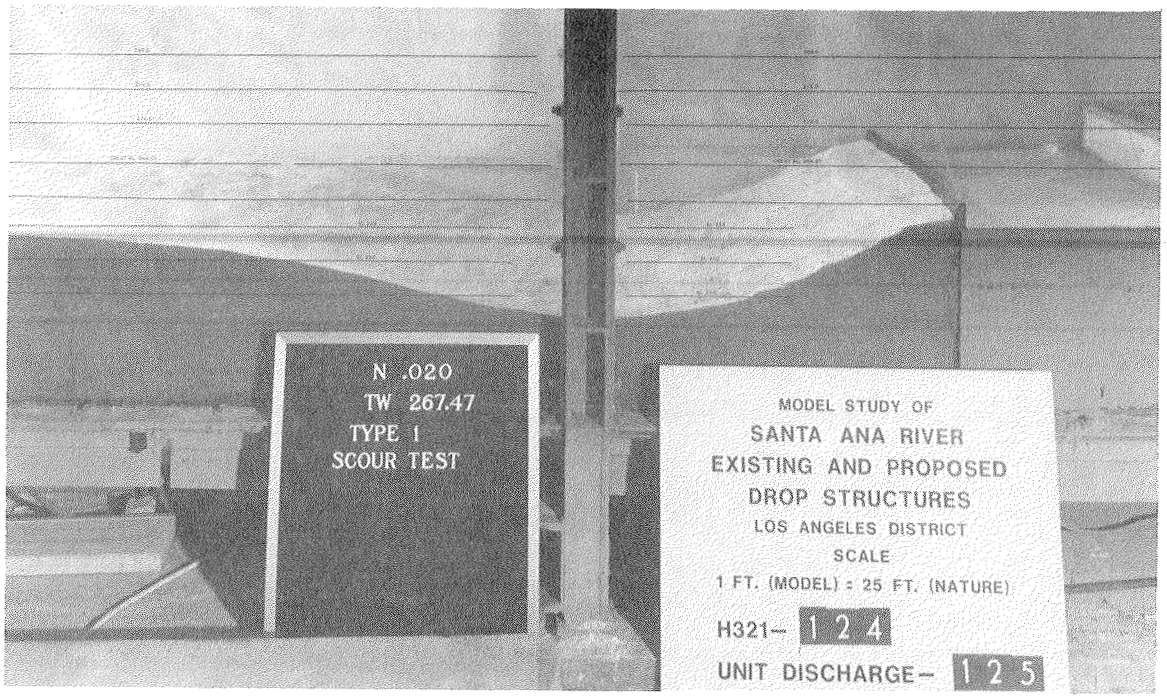


e. Unit discharge 150 cfs/ft, tailwater el 271.17

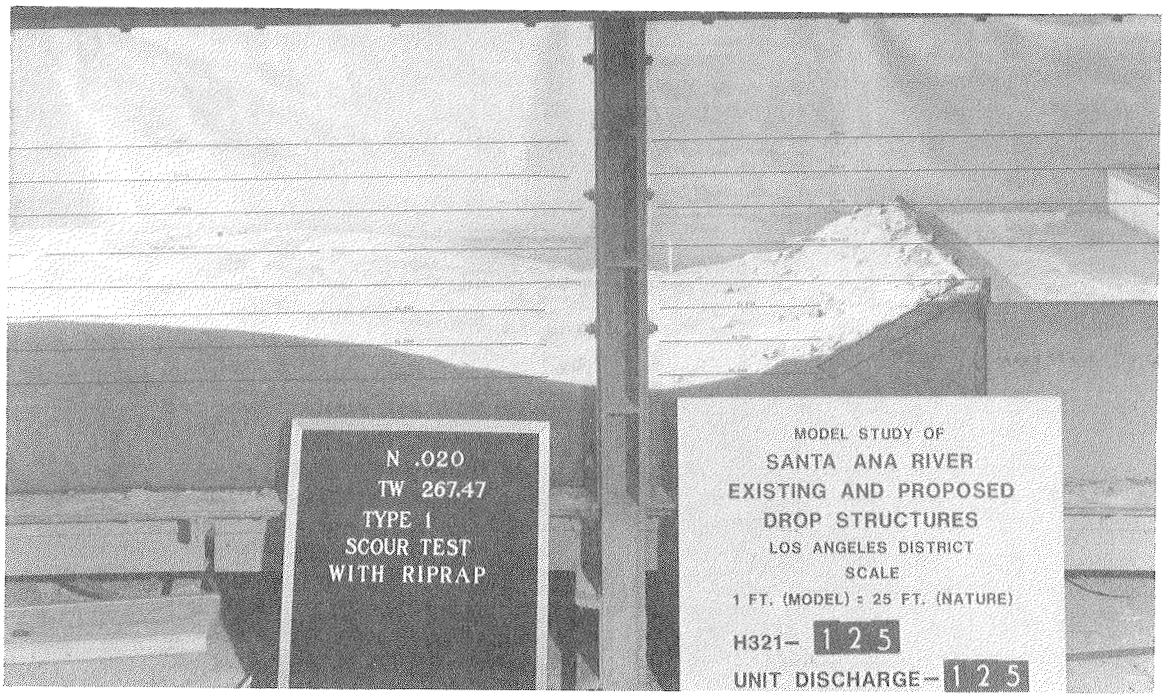


f. Unit discharge 165 cfs/ft, tailwater el 271.87

Photo 24. (Sheet 3 of 3)

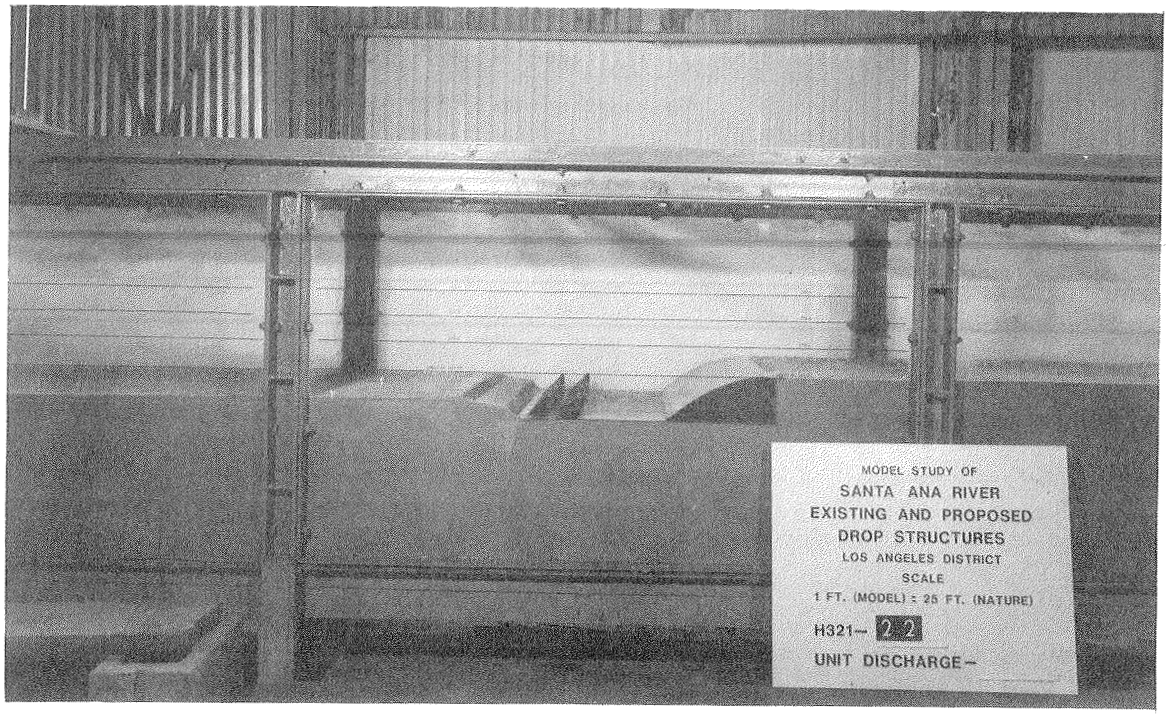


a. With only sand

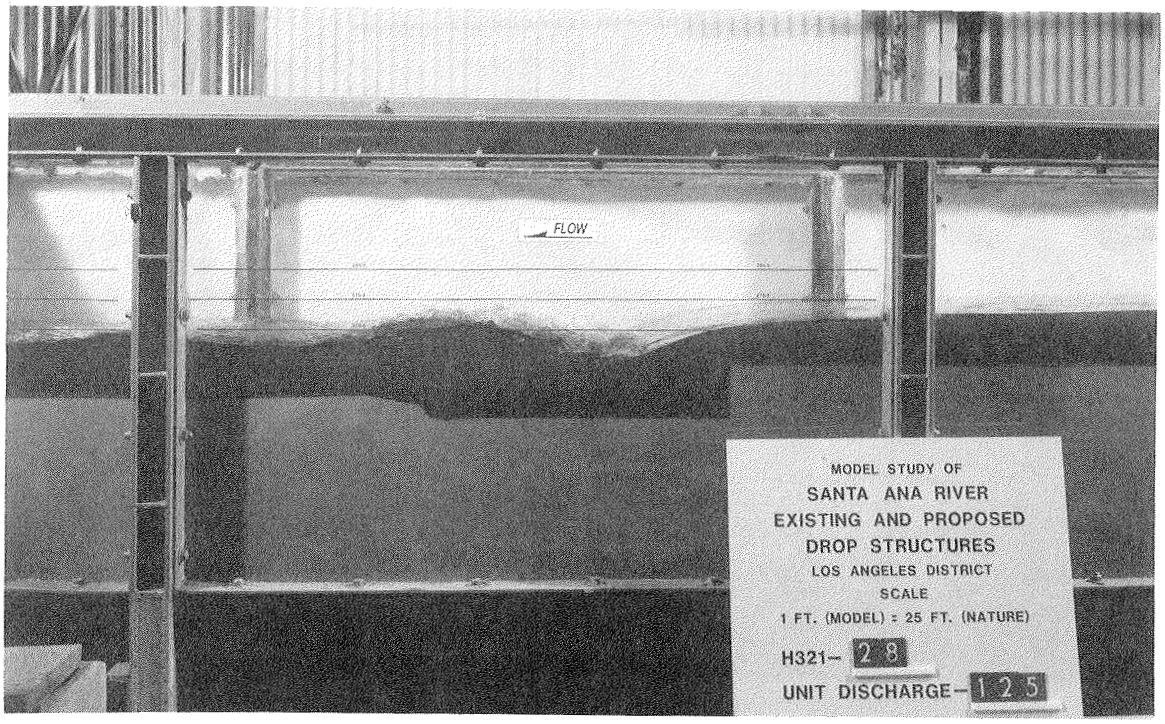


b. With riprap protection

Photo 25. Dry bed showing results of scour tests after 1 hr (prototype) with unit discharge 125 cfs/ft, tailwater el 267.47, and n of 0.02 (sta 1022+98.55)

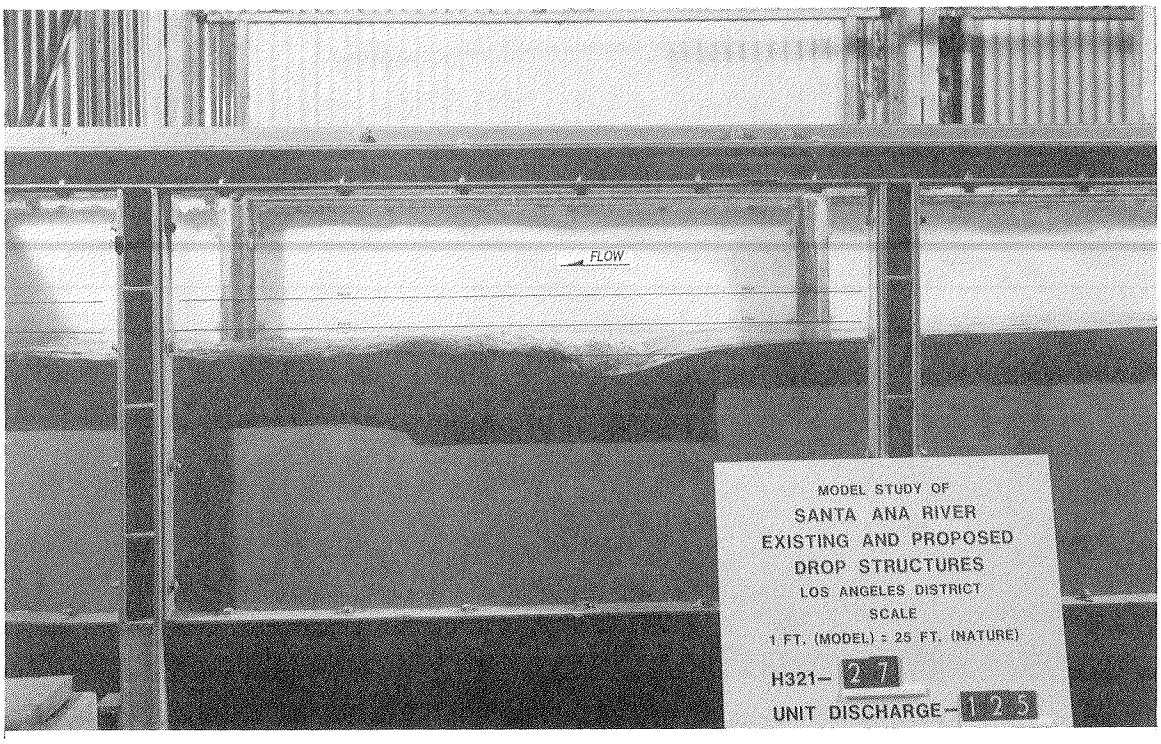


a. Dry bed



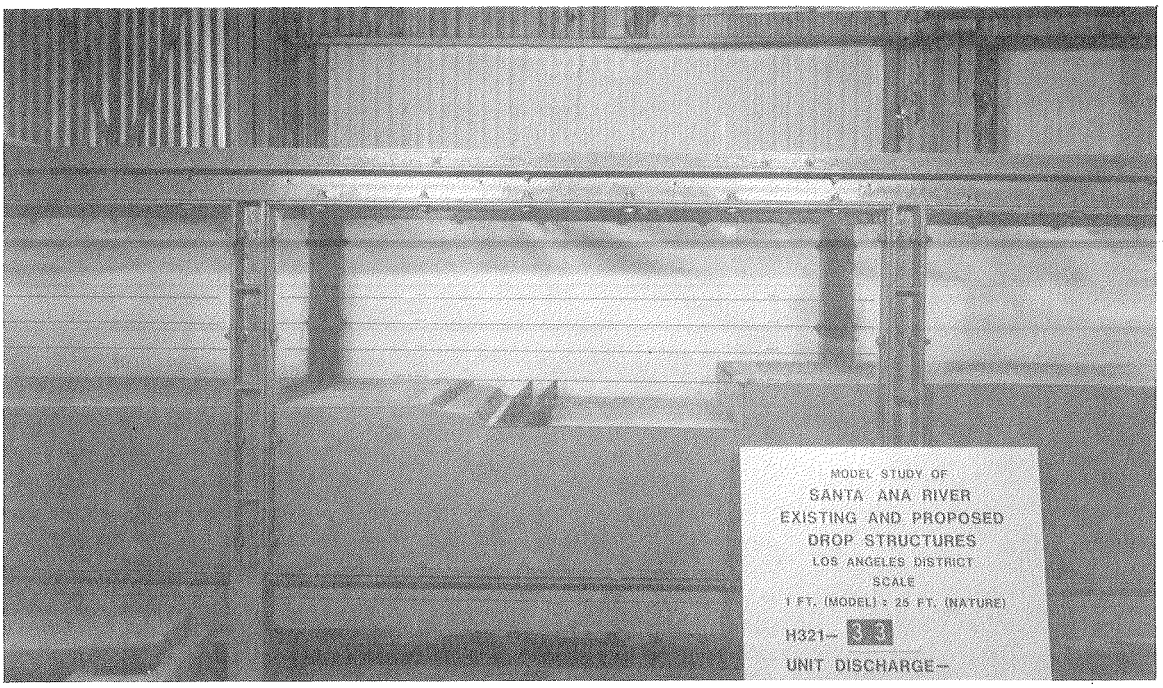
b. Tailwater el 267.47, n = 0.02

Photo 26. Type 2 design drop structure, sta 1022+98.55, unit discharge 125 cfs/ft (Continued)

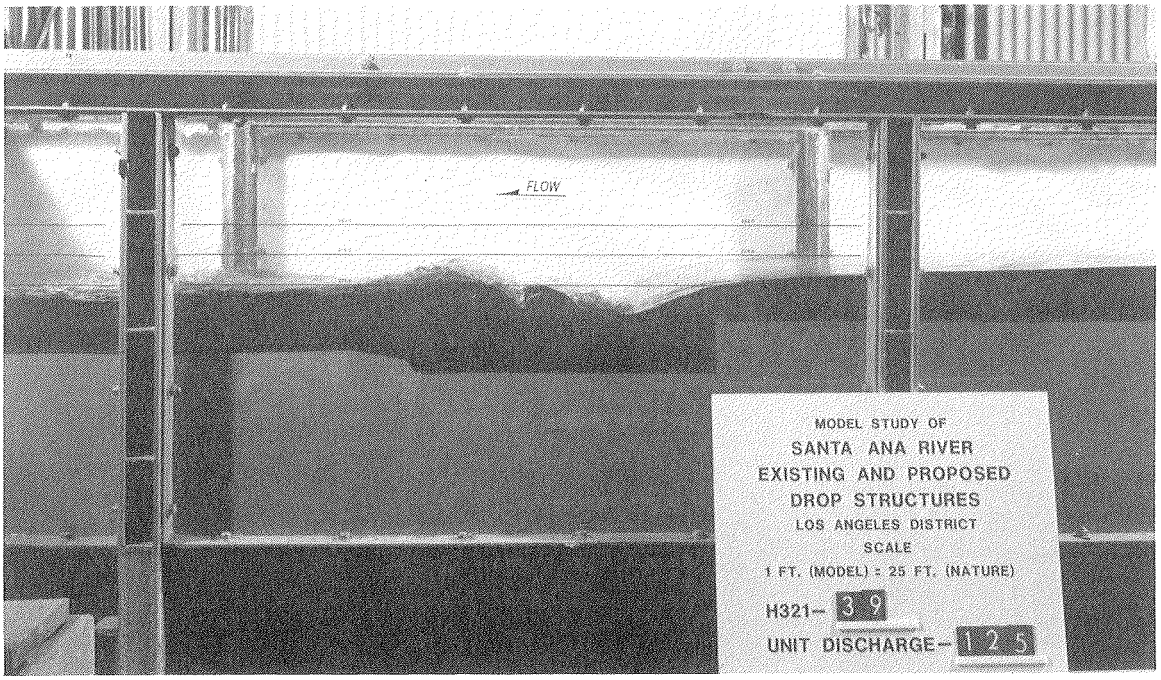


c. Tailwater el 269.87, n = 0.03

Photo 26. (Concluded)

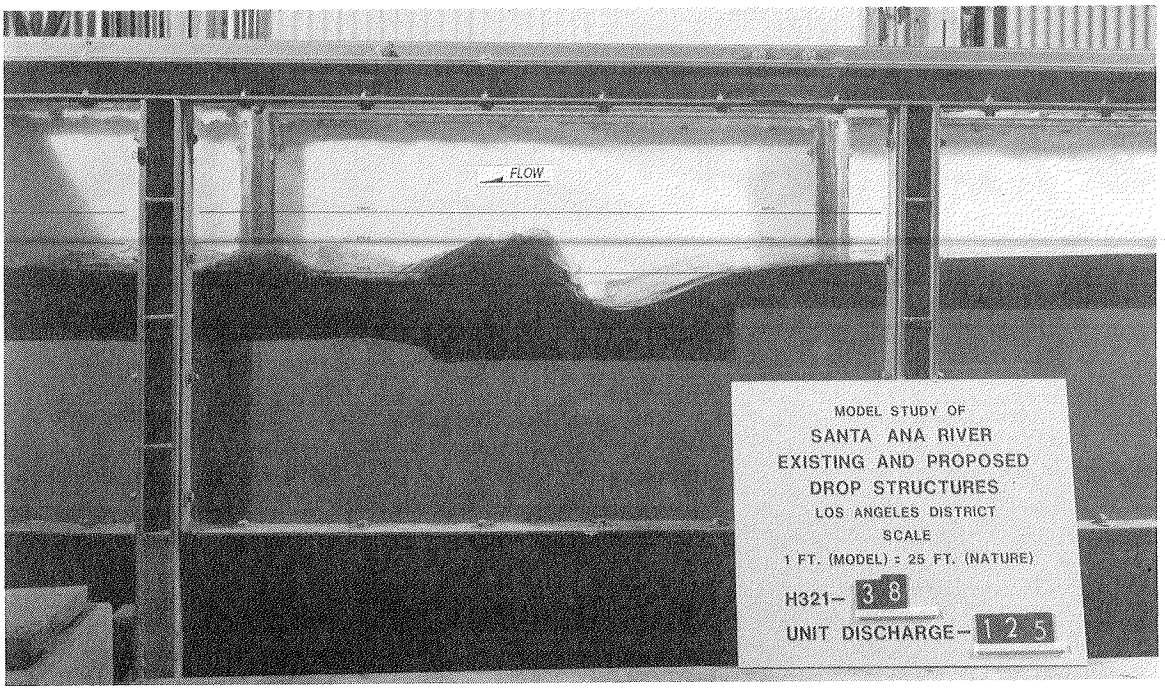


a. Dry bed



b. Tailwater el 267.47, n = 0.02

Photo 27. Type 3 design drop structure, sta 1022+98.55, unit discharge 125 cfs/ft (Continued)



c. Tailwater el 269.87, n = 0.03

Photo 27. (Concluded)

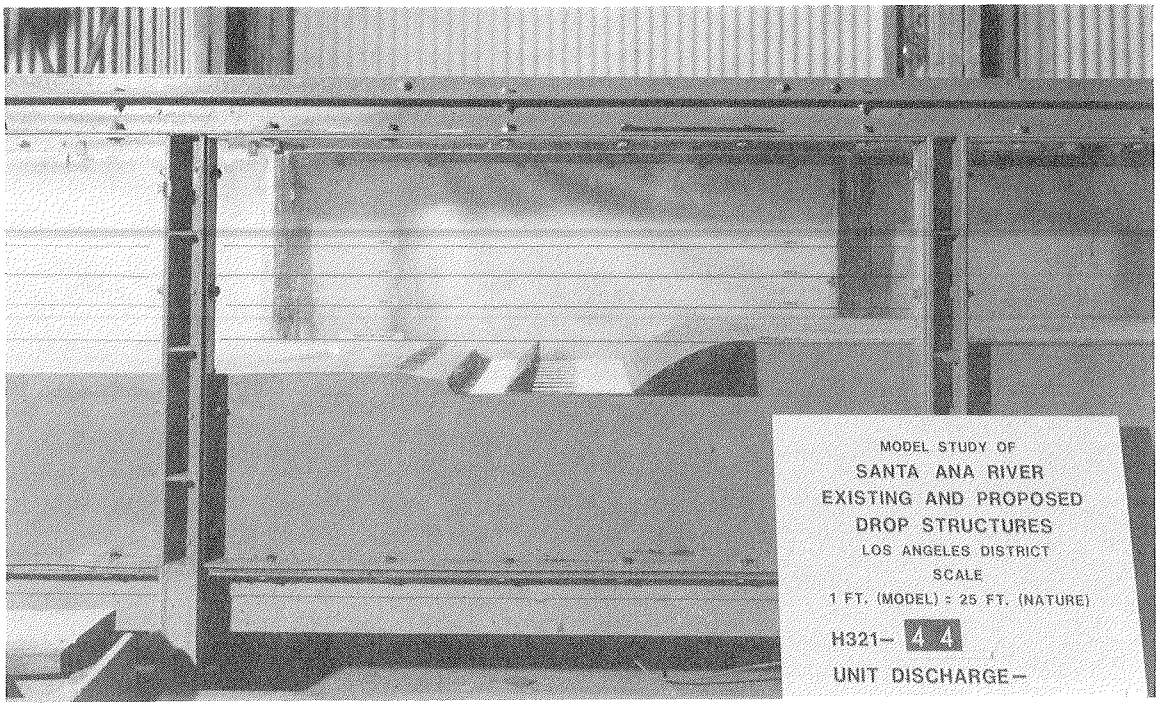
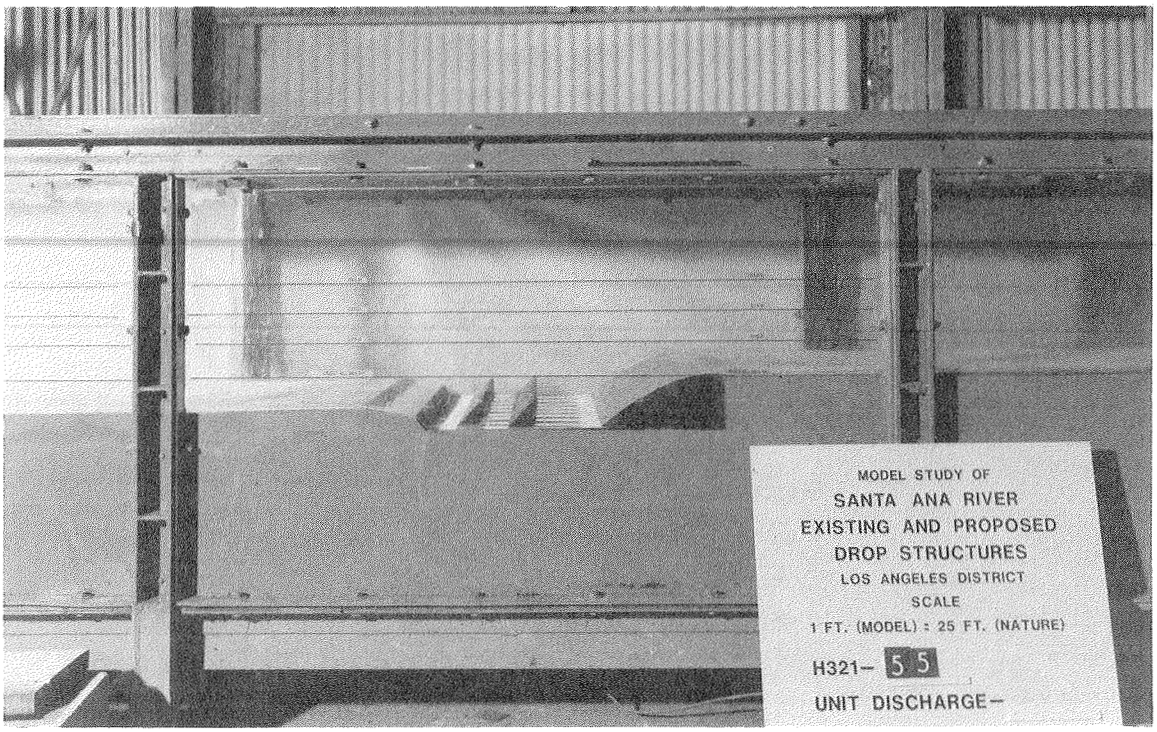
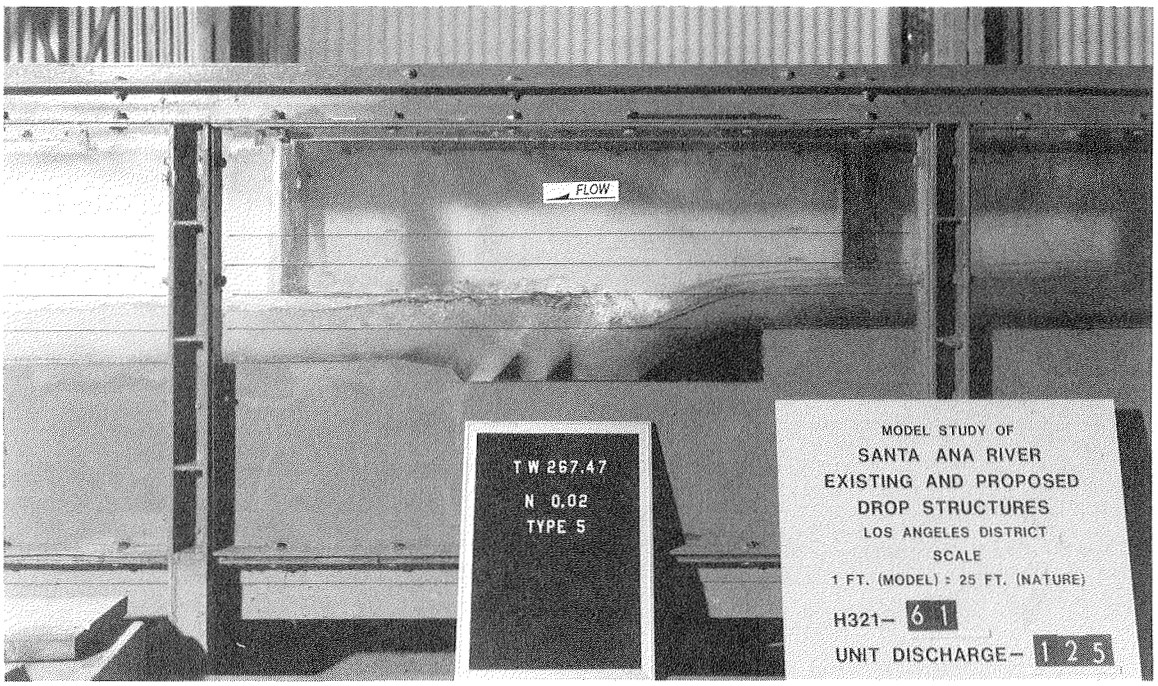


Photo 28. Type 4 design drop structure (sta 1022+98.55)

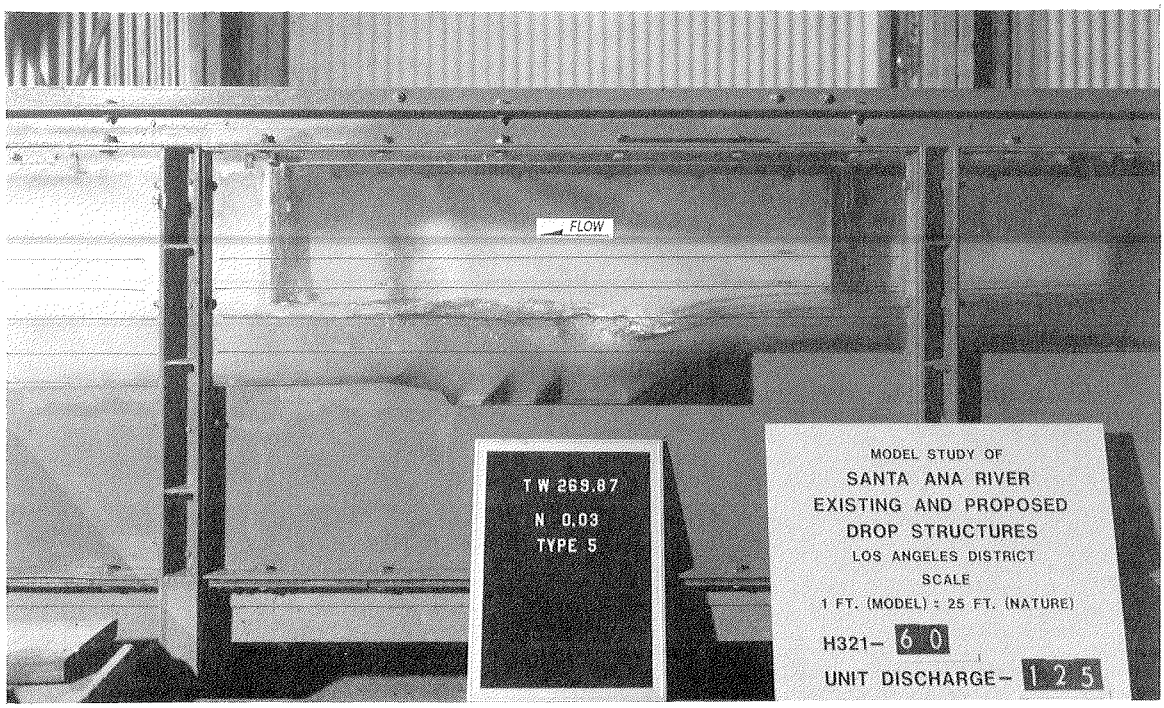


a. Dry bed



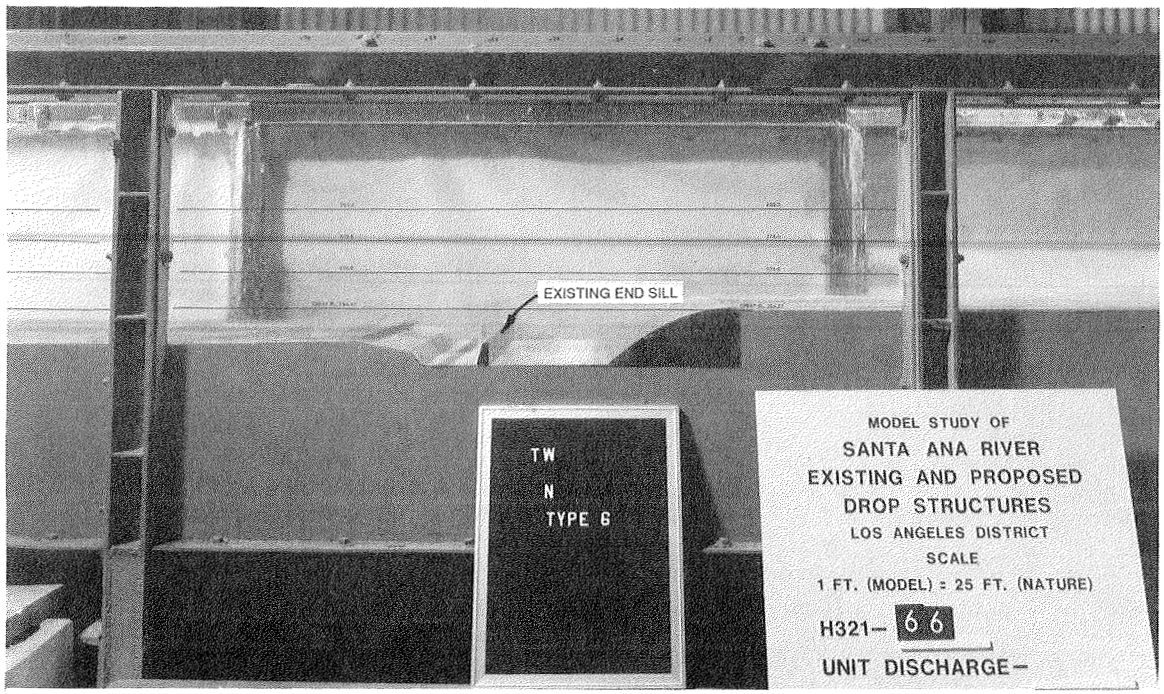
b. Tailwater el 267.47, n = 0.02

Photo 29. Type 5 design drop structure, sta 1022+98.55, unit discharge 125 cfs/ft (Continued)

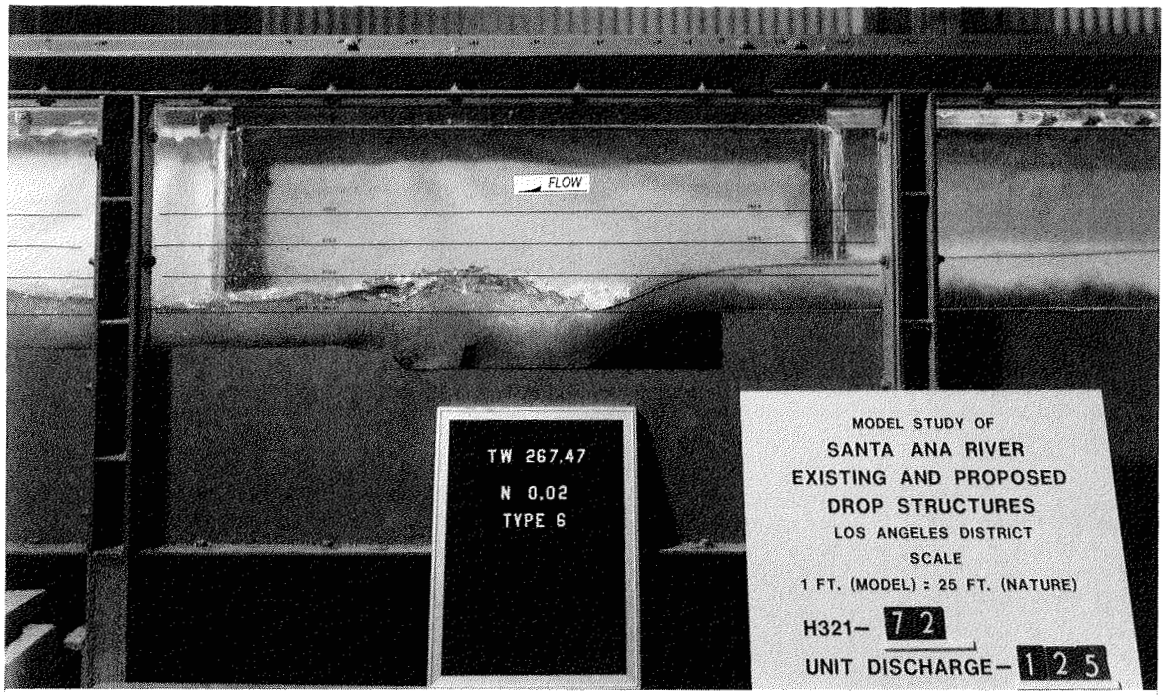


c. Tailwater el 269.87, n = 0.03

Photo 29. (Concluded)

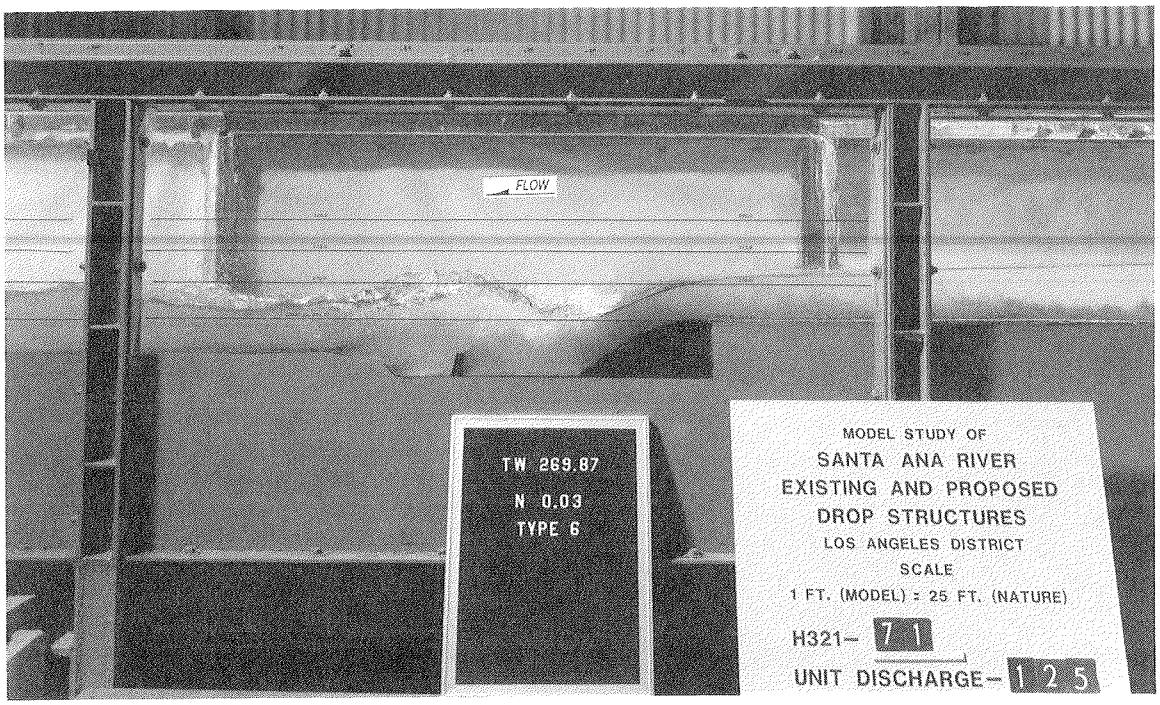


a. Dry bed



b. Tailwater el 267.47, n = 0.02

Photo 30. Type 6 design drop structure, sta 1022+98.55, discharge 125 cfs/ft (Continued)



c. Tailwater el 269.87, n = 0.03

Photo 30. (Concluded)

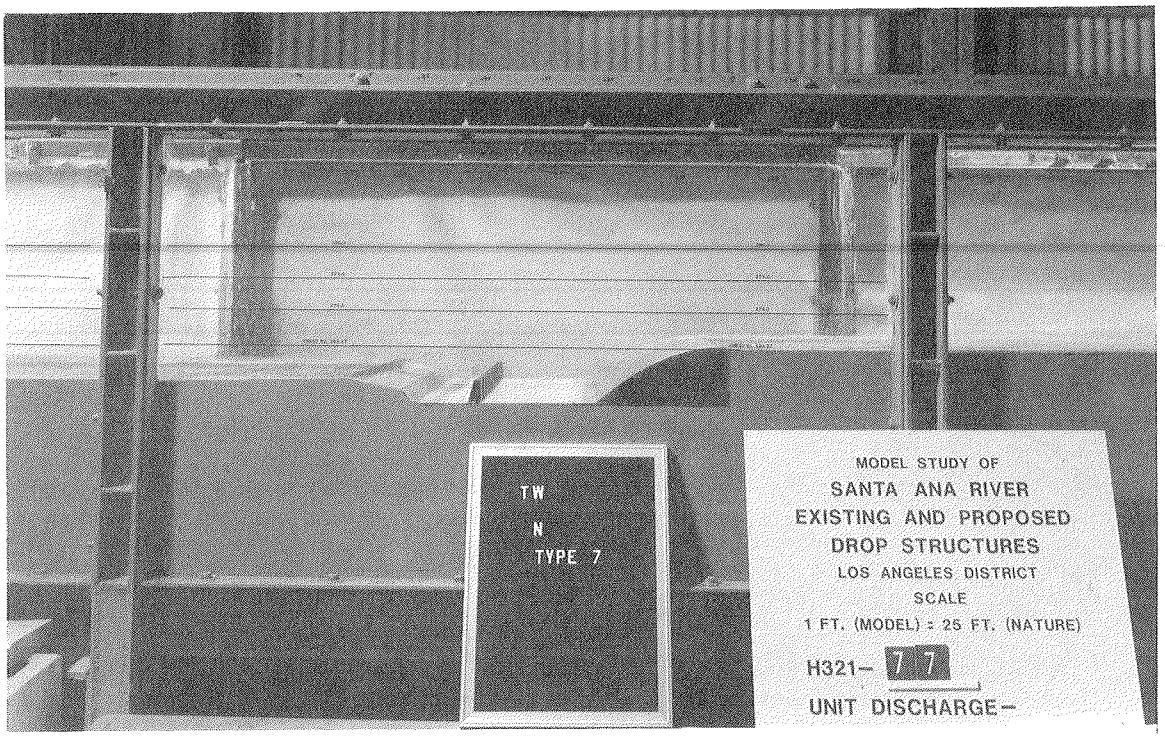
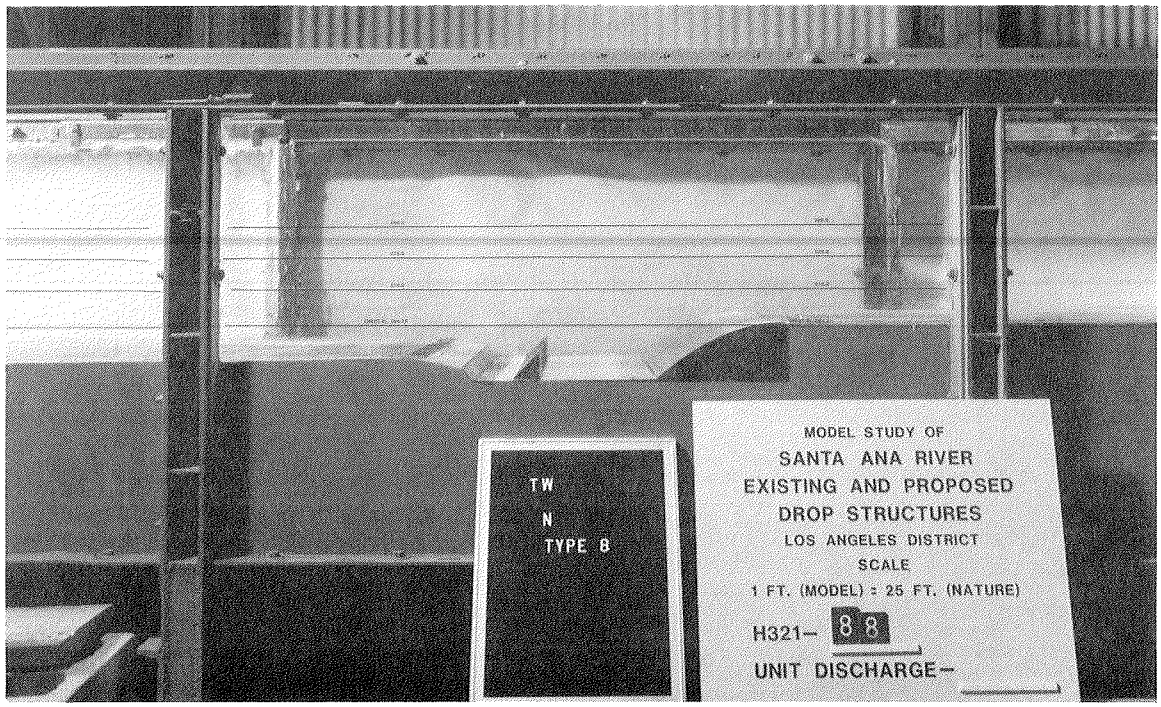
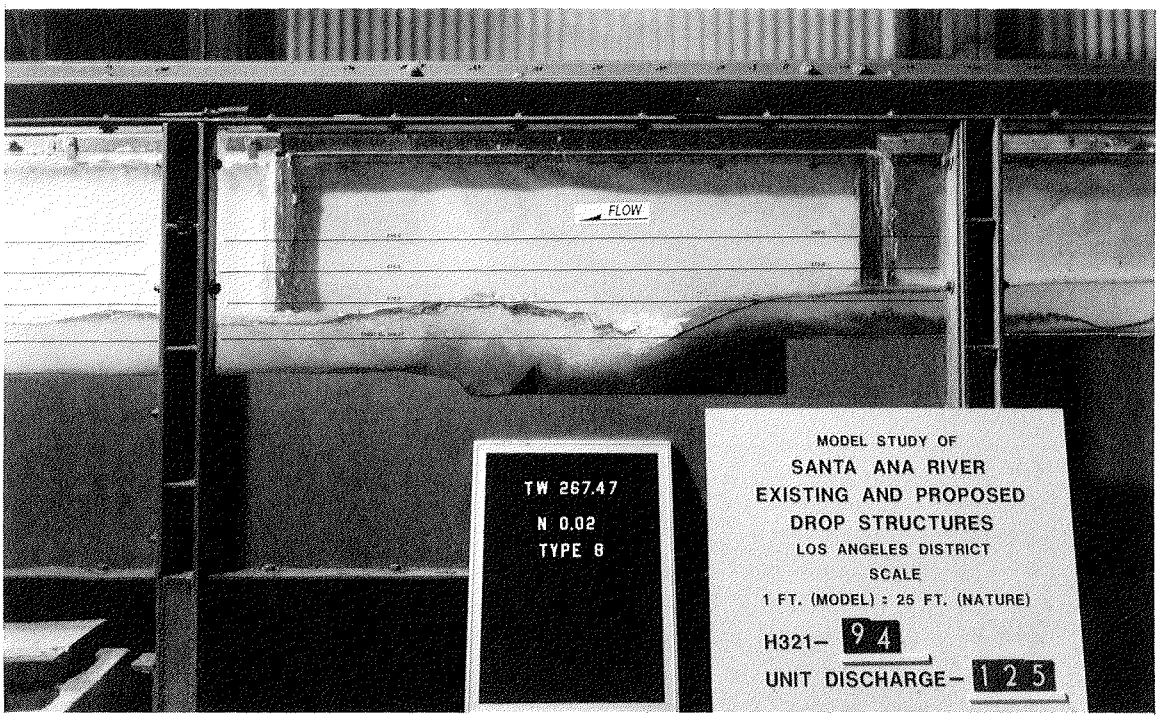


Photo 31. Type 7 design drop structure (sta 1022+98.55)

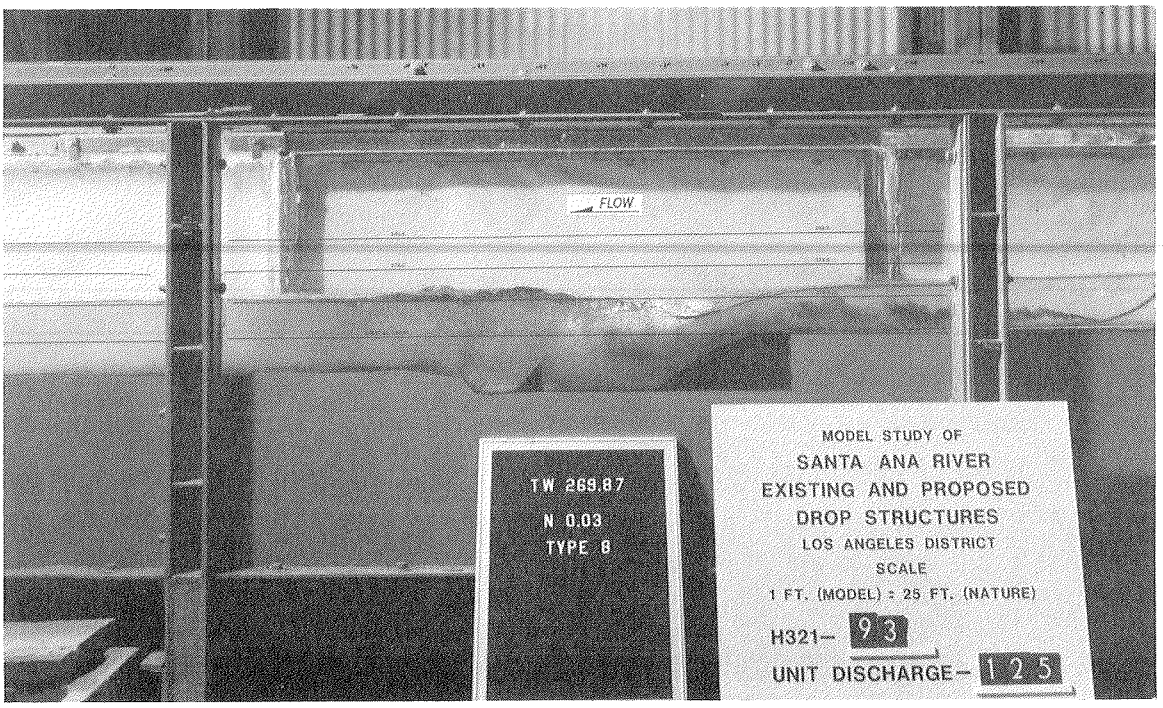


a. Dry bed



b. Tailwater el 267.47, n = 0.02

Photo 32. Type 8 design drop structure, sta 1022+98.55, unit discharge 125 cfs/ft (Continued)



c. Tailwater el 269.87, n = 0.03

Photo 32. (Concluded)

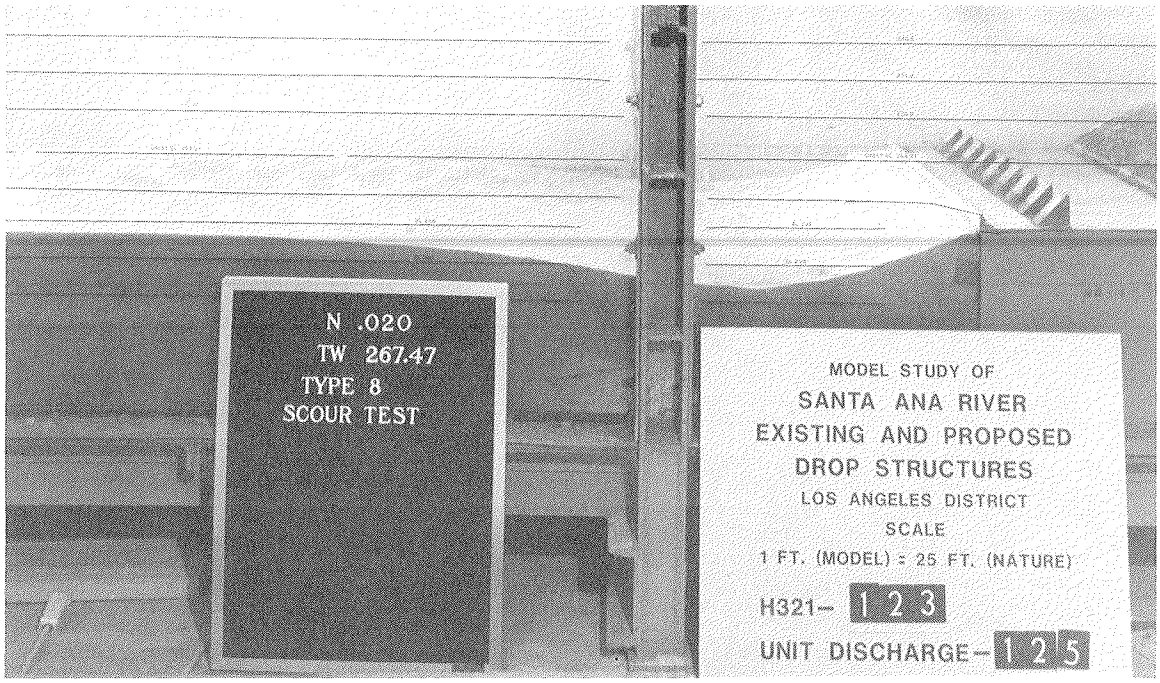
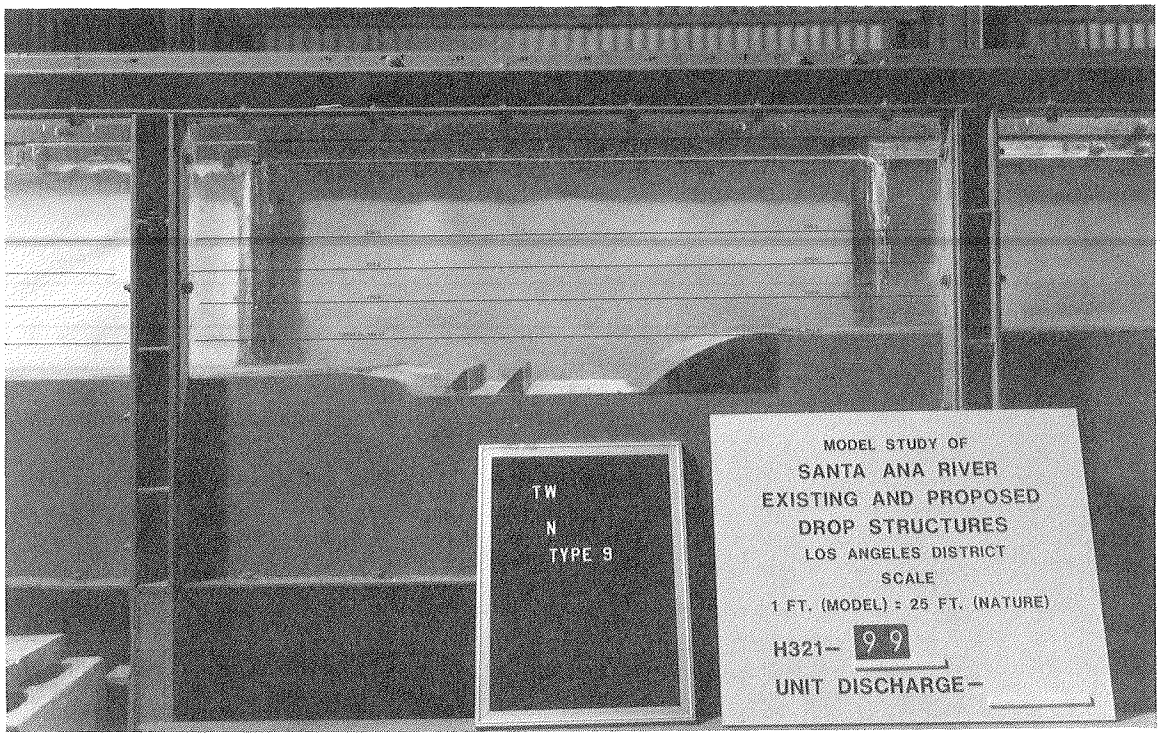
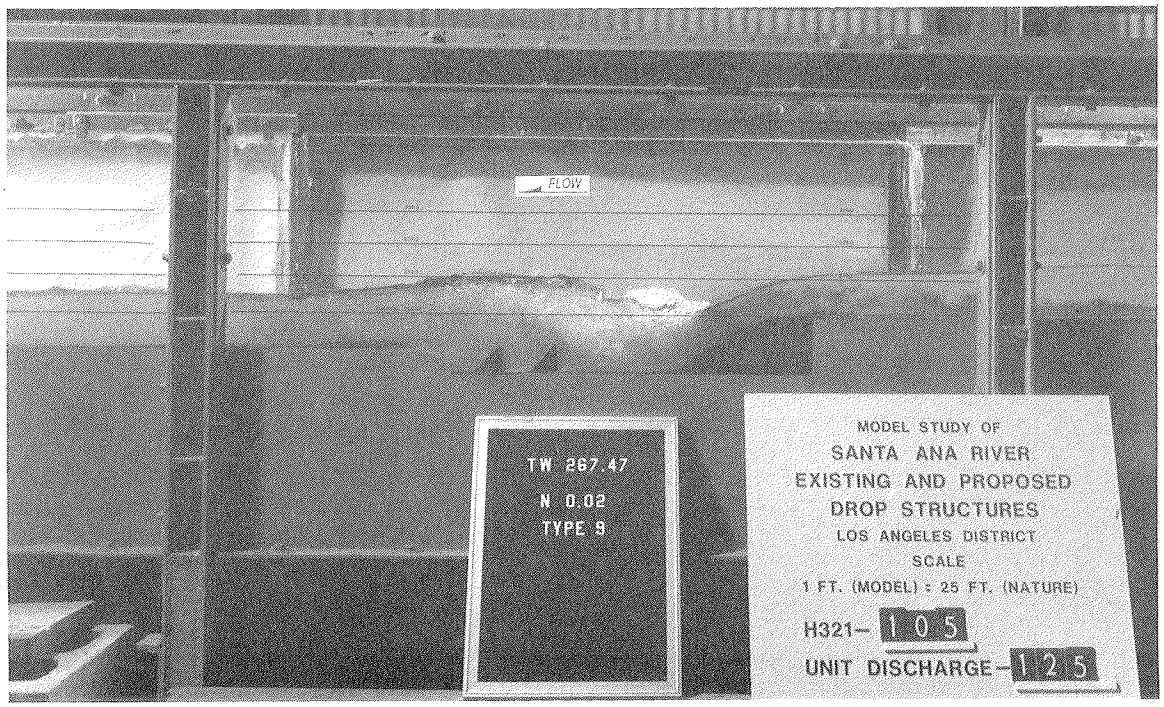


Photo 33. Type 8 design drop structure, sta 1022+98.55, results of scour tests after 1 hr (prototype) with unit discharge 125 cfs/ft, tailwater el 267.47, and n = 0.02 (sta 1022+98.55)

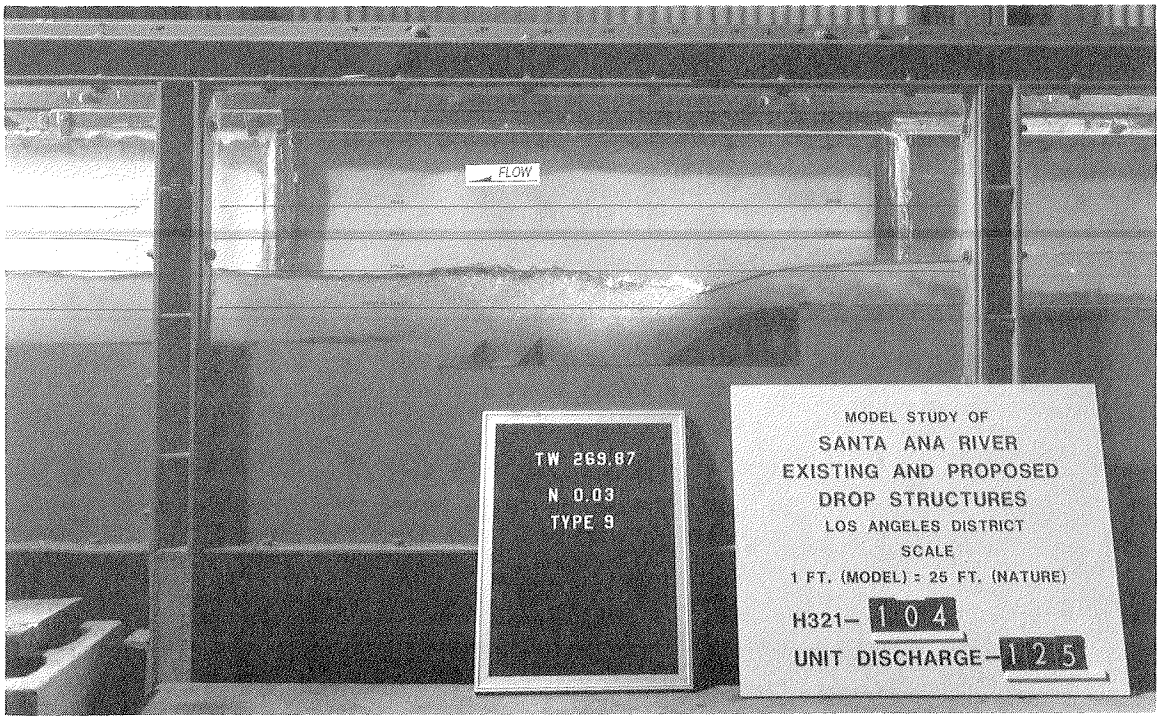


a. Dry bed



b. Tailwater el 267.47, n = 0.02

Photo 34. Type 9 design drop structure, sta 1022+98.55, unit discharge 125 cfs/ft (Continued)



c. Tailwater el 269.87, n = 0.03

Photo 34. (Concluded)

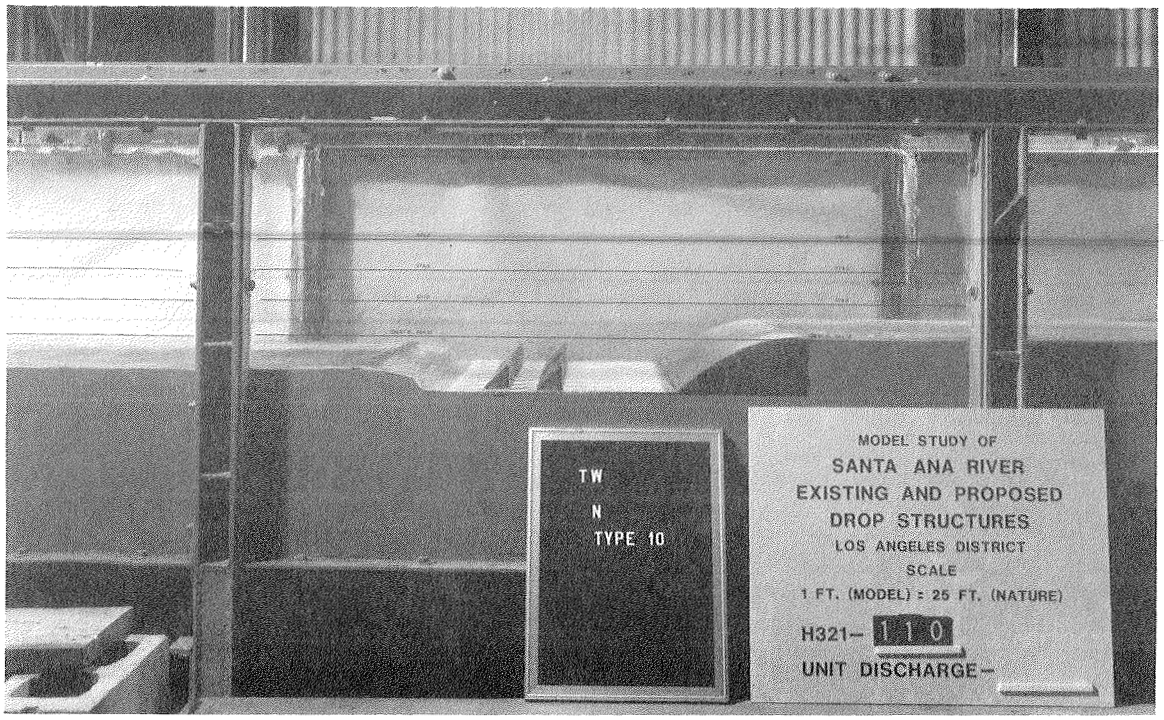
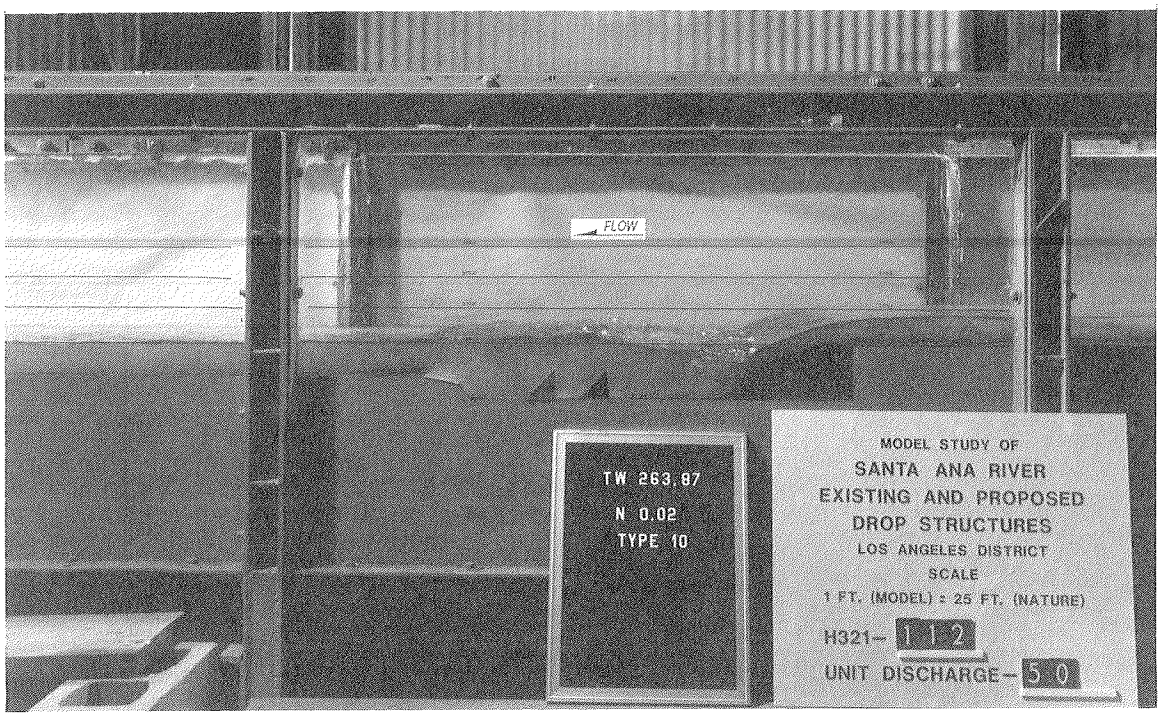
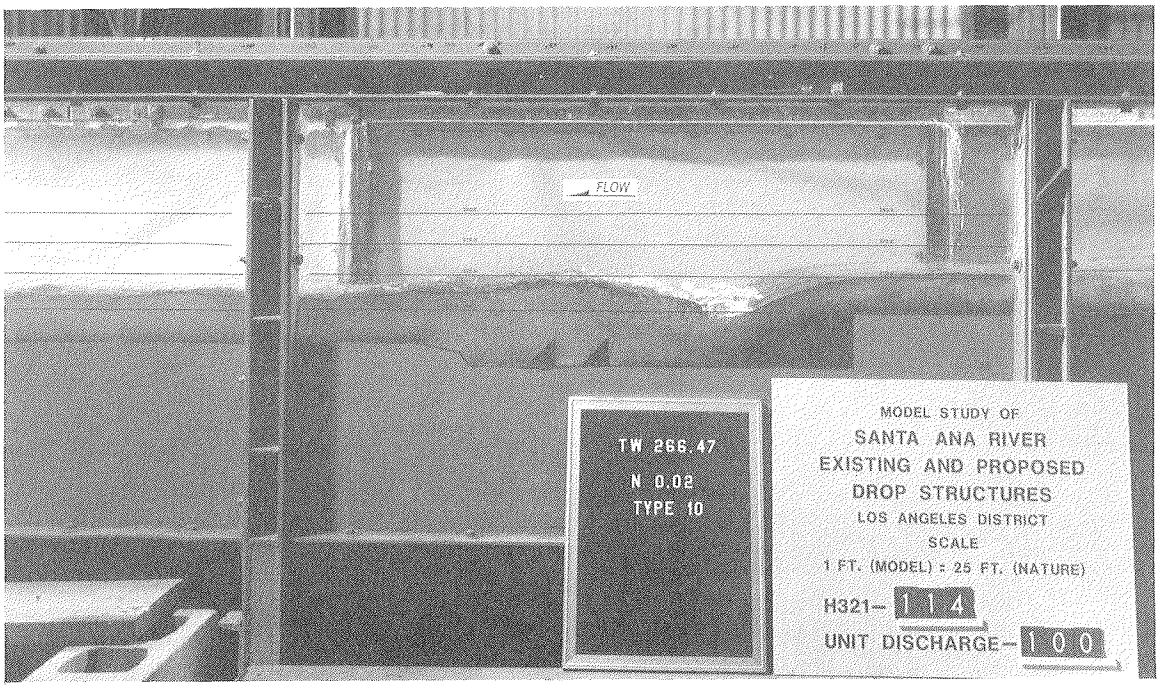


Photo 35. Type 10 design drop structure, sta 1022+98.55

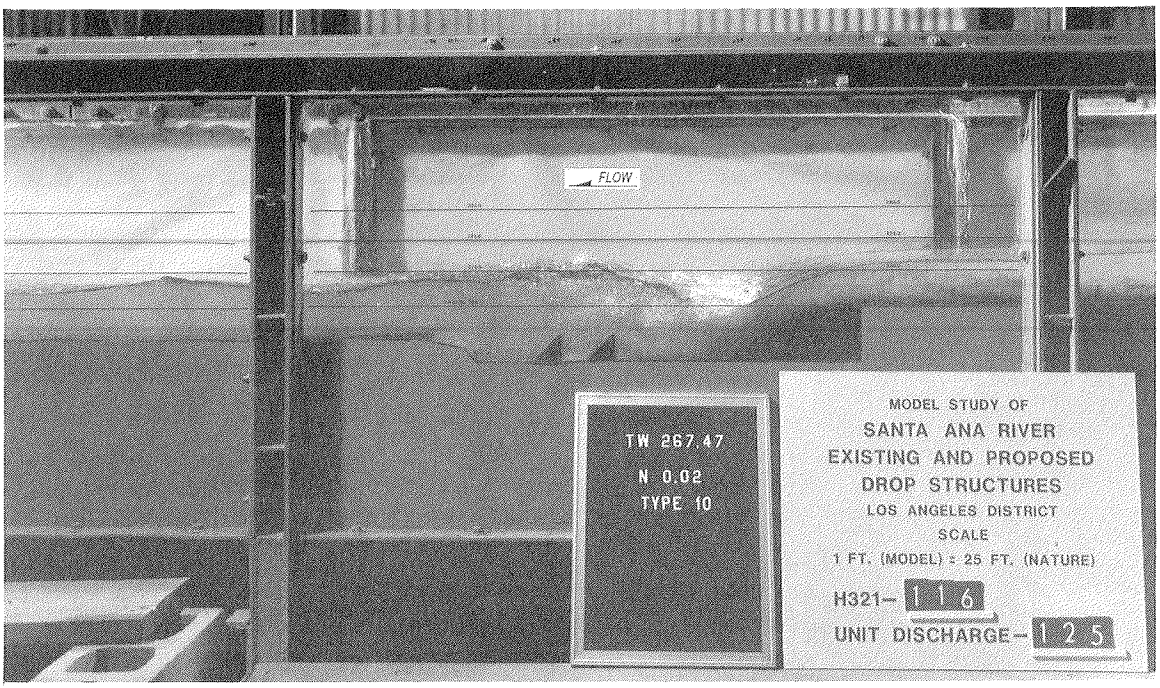


a. Unit discharge 50 cfs/ft, tailwater el 263.87

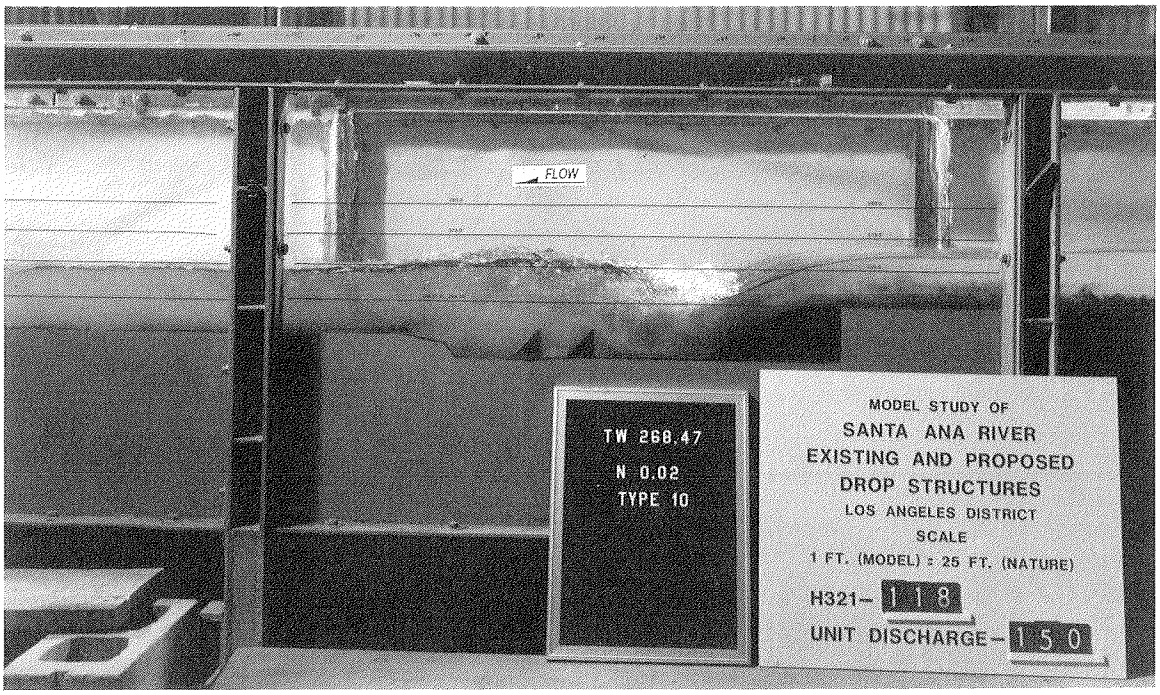


b. Unit discharge 100 cfs/ft, tailwater el 266.47

Photo 36. Flow conditions in the type 10 design drop structure, sta 1022+98.55, n = 0.02 (Sheet 1 of 3)

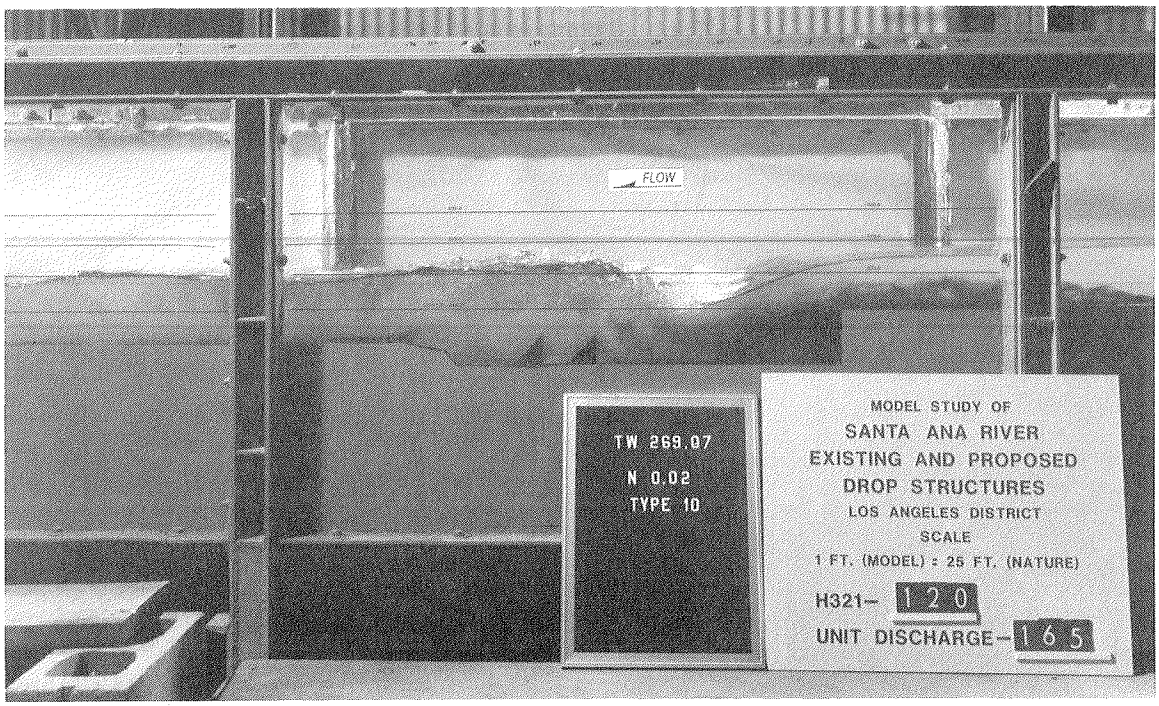


c. Unit discharge 125 cfs/ft, tailwater el 267.47



d. Unit discharge 150 cfs/ft, tailwater el 268.47

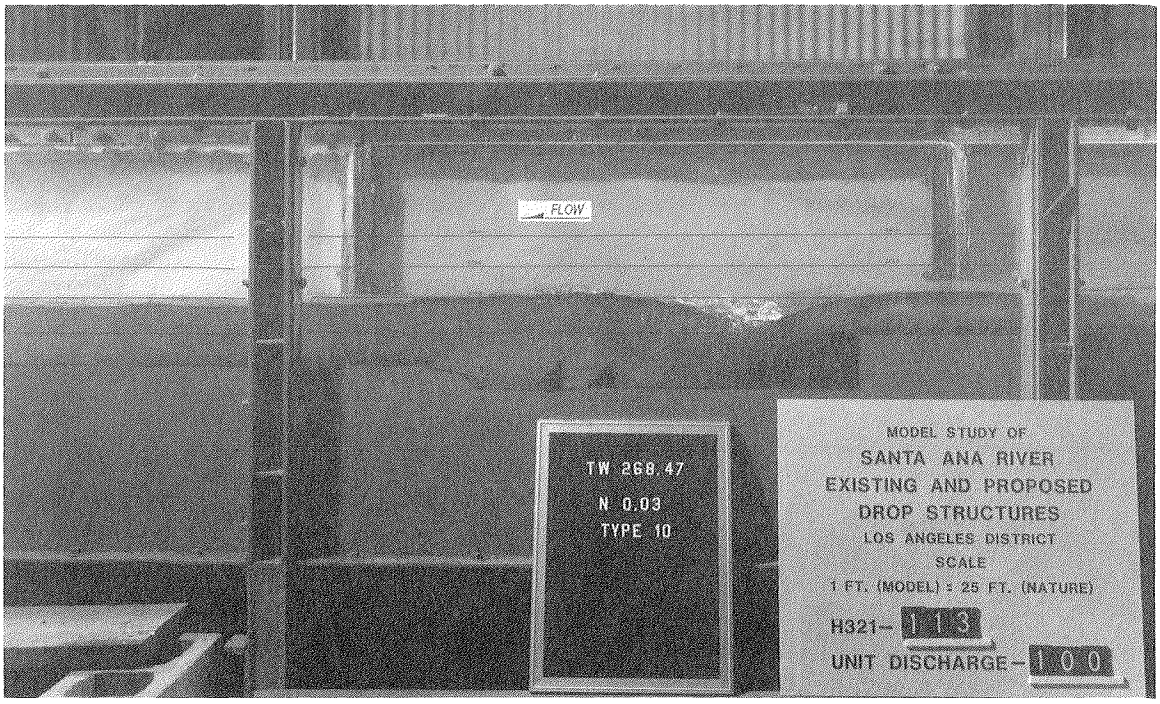
Photo 36. (Sheet 2 of 3)



e. Unit discharge 165 cfs/ft, tailwater el 269.07

Photo 36. (Sheet 3 of 3)

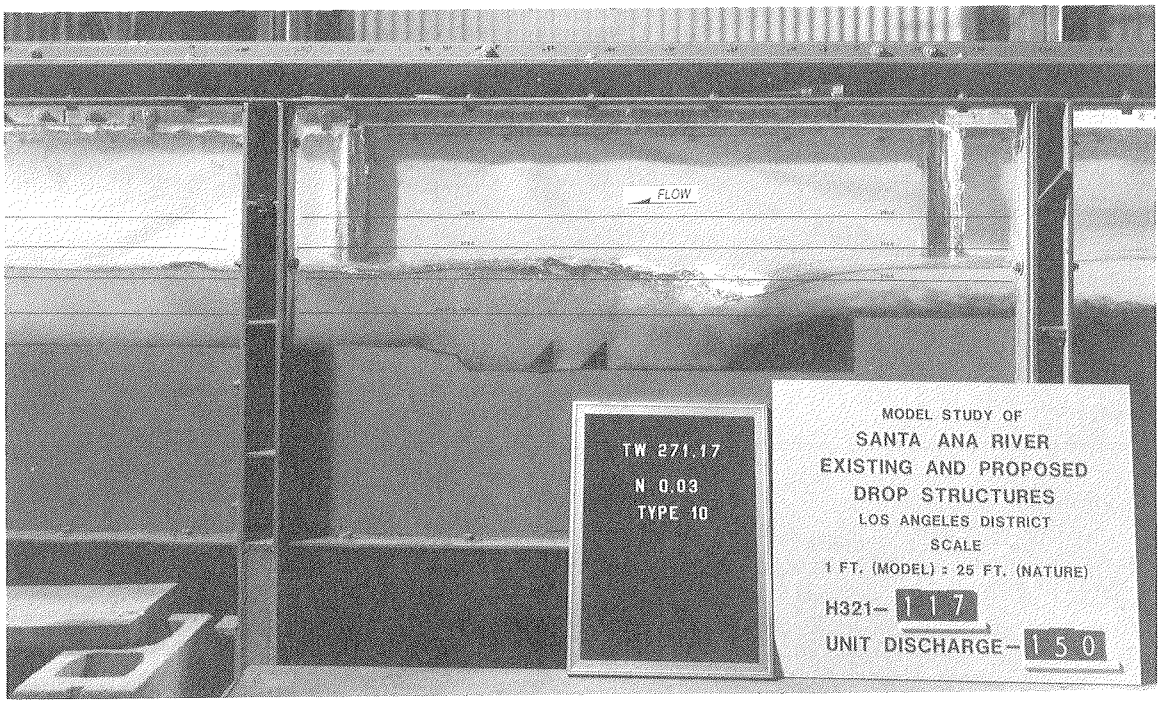
a. Unit discharge 50 cfs/ft, tailwater el 265.27



b. Unit discharge 100 cfs/ft, tailwater el 268.47

Photo 37. Flow conditions in the type 10 design drop structure, sta 1022+98.55, n = 0.03 (Sheet 1 of 3)

c. Unit discharge 125 cfs/ft, tailwater el 269.87

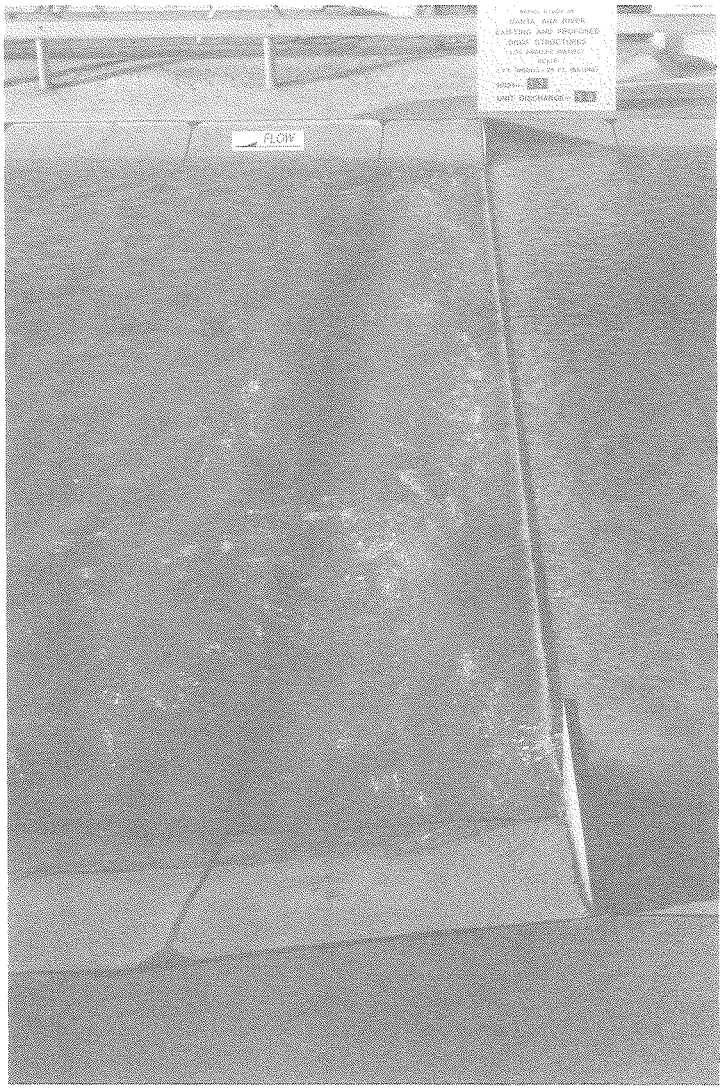


d. Unit discharge 150 cfs/ft, tailwater el 271.17

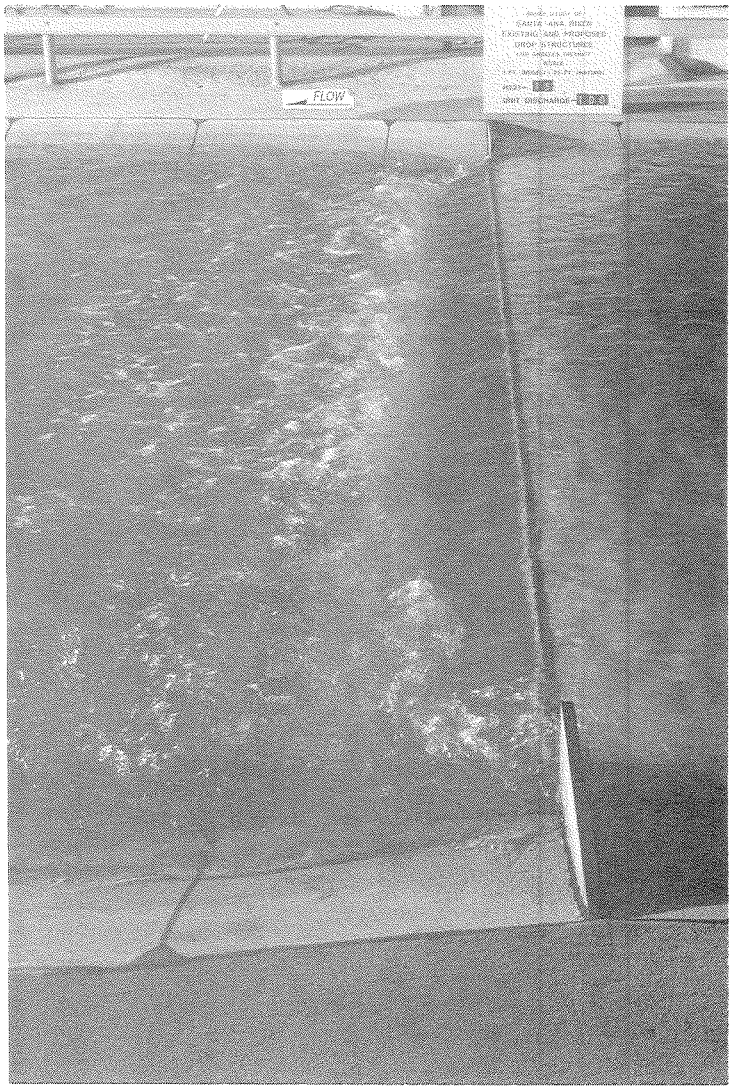
Photo 37. (Sheet 2 of 3)

e. Unit discharge 165 cfs/ft, tailwater el 271.87

Photo 37. (Sheet 3 of 3)

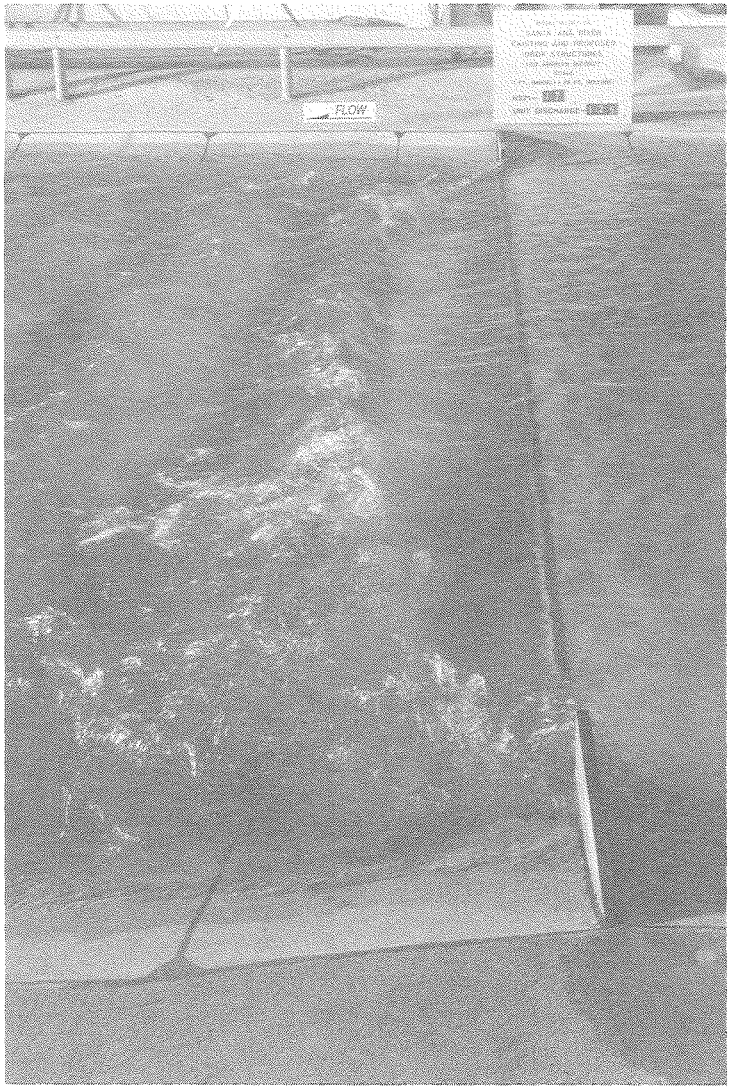


a. Unit discharge 50 cfs/ft, tailwater el 265.27

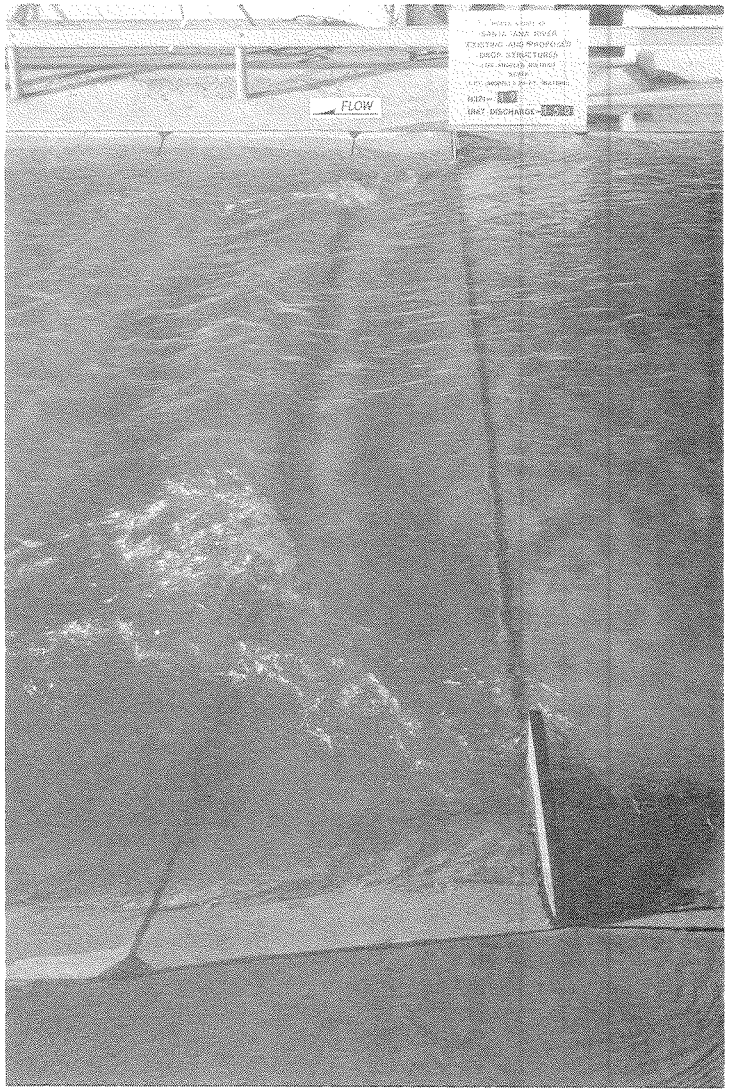


b. Unit discharge 100 cfs/ft, tailwater el 268.47

Photo 38. Flow conditions in the type 1 design drop structure (full-width model) at sta 1022+98.55, n = 0.03 (Sheet 1 of 3)

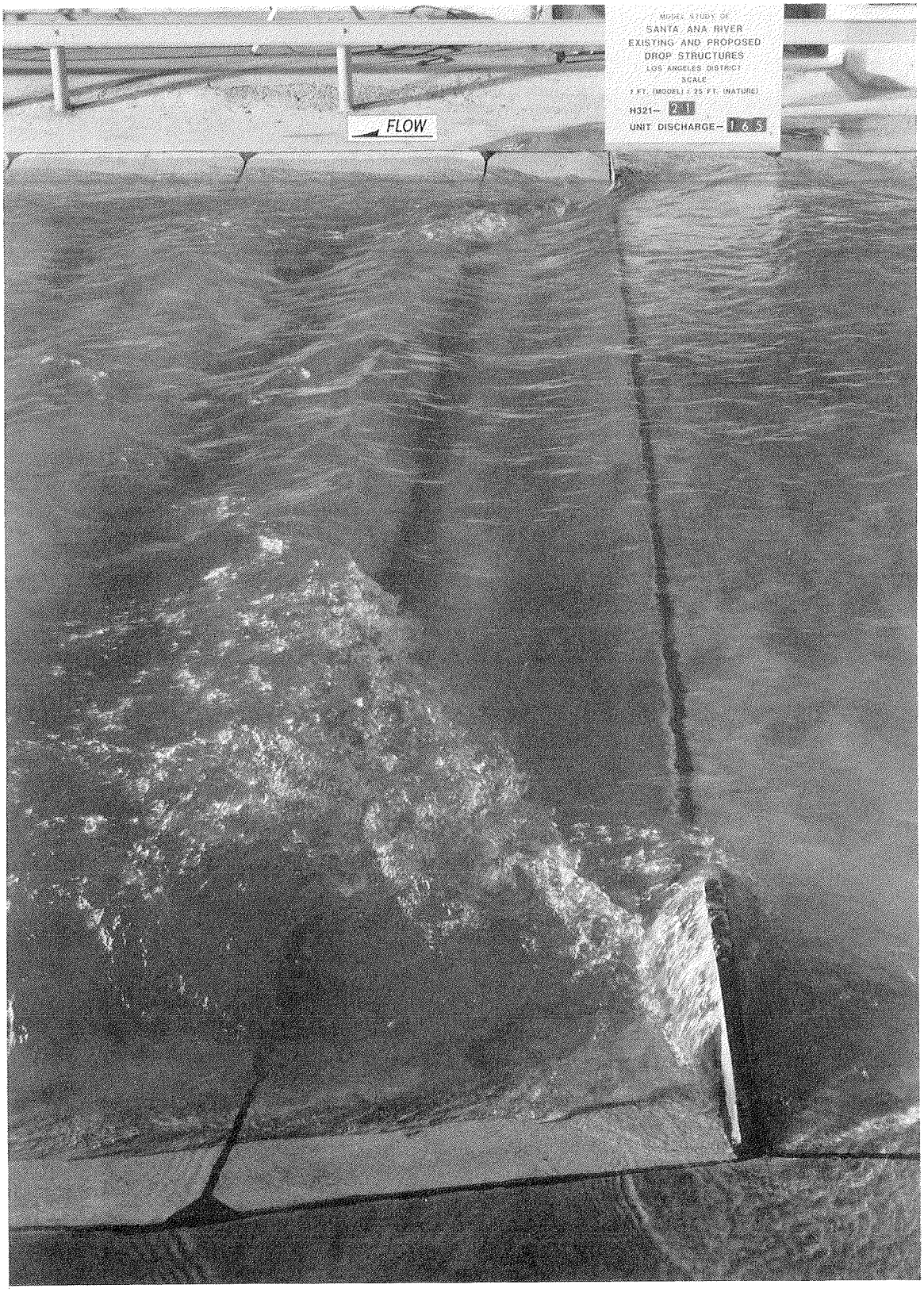


c. Unit discharge 125 cfs/ft, tailwater el 269.87



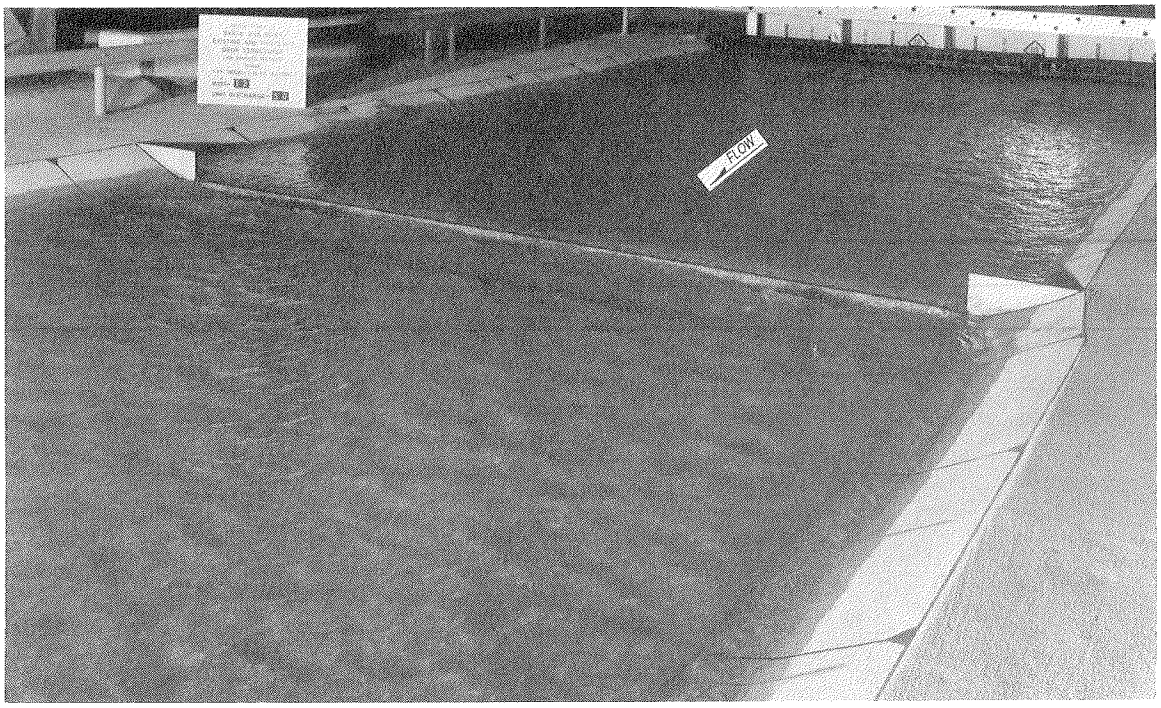
d. Unit discharge 150 cfs/ft, tailwater el 271.17

Photo 38. (Sheet 2 of 3)

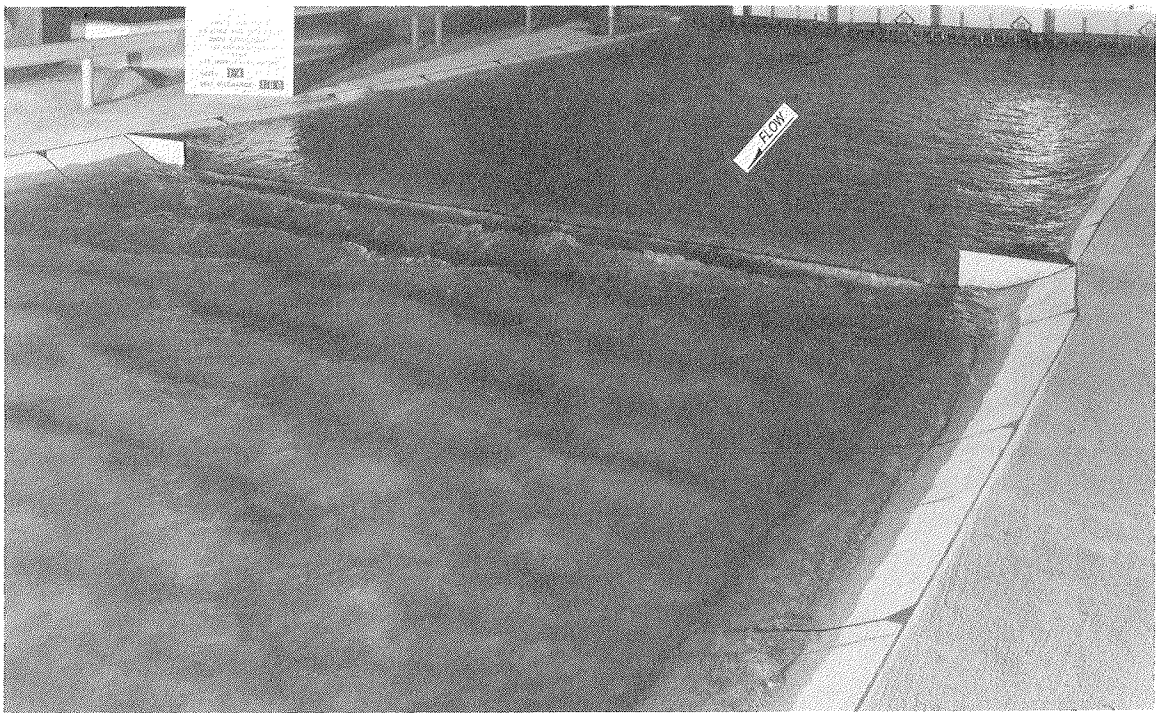


e. Unit discharge 165 cfs/ft, tailwater el 271.87

Photo 38. (Sheet 3 of 3)

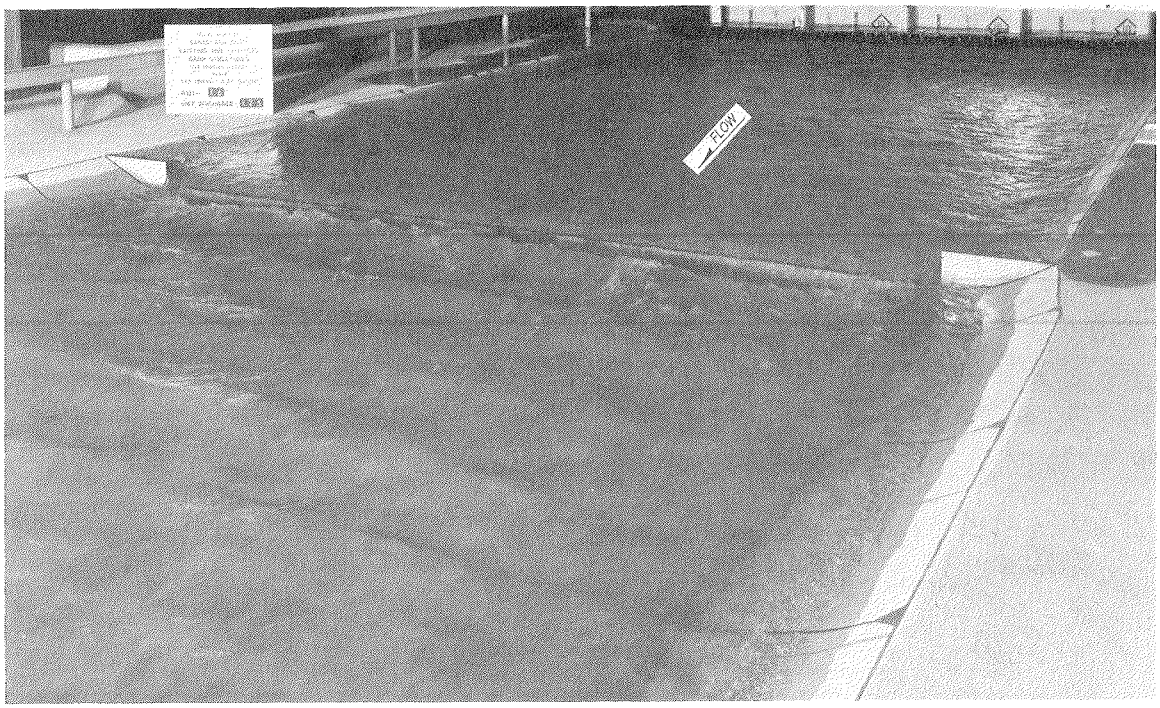


a. Unit discharge 50 cfs/ft, tailwater el 265.27

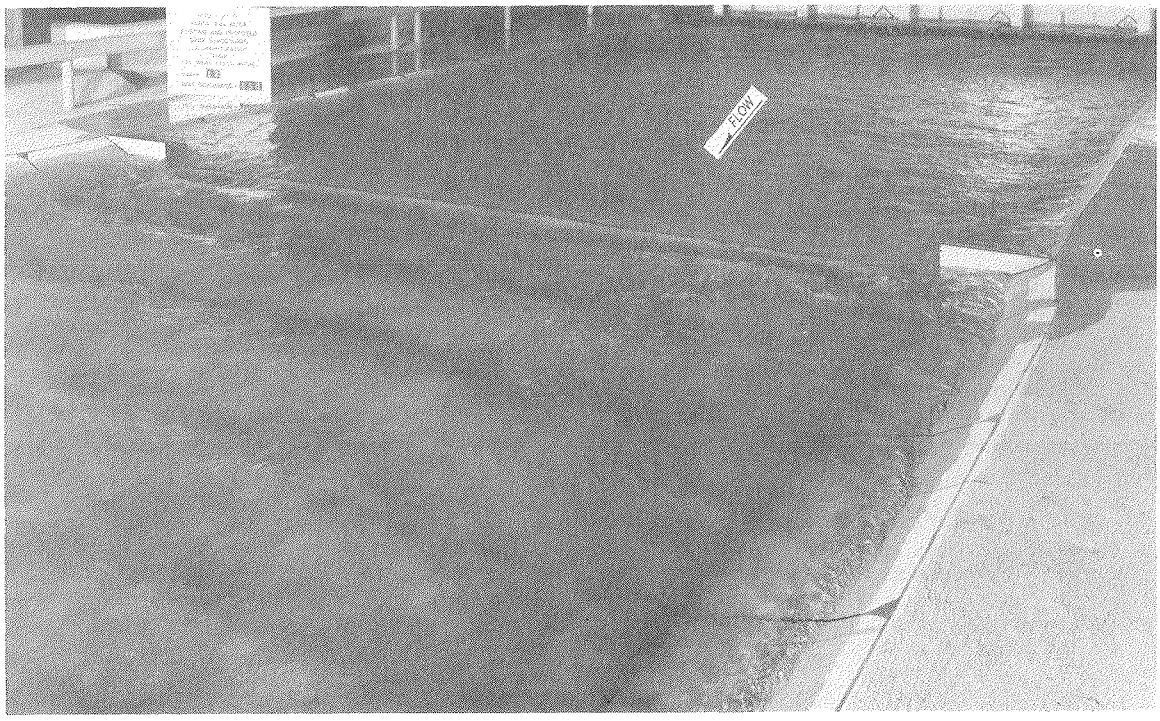


b. Unit discharge 100 cfs/ft, tailwater el 268.47

Photo 39. General view of flow conditions in the type 1 design drop structure (full-width model), n = 0.03 (Sheet 1 of 3)

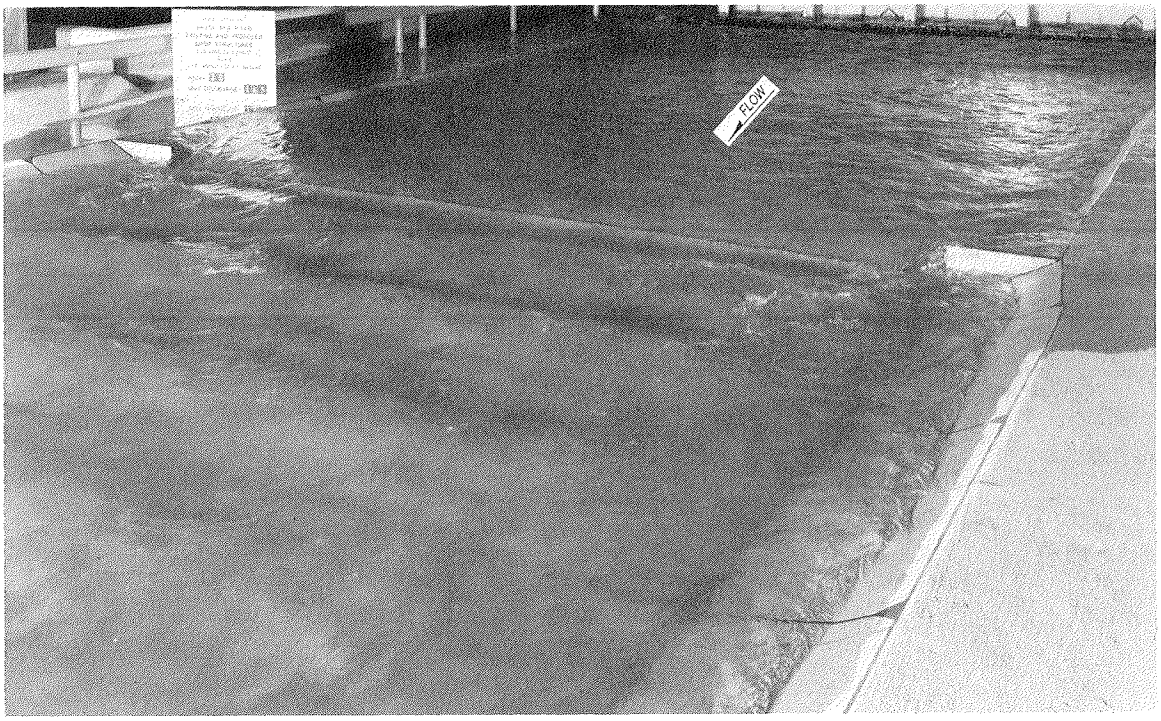


c. Unit discharge 125 cfs/ft, tailwater el 269.87



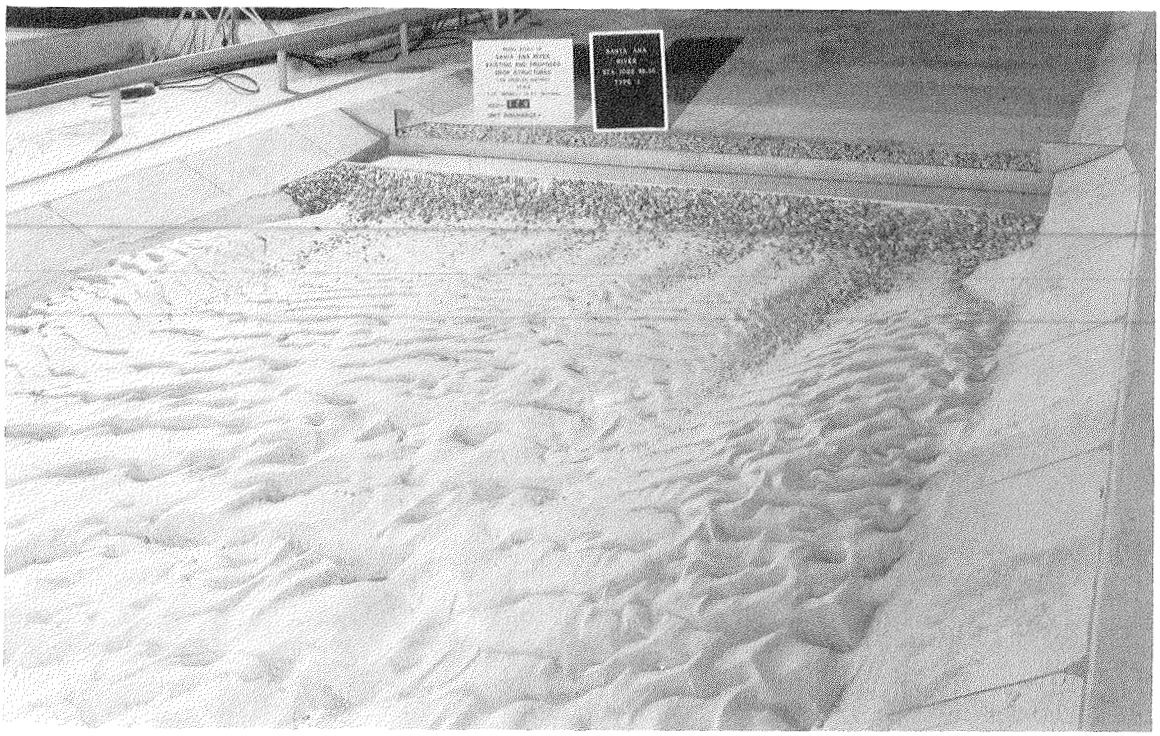
d. Unit discharge 150 cfs/ft, tailwater el 271.17

Photo 39. (Sheet 2 of 3)

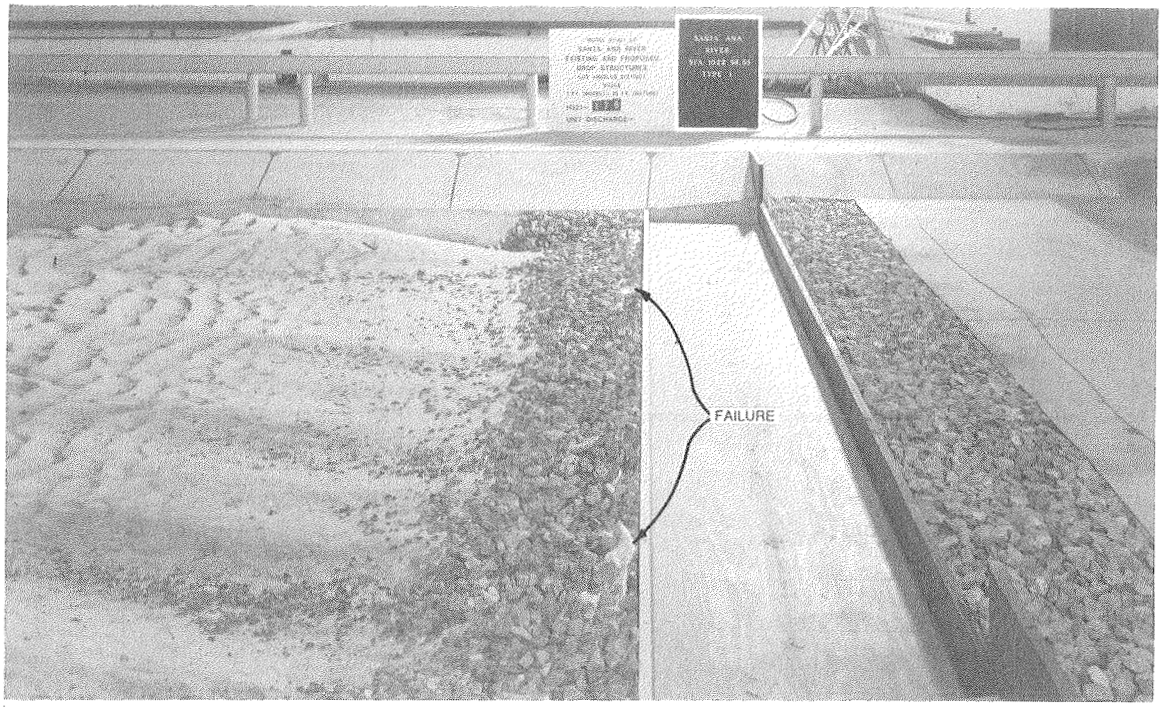


e. Unit discharge 165 cfs/ft, tailwater el 271.87

Photo 39. (Sheet 3 of 3)



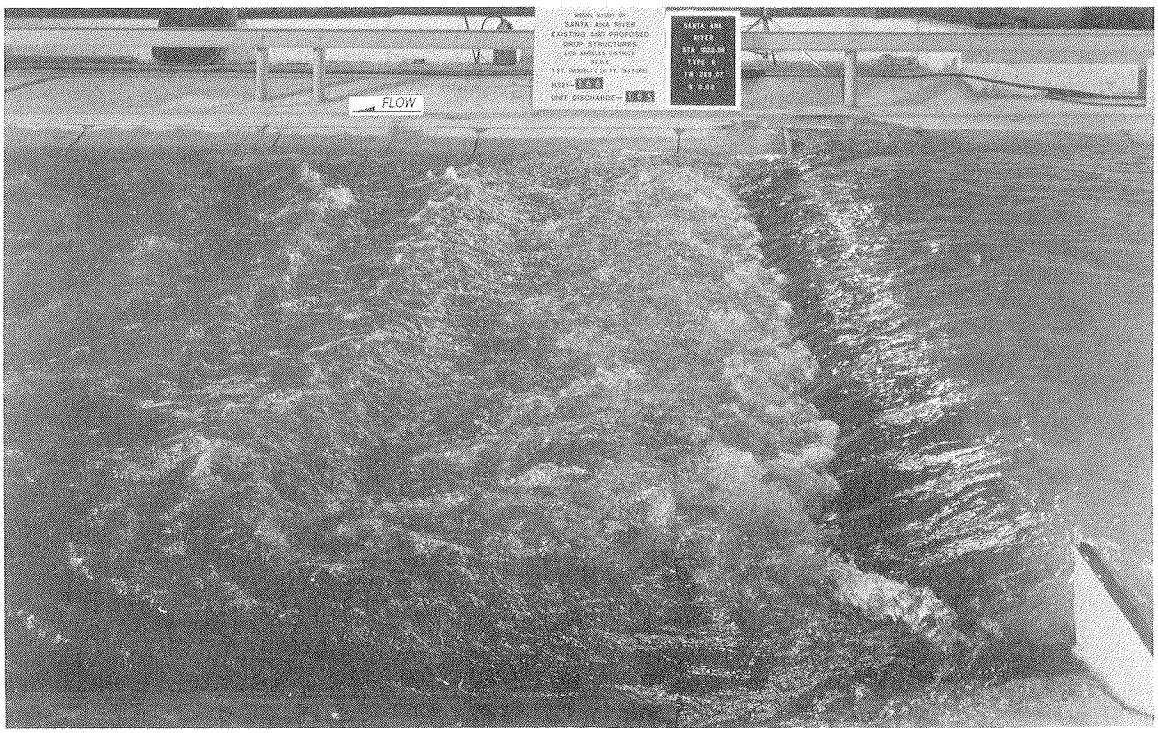
a. General view



b. Side view showing several areas of failure

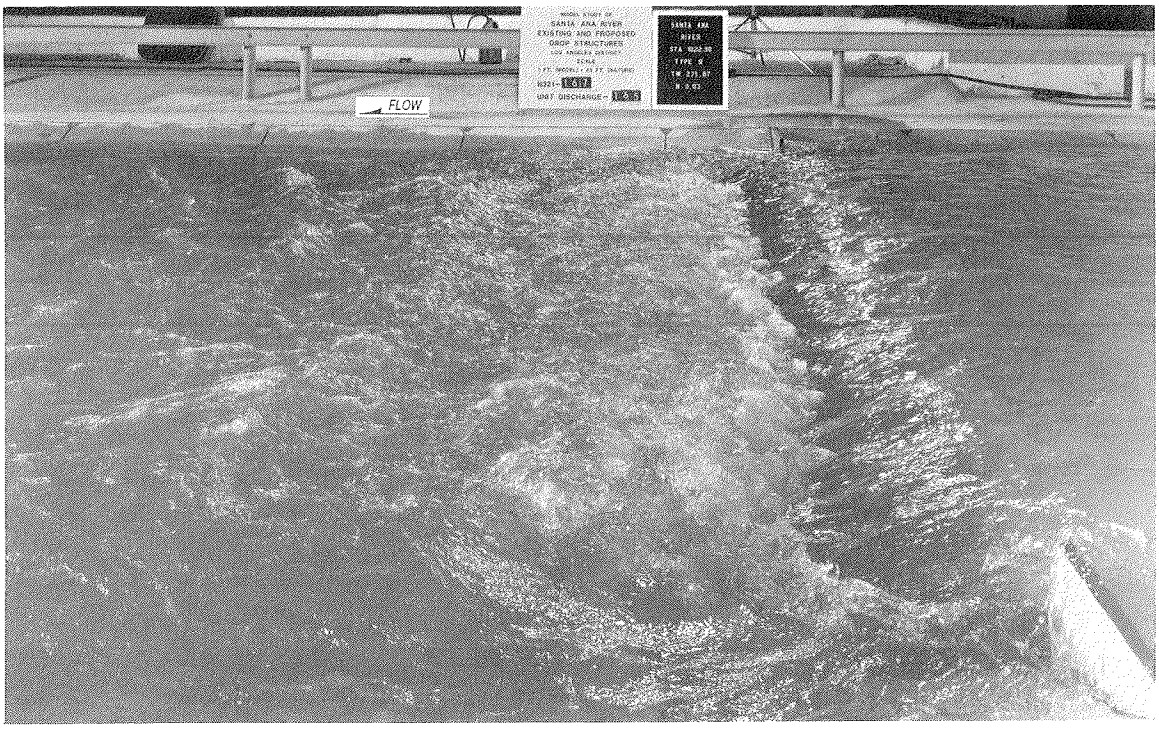
Photo 40. Type 1 design, sta 1022+98.55, results of scour tests after simulated stepped hydrograph

a. Dry bed



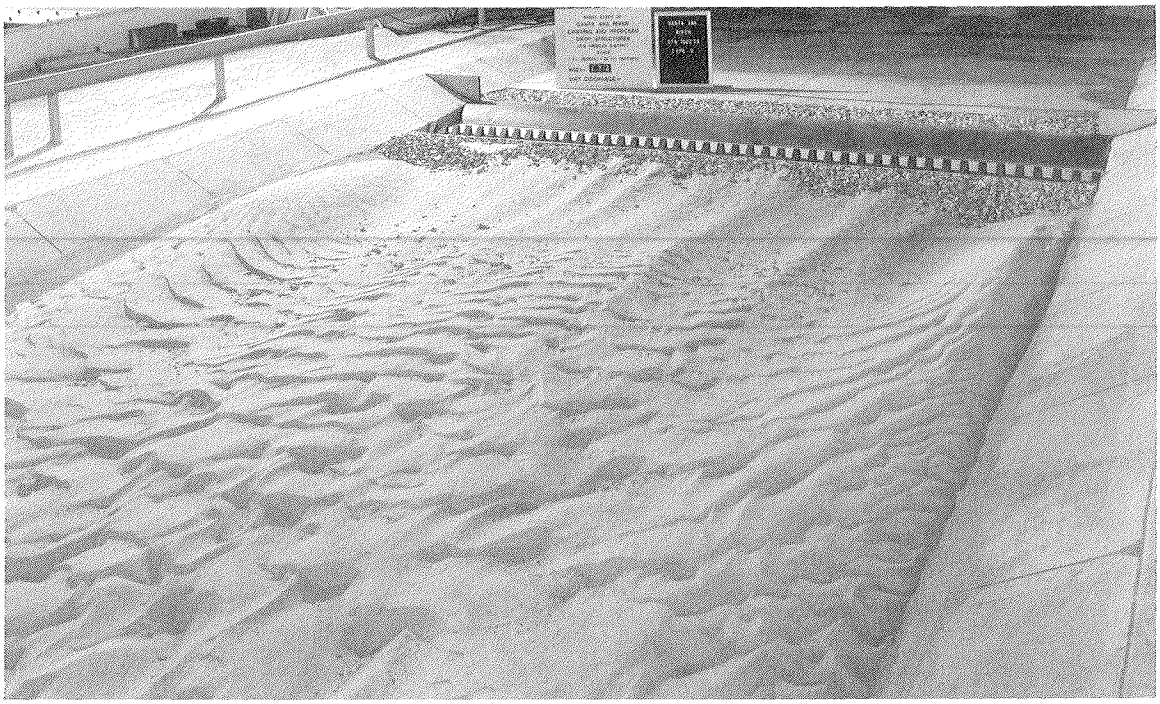
b. Tailwater el 269.07, n = 0.02

Photo 41. Type 8 design drop structure, sta 1022+98.55, unit discharge 165 cfs/ft (Continued)

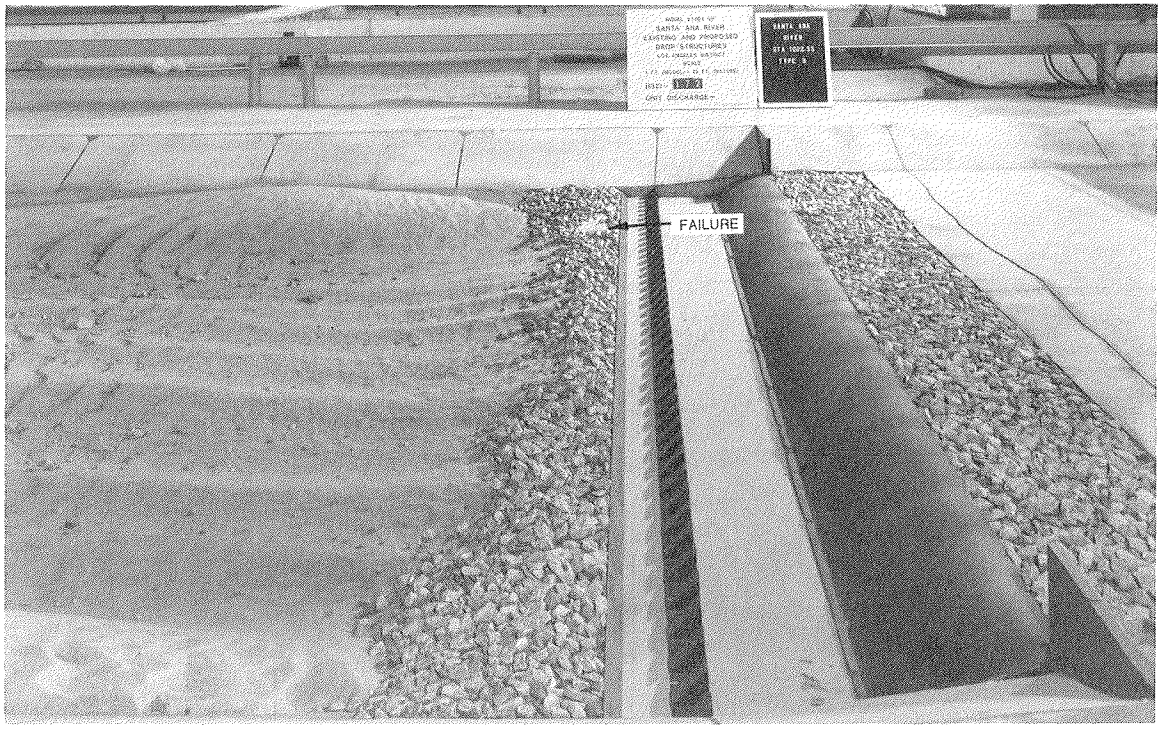


c. Tailwater el 271.87, n = 0.03

Photo 41. (Concluded)

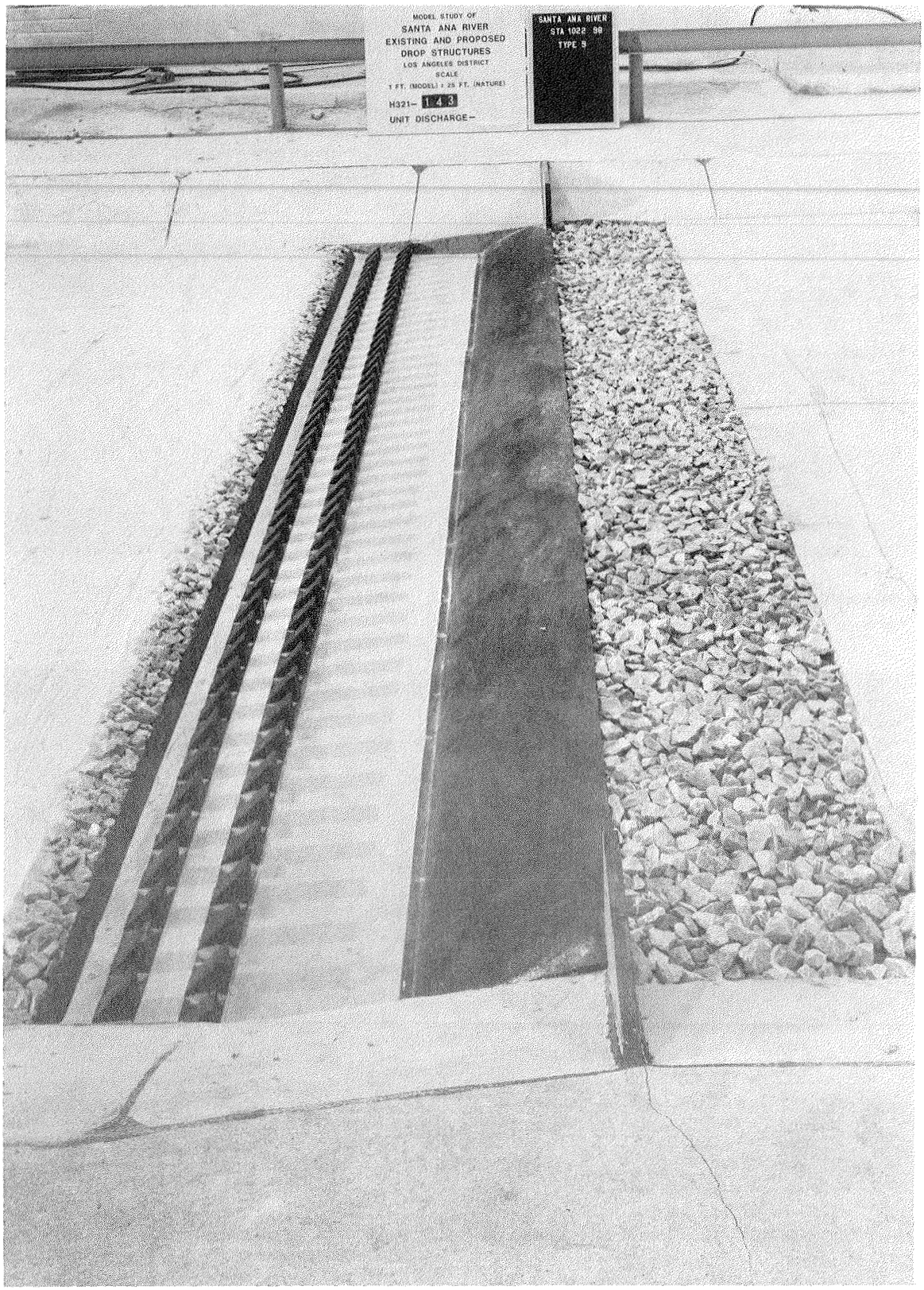


a. General view



b. Side view showing failure in riprap

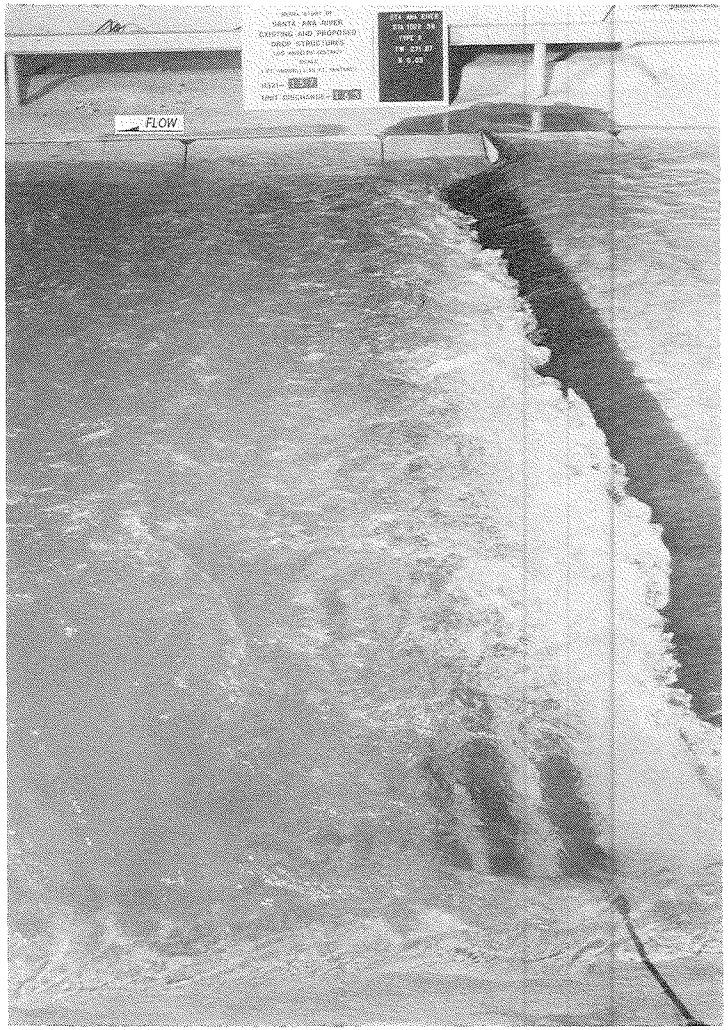
Photo 42. Scour pattern after simulated stepped hydrograph in type 8 design drop structure



a. Dry bed

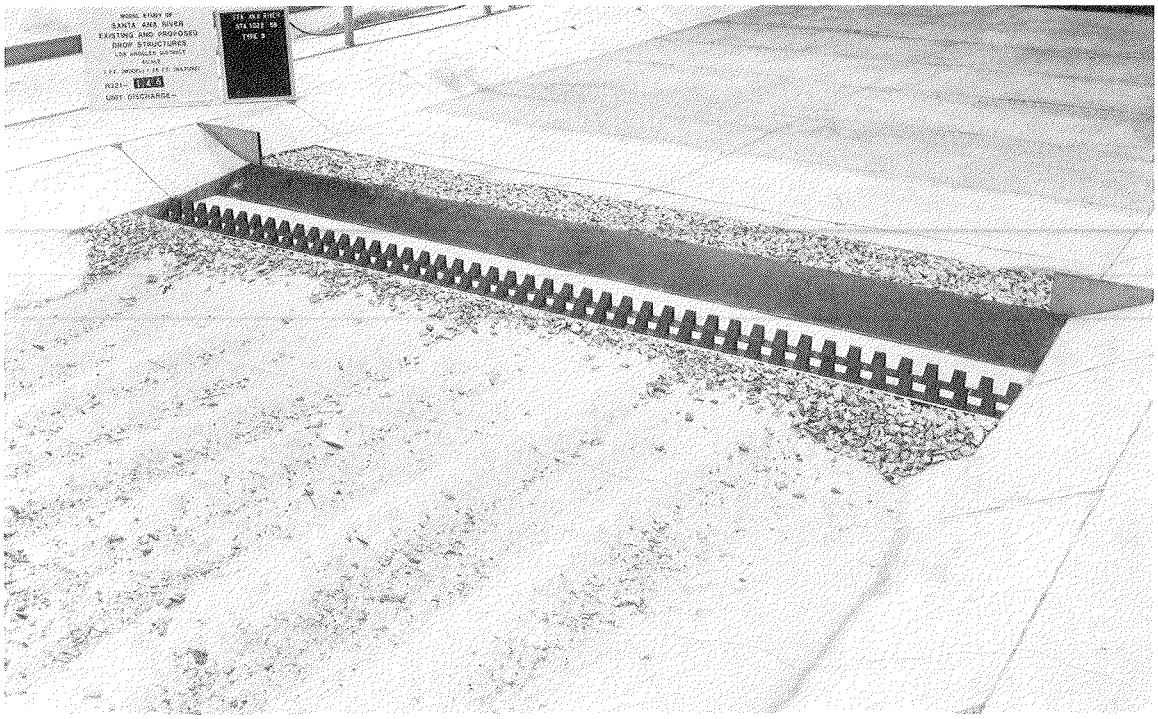
Photo 43. Type 9 design drop structure, sta 1022+98.55, discharge 165 cfs/ft (Continued)

b. Tailwater el 269.07, n = 0.02

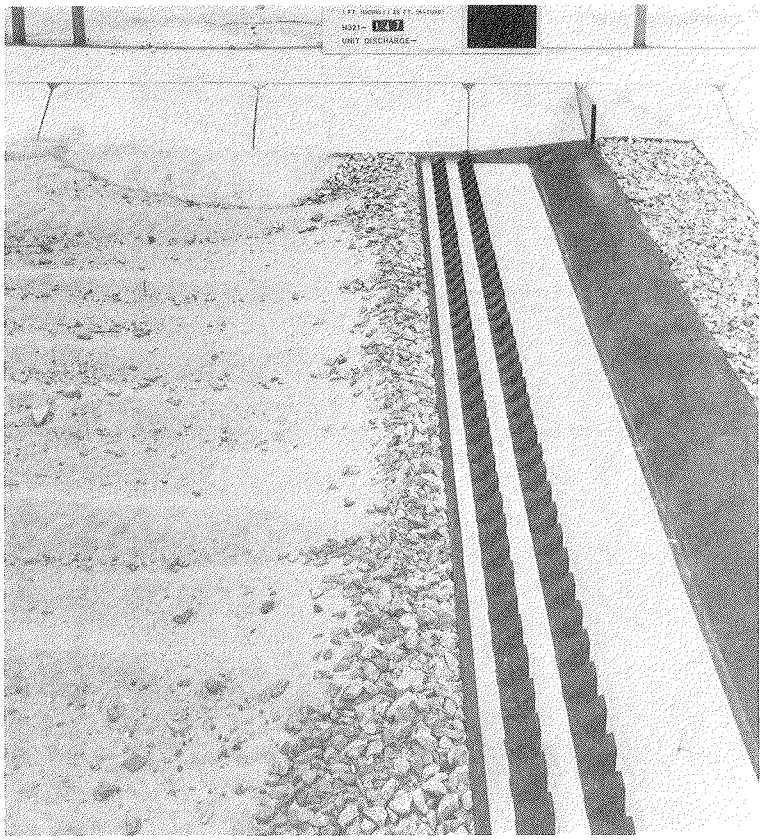


c. Tailwater el 271.87, n = 0.03

Photo 43. (Concluded)



a. General view



b. Side view showing only slight failure in riprap

Photo 44. Scour pattern after simulated stepped hydrograph in type 9 design drop structure

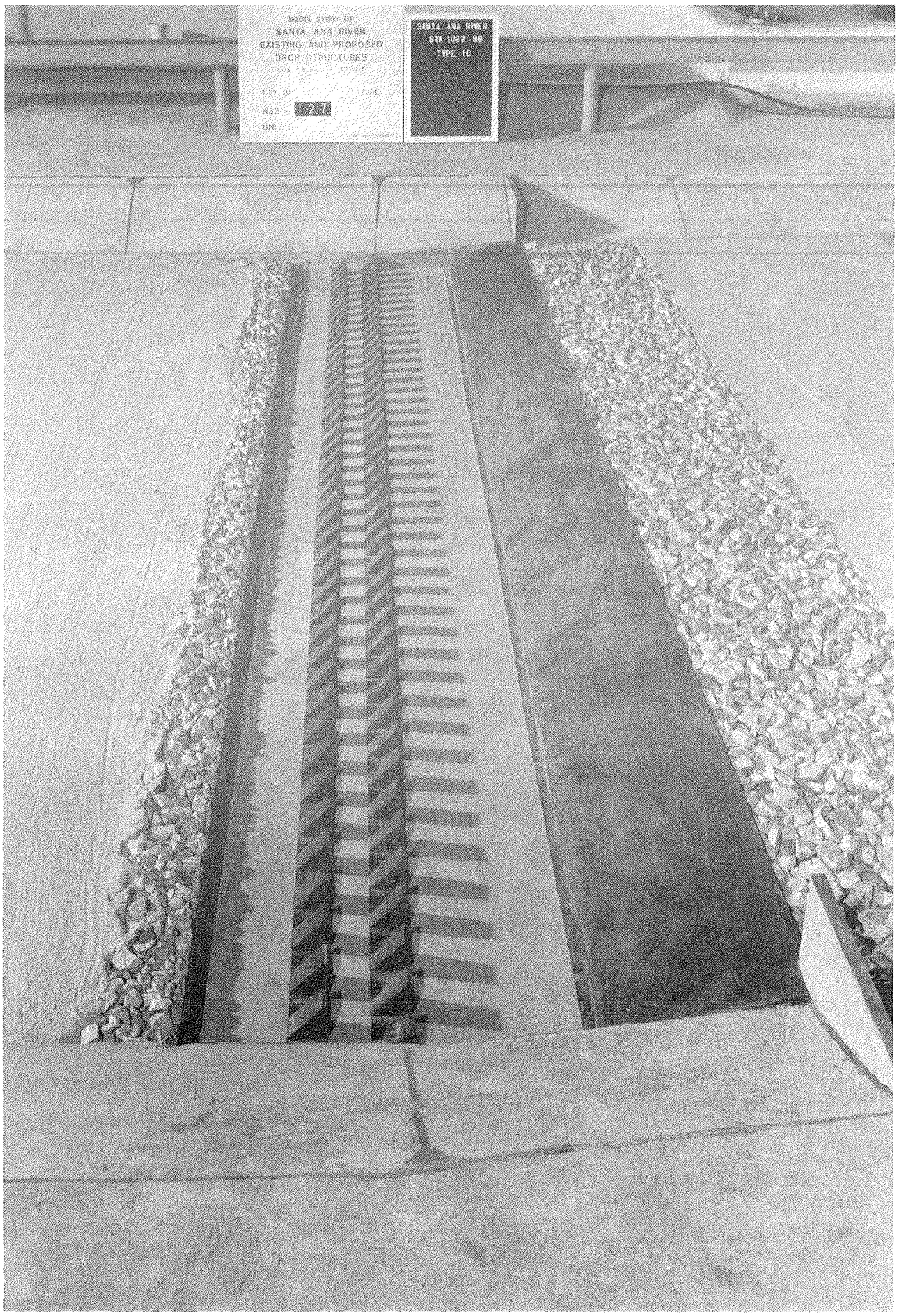
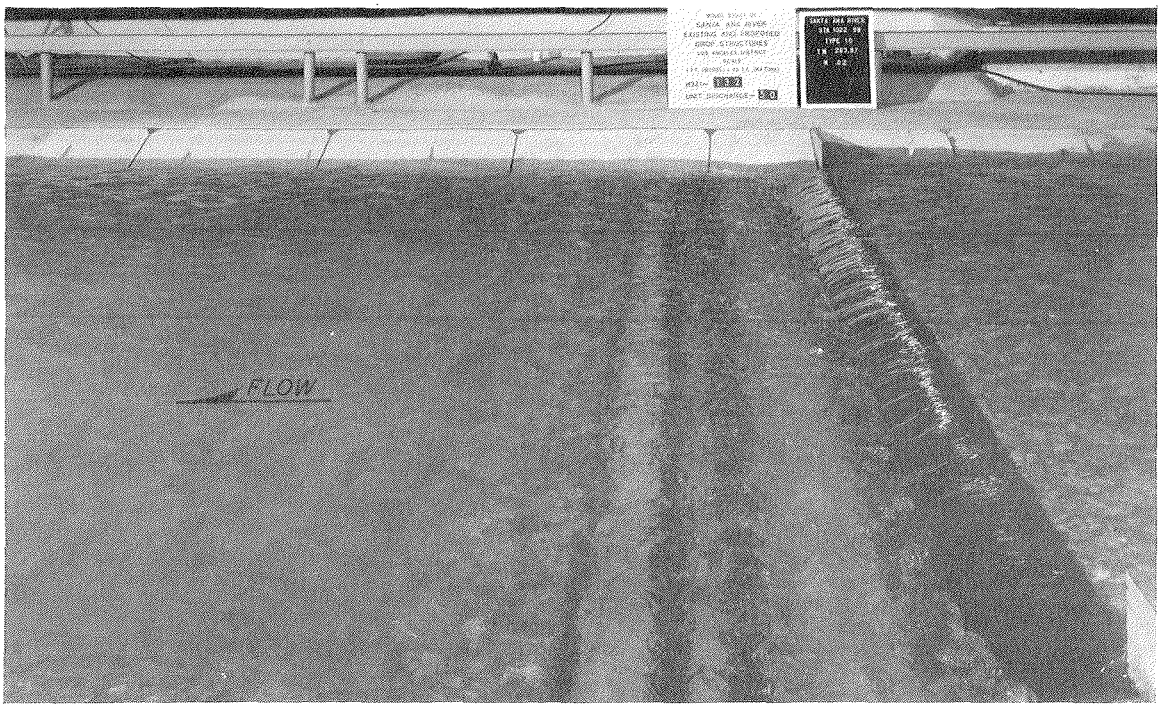
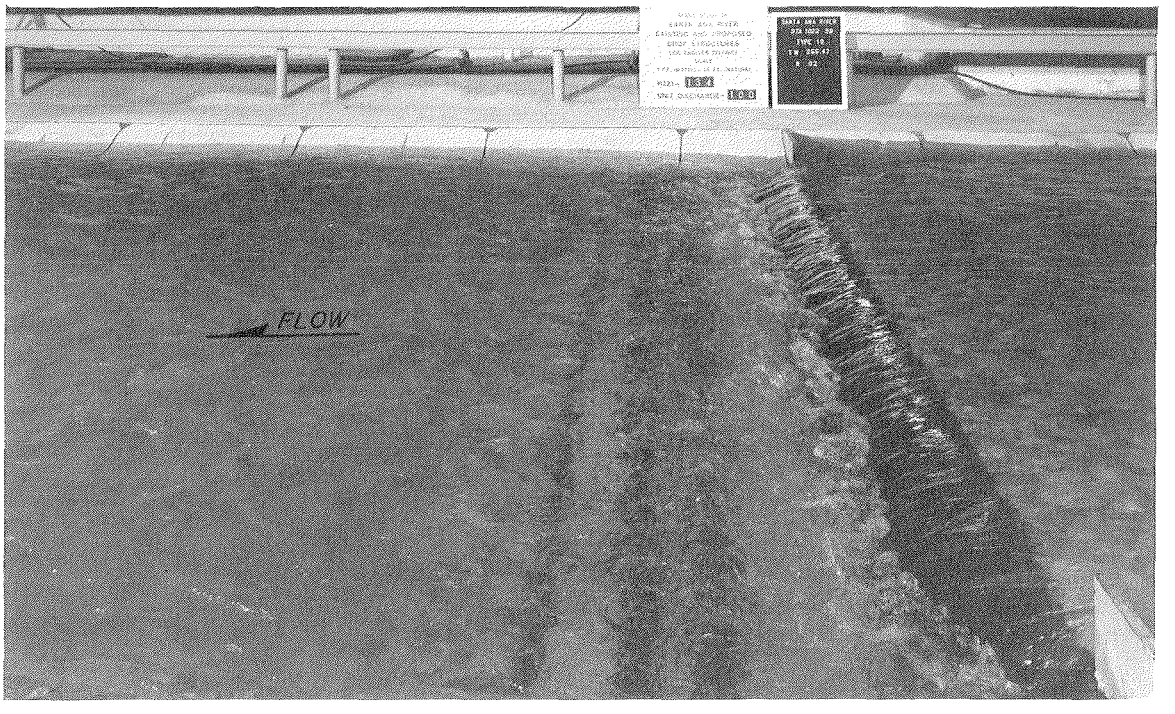


Photo 45. Type 10 design drop structure, sta 1022+98.55

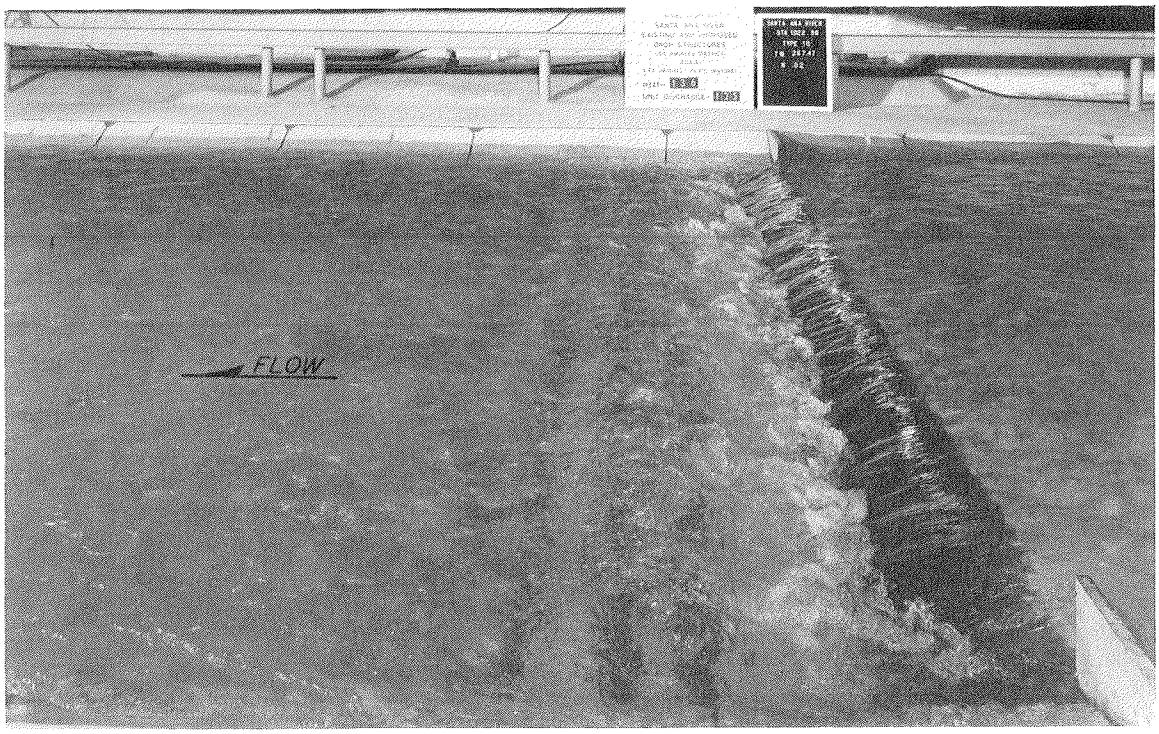


a. Unit discharge 50 cfs/ft, tailwater el 263.87

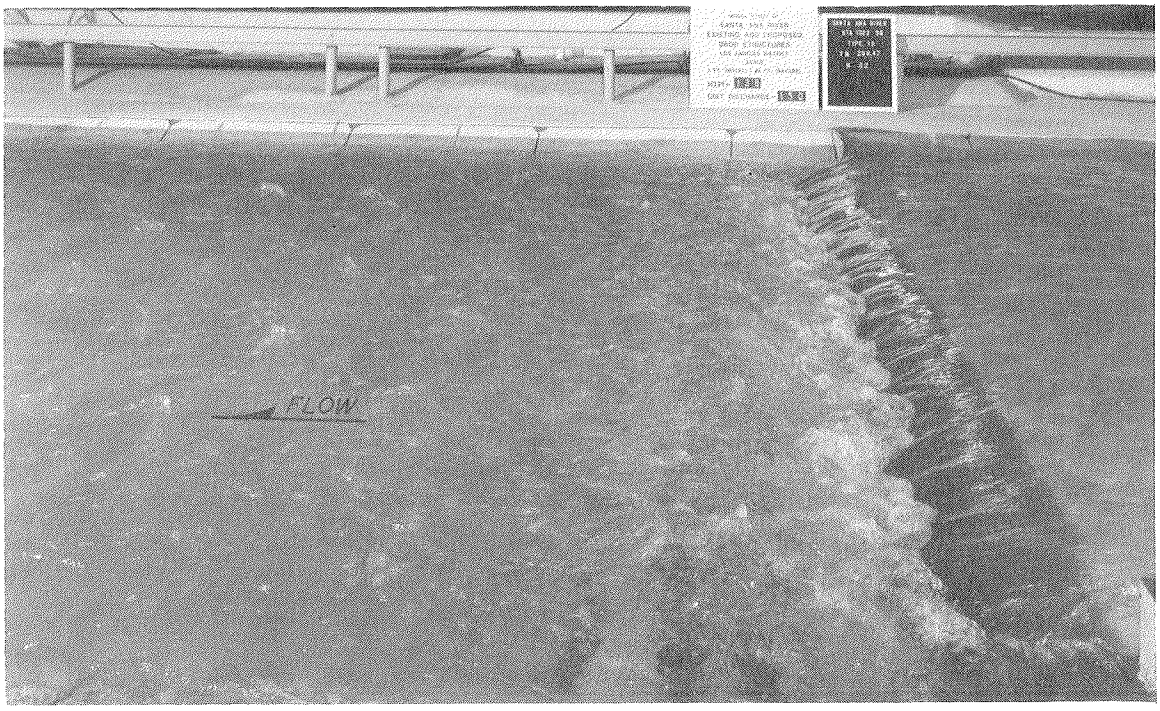


b. Unit discharge 100 cfs/ft, tailwater el 266.47

Photo 46. Flow conditions in the type 10 design drop structure, sta 1022+98.55, n = 0.02 (Sheet 1 of 3)

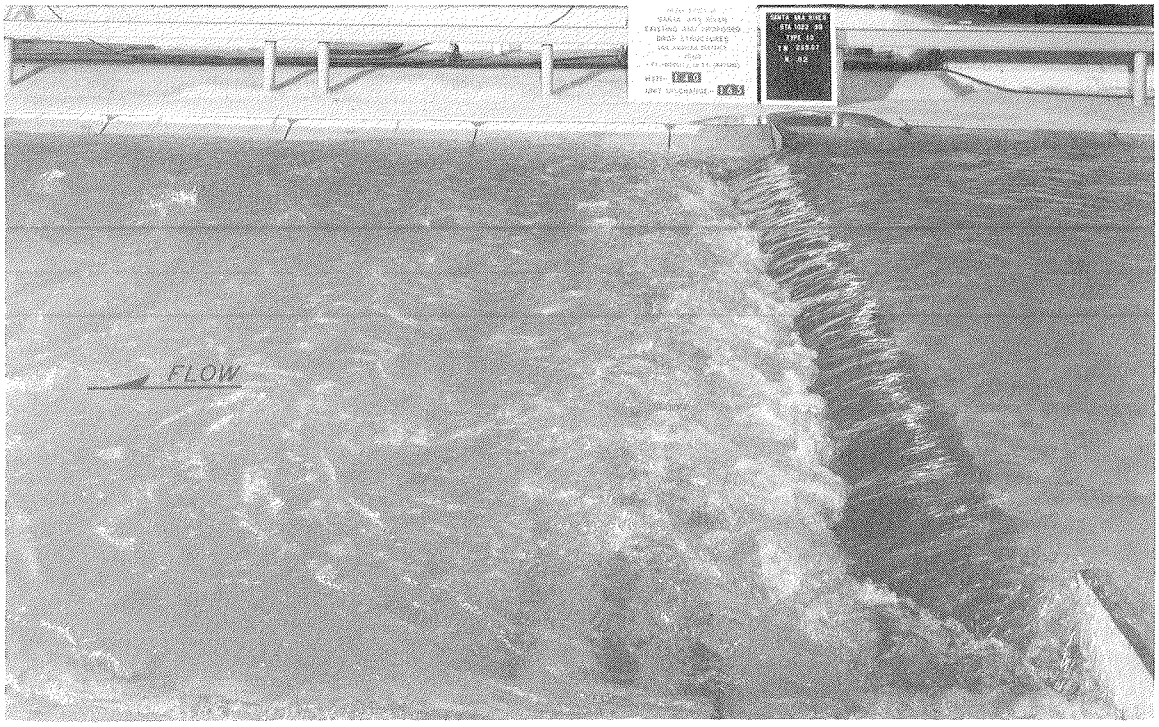


c. Unit discharge 125 cfs/ft, tailwater el 267.47



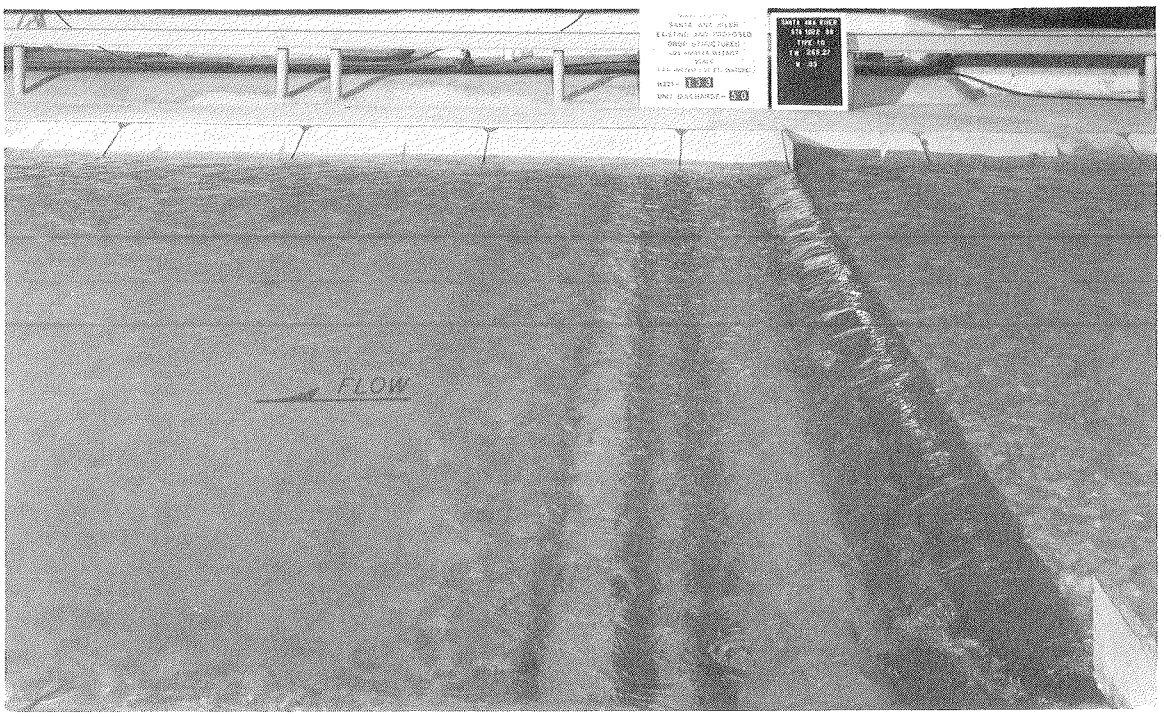
d. Unit discharge 150 cfs/ft, tailwater el 268.47

Photo 46. (Sheet 2 of 3)

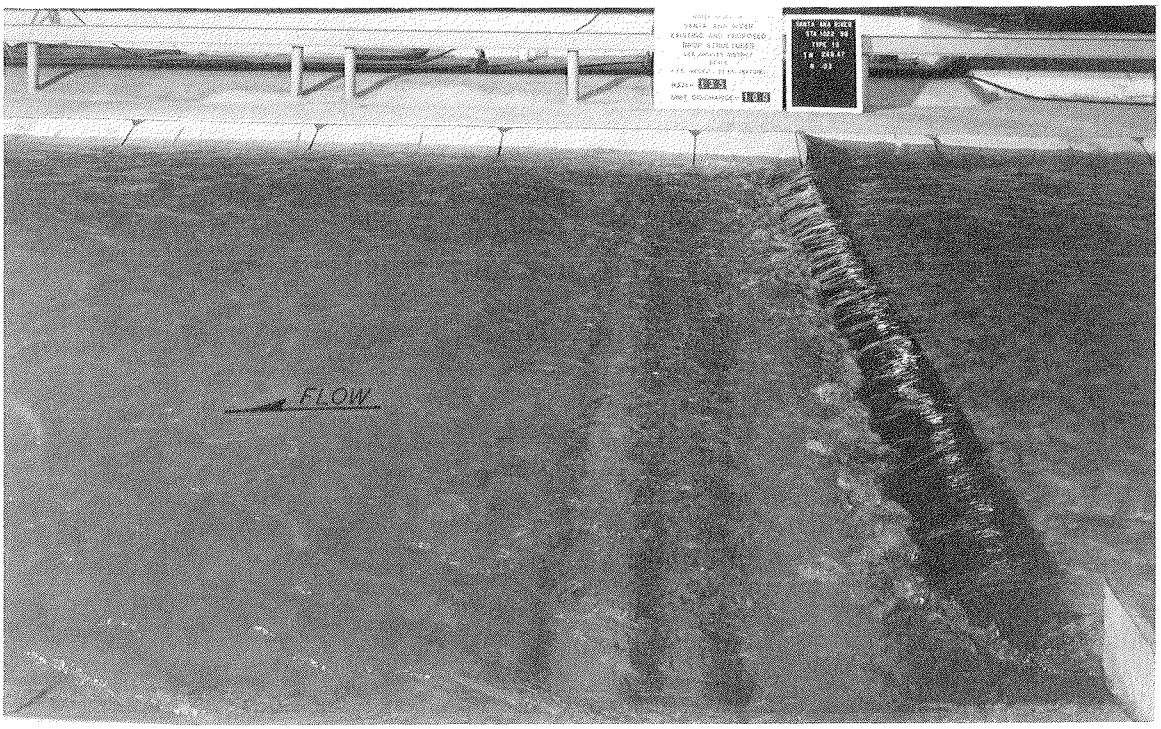


e. Unit discharge 165 cfs/ft, tailwater el 269.07

Photo 46. (Sheet 3 of 3)

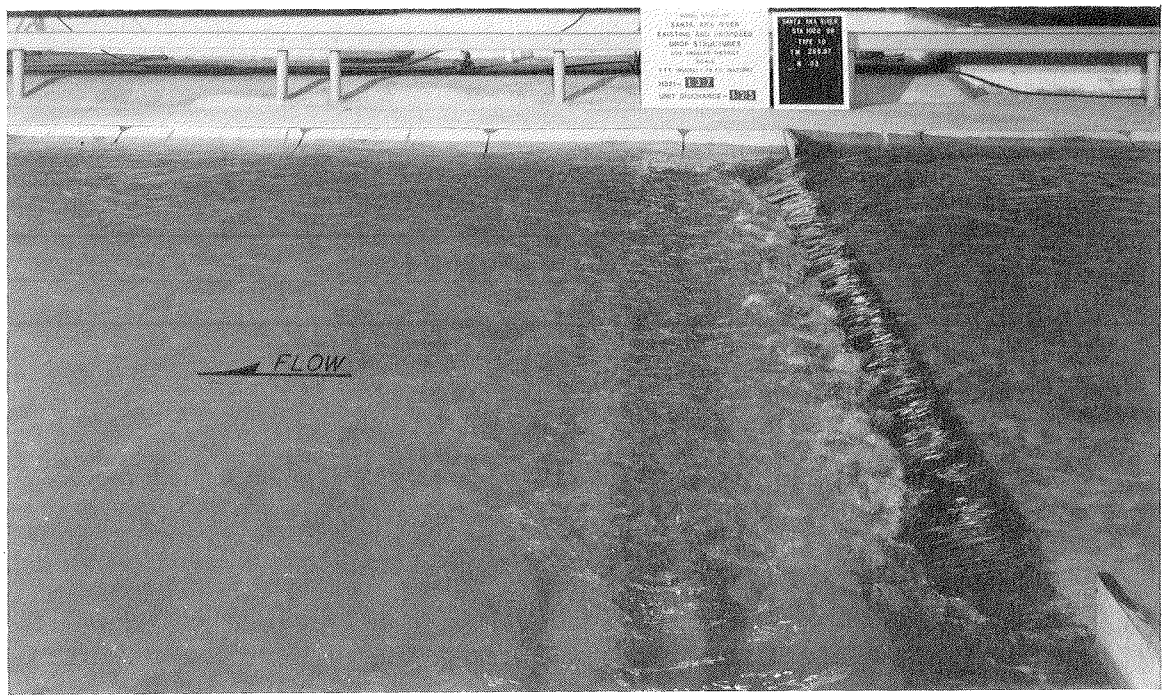


a. Unit discharge 50 cfs/ft, tailwater el 265.27

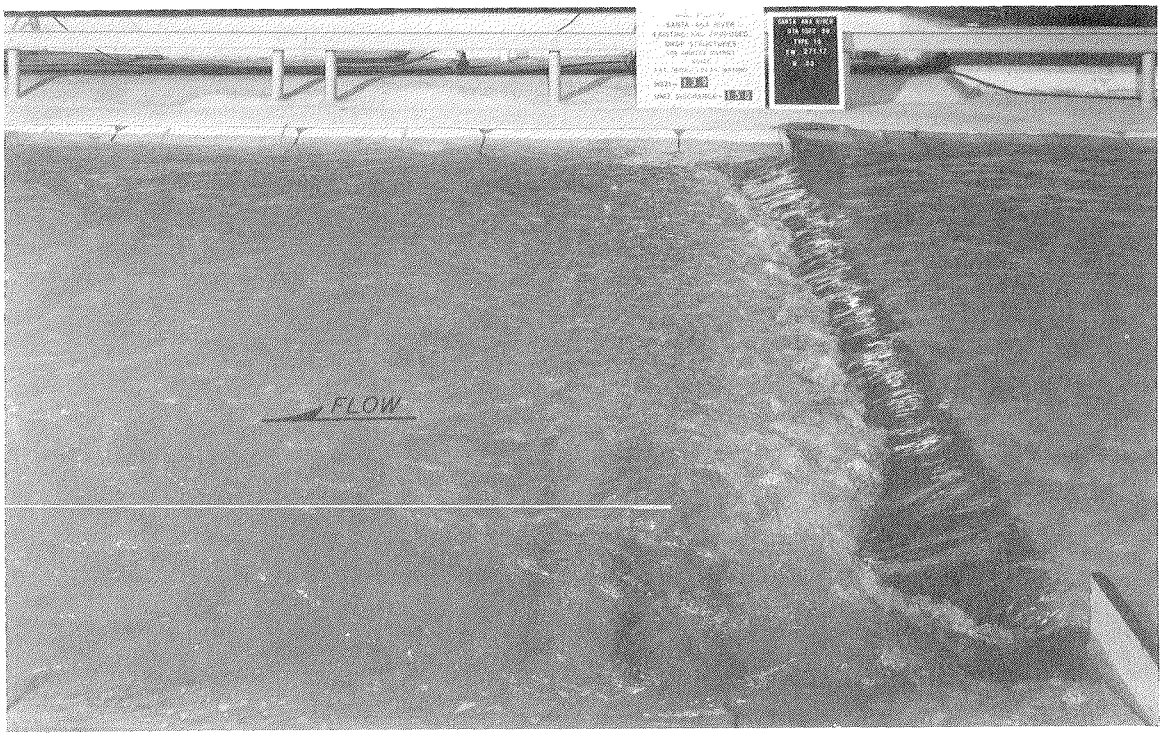


b. Unit discharge 100 cfs/ft, tailwater el 268.47

Photo 47. Flow conditions in the type 10 design drop structure, sta 1022+98.55, n = 0.03 (Sheet 1 of 3)

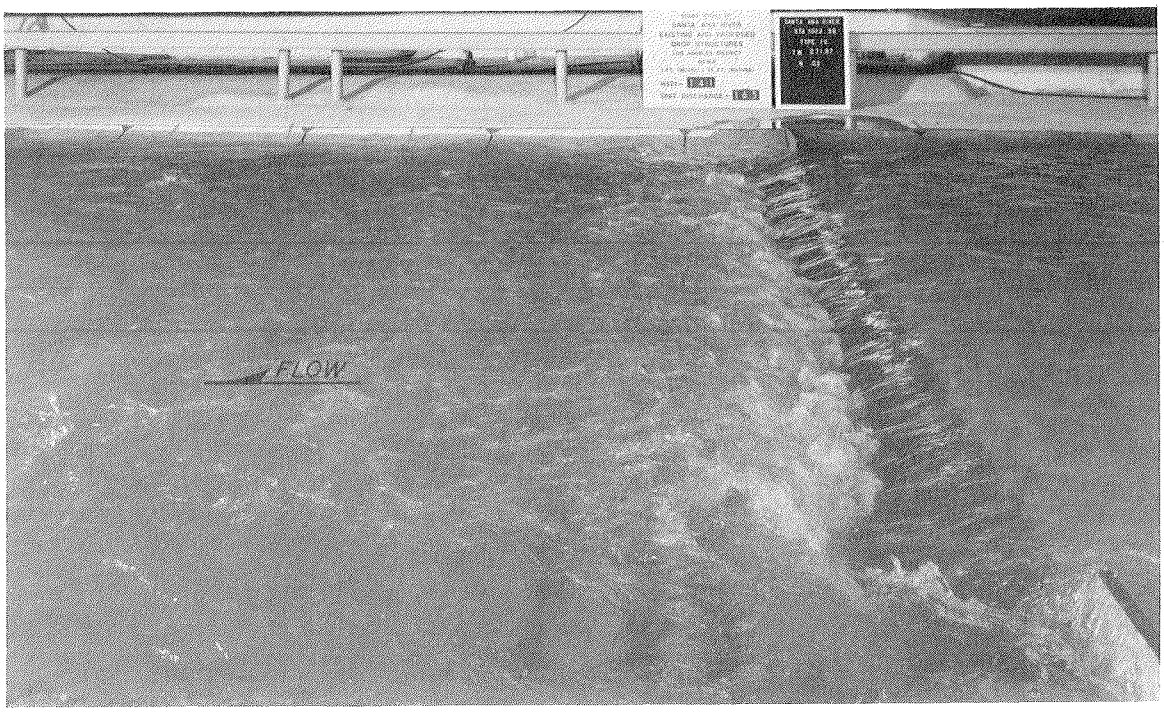


c. Unit discharge 125 cfs/ft, tailwater el 269.87



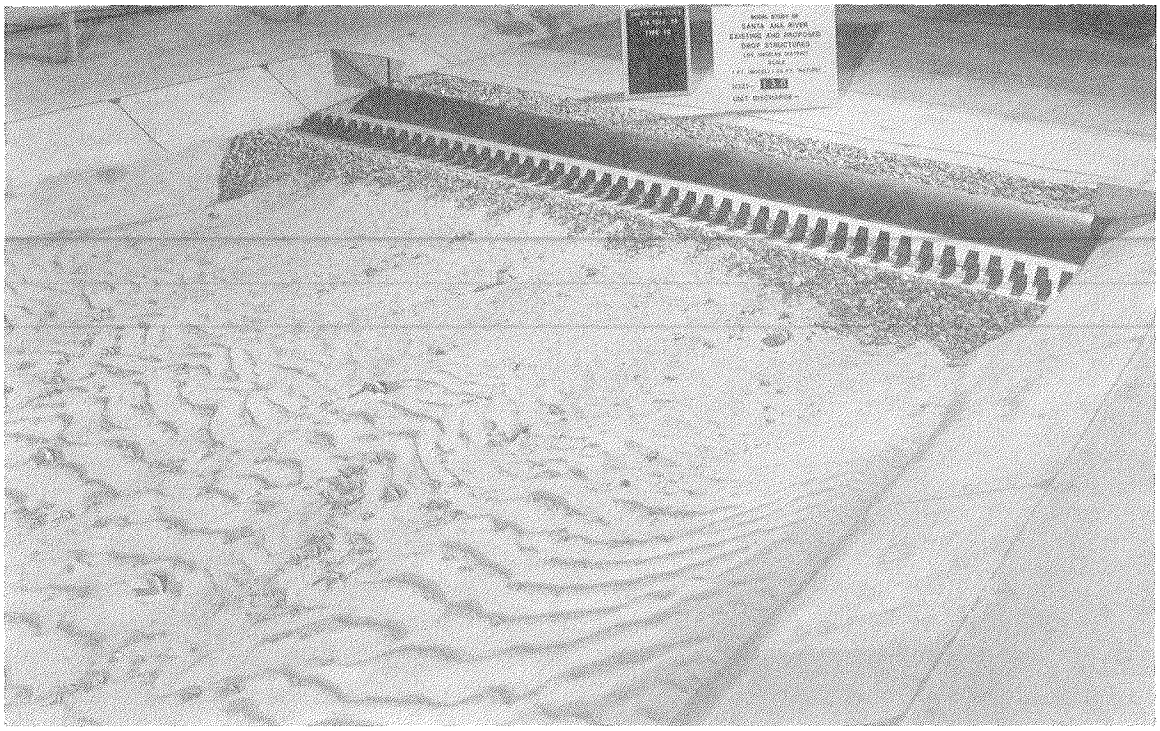
d. Unit discharge 150 cfs/ft, tailwater el 271.17

Photo 47. (Sheet 2 of 3)

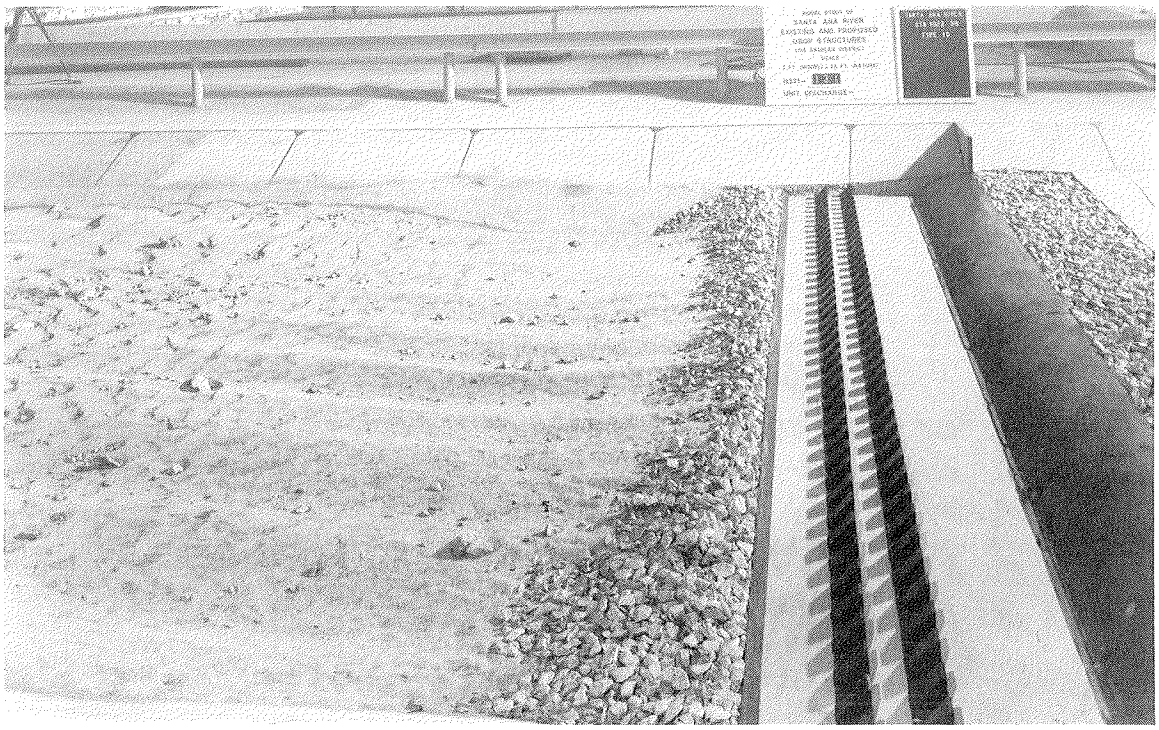


e. Unit discharge 165 cfs/ft, tailwater el 271.87

Photo 47. (Sheet 3 of 3)



a. General view



b. Side view

Photo 48. Scour pattern after simulated stepped hydrograph in the type 10 design drop structure

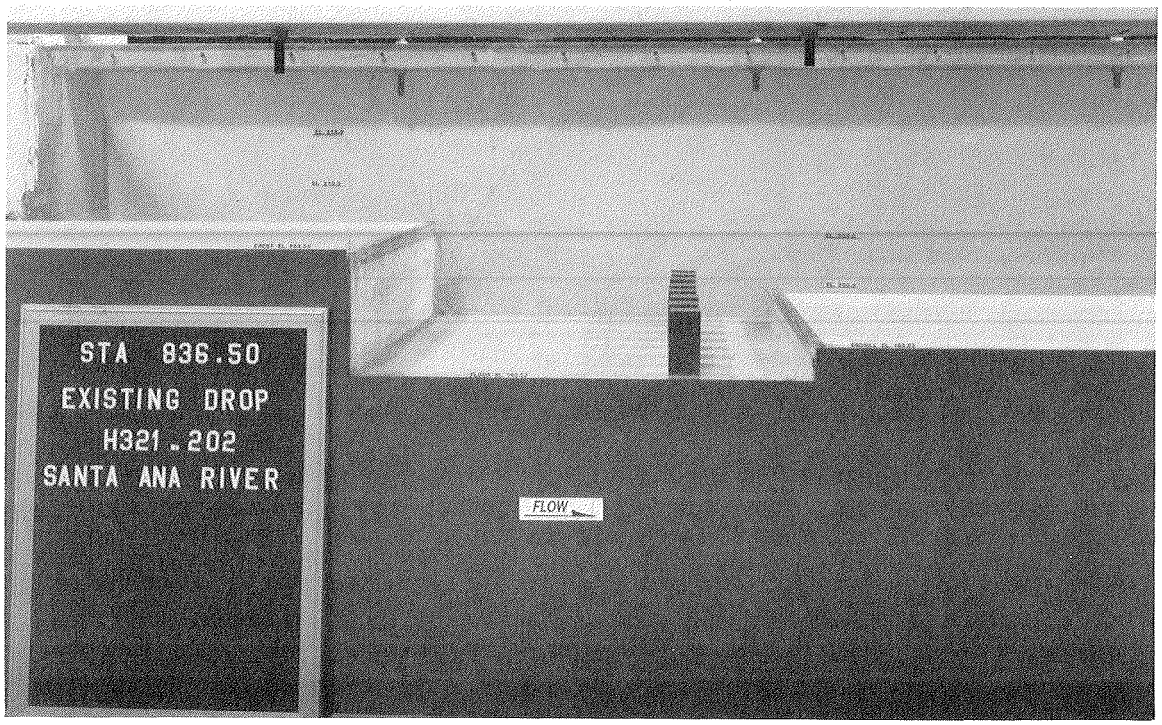
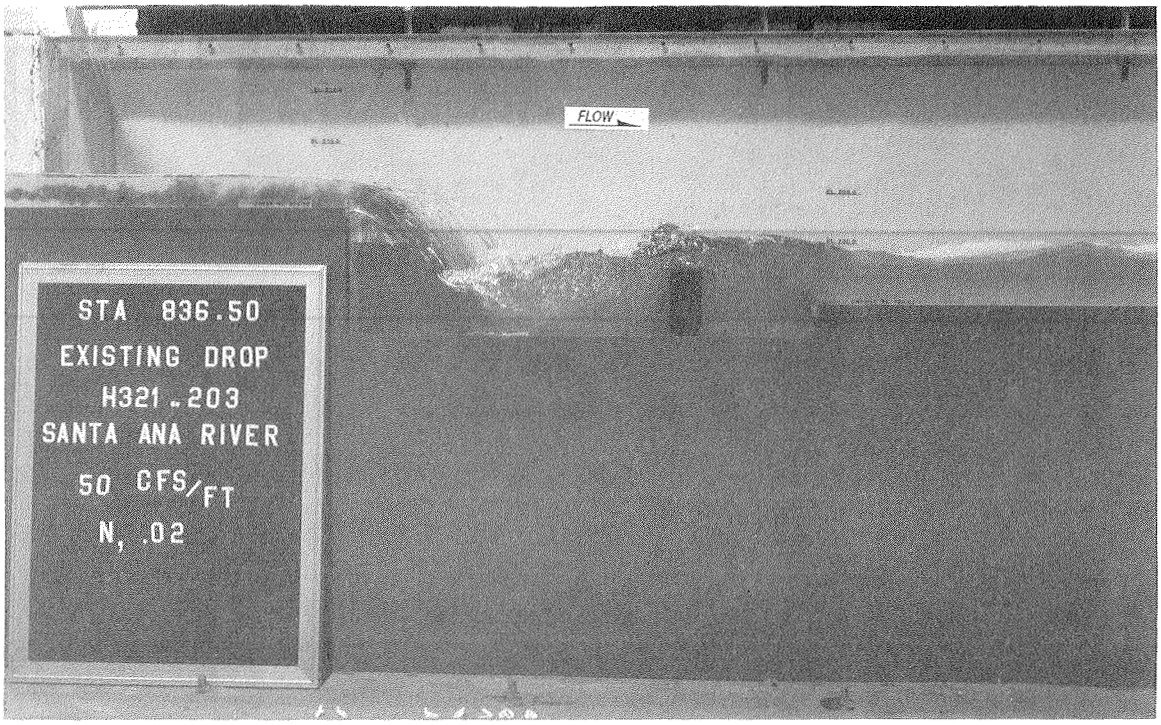
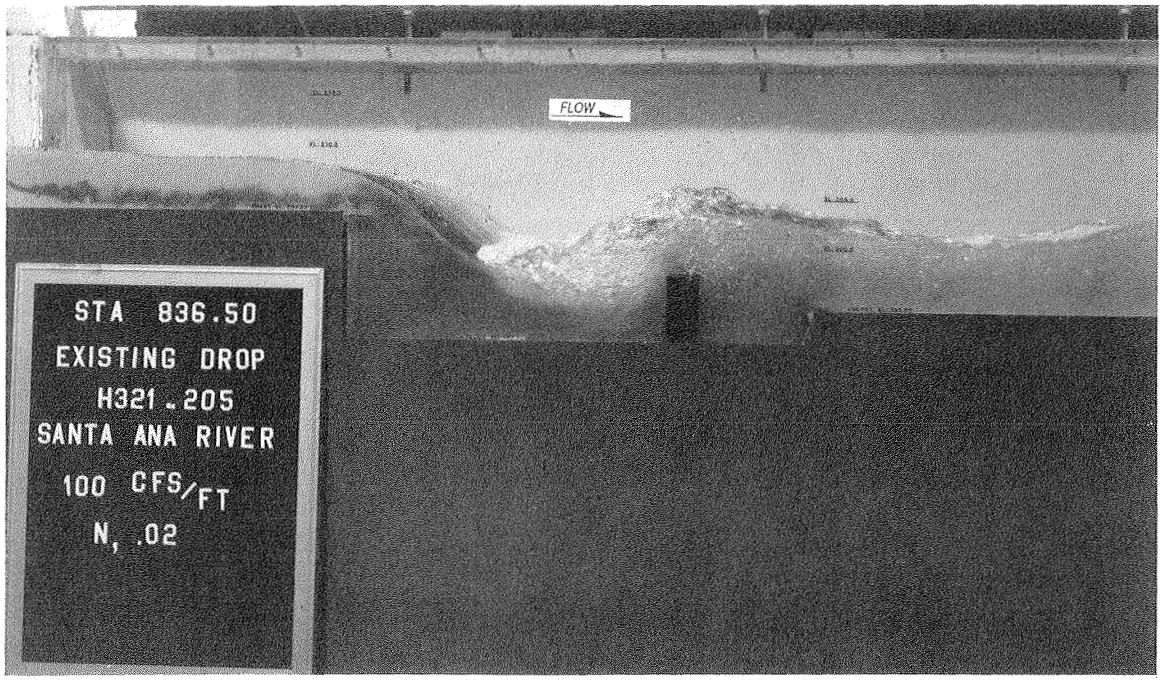


Photo 49. Type 1 design drop structure, sta 836+50

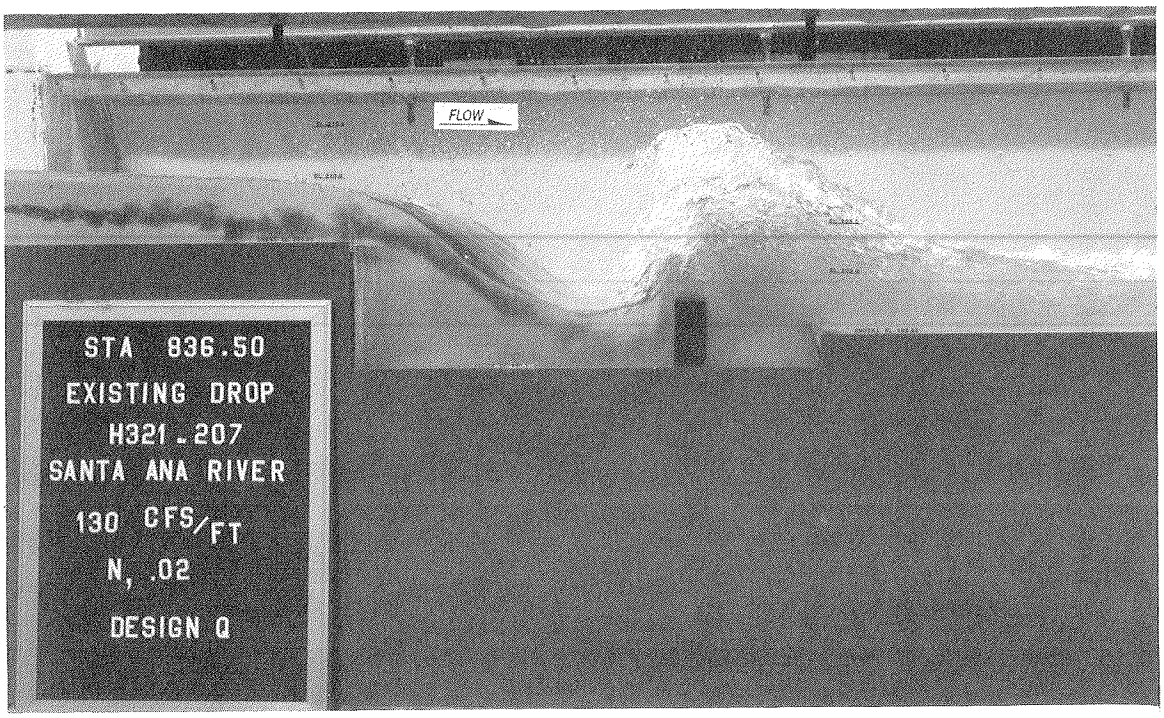


a. Unit discharge 50 cfs/ft, tailwater el 198.72

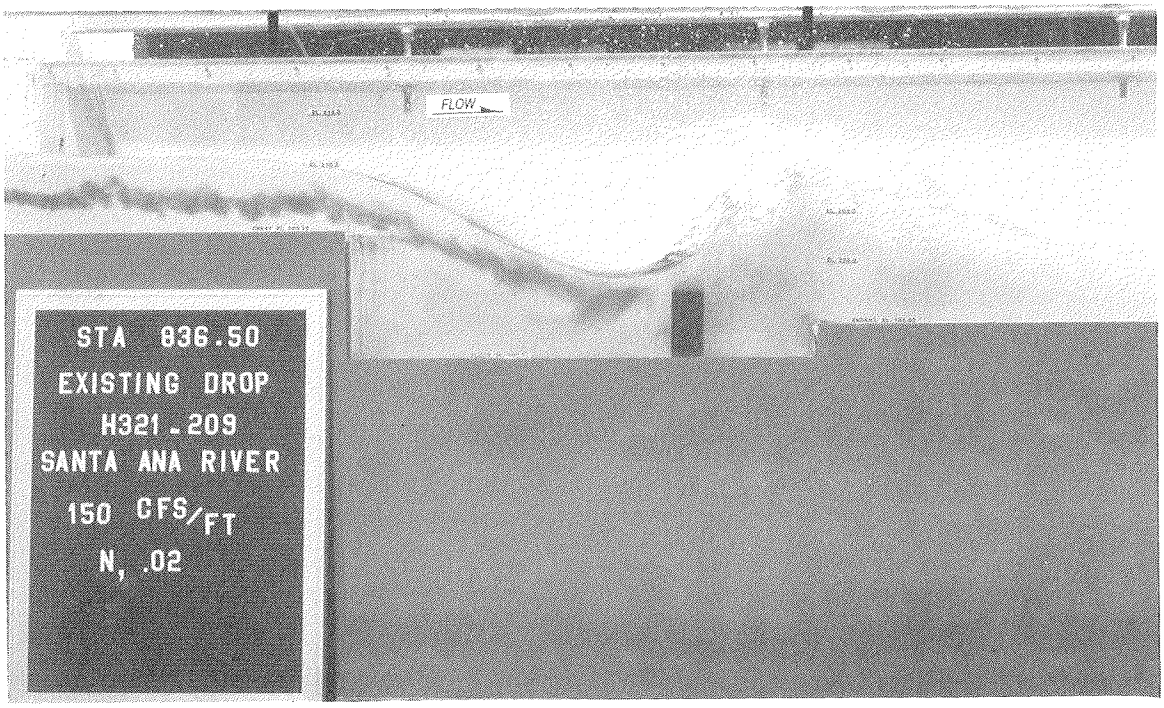


b. Unit discharge 100 cfs/ft, tailwater el 201.22

Photo 50. Flow conditions in the type 1 design drop structure at sta 836+50, n = 0.02 (Sheet 1 of 3)

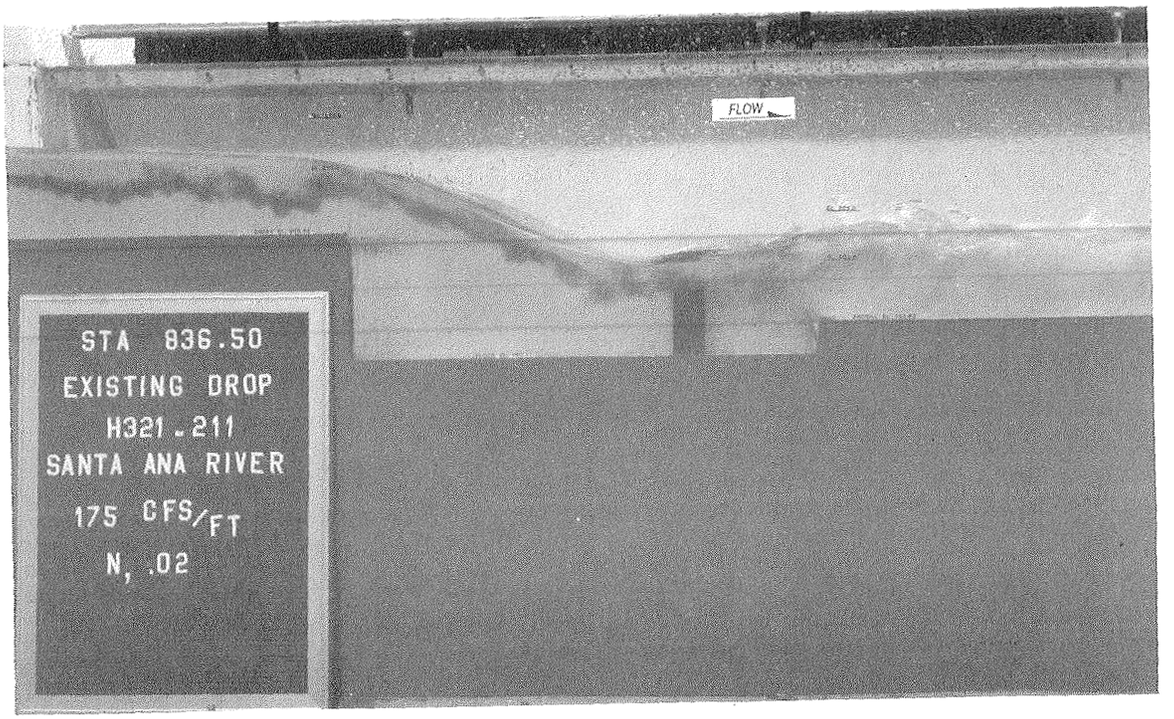


c. Unit discharge 130 cfs/ft, tailwater el 202.52



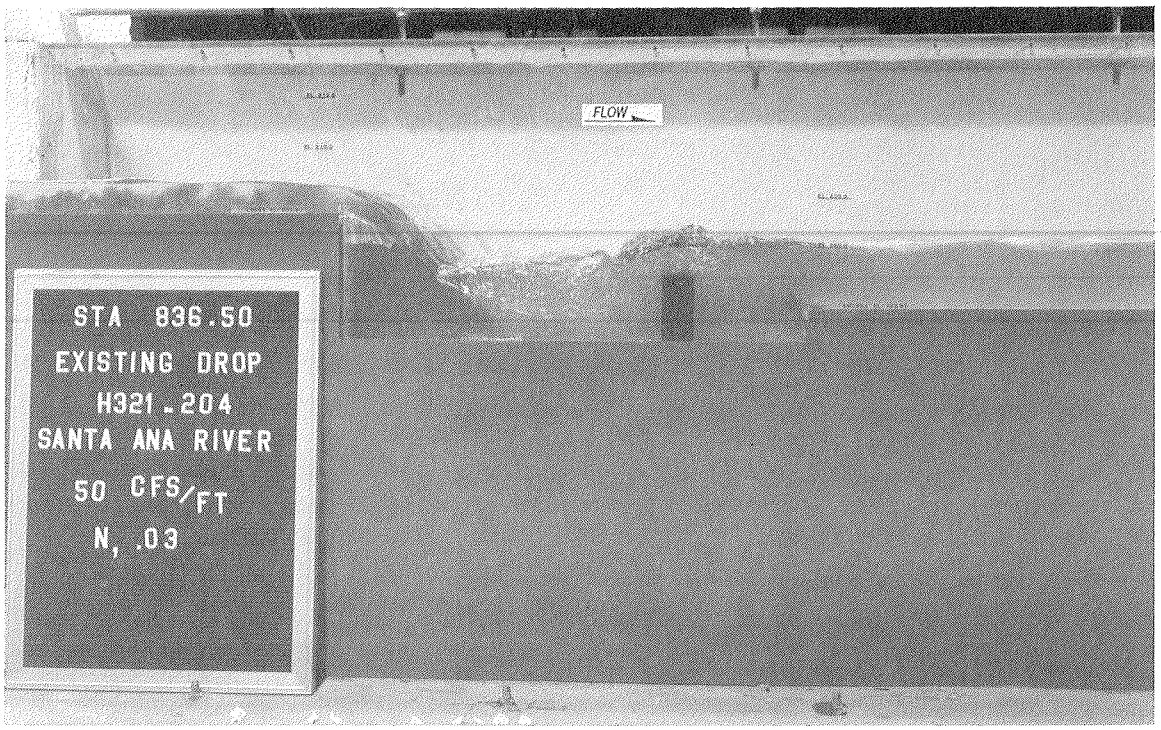
d. Unit discharge 150 cfs/ft, tailwater el 203.22

Photo 50. (Sheet 2 of 3)

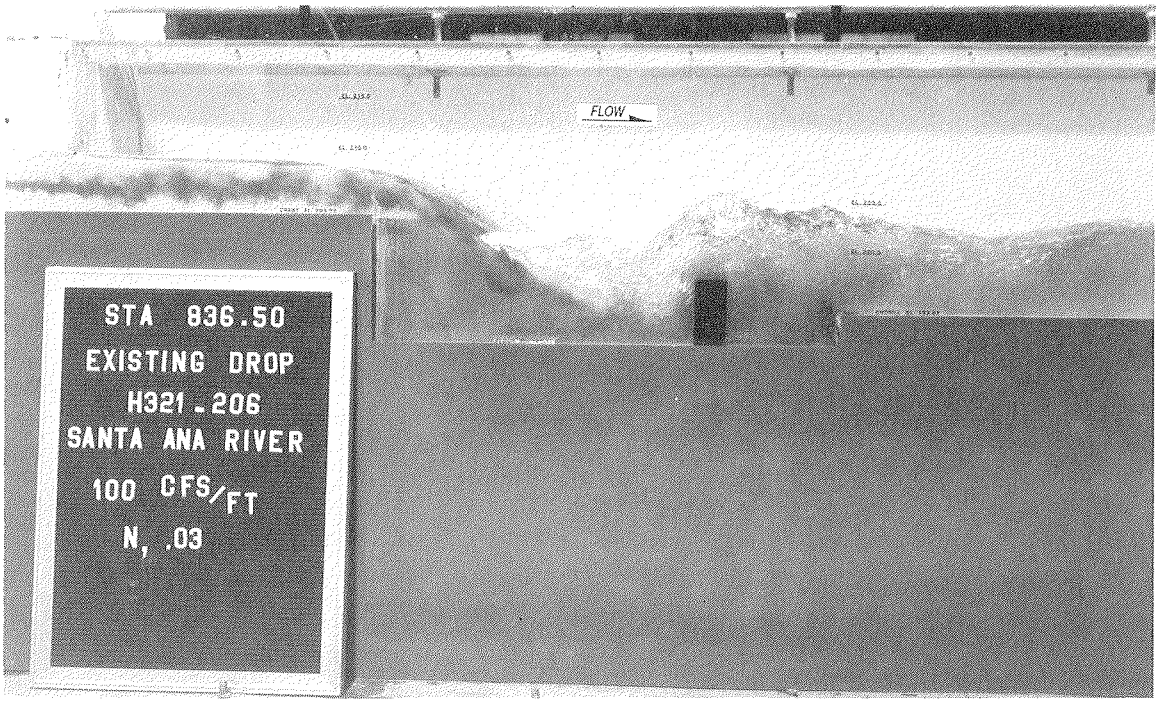


e. Unit discharge 175 cfs/ft, tailwater el 204.12

Photo 50. (Sheet 3 of 3)



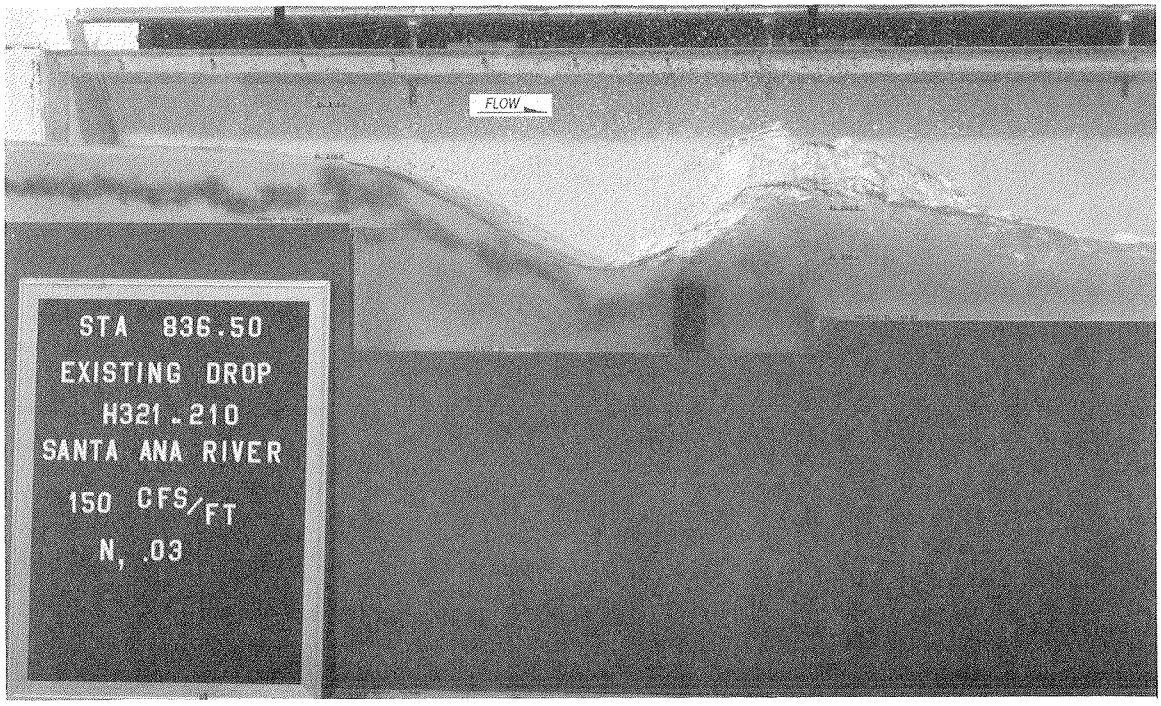
a. Unit discharge 50 cfs/ft, tailwater el 200.12



b. Unit discharge 100 cfs/ft, tailwater el 203.22

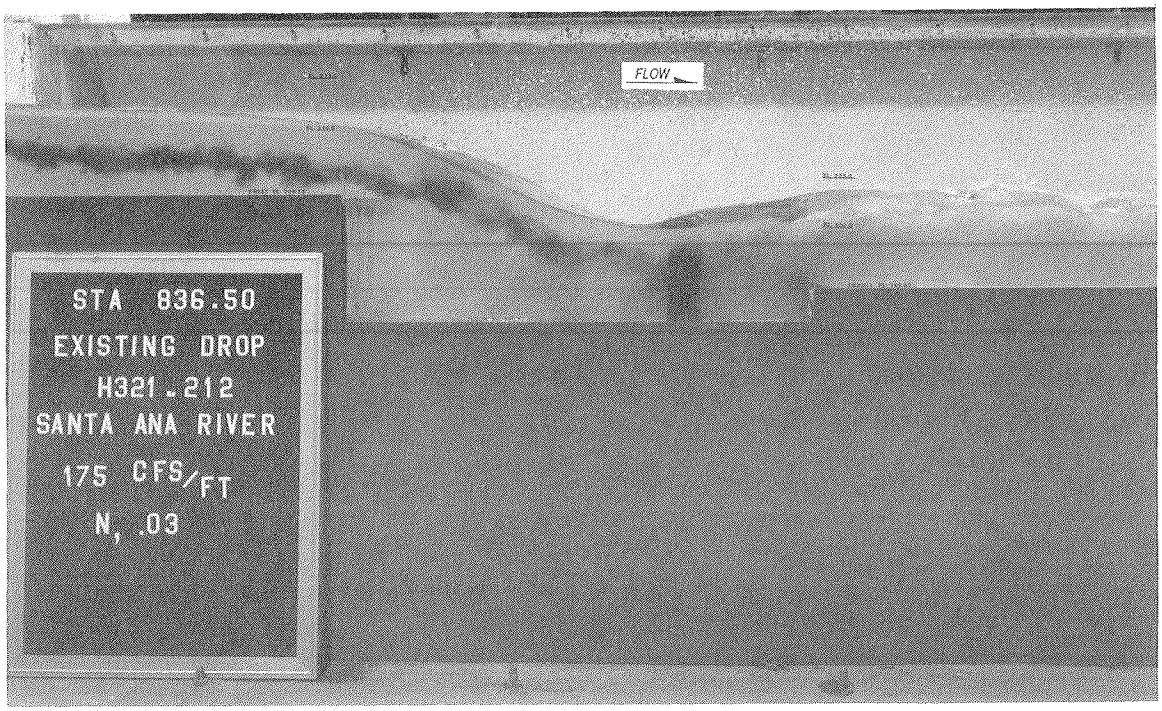
Photo 51. Flow conditions in the type 1 design drop structure at sta 836+50, n = 0.03 (Sheet 1 of 3)

c. Unit discharge 130 cfs/ft, tailwater el 204.92



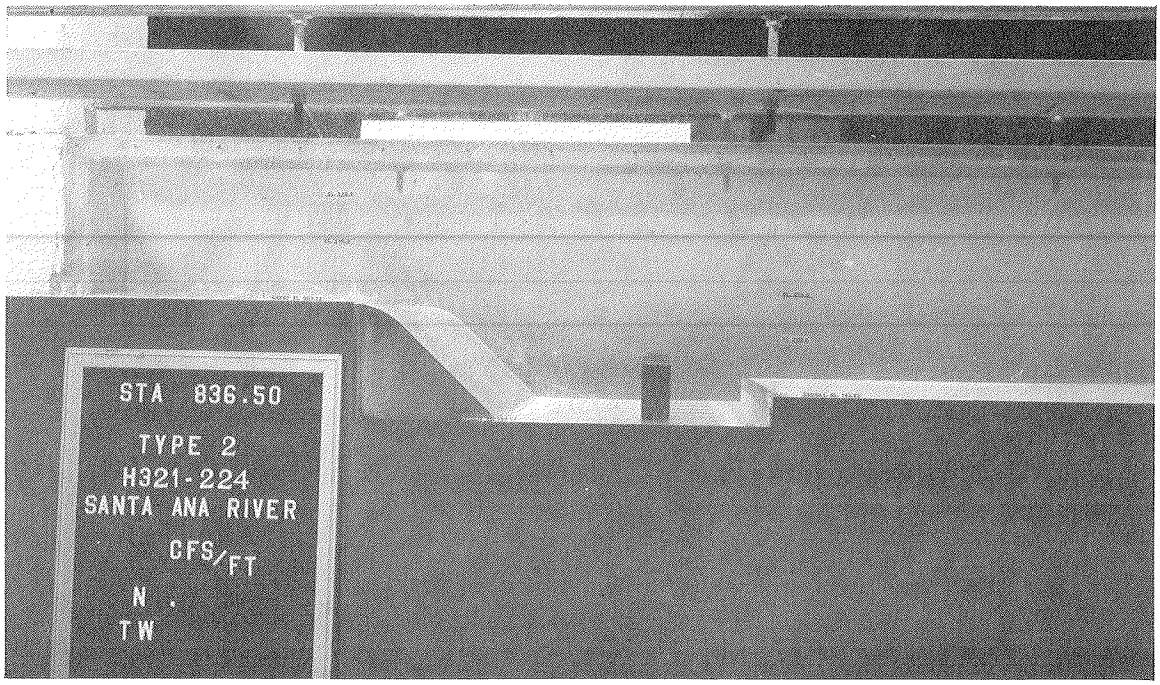
d. Unit discharge 150 cfs/ft, tailwater el 205.82

Photo 51. (Sheet 2 of 3)

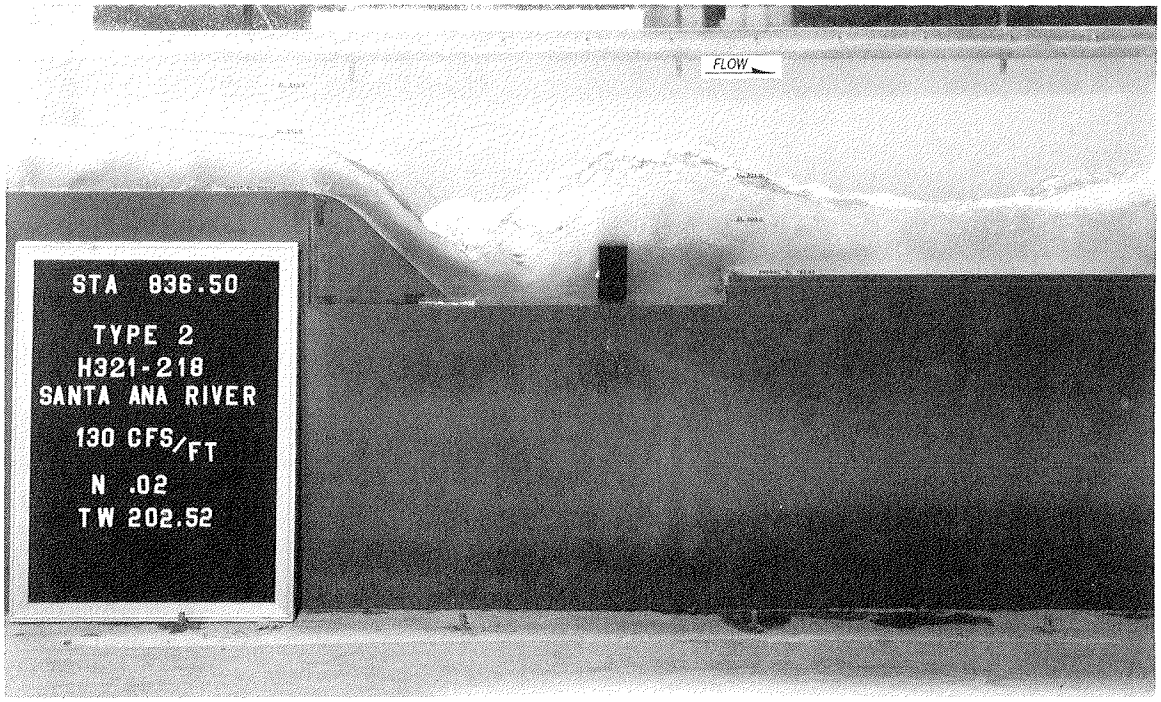


e. Unit discharge 175 cfs/ft, tailwater el 207.02

Photo 51. (Sheet 3 of 3)

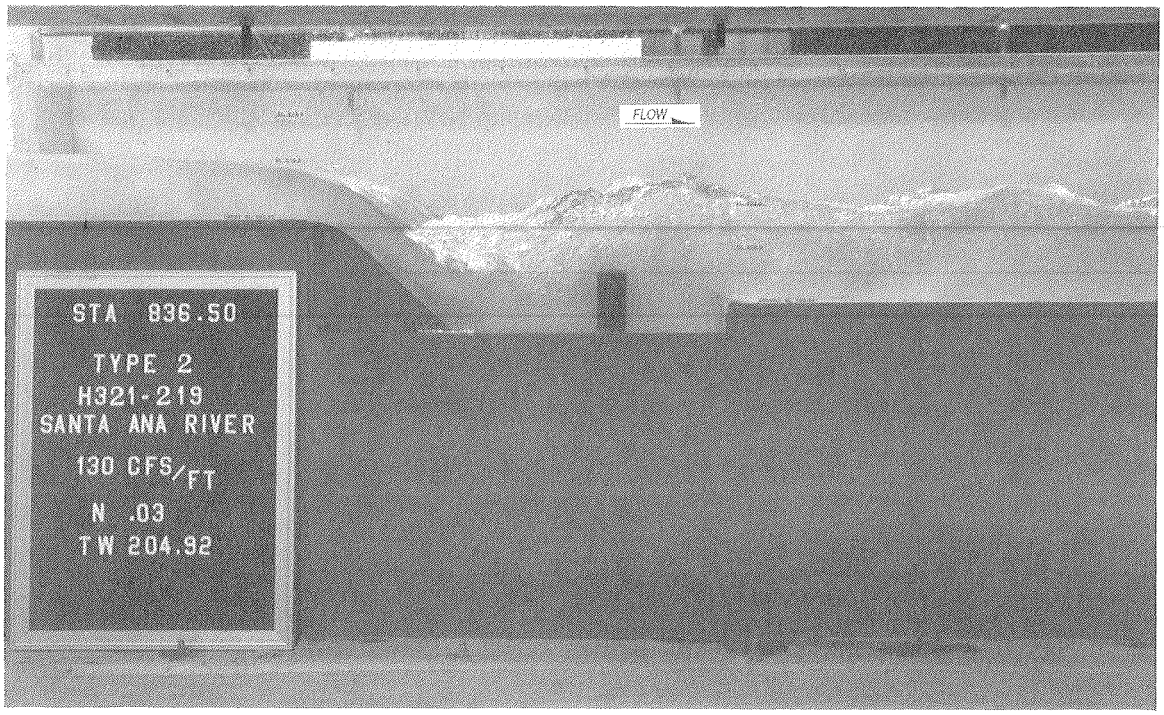


a. Dry bed

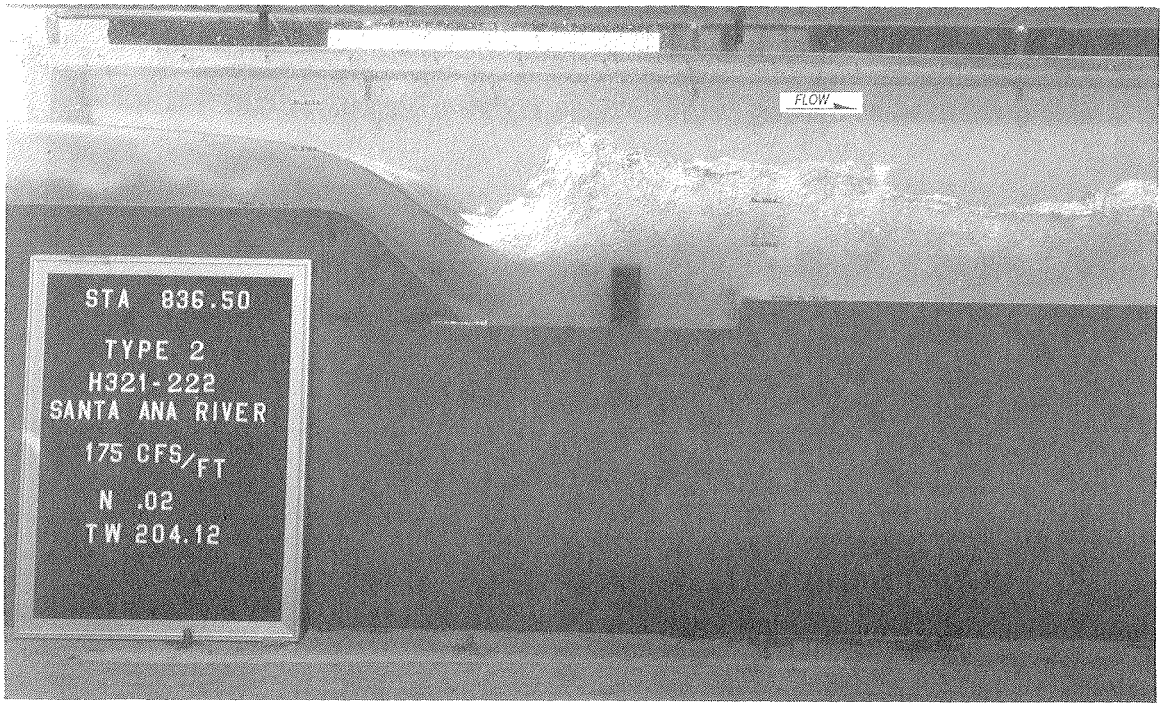


b. Unit discharge 130 cfs/ft, tailwater el 202.52, n = 0.02

Photo 52. Type 2 design drop structure, sta 836+50 (Continued)

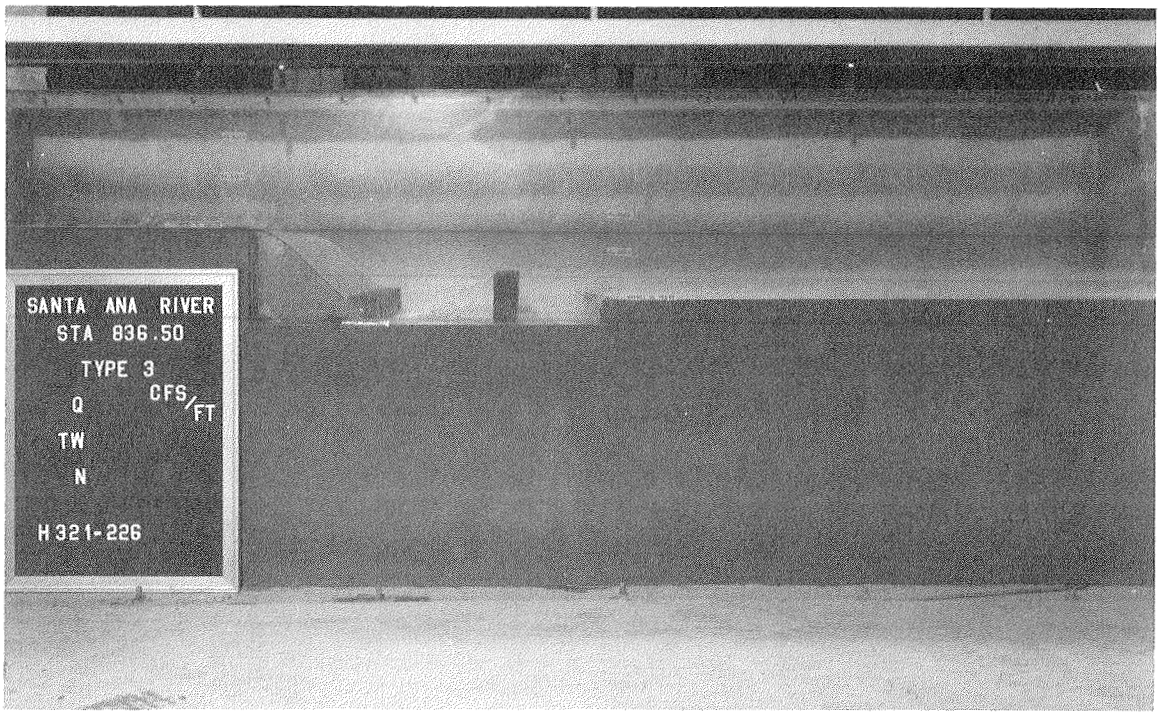


c. Unit discharge 130 cfs/ft, tailwater el 204.92, n = 0.03

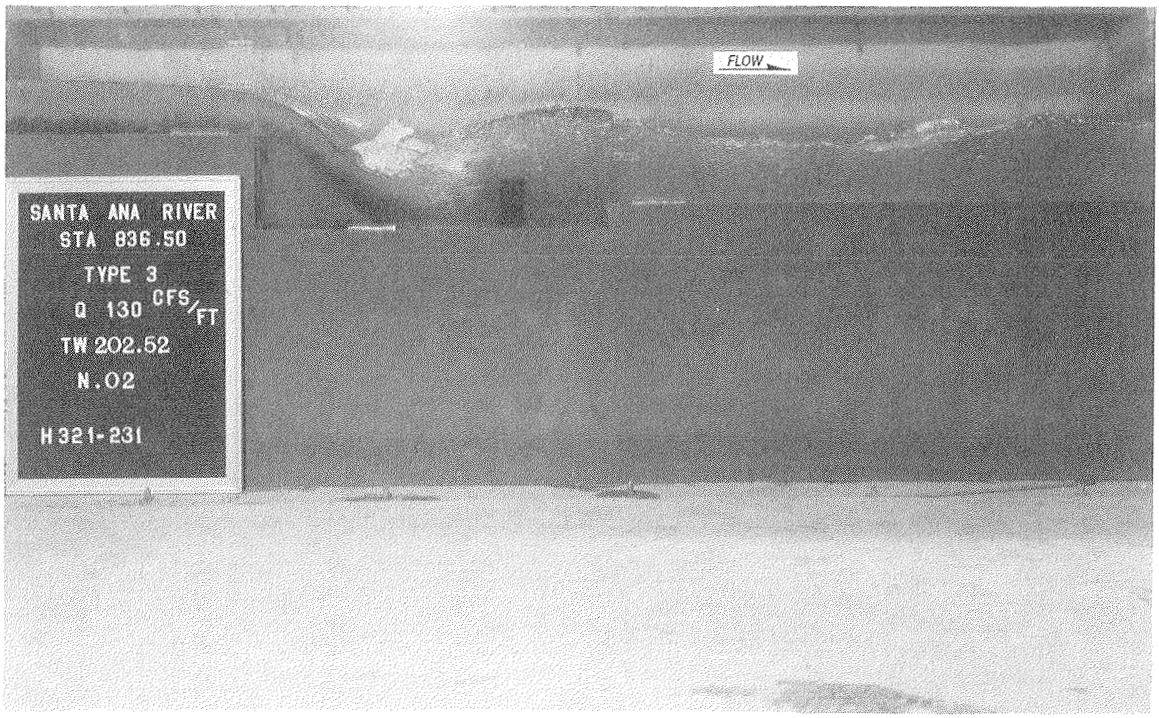


d. Unit discharge 175 cfs/ft, tailwater el 204.12, n = 0.02

Photo 52. (Concluded)

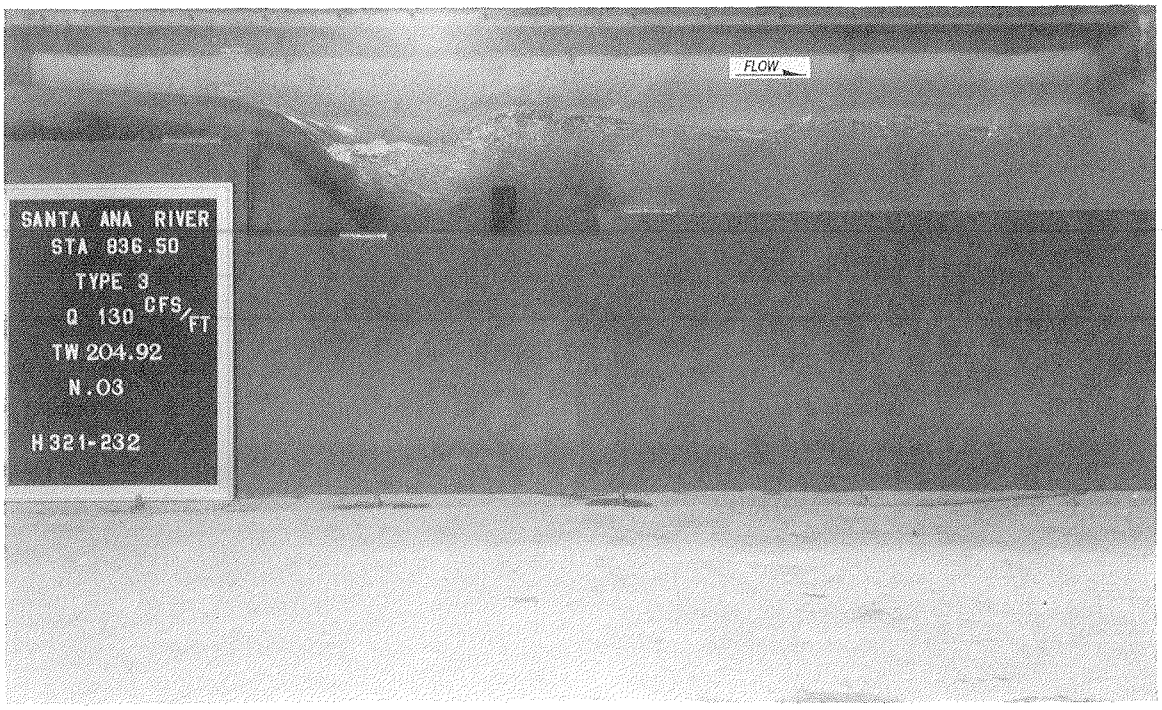


a. Dry bed



b. Tailwater el 202.52, n = 0.02

Photo 53. Type 3 design drop structure, sta 836+50, discharge 130 cfs/ft (Continued)



c. Tailwater el 204.92, n = 0.03

Photo 53. (Concluded)

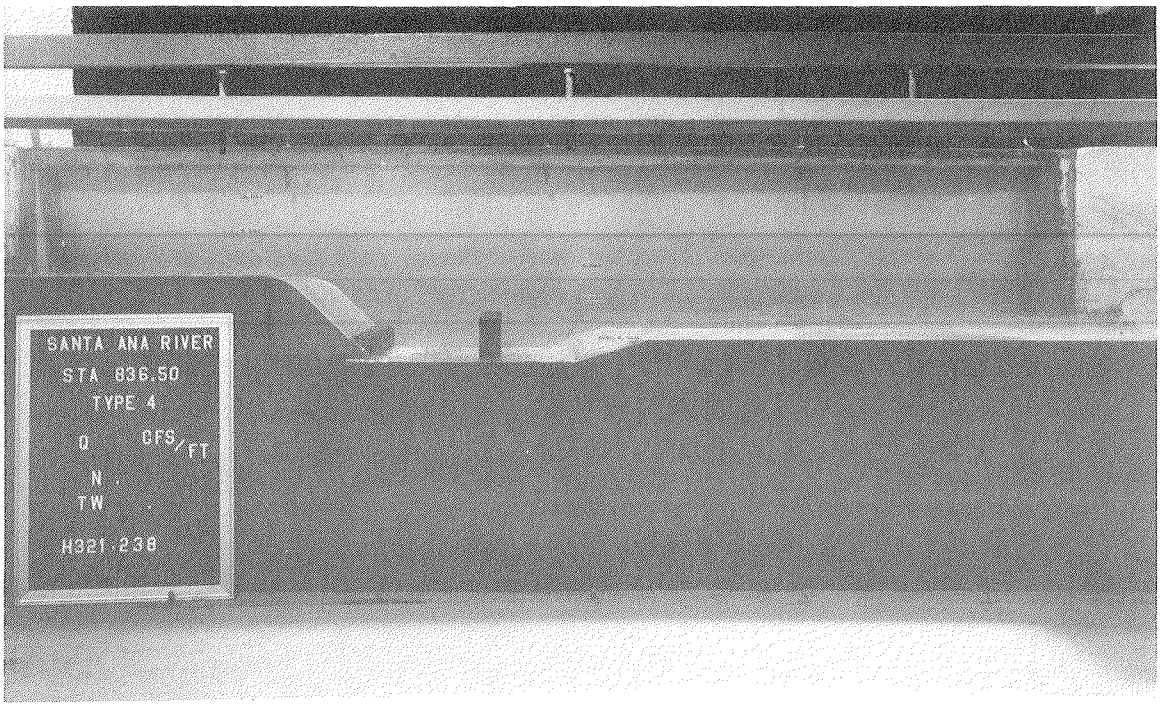


Photo 54. Type 4 design drop structure (sta 836+50)

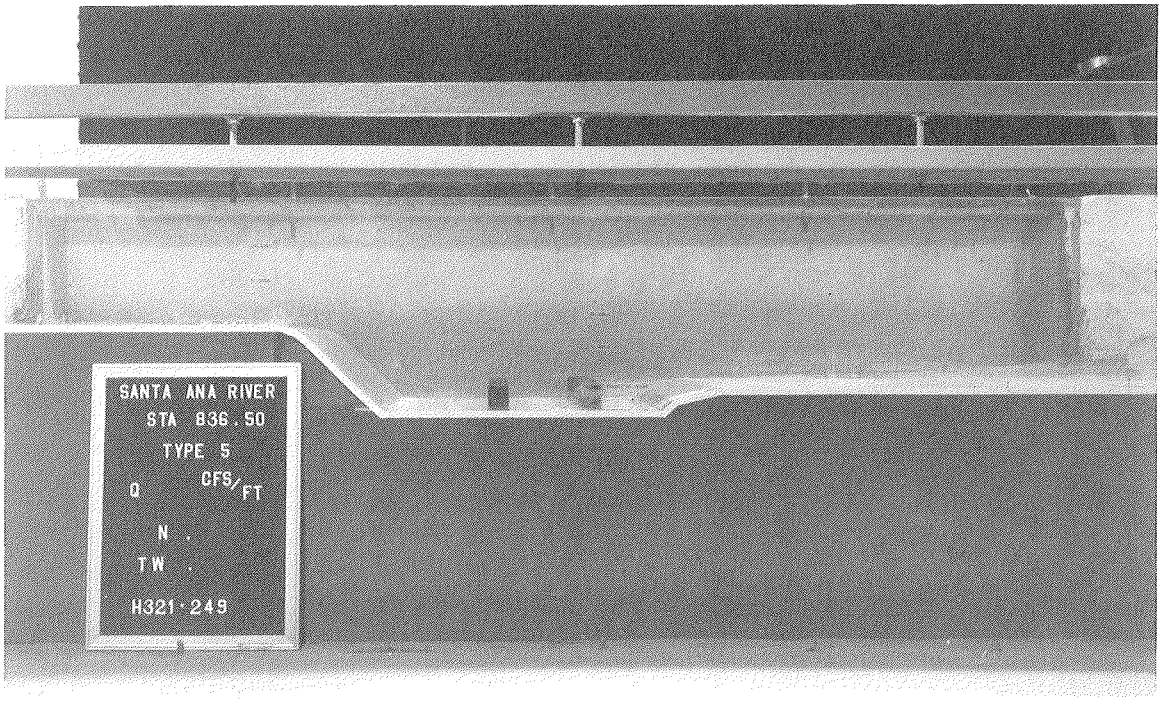


Photo 55. Type 5 design drop structure (sta 836+50)

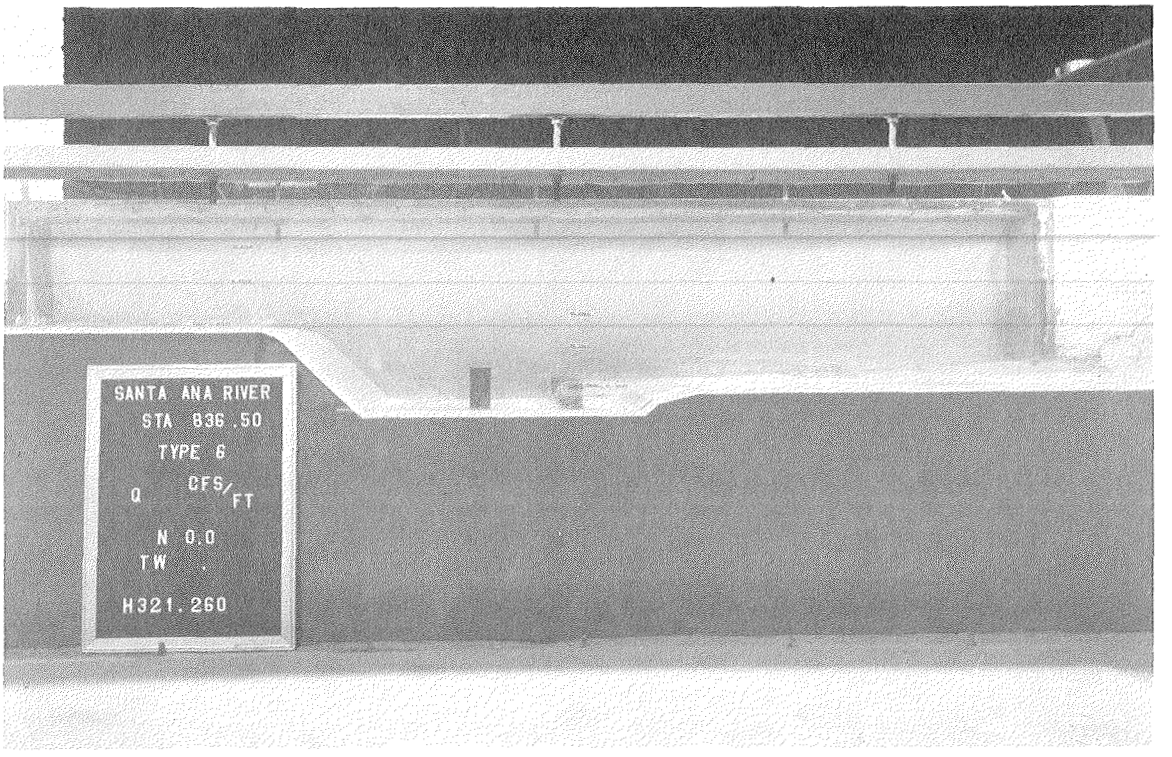
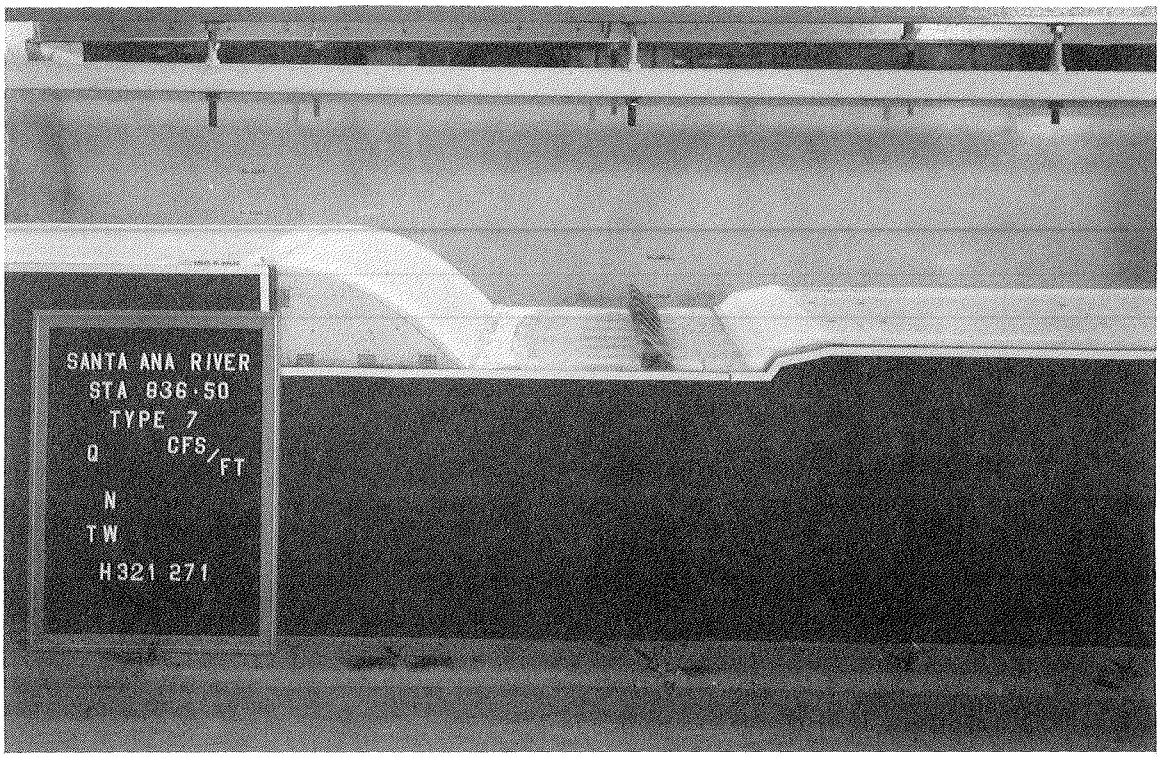
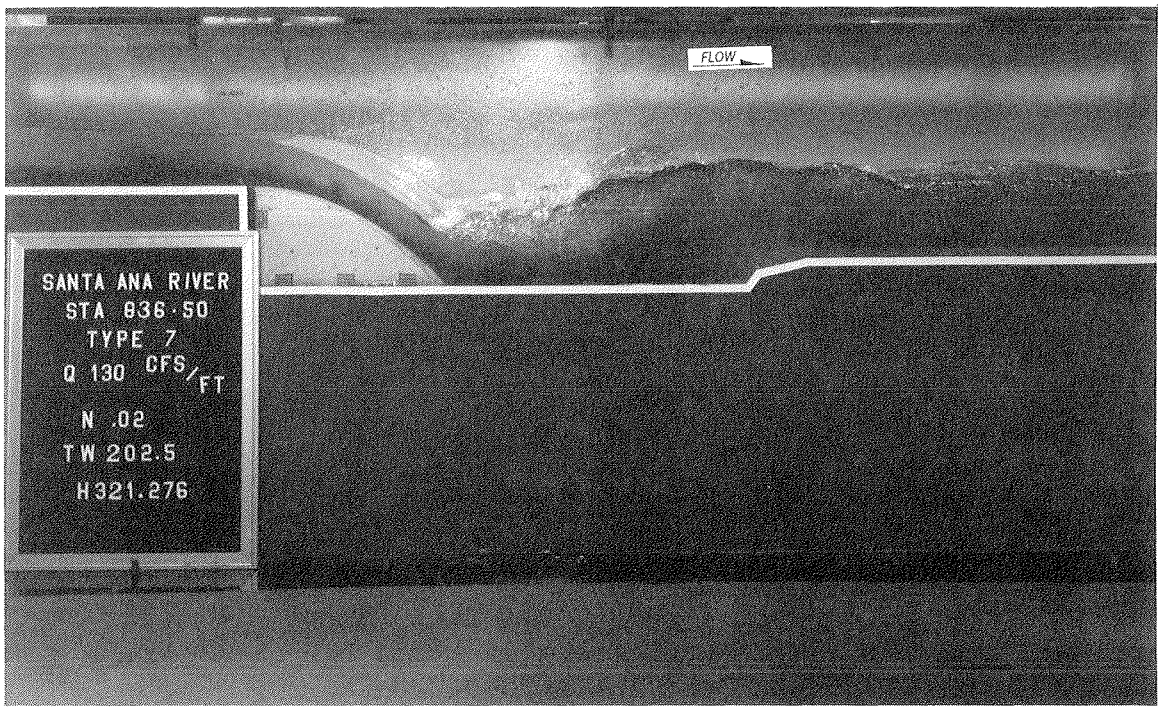


Photo 56. Type 6 design drop structure (sta 836+50)

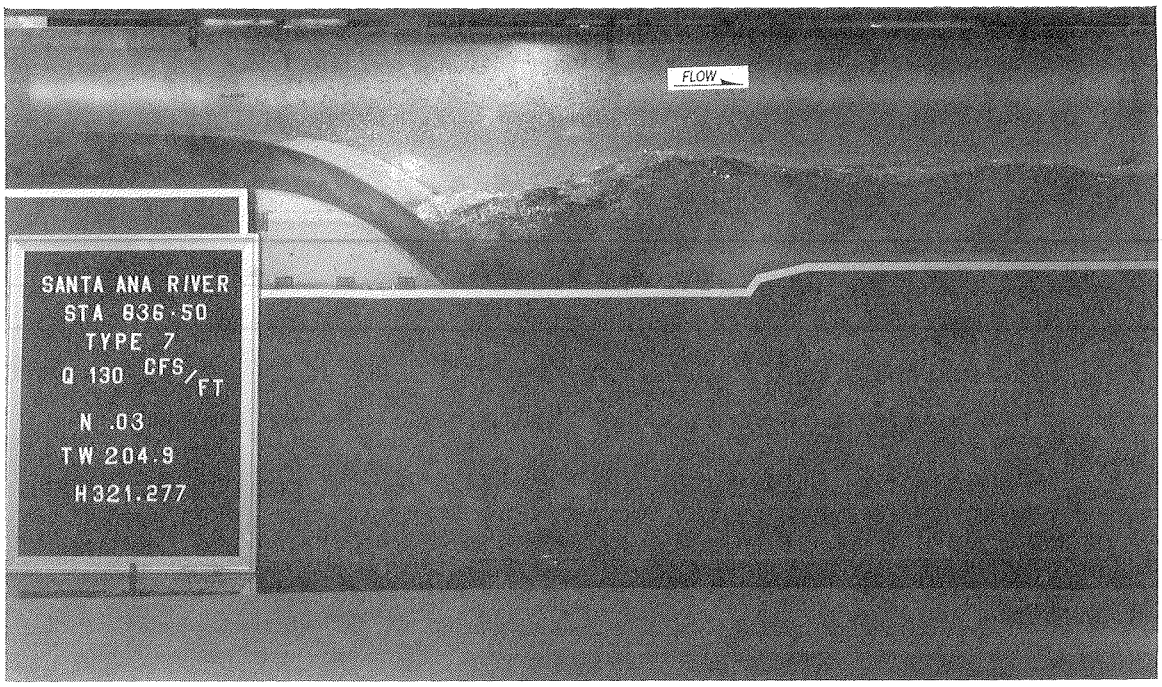


a. Dry bed

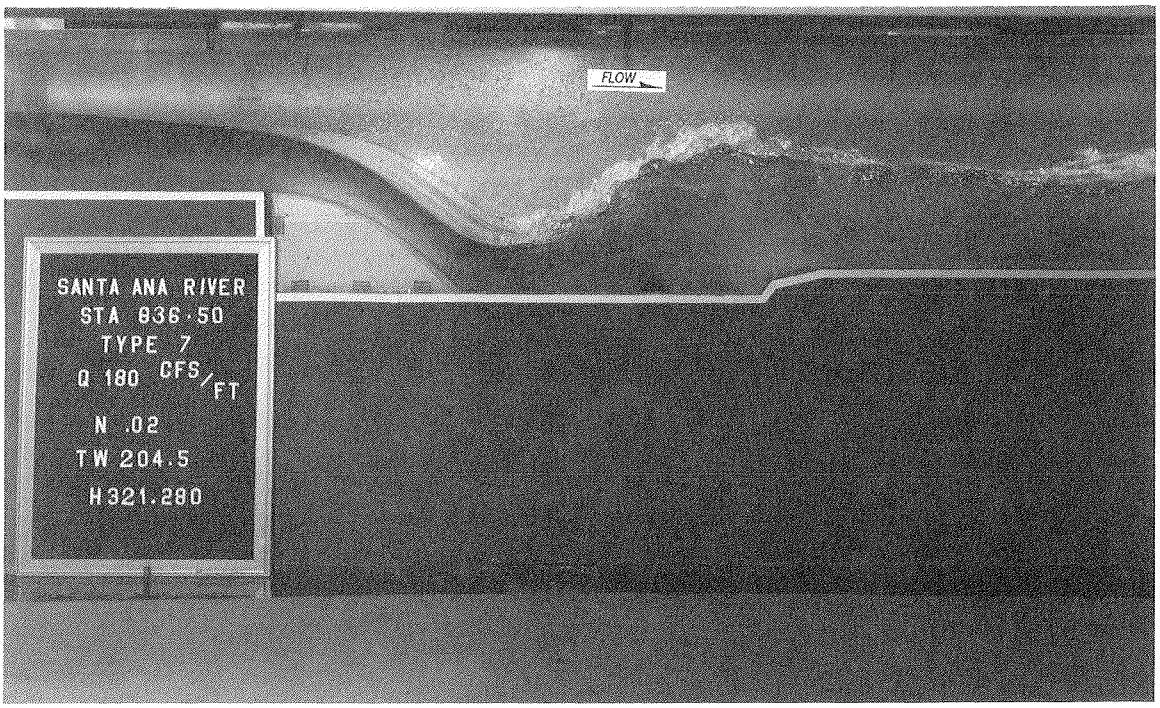


b. Unit discharge 130 cfs/ft, tailwater el 202.5, n = 0.02

Photo 57. Flow conditions in the type 7 design drop structure, sta 836+50 (Continued)

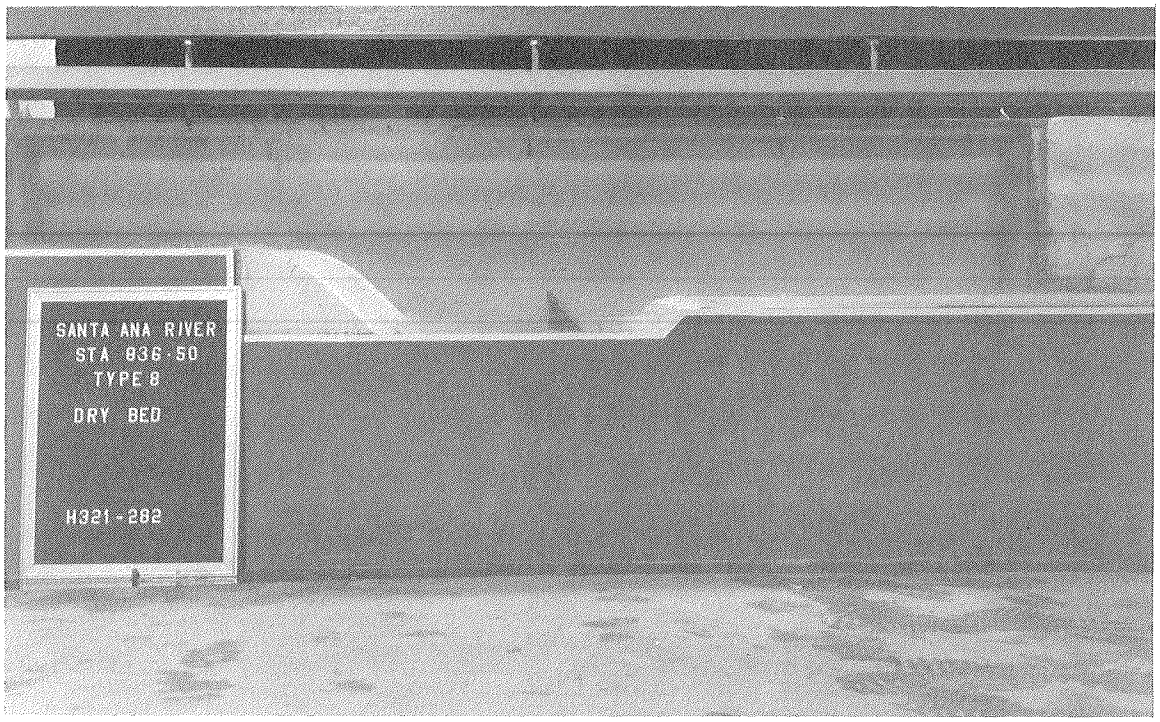


c. Unit discharge 130 cfs/ft, tailwater el 204.9, n = 0.03

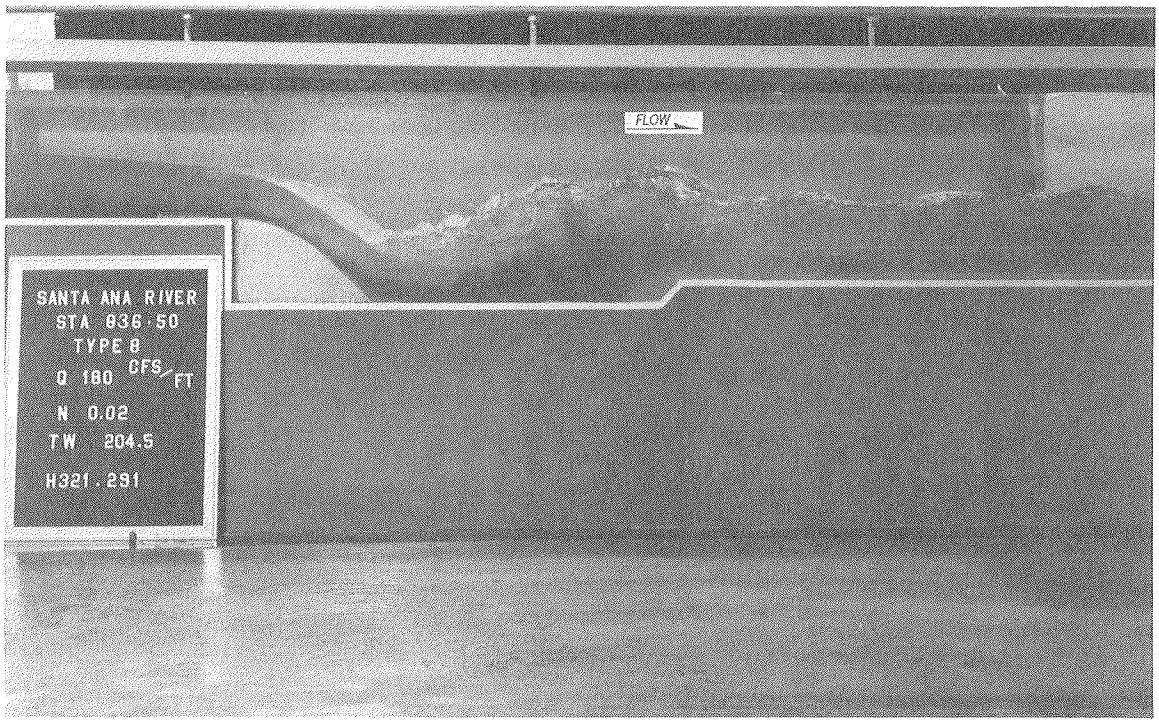


d. Unit discharge 180 cfs/ft, tailwater el 204.5, n = 0.02

Photo 57. (Concluded)

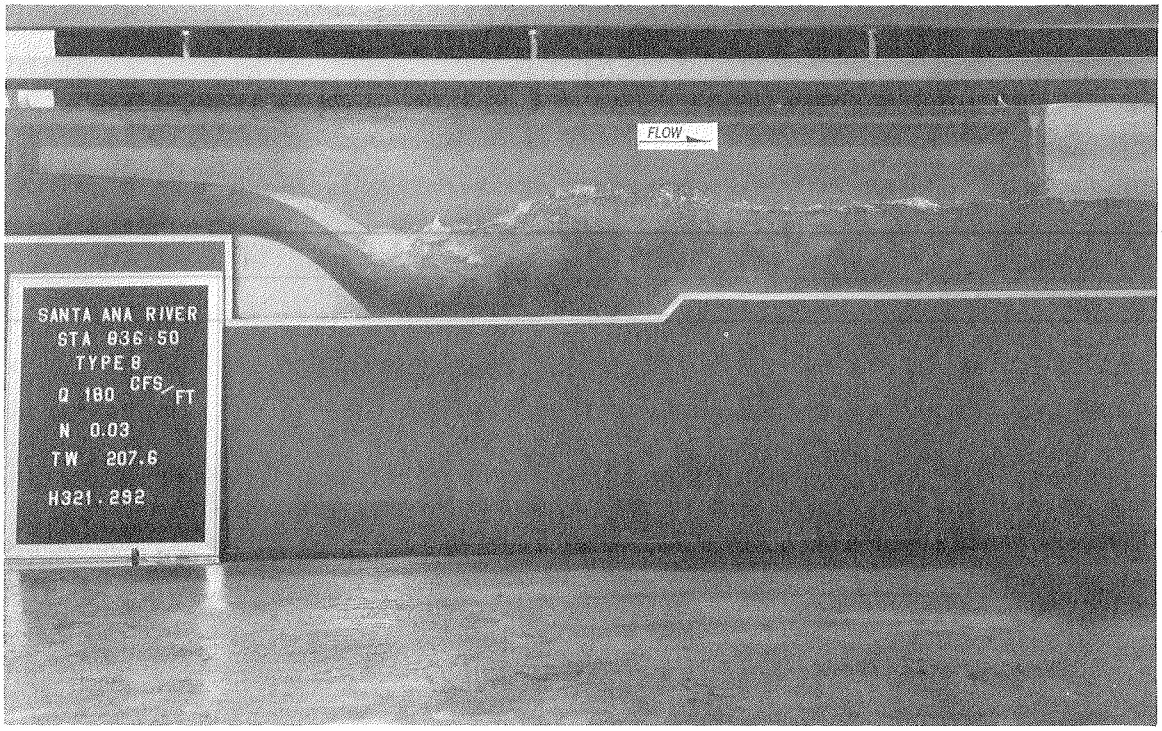


a. Dry bed



b. Tailwater el 204.5, n = 0.02

Photo 58. Flow conditions in the type 8 design drop structure, sta 836+50, unit discharge 180 cfs/ft (Continued)



c. Tailwater el 207.6, n = 0.03

Photo 58. (Concluded)

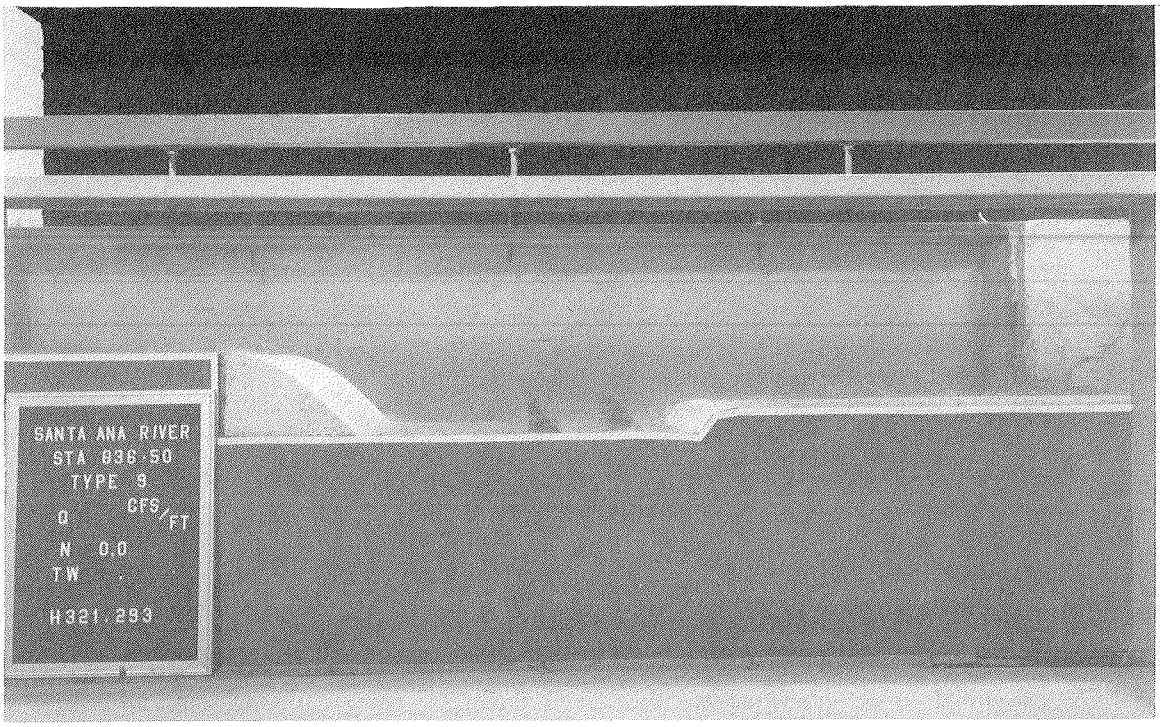


Photo 59. Type 9 design drop structure, sta 836+50

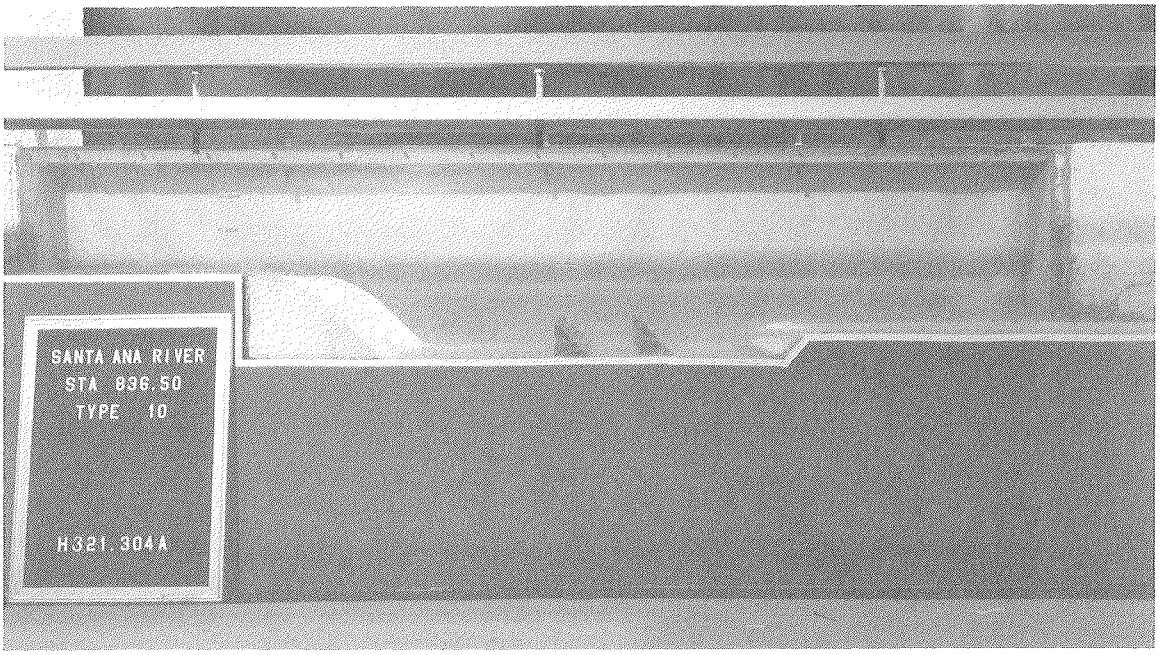
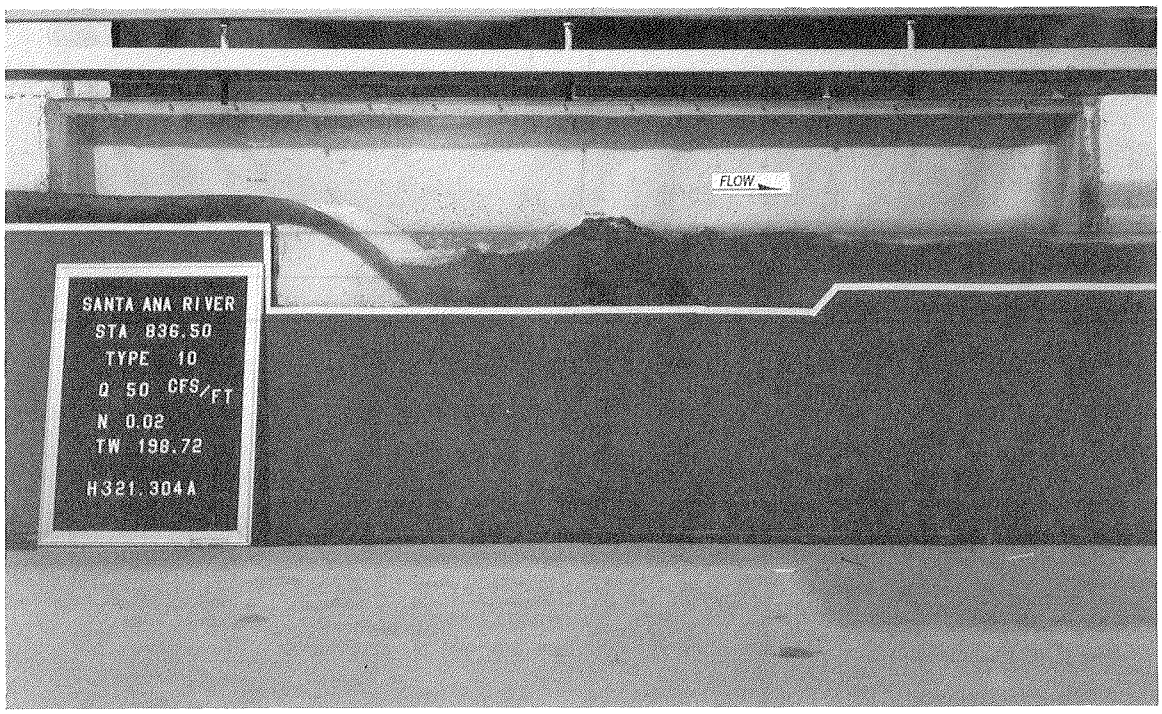
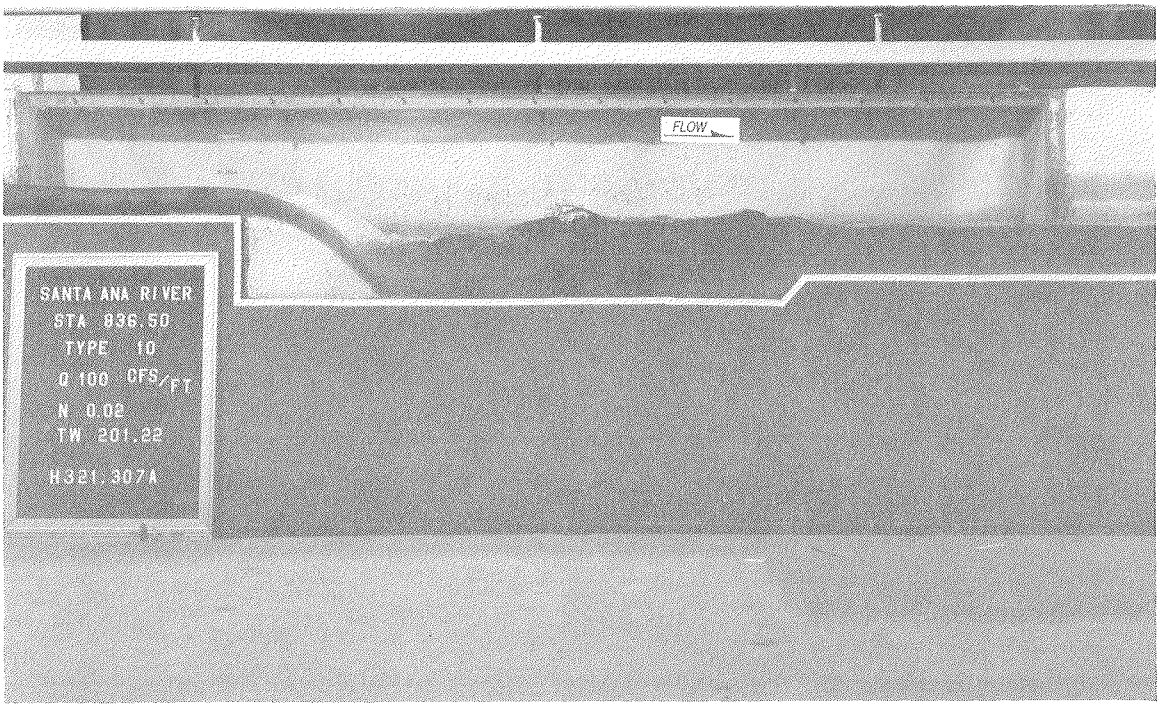


Photo 60. Type 10 design drop structure, sta 836+50

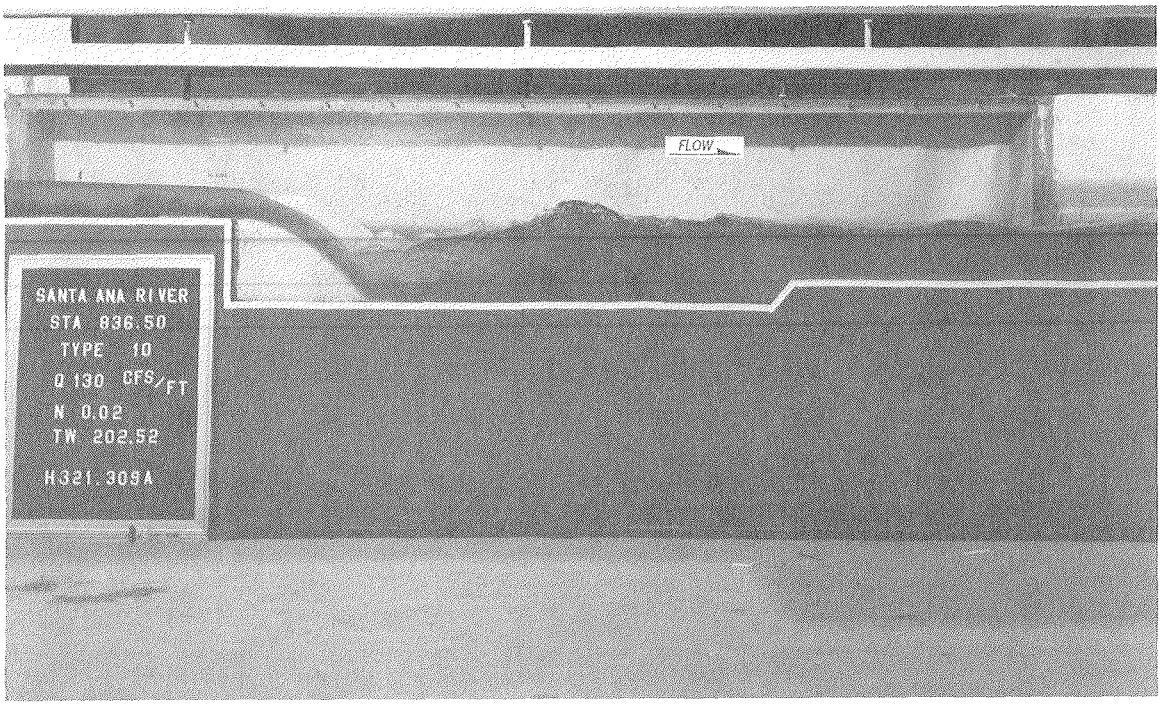


a. Unit discharge 50 cfs/ft, tailwater el 198.72

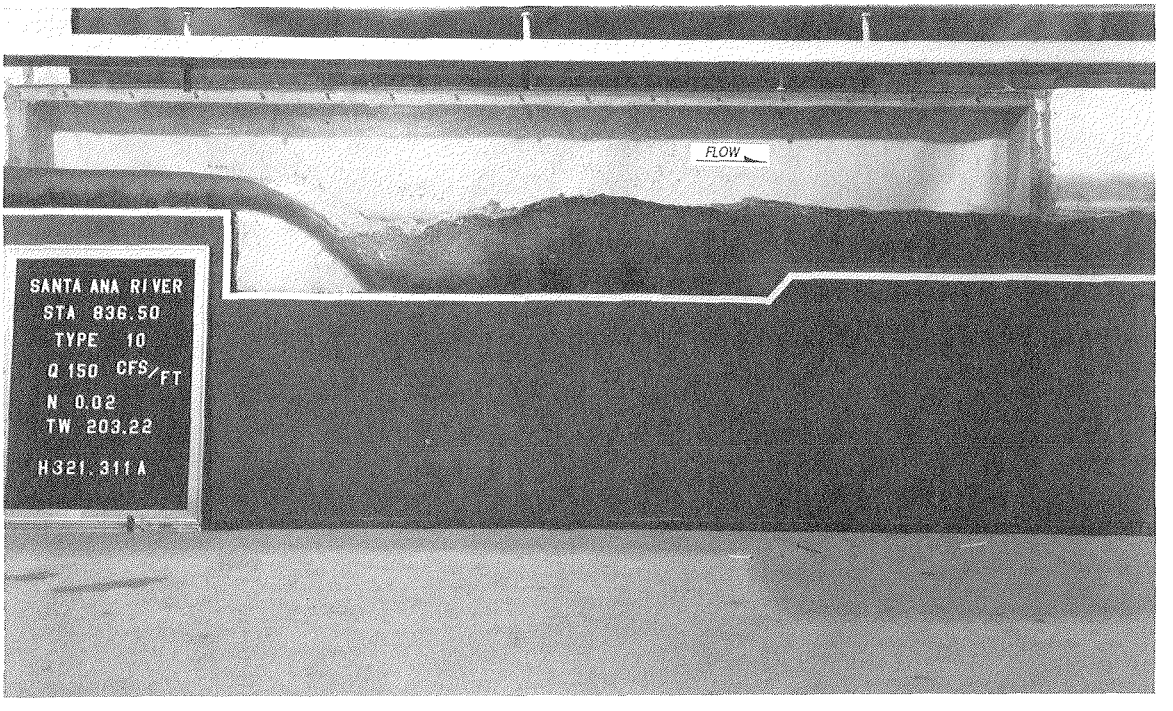


b. Unit discharge 100 cfs/ft, tailwater el 201.22

Photo 61. Flow conditions in the type 10 design drop structure, sta 836+50, n = 0.02 (Sheet 1 of 3)

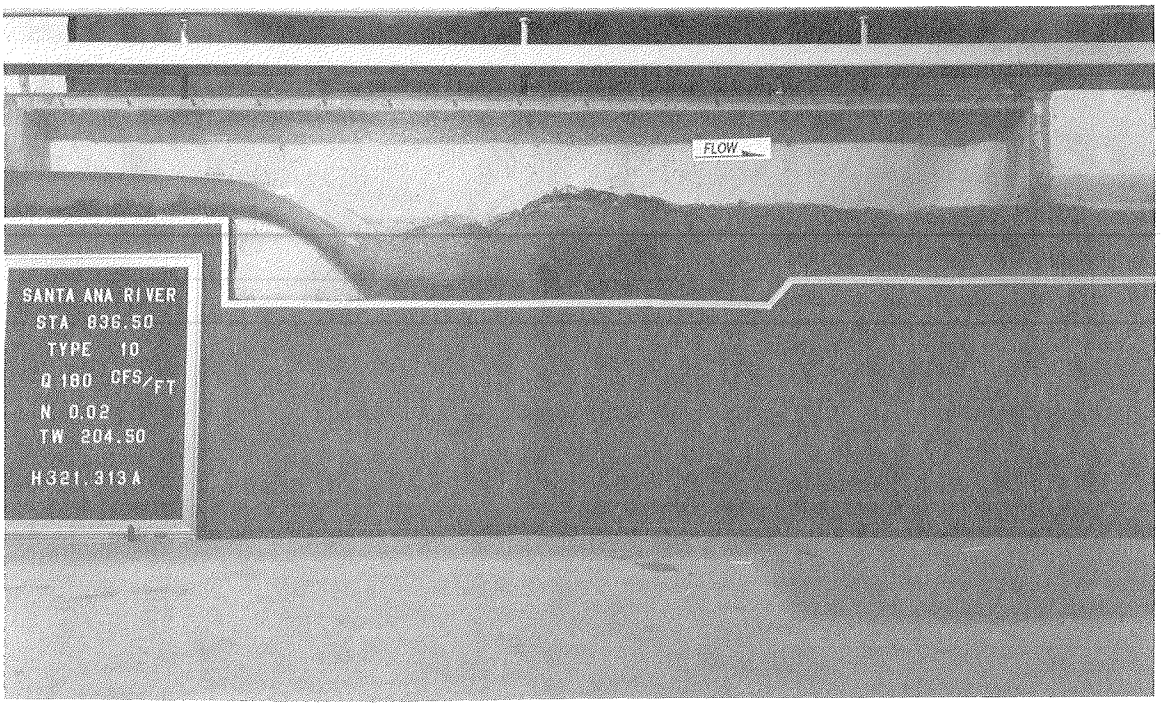


c. Unit discharge 130 cfs/ft, tailwater el 202.52



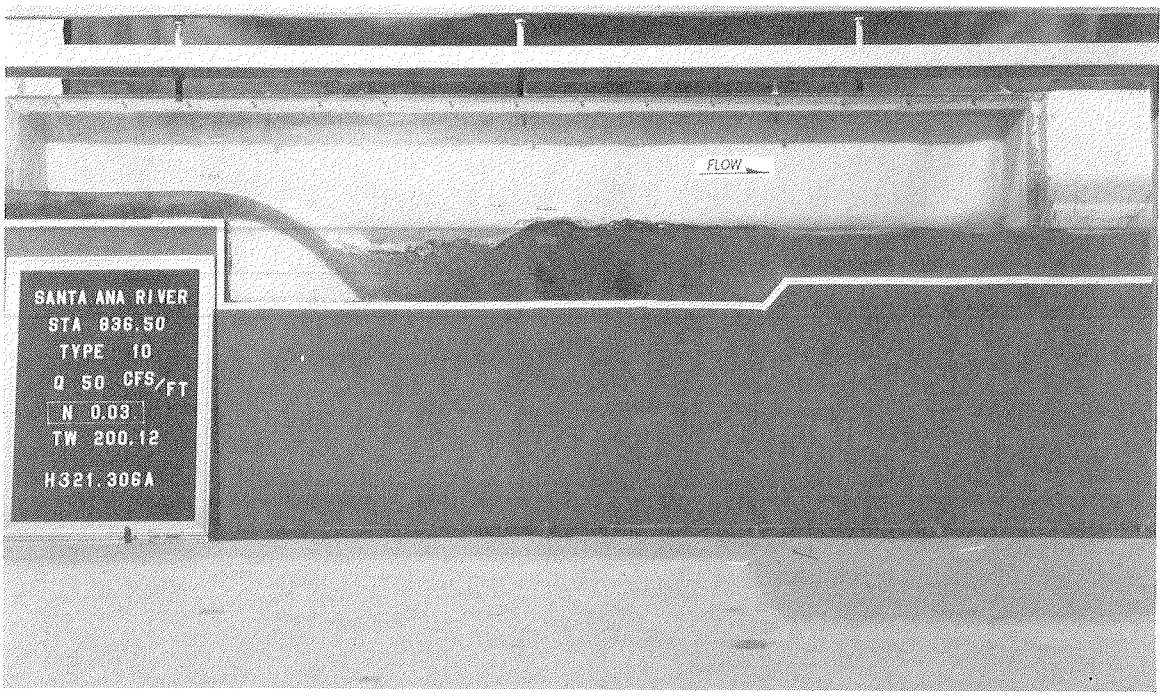
d. Unit discharge 150 cfs/ft, tailwater el 203.22

Photo 61. (Sheet 2 of 3)

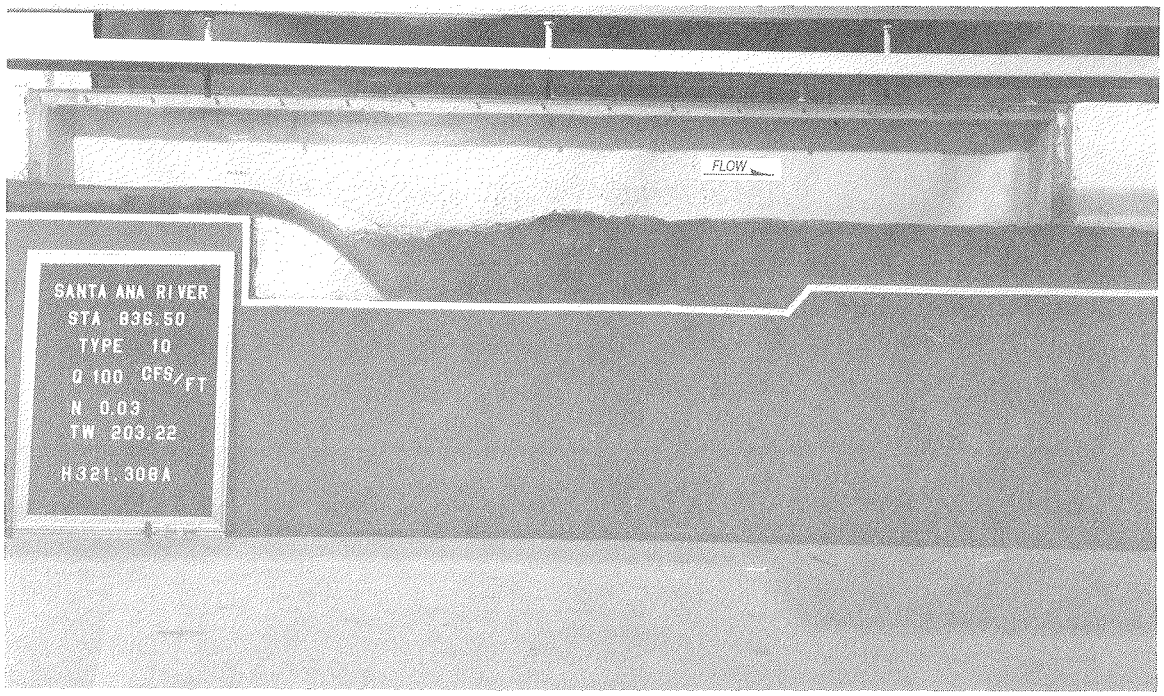


e. Unit discharge 180 cfs/ft, tailwater el 204.50

Photo 61. (Sheet 3 of 3)

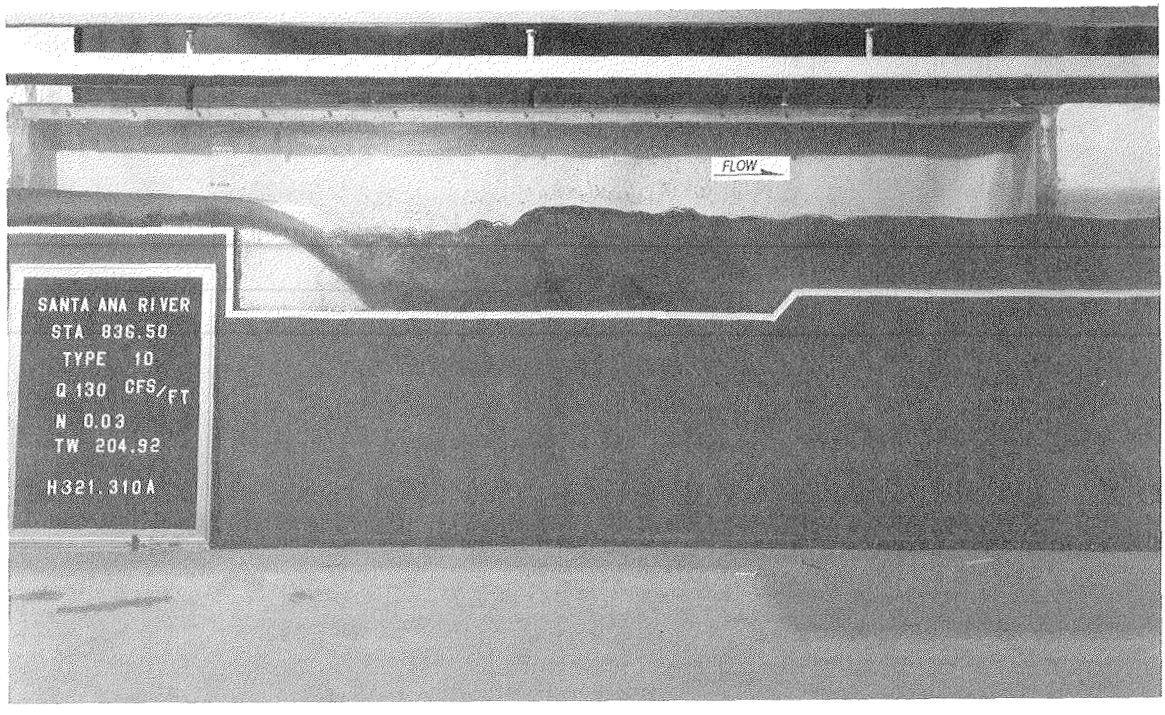


a. Unit discharge 50 cfs/ft, tailwater el 200.12

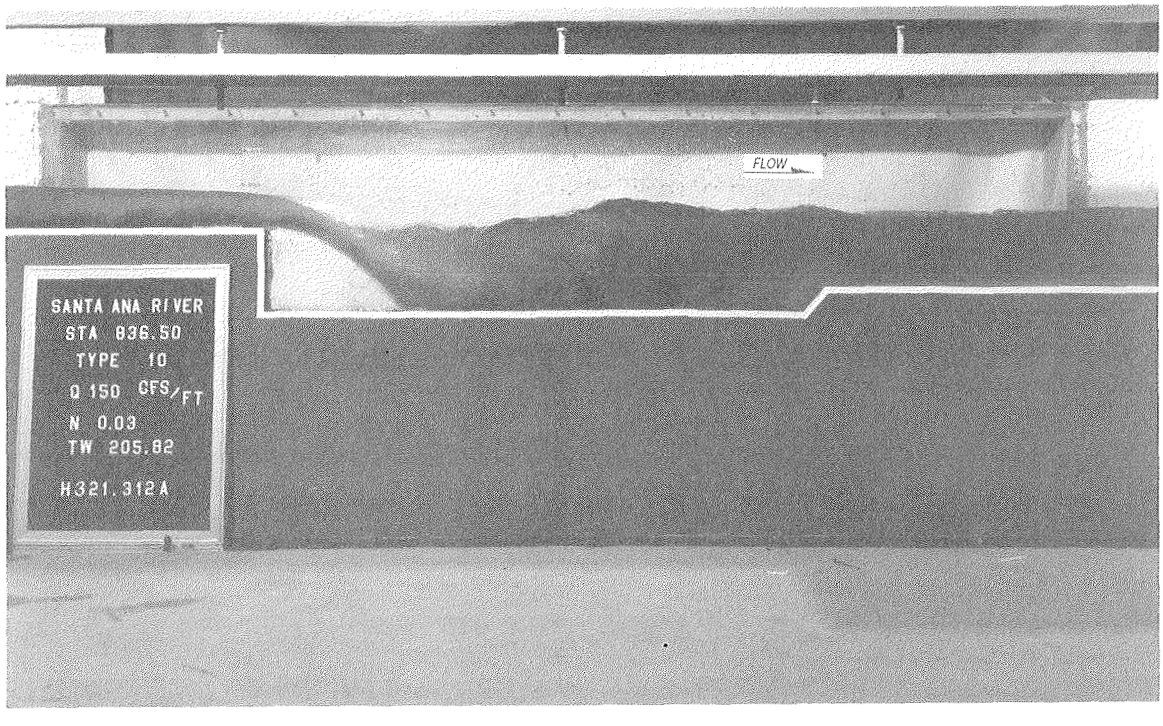


b. Unit discharge 100 cfs/ft, tailwater el 203.22

Photo 62. Flow conditions in the type 10 design drop structure, sta 836+50, n = 0.03 (Sheet 1 of 3)

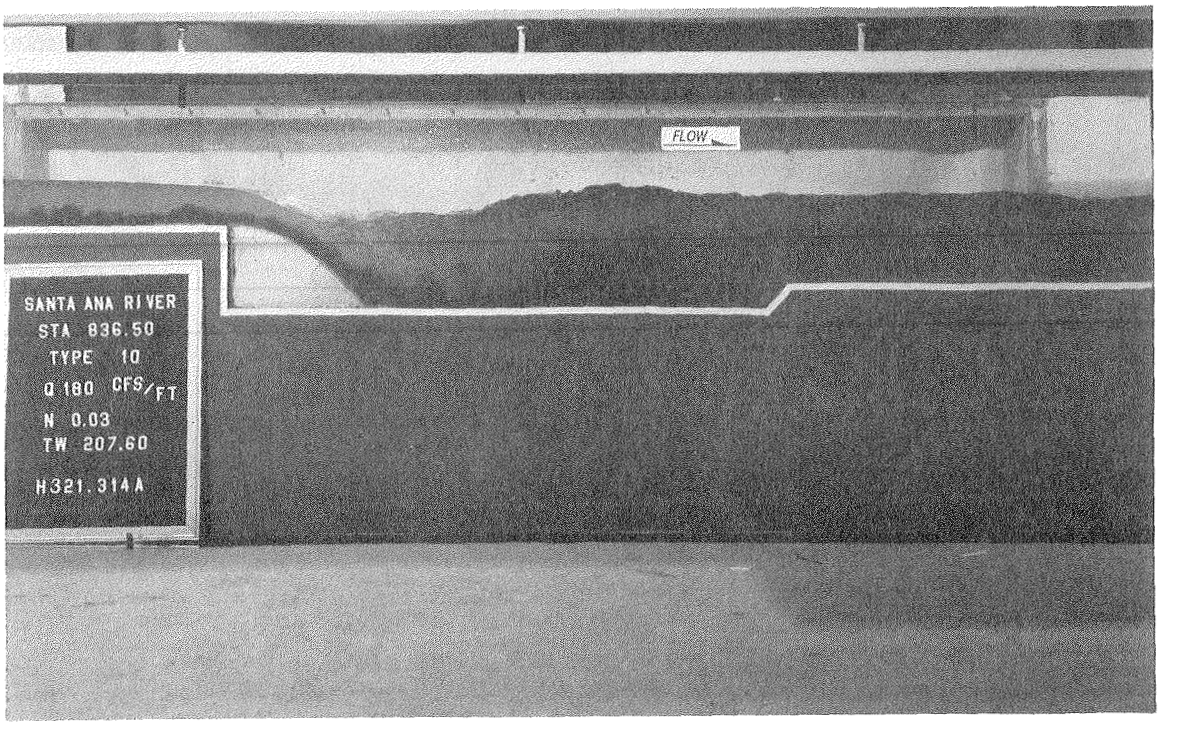


c. Unit discharge 130 cfs/ft, tailwater el 204.92



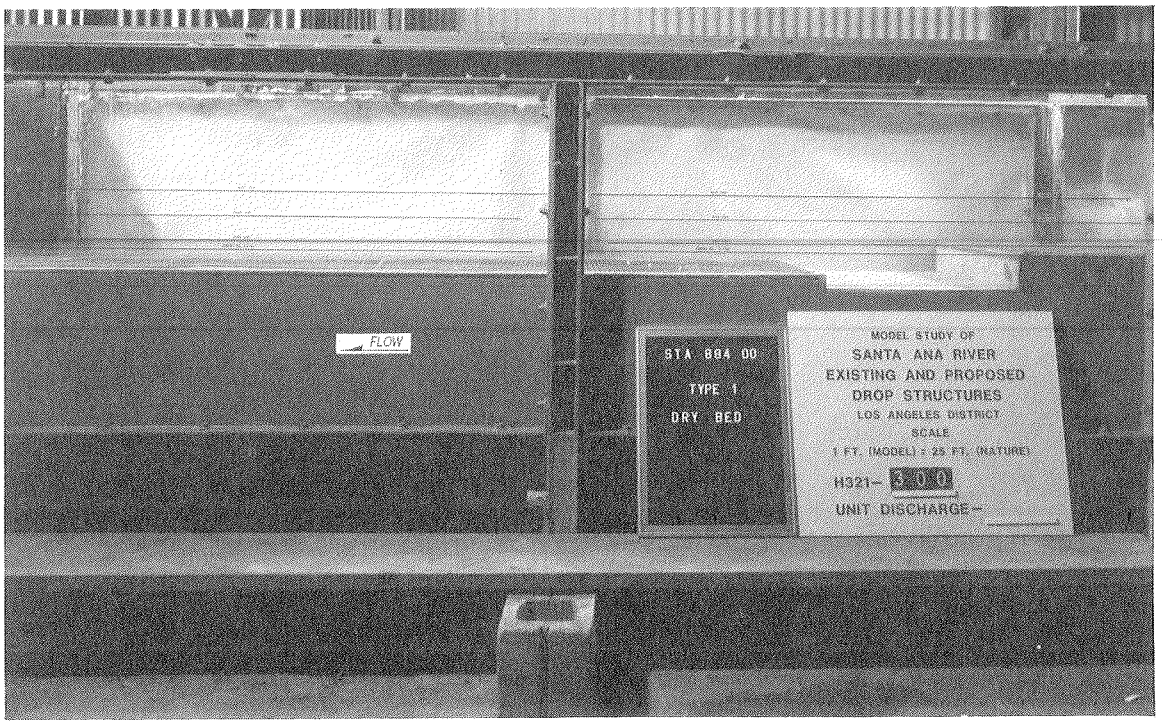
d. Unit discharge 150 cfs/ft, tailwater el 205.82

Photo 62. (Sheet 2 of 3)



e. Unit discharge 180 cfs/ft, tailwater el 207.60

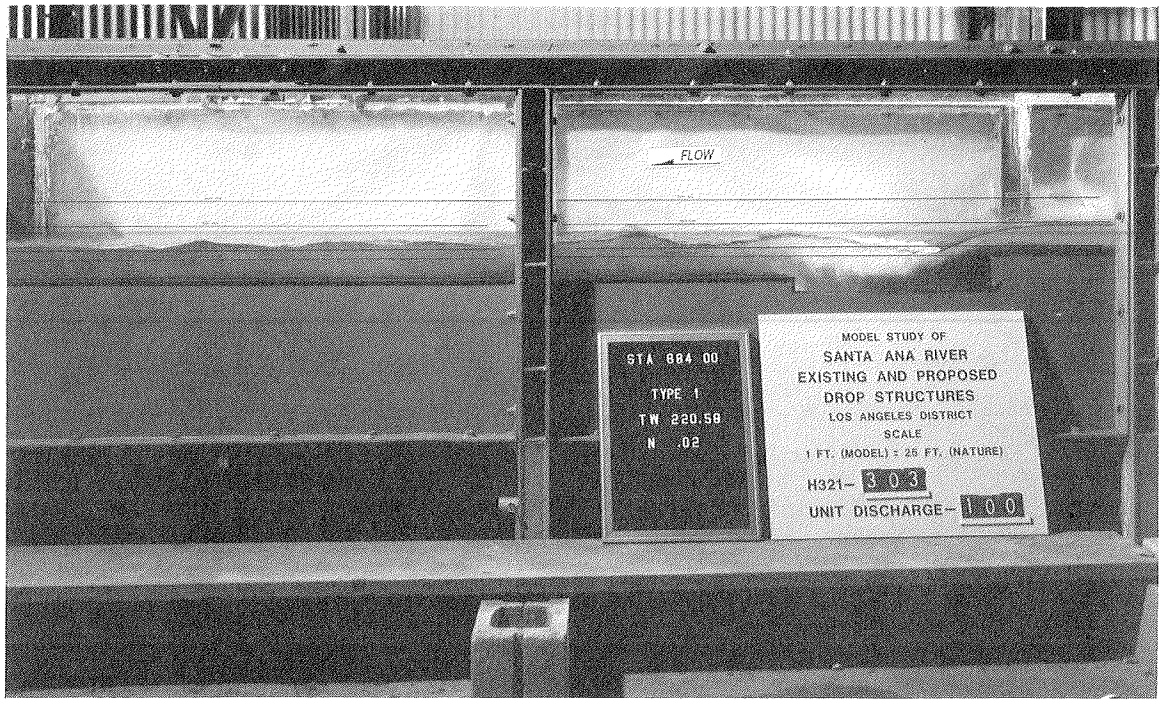
Photo 62. (Sheet 3 of 3)



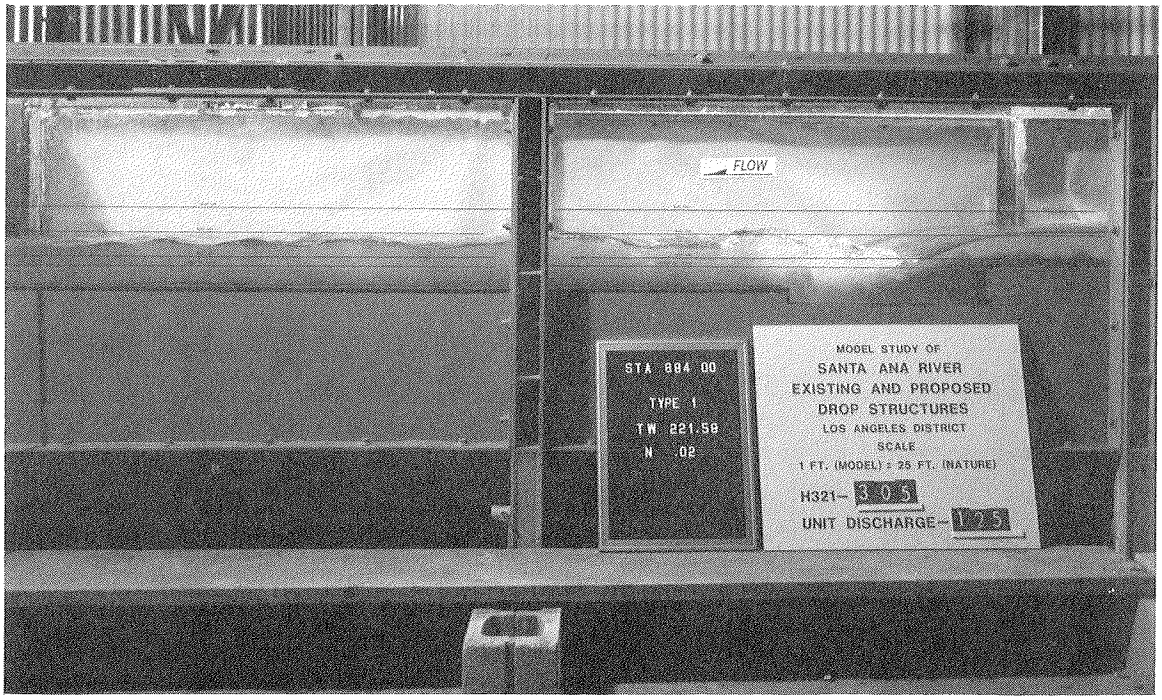
a. Dry bed

b. Unit discharge 50 cfs/ft, tailwater el 218.08

Photo 63. Flow conditions in the type 1 design drop structure, sta 884+00, n = 0.02 (Sheet 1 of 3)

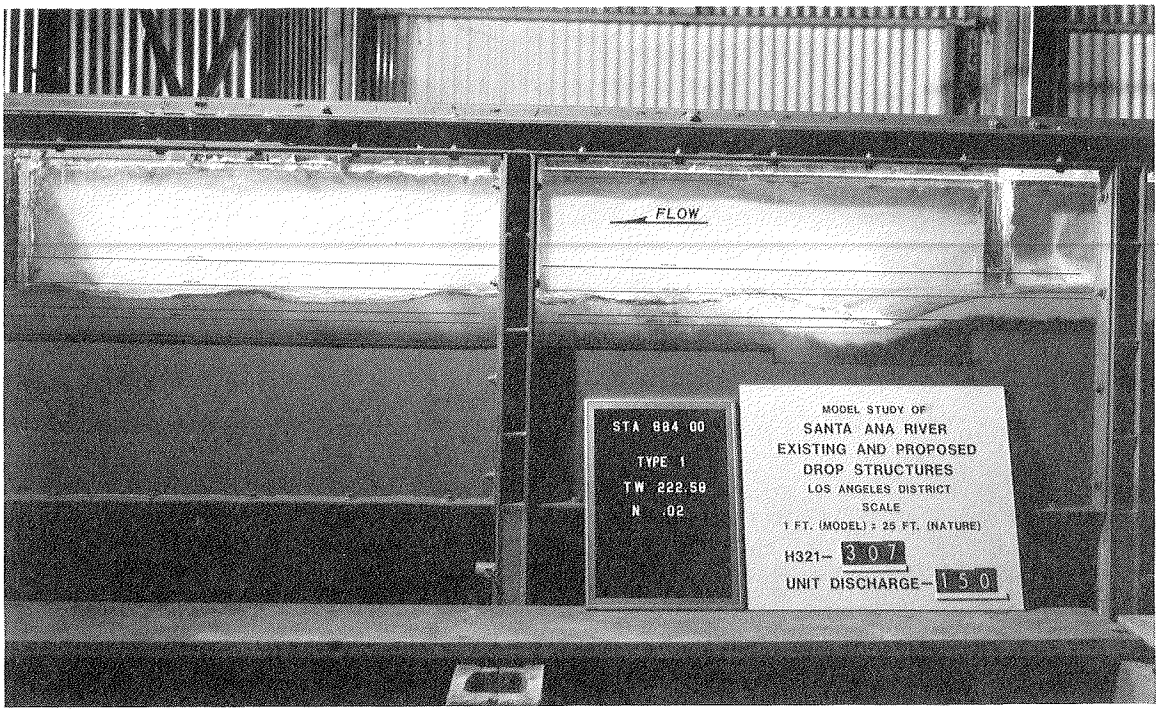


c. Unit discharge 100 cfs/ft, tailwater el 220.58

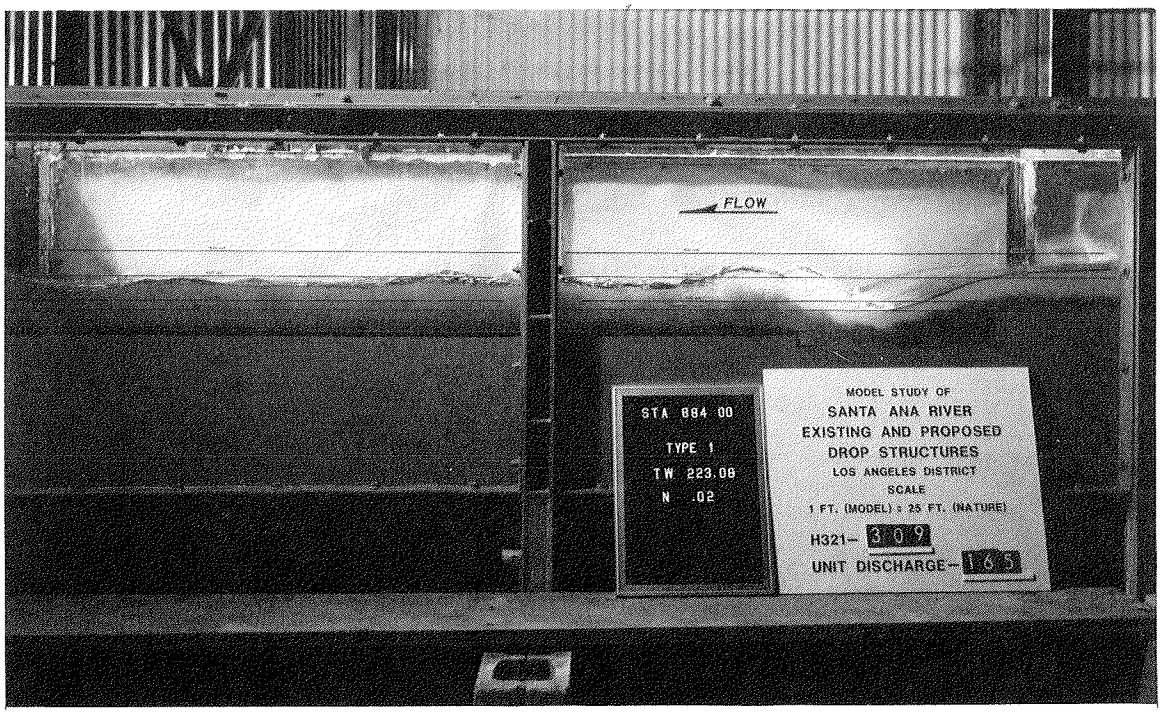


d. Unit discharge 125 cfs/ft, tailwater el 221.58

Photo 63. (Sheet 2 of 3)

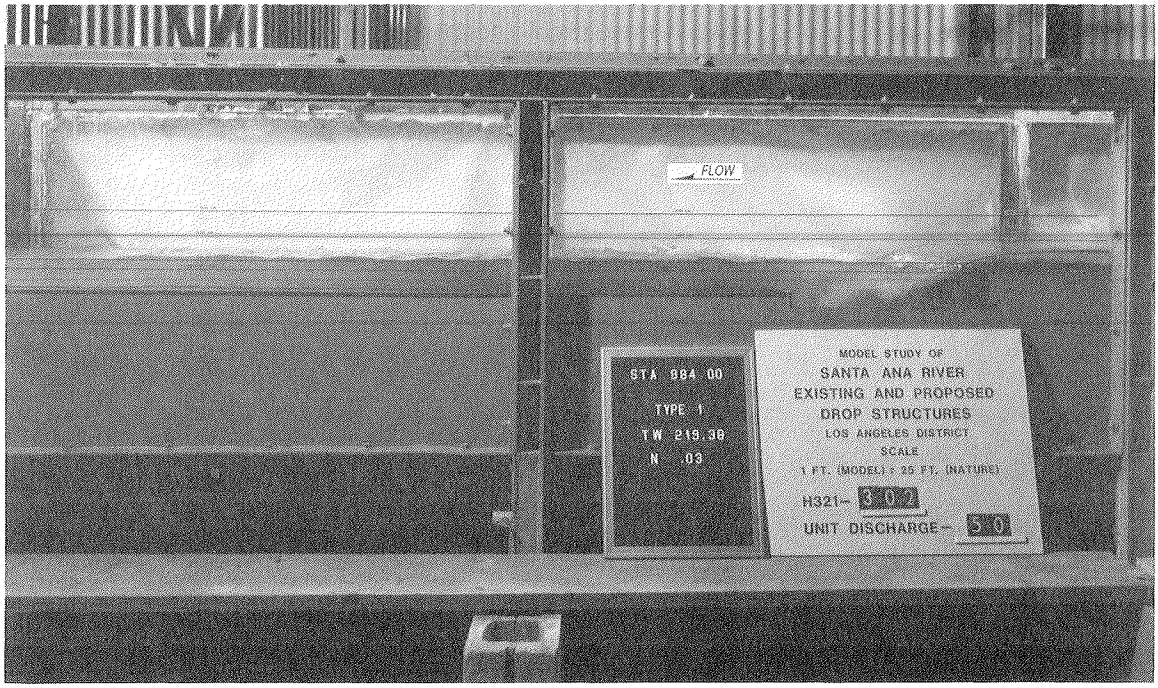


e. Unit discharge 150 cfs/ft, tailwater el 222.58



f. Unit discharge 165 cfs/ft, tailwater el 223.08

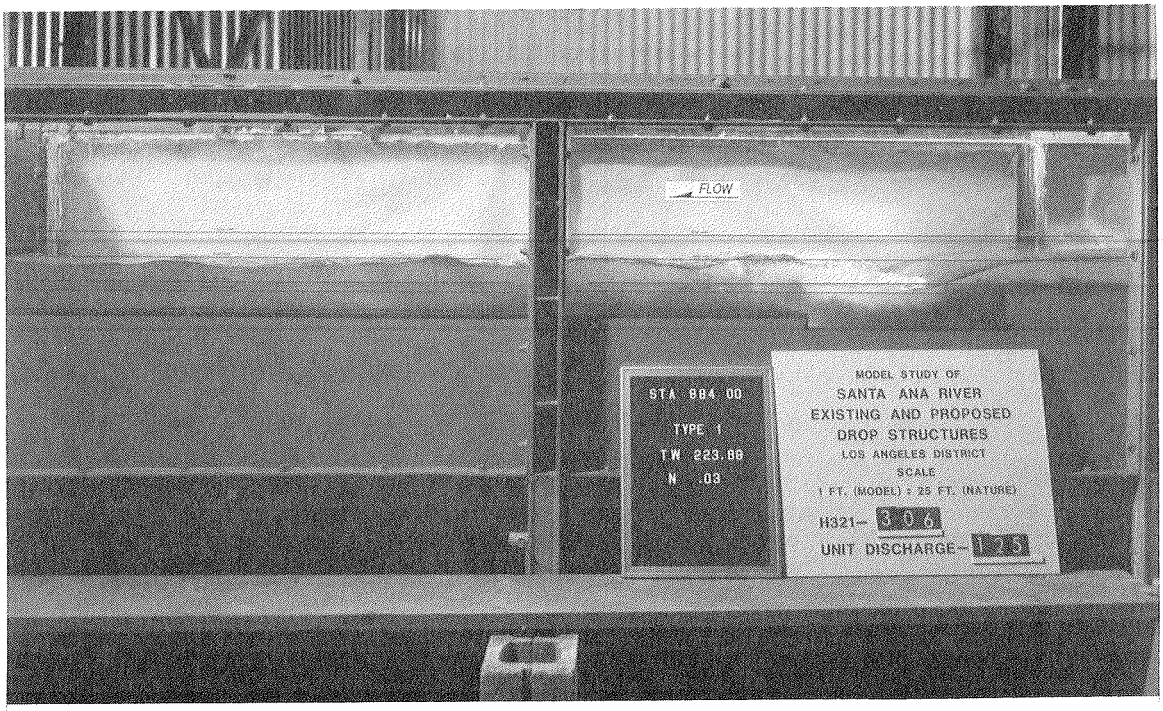
Photo 63. (Sheet 3 of 3)



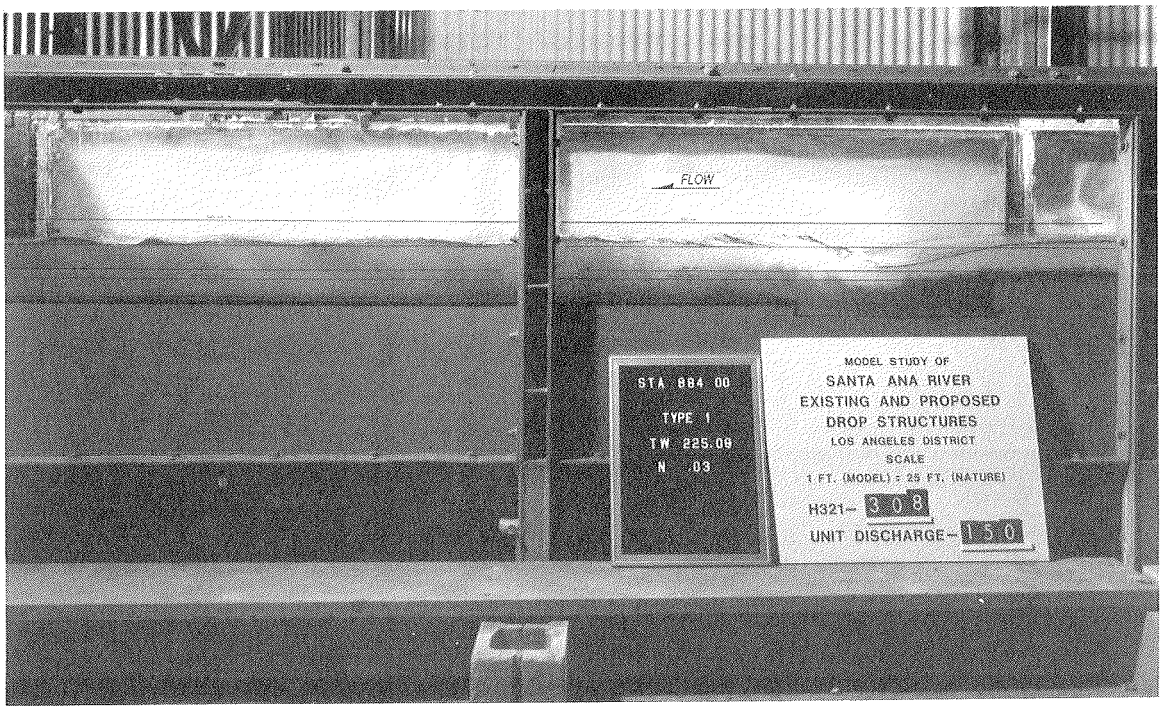
a. Unit discharge 50 cfs/ft, tailwater el 219.38

b. Unit discharge 100 cfs/ft, tailwater el 222.58

Photo 64. Flow conditions in the type 1 design drop structure, sta 884+00, n = 0.03 (Sheet 1 of 3)

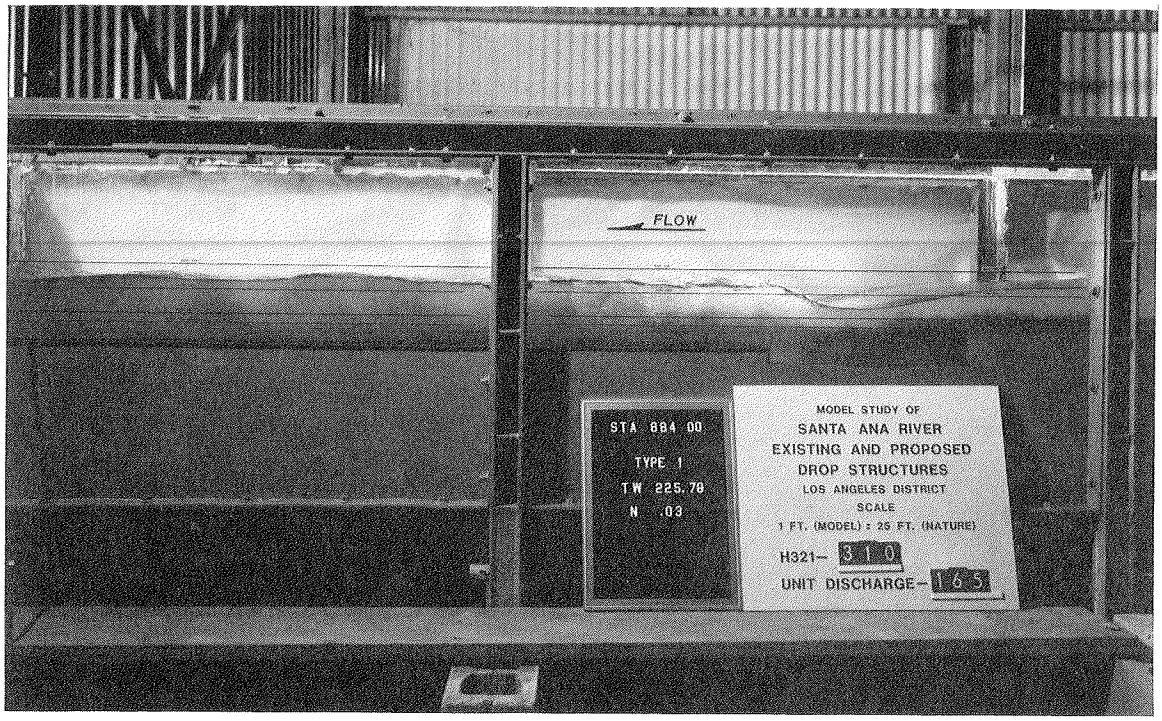


c. Unit discharge 125 cfs/ft, tailwater el 223.88



d. Unit discharge 150 cfs/ft, tailwater el 225.08

Photo 64. (Sheet 2 of 3)



e. Unit discharge 165 cfs/ft, tailwater el 225.78

Photo 64. (Sheet 3 of 3)

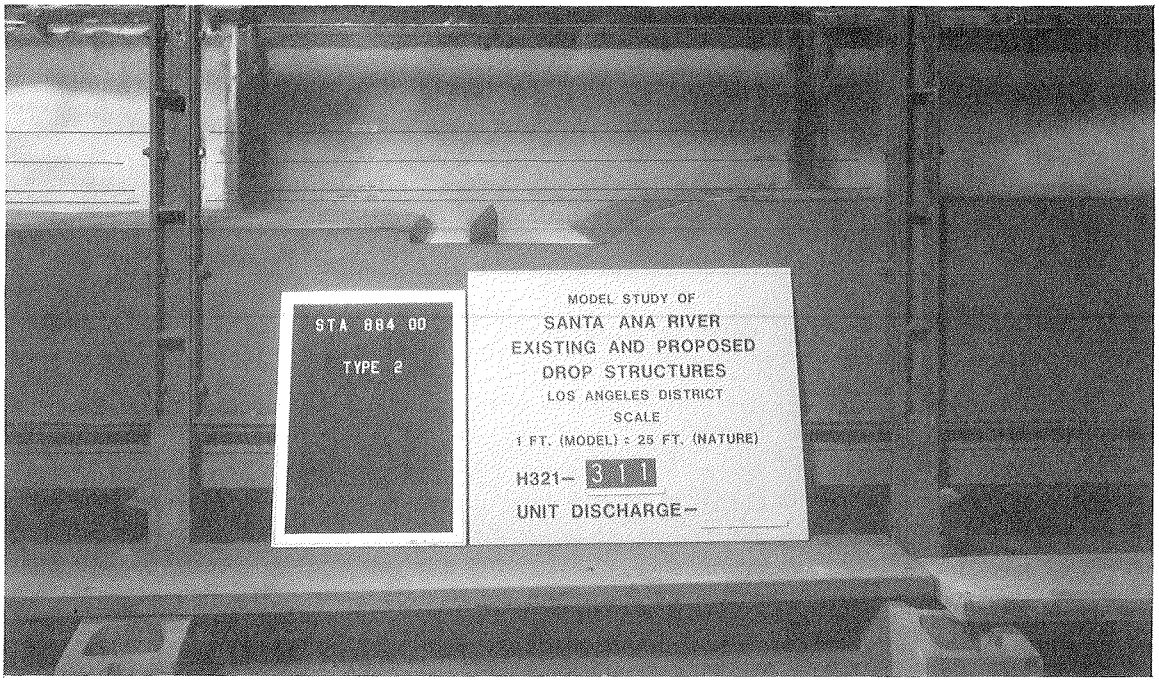


Photo 65. Type 2 design drop structure, sta 884+00

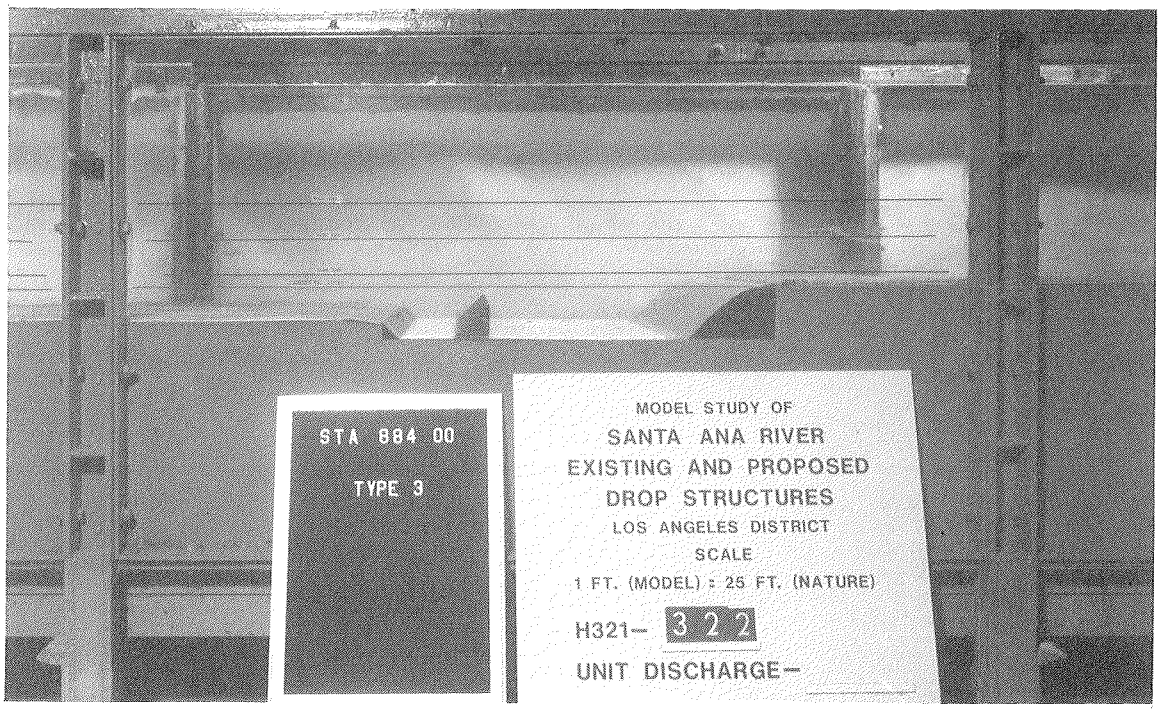


Photo 66. Type 3 design drop structure, sta 884+00

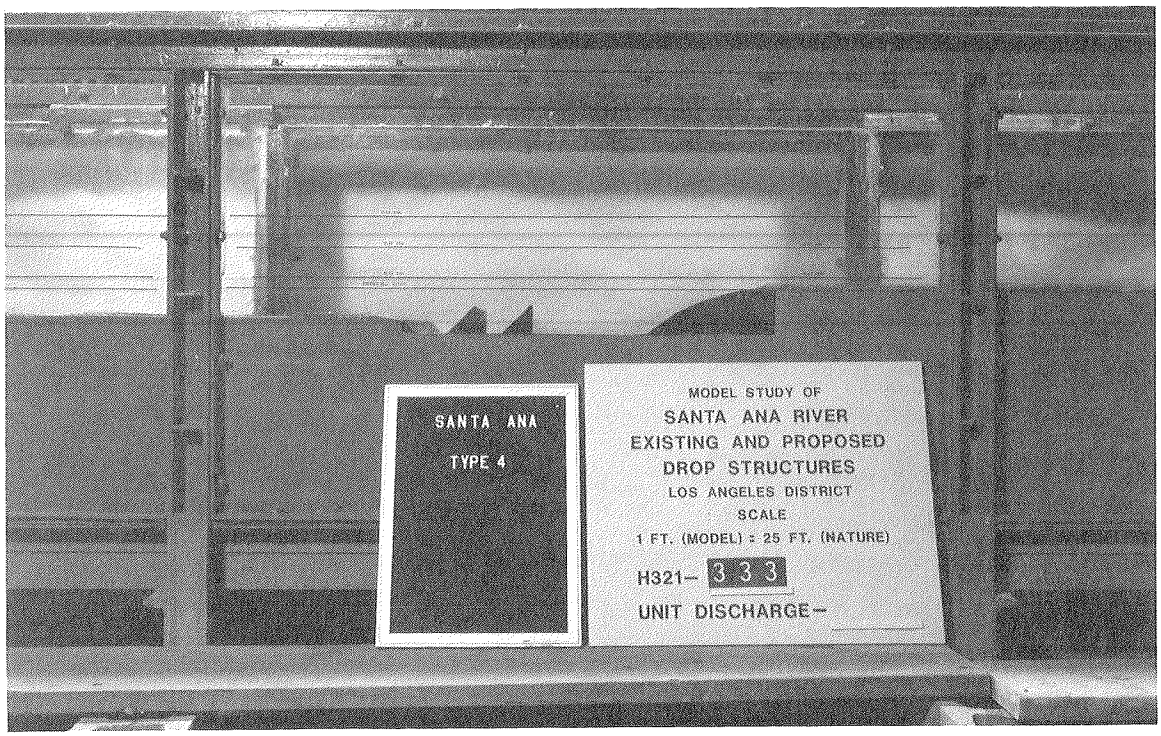
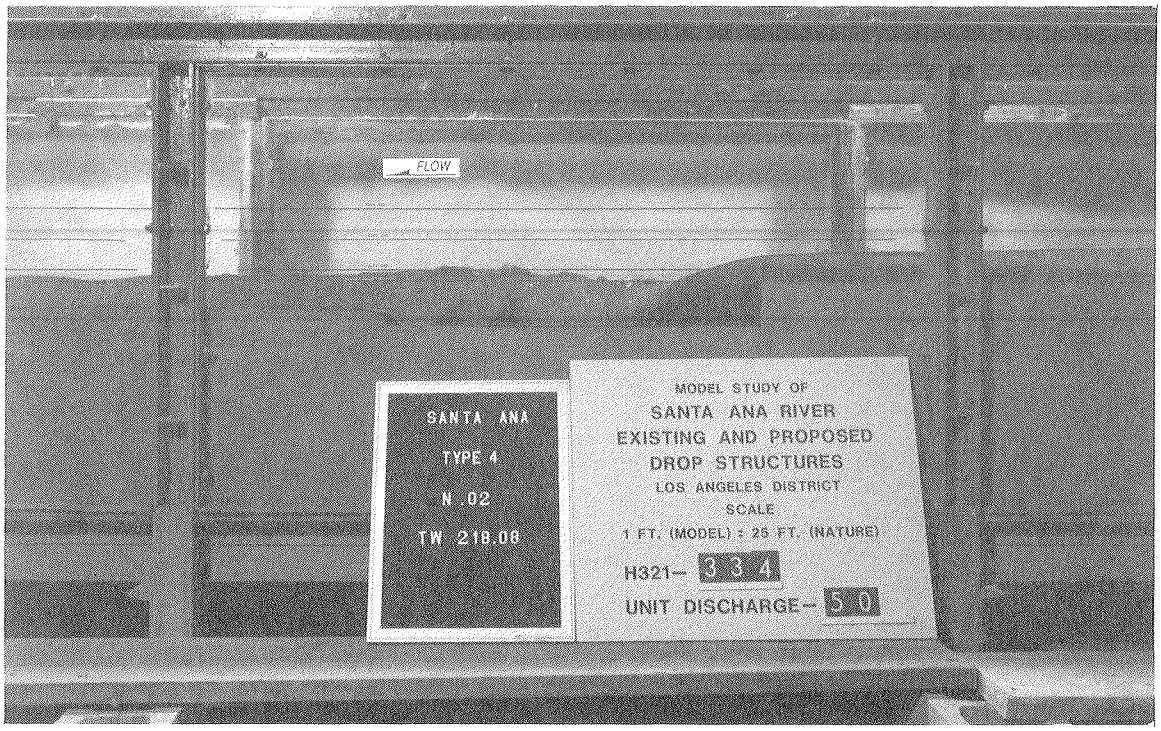
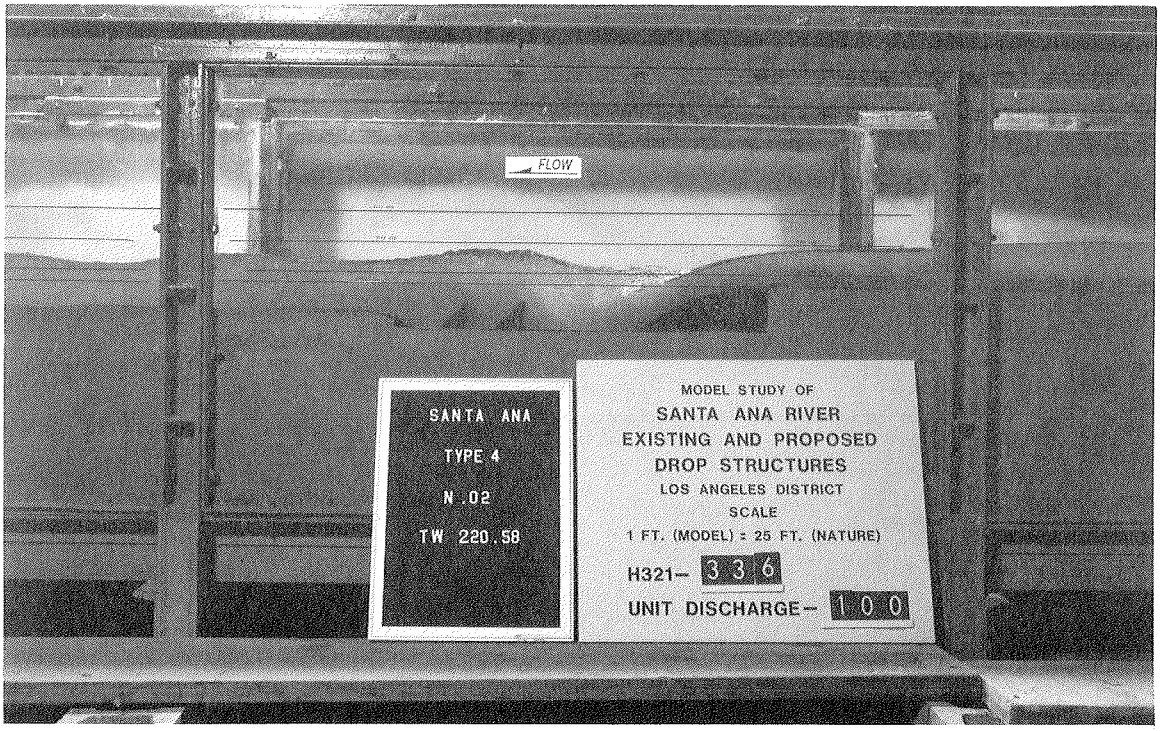


Photo 67. Type 4 design drop structure, sta 884+00

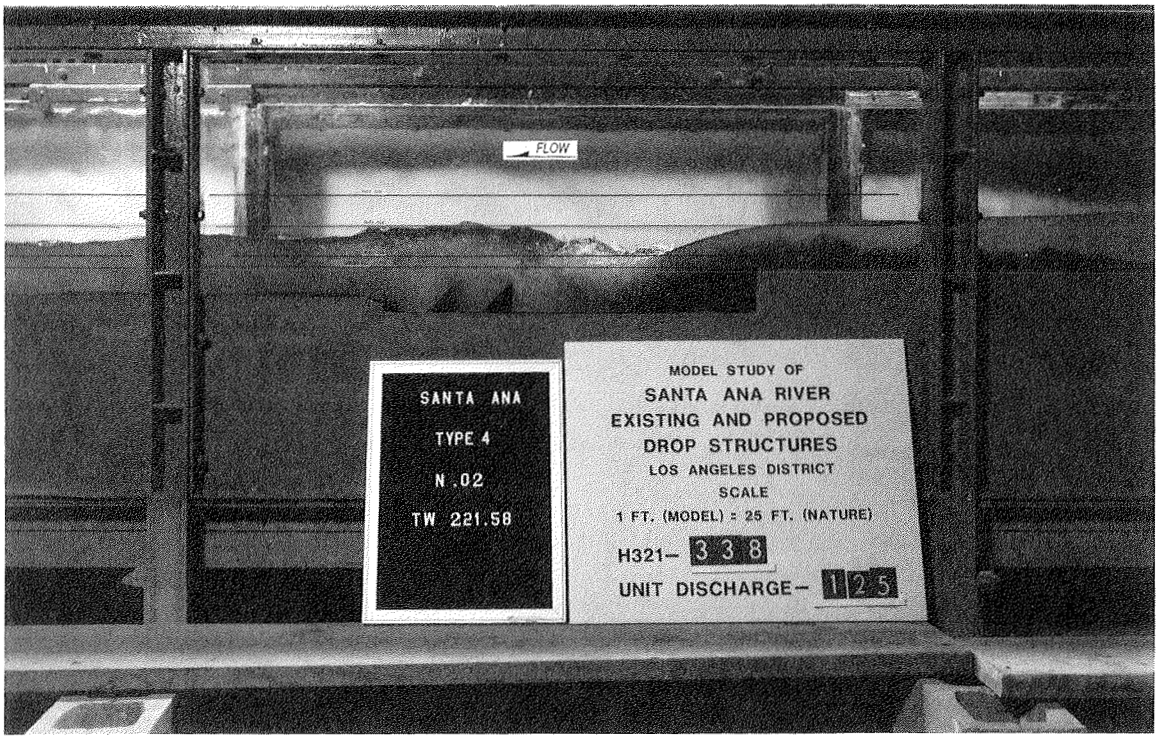


a. Unit discharge 50 cfs/ft, tailwater el 218.08

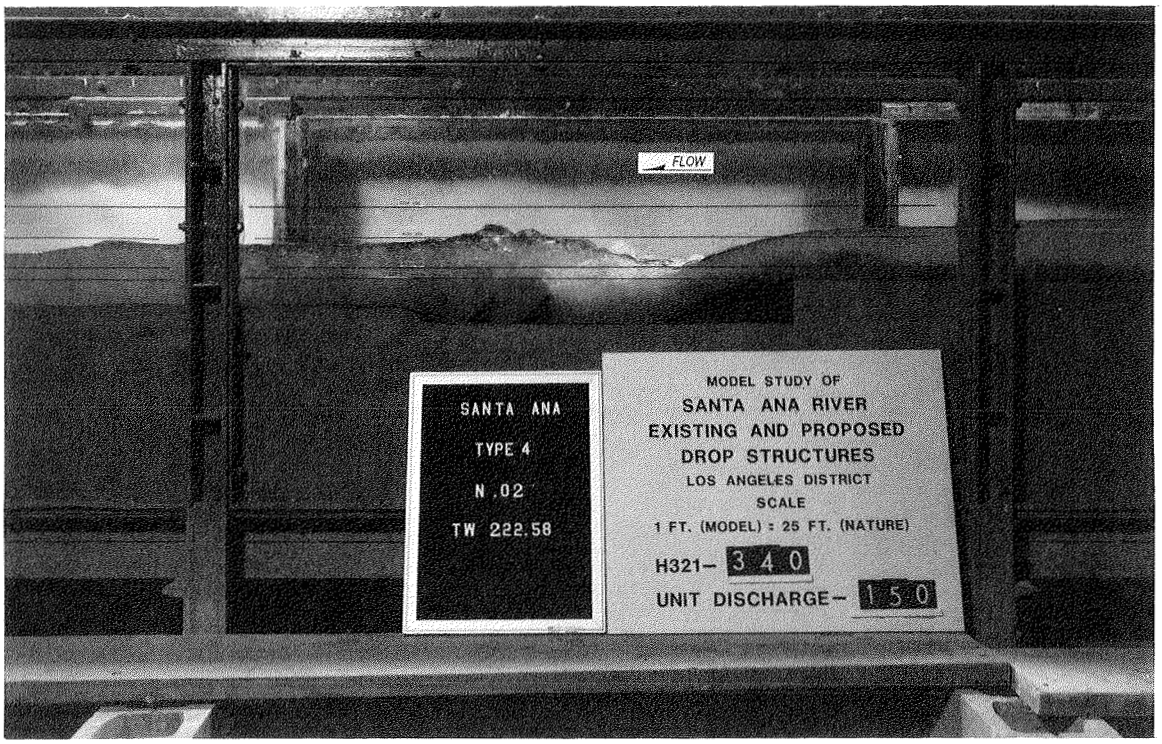


b. Unit discharge 100 cfs/ft, tailwater el 220.58

Photo 68. Flow conditions in the type 4 design drop structure, sta 884+00, n = 0.02 (Sheet 1 of 3)

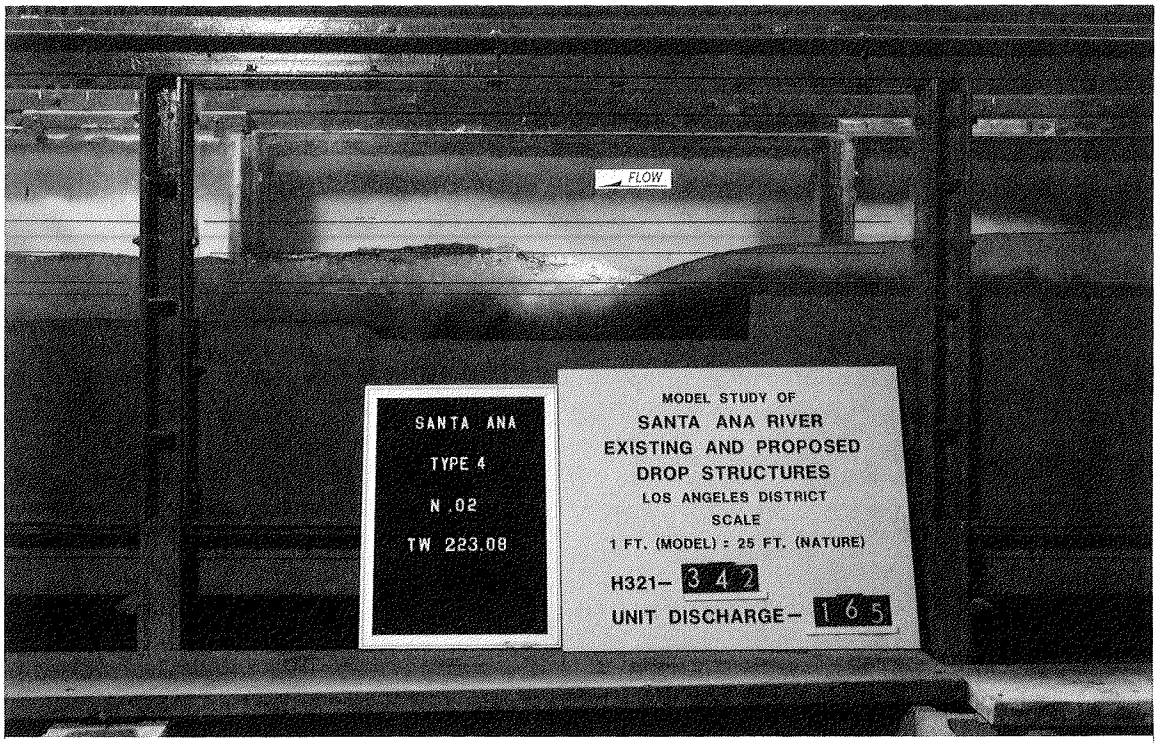


c. Unit discharge 125 cfs/ft, tailwater el 221.58



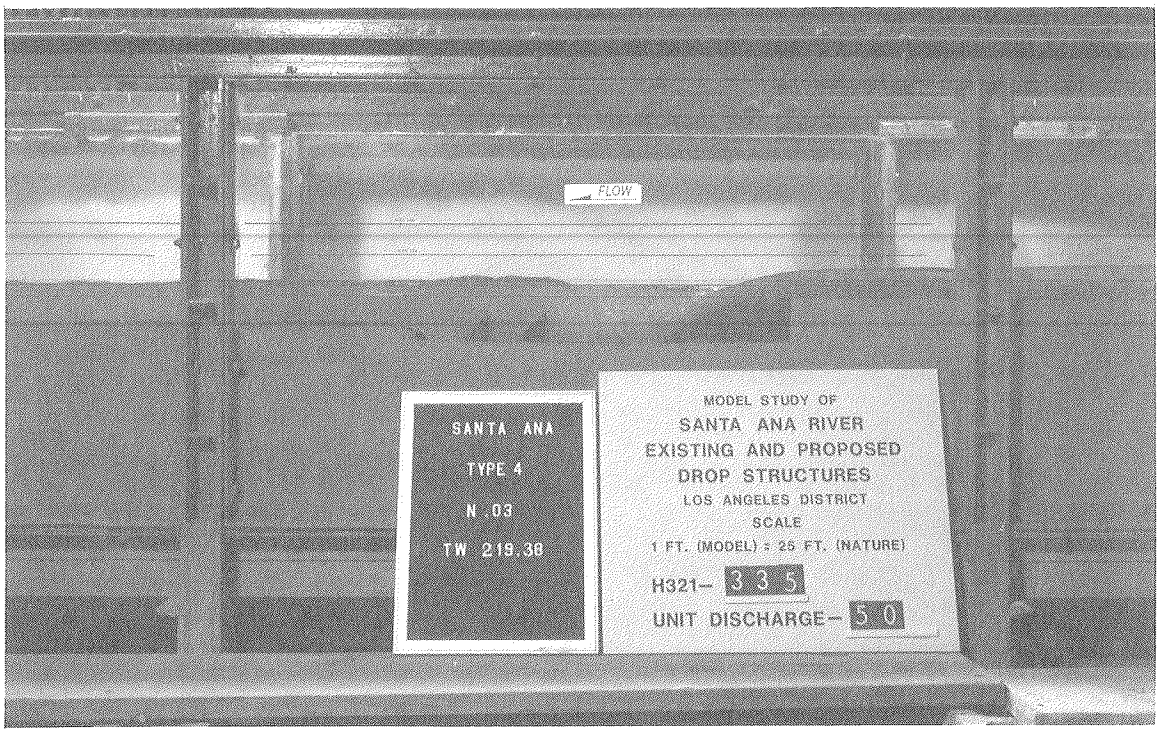
d. Unit discharge 150 cfs/ft, tailwater el 222.58

Photo 68. (Sheet 2 of 3)

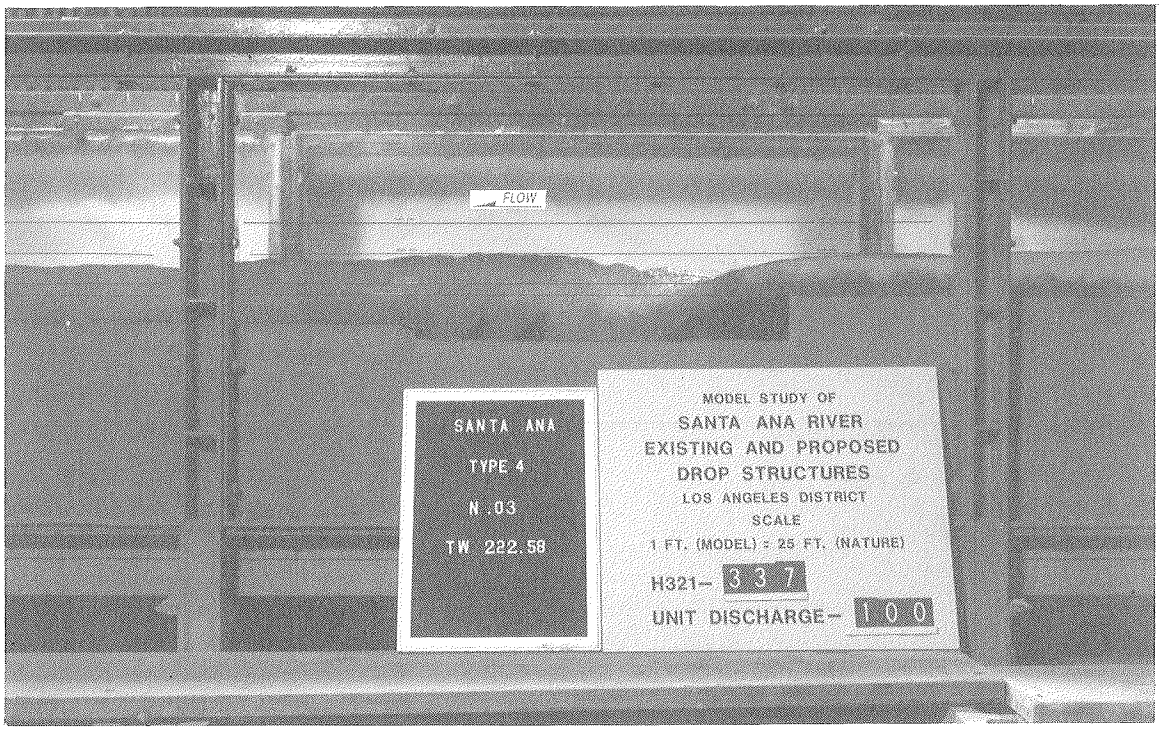


e. Unit discharge 165 cfs/ft, tailwater el 223.08

Photo 68. (Sheet 3 of 3)

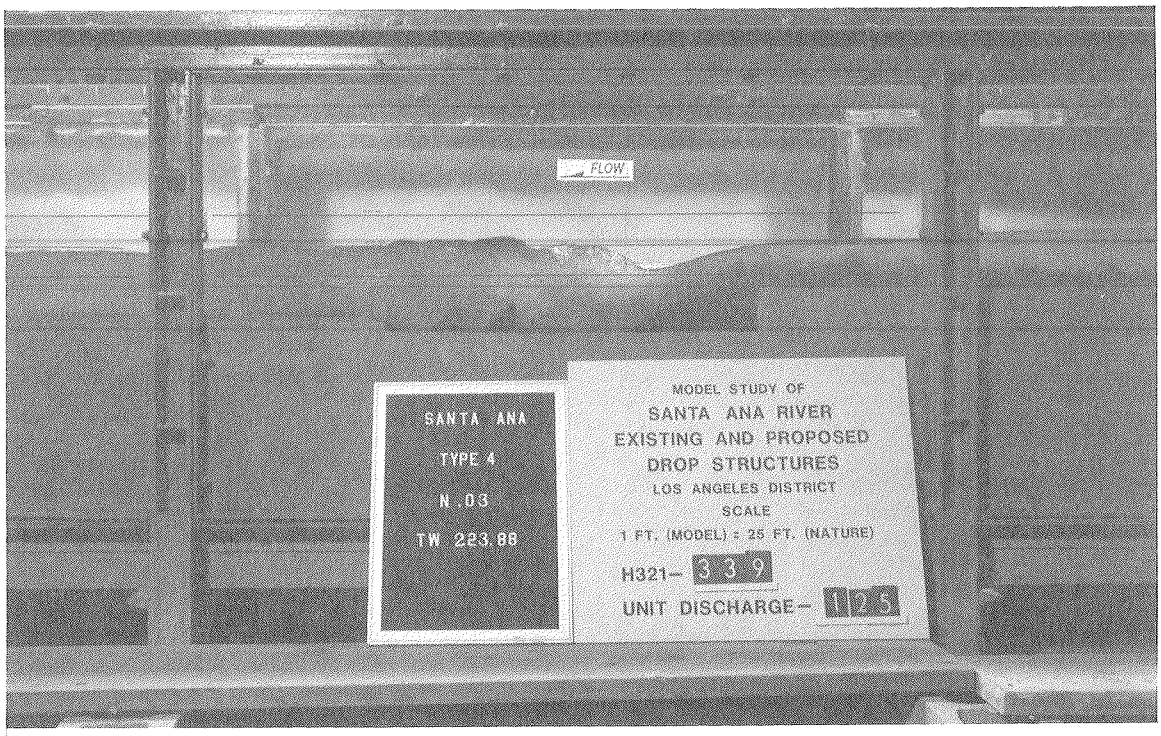


a. Unit discharge 50 cfs/ft, tailwater el 219.38

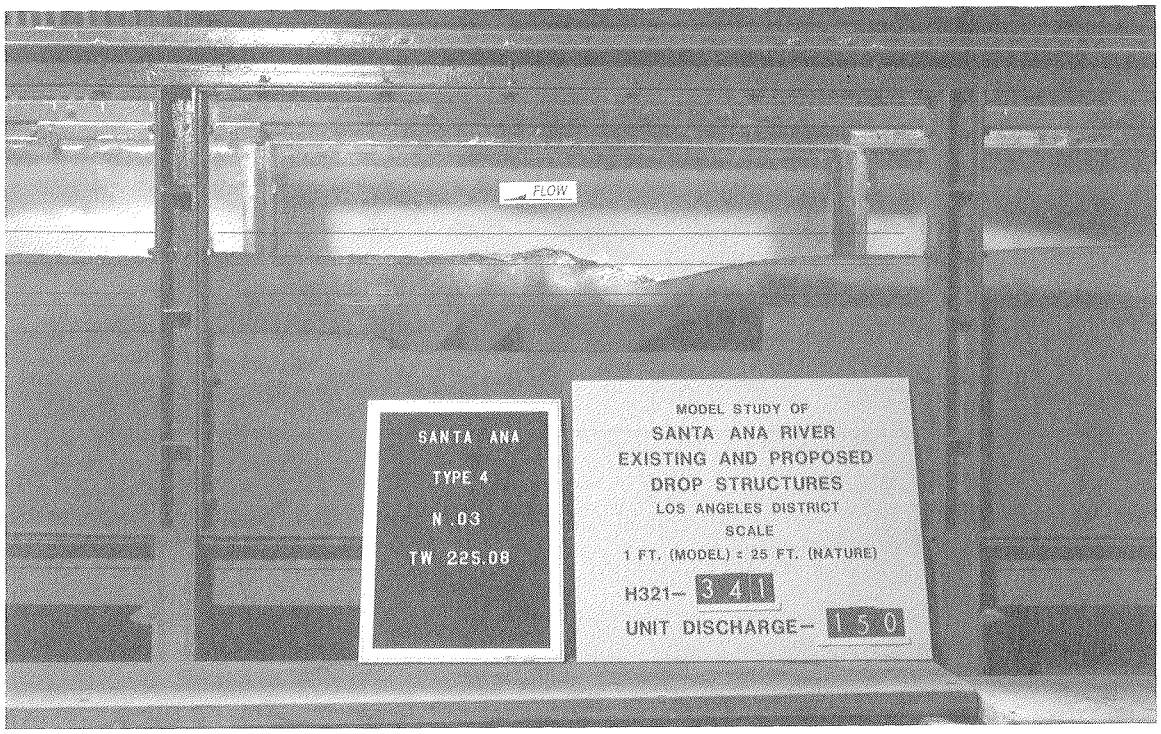


b. Unit discharge 100 cfs/ft, tailwater el 222.58

Photo 69. Flow conditions in the type 4 design drop structure, sta 884+00, n = 0.03 (Sheet 1 of 3)

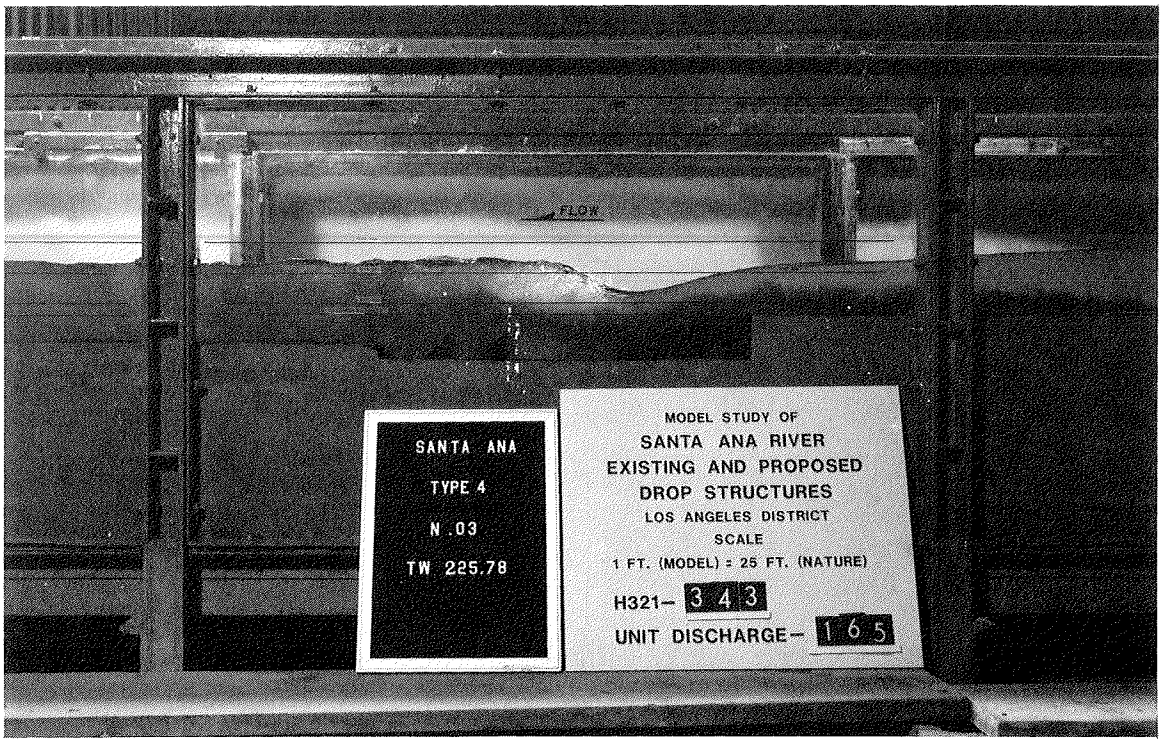


c. Unit discharge 125 cfs/ft, tailwater el 223.88



d. Unit discharge 150 cfs/ft, tailwater el 225.08

Photo 69. (Sheet 2 of 3)



e. Unit discharge 165 cfs/ft, tailwater el 225.78

Photo 69. (Sheet 3 of 3)

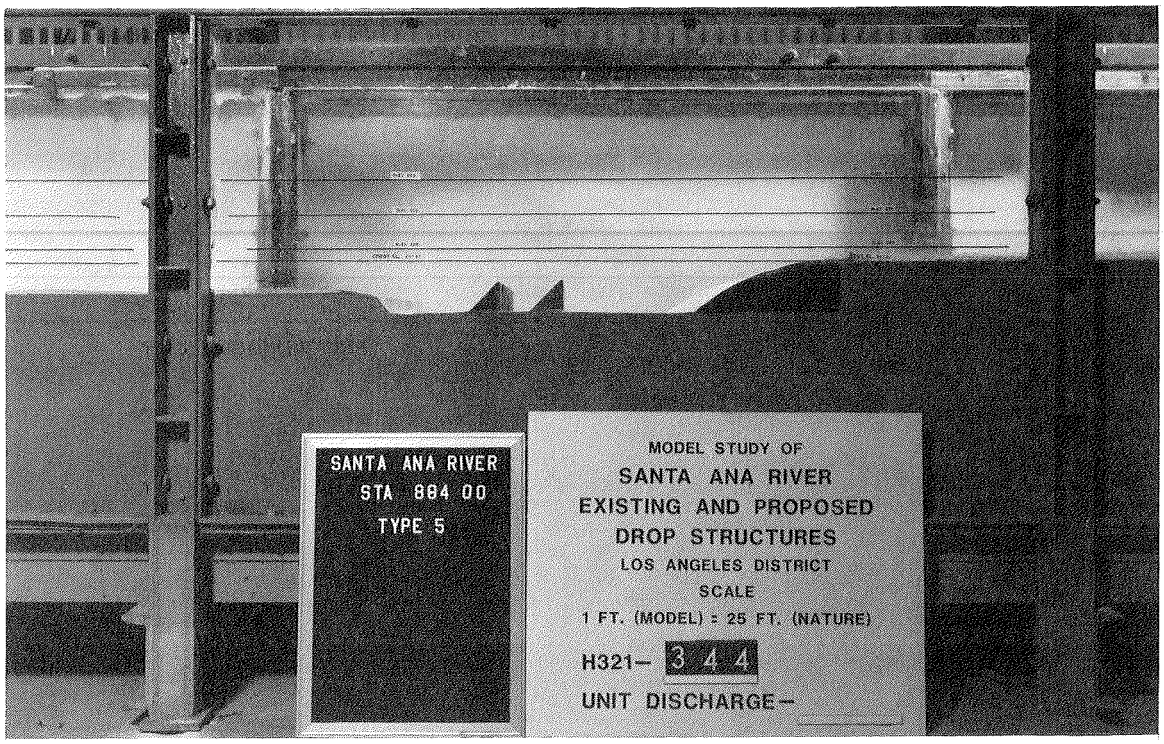
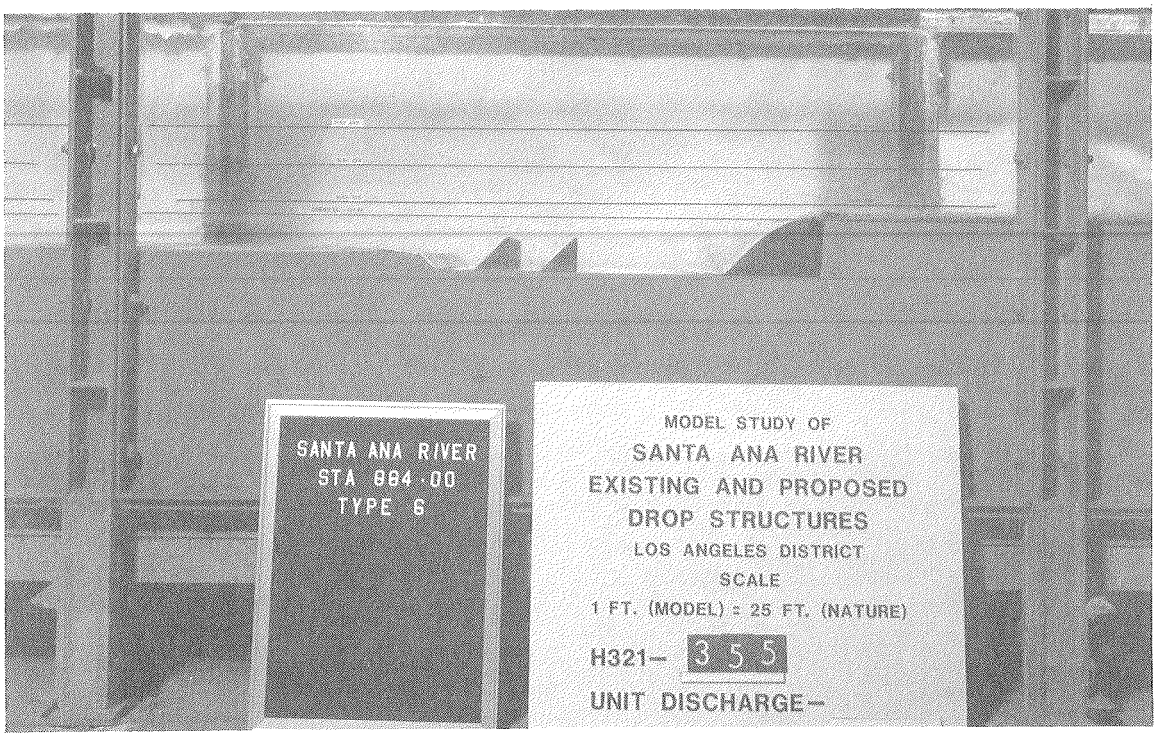


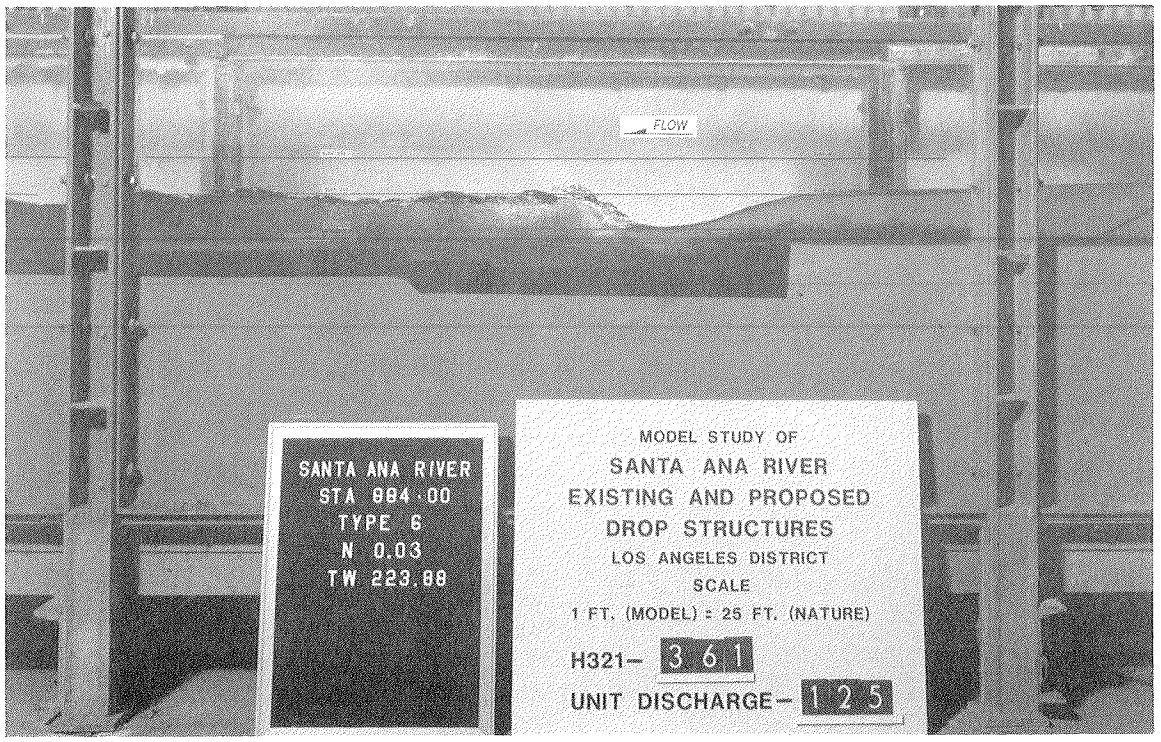
Photo 70. Type 5 design drop structure, sta 884+00



a. Dry bed

b. Tailwater el 221.58, n = 0.02

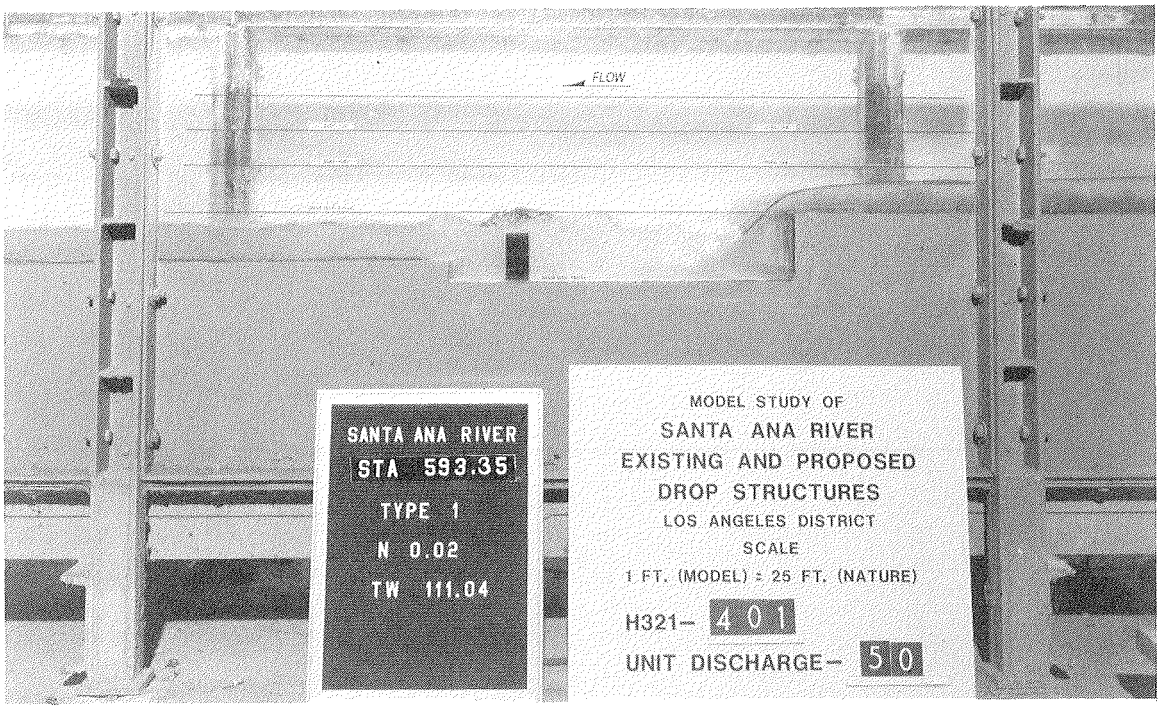
Photo 71. Flow conditions in the type 6 design drop structure (sta 884+00), unit discharge 125 cfs/ft (Continued)



c. Tailwater el 223.88, n = 0.03

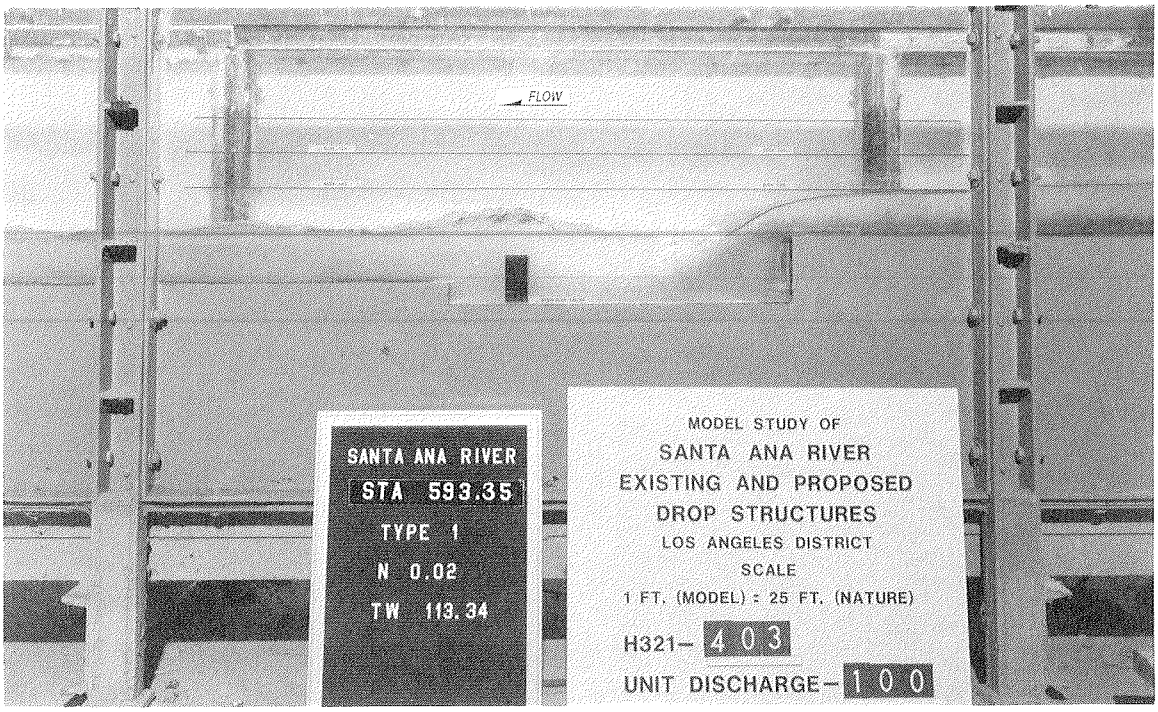
Photo 71. (Concluded)

a. Dry bed

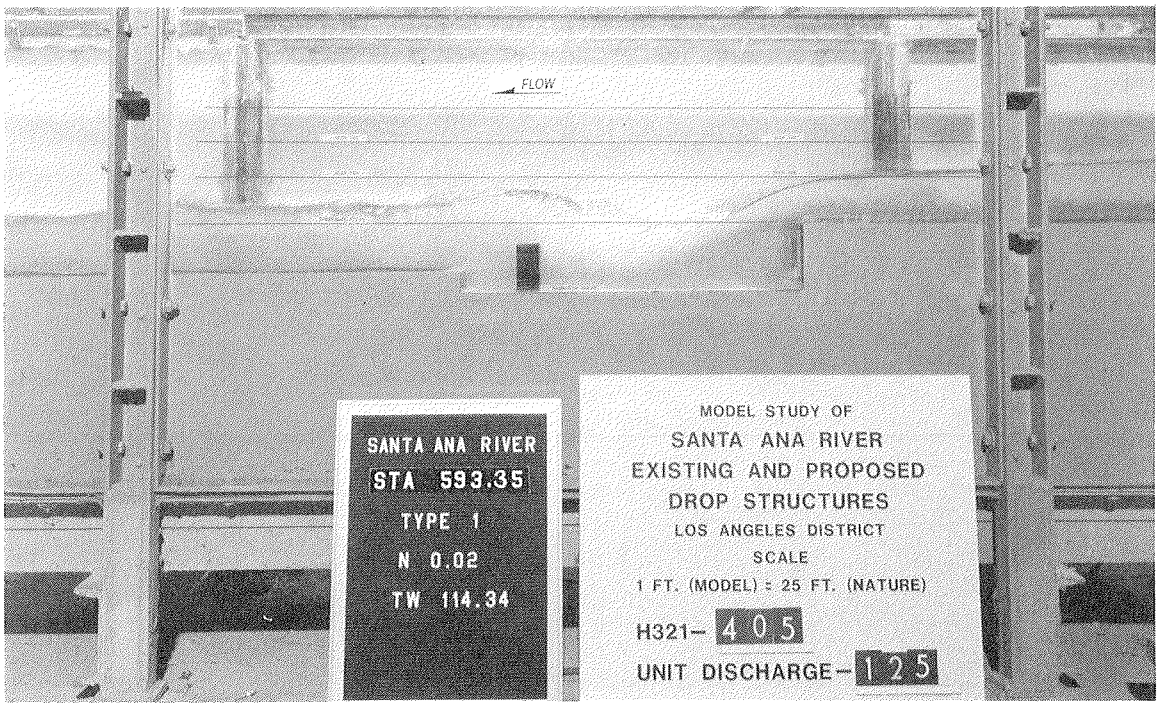


b. Unit discharge 50 cfs/ft, tailwater el 111.04

Photo 72. Flow conditions in the type 1 design drop structure, sta 593+35, n = 0.02 (Sheet 1 of 3)

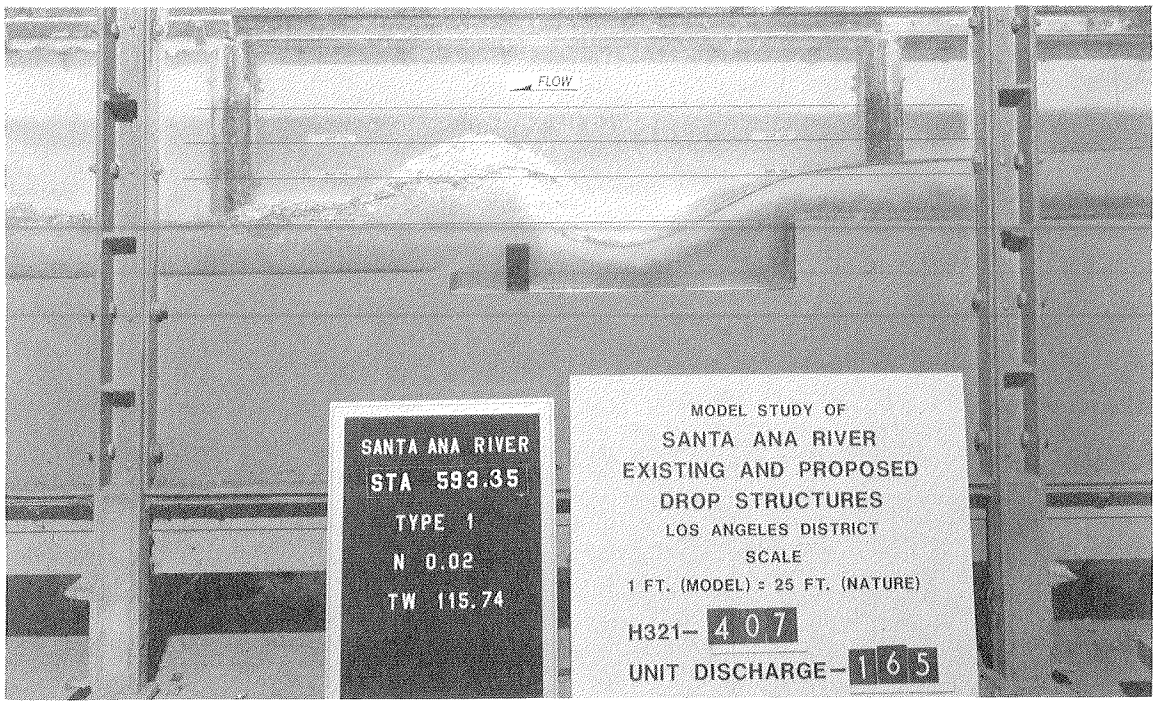


c. Unit discharge 100 cfs/ft, tailwater el 113.34

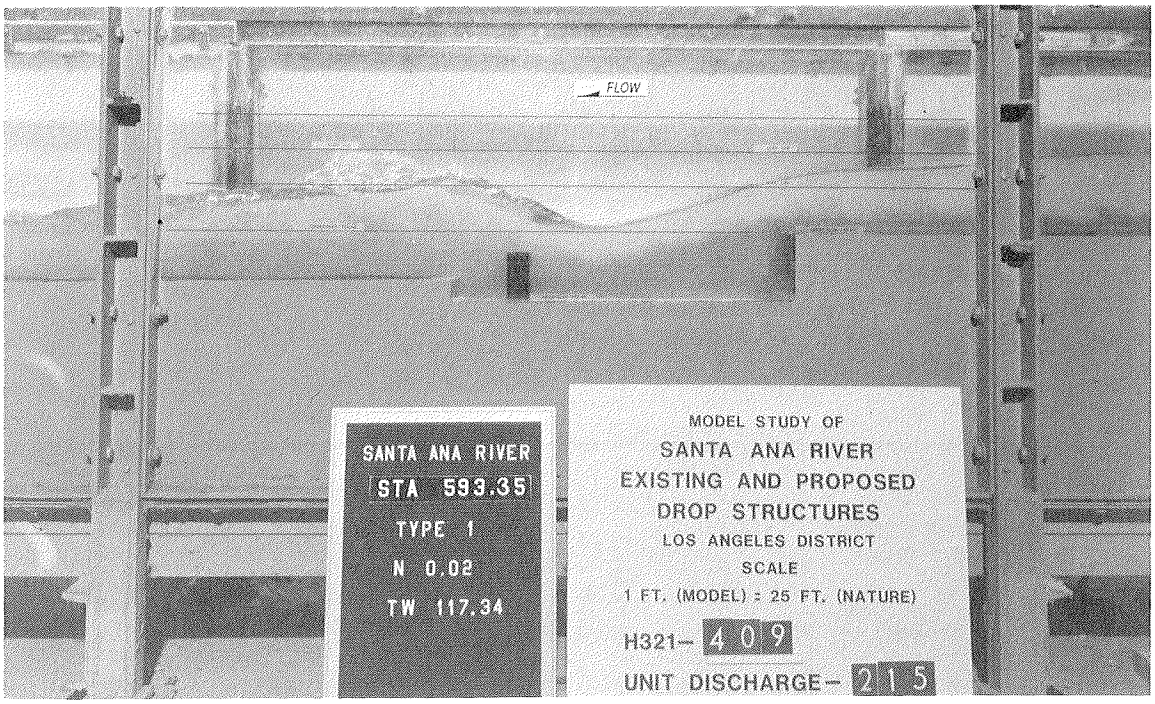


d. Unit discharge 125 cfs/ft, tailwater el 114.34

Photo 72. (Sheet 2 of 3)

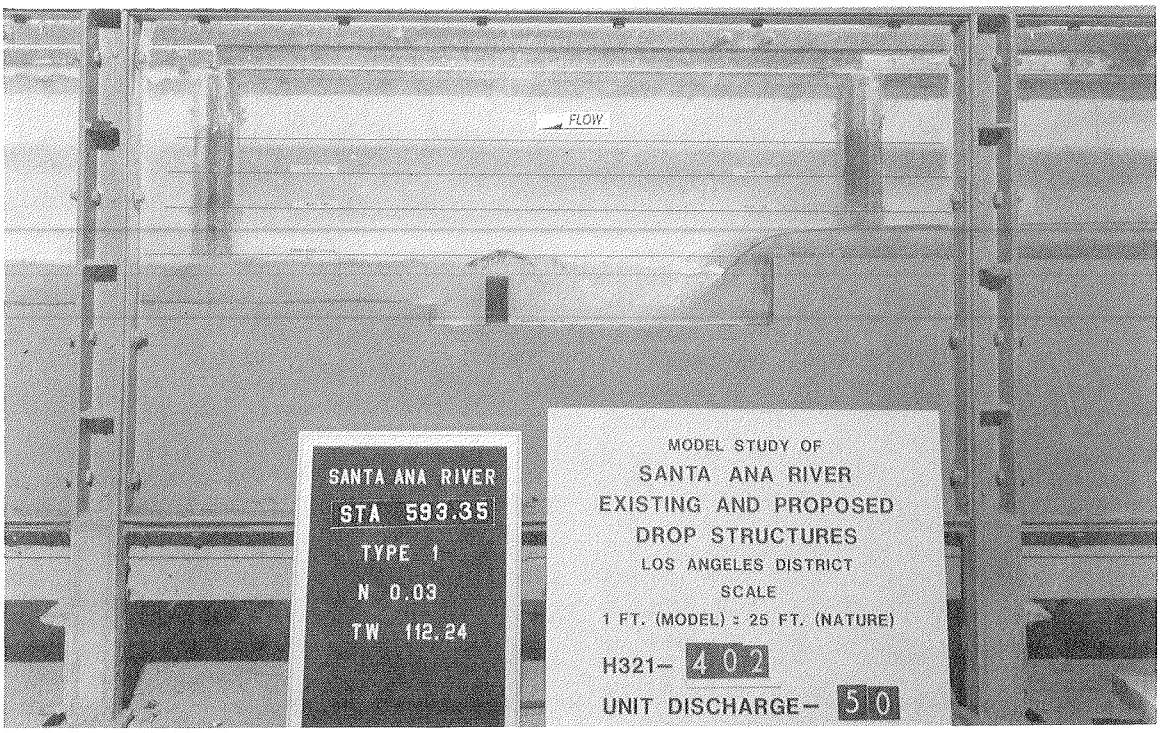


e. Unit discharge 165 cfs/ft, tailwater el 115.74

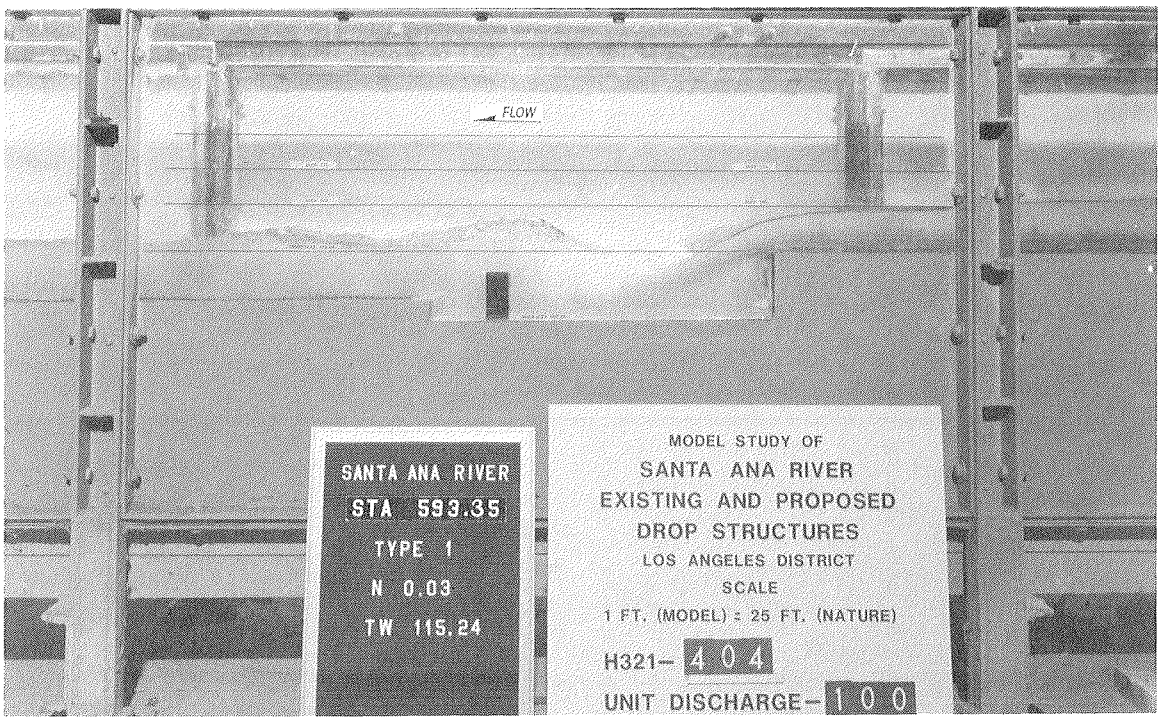


f. Unit discharge 215 cfs/ft, tailwater el 117.34

Photo 72. (Sheet 3 of 3)

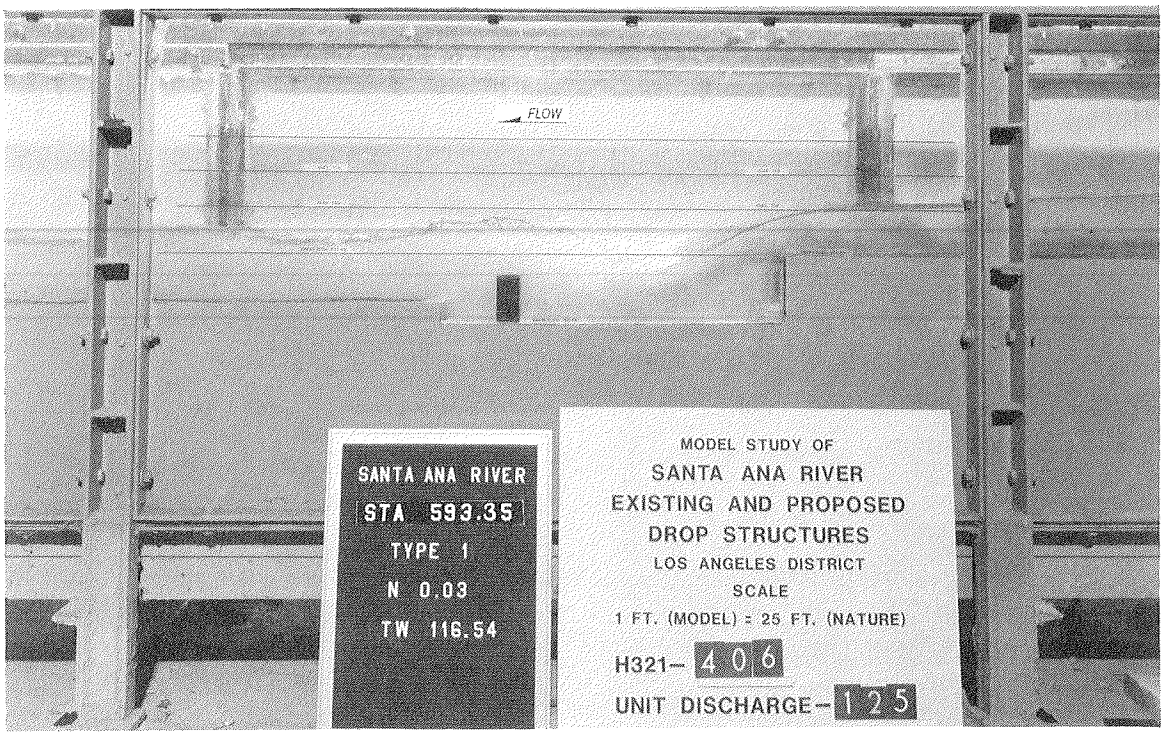


a. Unit discharge 50 cfs/ft, tailwater el 112.24

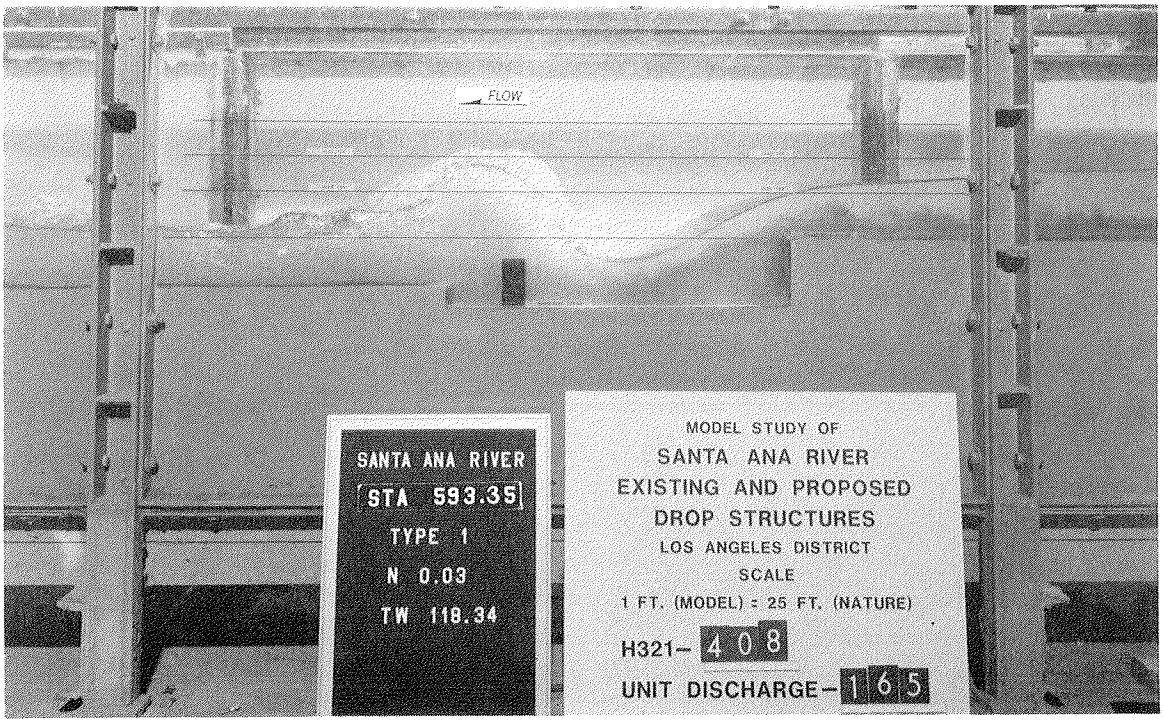


b. Unit discharge 100 cfs/ft, tailwater el 115.24

Photo 73. Flow conditions in the type 1 design drop structure, sta 593+95, n = 0.03 (Sheet 1 of 3)



c. Unit discharge 125 cfs/ft, tailwater el 116.54



d. Unit discharge 165 cfs/ft, tailwater el 118.34

Photo 73. (Sheet 2 of 3)

e. Unit discharge 215 cfs/ft, tailwater el 120.34

Photo 73. (Sheet 3 of 3)

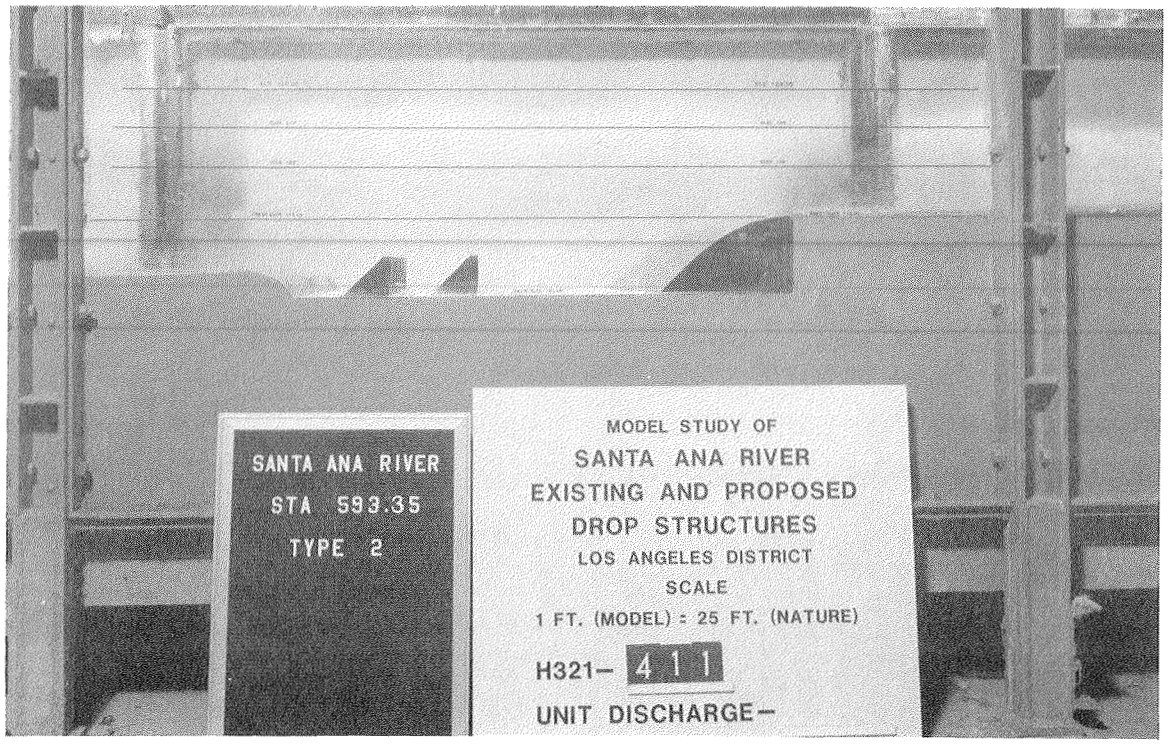
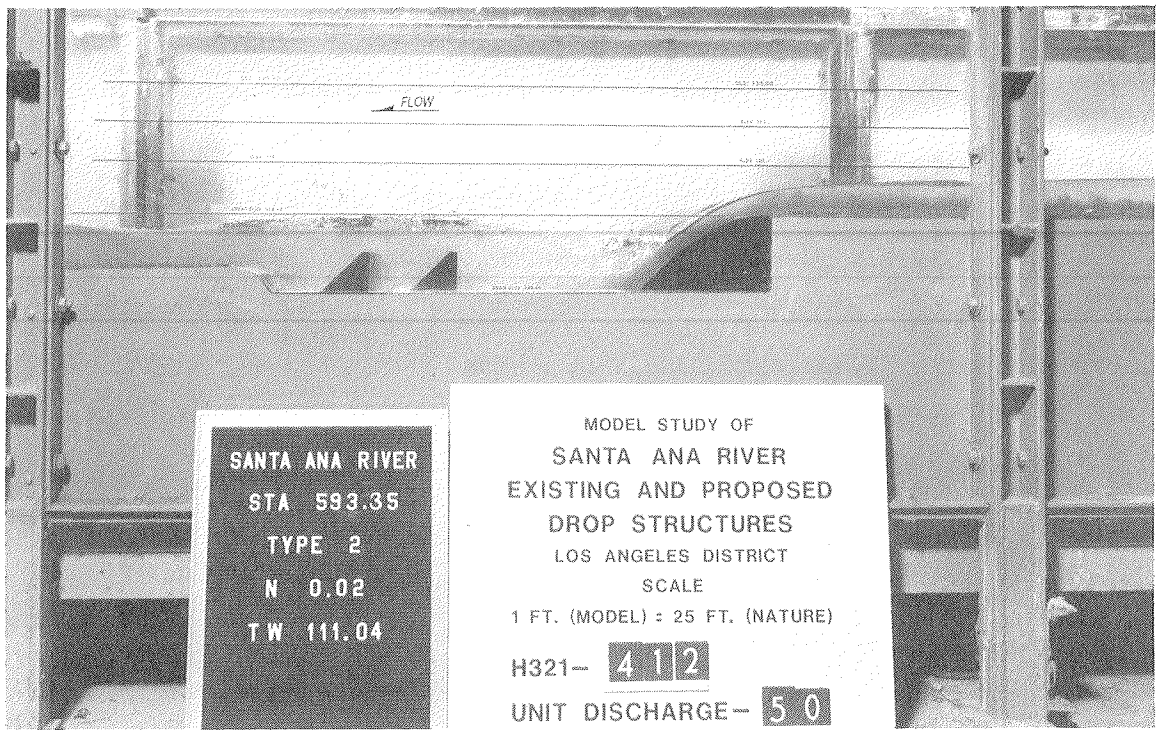
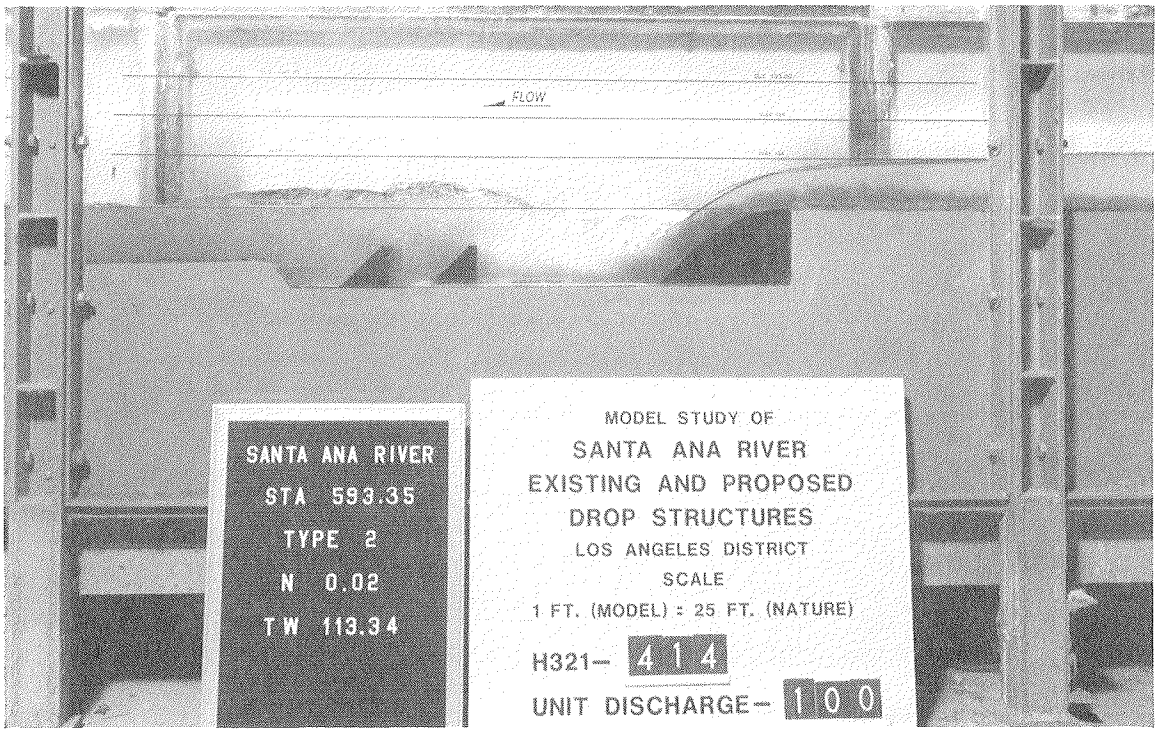


Photo 74. Type 2 design drop structure, sta 593+35

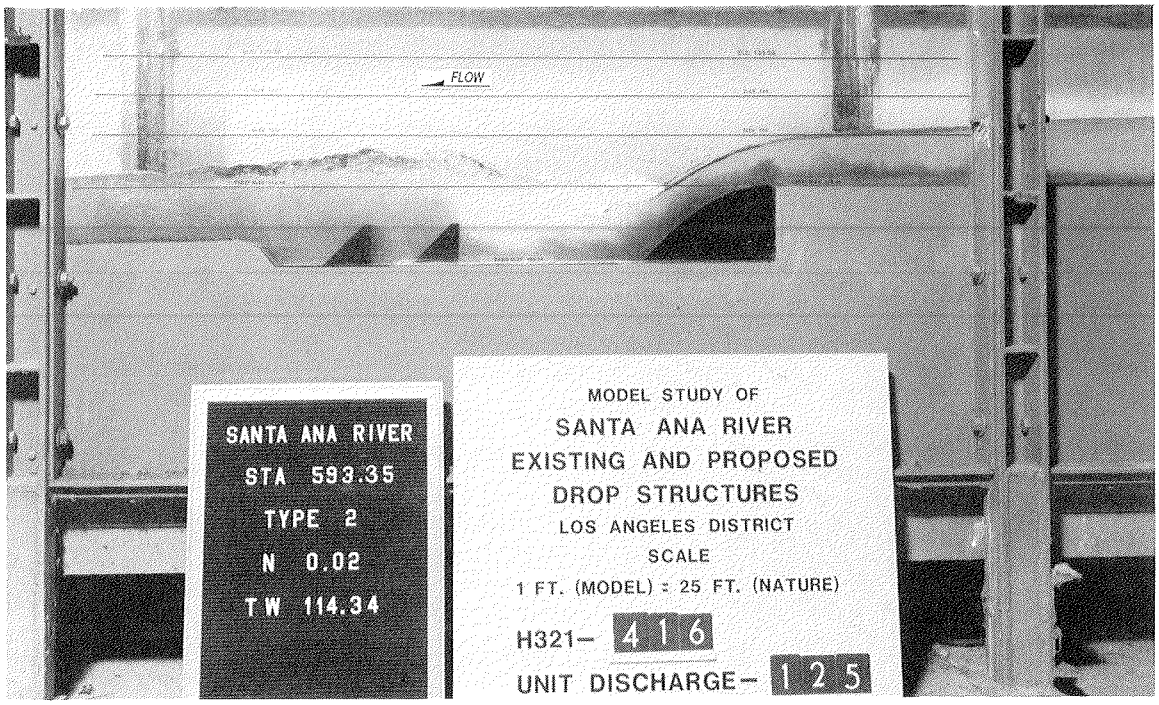


a. Unit discharge 50 cfs/ft, tailwater el 111.04

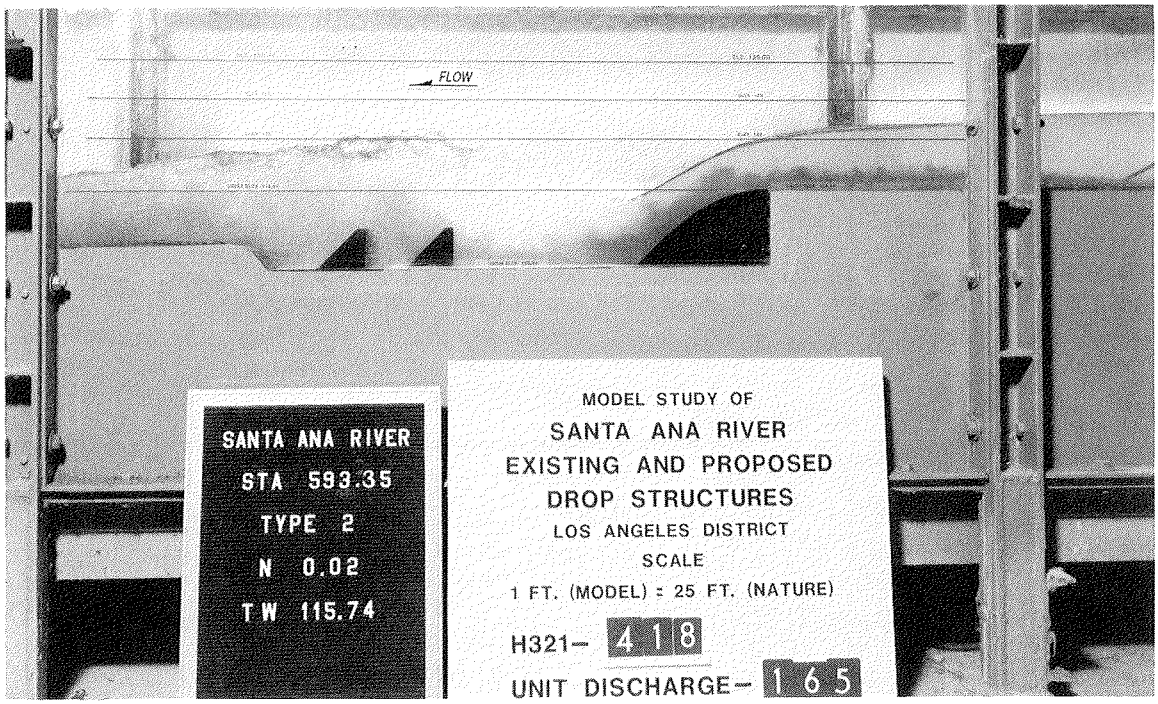


b. Unit discharge 100 cfs/ft, tailwater el 113.34

Photo 75. Flow conditions in the type 2 design drop structure, sta 593+35, n = 0.02 (Sheet 1 of 3)

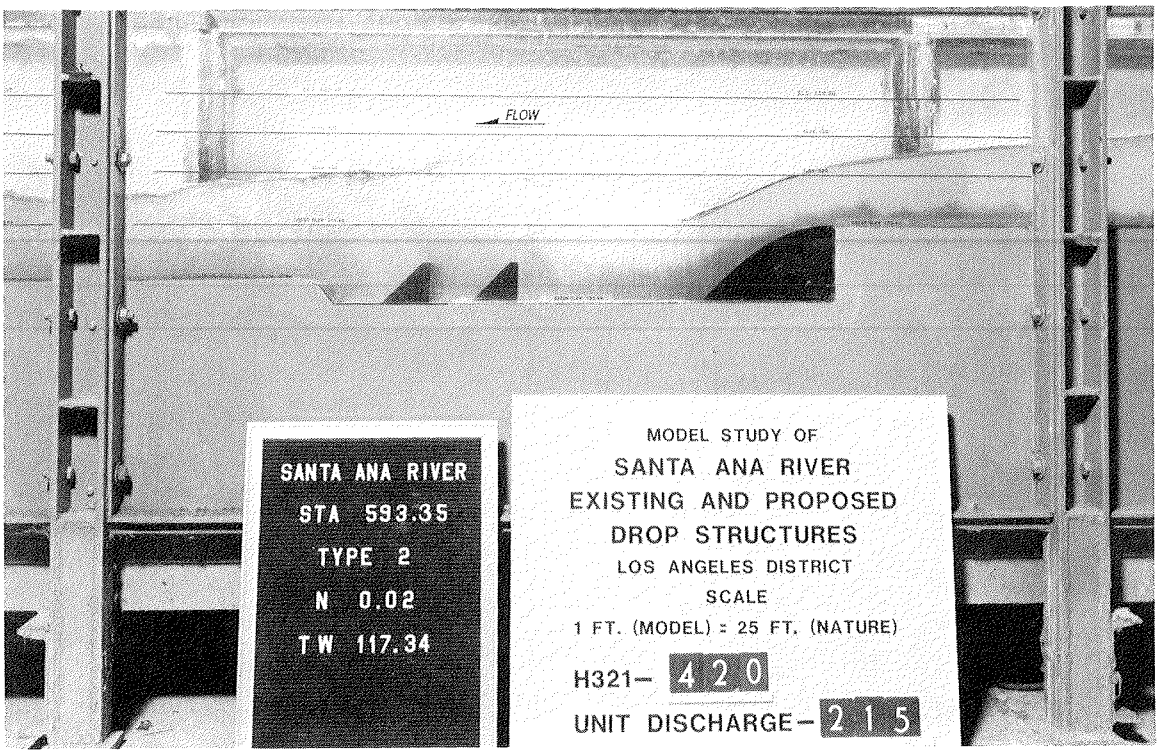


c. Unit discharge 125 cfs/ft, tailwater el 114.34



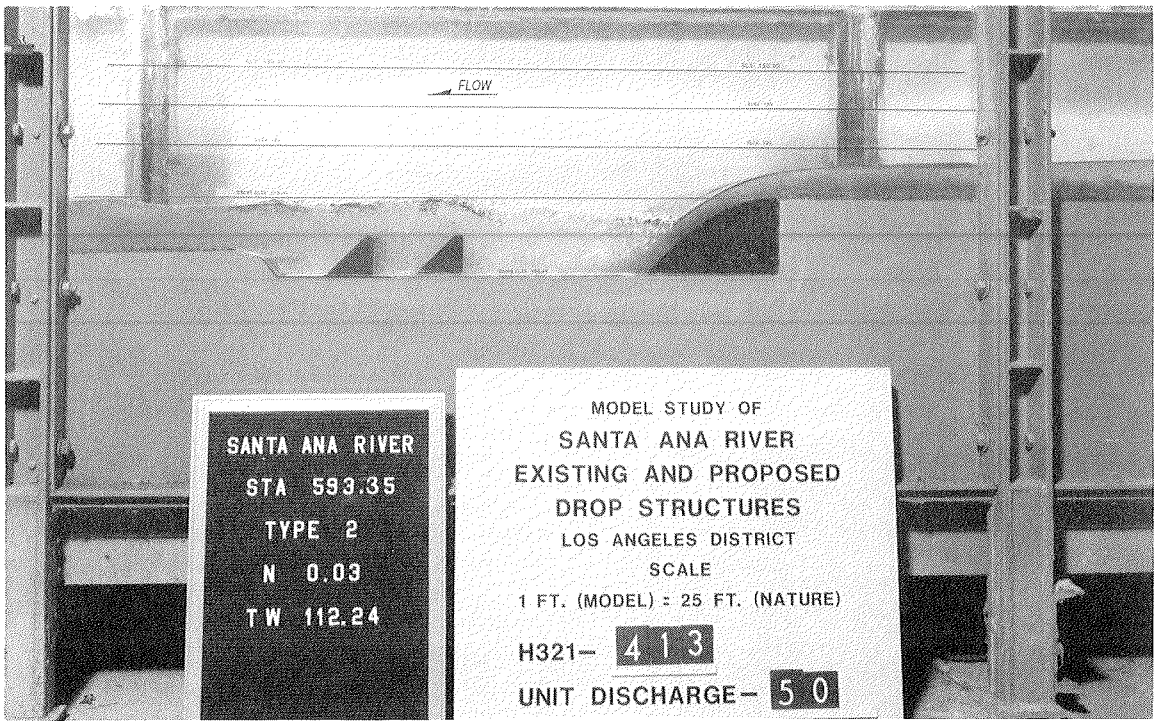
d. Unit discharge 165 cfs/ft, tailwater el 115.74

Photo 75. (Sheet 2 of 3)

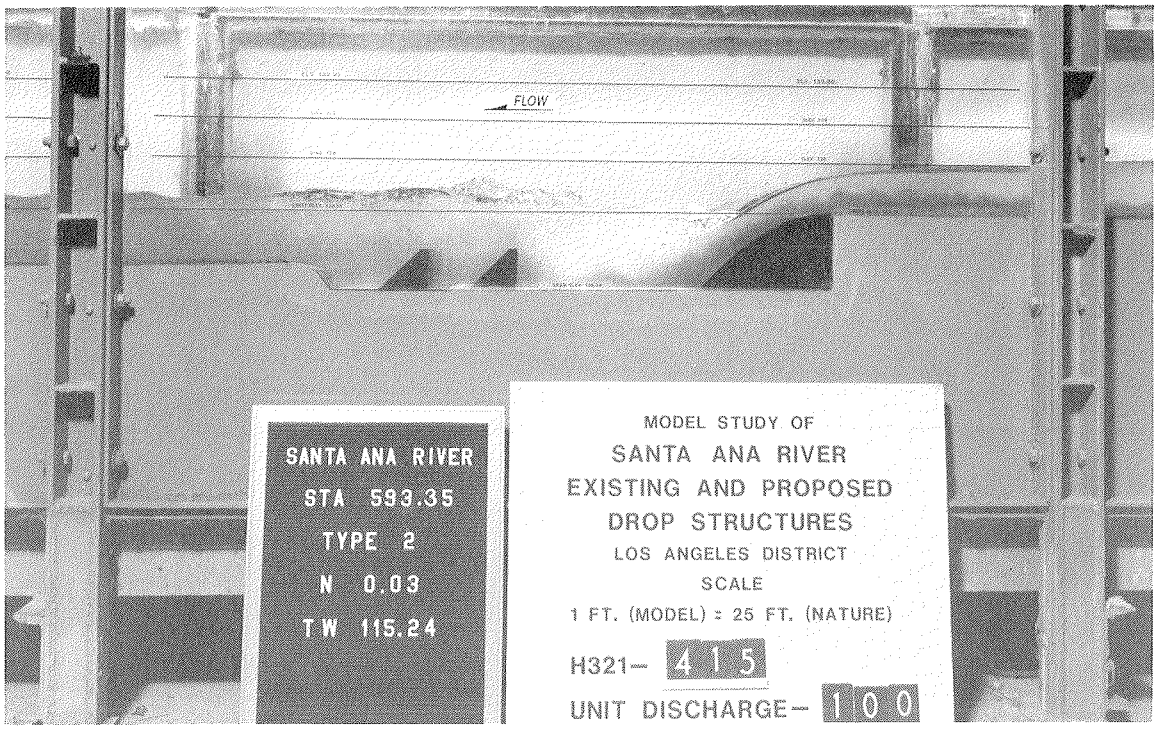


e. Unit discharge 215 cfs/ft, tailwater el 117.34

Photo 75. (Sheet 3 of 3)

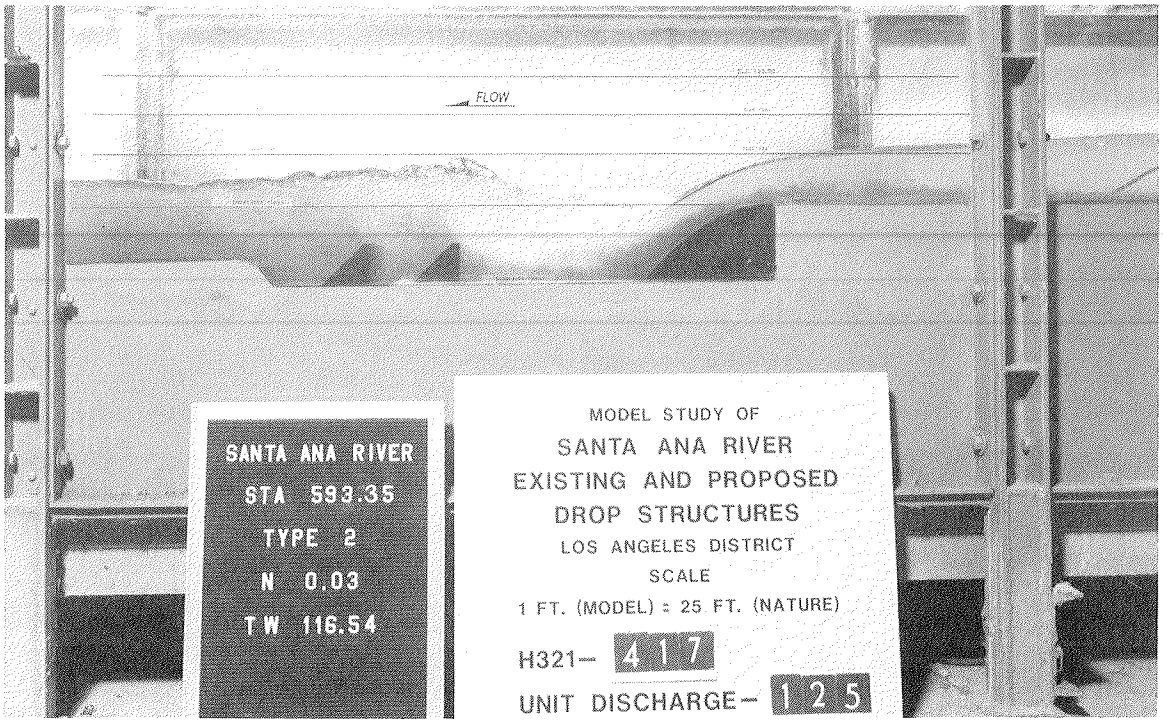


a. Unit discharge 50 cfs/ft, tailwater el 112.24

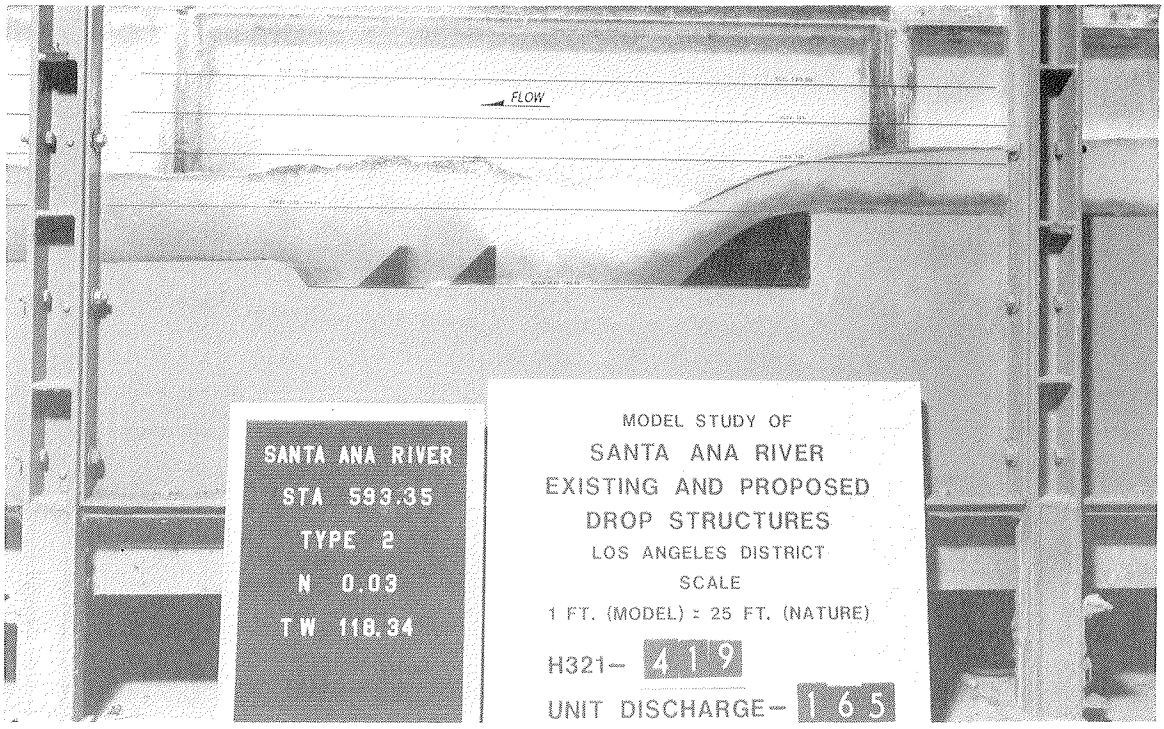


b. Unit discharge 100 cfs/ft, tailwater el 115.24

Photo 76. Flow conditions in the type 2 design drop structure, sta 593+35, n = 0.03 (Sheet 1 of 3)

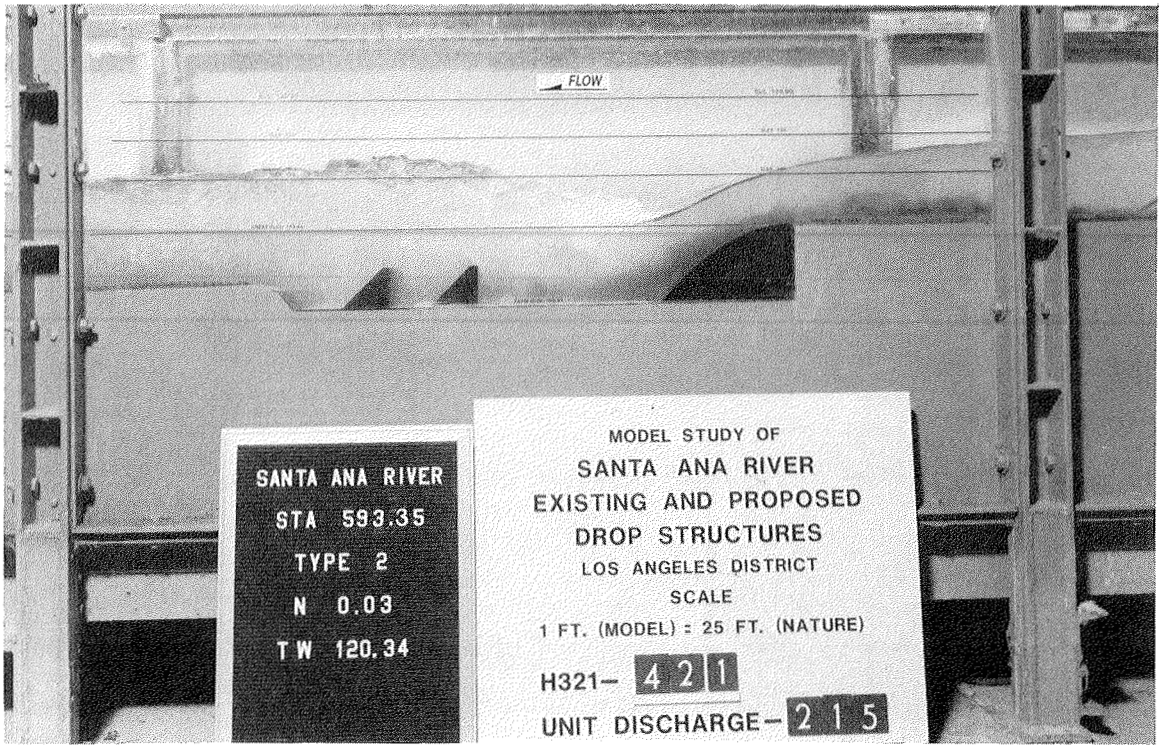


c. Unit discharge 125 cfs/ft, tailwater el 116.54



d. Unit discharge 165 cfs/ft, tailwater el 118.34

Photo 76. (Sheet 2 of 3)



e. Unit discharge 215 cfs/ft, tailwater el 120.34

Photo 76. (Sheet 3 of 3)

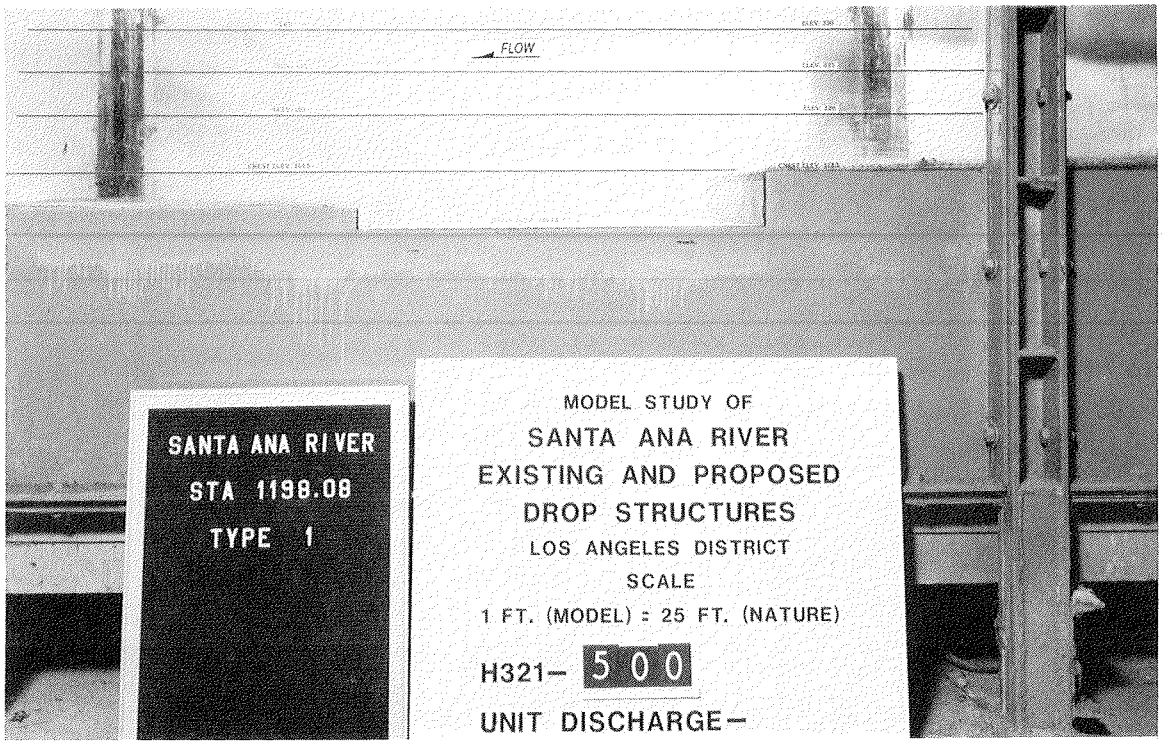
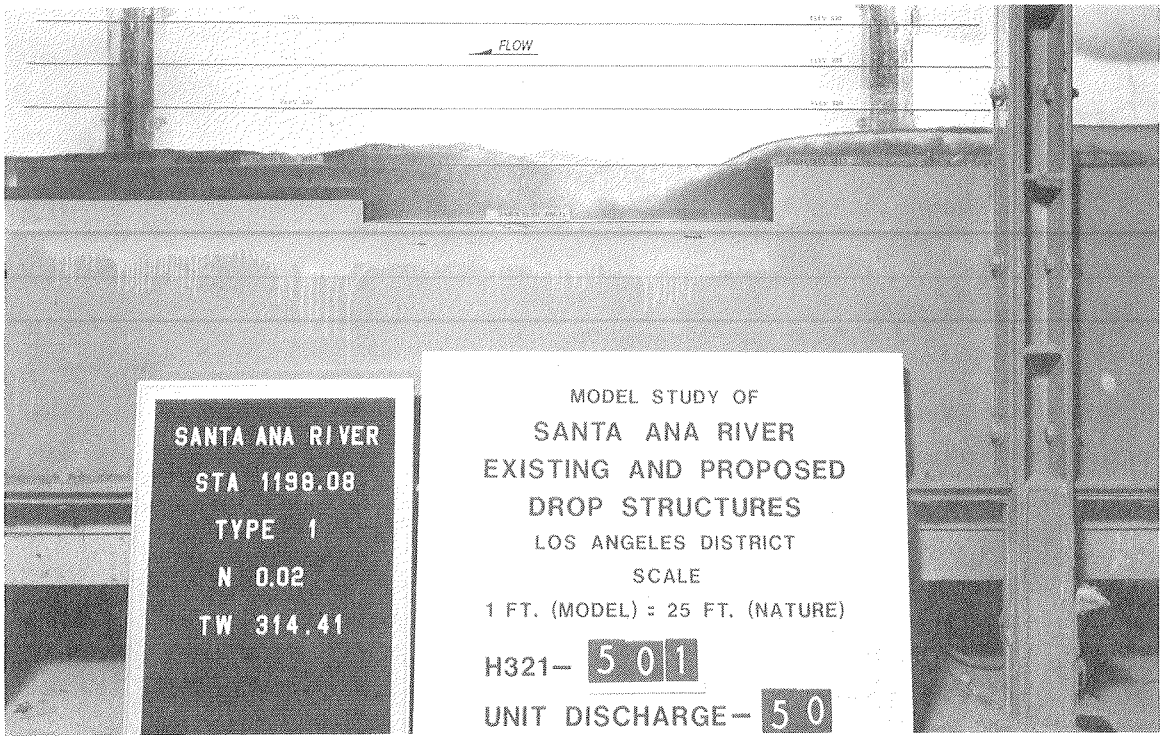
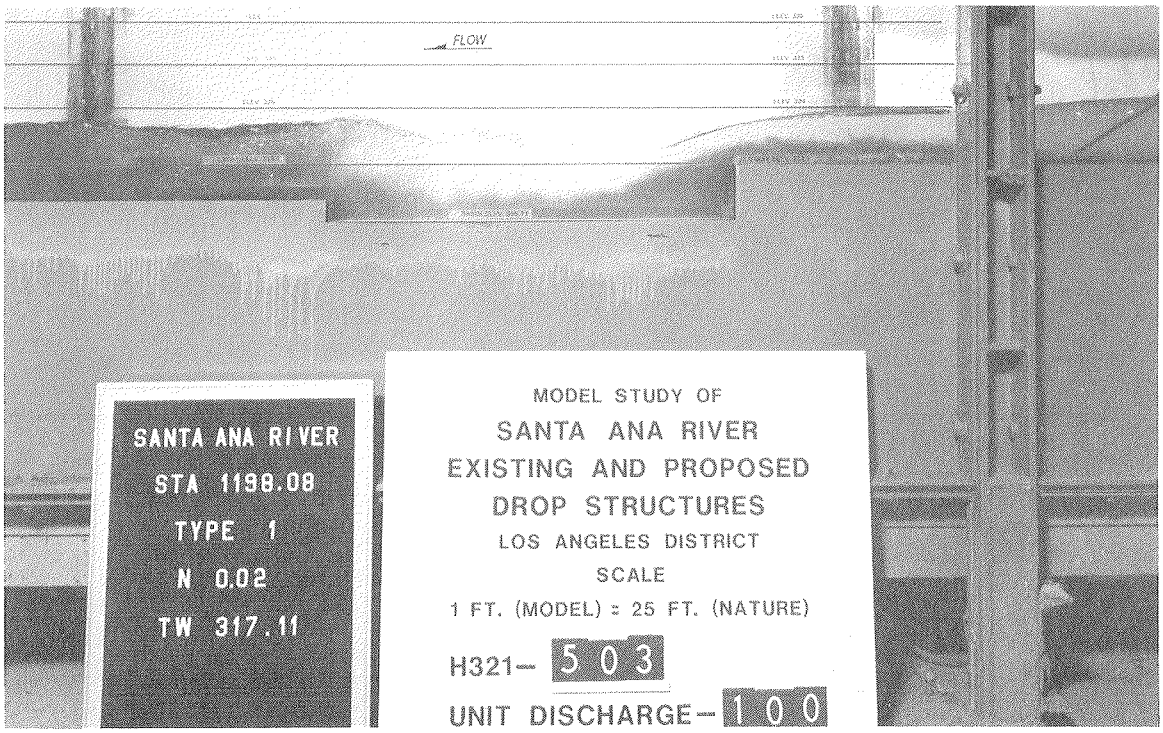


Photo 77. Type 1 design drop structure, sta 1198+08

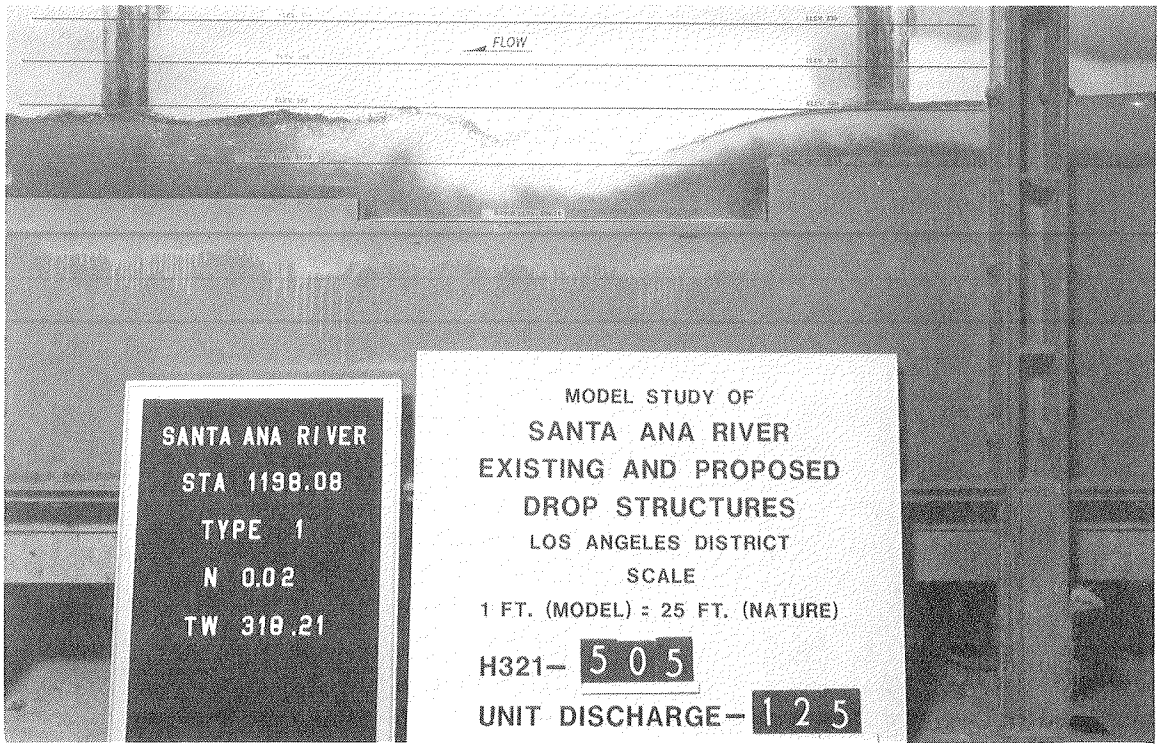


a. Unit discharge 50 cfs/ft, tailwater el 314.41

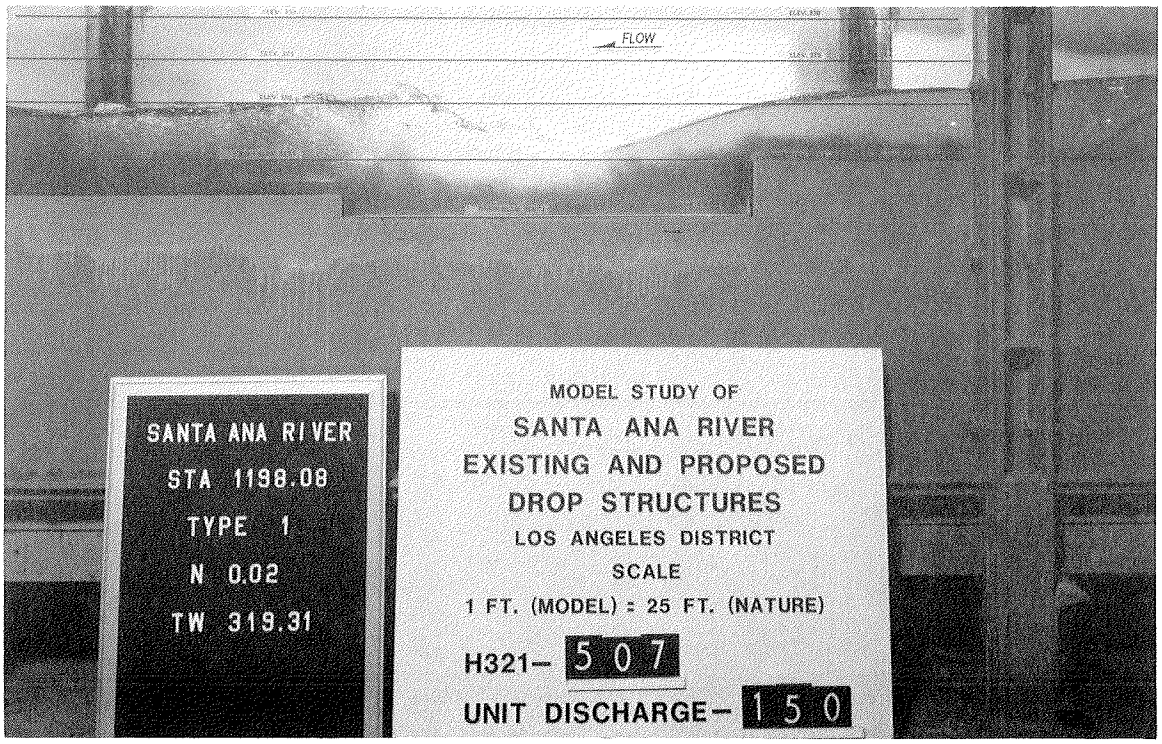


b. Unit discharge 100 cfs/ft, tailwater el 317.11

Photo 78. Flow conditions in the type 1 design drop structure, sta 1198+08, n = 0.02 (Sheet 1 of 3)

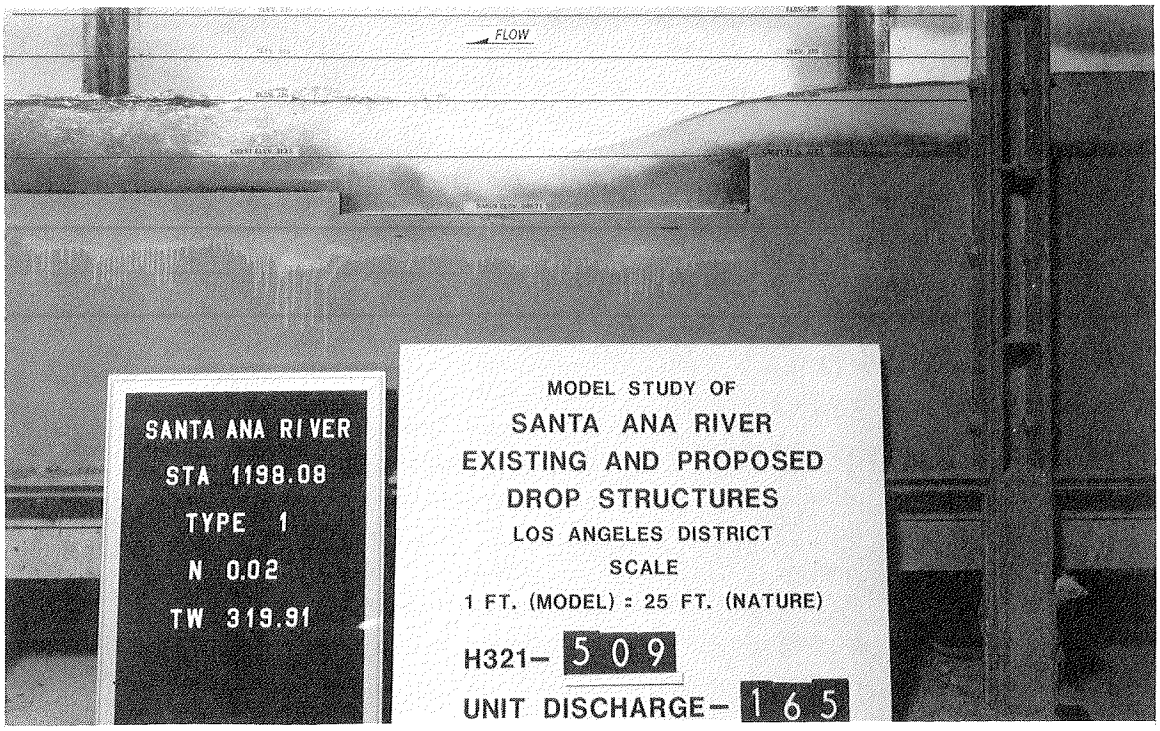


c. Unit discharge 125 cfs/ft, tailwater el 318.21



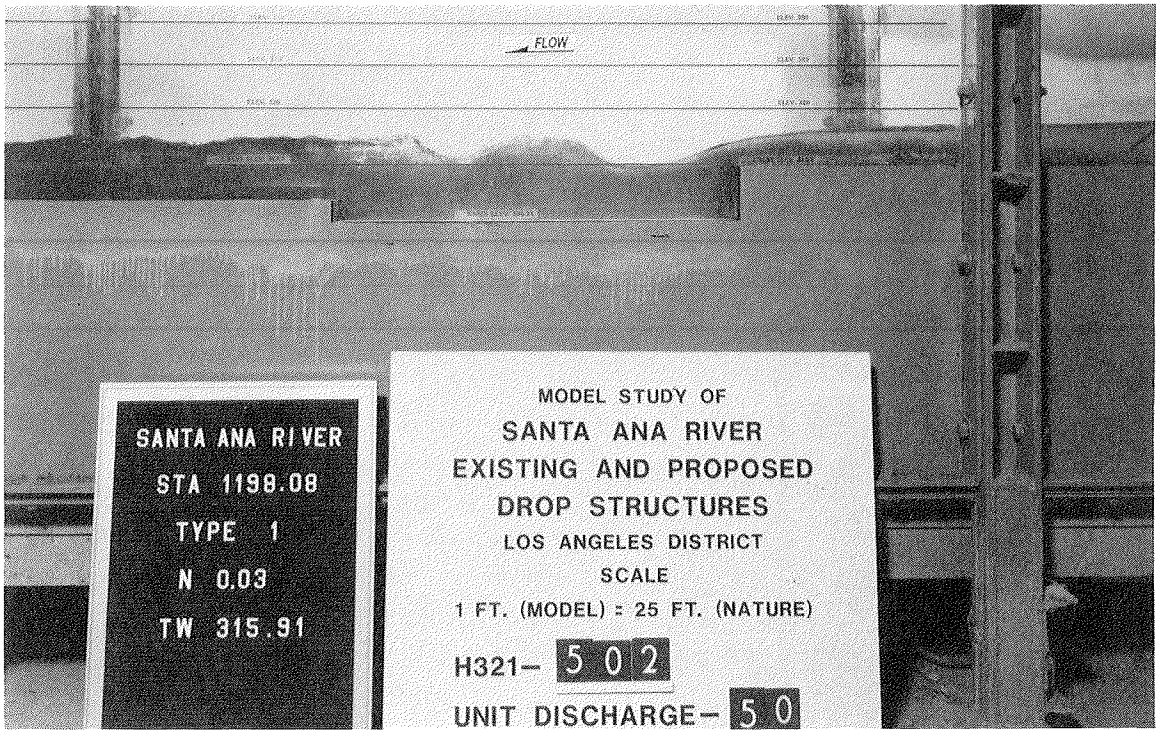
d. Unit discharge 150 cfs/ft, tailwater el 319.31

Photo 78. (Sheet 2 of 3)

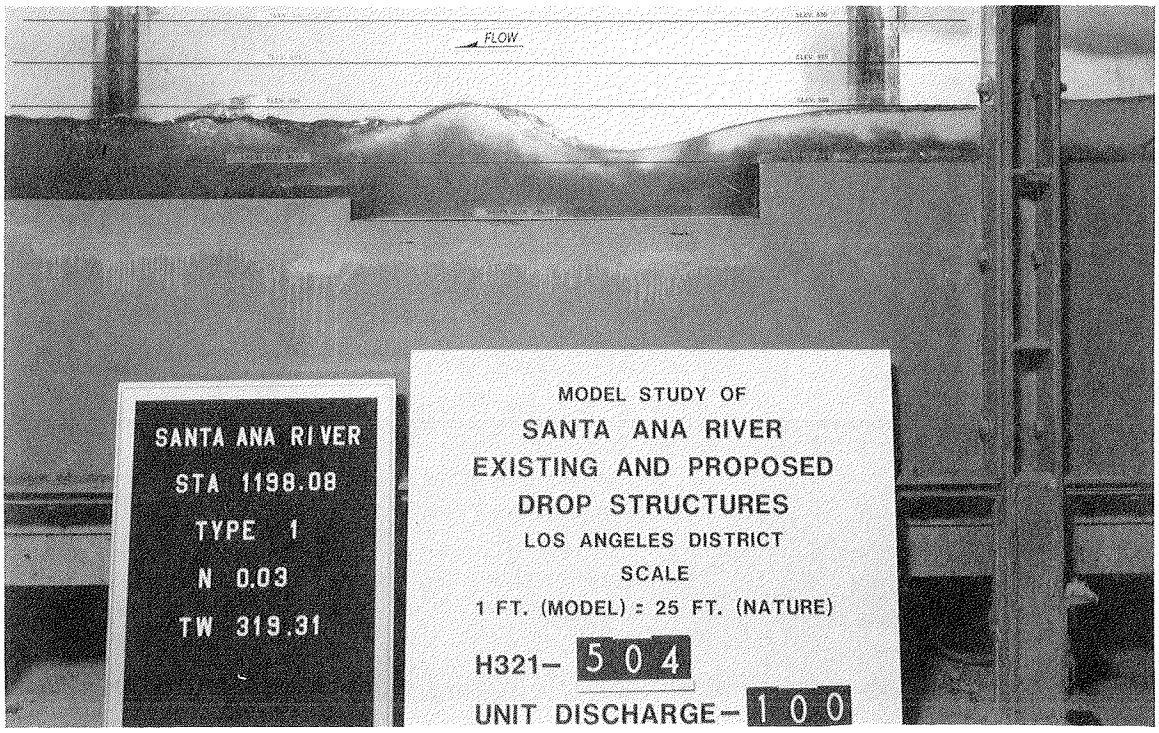


e. Unit discharge 165 cfs/ft, tailwater el 319.91

Photo 78. (Sheet 3 of 3)

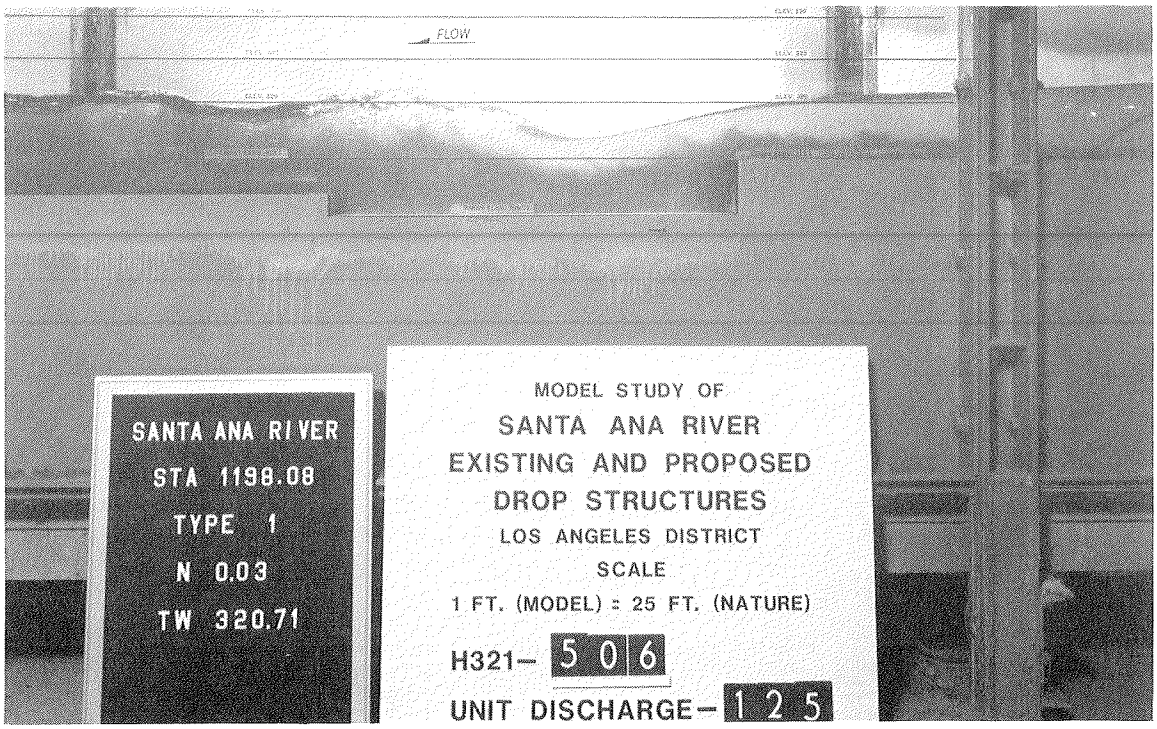


a. Unit discharge 50 cfs/ft, tailwater el 315.91

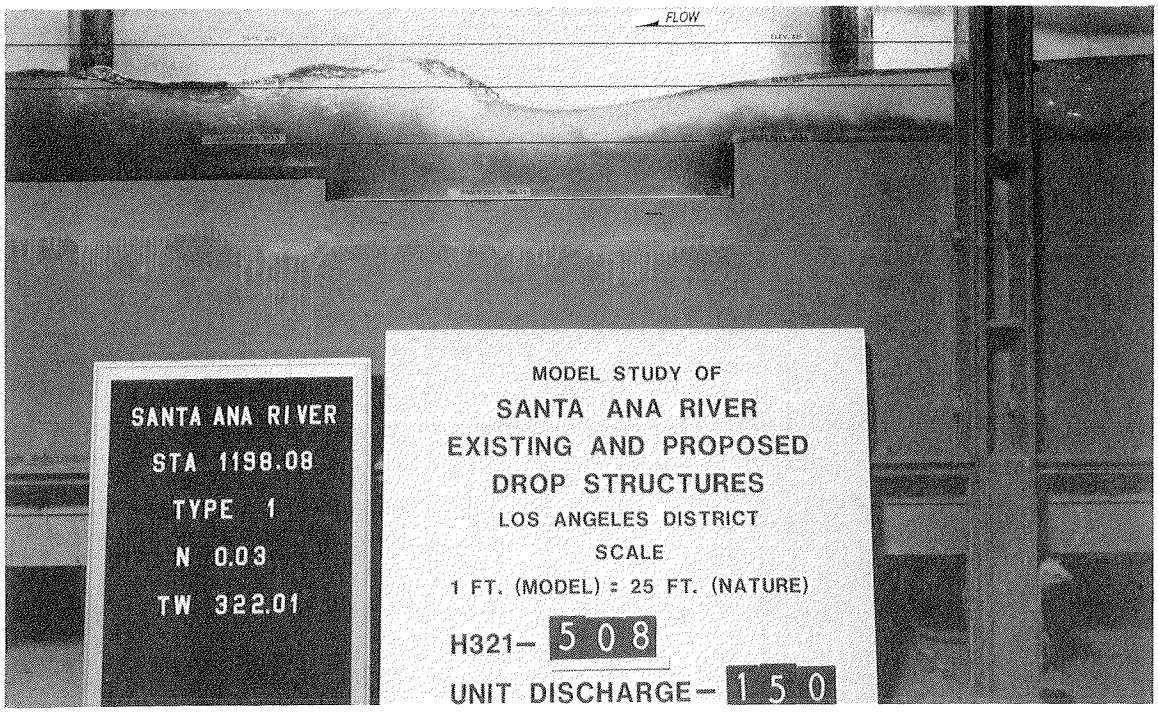


b. Unit discharge 100 cfs/ft, tailwater el 319.31

Photo 79. Flow conditions in the type 1 design drop structure, sta 1198+08, n = 0.03 (Sheet 1 of 3)

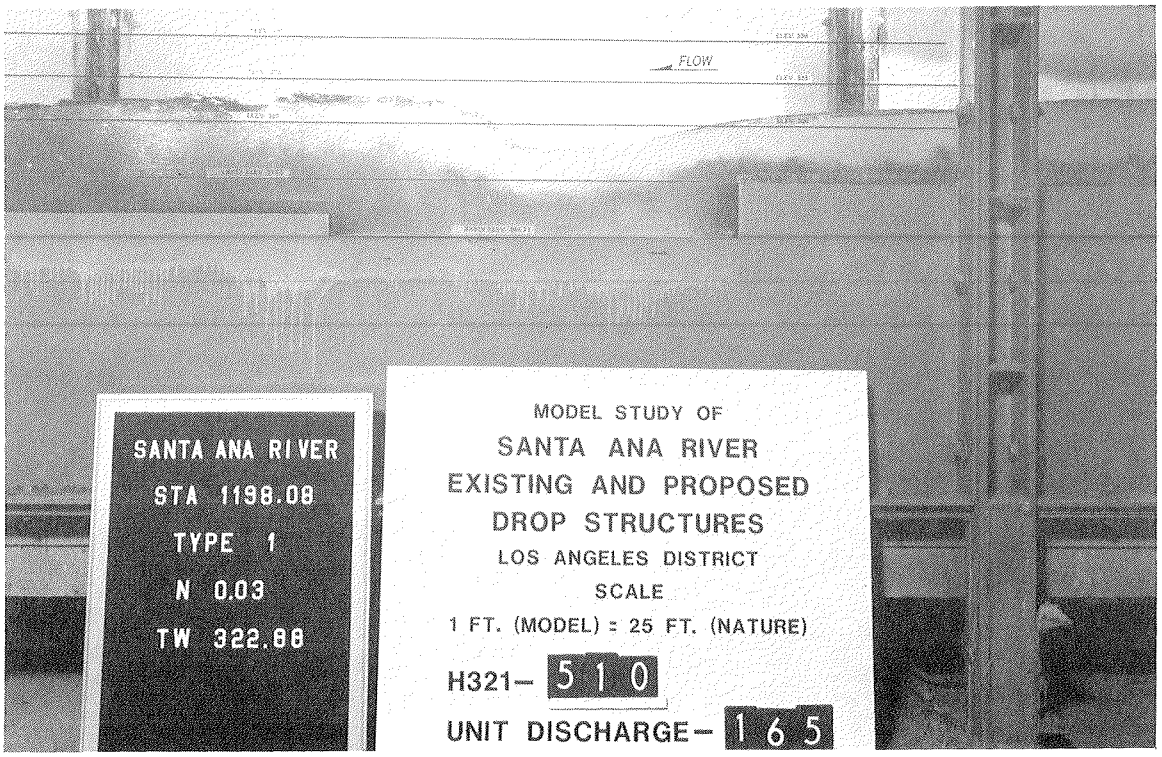


c. Unit discharge 125 cfs/ft, tailwater el 320.71



d. Unit discharge 150 cfs/ft, tailwater el 322.01

Photo 79. (Sheet 2 of 3)



e. Unit discharge 165 cfs/ft, tailwater el 322.88

Photo 79. (Sheet 3 of 3)

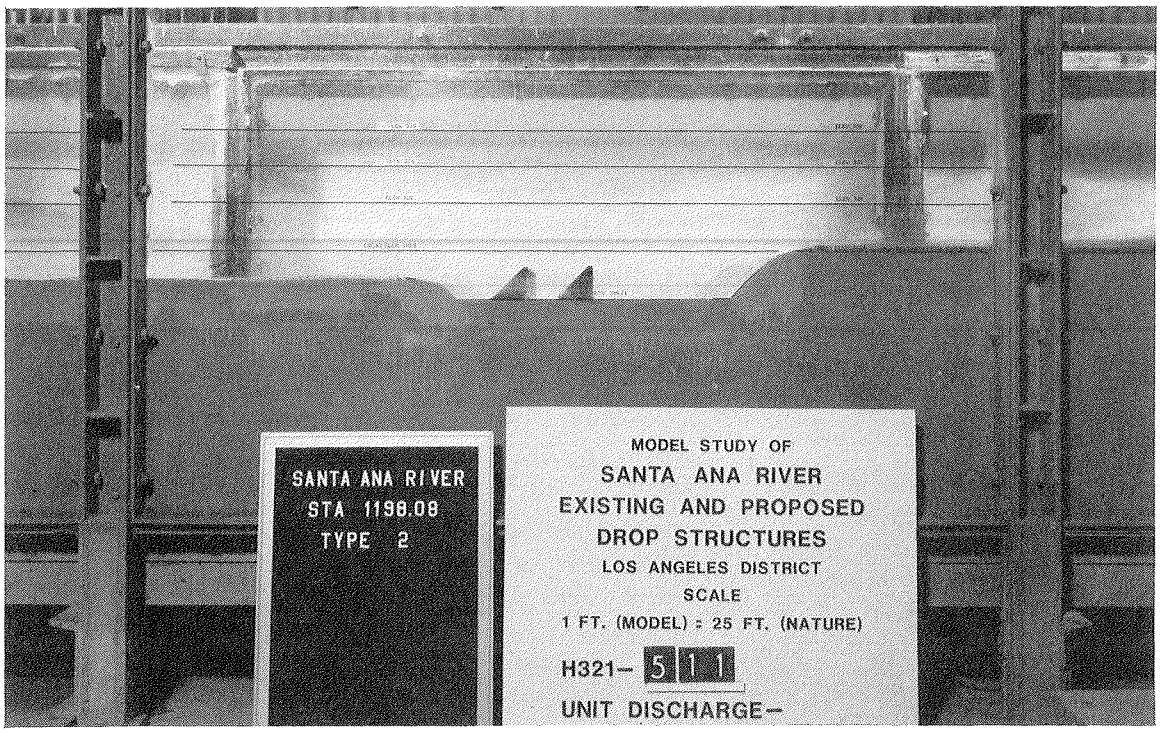
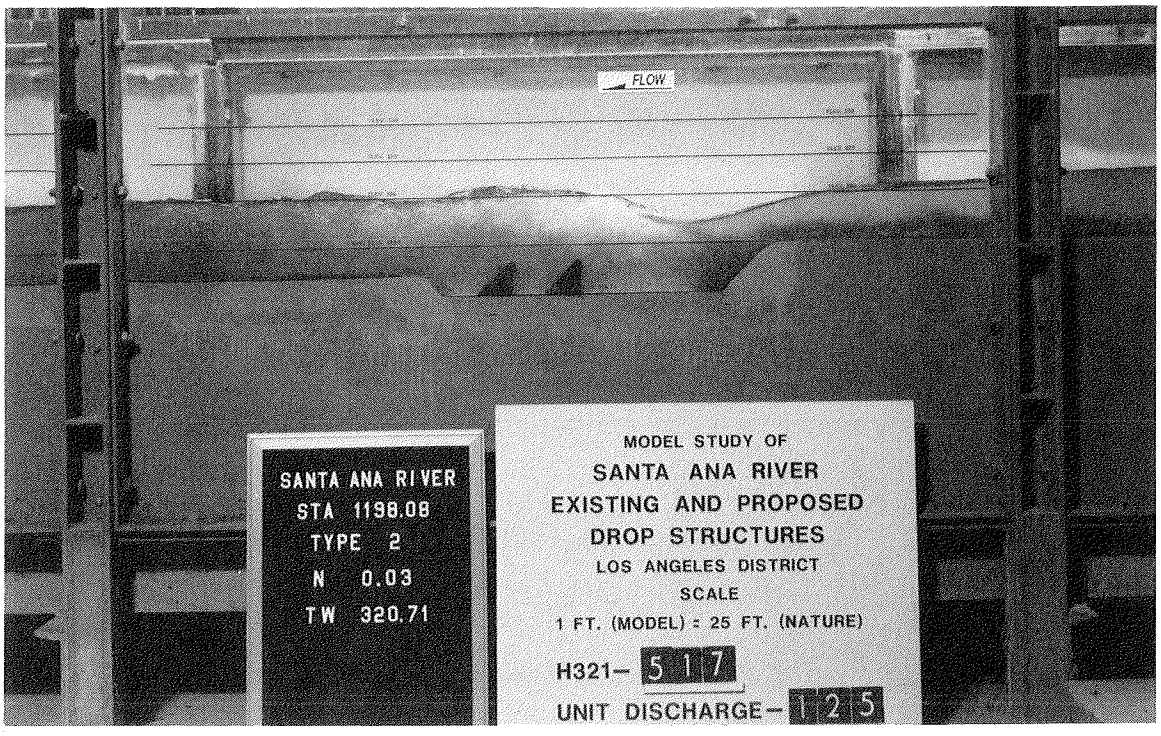


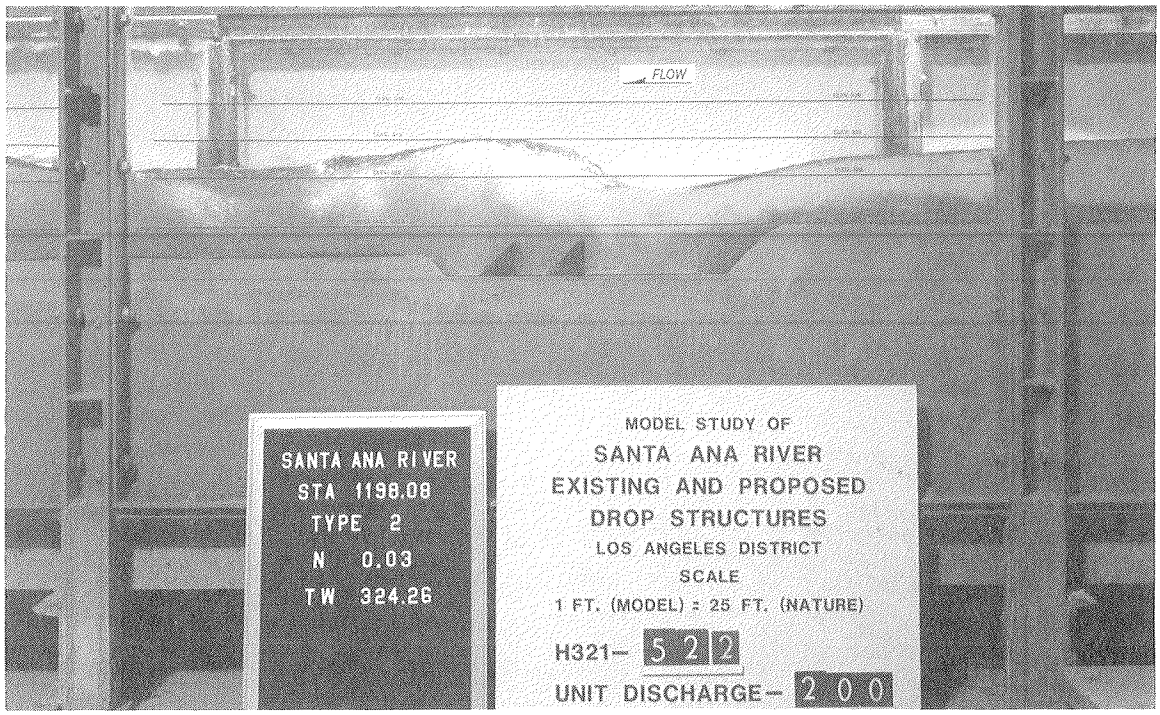
Photo 80. Type 2 design drop structure, sta 1198+08

a. Tailwater el 318.21, n = 0.02

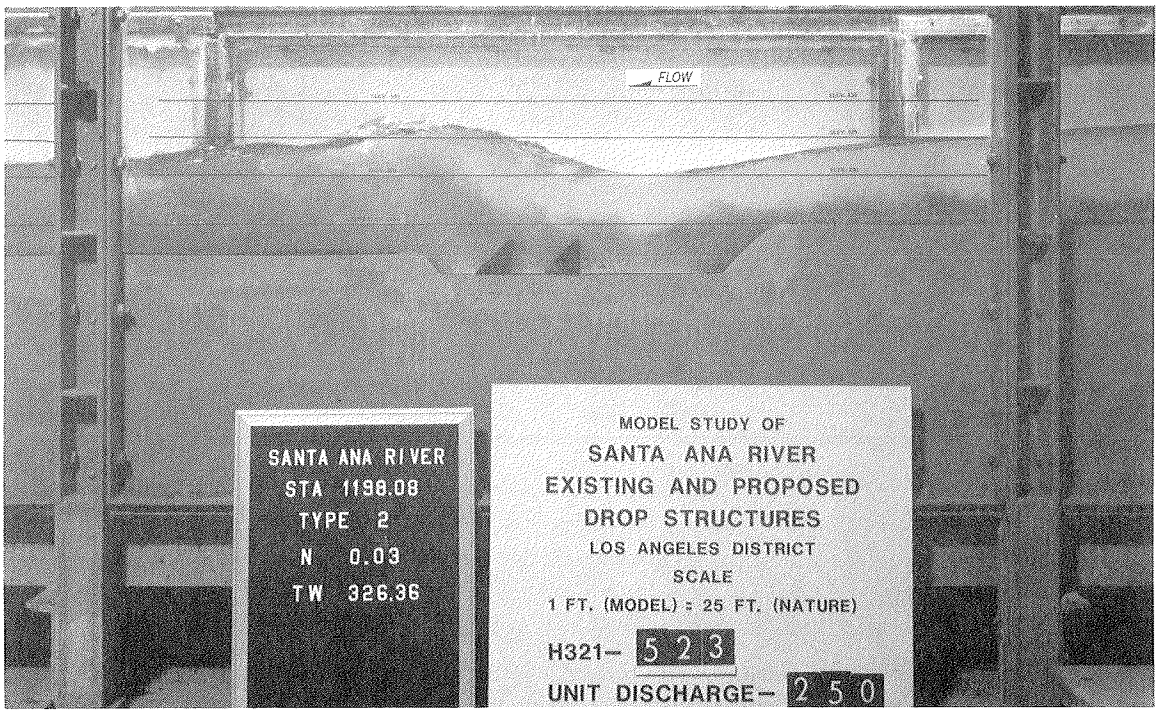


b. Tailwater el 320.71, n = 0.03

Photo 81. Flow conditions in the type 2 design drop structure, sta 1198+08, unit discharge 125 cfs/ft

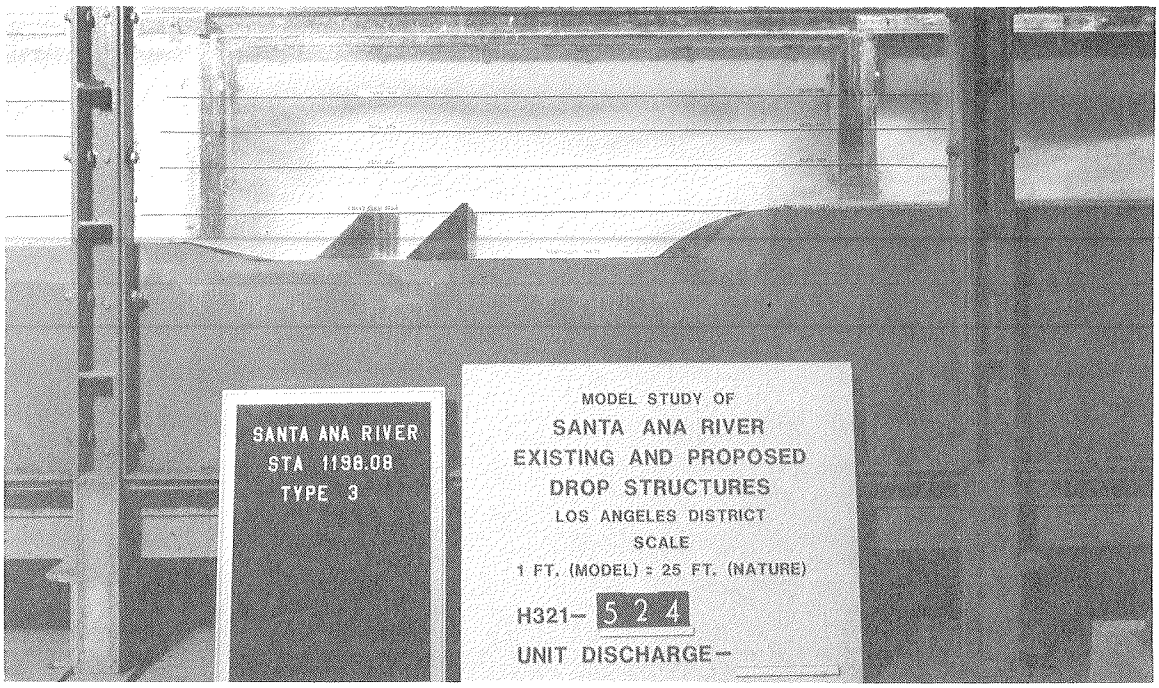


a. Unit discharge 200 cfs/ft, tailwater el 324.26

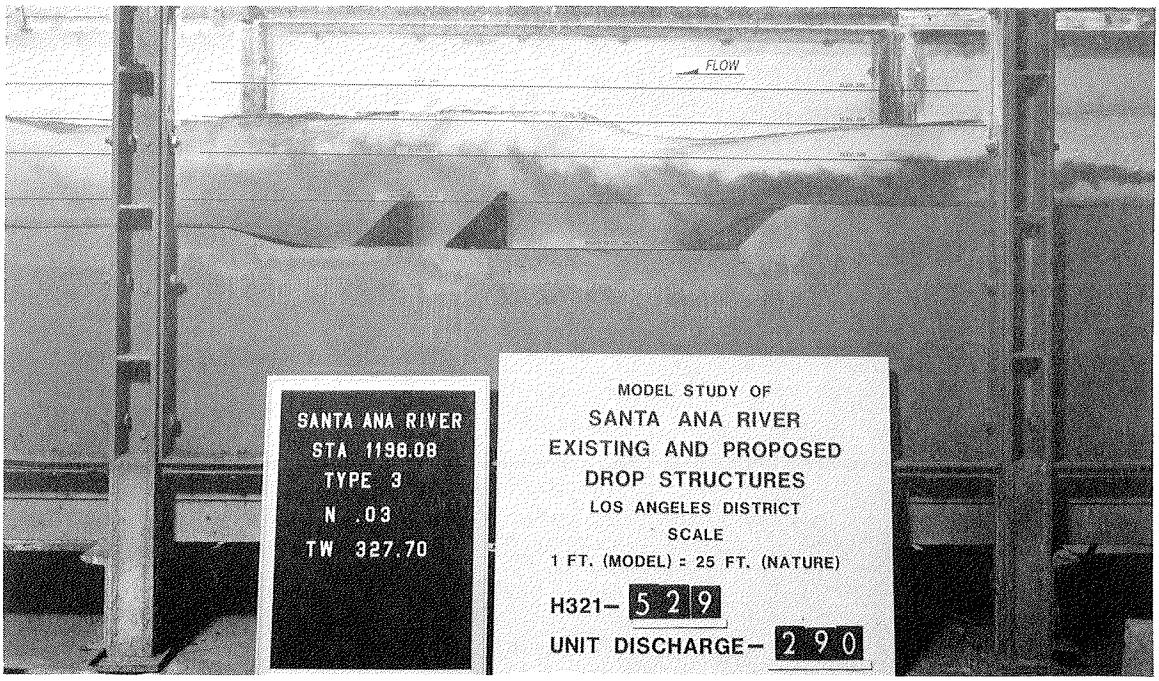


b. Unit discharge 250 cfs/ft, tailwater el 326.36

Photo 82. Flow conditions in the type 2 design drop structure, sta 1198+08, with higher unit discharge, n = 0.03

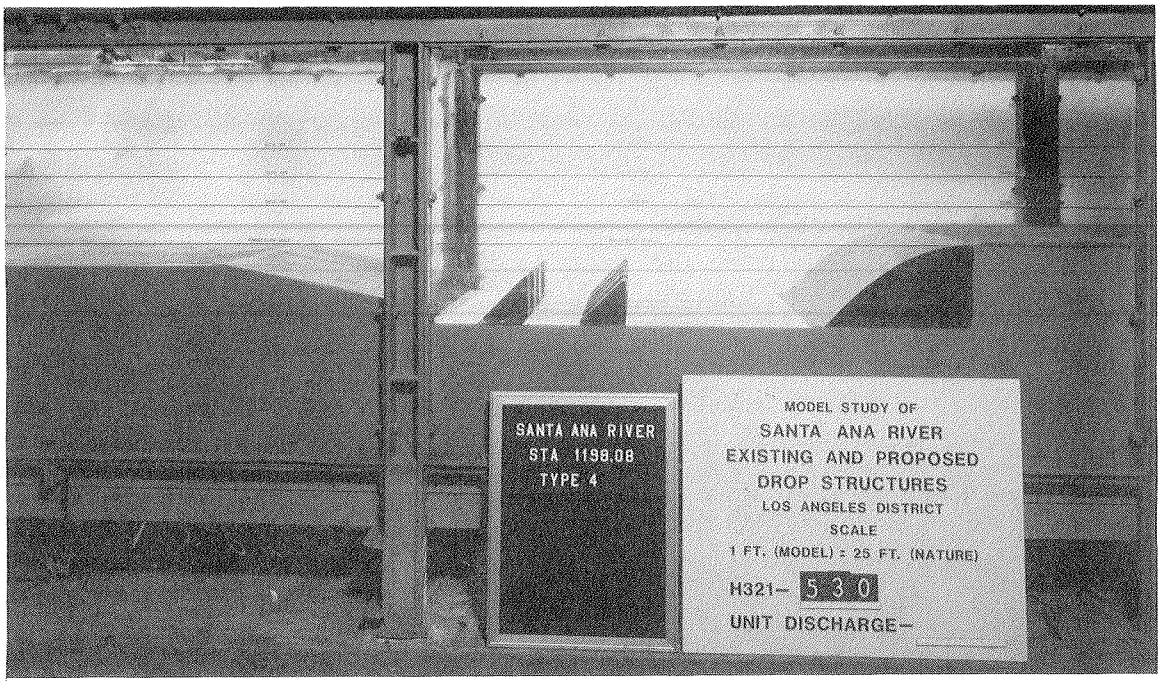


a. Dry bed

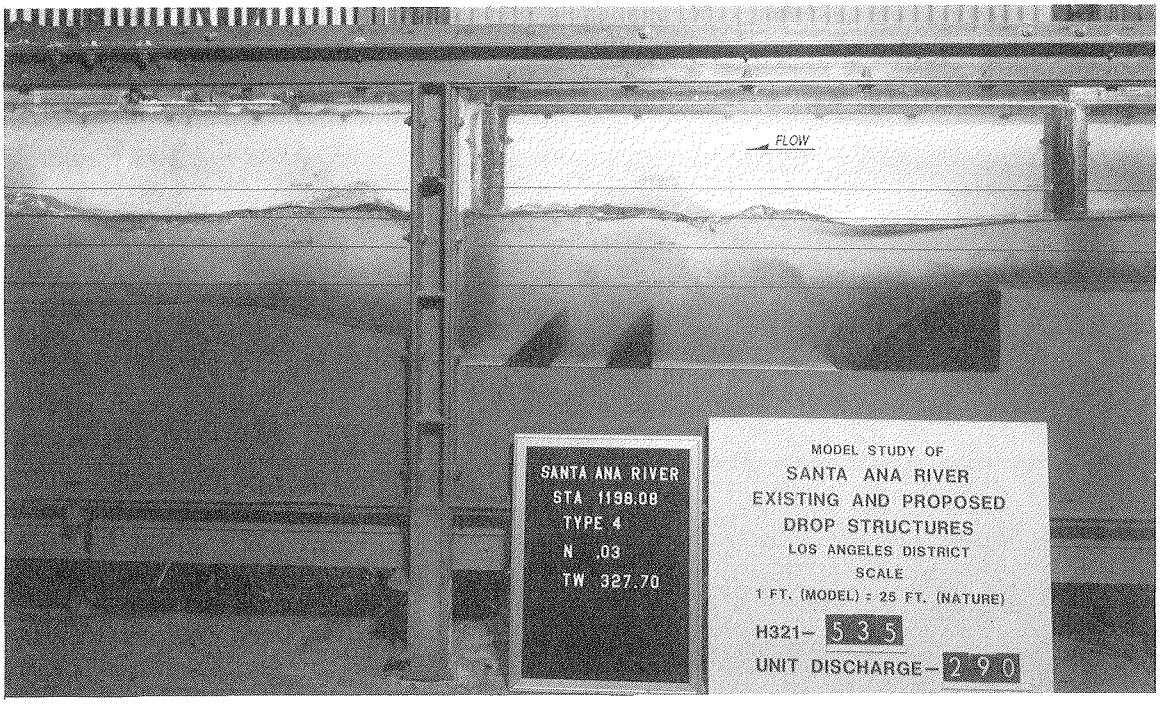


b. Unit discharge 290 cfs/ft, tailwater el 327.70, n = 0.03

Photo 83. Type 3 design drop structure, sta 1198+08



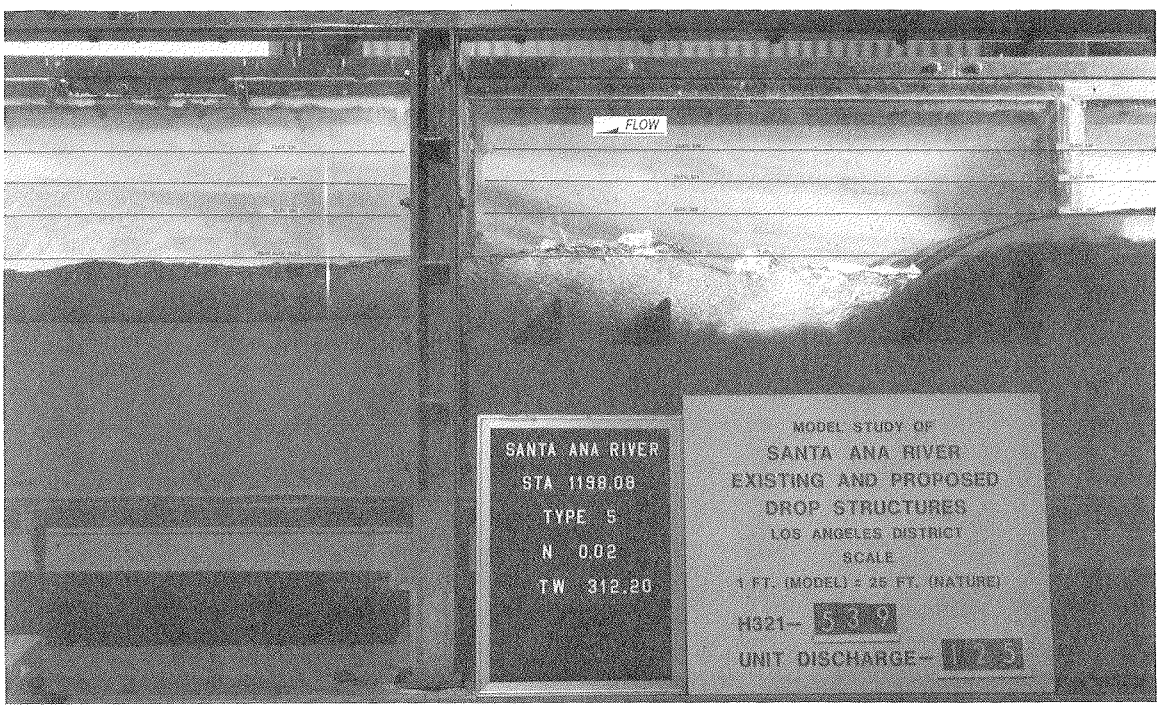
a. Dry bed



b. Unit discharge 290 cfs/ft, tailwater el 327.70, n = 0.03

Photo 84. Type 4 design drop structure, sta 1198+08

a. Unit discharge 50 cfs/ft, tailwater el 308.40

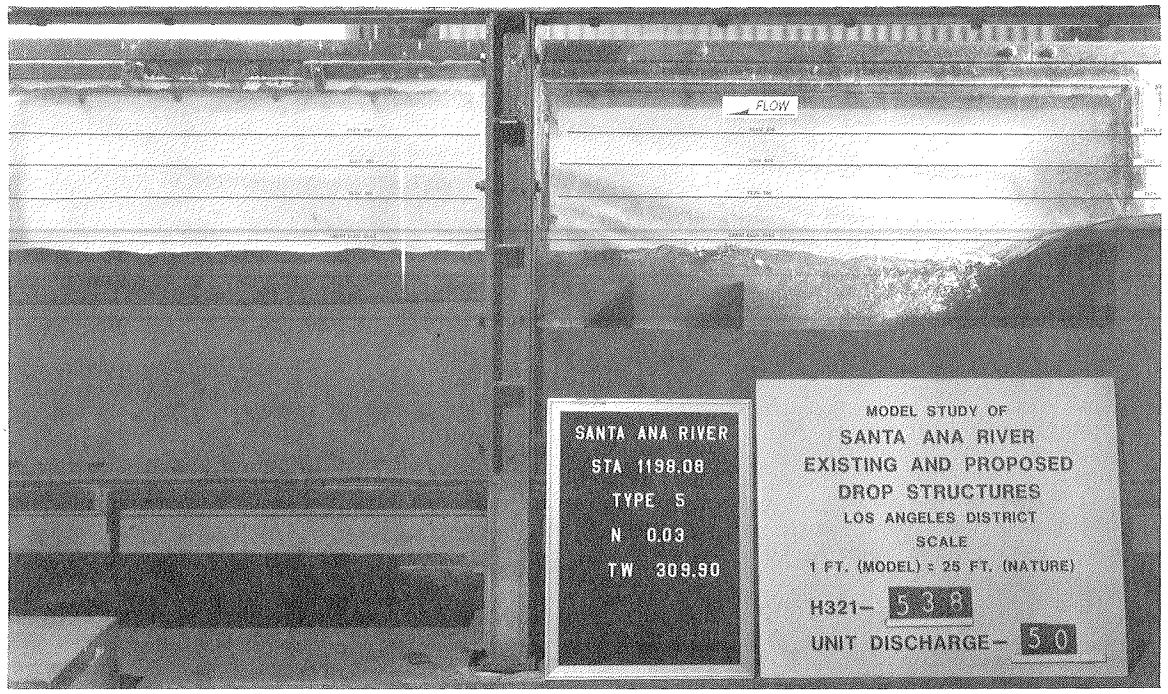


b. Unit discharge 125 cfs/ft, tailwater el 312.20

Photo 85. Flow conditions in the type 5 design drop structure with downstream channel invert lowered to el 303.20, sta 1198+08, n = 0.02 (Continued)

c. Unit discharge 165 cfs/ft, tailwater el 313.90

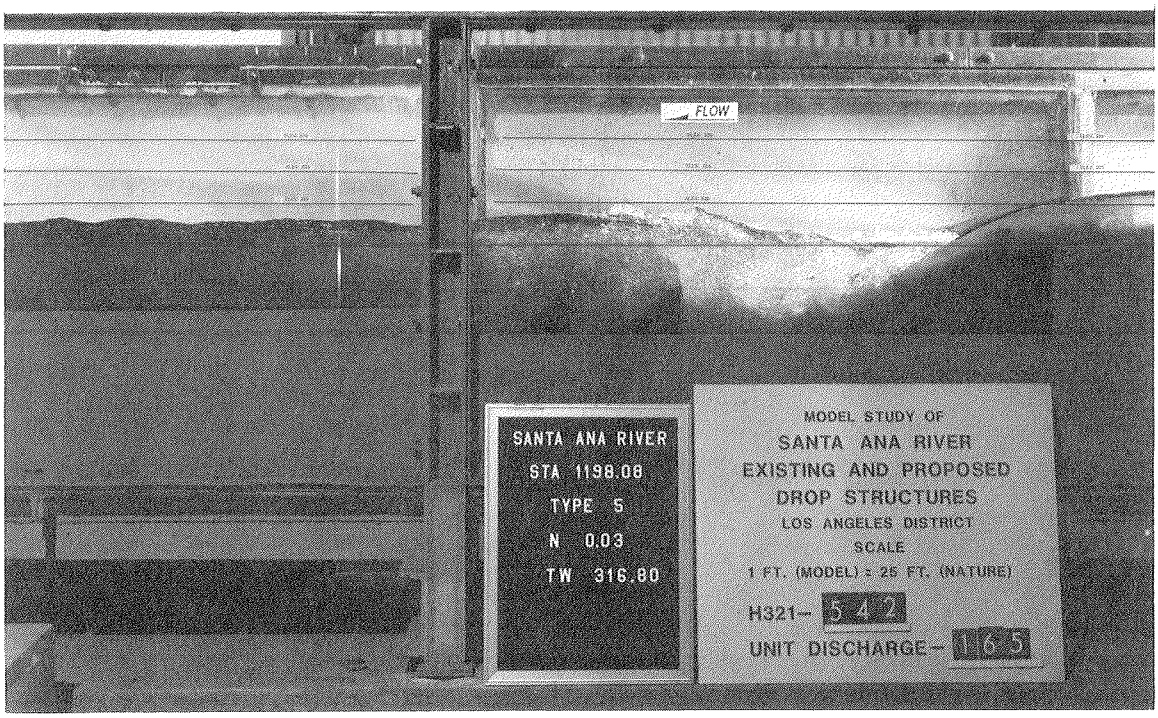
Photo 85. (Concluded)



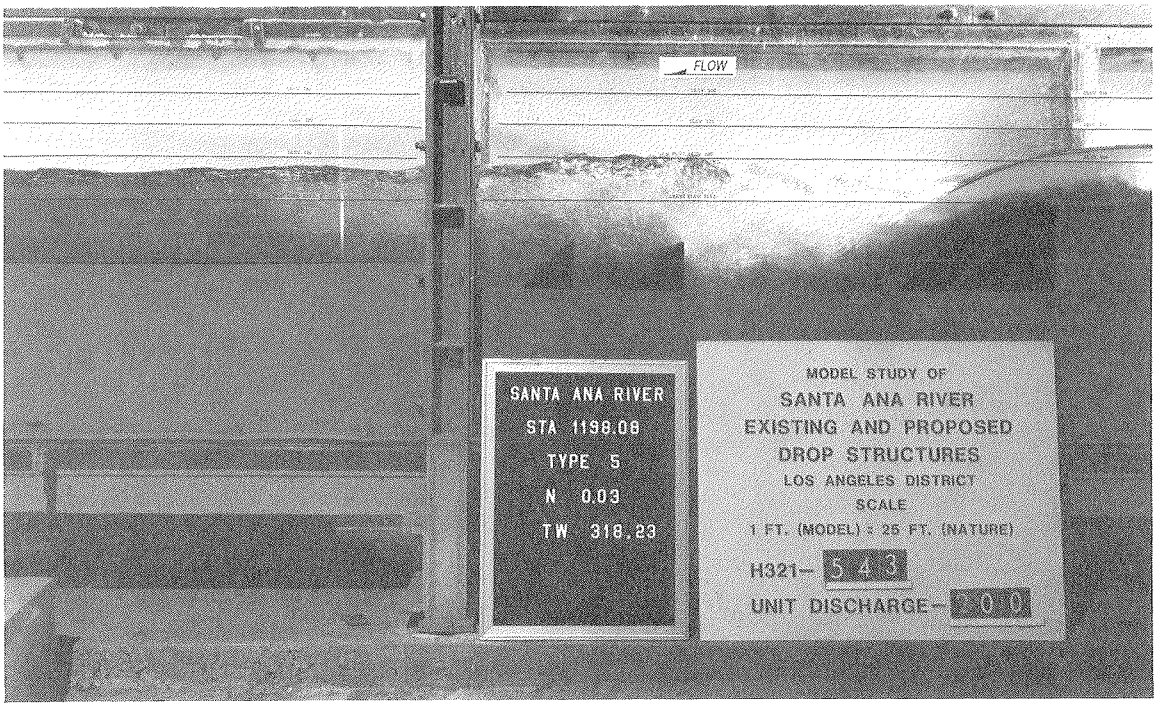
a. Unit discharge 50 cfs/ft, tailwater el 309.90

b. Unit discharge 125 cfs/ft, tailwater el 314.70

Photo 86. Flow conditions in the type 5 design drop structure with downstream channel invert lowered to el 303.20, sta 1198+08, n = 0.03 (Sheet 1 of 3)

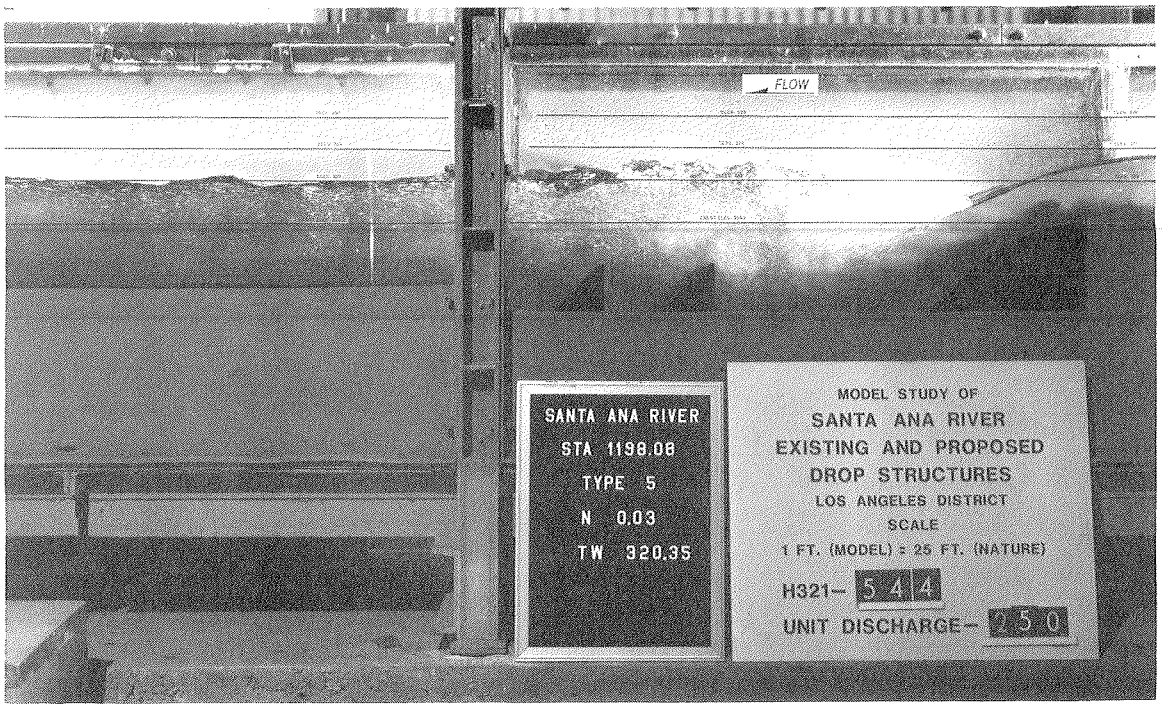


c. Unit discharge 165 cfs/ft, tailwater el 316.80

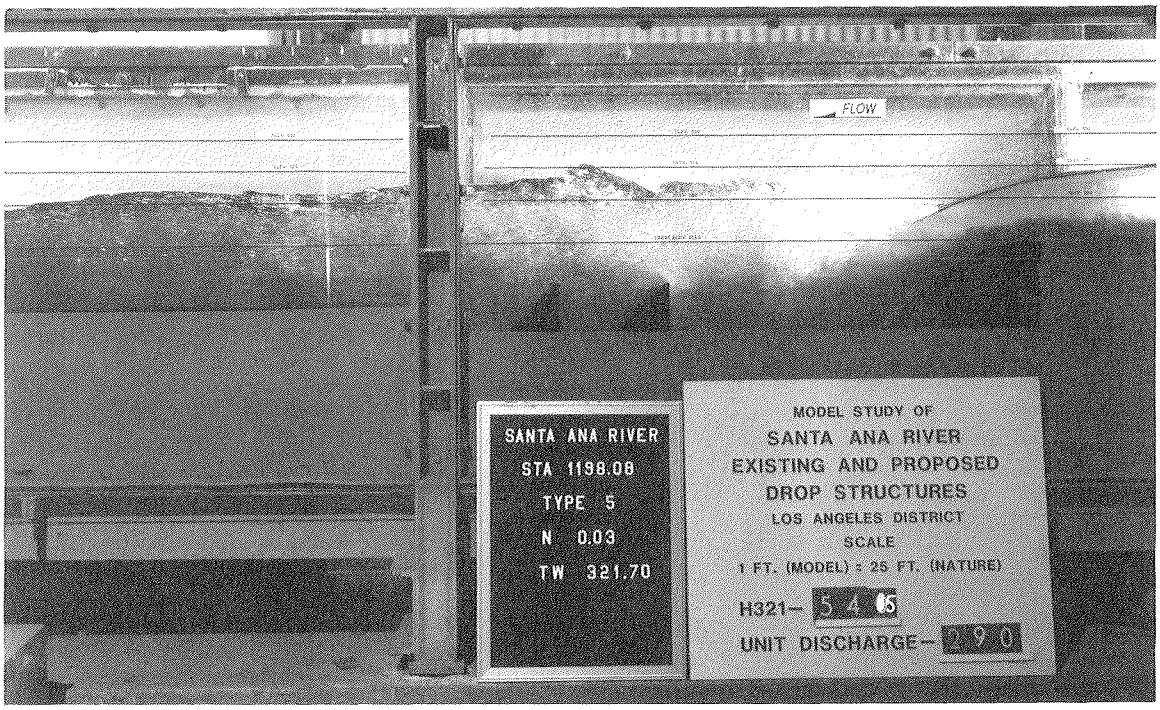


d. Unit discharge 200 cfs/ft, tailwater el 318.23

Photo 86. (Sheet 2 of 3)

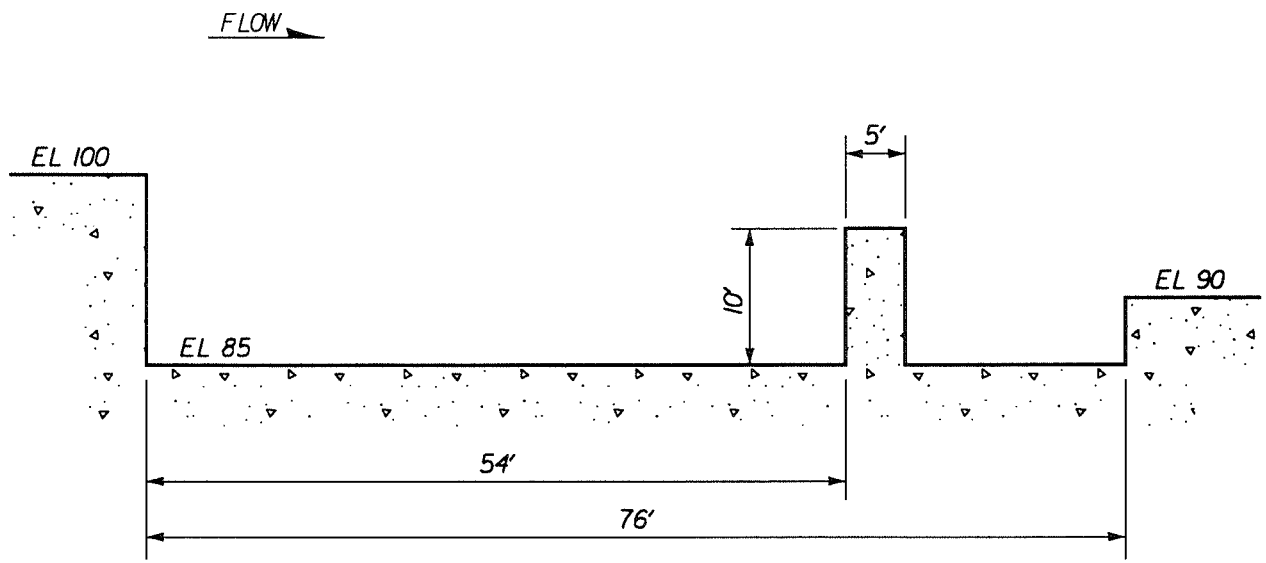


e. Unit discharge 250 cfs/ft, tailwater el 320.35



f. Unit discharge 290 cfs/ft, tailwater el 321.70

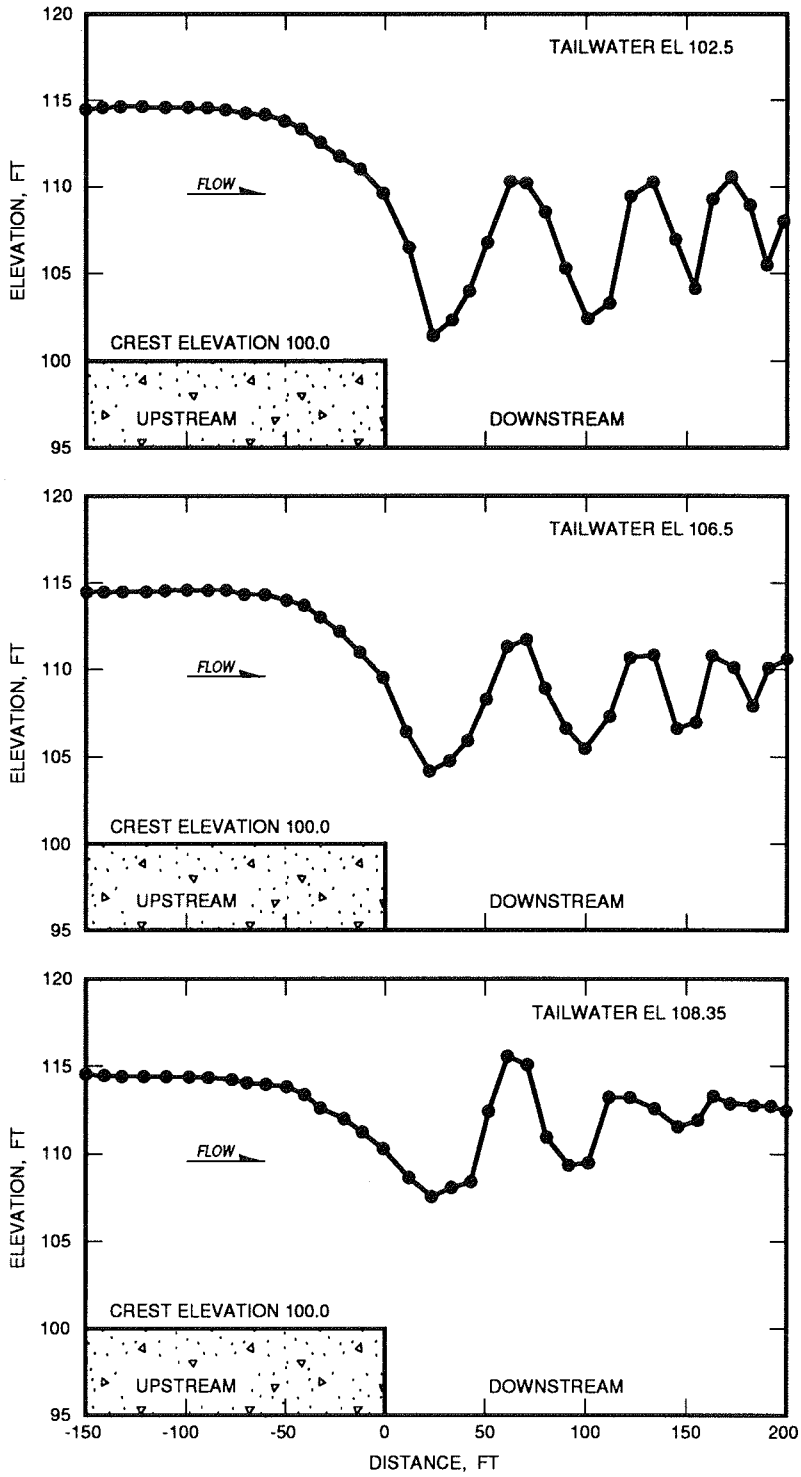
Photo 86. (Sheet 3 of 3)



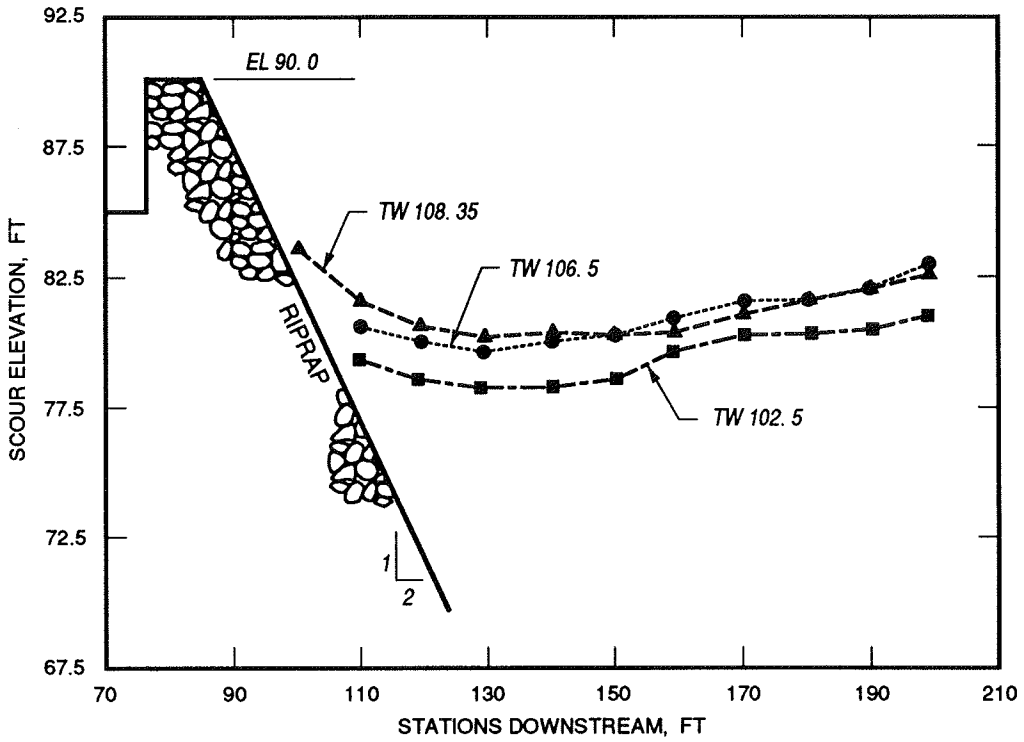
ELEVATION

TYPE 1 DESIGN
DROP STRUCTURE

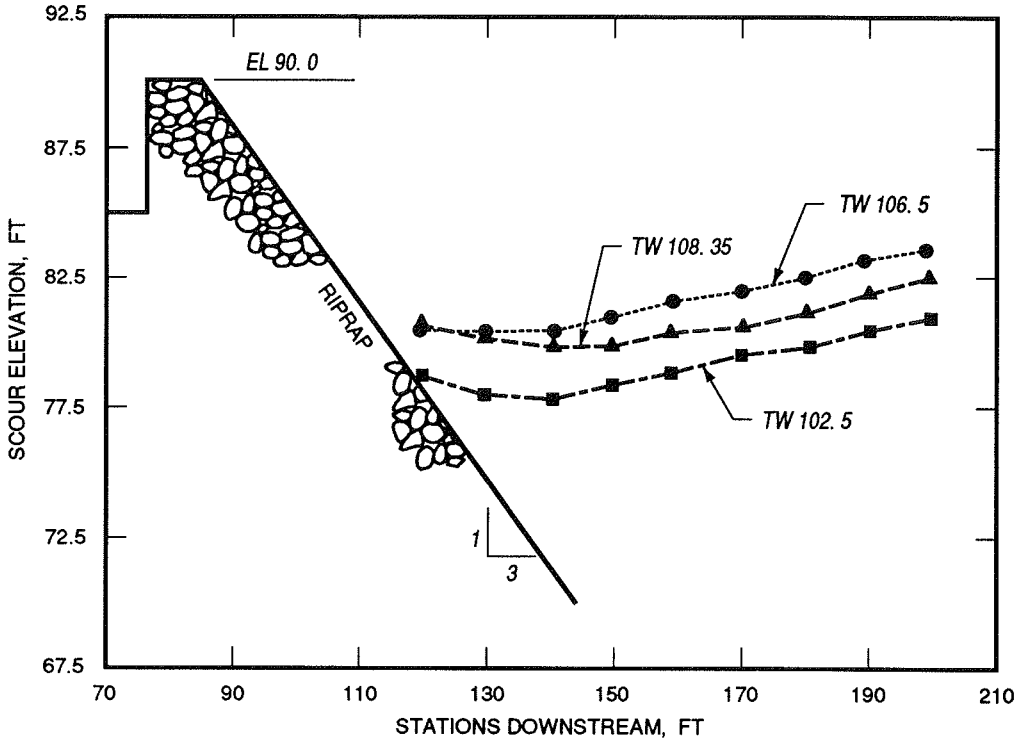
PLATE 1



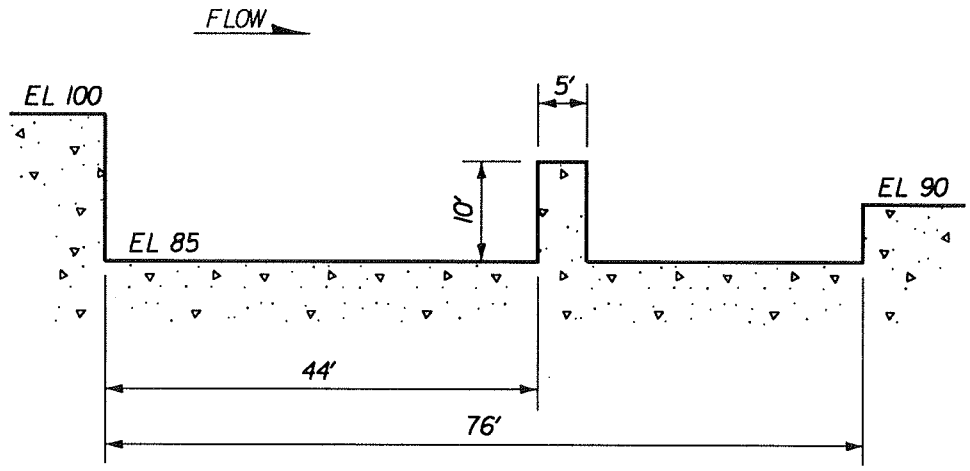
TYPE 1 DESIGN
DROP STRUCTURE
WATER-SURFACE PROFILES
DISCHARGE 250 CFS/FT



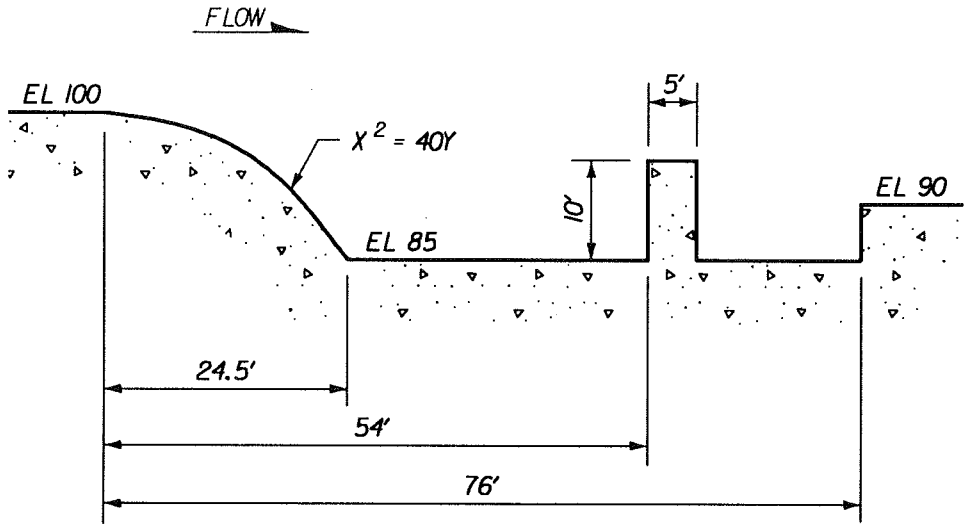
TYPE 1 DESIGN DROP STRUCTURE
RESULTING SCOUR AFTER
5 HR (PROTOTYPE) FOR
VARIOUS TAILWATER ELEVATIONS
DISCHARGE 250 CFS/FT
IV ON 2H RIPRAP SLOPE



TYPE 1 DESIGN DROP STRUCTURE
RESULTING SCOUR AFTER
5 HR (PROTOTYPE) FOR
VARIOUS TAILWATER ELEVATIONS
DISCHARGE 250 CFS/FT
IV ON 3H RIPRAP SLOPE

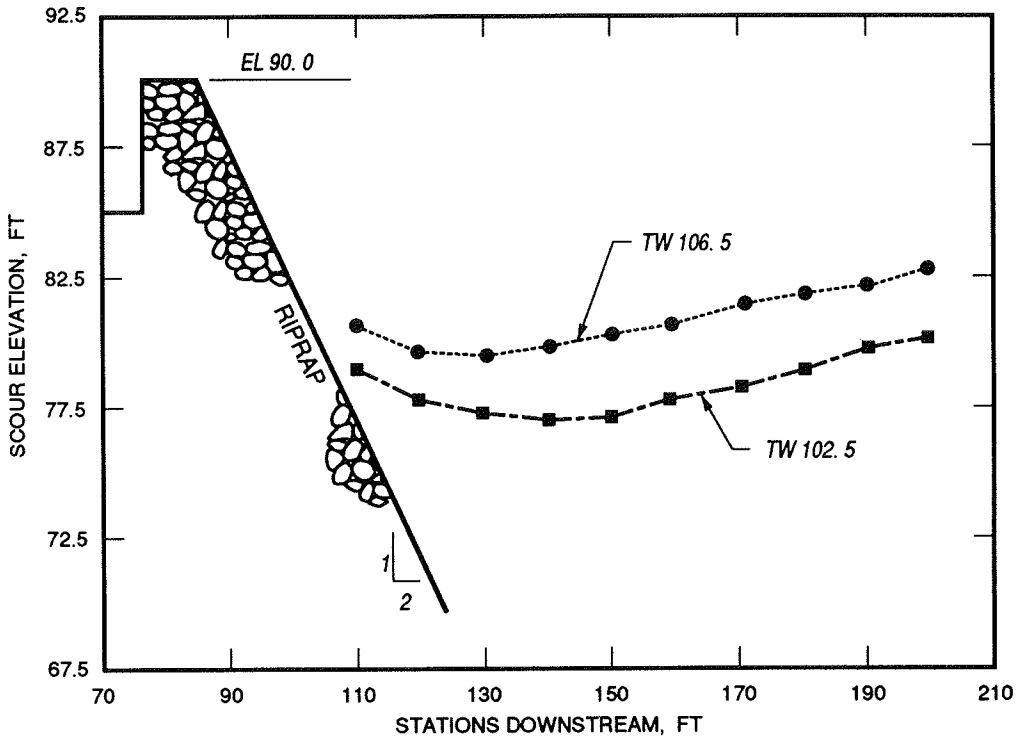


TYPE 2 DESIGN

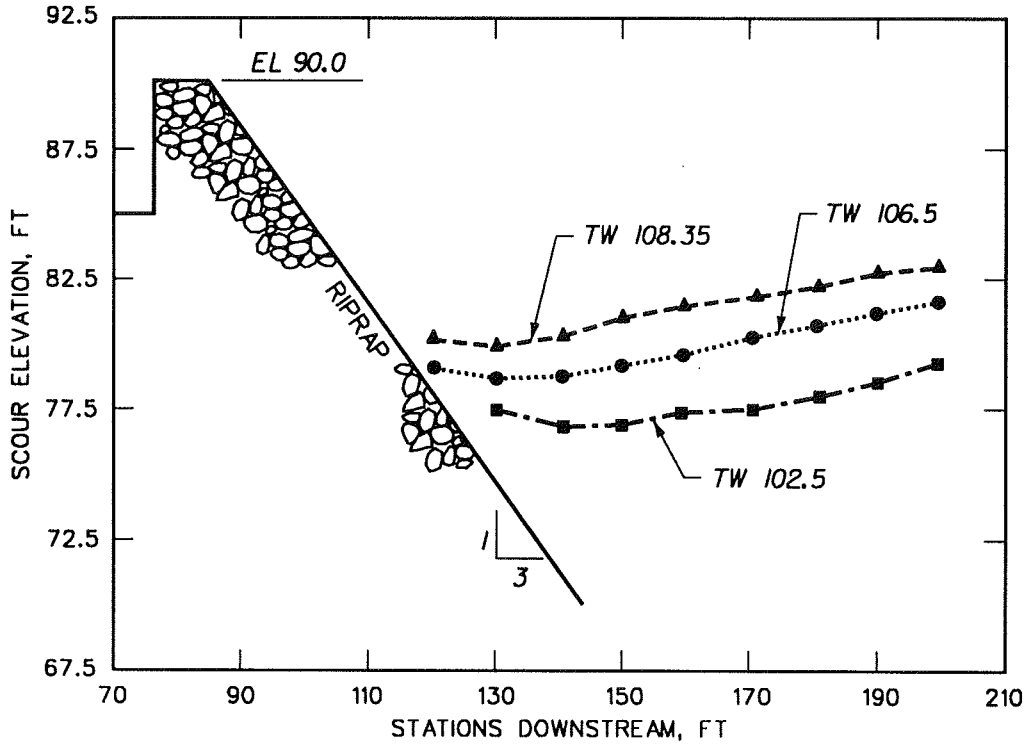


TYPE 3 DESIGN

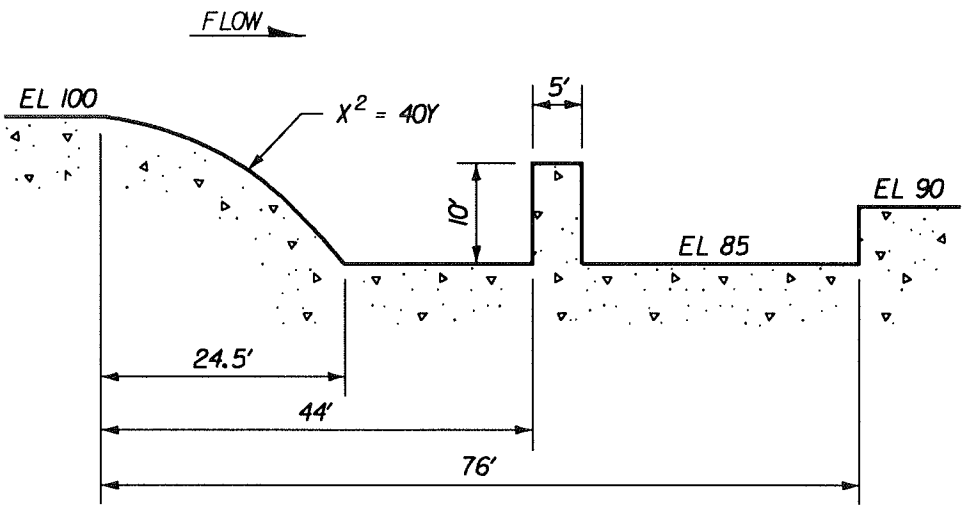
TYPE 2 AND 3 DESIGN
DROP STRUCTURES



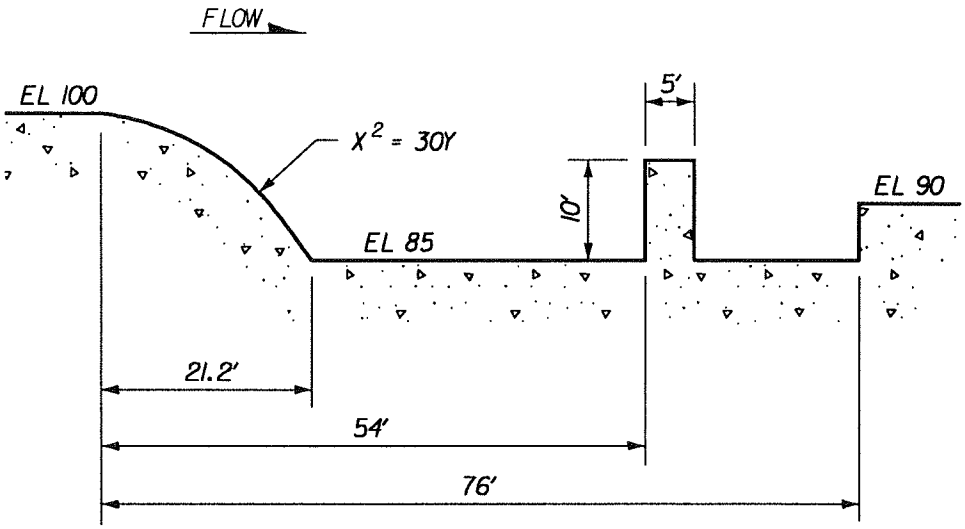
TYPE 3 DESIGN DROP STRUCTURE
RESULTING SCOUR AFTER
5 HR (PROTOTYPE) FOR
VARIOUS TAILWATER ELEVATIONS
DISCHARGE 250 CFS/FT
IV ON 2H RIPRAP SLOPE



TYPE 3 DESIGN DROP STRUCTURE
RESULTING SCOUR AFTER
5 HR (PROTOTYPE) FOR
VARIOUS TAILWATER ELEVATIONS
DISCHARGE 250 CFS/FT
IV ON 3H RIPRAP SLOPE

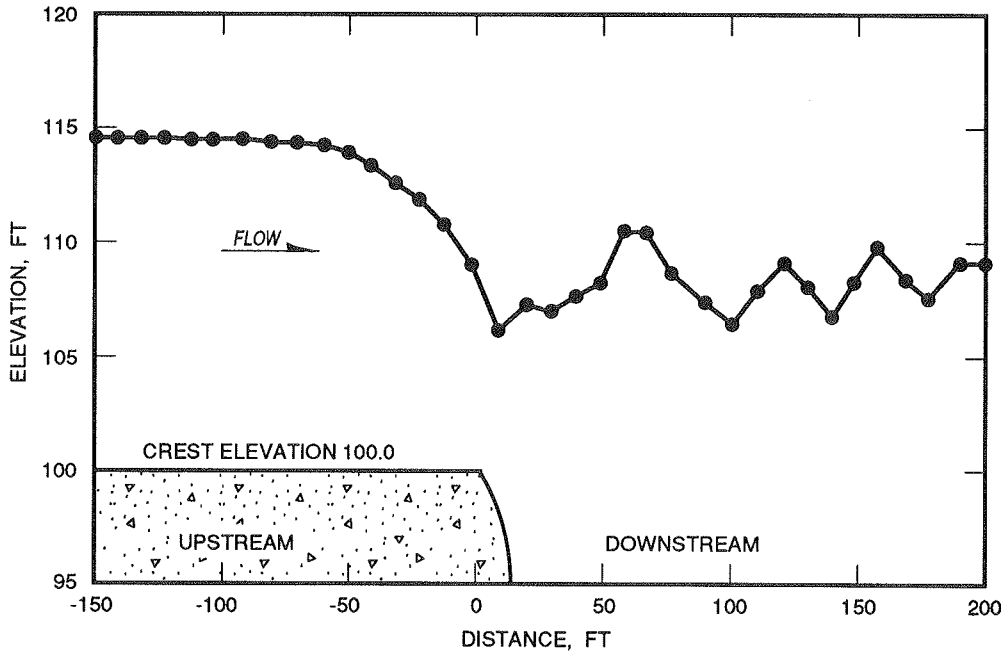


TYPE 4 DESIGN

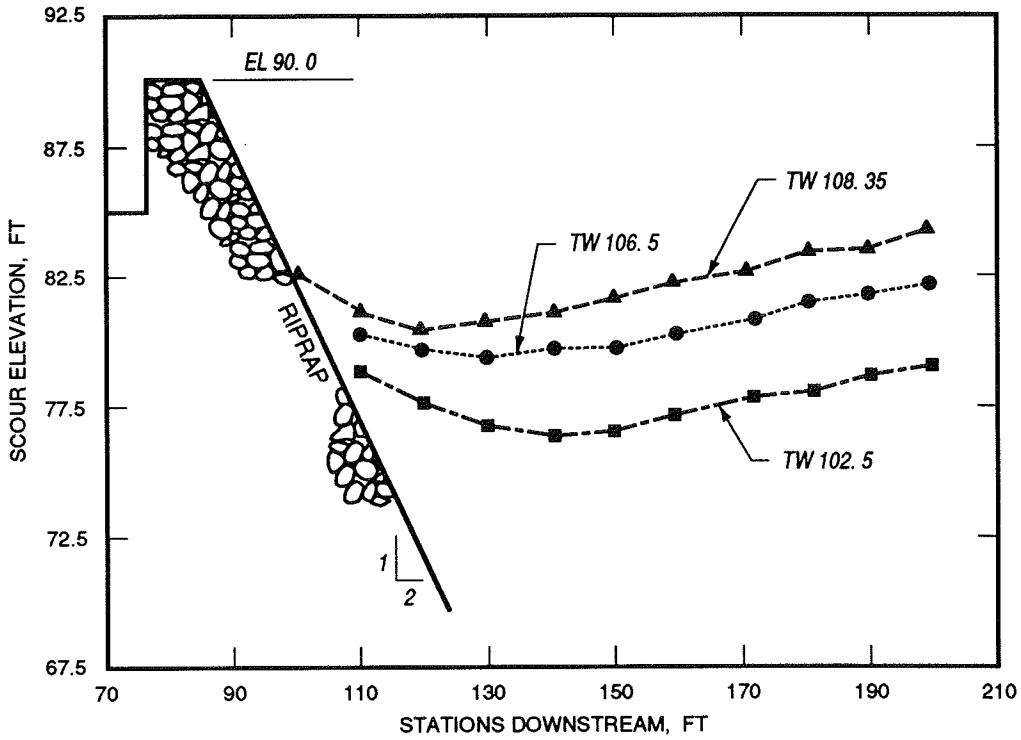


TYPE 5 DESIGN

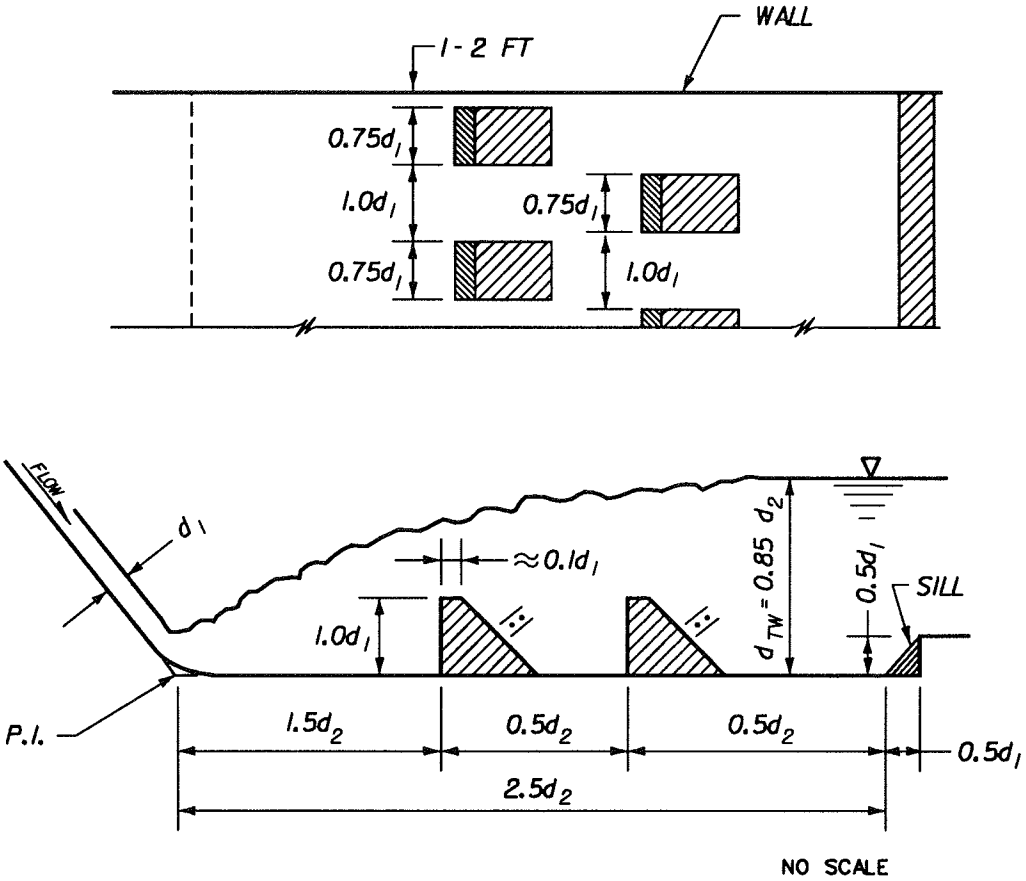
TYPE 4 AND 5 DESIGN
DROP STRUCTURES



TYPE 5 DESIGN
DROP STRUCTURE
WATER-SURFACE PROFILE
DISCHARGE 250 CFS/FT
TAILWATER EL 106.5

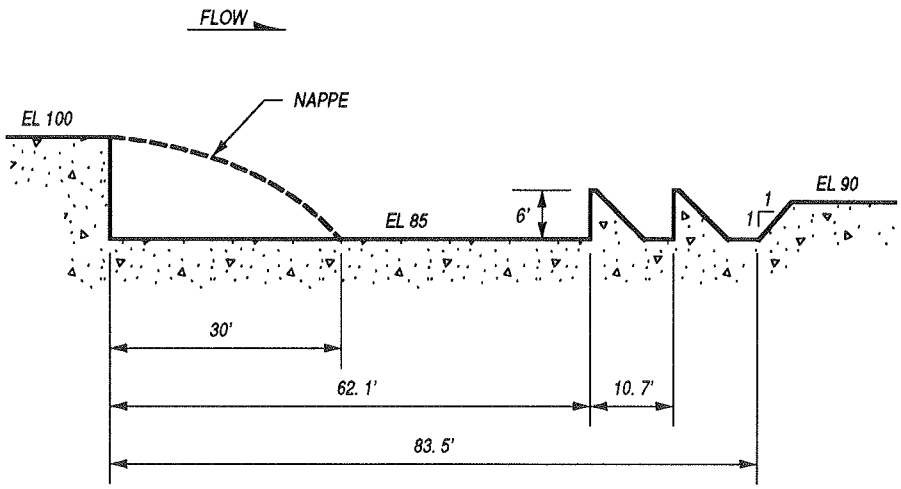


TYPE 5 DESIGN DROP STRUCTURE
RESULTING SCOUR AFTER
5 HR (PROTOTYPE) FOR
VARIOUS TAILWATER ELEVATIONS
DISCHARGE 250 CFS/FT
IV ON 2H RIPRAP SLOPE

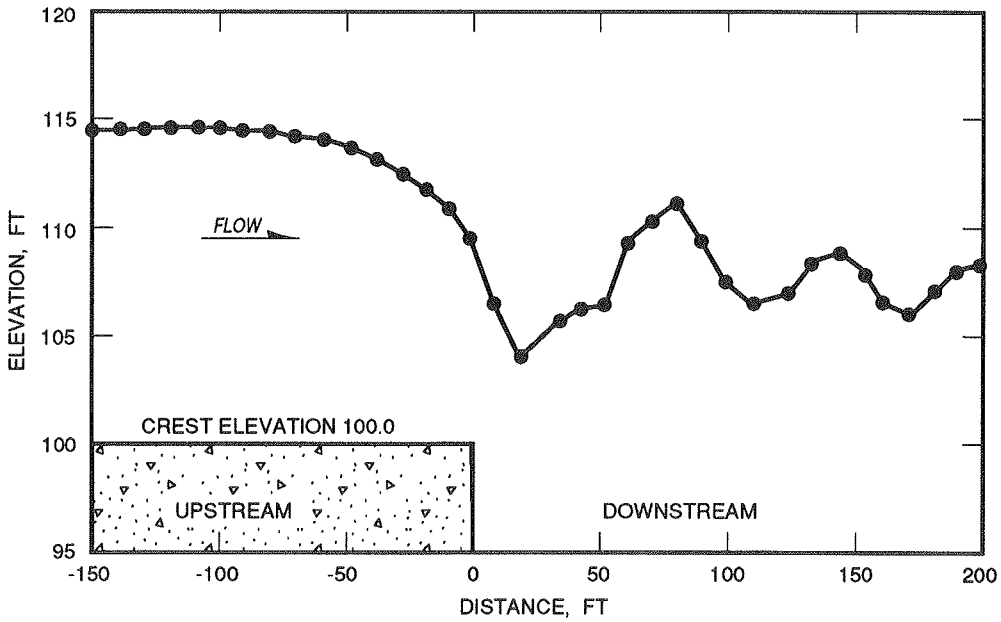


NOTE: BASED ON GUIDANCE FROM BASCO (1969)

DESIGN GUIDANCE

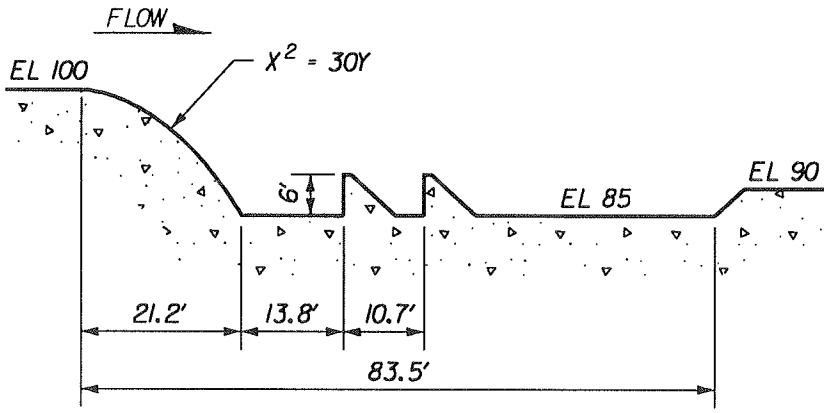


ELEVATION

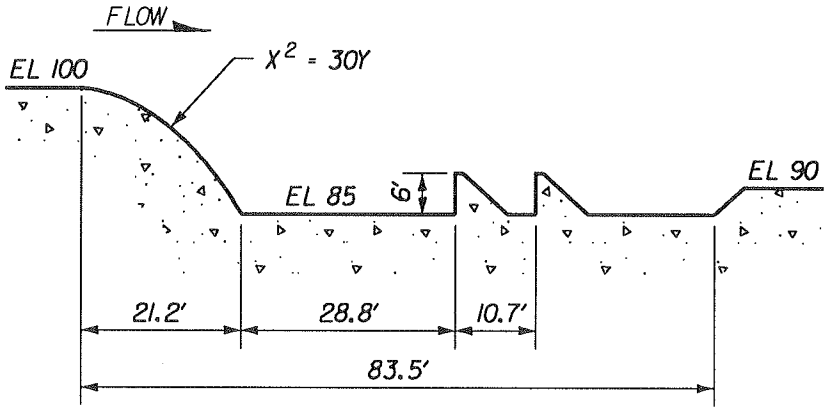


WATER-SURFACE PROFILE

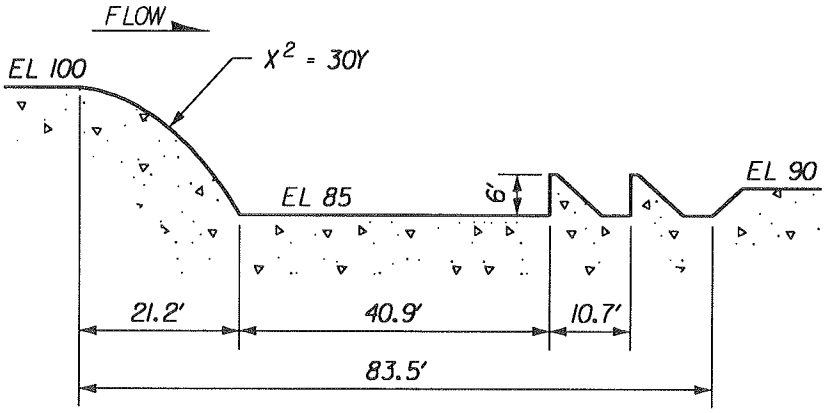
TYPE 7 DESIGN
DROP STRUCTURE AND
WATER-SURFACE PROFILE
DISCHARGE 250 CFS/FT
TAILWATER EL 106.5



TYPE 10 DESIGN

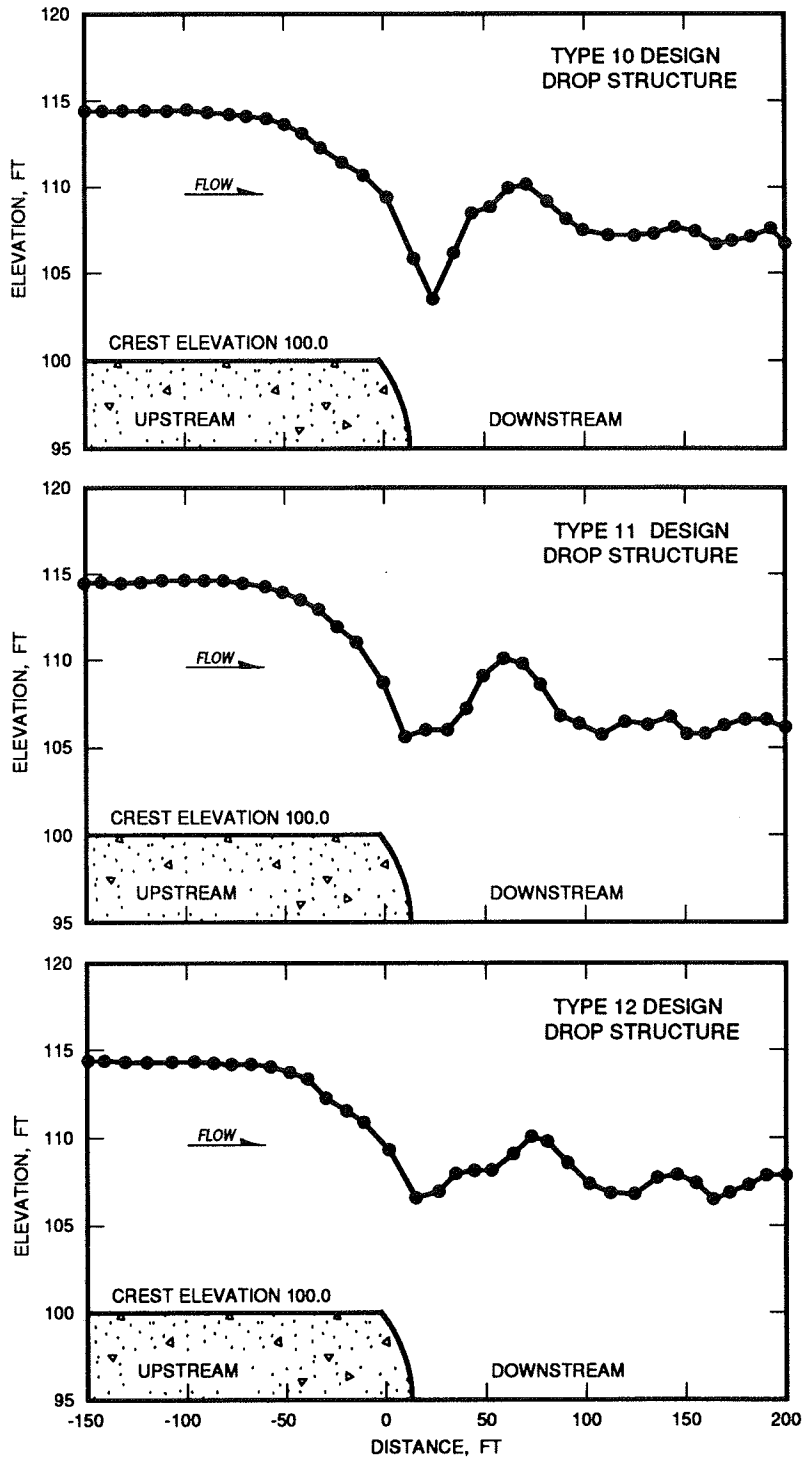


TYPE 11 DESIGN

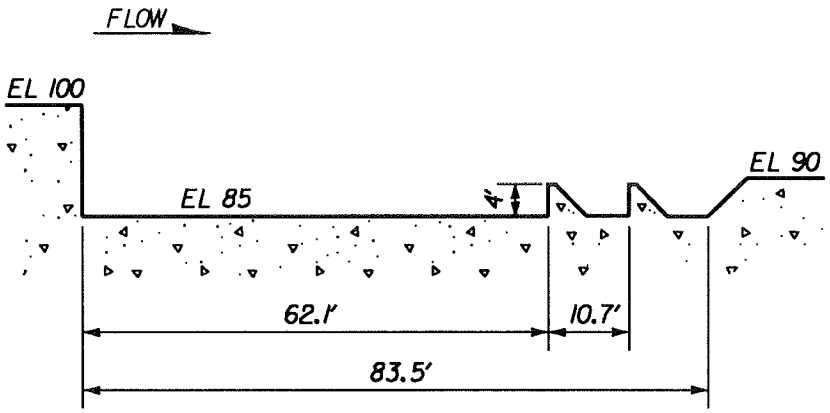


TYPE 12 DESIGN

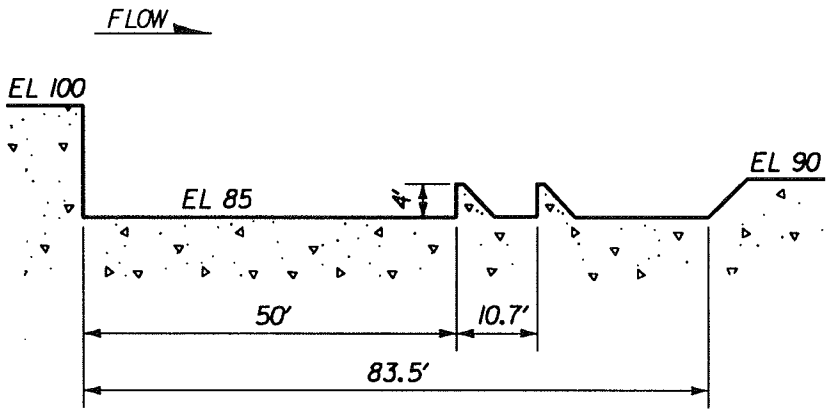
TYPE 10, 11, AND 12 DESIGN
DROP STRUCTURES



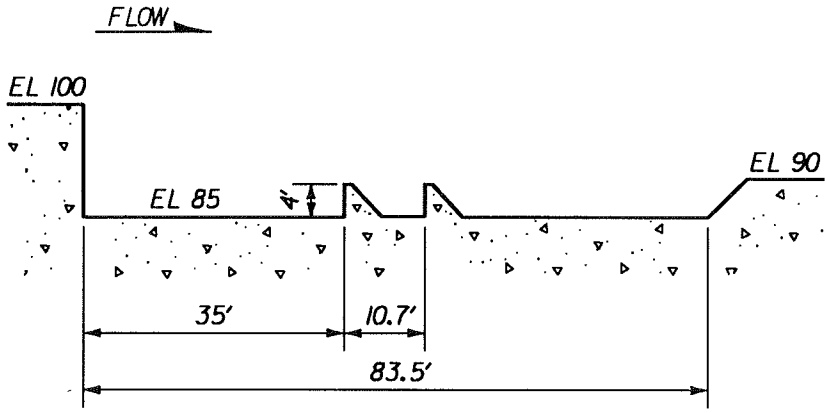
TYPE 10, 11, AND 12
DESIGN DROP STRUCTURES
WATER-SURFACE PROFILES
DISCHARGE 250 CFS/FT
TAILWATER EL 106.5



TYPE 13 DESIGN

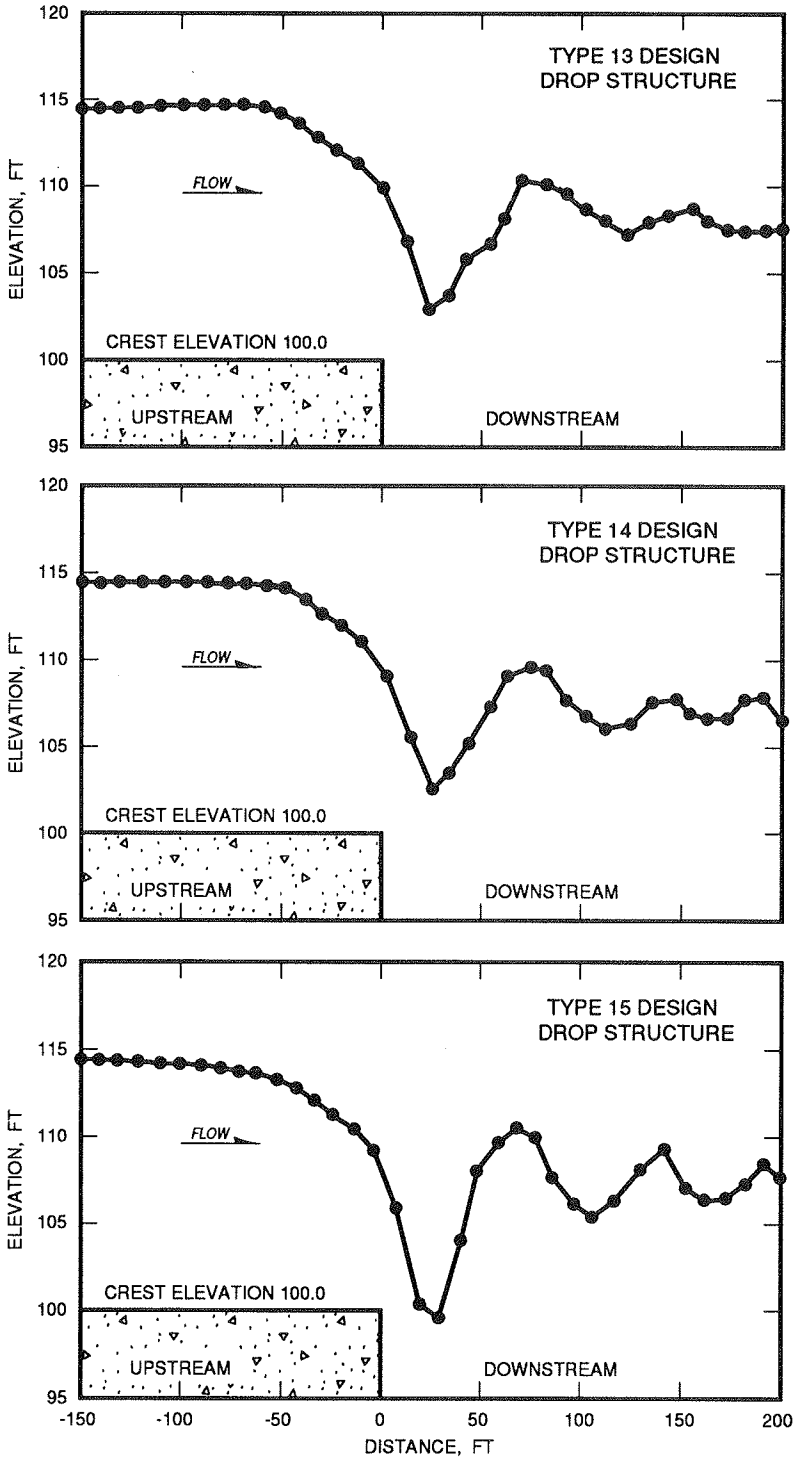


TYPE 14 DESIGN

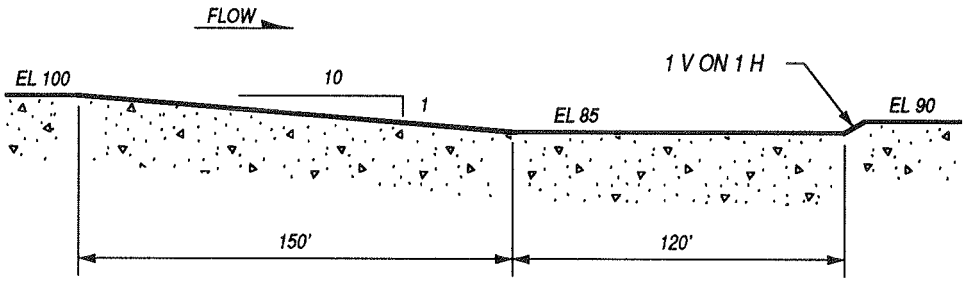


TYPE 15 DESIGN

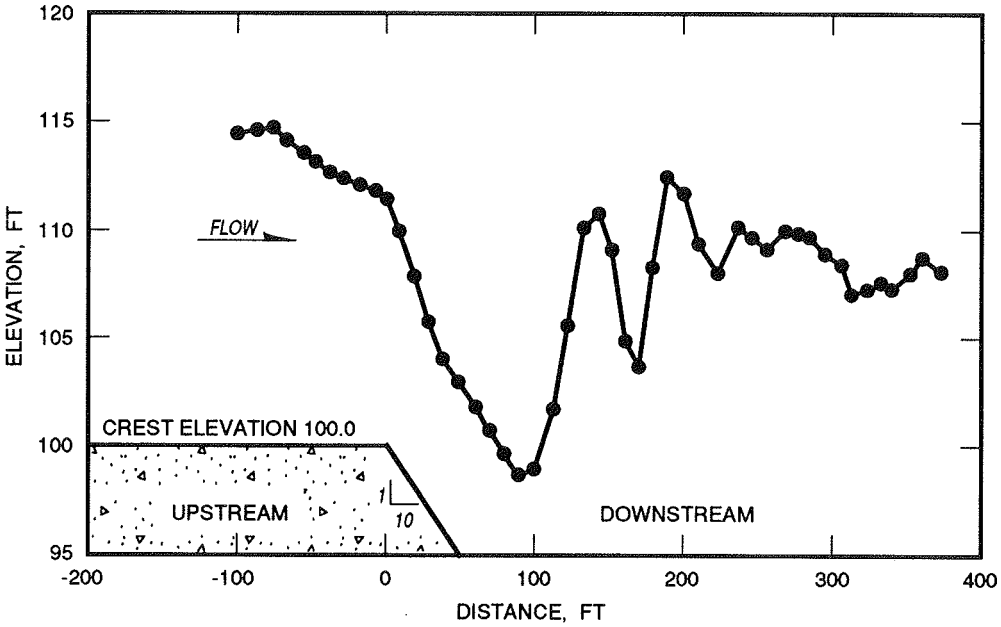
TYPE 13, 14, AND 15 DESIGN
DROP STRUCTURES



TYPE 13, 14, AND 15 DESIGN
DROP STRUCTURES
WATER-SURFACE PROFILES
DISCHARGE 250 CFS/FT
TAILWATER EL 106.5

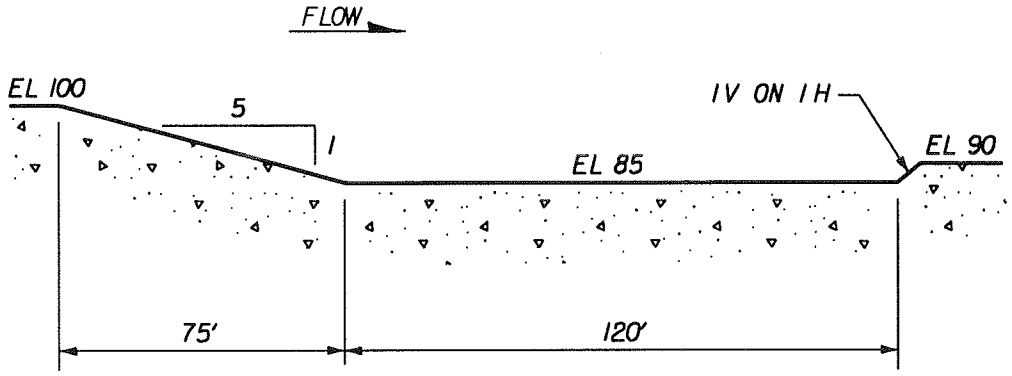


ELEVATION

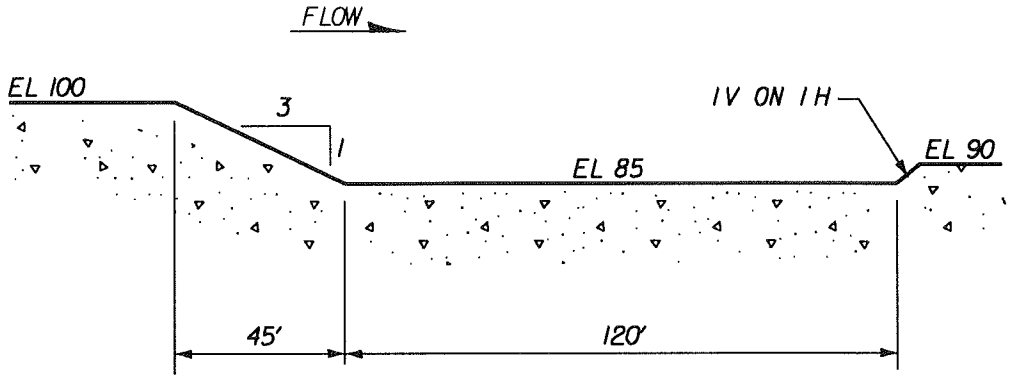


WATER-SURFACE PROFILE

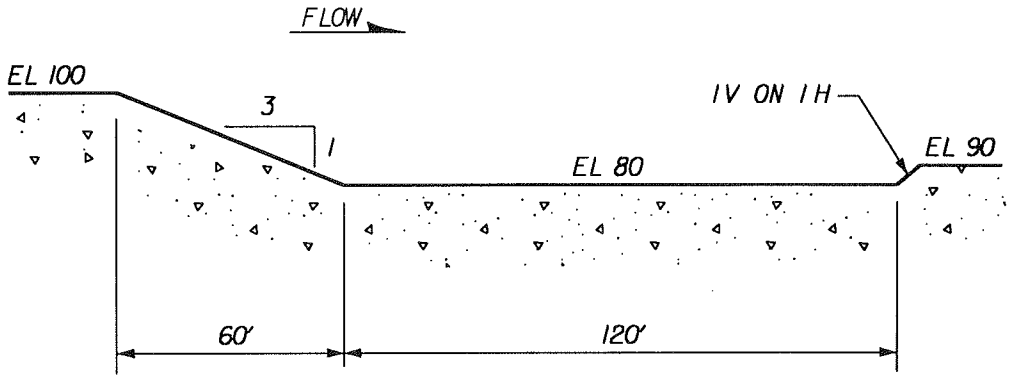
TYPE 100 DESIGN
GROUTED STONE DROP STRUCTURE
WATER-SURFACE PROFILE
DISCHARGE 209.3 CFS/FT
TAILWATER EL 108.4



TYPE 101 DESIGN

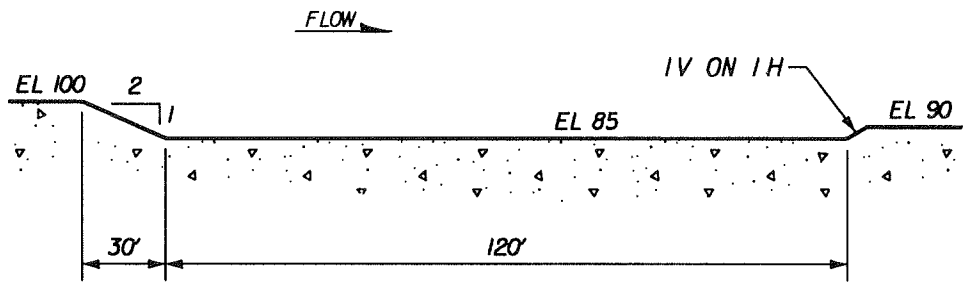


TYPE 102 DESIGN

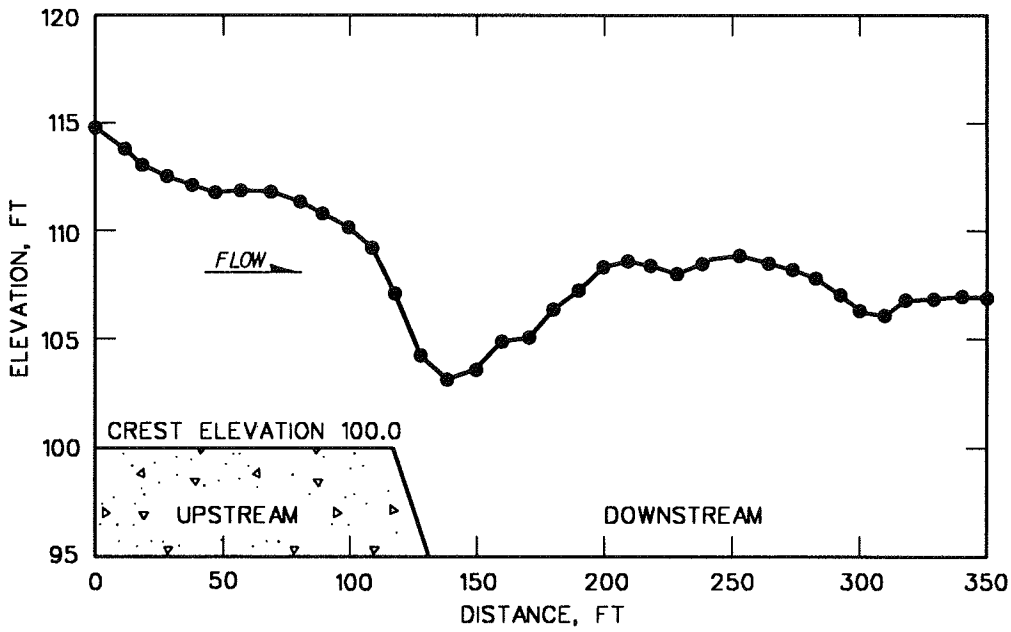


TYPE 103 DESIGN

TYPE 101, 102, AND 103 GROUTED DROP STRUCTURES

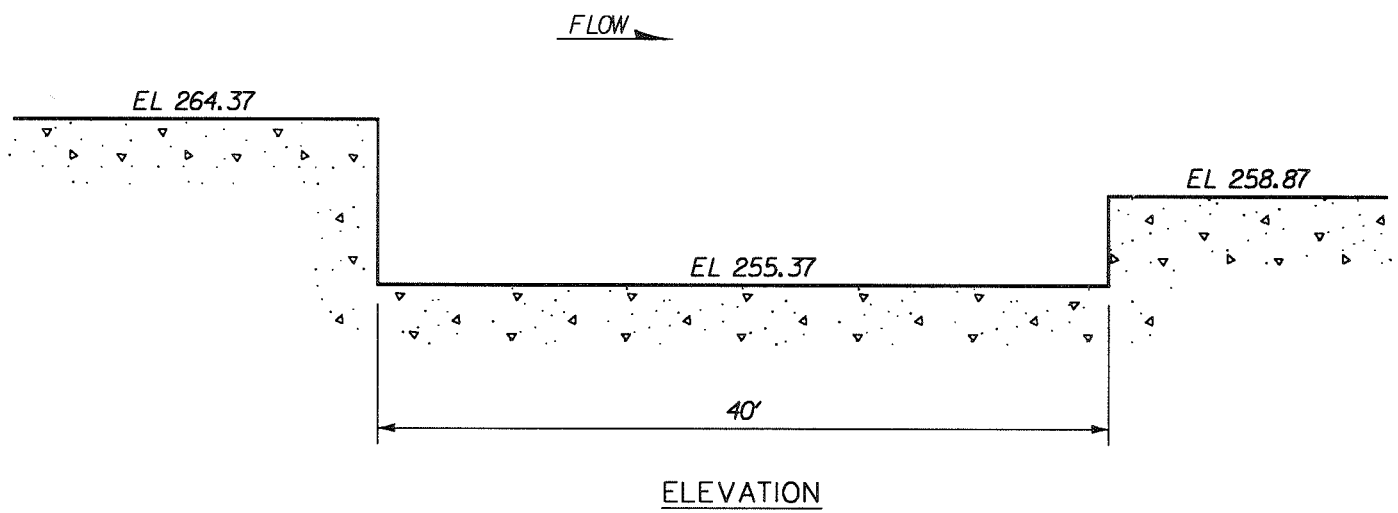


ELEVATION

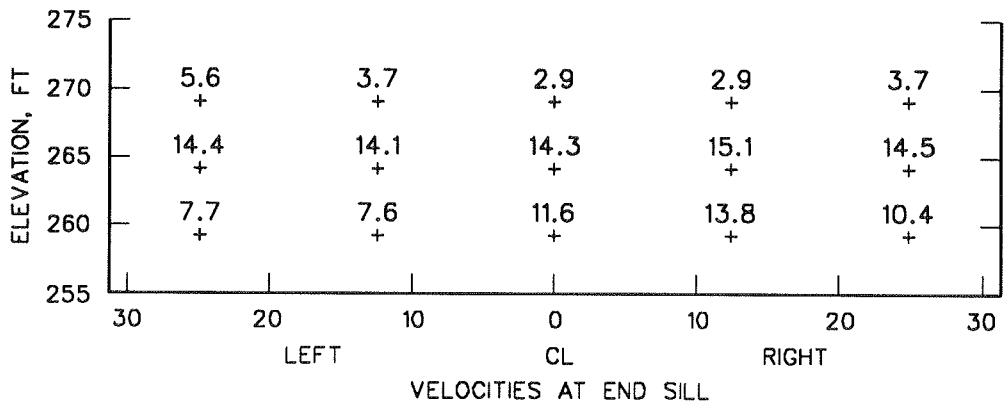


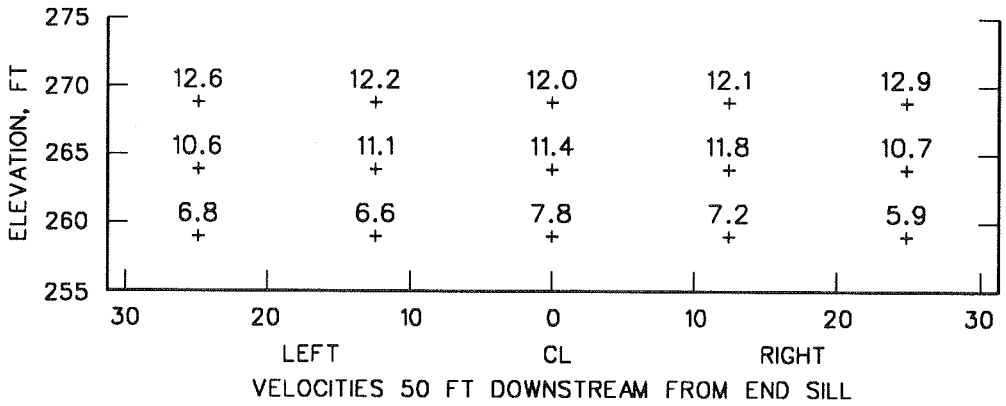
WATER-SURFACE PROFILE

TYPE 104 DESIGN
GROUTED STONE DROP STRUCTURE
WATER-SURFACE PROFILE
DISCHARGE 209.3 CFS/FT
TAILWATER EL 108.4

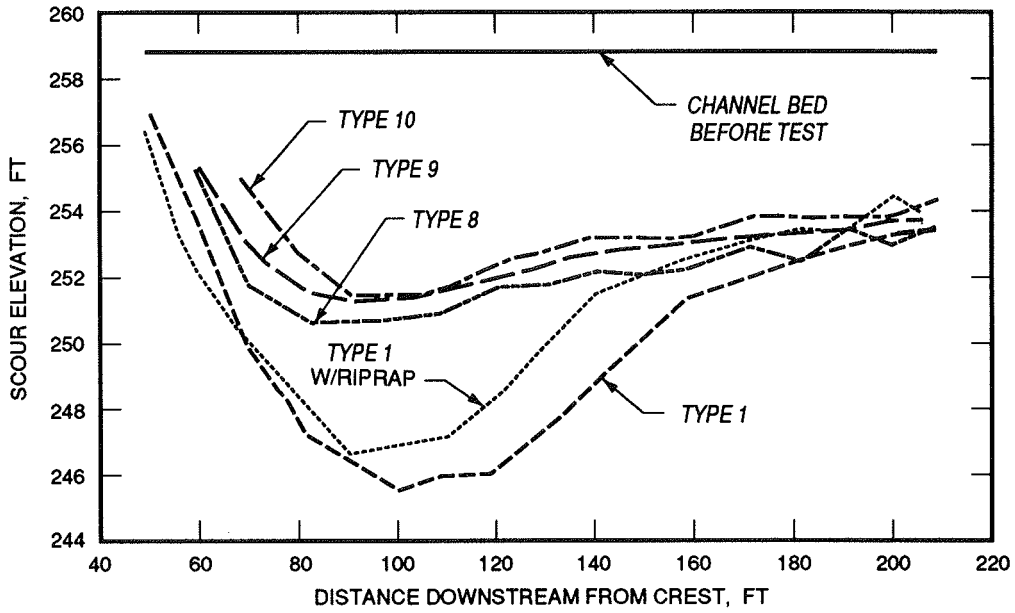


TYPE 1 DESIGN
DROP STRUCTURE
STA 1022+98.55

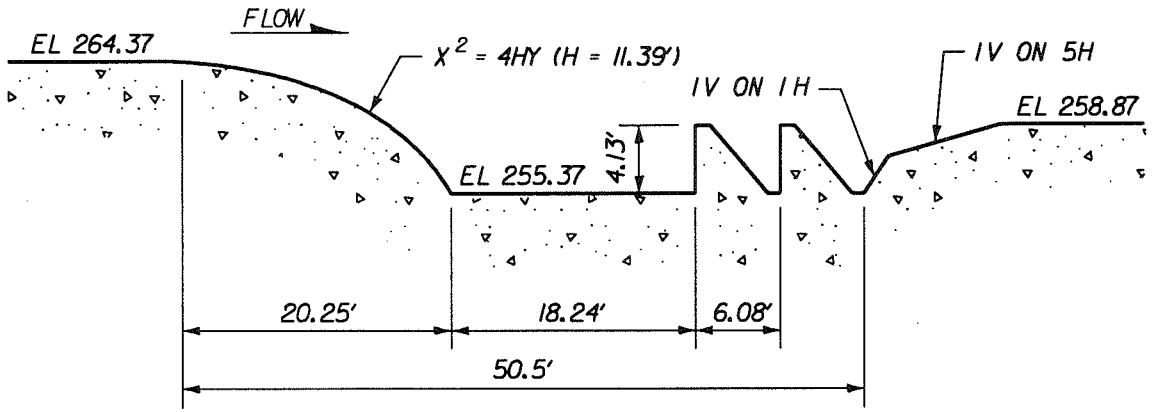




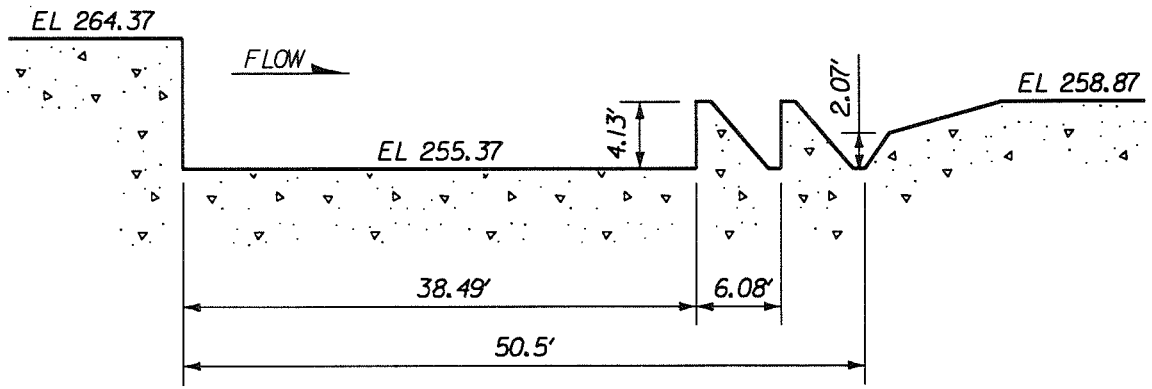
TYPE 1 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 1022 + 98.55
DISCHARGE 125 CFS/FT
TAILWATER EL 269.87, n = 0.03
LOOKING DOWNSTREAM



RESULTS OF SCOUR TESTS
5 HR PROTOTYPE
DISCHARGE 125 CFS/FT
n = 0.02
STA 1022 + 98.55

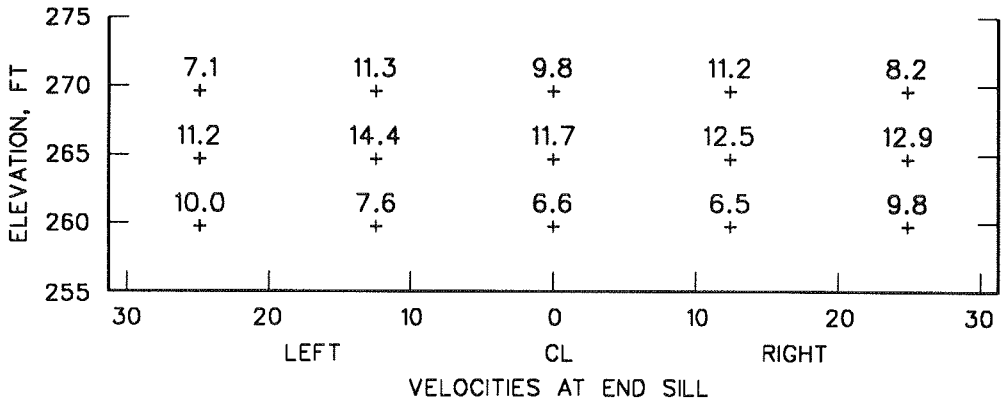


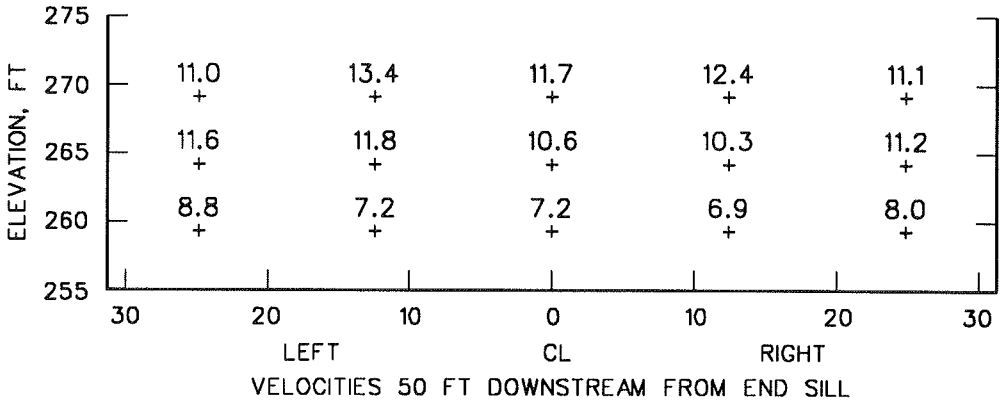
TYPE 2 DESIGN



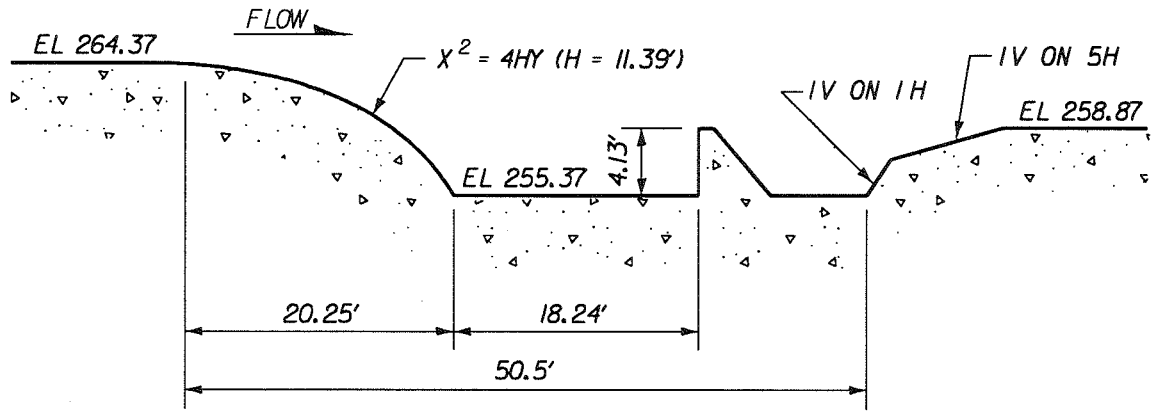
TYPE 3 DESIGN

TYPE 2 AND 3 DESIGN
DROP STRUCTURES
STA 1022+98.55

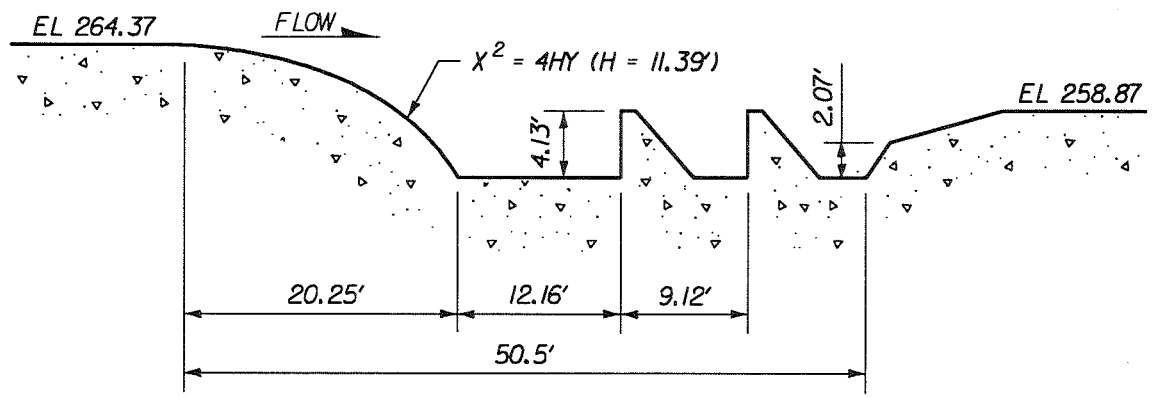




TYPE 2 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 1022 + 98.55
DISCHARGE 125 CFS/FT
TAILWATER EL 269.87, n = 0.03
LOOKING DOWNSTREAM

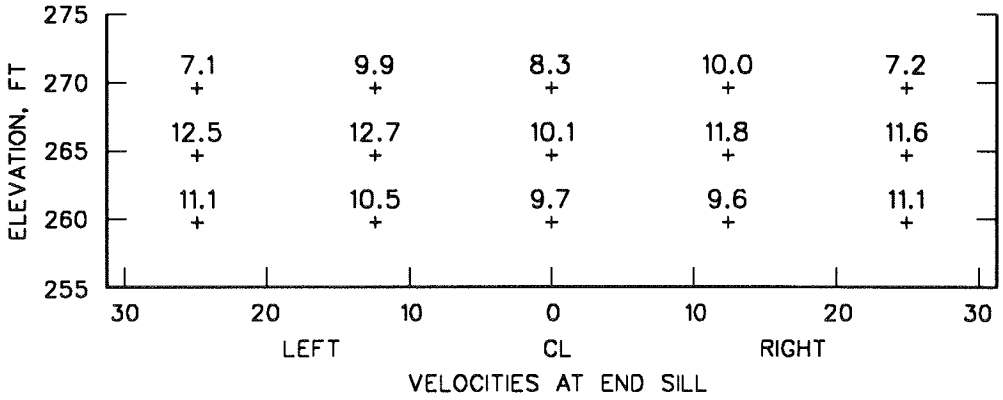


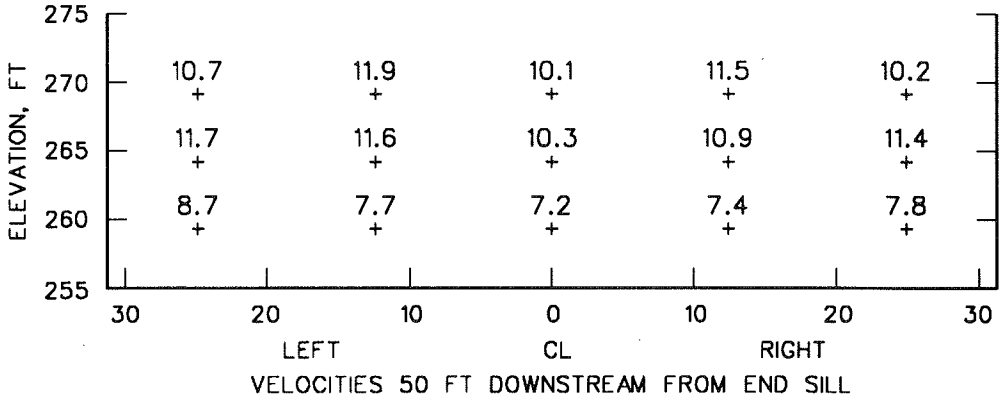
TYPE 4 DESIGN



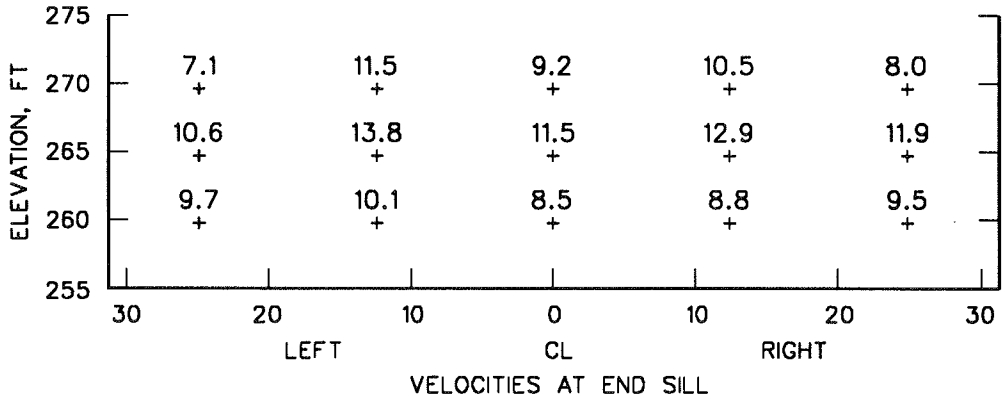
TYPE 5 DESIGN

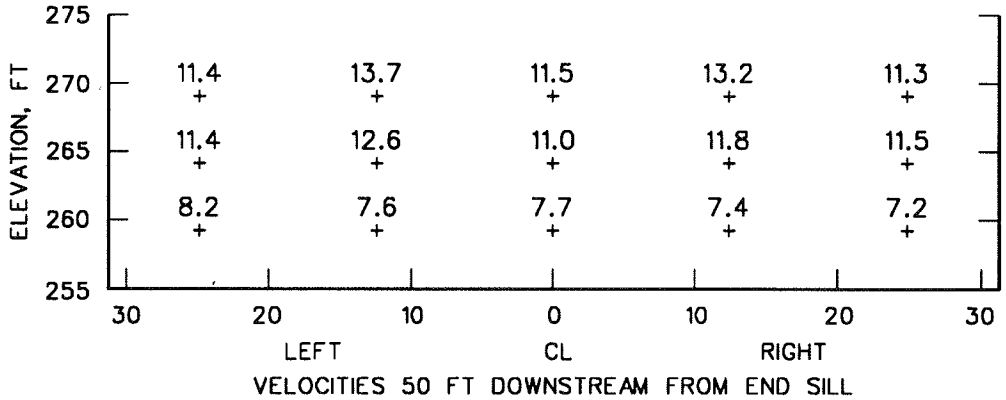
TYPE 4 AND 5 DESIGN
DROP STRUCTURES
STA 1022+98.55



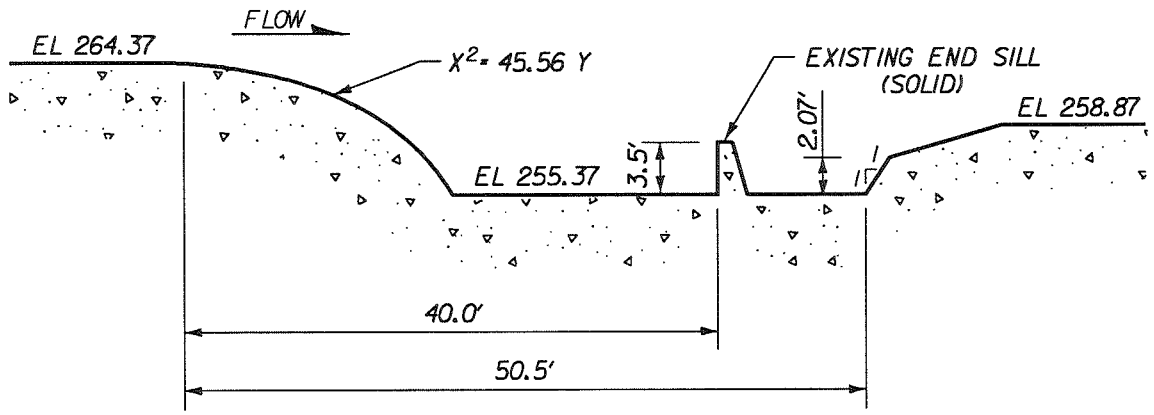


TYPE 4 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 1022 + 98.55
DISCHARGE 125 CFS/FT
TAILWATER EL 269.87, n = 0.03
LOOKING DOWNSTREAM

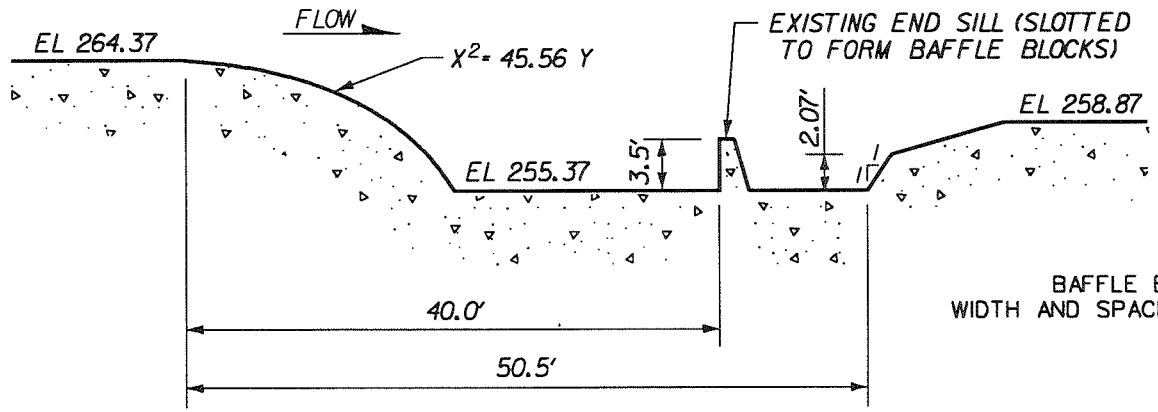




TYPE 5 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 1022 + 98.55
DISCHARGE 125 CFS/FT
TAILWATER EL 269.87, n = 0.03
LOOKING DOWNSTREAM



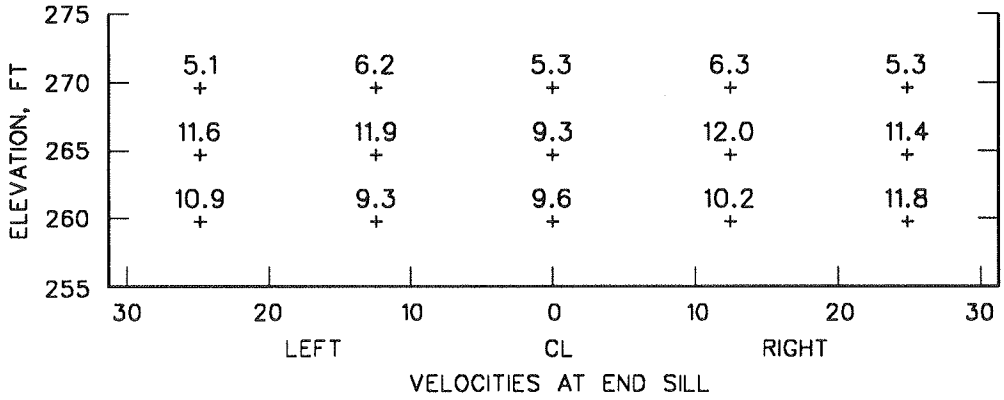
TYPE 6 DESIGN

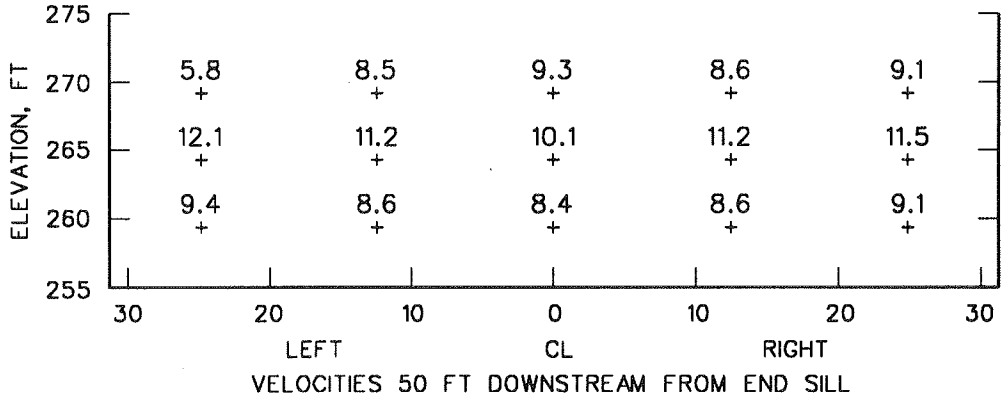


BAFFLE BLOCK
WIDTH AND SPACING = 4.19 FT

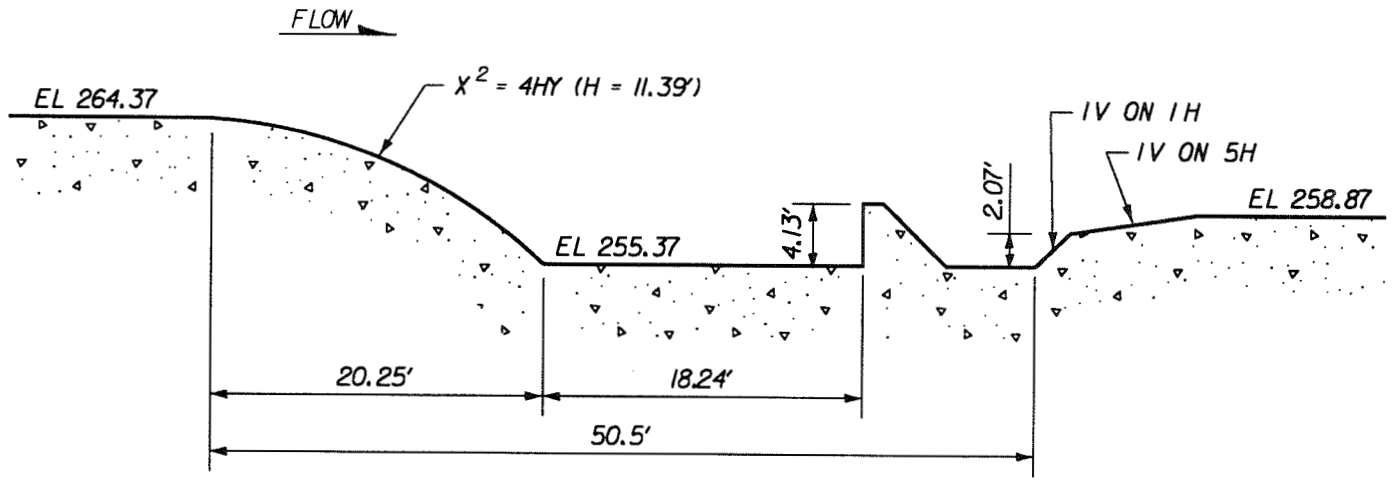
TYPE 7 DESIGN

TYPE 6 AND 7 DESIGN
DROP STRUCTURES
STA 1022+98.55



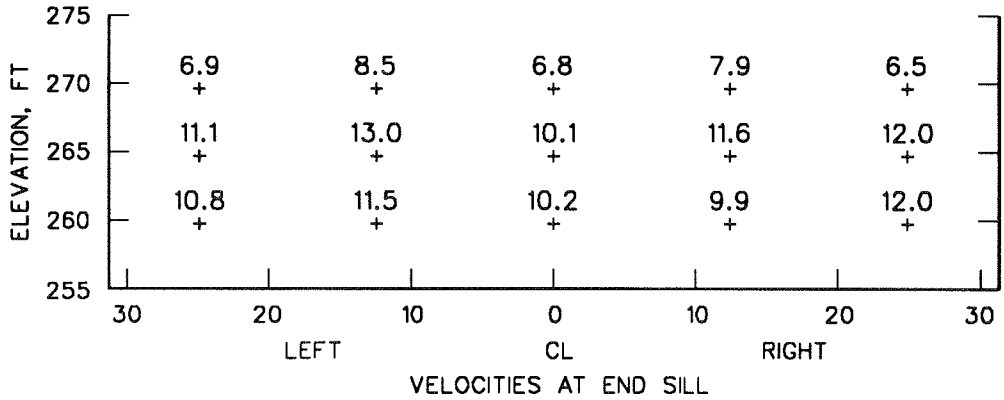


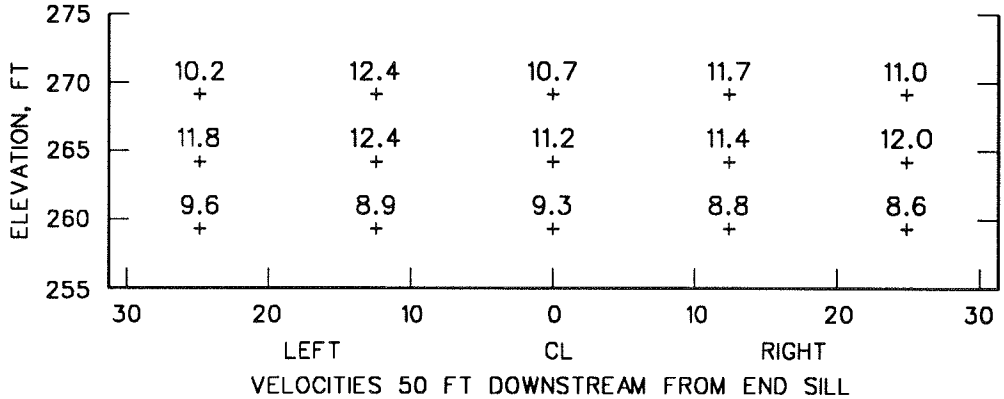
TYPE 7 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 1022 + 98.55
DISCHARGE 125 CFS/FT
TAILWATER EL 269.87, n = 0.03
LOOKING DOWNSTREAM



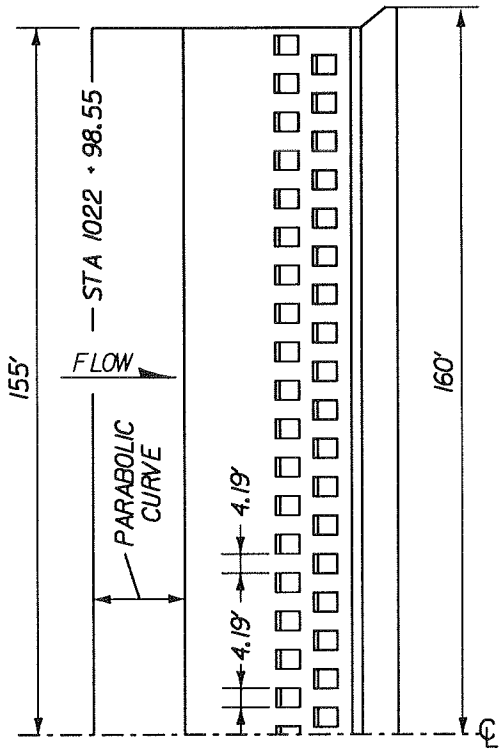
ELEVATION

TYPE 8 DESIGN
DROP STRUCTURE
STA 1022+98.55

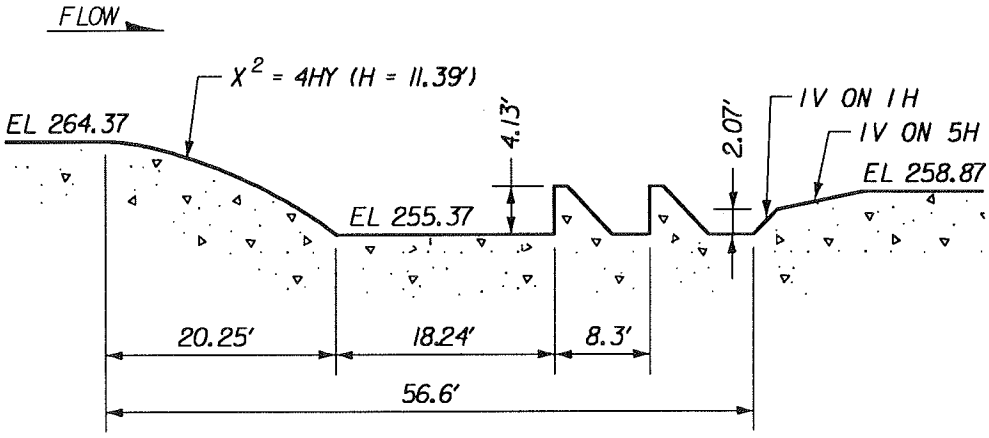




TYPE 8 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 1022 + 98.55
DISCHARGE 125 CFS/FT
TAILWATER EL 269.87, n = 0.03
LOOKING DOWNSTREAM

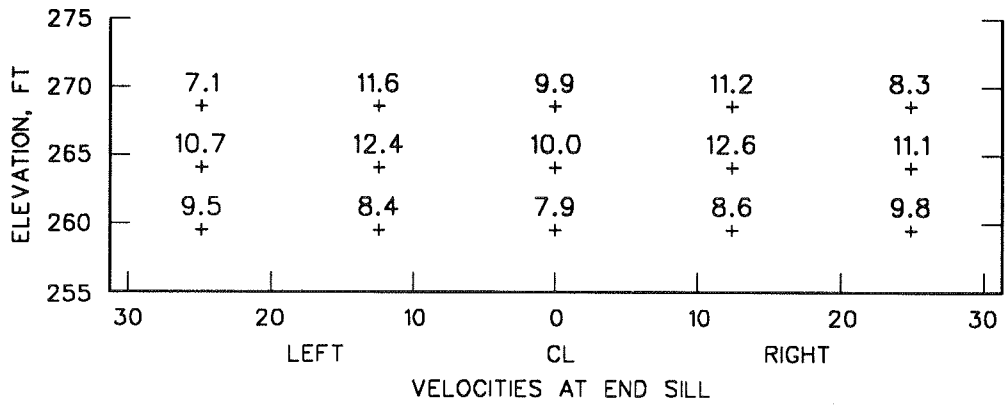


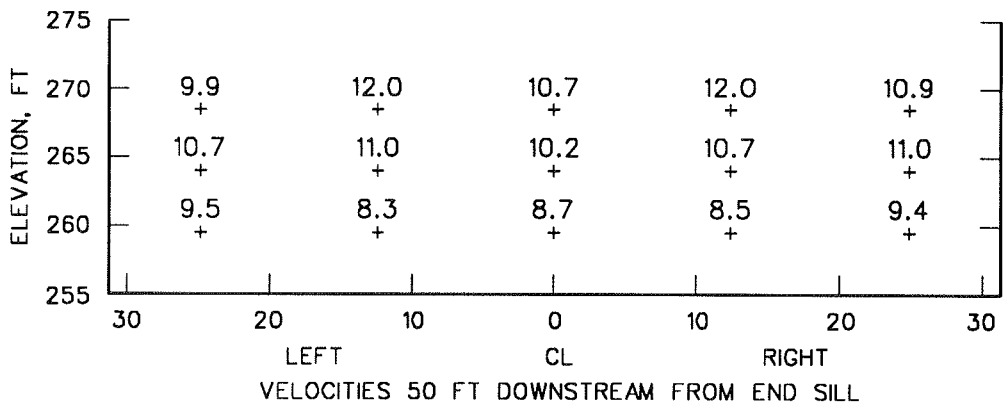
HALF PLAN



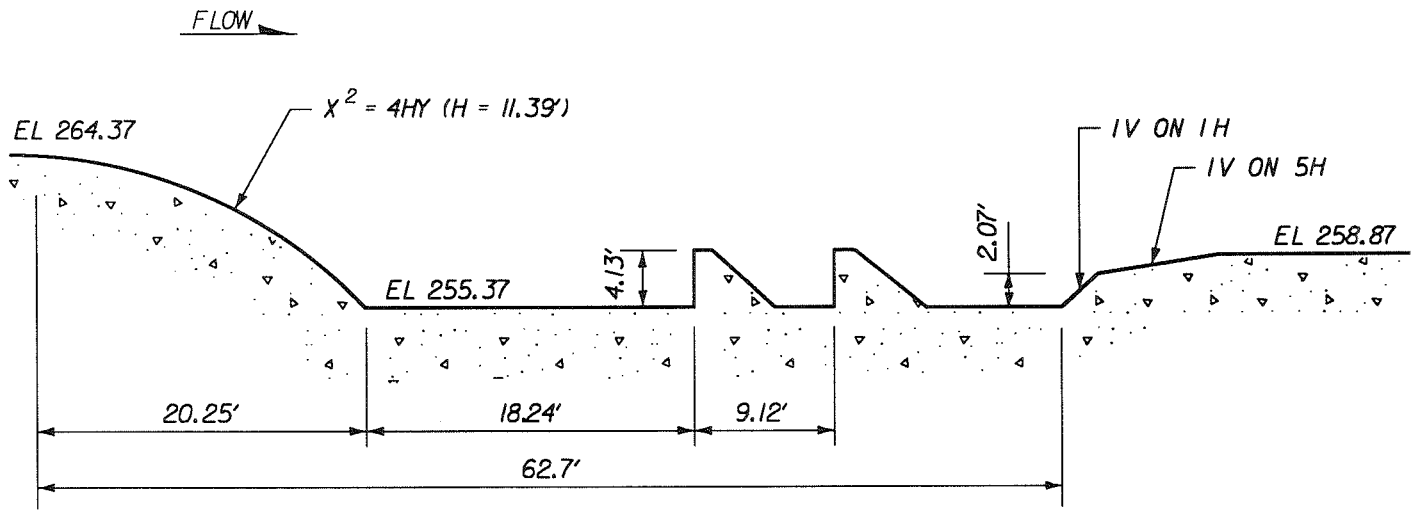
ELEVATION

DETAILS OF TYPE 9
DESIGN DROP STRUCTURE
STA 1022+98.55



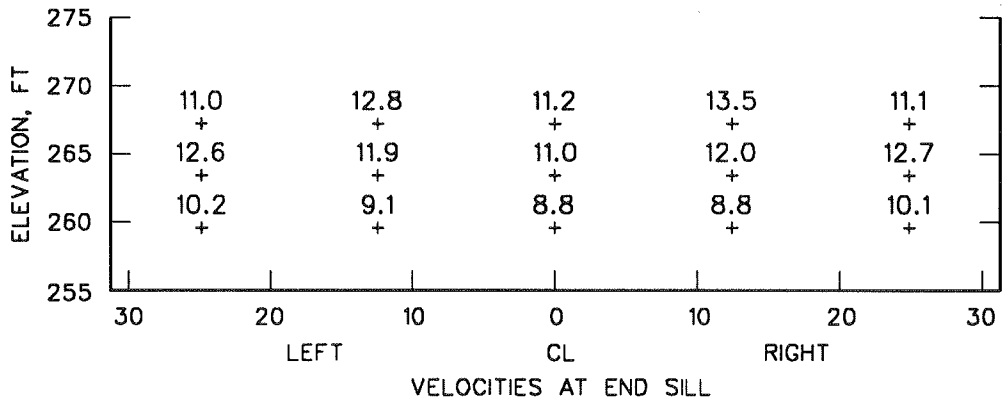


TYPE 9 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 1022 + 98.55
DISCHARGE 125 CFS/FT
TAILWATER EL 269.87, n = 0.03
LOOKING DOWNSTREAM

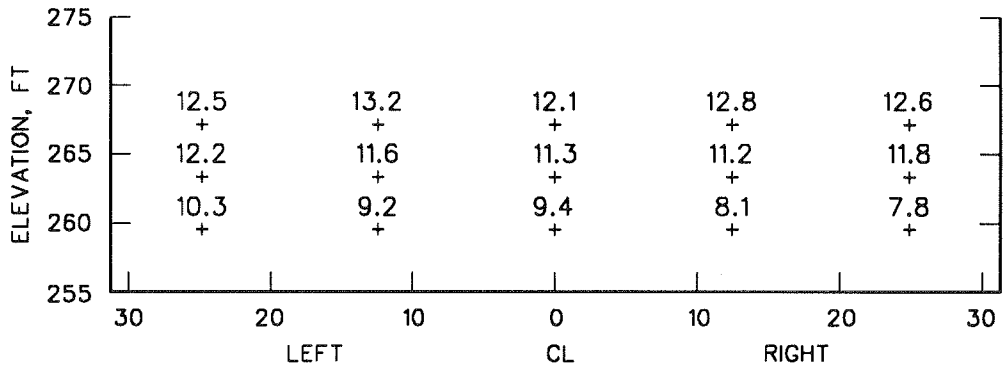


ELEVATION

TYPE 10 DESIGN
DROP STRUCTURE
STA 1022+98.55

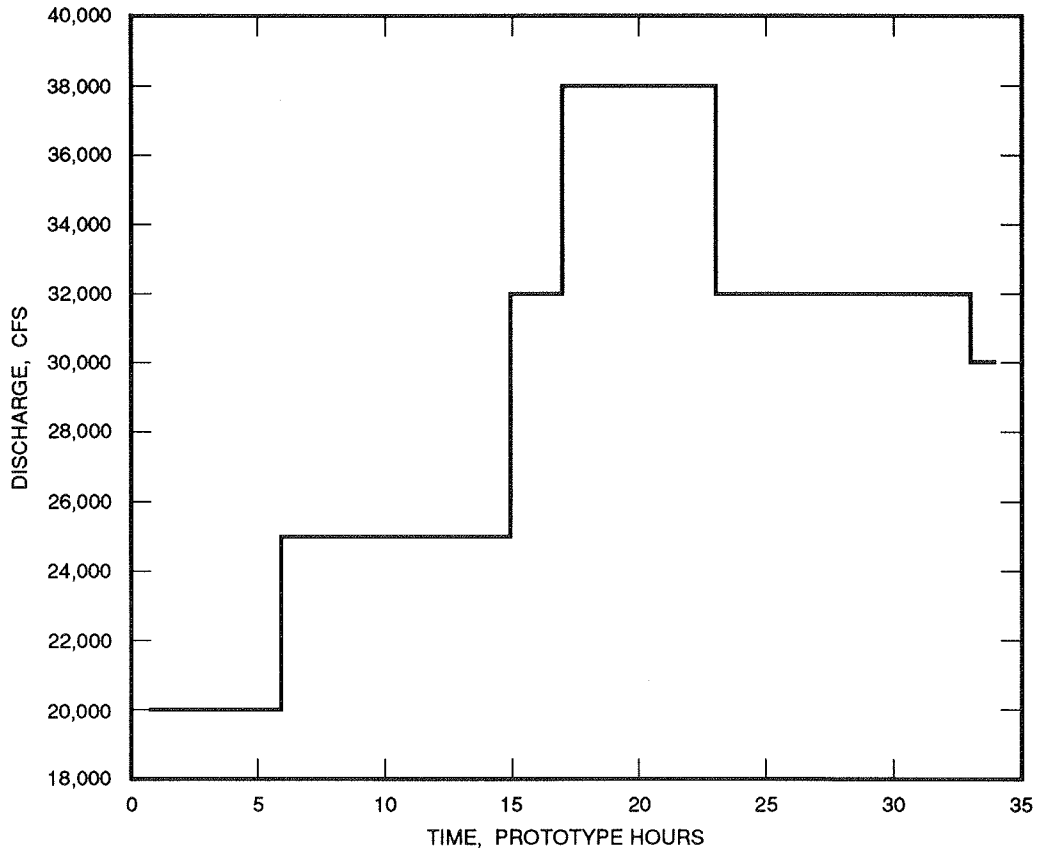


VELOCITIES AT END SILL

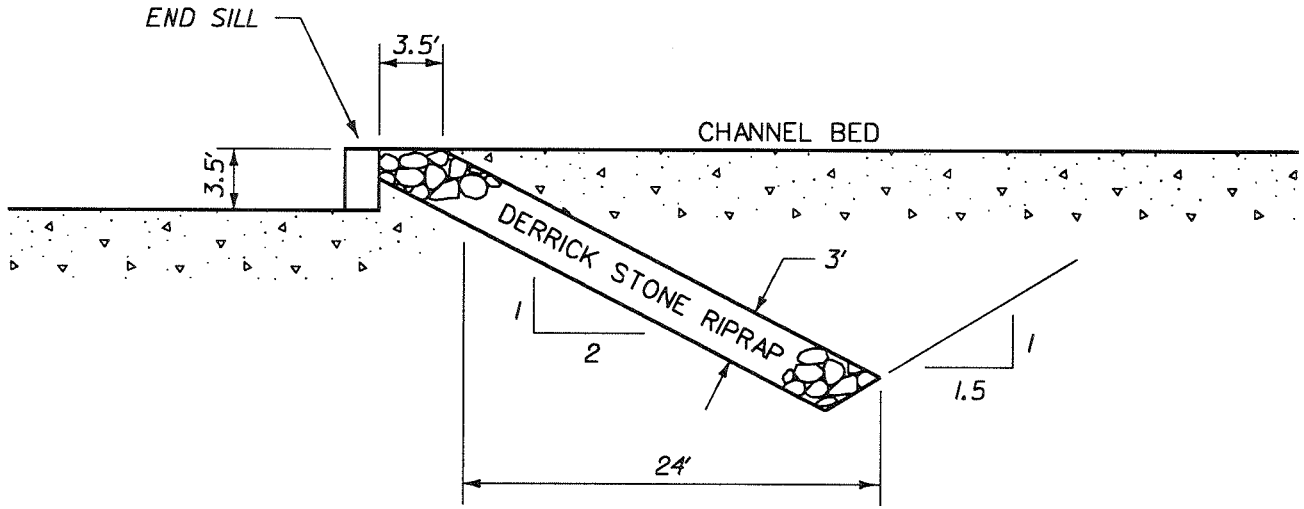


VELOCITIES 50 FT DOWNSTREAM FROM END SILL

TYPE 10 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 1022 + 98.55
DISCHARGE 125 CFS/FT
TAILWATER EL 269.87, n = 0.03
LOOKING DOWNSTREAM

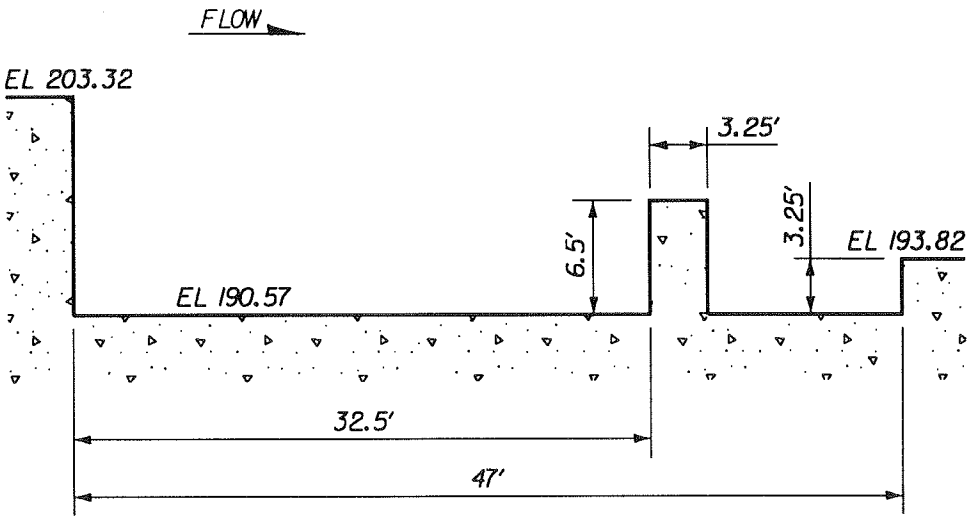


STEPPED HYDROGRAPH
USED FOR DROP STRUCTURE
AT STA 1022 + 98.55

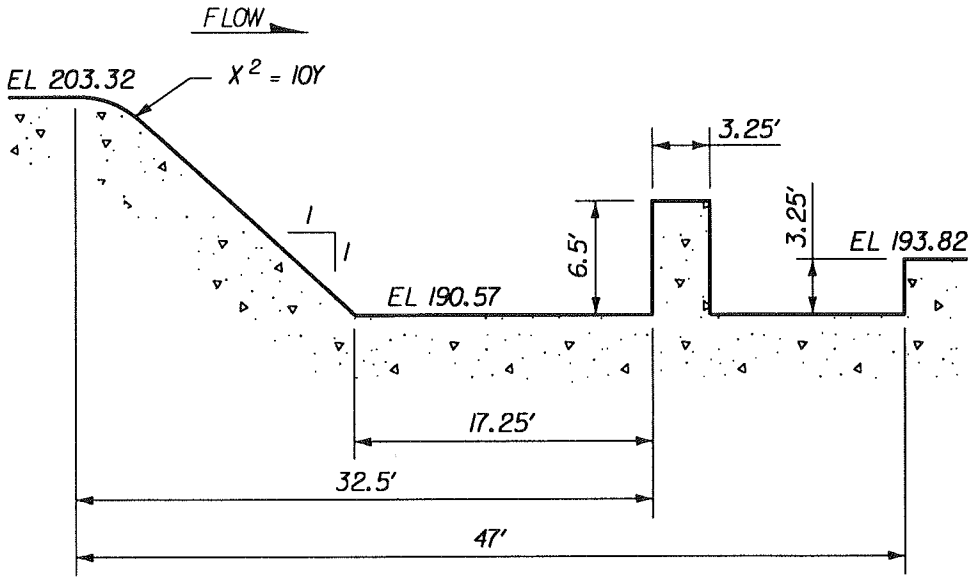


ELEVATION

TYPE 1 RIPRAP PLAN
STA 1022+98.55

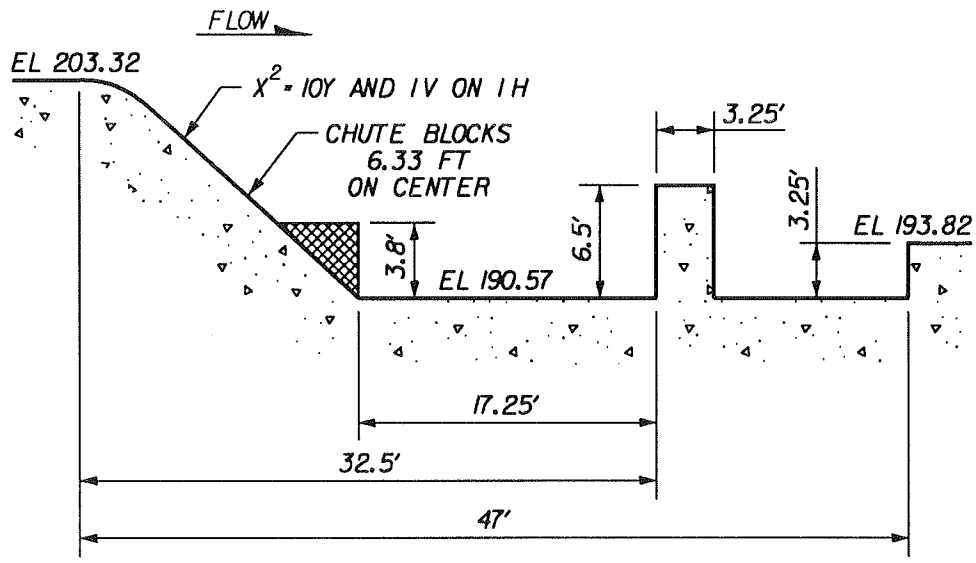


TYPE 1 DESIGN

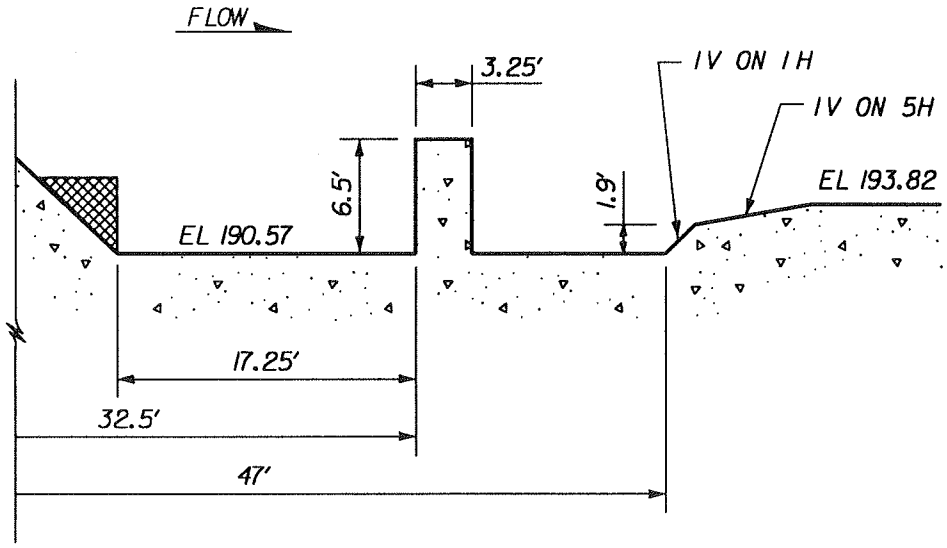


TYPE 2 DESIGN

TYPE 1 AND 2 DESIGN
DROP STRUCTURES
STA 836+50

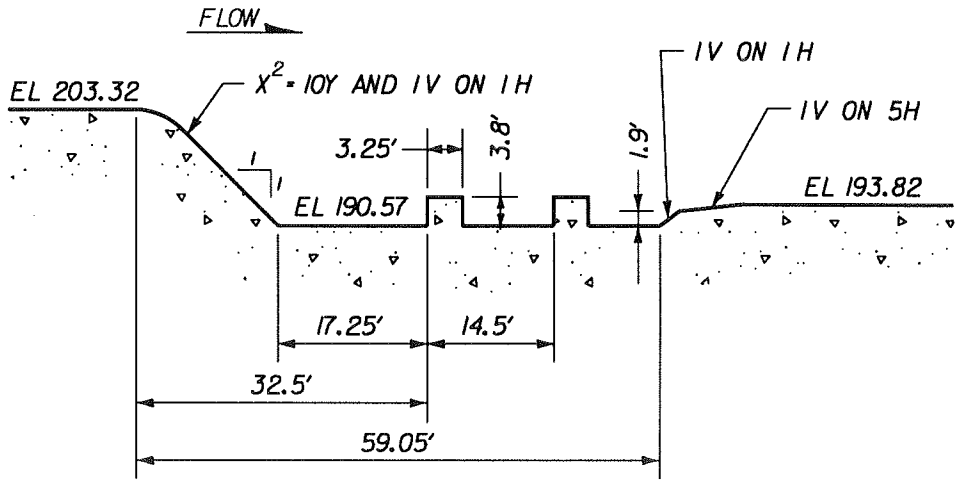


TYPE 3 DESIGN

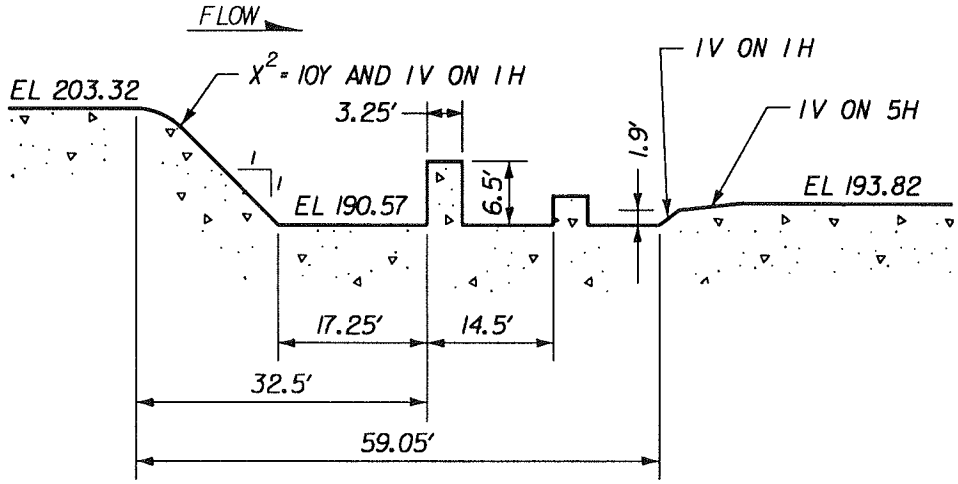


TYPE 4 DESIGN

TYPE 3 AND 4 DESIGN
DROP STRUCTURES
STA 836+50

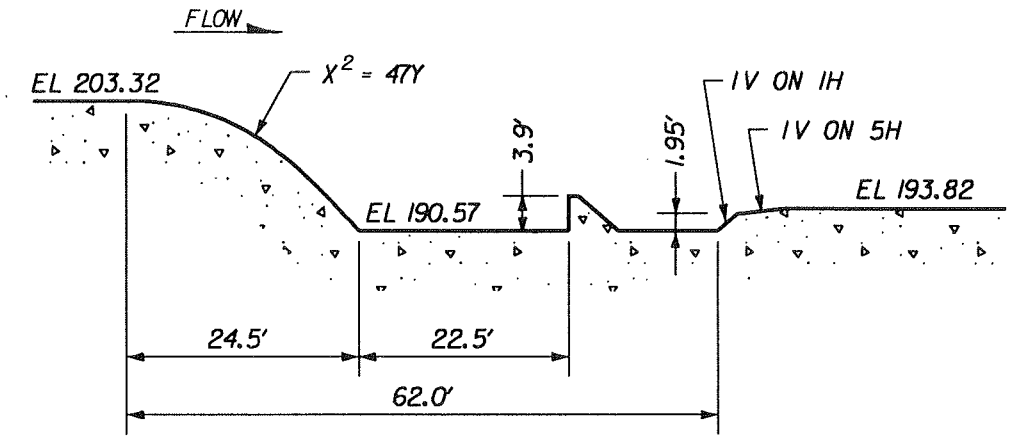


TYPE 5 DESIGN

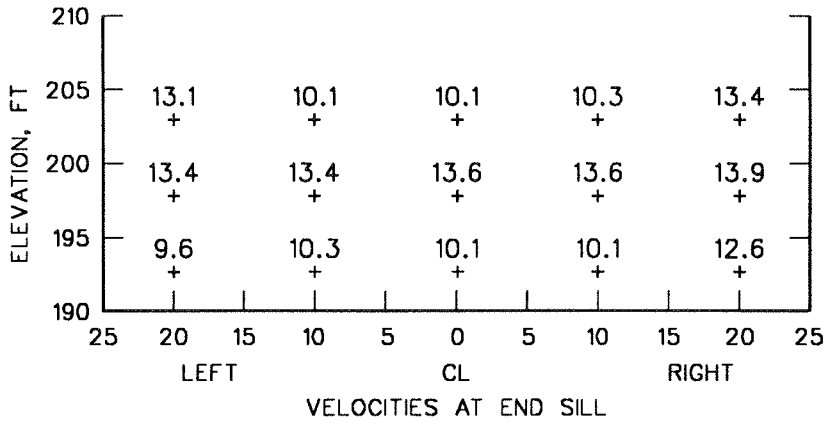


TYPE 6 DESIGN

TYPE 5 AND 6 DESIGN
DROP STRUCTURES
STA 836+50

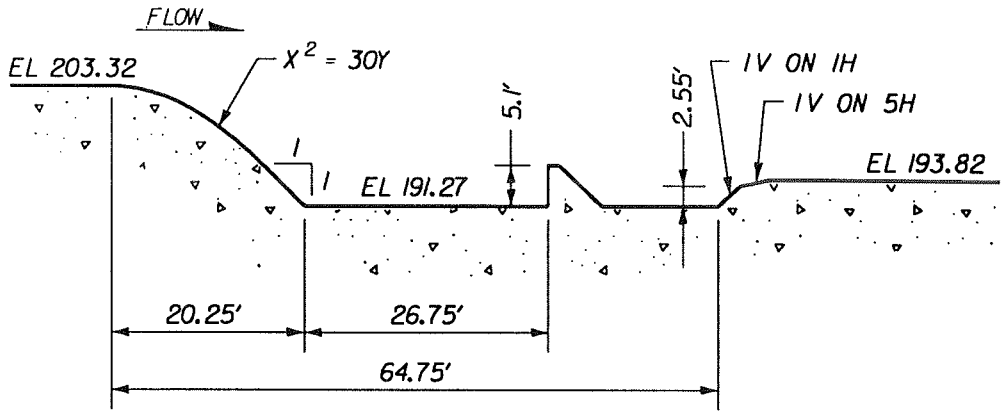


ELEVATION

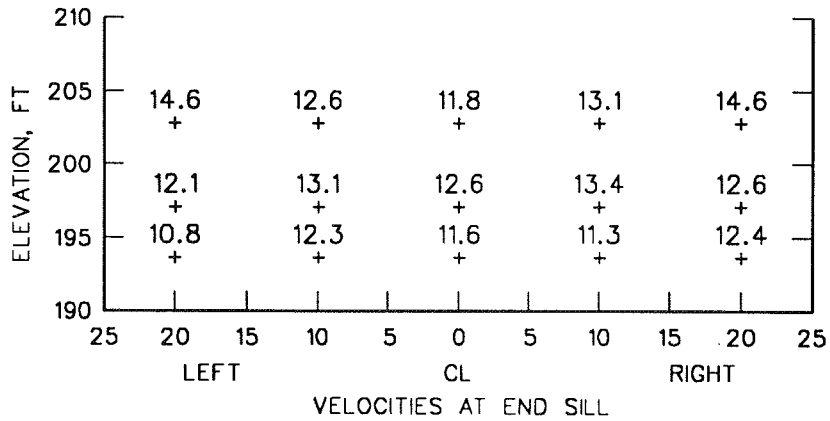


DISCHARGE 130 CFS/FT, TAILWATER EL 204.92, n = 0.03

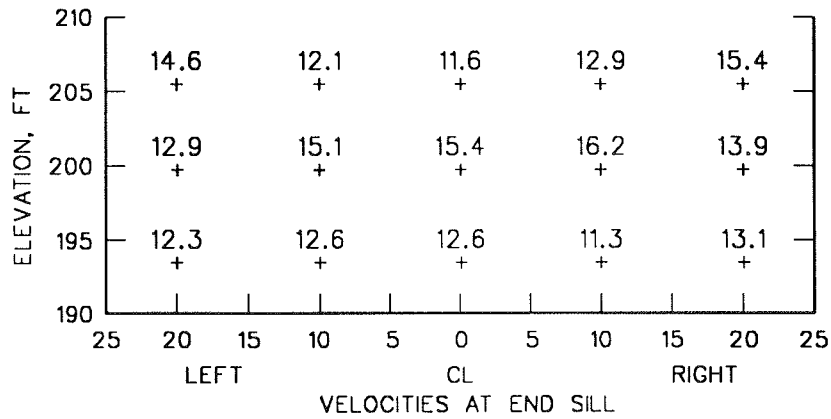
TYPE 7 DESIGN
DROP STRUCTURE
AVERAGE VELOCITIES MEASURED
STA 836 + 50



ELEVATION

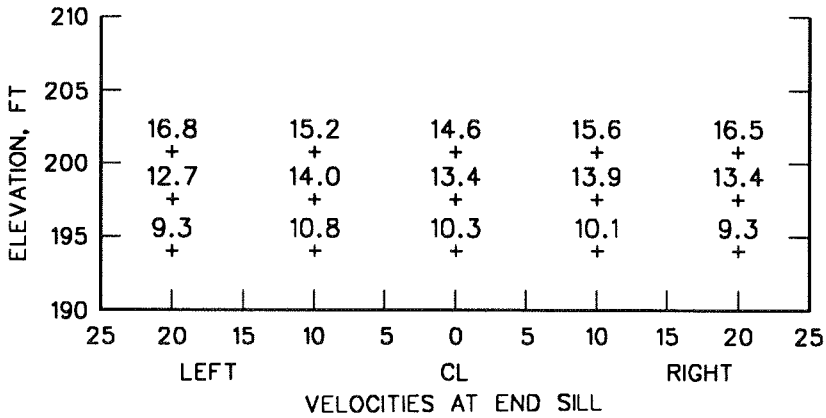


DISCHARGE 130 CFS/FT, TAILWATER EL 204.92, n = 0.03

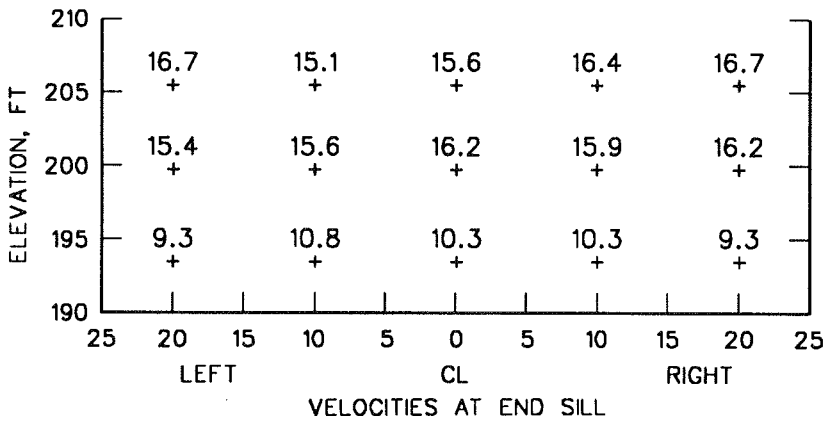


DISCHARGE 180 CFS/FT, TAILWATER EL 207.6, n = 0.03

TYPE 8 DESIGN
DROP STRUCTURE
AVERAGE VELOCITIES MEASURED
STA 836 + 50

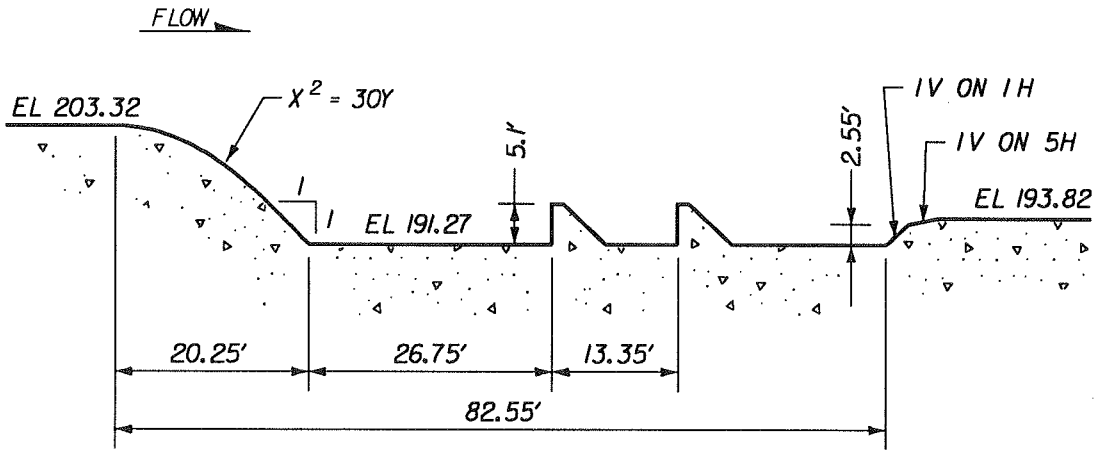


DISCHARGE 130 CFS/FT, TAILWATER EL 204.92, n = 0.03

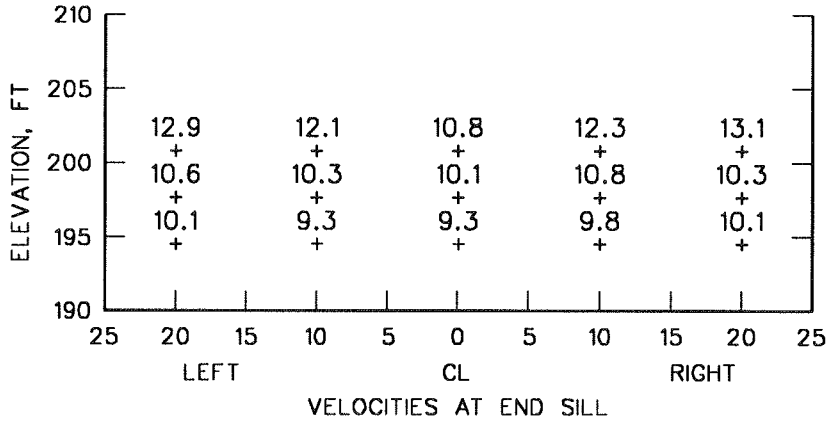


DISCHARGE 180 CFS/FT, TAILWATER EL 207.6, n = 0.03

TYPE 9 DESIGN
DROP STRUCTURE
AVERAGE VELOCITIES MEASURED
STA 836 + 50

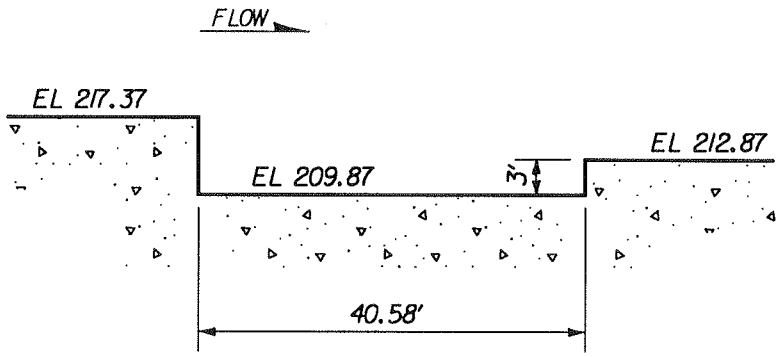


ELEVATION

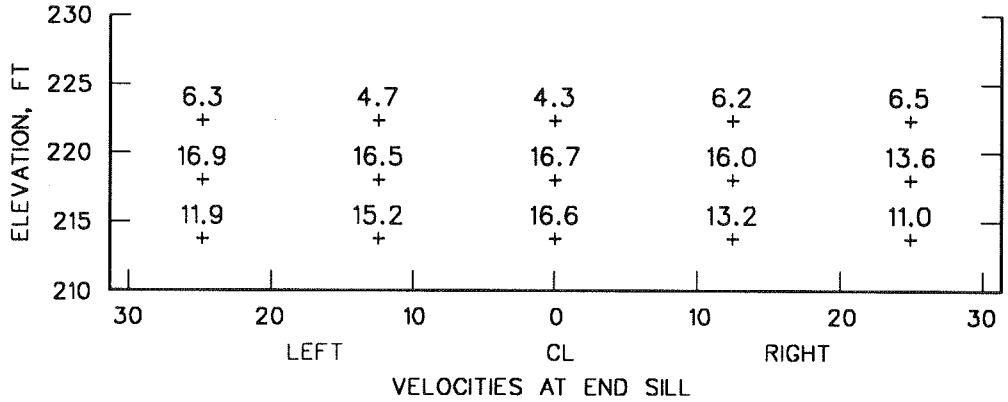


DISCHARGE 130 CFS/FT, TAILWATER EL 204.92, n = 0.03

TYPE 10 DESIGN
DROP STRUCTURE
AVERAGE VELOCITIES MEASURED
STA 836 + 50



ELEVATION

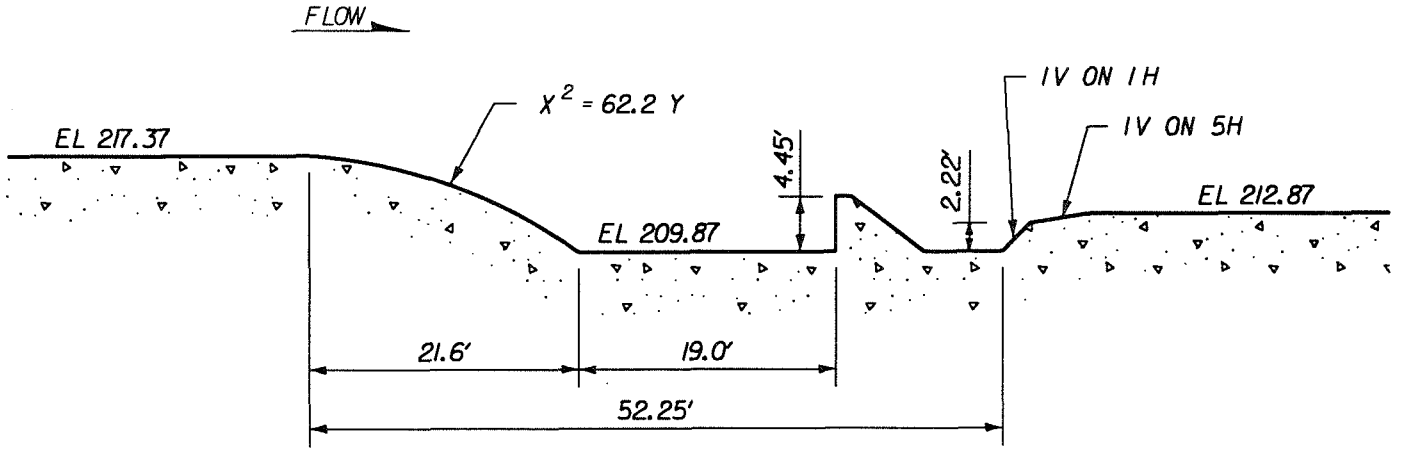


VELOCITIES AT END SILL

DISCHARGE 125 CFS/FT, TAILWATER EL 223.88, n = 0.03

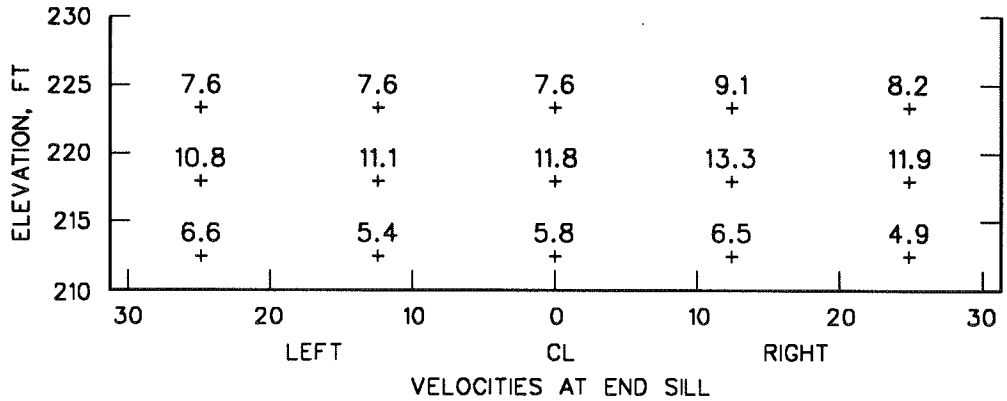
LOOKING DOWNSTREAM

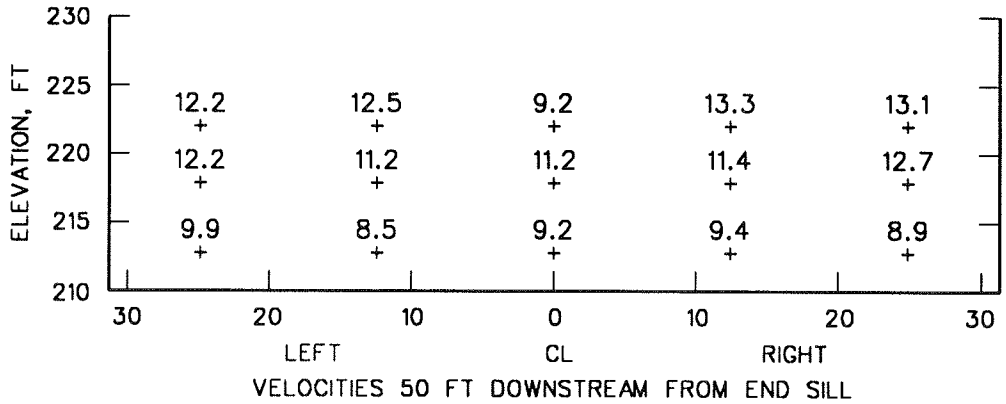
TYPE 1 DESIGN
DROP STRUCTURE
AVERAGE VELOCITIES MEASURED
STA 884 + 00



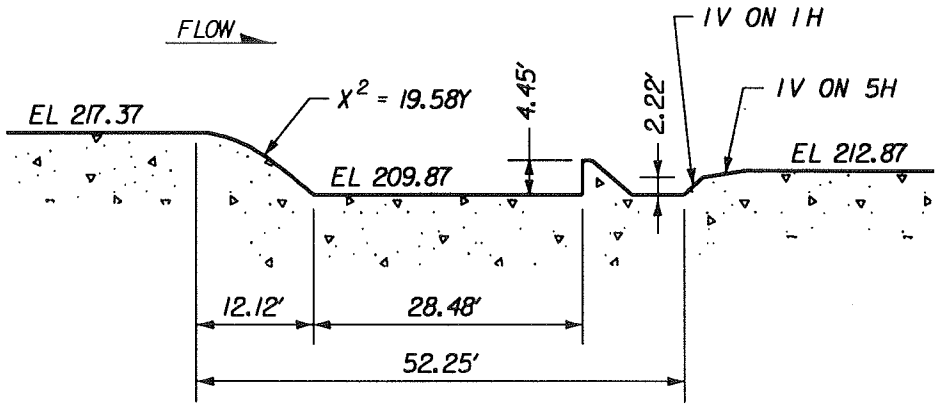
ELEVATION

TYPE 2 DESIGN
DROP STRUCTURE
STA 884+00

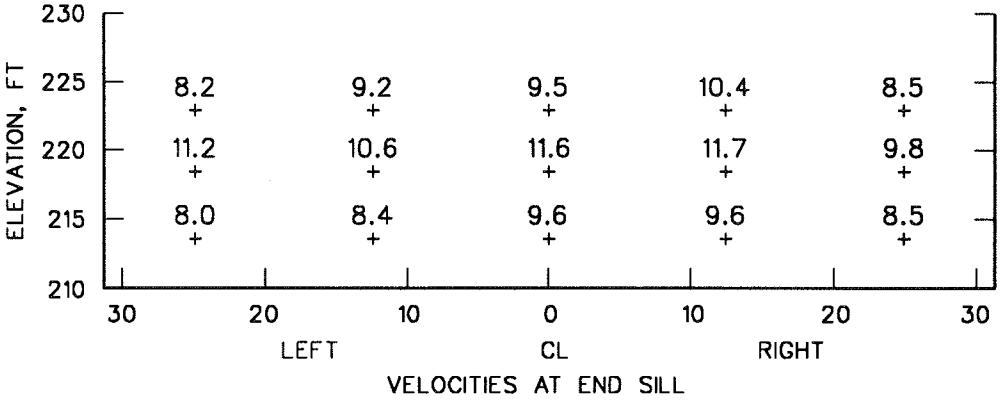




TYPE 2 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 884 + 00
DISCHARGE 125 CFS/FT
TAILWATER EL 223.88, n = 0.03
LOOKING DOWNSTREAM



ELEVATION

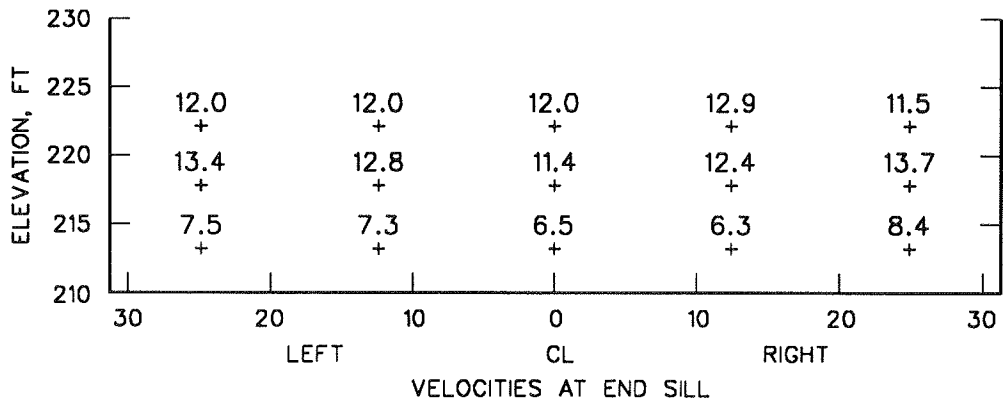


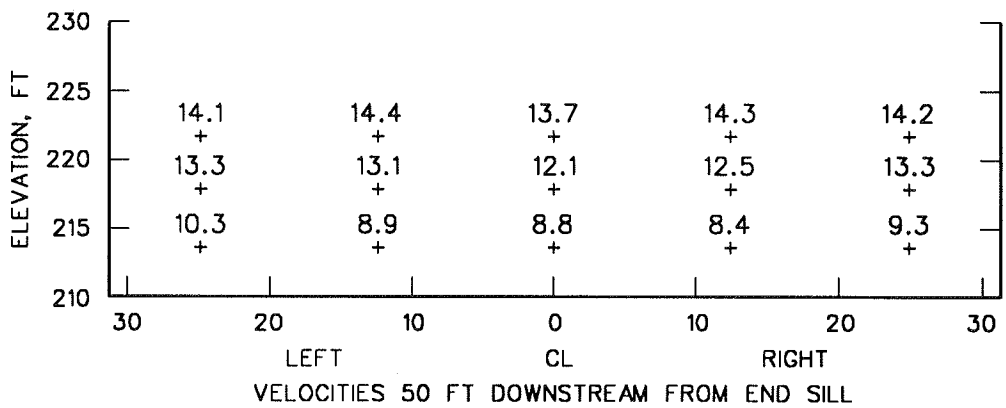
VELOCITIES AT END SILL

DISCHARGE 125 CFS/FT, TAILWATER EL 223.88, n = 0.03

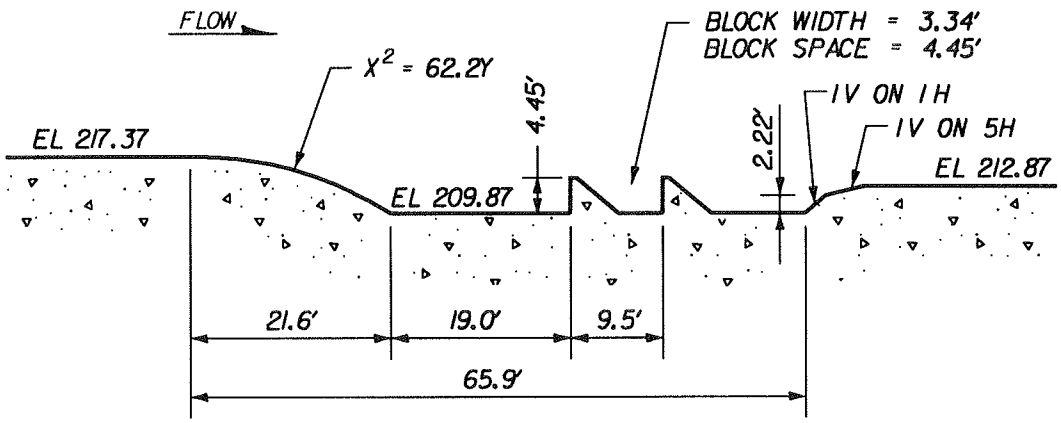
LOOKING DOWNSTREAM

TYPE 3 DESIGN
DROP STRUCTURE
AVERAGE VELOCITIES MEASURED
STA 884 + 00

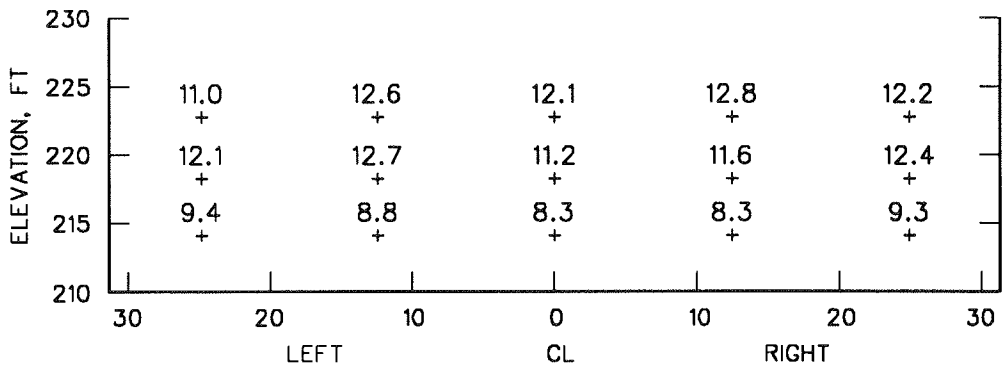




TYPE 4 DESIGN DROP STRUCTURE
AVERAGE VELOCITIES
STA 884 + 00
DISCHARGE 125 CFS/FT
TAILWATER EL 223.88, n = 0.03
LOOKING DOWNSTREAM



ELEVATION

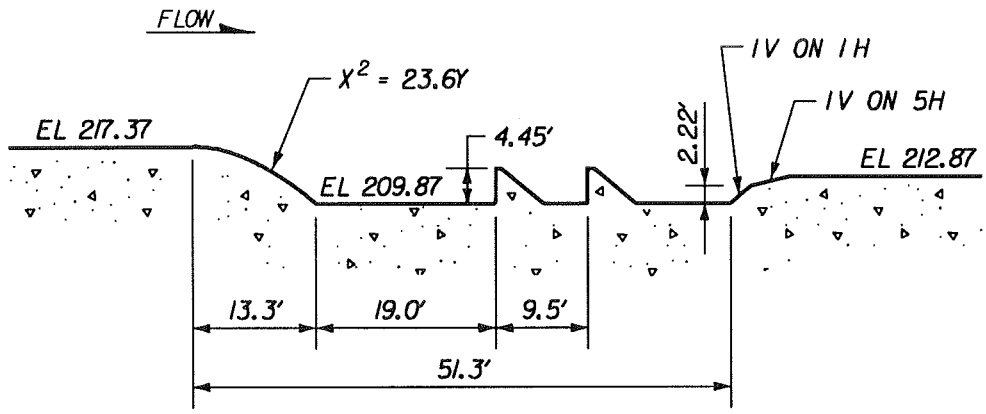


VELOCITIES AT END SILL

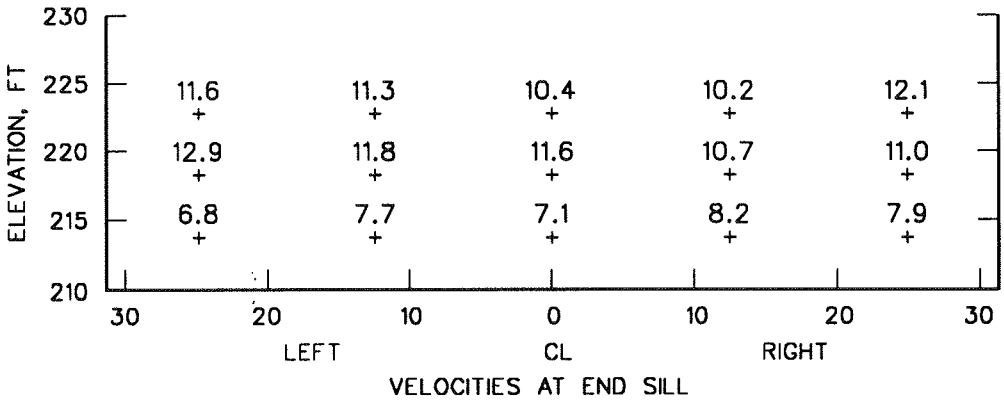
DISCHARGE 125 CFS/FT, TAILWATER EL 223.88, n = 0.03

LOOKING DOWNSTREAM

TYPE 5 DESIGN
DROP STRUCTURE
AVERAGE VELOCITIES MEASURED
STA 884 + 00



ELEVATION

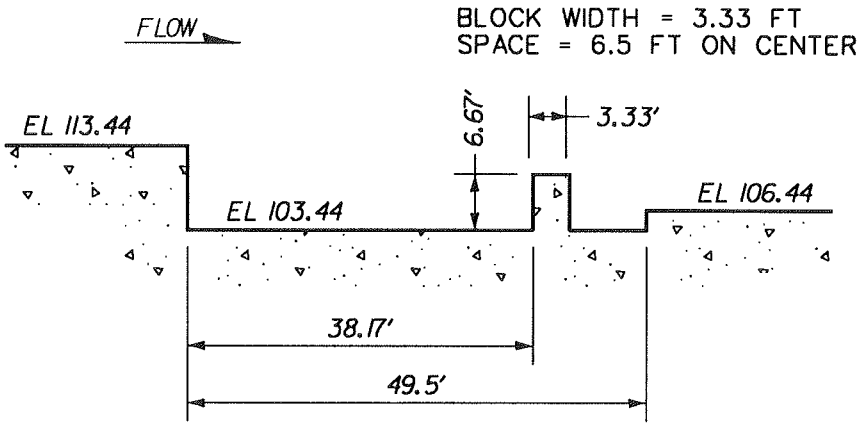


VELOCITIES AT END SILL

DISCHARGE 125 CFS/FT, TAILWATER EL 223.88, n = 0.03

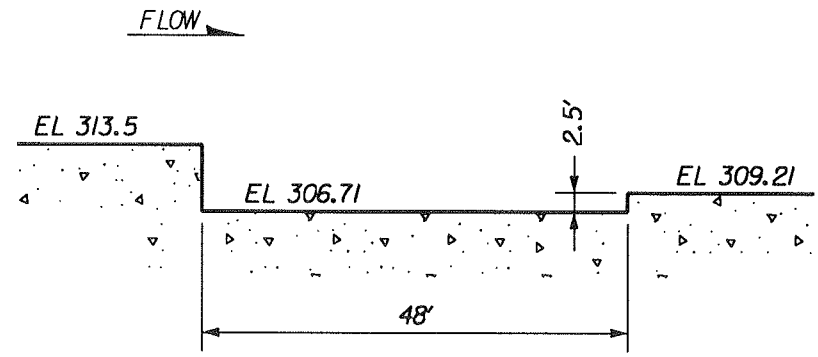
LOOKING DOWNSTREAM

TYPE 6 DESIGN
DROP STRUCTURE
AVERAGE VELOCITIES MEASURED
STA 884 + 00

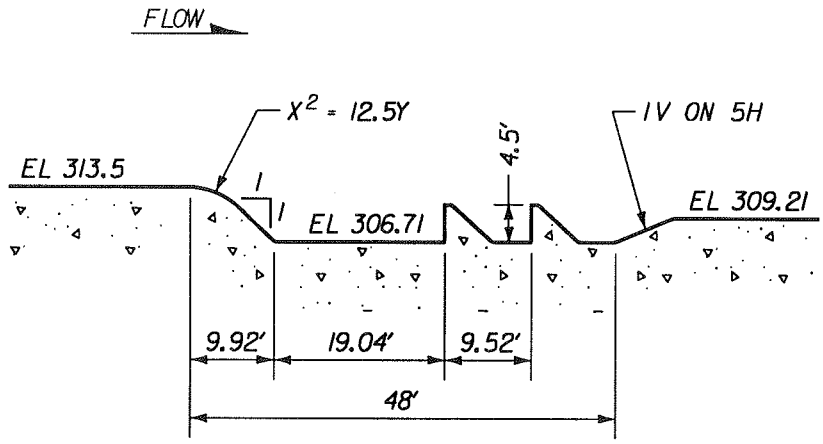


ELEVATION

TYPE 1 DESIGN
DROP STRUCTURE
STA 593+35

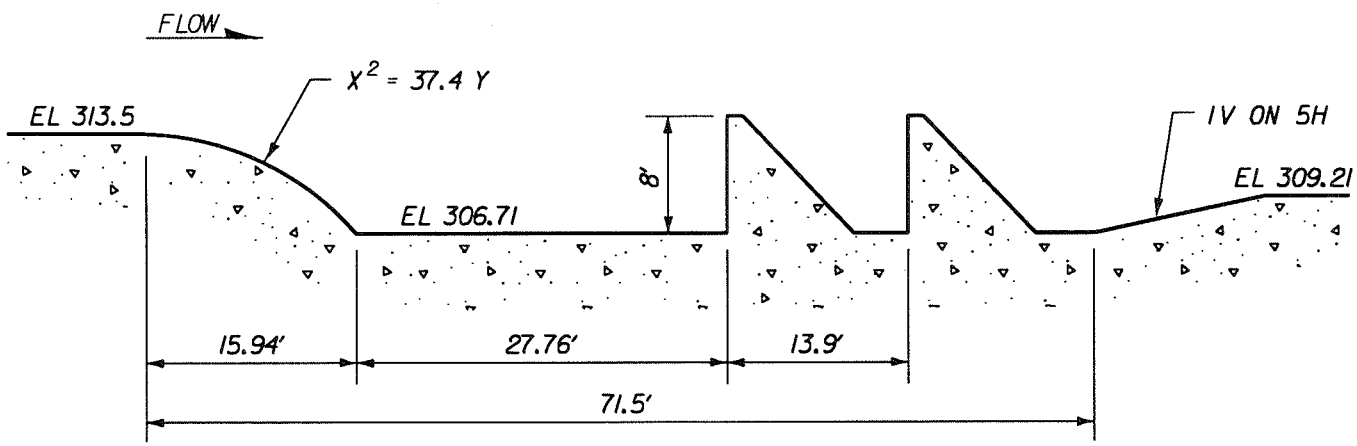


TYPE 1 DESIGN



TYPE 2 DESIGN

TYPE 1 AND 2 DESIGN
DROP STRUCTURES
STA 1198+08



ELEVATION

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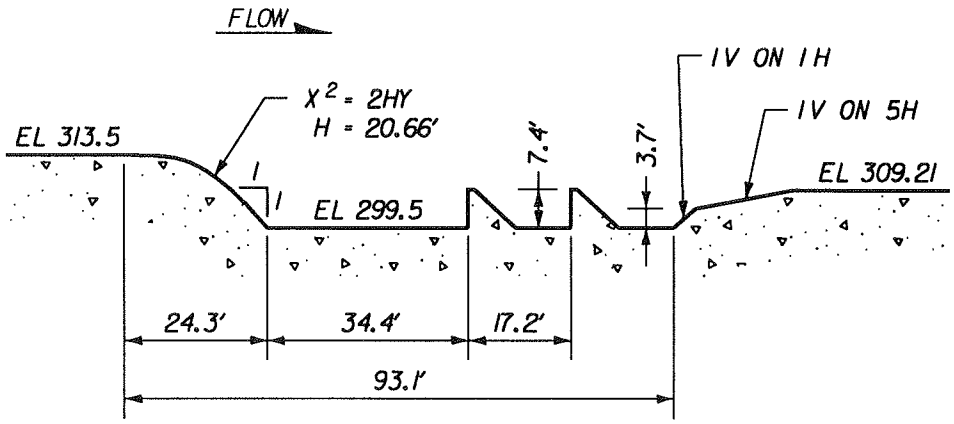

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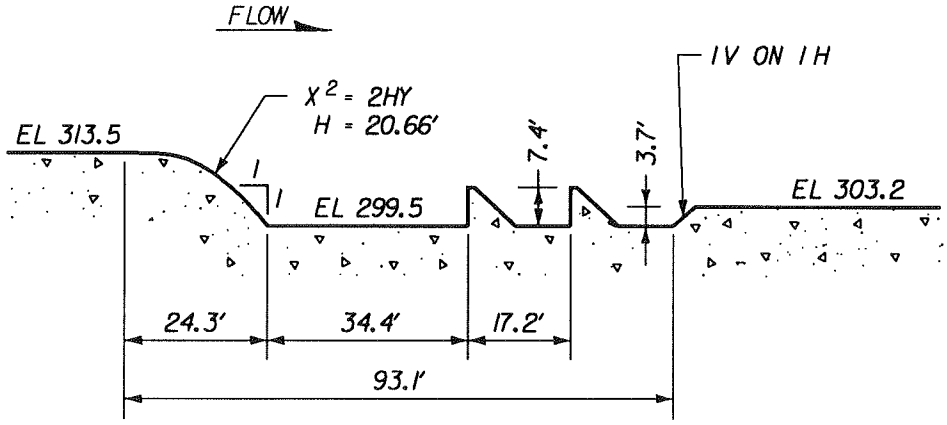

TYPE 5 DESIGN

TYPE 4 AND 5 DESIGN
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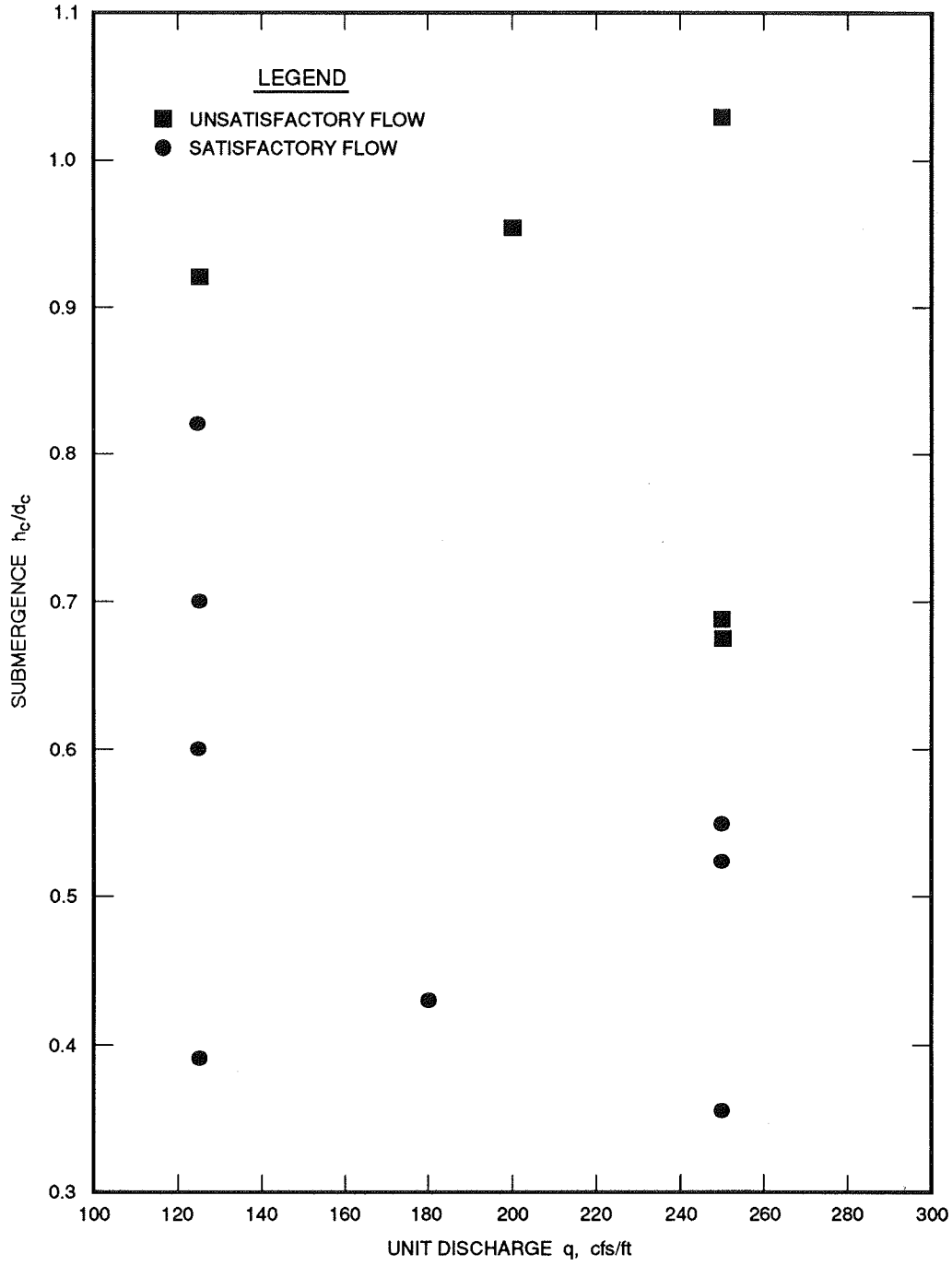

UNIT DISCHARGE
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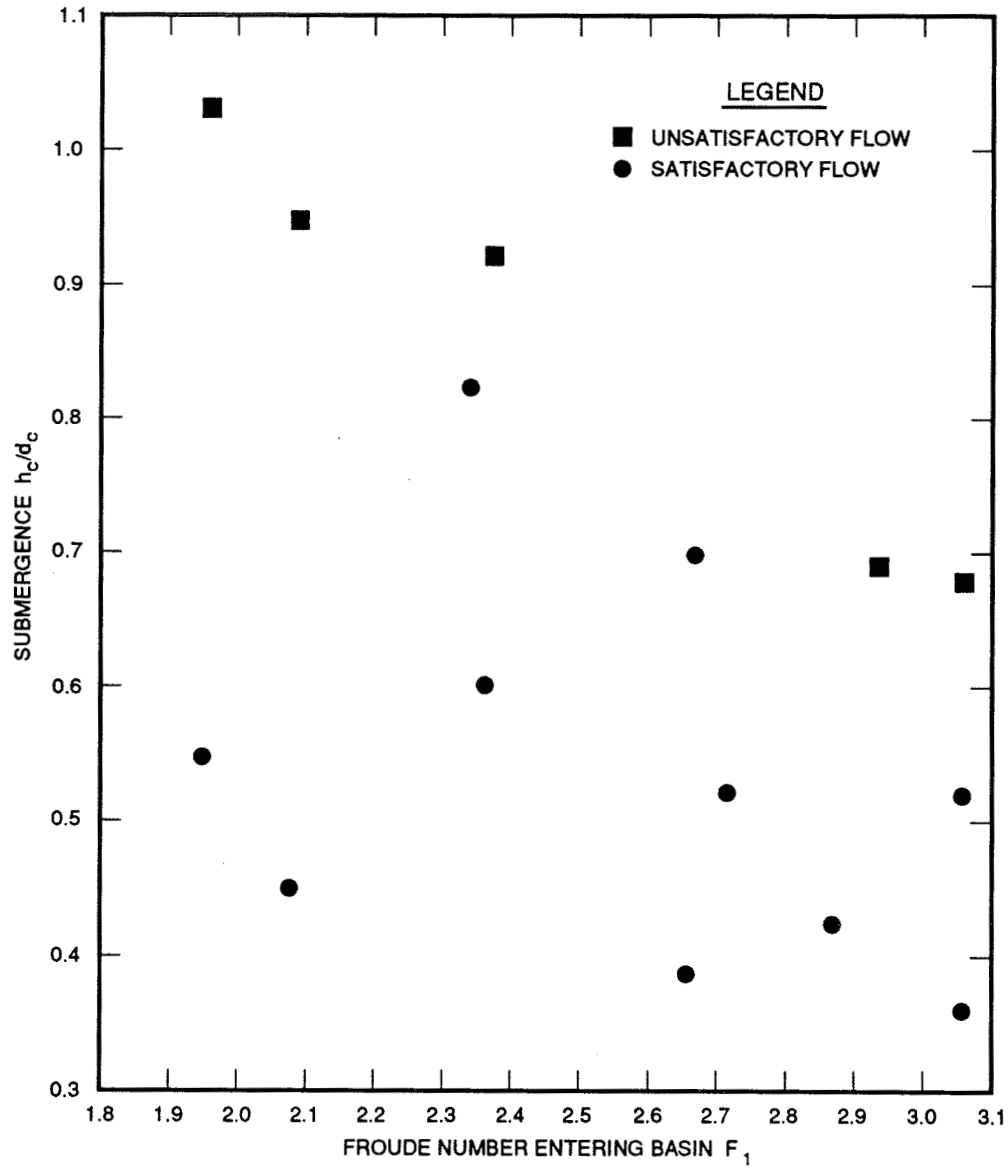

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VERSUS SUBMERGENCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1994

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
General Design for Replacement of or Modifications to the Lower Santa Ana River Drop Structures, Orange County, California; Hydraulic Model Investigation

5. FUNDING NUMBERS

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report
HL-94-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Engineer District, Los Angeles, PO Box 2711,
Los Angeles, CA 90053-2325

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The lower basin of the Santa Ana River is located in Orange County, California, and is 30.5 miles in length. Flood protection for the lower basin is provided by Prado Dam and Reservoir. When completed in 1941, Prado Dam was designed to control a 200-year flood. However, recent projections have shown that Prado Dam now offers only a 70-year flood protection based upon the following factors: urbanization in the drainage area, additional historical data on rainfall and runoff, and advances in predicting future flood potential.

According to Santa Ana River hydraulic studies, the existing lower basin channel is inadequate to convey a large flood flow safely to the ocean. Existing flood control improvements built by local interests have reduced damages from small floods. As part of these channel improvements there are 11 existing vertical concrete drop structures. However, these improvements fail to provide protection for the highly urbanized lower Santa Ana River floodplain. About 2 million people live and work in this floodplain.

Since additional channel right-of-way is not available because of urbanization, increased channel capacity can only be achieved by additional depth of flow. The increased channel flow will require drop structures designed for higher unit discharges. An improved channel design will require the removal or modification of the existing drop structures in order to implement a new drop structure configuration.

(Continued)

14. SUBJECT TERMS
Drop structures
Grade control structures
Hydraulic model investigation
Santa Ana River
Stilling basins

15. NUMBER OF PAGES
306

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

13. (Concluded).

The first part of this report presents the results of a model study conducted at the U.S. Army Engineer Waterways Experiment Station (WES) to investigate the possibility of designing new vertical drop structures and sloping grouted stone drop structures to replace the existing structures. The results of this model study showed that drop structures can be designed to adequately convey the increased discharges expected.

Section models of drop structures constructed at a scale of 1:25 were used to determine if preliminary designs were adequate, and if not, then what modifications to the structures would be needed. Vertical drop structures with changes in elevation of the channel invert of 8, 10, and 12 ft were tested.

Initial tests on the preliminary designs showed than an oscillating hydraulic jump would form at discharges expected during a flood event. Various modifications were tested on these preliminary designs without success. The drop structures were then redesigned to incorporate elements based on the sequent depths of the hydraulic jump. Modifications tested included a parabolic drop, one row and two rows of baffle blocks, and a sloping end sill. Sloping drop structures constructed of grouted stone were also tested using a 1:25-scale section model and a 1:40-scale full-width model. The initial design incorporated a 1V on 10H slope, which produced unsatisfactory results. Test results indicated that with a 1V on 2H slope, a satisfactory hydraulic jump would occur for the various flow conditions observed.

The second part of this report concerns model studies conducted at WES to investigate the possibility of using the existing drop structures of the Santa Ana River. The results of these model studies showed that the existing drop structures will not adequately convey the increased discharges expected. Unless modification or replacement measures are taken, severe scour to the streambed and even structural failure could result.

Several 1:25-scale section models of selected drop structures and a 1:25-scale full-width model were used to determine if the existing structures were adequate, and if not, then what modifications to the structures would be needed. A general design was developed from these tests for the other existing drop structures on the Santa Ana that were not model tested.

Initial tests on the existing drop structures showed that an oscillating hydraulic jump would form at discharges expected during a flood event. A sequent depth analysis using guidance from a previous study was performed on each drop structure tested. From these sequent depths, dimensions of the modifications were sized. Modifications tested included a parabolic-shaped drop downstream from the crest, one row and two rows of baffle blocks, and a sloping end sill.

The resulting general drop structure design is based upon energy head and the sequent depths. This general design has application for all drop structures that have a Froude number of less than 4.5.