UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES OF THE OVERFLOW SPILLWAY OF BHAKRA DAM, INDIA

Hydraulic Laboratory Report No. Hyd-367

ENGINEERING LABORATORIES BRANCH

DESIGN AND CONSTRUCTION DIVISION
DENVER, COLORADO

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Laboratory Report No. Hyd-367
Hydraulic Laboratory Section
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Subject: Hydraulic model studies of the overflow spillway of Bhakra Dam, India

SUMMARY

Model studies were made on the overflow spillway of Bhakra Dam, India, in connection with a redesign of the spillway to provide for an increase in the discharge capacity. The spillway design and model studies were performed in the Denver offices of the United States Bureau of Reclamation. A sectional model of the spillway, approximately 4 feet wide, was constructed to a scale of 1:50 and used to study the performance of the spillway in detail.

Tests were run on the spillway shown in Figure 2 for all ranges of spillway operating conditions. The discharge capacity of the overflow section for the entire head range was determined along with pressure measurements and water surface profiles. These studies showed that the crest shape and general dimensions of the spillway were satisfactory.

Tests on the proposed stilling basin, Basin No. 1, Figure 7, showed satisfactory performance with regard to erosion and wave heights, while the jump sweep-out tests indicated that the tail water could be lowered 9 feet below normal before the jump was swept out of the basin. Two additional stilling basins, Figure 7, were tested which had more volume due to lowering of the upstream floor sections. These basins did not perform as well as the first basin. Baffle piers 20 feet high and an end sill also 20 feet high were tested with Basin No. 3, Figure 16, and they improved the performance of the stilling basin. Their use, however, cannot be recommended without qualification because of the severe operating conditions in a structure of this size. The proposed basin, Basin No. 1, Figure 7, was considered most satisfactory. Basin No. 1 would, however, provide even better performance if the entire basin, including the curved bucket, were lowered 5 to 10 feet; or, by constructing a downstream river control, the tail water could be raised an equal amount for the 290,000 cfs discharge. The additional

depth of water on the apron would provide additional jump stability, lower waves and surges, and a greater margin of safety against jump sweep-out at the higher discharges.

Motion pictures of the three stilling basins were taken during the tests. A copy of these films is submitted with the report to illustrate, in motion, the action in the stilling basins.

INTRODUCTION

Bhakra Dam is located on the Sutlej River in the eastern section of the State of East Punjab, India, Figure 1. It is under construction by the Punjab Irrigation Department. The dam is a concrete gravity type, about 680 feet high with a maximum reservoir capacity of 7,600,000 acre feet. The drainage area upstream from the dam involves 21,950 square miles. The project will provide flood control, hydroelectric power, and irrigation for the whole of the Province of East Punjab and Delhi.

The design of Bhakra Dam, prepared in 1949 by the International Engineering Company, Incorporated, was investigated by hydraulic models. 1/ Two spillways were provided for the major flood flows passing the dam—one a centrally located overflow, or main spillway controlled by two drum gates, and the other a tunnel spillway controlled by two radial gates. In addition, 24 river outlets were provided which passed through the main spillway and discharged onto the spillway face. The combined discharge of this system was sufficient to accommodate the probably maximum flood of 400,000 cfs. Under these plans, the upper 5 feet of reservoir storage or surcharge was reserved as a safety factor.

In a recent review by the Bhakra Control Board the 5 feet of reservoir surcharge was utilized in routing the flood of 400,000 cfs through the reservoir. This procedure resulted in reducing the maximum flood to be passed to 290,000 cfs. The reduction of 110,000 cfs in flow made it possible to eliminate the tunnel spillway on the left, provided the center overflow spillway was modified to provide for 290,000 cfs. Thus it was necessary that a redesign of the spillway be made. The new spillway design and accompanying hydraulic model studies were undertaken by the United States Bureau of Reclamation, Denver, Colorado, in an agreement with the Central Water and Power Commission, India.

1/ Hydraulic Model Studies of Bhakra Dam—Colorado A&M College, November 1949.

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The overflow spillway as first designed and tested is shown in Figure 2. The over-all width of the spillway is 260 feet, and it is divided into two sections by a wall 10 feet wide running the length of the spillway from the end of the spillway pier to the downstream end of the stilling basin. The maximum capacity of the overflow section is 210,000 cfs, and the crest is controlled by four radial gates each 57.5 feet in length by 37.4 feet high. The river outlets discharging down the face of the spillway have a capacity of 80,000 cfs which results in a maximum flow through the stilling basin of 290,000 cfs.

Since the outlets were not constructed in the sectional model, it was necessary when making stilling basin tests above 210,000 cfs to pass the water, which would ordinarily be discharged through the outlets, over the spillway crest. The over-all quantity of water entering the stilling basin was therefore correct, the total energy entering the basin was very nearly correct, and the direction of the flow entering the basin was correct. Therefore, the stilling basin studies are believed to be as accurate as though the outlets had been modeled and operated.

THE 1:50 MODEL

To construct a model of the entire spillway and adjacent area to a scale sufficient to make a detailed study of the spillway and stilling basin would have required special and costly modifications to the laboratory equipment. Instead of this complete model, it was decided to build a sectional model which would give just as reliable results for crest and stilling basin studies at less cost.

The model was constructed in the permanent laboratory flume, and the upstream walls were raised 4 feet in order to build the model to a scale of 1:50. The flume width of 47.6 inches was equivalent to a prototype spillway width of 198 feet. Thus 198 of the total over-all width of 260 feet was represented. Use of the laboratory flume provided not only the advantages of a large model, but the flow in the stilling basin could be observed through the glass wall on the right side of the flume. The maximum flow of 1,160 cfs per foot of stilling basin width, for 198 feet of width, was represented by 13.03 cfs in the model.

The model as installed in the flume is shown in Figure 3. The overflow section, made of sheet metal, was placed above a steel bulkhead which acted as the upstream face of the dam. The spillway surface and stilling basin sections were made of sheet metal screwed to wooden frames cut to the shape of the spillway profile. This portion of the model was made of several separate units to facilitate changes in the model. A movable riverbed of gravel averaging about 1/4 inch in diameter was placed downstream from the stilling basin. Water was supplied to the model from the permanent laboratory supply lines connected to fixed pumps and venturi meters for measuring the discharge. A tailgate was used to control the elevation of the tail water which was read from a scale on a glass manometer connected to a piezometer in the side of the flume. The reservoir elevation was read using a point gage in a stilling-well connected to the side of the head box.

THE INVESTIGATION

Tests on the Overflow Section

General performance and pressures. Two bays 57.5 feet wide with gates and piers were represented in the model which was one-half the overflow section of the spillway. The maximum discharge was 105,000 cfs for the two bays which was represented by 5.94 cfs in the model. The shape of the overflow section and gates are shown in Figure 2.

The model was operated at various discharges including the maximum and the appearance of the flow was observed. The contractions of the flow occurring at the upstream end of the piers was not considered excessive even at the maximum discharge, Figure 4A. The disturbance caused by the piers is reflected in the water surface downstream from the crest, Figure 4B. A fin of water, caused by the intersection of the flow from the two bays, originated at the tail of the center pier. At the maximum discharge the fin rose several feet above the face of the spillway, but it was not considered a harmful flow condition. Piers gradually tapered in the downstream direction might help to reduce this fin, but they were not tested.

Pressures and water surface profiles were taken on the overflow section for various conditions of flow, Figure 5. The discharges shown in the figure represent the total discharge with four gates operated equally. Pressure variations were small between the various flow conditions except for the region upstream from the gate. Since the lowest pressure was only 3.5 feet of water prototype below atmospheric, the overflow section was considered satisfactory. The water surface profiles shown in the figure also indicate uniform and satisfactory flow conditions.

Discharge calibration. The overflow section was calibrated with free flow over the crest and with the gates at fixed openings. Although the tests were made using two 57.5-foot radial gates the discharge capacity curves, Figure 6, were made by doubling the model results

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to obtain the total discharge for the complete spillway with four gates operated symmetrically. The total head over the crest was 38.50 feet for the maximum discharge of 210,000 cfs which resulted in a coefficient of discharge C of 3.82 in the equation $C = \frac{Q}{LH^{3/2}}$. The studies made on the overflow section did not show any favorable hydraulic conditions, and no modifications to the proposed design were considered necessary.

Tests on the Stilling Basin

Stilling Basin No. 1. The stilling basin first tested in the model had a relatively short horizontal floor 165 feet long at elevation 1095, Figure 7A, and the upstream floor section had a slope of 10:1. In the prototype the stilling basin is divided into two sections, 125 feet wide, by a center wall, but this wall was not used in the sectional model. The performance of the stilling basin was observed for various discharges. The appearance of the flow as seen through the glass wall is shown in Figure 8, for discharges of 200,000 and 290,000 cfs. The operation is better illustrated by the motion pictures taken through the glass panel. At the maximum discharge the waves downstream from the basin in the river channel had an amplitude, or maximum variation in water surface, of 8.3 feet, Figure 9. The waves heights were measured and recorded electronically and give an accurate value for the maximum waves in the channel.

The lowering of the tail-water elevation 9 feet below normal for maximum discharge caused the jump to sweep out of the basin as shown by the sweep-out curve A in Figure 10. The amount the tail water had to be lowered to cause sweep-out increased for lower discharges.

The performance of the basin with normal tail water was better for all discharges less than 200,000 cfs than for discharges above 200,000 cfs. Thus, the operation below 200,000 cfs may be called excellent and that above 200,000 cfs satisfactory. The average water surface profile at a discharge of 290,000 cfs is shown in Figure 11A with normal tail-water elevation.

To determine the erosion in the riverbed, the model was operated for 1 hour at the maximum discharge with normal tail-water elevation. The lowest riverbed elevation was 1086 which was 9 feet lower than the horizontal floor of the stilling basin, Figure 12A. The material moved by the flow is represented by the area between the original bed and eroded bed. After the studies on Basin No. 1, it was decided to increase the volume of the basin by extending the horizontal floor upstream to determine whether the performance could be improved.

Stilling Basin No. 2. For Basin No. 2, Figure 7B, the horizontal length of floor was extended upstream 117.5 feet and a slope of 5:1 was used for the upstream floor. The operation of the basin for discharges of 200,000 and 290,000 cfs was in most respects similar to the previous basin and is shown in Figure 13. The surging action was more pronounced with Basin No. 2, however. This action can observed by comparing the operation as shown in the motion pictures. The amplitude of the waves at the maximum discharge was 17.5 feet, Figure 9, or about twice the value for Basin No. 1.

The sweep-out curve was unchanged from Basin No. 1, Figure 10, because the downstream end of the basin, which controls the sweep-out, was the same for the two basins. The average water surface profile, Figure 11B, showed the depths at corresponding sections to be very similar to those for Basin No. 1. In other words, lowering the floor of the basin caused a lowering of the water surface elevation. Pressures were measured on the portions of the floor sections shown by the piezometer locations in Figure 14A. The results shown in the figure indicate a similarity between the pressures and the depth of water over the floor.

An erosion test was run for 1 hour with maximum discharge and normal tail-water elevation. The shape of the riverbed resulting from this test is shown in Figure 12B and was very similar to that obtained with Basin No. 1. One additional modification to the basin floor was believed desirable in the study of the stilling basin.

Stilling Basin No. 3. Additional volume was given Basin No. 3, Figure 7C, by using a full length horizontal floor which required lowering of the curve connecting the spillway face and the floor. The appearance of the flow in the stilling basin for a discharge of 200,000 and 290,000 cfs is shown in Figure 15. The performance and surging action was similar to that of Basin No. 2 which can be seen by observing the motion pictures taken through the glass panel. The amplitude of the waves at the maximum discharge was 15.0 feet, Figure 9, or about the same as measured with the second basin.

The sweep-out curve, Figure 10, was the same as found for Stilling Basin No. 1 and No. 2. The average water surface profile, Figure 11, showed a similarity of depth to the two previous basins. Pressures were measured at the six piezometer locations shown in Figure 14B. The pressures were greater at higher discharges, and there was a drop in pressure at the two downstream piezometers. The reason is not known.

To increase the effectiveness of the basin a row of 20-foot baffle piers and a 20-foot end sill were installed as shown in Figure 16A.

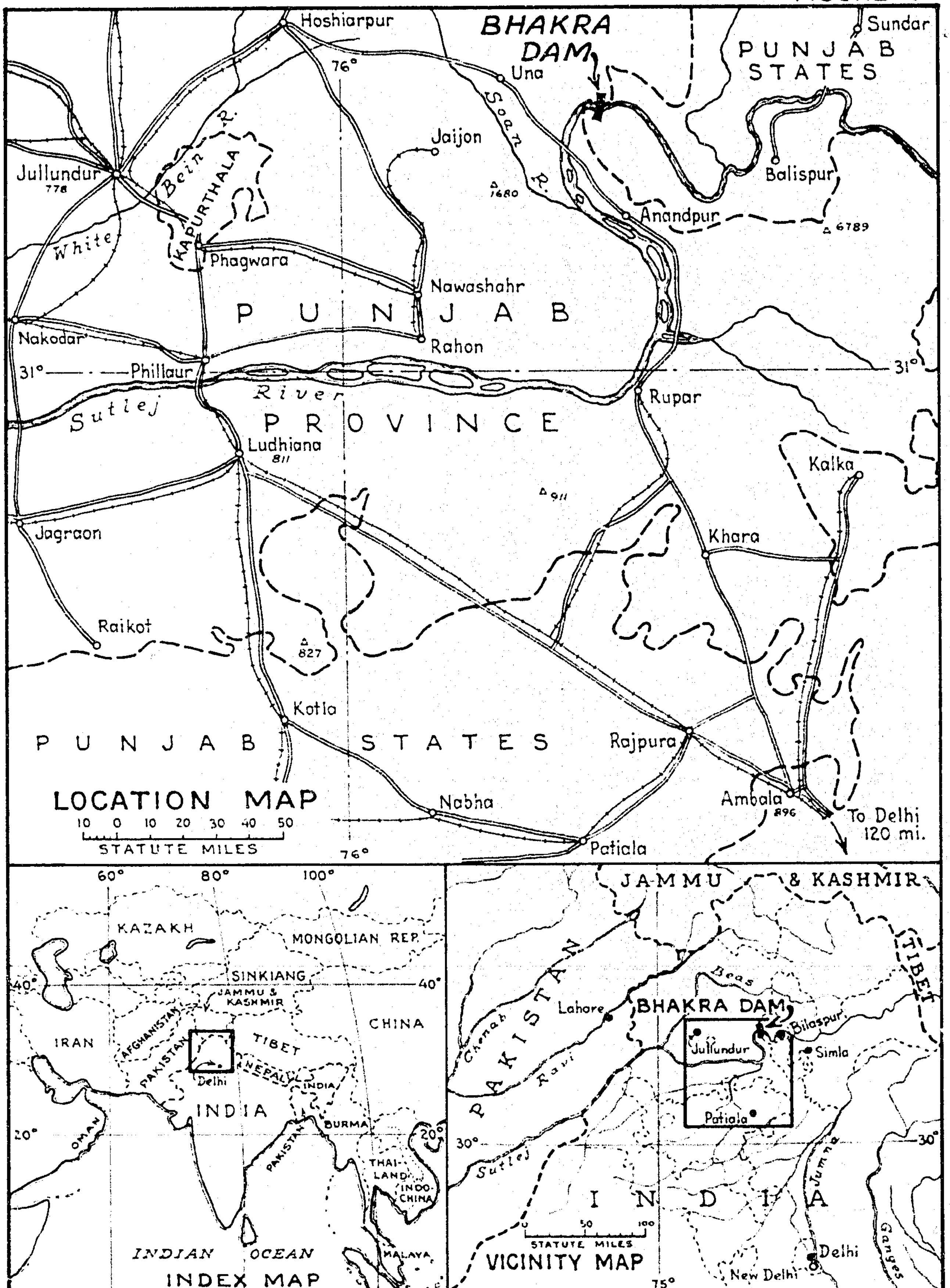
B

The performance was improved as indicated by the appearance of the flow for a discharge of 290,000 cfs, Figure 16B. The amplitude of the waves in the channel downstream from the basin was reduced to 6.9 feet for the maximum discharge, Figure 9. Although exact measurements were not taken the erosion close to the end sill was not as deep as occurred with the other basins. The sweep-out tests showed a greater margin of safety, Figure 10, requiring 17 feet of tail water reduction before the jump was swept out at the maximum discharge. The water surface profile in the stilling basin with the 20-foot baffle piers and sill is shown by the dotted line in Figure 11C.

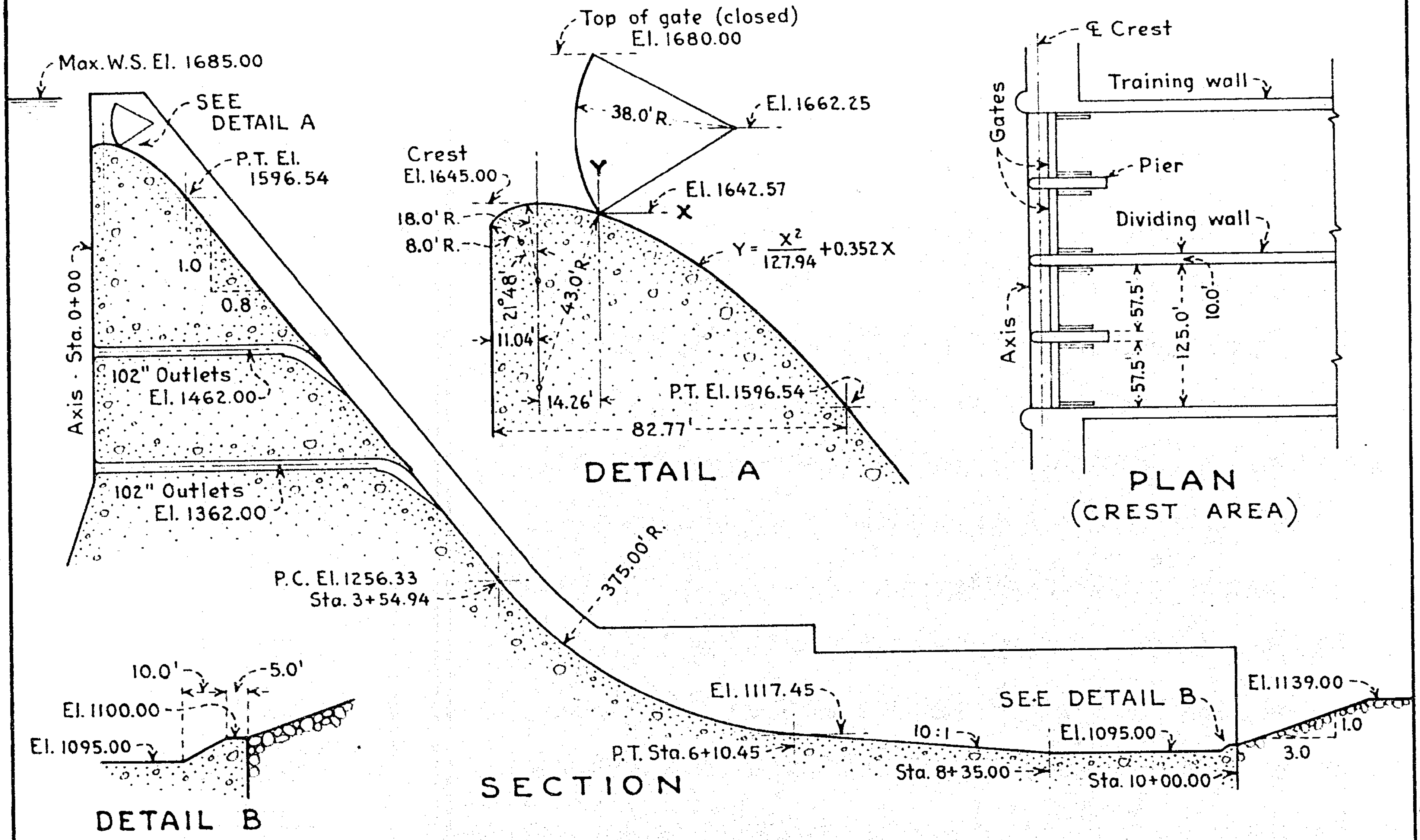
A piezometer was installed on the side of one of the baffle piers as shown in Figure 16A. Tests on other models had indicated that the lowest pressure to be expected on a baffle pier of this type occurred in this general location. Pressures obtained for three discharges are also shown in the figure and were all well above atmospheric. The velocity of the water impinging on the face of the piers was measured and found to be as high as 135 feet per second at the maximum discharge. While these additions to the basin improved the performance, the life of the baffle piers would be limited under such severe conditions, and their installation is not considered good practice.

Although the limited tests made to measure pressures showed cavitation-free pressures, it is possible that local conditions in the prototype might produce local cavitation with resultant pitting. With the high velocities present on the apron, ordinary abrasive action might cause severe damage since the baffle piers might direct the flow into the apron itself. The hydraulic performance of Basin No. 1 was considered to be the most satisfactory of the three basins tested.

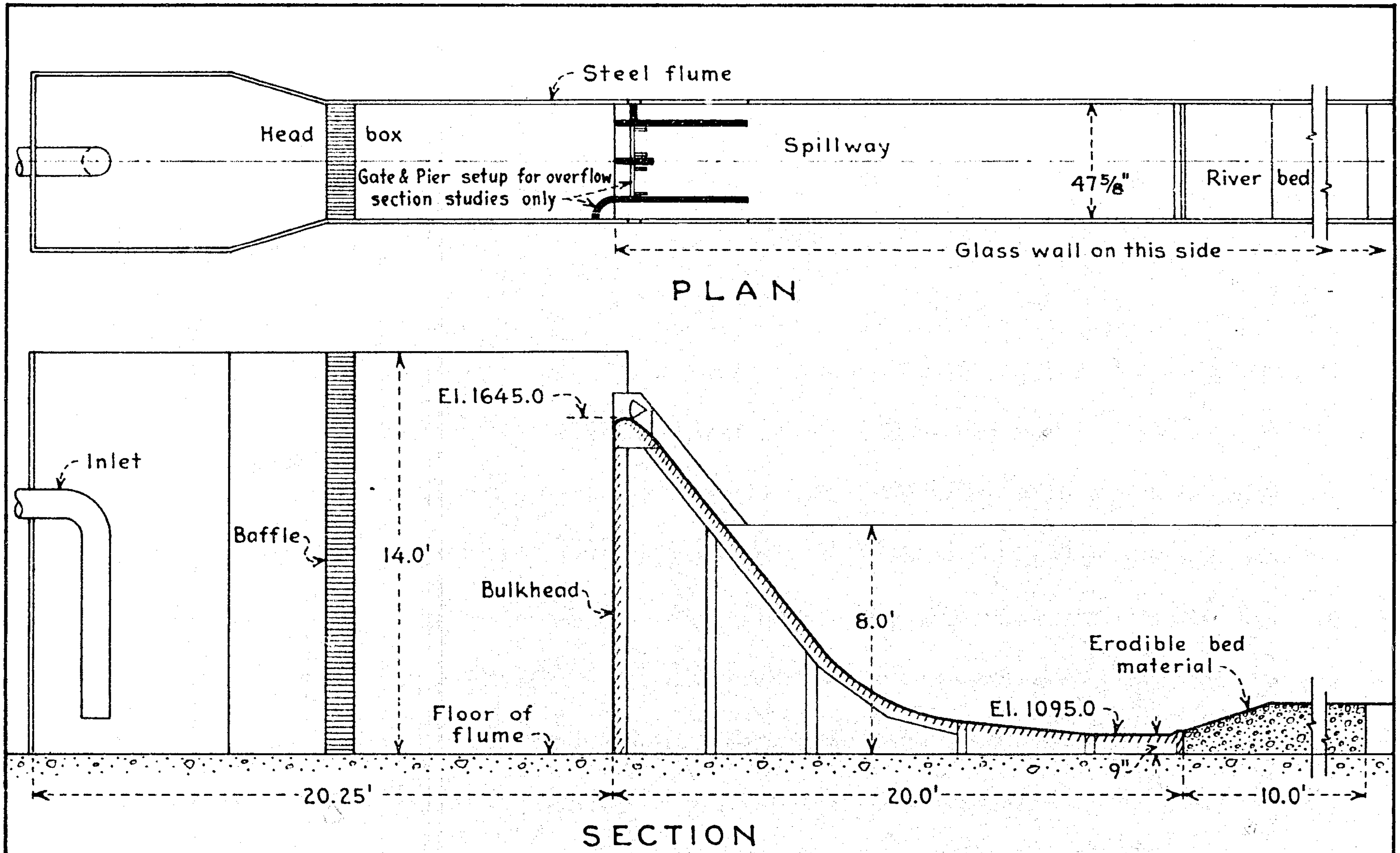
FIGURE 1



BHAKRA DAM LOCATION MAP



BHAKRA DAM
OVERFLOW SPILLWAY



BHAKRA DAM
OVERFLOW SPILLWAY
1:50 SCALE SECTIONAL MODEL

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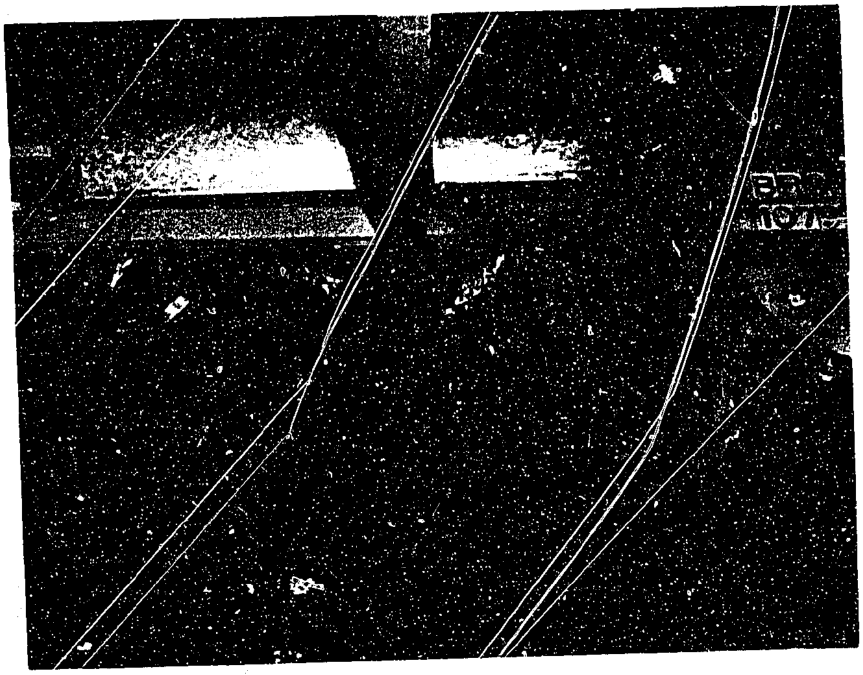
FIGURE 3

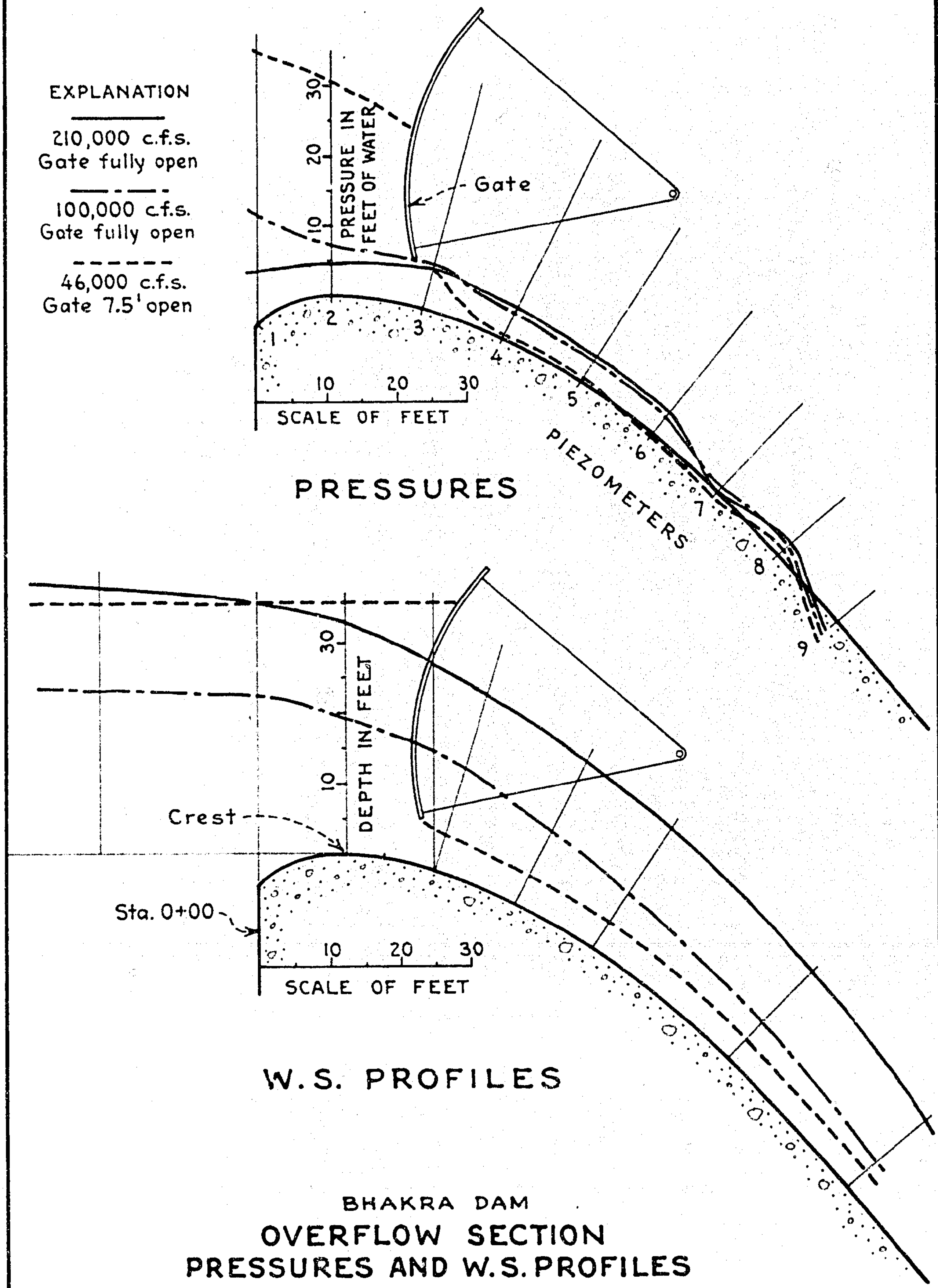


A. 105,000 cfs at entrance

B. 105,000 cfs downstream from gates

OVERFLOW SECTION

FIGURE 5



BHAKRA DAM
OVERFLOW SECTION
PRESSURES AND W.S. PROFILES
1:50 SCALE MODEL

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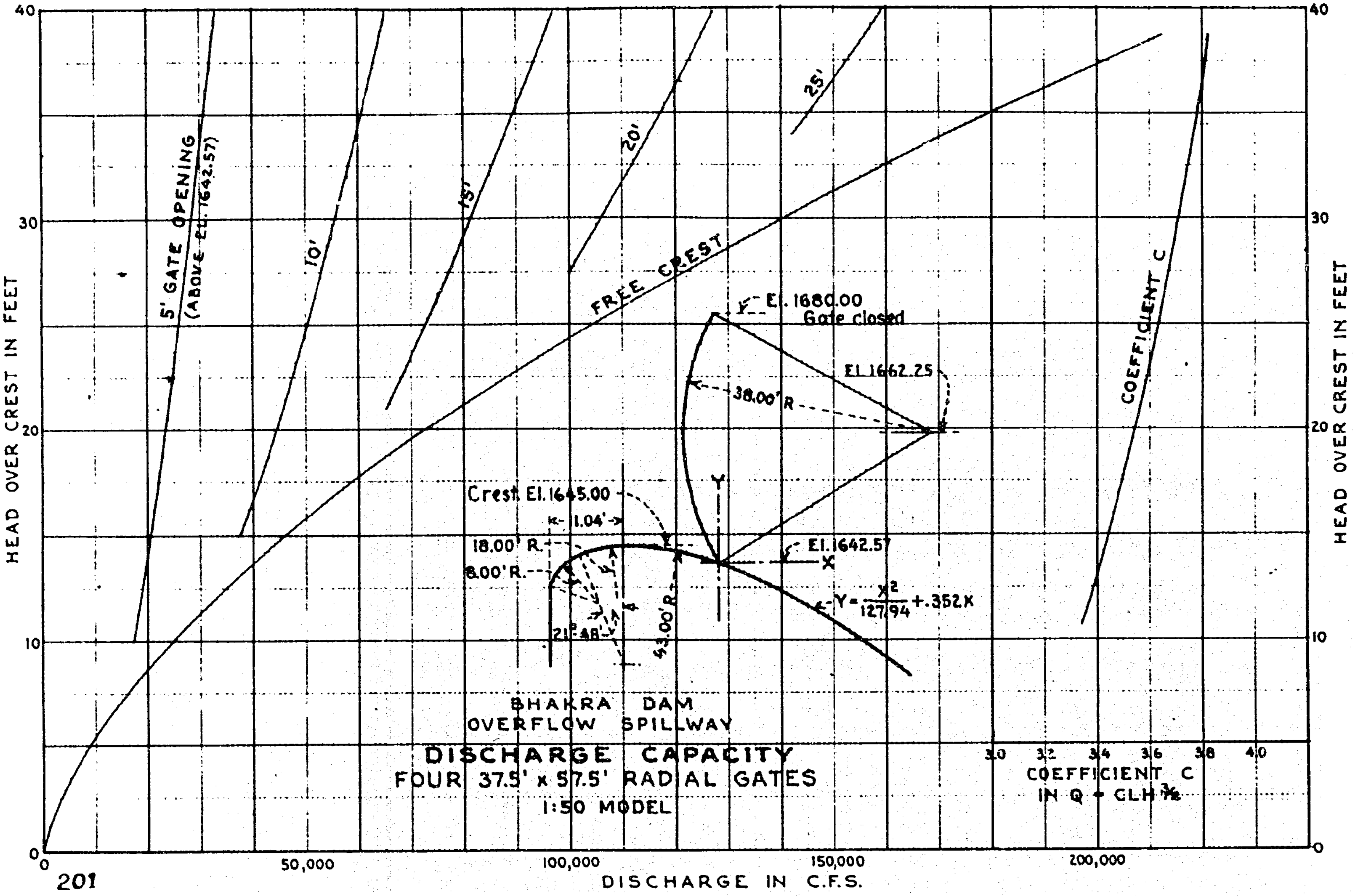
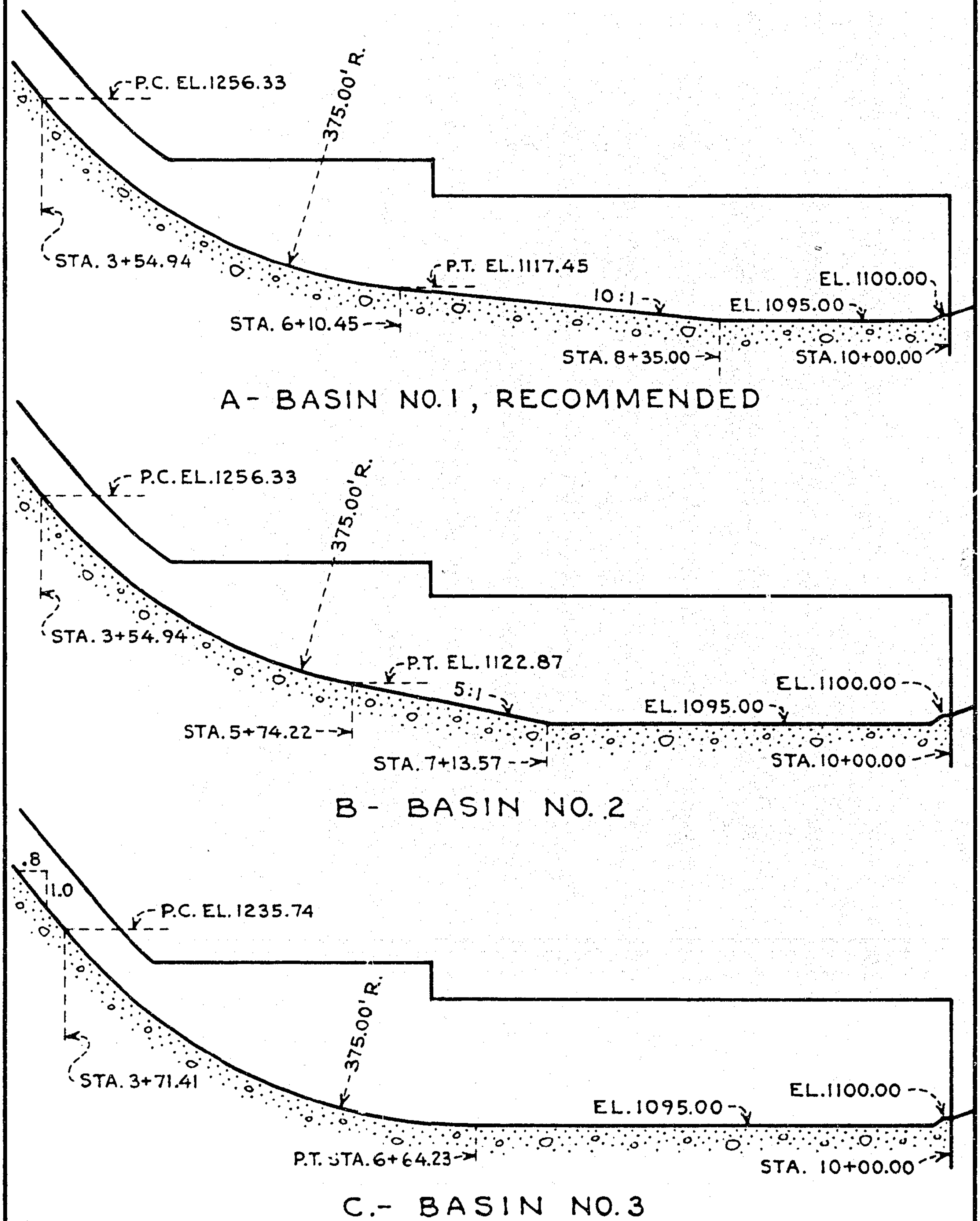


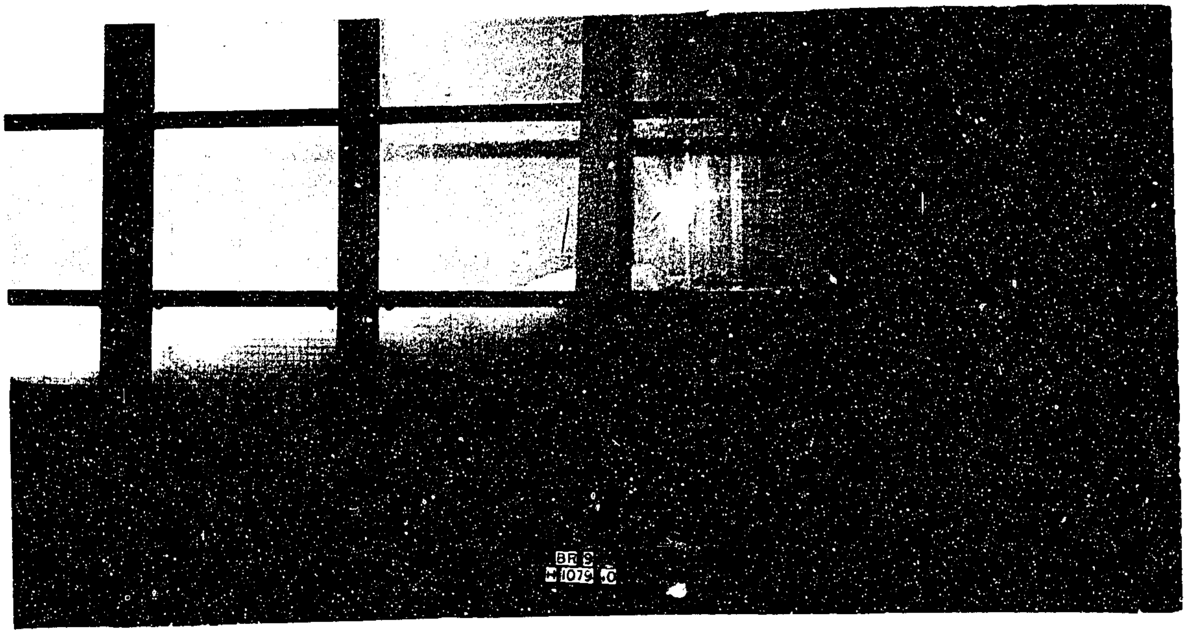
$$Y = \frac{X^2}{127.94} + .352X$$

FIGURE 6

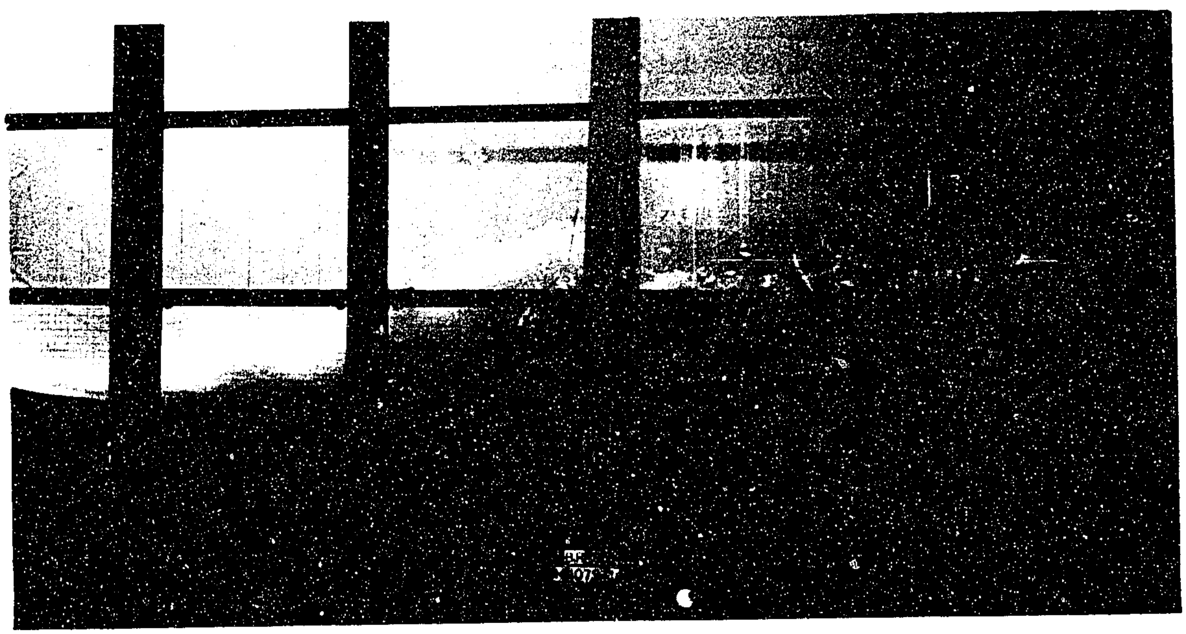


BHAKRA DAM
STILLING BASINS TESTED
1:50 SCALE MODEL

Figure 8



A. Discharge 200,000 cfs



B. Discharge 290,000 cfs

SPILLWAY
STILLING BASIN NO. 1
BHAKRA DAM - 1:50 MODEL

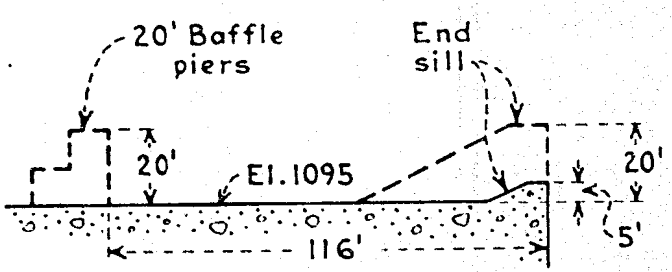
Basin No.	Discharge	Wave Amplitude	Wave Period	Remarks
1	100,000	5.0	8.5	
1	200,000	6.2	7.1	
1	290,000	8.3	7.1	
2	100,000	5.2	7.8	
2	200,000	7.5	7.8	
2	290,000	17.5	6.0	
3	100,000	4.6	6.4	
3	200,000	9.2	5.7	
3	290,000	15.0	5.7	
3	100,000	5.4	6.4	20-foot
3	200,000	8.8	5.7	baffle piers
3	290,000	6.9	5.7	and end sill

The wave measurements were made in the channel 380 feet downstream from the end sill.

The amplitude of the waves is in feet prototype and the period is in seconds.

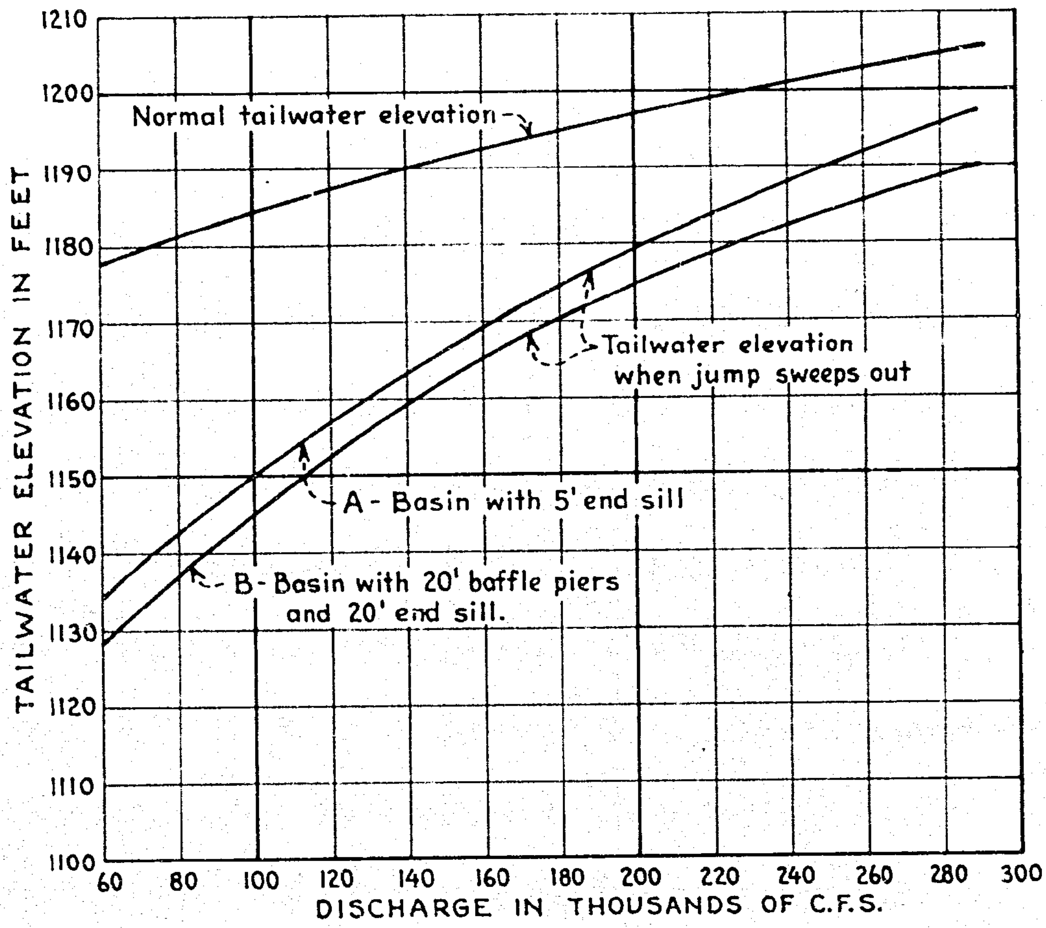
Waves in the River Channel
Overflow Spillway
Bhakra Dam - 1:50 Model

NOTE
Curve A applies to all three basin designs tested.



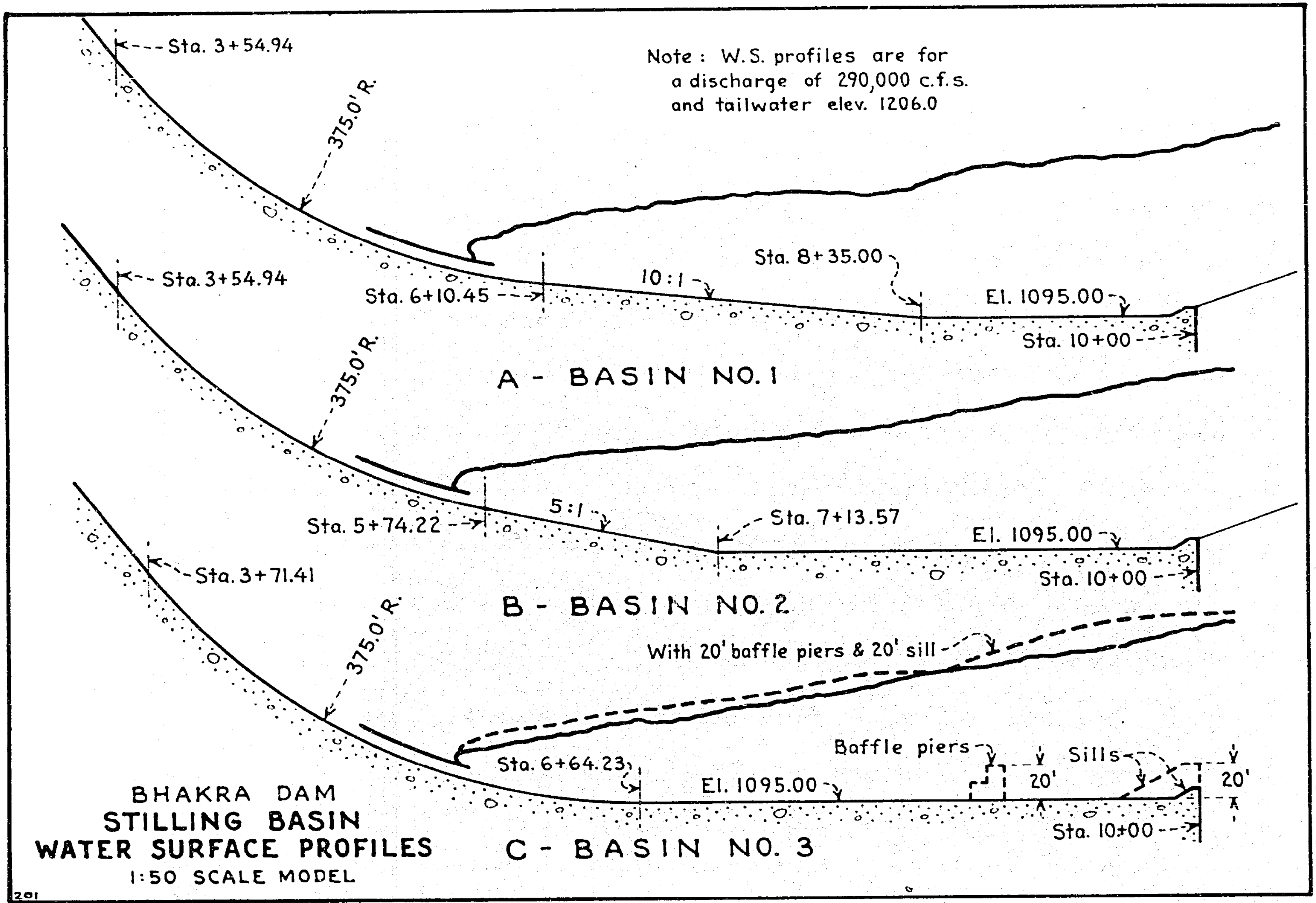
SECTION

DOWNSTREAM END OF STILLING BASIN

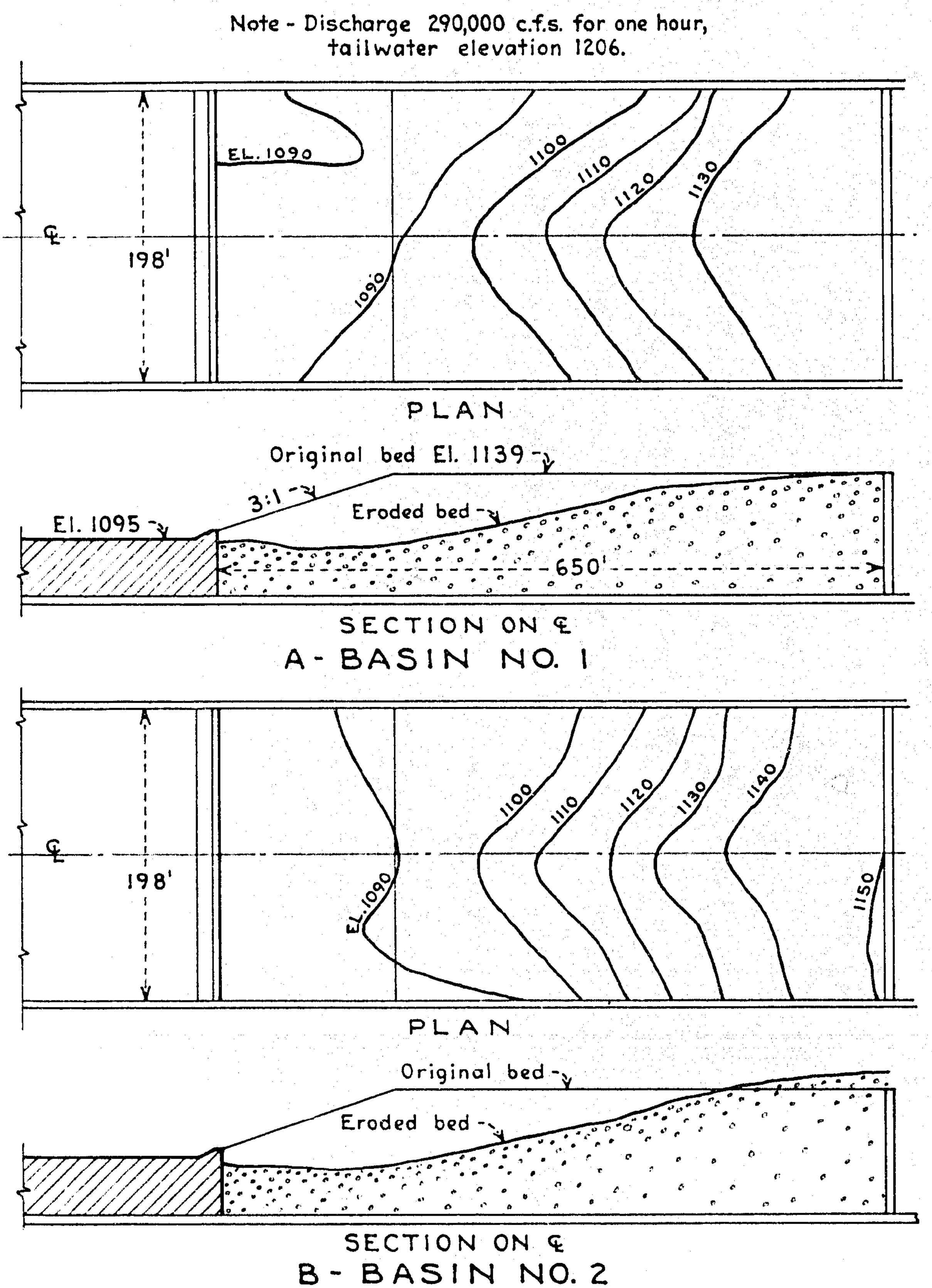


BHAKRA DAM
STILLING BASIN TESTS
TAILWATER AND SWEEPOUT CURVES
1:50 SCALE MODEL

FIGURE 10



BHAKRA DAM
STILLING BASIN
WATER SURFACE PROFILES
1:50 SCALE MODEL



BHAKRA DAM
STILLING BASIN
EROSION TESTS
1:50 SCALE MODEL

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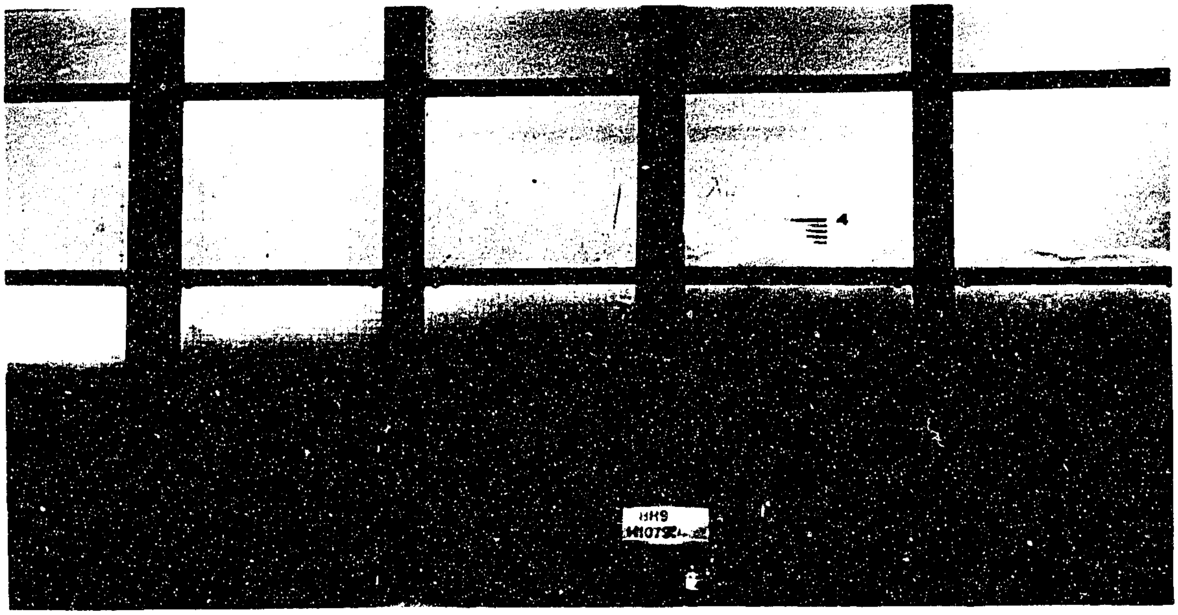
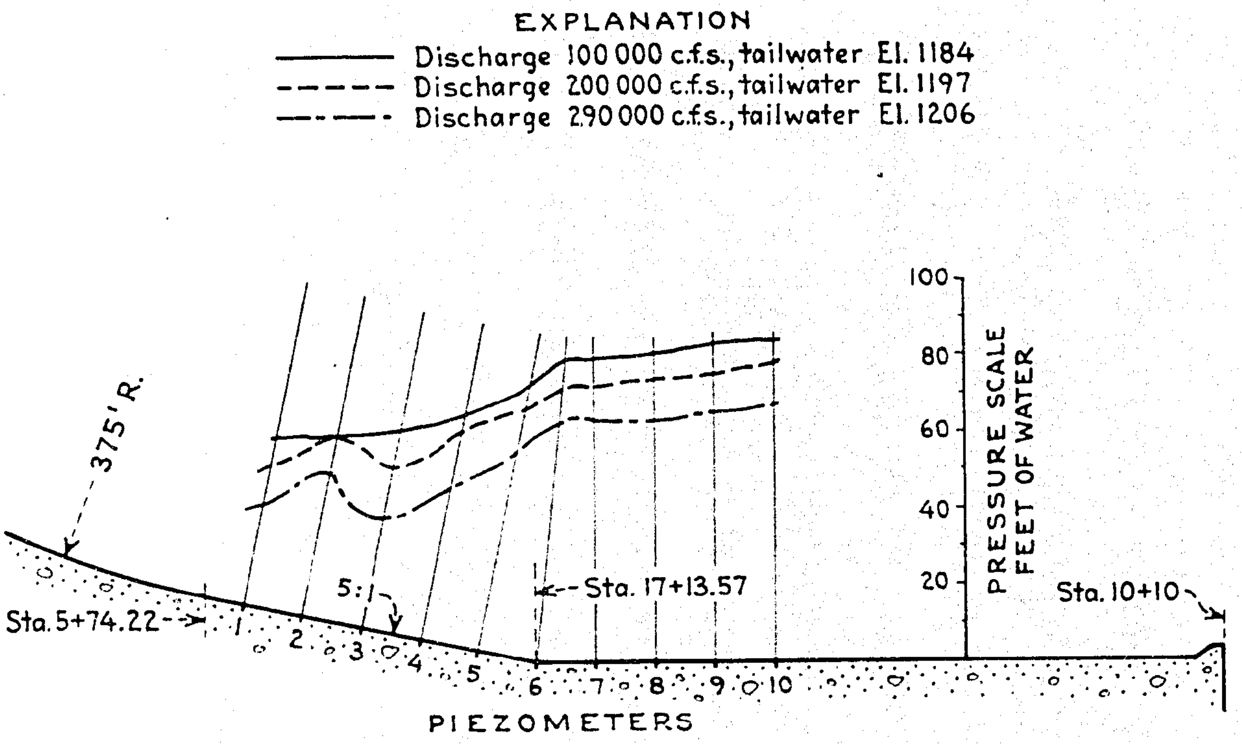
Figure 13

A. Discharge 200,000 cfs

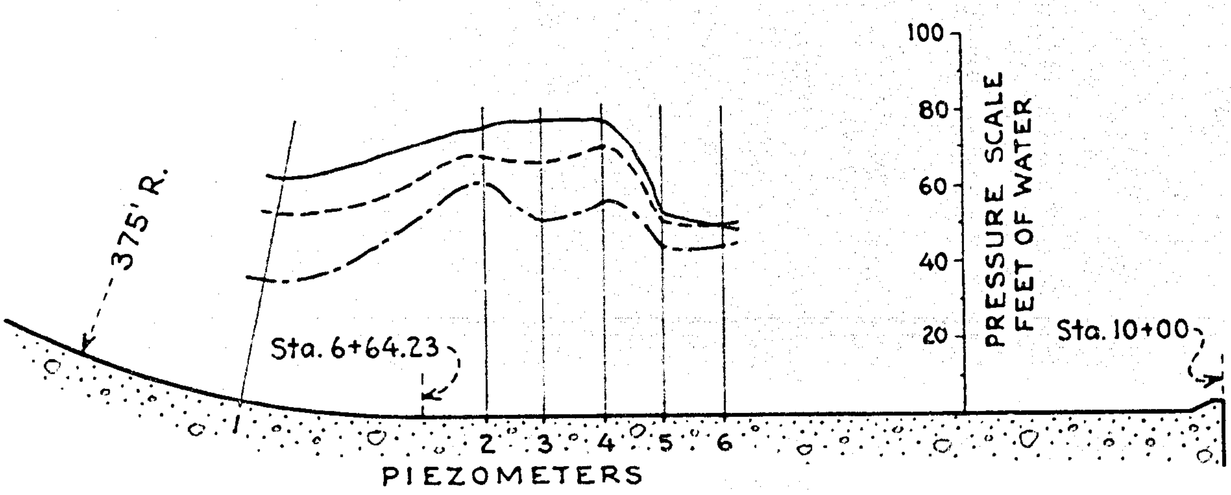


B. Discharge 290,000 cfs

SPILLWAY
STILLING BASIN NO. 2
BHAKRA DAM - 1:50 MODEL



A - BASIN NO. 2

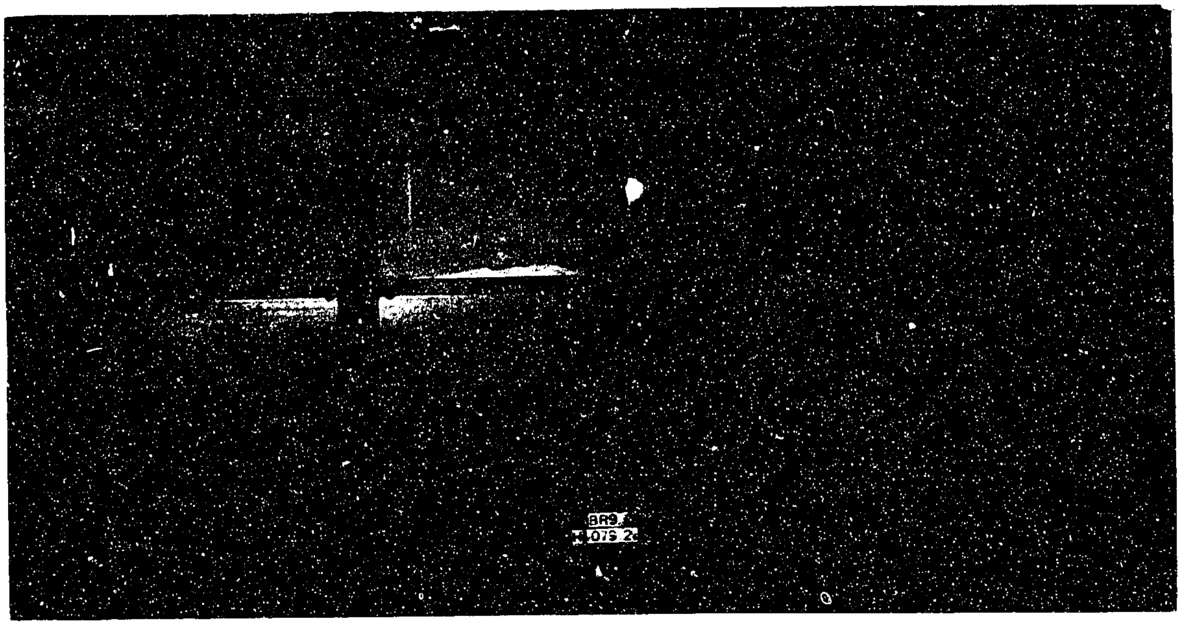


B - BASIN NO. 3

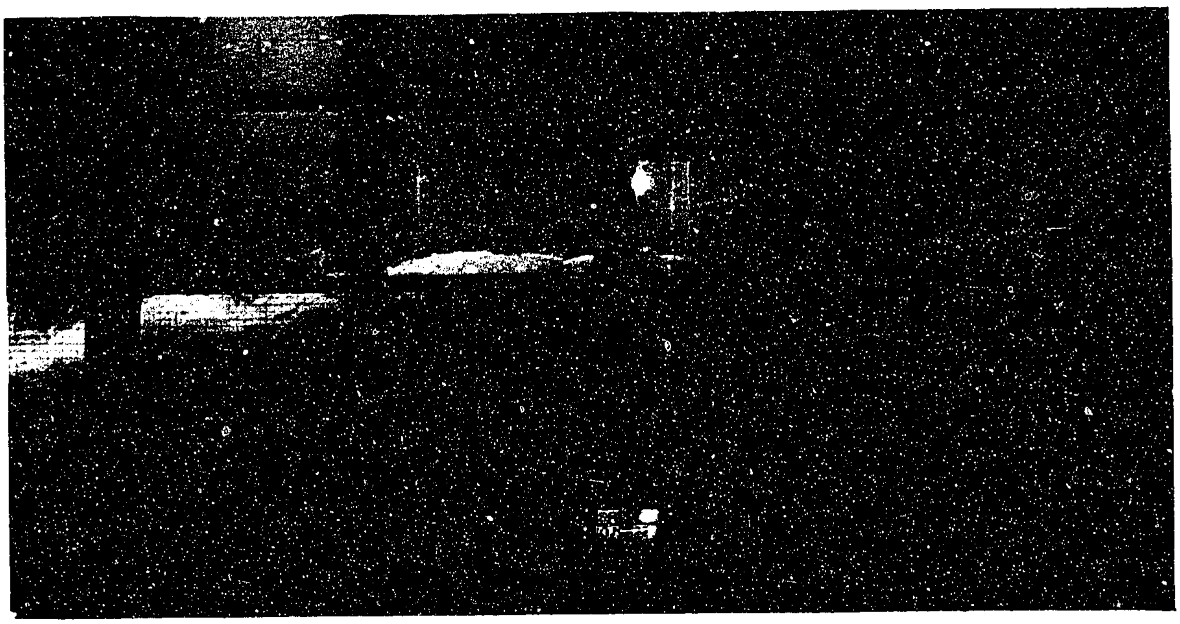
BHAKRA DAM

FLOOR PRESSURES IN STILLING BASIN

1:50 SCALE MODEL



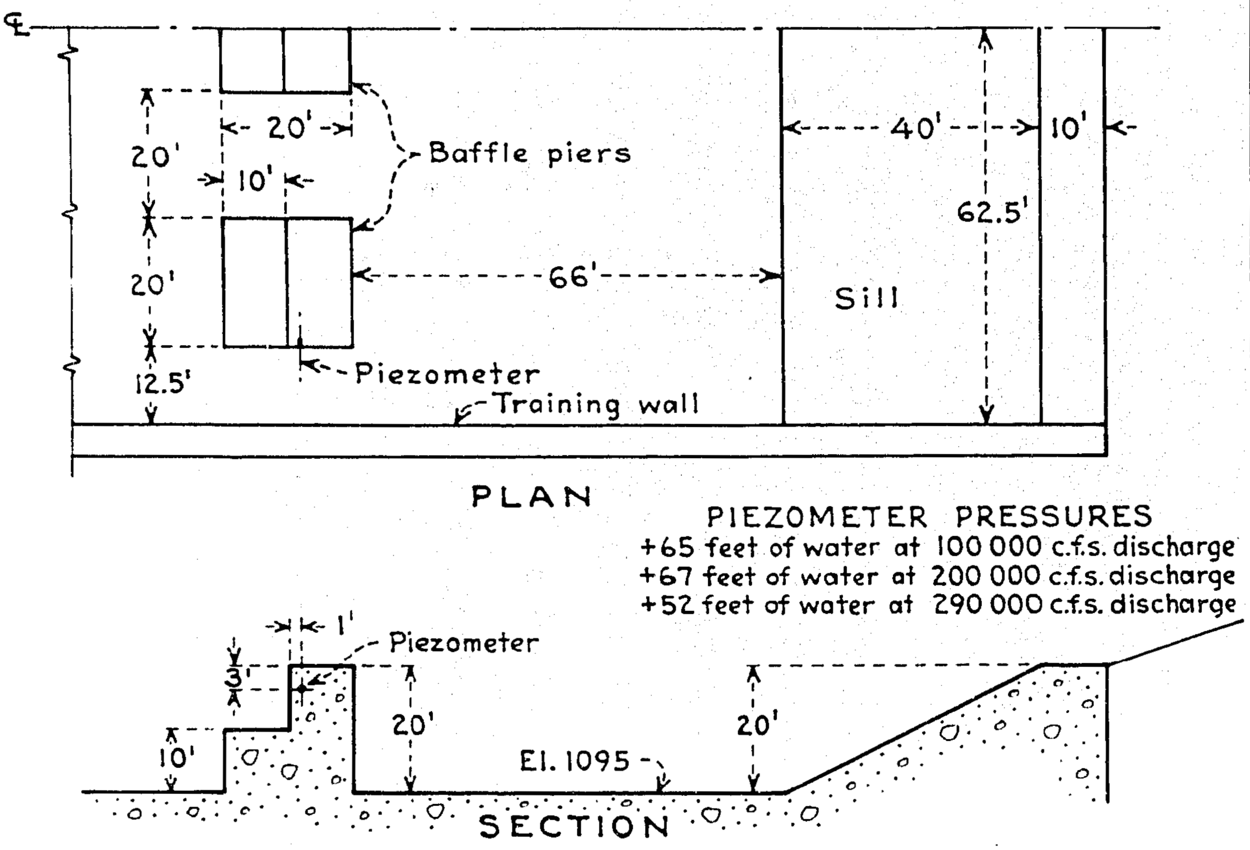
A. Discharge 200,000 cfs



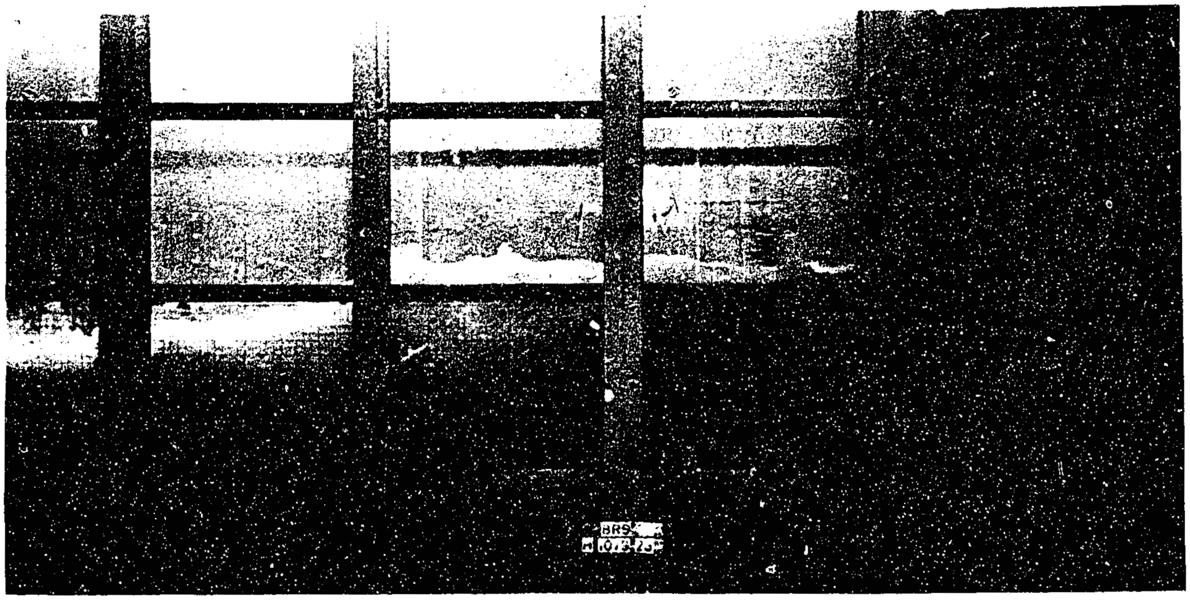
B. Discharge 290,000 cfs

SPILLWAY
STILLING BASIN NO. 3
BHAKRA DAM - 1:50 MODEL

FIGURE 16



A - DETAIL OF BAFFLE PIERS & SILL



B - DISCHARGE 290,000 C.F.S. - NORMAL TAILWATER

BHAKRA DAM

STILLING BASIN NO. 3

WITH BAFFLE PIERS AND 20' SILL

1:50 SCALE MODEL