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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES OF KEYHOLE DAM SPILLWAY

Hydraulic Laboratory Report No. HYD-271

ENGINEERING LABORATORIES BRANCH

DESIGN AND CONSTRUCTION DIVISION
DENVER, COLORADO

January 8, 1952

FOREWORD

Hydraulic model studies of the Keyhole Dam Spillway, a part of the Missouri River Basin Project, were conducted in the Hydraulic Laboratory of the Bureau of Reclamation at Denver, Colorado, during the period April 26, 1949 to December 20, 1949.

The final plans evolved from this study were developed through the cooperation of the staffs of the Spillway and Outlet Section No. 2 and the Hydraulic Laboratory.

During the course of the model studies, Messrs. H. W. Tabor, R. W. Whinnerah, and H. E. Miller of the Spillway and Outlet Design Section No. 2 frequently visited the laboratory to observe the model tests and discuss the results.

These studies were conducted by G. L. Beichley under the direct supervision of W. E. Wagner, A. J. Peterka, and J. N. Bradley.

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Laboratory Report No. HYD-271
Hydraulic Laboratory
Compiled by: G. L. Beichley
Reviewed by: A. J. Peterka

Subject: Hydraulic model studies of Keyhole Dam Spillway

SUMMARY

Hydraulic model studies of Keyhole Dam Spillway (Figures 1, 2, and 3) were made on a 1:24 scale model (Figures 4 and 5) for the purpose of developing and checking the hydraulic design. Data and notes taken on the flow in the model showed the preliminary design of the structure in general to be satisfactory except that for reservoir elevation 4111.5 the capacity of the spillway was greater than the designers had specified. By reducing the crest length from 21 to 19.25 feet the designers' specification was fulfilled.

Performance tests showed the approach to the spillway crest (Figure 6) to be satisfactory for all discharges. Calibration of the model crest showed the discharge coefficient to be about 3.61 for the design reservoir elevation 4111.5 (Figure 9) which indicated an efficient crest shape for existing limitations. Pressure tests showed no subatmospheric pressures existing on the crest for any discharge (Figure 11). Since the preliminary crest shape was found to be efficient and no subatmospheric pressures were present, it was therefore recommended for the prototype.

Tests conducted to check the performance of the preliminary spillway chute and preliminary long radius deflector, radius 15 feet, (Figure 12) showed the flow in the chute to be smooth and evenly distributed from one training wall to the other (Figure 13). The performance of the deflector at the downstream end of the chute (Figure 14) also proved to be satisfactory; however, tests were made to improve its performance by increasing the throw of the jet trajectory (Figures 15 through 18) particularly for the smaller flows. The preliminary deflector design, however, proved to be the most economical.

The spillway chute was shortened during the investigation as a result of additional field data received by the designers. The designers shortened the chute 91 feet and thus reduced the width of the preliminary deflector from 50 to 40 feet. Tests showed this shorter chute and deflector to perform equally satisfactory (Figures 19 and 20) to that of the preliminary design.

Erosion tests conducted to define the scour pattern showed that erosion did not occur adjacent to the deflector (Figures 23 through 26). The water-surface profile throughout the entire length of the spillway chute along the left training wall (Figure 27) was recorded for determining the necessary height of the training walls. This shorter chute and narrower deflector is recommended for the prototype. The complete recommended spillway structure is shown in Figure 3.

INTRODUCTION

Keyhole Dam is a part of the Keyhole Unit of the Cheyenne Division of the Missouri River Basin Project. It is located on the Belle Fourche River about 16 miles northeast of Moorcroft, Wyoming, as shown in Figure 1. The dam, shown in Figure 2, is earth-fill approximately 3,420 feet long at the crest, with a maximum height of approximately 125 feet above the riverbed.

The spillway, shown in Figure 3, has an uncontrolled crest discharging into an open channel chute on the right abutment. The spillway is 19.25 feet wide at the crest, Station 2+11.67, and the chute continues at this width to Station 3+21; at which point it flares uniformly to the end of the structure, Station 4+91. The structure is 40 feet wide at the end, measured between training walls and contains a 15-foot radius deflector bucket 10 feet long for pitching the flows downstream away from the structure. The spillway is 279.33 feet long measured horizontally from the spillway crest axis to the end of the deflector, with a slope of 0.0629 in the open channel chute. The crest is at elevation 4099.3, 28.9 feet below the maximum water surface of the reservoir. The spillway is designed to pass a maximum discharge of 10,600 second feet with the reservoir at maximum water surface which corresponds to about 550 second feet per lineal foot of crest length or 265 second feet per lineal foot of deflector. It was desired, however, that the flow at reservoir elevation 4111.5 not exceed 3,000 second feet.

THE MODEL

The model was constructed and tested in the Bureau of Reclamation Hydraulic Laboratory at the Denver Federal Center. It was a 1:24 scale reproduction of the spillway and surrounding area as shown in Figures 4 and 5. Topography in the reservoir area was reproduced for a distance of 240 feet upstream from the spillway crest and for 150 feet to the right and left of the crest. Downstream from the end of the preliminary spillway chute and deflector the topography was reproduced for a distance of 288 feet and for 120 feet on each side.

Water was supplied to the model by means of a 6-inch portable pump through an 8-inch line. The discharges were measured with an 8-inch orifice-venturi meter placed in the supply line. The reservoir elevation was measured by use of a hook-gage-in-well. Crest pressures were measured using 10 piezometers placed near the centerline of the spillway.

Topography in the reservoir area of the model was molded of concrete mortar placed on metal lath which had been nailed over wooden templates cut to the ground-surface contour. Model concrete surfaces, simulating nonconcrete surfaces of the prototype, such as topography, were given a rough finish, while concrete surfaces simulating prototype concrete surfaces were given a smooth finish. The spillway approach crest, chute, and deflector bucket were molded in cement mortar against sheet-metal templates accurately cut and placed. A 1/2-inch-wide strip of sheet metal was fastened normal to the template located on the centerline of the spillway, and piezometers which consisted of 1/16-inch inside diameter copper tubing were inserted. The piezometers were inserted normal to the surface determined by the metal strip and dressed flush. Thus, the piezometer openings were on a smooth polished, metal strip which conformed exactly to the spillway profile. The slope of the open channel chute floor of the model was constructed steeper than that of the prototype for the purpose of maintaining hydraulic similitude, as will be discussed later in this report.

The sandstone sublayer in the area downstream from the prototype structure was modeled, while the overburden was omitted entirely. It was felt that the first spillway flow of any size occurring in the prototype would wash the overburden away, leaving the rock sublayer exposed. The sublayer is a soft thin-bedded sandstone with layers not bonded together. During the preliminary test the contours of this sublayer were formed in pea gravel, but the pea gravel was found to be unsatisfactory because the sides of the eroded hole were not stable. During a test they were continually collapsing, producing an erosion pattern that could not occur in the prototype. Consequently, a material was used which would erode easily in the model and which would stand vertically without collapsing. The material was a lean mixture of sand, cement, and water which was cured for a specified time, and which by actual test resisted erosion up to a predetermined velocity. It is believed that this bed material represented the prototype material as closely as is possible in a model. Further discussion of the mixture used and the erosion tests are discussed in the investigation section of this report.

THE INVESTIGATION

The investigation was concerned with the over-all performance of the spillway and with the erosion caused by the jet from the spillway deflector bucket. The maximum discharge of 10,600 second feet was of primary concern. This discharge corresponds to about 550 second feet per linear foot of crest length with a head of 28.9 feet on the crest. To a lesser degree, the investigation was concerned with the spillway discharging 1,000 second feet and the design discharge of 3,000 second feet.

Tests for these lower discharges were made primarily to be certain that the structure operated as intended and that the erosion pattern was satisfactory over the entire discharge range. The investigation included the testing of the spillway approach, the spillway crest, the spillway chute, and the deflector at the end of the chute, as well as observation of the erosion caused by the jet leaving the deflector.

Spillway Approach

The spillway approach area is shown in Figure 3. Flow conditions for the entire range of discharges were investigated in this area. Only a very slight disturbance occurred around the left and right wing walls. An almost insignificant wave formed along each approach wall which was most evident for the maximum flow shown in Figure 6. Flow conditions were considered satisfactory, and no changes in the preliminary design are recommended in this area.

Spillway Crest

Predicting the Coefficient

Prior to determining the discharge coefficient by model calibration tests, the coefficient of discharge was predicted by comparing the crest profile shown in Figure 3 with other crest profiles whose coefficients were known. Predictions were made to determine the degree of accuracy in predicting coefficients by this method.

Dimensionless plots of the crest profile were made for the design reservoir elevation 4111.5 and the maximum reservoir elevation 4128.2 as shown in Figures 7(a) and 7(b), respectively. The ratio y/H_o was plotted against x/H_o, where the origin of coordinates of the two axes is on the crest of the overflow section, and H_o is the height of reservoir elevation above the crest. The plots were made to the same scale as similar plots of other crest profiles shown in Figure 21 of Hydraulic Laboratory Report No. HYD-208, 1/ reproduced in this report as Figure 8. The solid-line plots in Figure 8 are the actual model crest profiles, while the dashed-line plots are the datum or experimental shapes. By datum shape is meant the shape that coincides with the natural under nappe profile of the jet leaving a sharp edge weir having the same slope as the upstream face of the actual crest. This will be the smallest cross section as well as the most efficient shape, on which no significant subatmospheric pressures will exist. The C_M values are the discharge

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1/HYD-208, "Comparison of Discharge Coefficients for Various Types of Overflow Spillway Sections" by J. N. Bradley.

coefficients for the actual shapes or solid-line plots and were obtained from the model tests. The C_D values are the discharge coefficients of the datum shapes or dashed-line plots.

The dimensionless plot of Keyhole Dam Spillway crest profile in Figure 7(a) seemed to compare in shape most nearly with the Bull Lake Dam Spillway in Figure 8; therefore, the coefficient for the Keyhole shape was estimated to be about 3.58 for reservoir elevation 4111.5. Model tests, which will be described subsequently, showed the coefficient to be 3.61, which is an error in the estimate of only about 0.83 percent. The shape of Figure 7(b) seemed to fall between the actual profile and datum profile of Unity Dam Spillway in Figure 8. By comparing Figure 7(b) with these two profiles, it was estimated that the coefficient was greater than the value of C_M but less than that of C_D. Averaging C_M and C_D gave an estimated coefficient of 3.63 for reservoir elevation 4128.2 as compared to 3.57 obtained from the model test which will be described later. This was an error of only 1.65 percent in the estimate.

In making the comparisons, it is not necessary to match the x/H_o and y/H_o axes of the crest profiles. It is only necessary that the outline of the profile in question match the outline of the profile having the known coefficient as closely as possible. Either actual or datum shapes may be used. The matching was done on a light table by shifting the profiles of Figure 7 over the profiles of Figure 8 until a profile on Figure 8 was found to match the one on Figure 7 as closely as possible. With a greater number of crest profiles with known coefficients available and with more practice in estimating the effects of variation from the known profile, closer estimates could be made.

Model Calibration

The preliminary crest was 21 feet long between training walls; it was calibrated by model tests to determine its capacity at design reservoir elevation 4111.5 and maximum reservoir elevation 4128.2, and to determine the value of the coefficient of discharge "C" in the equation

$$Q = CLH^{3/2}$$

where Q is the discharge,
L is the crest length, and
H is the total head or difference in elevation of reservoir and crest.

The spillway capacity curve and coefficient curve as determined from the test data are shown in Figure 9.

The designers specified that the spillway should pass not more than 3,000 second feet for reservoir elevation 4111.5. From the spillway capacity curve in Figure 9 for the preliminary crest length, the spillway discharge exceeded the limit by approximately 270 second feet. Consequently, the crest length was shortened an amount calculated to be necessary to reduce the discharge by 270 second feet. As a result, the crest length was shortened from 21 feet to 19 feet 3 inches.

Calibration of this shorter crest showed that the discharge was approximately 2,960 second feet for reservoir elevation 4111.5 which meets the limitation specified. The calibrated spillway capacity curve for the recommended crest length is also shown in Figure 9. The maximum discharge over the shorter crest was found to be 10,600 second feet for maximum reservoir elevation which was considered close enough to the 10,800 second feet anticipated by the designers.

From the spillway capacity curves the coefficient curves were determined for the preliminary crest length and for the shorter crest length. For all practical purposes, the two coefficient curves were found to be identical and are shown as a single solid line in Figure 9. Greatest deviation was to a smaller coefficient by less than 1 percent at the higher heads which can be considered experimental error.

The coefficient curve shows a value of 3.61 at design reservoir elevation 4111.5 and reaches a maximum value of 3.65 at about reservoir elevation 4116.5. The coefficient then decreases to 3.57 at maximum reservoir elevation 4128.2. A coefficient value in this range is about as high as can be expected without increasing the vertical drop from the crest to the upstream end of the chute, which was economically not feasible on this structure. Therefore, the crest shape is as efficient as can be expected.

At reservoir elevation 4116.5, 17.2 feet above the crest, the spillway discharged approximately 5,000 second feet and the value of the coefficient was about 3.65. As the discharge was increased, the coefficient decreased until for maximum discharge the coefficient decreased to 3.57. This condition is unusual; therefore, several checks were made to insure the greatest degree of accuracy in the measurements of discharge, head, and crest length. Further checking indicated that the decreasing coefficient was caused by the presence of the chute training walls downstream from the crest. It is not practical, of course, to eliminate the training walls in the prototype; however, it was found that with the training walls removed downstream from the crest profile the coefficient decreased only slightly as the discharge was increased above 5,000 second feet, as shown in Figure 9. Therefore, for flows of more than 5,000 second feet it is evident that the crest is more efficient with the training walls absent. With the walls in place there is a backwater effect which reduces the discharge. Removing the walls drops the water surface and relieves this condition to some extent. This evidence is substantiated by the water-surface profiles shown in Figure 10 and the crest pressures shown in Figure 11.

Apparently, for flows of 5,000 second feet or greater the critical depth or the true critical depth as referred to by Rouse in his text[2/] occurred some distance downstream from the crest profile since quantity of flow in that range was affected by the absence or presence of the training walls in this vicinity. Computations for the location of the critical depth cannot be made with certainty because the flow in the vicinity of the crest is curvilinear.

Crest Water-surface Profiles

Water-surface profiles over the spillway crest, on the centerline shown in Figure 10, were measured for the maximum flow of 10,600, 5,000, and 3,000 second feet. The profiles were used to aid in determining the height of training walls for the prototype and also for obtaining data which it is contemplated will eventually be used to establish general design information for low dams.

Profiles were also recorded with the chute training walls removed as previously described for substantiating the evidence from the calibration test that the crest is more efficient without the chute training walls. For the maximum flow of 10,600 second feet, the profiles show that the spillway is more efficient without the training walls than with them, since the profile upstream from the crest is lower when no training walls are used. For flows of 5,000 second feet and lower, where the discharge coefficient is the same with or without training walls, the profiles upstream from the crest are also identical which further substantiates the calibration data.

Crest Pressures

Pressures on the centerline of the spillway crest were recorded with the reservoir at elevation 4111.5 and at maximum elevation 4128.2. All pressures were above atmospheric as shown in Figure 11. Since no subatmospheric pressures were encountered and the discharge coefficient was satisfactory, the preliminary crest shape is recommended for the prototype structure.

2/Fluid Mechanics for Engineers.

Pressures were also recorded at Piezometers No. 8, 9, and 10 with the chute training walls removed and with training walls in place for flows of 10,600, 5,000, and 3,000 second feet. In conformance with the crest calibration and water-surface profile tests, the pressures with the training walls removed were less for 10,600 second feet and about the same for 5,000 and 3,000 second feet at the piezometer locations shown in Figure 11.

Spillway Chute and Deflector

Preliminary Chute and Deflector

Description. Head losses due to friction in a model are usually greater than the proportion indicated by the model scale because surfaces sufficiently smooth to represent prototype surfaces to scale do not exist. Therefore, to maintain the scale velocity throughout the model chute, it was necessary to either increase the slope of the chute or reduce the chute length. For this structure the slope was increased, since with this method, the geometrical similitude of the diverging chute in plan was unaltered, making it possible to observe and study the flow pattern throughout the chute as it would occur in the prototype.

The slope required for the model chute was computed by a method somewhat similar to that outlined in Hydraulic Laboratory Report No. 158,[3]. The slope of the model chute was computed to be 0.0818 as compared to 0.0629 in the prototype which increased the amount of fall throughout the chute length from 21.11 to 27.46 feet, prototype. With this slope correction, velocities at the end of the model chute represented those of the prototype. The pattern of the flow leaving the deflector bucket could then be depended upon to indicate the action to be expected in the prototype.

The preliminary chute and deflector are shown in Figure 12. The chute was 21 feet wide at the upstream end since the width of the preliminary crest was 21 feet. The chute extended 110.32 feet downstream from the crest at which point it began to diverge. Divergence continued uniformly for 260 feet to a 50-foot chute width, the last 10 feet of which contained a bucket deflector which terminated the structure. The preliminary deflector is the long-radius deflector shown in Figure 12. It had a bucket radius of 15 feet and is called

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[3] HYD-158, "Hydraulic Model Studies for the Design of the Spillway and Automatic Spillway Gates at Moon Lake Dam, Moon Lake Project" by J. E. Warnock, page 54.

"long-radius deflector" merely to distinguish it from the shorter radius bucket which was also tested and is discussed later in this report.

Performance. Flow throughout the chute for all discharges was smooth and evenly distributed from one training wall to the other. The flow pattern for 3,000 second feet is shown in Figure 13. The jet leaving the bucket deflector was projected into the air in the form of a sheet, striking the ground surface some distance downstream as shown in Figure 14. For flows not exceeding 550 second feet, a hydraulic jump was formed in the bucket and the flow spilled over the end causing slight erosion along the end of the structure.

Diverging deflector training walls versus parallel walls. Since the purpose of the deflector bucket was to throw the flow as far downstream as possible with the least detrimental effect, the first modifications were made to increase the length of jet trajectory, particularly for the smaller flows. The preliminary training walls along the sides of the deflector bucket were a continuation of the chute training walls which were diverging. Flow velocity near the training walls was less than the velocity toward the center of the deflector; and, therefore, the jet near the sides was not projected as far downstream as at the center, Figure 14. To increase the distance that the jet would spring from the deflector, particularly at the ends, the training walls at the ends of the deflector were made parallel.

At low flows, for which the increase in distance was most needed, the gain was slight, amounting to approximately 1 or 2 feet prototype as shown in Figure 15. It was also found that the parallel deflector training walls increased the height of water-surface profile along the training walls by as much as 1-1/2 feet above that recorded for the diverging walls as shown in Figure 16. The higher water-surface profile necessarily required that the parallel training walls be constructed higher than the diverging ones, offsetting the slight advantage gained in the spring distance of the jet. The preliminary divergent training walls, therefore, were recommended for the prototype.

Long-radius deflector versus short-radius deflector. To continue the tests to obtain a longer jet trajectory the preliminary deflector was replaced by a 12.5-foot-radius deflector. It is shown in Figure 12 and is called the "short-radius deflector." Essentially, it was the same as the preliminary except for the shorter radius and higher lip elevation. Training walls were made divergent as a result of the preceding tests.

Figure 17 shows the short-radius deflector bucket in operation. The jet springing from this deflector pitched higher into the air and farther downstream than the jet in the preliminary design as shown in

Figure 18. The minimum horizontal spring distance from the deflector to the jet downstream along datum elevation 4071.41 was again measured for several increments of discharge and plotted in Figure 15. The spring distance was found to be considerably greater than for the preliminary design, especially so for discharges of 1,500 second feet or greater. However, to offset this advantage, the water-surface profiles shown in Figure 16 plotted for 3,000 and 10,600 second feet indicate that a training wall approximately 3 feet higher than that of the preliminary design would be required at the ends of the deflector. Also a little deeper scour occurred in pea gravel for the shorter radius bucket as shown in Figure 18. This was caused by an increased vertical component in the velocity of the jet. A third disadvantage to the shorter radius deflector was that a discharge of 850 second feet was required before the jet would spring from the downstream end of the deflector as compared to 550 second feet for the preliminary design. For flows below these critical points a jump formed in the chute, and the water falling over the deflector caused erosion along the end of the structure. More and deeper erosion therefore occurred with the short-radius deflector than with the preliminary deflector. These three disadvantages offset the one advantage of throwing the jet and, consequently, the scour farther downstream. The preliminary long-radius, 15-foot, deflector was therefore preferred.

Recommended Chute and Long-radius Deflector

Description. The 21-foot-wide section of chute was reduced to 19 feet 3 inches to conform to the recommended crest width. Then a further revision was made by the designers. They had received additional foundation data from the field which allowed them to reduce the length of the spillway chute. Therefore, they requested that the chute be terminated at Station 4+91, making the chute 91 feet shorter than the preliminary design. The chute training wall divergence was begun 1 foot farther upstream than in the preliminary chute, keeping the same angle of divergence. This resulted in a chute width of 40 feet at the end of the structure compared to 50 feet in the preliminary design. The long-radius deflector bucket of the preliminary design, reduced to a 40-foot width, was used at the end of the chute. The training walls remained divergent throughout the deflector.

Performance. Operation of the model with discharges of 3,000 and 10,600 second feet showed the flow to be smooth and evenly distributed across the width of the chute throughout its length. The performance was very similar to that in the preliminary design shown in Figure 13.

The deflector in operation is shown in Figure 19. The trajectory of the jet springing from the deflector was flatter than that in the preliminary design as shown by comparing Figure 20 with Figure 18. The flatter trajectory in the latter design is caused by the increased concentration of flow at the deflector. The flow concentration at the deflector in the latter design is 260 second feet per lineal foot of crest width for the maximum flow as compared to 210 second feet in the preliminary design. The flatter trajectory produced a shorter spring distance for all flows between 3,000 and 10,600 second feet, but the depth of scour in pea gravel was less with these flows as can be seen by comparing Figure 20 with Figure 18. The spring distance for small flows of less than 3,000 second feet was nearly the same in either design. In general, on the basis of these performance tests, this chute and deflector design proved to be satisfactory for prototype construction.

Erosion. The model topography in the area downstream from the deflector had been molded to represent the prototype sandstone sublayer which in the prototype was under an overburden of approximately 5 to 10 feet of earth. The overburden was omitted in the model. This procedure was followed because it had been assumed that the overburden had no resistance to erosion and would quickly be washed away leaving the sandstone exposed.

The sandstone topography was first molded with pea gravel, but the jet scoured so deep that the sides of the hole continually collapsed and slid to the angle of repose of the loose gravel causing the area surrounding the jet to lower and become submerged. This action was not representative of the prototype. This action permitted a large eddy to form on each side of the jet. The eddies in turn rapidly cut away the bank around the jet back to and under the deflector, a condition which could not occur in the prototype in any reasonable length of time. In order to get a more truthful determination of the early scour pattern that might occur in the prototype, a very lean sand-cement mixture was used to simulate the prototype sandstone sublayer.

To simulate the erosion characteristics of the prototype sandstone as closely as possible, an undisturbed sample of the prototype sublayer was taken from the area in which the scouring would occur and brought to the laboratory for tests. In a specially built test rig tests were made on the sample to determine its erosion resistance by determining the velocities of flow that it would withstand before erosion occurred. The tests are described in detail in Hydraulic Laboratory Report No. 272.[4] From these tests it was found that the prototype sample would withstand an average prototype velocity of 4 feet per second under expected flow

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4/HYD-272, "Erosion Tests on an Earth Sample Taken at Elevation 4065.3 on the Spillway Centerline 70 Feet Downstream from the End of the Proposed Spillway" by W. Simmons.

conditions. The erosion-resistant characteristics of the prototype sample were then duplicated in model material as closely as possible. The model material was made from a mixture of sand, cement, and water placed and tamped in 2-inch layers after which it was allowed to cure approximately 48 hours. Tests were made on different sample model mixtures to determine the exact quantity of cement necessary to provide just the right amount of resistance to erosion.

The apparatus used to test the sample mixtures is shown in Figure 21. In the test apparatus the sample mixtures were also placed and tamped in 2-inch layers and allowed to cure 48 hours before being tested for erosion resistance. After the sample had cured, water was allowed to flow over it at some desired velocity. Velocities were determined by timing, with a stop watch, a particle of paper traveling a distance of 1 foot over the sample. The water was allowed to run over the sample for approximately 30 minutes. If no noticeable erosion occurred, the velocity was increased by small increments until it was determined at which velocity each sample would erode.

Results of these tests on the sample mixtures are plotted in Figure 22 and a curve drawn connecting the test points approximately. From these results it was found that a very lean mixture of sand and cement was required for erosion to start at 4 feet per second. On the other hand, such a lean mixture would not hold an undercut; like the pea gravel topography, the eroded side walls of the sample would collapse, slide into the channel, and wash away, a condition that was believed could not occur in the prototype. The difficulty in satisfying both conditions was caused by the small scale of the model. Had the scale of the model been larger, a richer mixture could have been used which would have eroded at the correct model velocity representing 4 feet per second in the prototype, and near vertical cuts would have been firm enough to resist sloughing. As it was impractical to change the scale of the model, it was decided that it was more important to obtain a mixture sufficiently stable to prevent the collapse of eroded banks than to have the velocity characteristic exactly correct. From the sample tests, it was found that a mixture of 1 part cement to 150 parts sand by weight was necessary to prevent sloughing so it was decided to use this mixture for the model erosion tests; however, the velocity necessary to erode this sample was 7.4 feet per second as shown in Figure 22.

Figure 5 shows the model ready for the erosion testing. A 30-minute model erosion test, corresponding to 3 hours in the prototype, was first run with a discharge of 1,000 second feet. Photographs of the test in progress and the scour resulting from the test are shown in Figure 23. Leaving the resulting scour pattern unchanged, an additional 30-minute test with 3,000 second feet was run. This test in progress and the scour resulting from it are shown in Figure 24. Next, leaving this scour pattern unchanged, an additional 30-minute test with 10,600 second feet was run. The test is progress and scour pattern results are shown in Figure 25. Once again leaving the scour pattern unchanged, the discharge was reduced to 1,000 second feet for a model test period of 10 minutes then increased to 3,000 second feet for another period of 10 minutes. This test in progress and the scour pattern result are shown by the photographs in Figure 26.

These successive erosion test runs represent successive floods that may occur in the prototype; the scour is seen to be quite extensive, but inasmuch as the topography adjacent to the deflector remained uneroded at elevation 4075 there was no tendency to undermine or damage the structure. Additional floods could probably increase the erosion downstream, but it is believed that very little increase in erosion would occur at the downstream edge of the structure. Erosion adjacent to the end of the structure occurs only for small flows of less than approximately 1,000 second feet in which case the erosion appears to be minor. In general, the erosion tests show that this chute and deflector design provide as much protection to the structure as can be expected from this type of bucket.

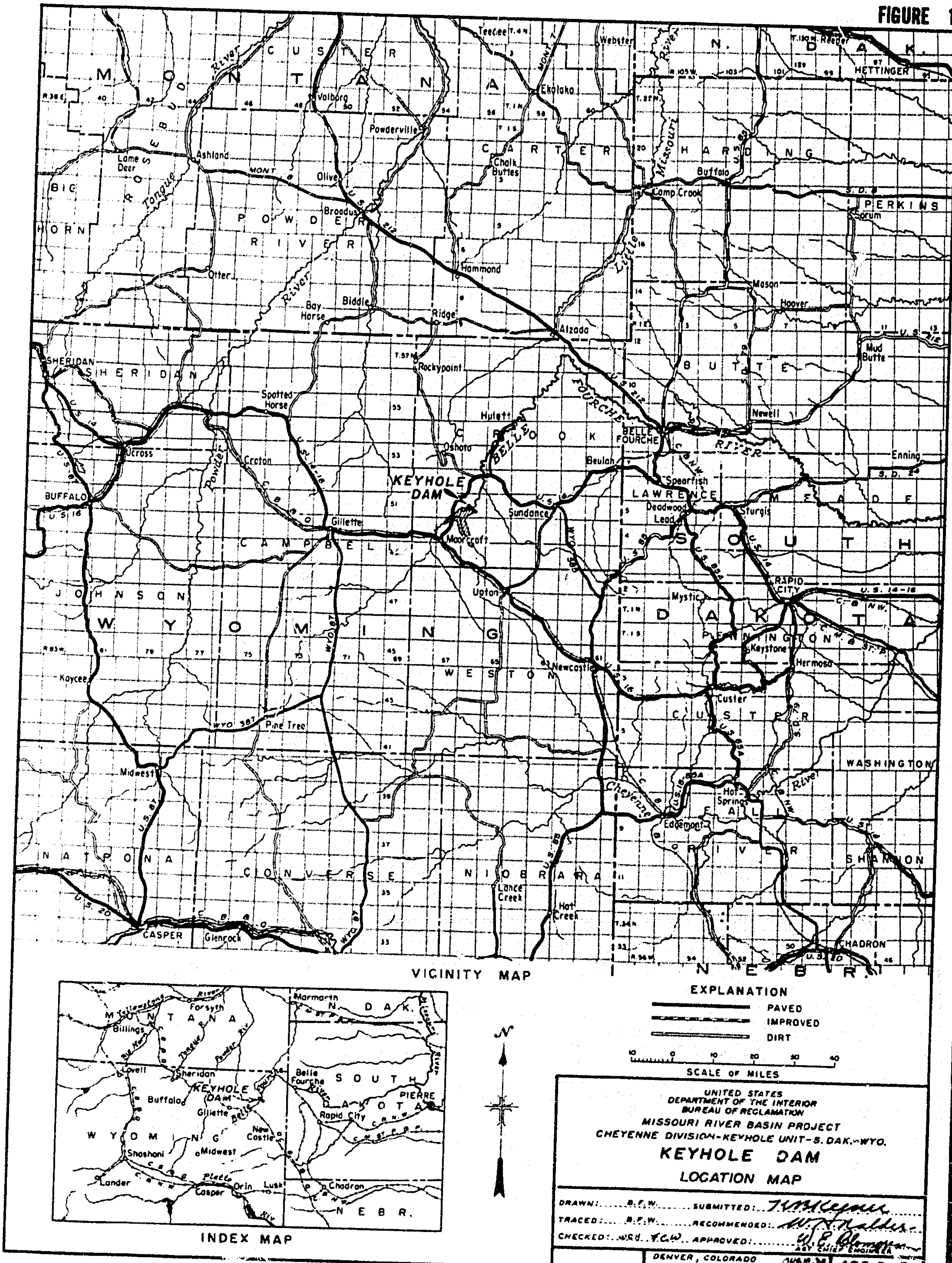
Water-surface profile. The water-surface profile for 10,600 second feet was measured along the left training wall of the model spillway chute and is shown in Figure 27. Due to air insufflation that would occur in the prototype, because of the proportionally higher velocities, the water-surface profile in the prototype was estimated to be from zero percent higher at the crest, to 25 percent higher at the deflector than that obtained from model tests as shown in Figure 27. The estimate was based on a limited amount of field data from similar prototype structures as reported in Hydraulic Laboratory Reports No. 35,5/and 40.6/ The designers, with the aid of these data, determined the height of the training walls required for the prototype structure shown in Figure 3.

For flows of 10,600 and 3,000 second feet the water-surface profiles along the left wall of the deflector are shown in Figure 28. The water surface here is higher than in the long-radius deflector of the preliminary design, but the additional cost of the higher training wall required will be more than offset by the 91-foot reduction in chute length. On the basis of the performance, erosion, and water-surface profile test this chute and long-radius deflector design is recommended for prototype construction.

5/HYD-35, "Progress Report on Studies of the Flow of Water in Open Channels with High Gradients" by C. W. Thomas.

6/HYD-40, "Second Progress Report on Studies of the Flow of Water in Open Channels with High Gradients" by V. L. Streeter.

FIGURE 1



KEYHOLE DAM
VICINITY MAP
INDEX MAP
EXPLANATION
PAVED
IMPROVED
DIRT
SCALE OF MILES
MONTANA
WYOMING
SOUTH DAKOTA
N. DAK.
NEBR.
CUSTER
CARTER
HARDING
PERKINS
POWDER RIVER
ROSEBUD
BIG HORN
SHERIDAN
JOHNSON
CAMPBELL
CROOK
WESTON
BUTTE
LAWRENCE
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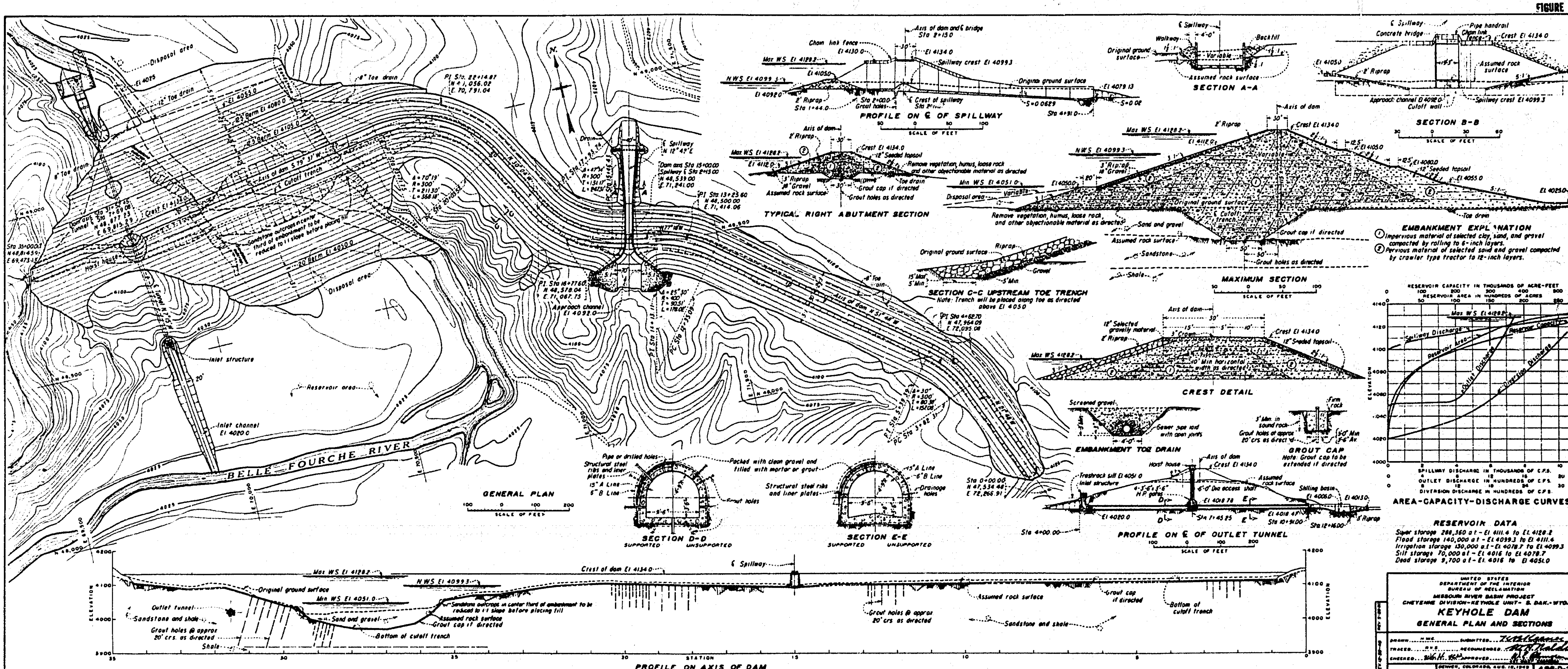
Edgemont
Casper
Glenrock
Midwest
Kaycee
Alzada
Hammond
Broadus
Ekalaka
Buffalo
Camp Crook
Hulett
Oshoto
Beulah
Custer
Keystone
Hermosa
Chadron
Lance Creek
Hat Creek
Pine Tree
Ucross
Croton
Spotted Horse
Rockypoint
Biddle
Bay Horse
Ridge
Otter
Ashland
Lame Deer
Olive
Powderville
Volborg
Teedee
Webster
Reeder
Hettinger
Mason
Hoover
Mud Butte
Newell
Enning
Mystic
Sorum
Belle Fourche River
Cheyenne River
Little Missouri River
Powder River
Tongue River
Billings
Forsyth
Marmarth
Lovell
Shoshoni
Lander
Orin
Lusk
New Castle
Pierre
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
CHEYENNE DIVISION-KEYHOLE UNIT-S. DAK.-WYO.
KEYHOLE DAM
LOCATION MAP
DRAWN: B.F.W.
TRACED: B.F.W.
CHECKED:
SUBMITTED:
RECOMMENDED:
APPROVED:
ASST. CHIEF ENGINEER
DENVER, COLORADO
486-D-

FIGURE 2



GENERAL PLAN
BELLE FOURCHE RIVER
PROFILE ON ℄ OF SPILLWAY
SECTION A-A
SECTION B-B
TYPICAL RIGHT ABUTMENT SECTION
MAXIMUM SECTION
EMBANKMENT EXPLANATION
Impervious material of selected clay, sand, and gravel compacted by rolling to 6-inch layers.
Pervious material of selected sand and gravel compacted by crawler type tractor to 12-inch layers.
SECTION C-C UPSTREAM TOE TRENCH
CREST DETAIL
EMBANKMENT TOE DRAIN
GROUT CAP
SECTION D-D
SECTION E-E
PROFILE ON ℄ OF OUTLET TUNNEL
AREA-CAPACITY-DISCHARGE CURVES
RESERVOIR DATA
PROFILE ON AXIS OF DAM
UNITED STATES DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
CHEYENNE DIVISION-KEYHOLE UNIT-S. DAK.-WYO.
KEYHOLE DAM
GENERAL PLAN AND SECTIONS
DENVER, COLORADO
486-D-26

FIGURE 3

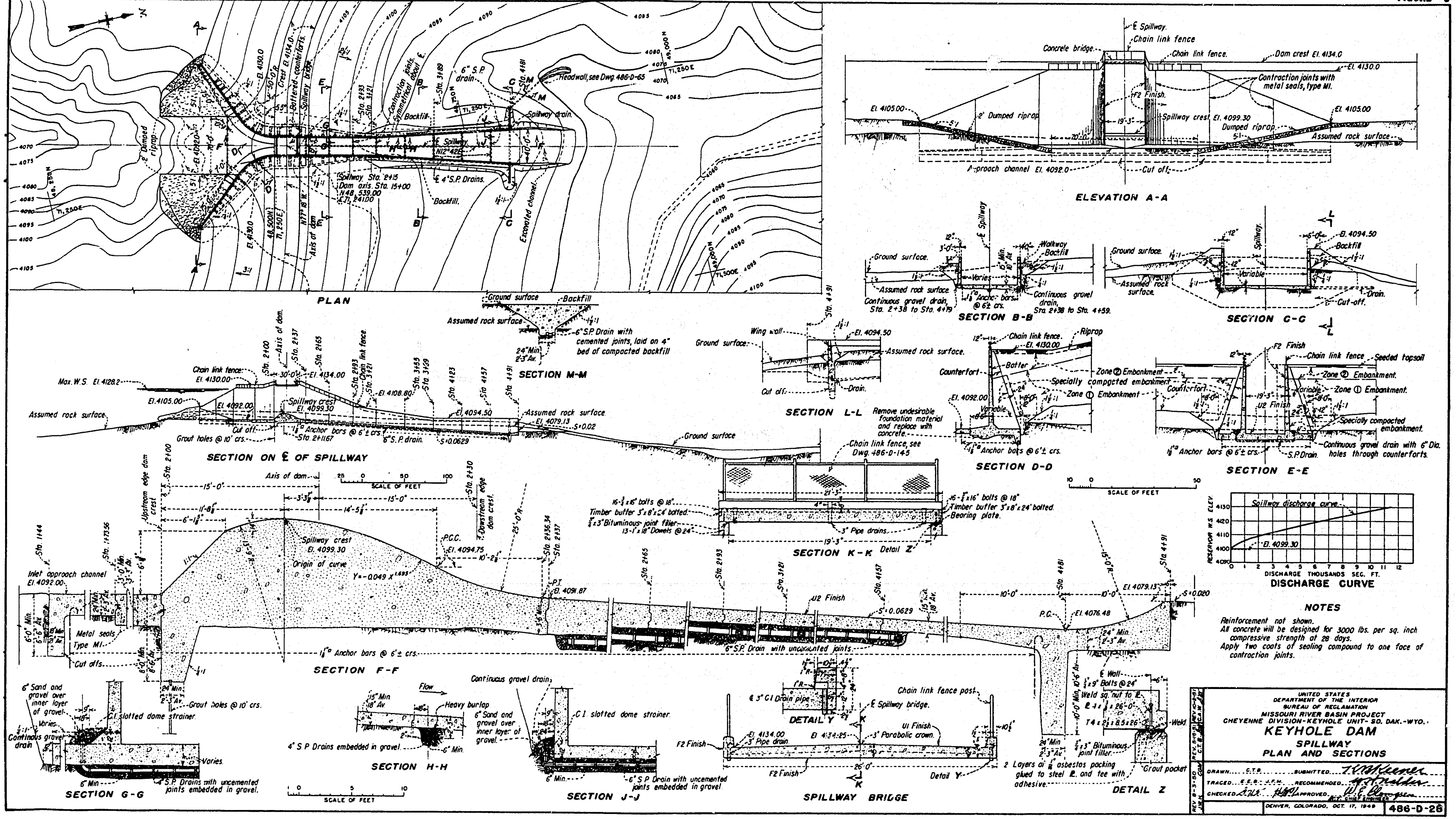
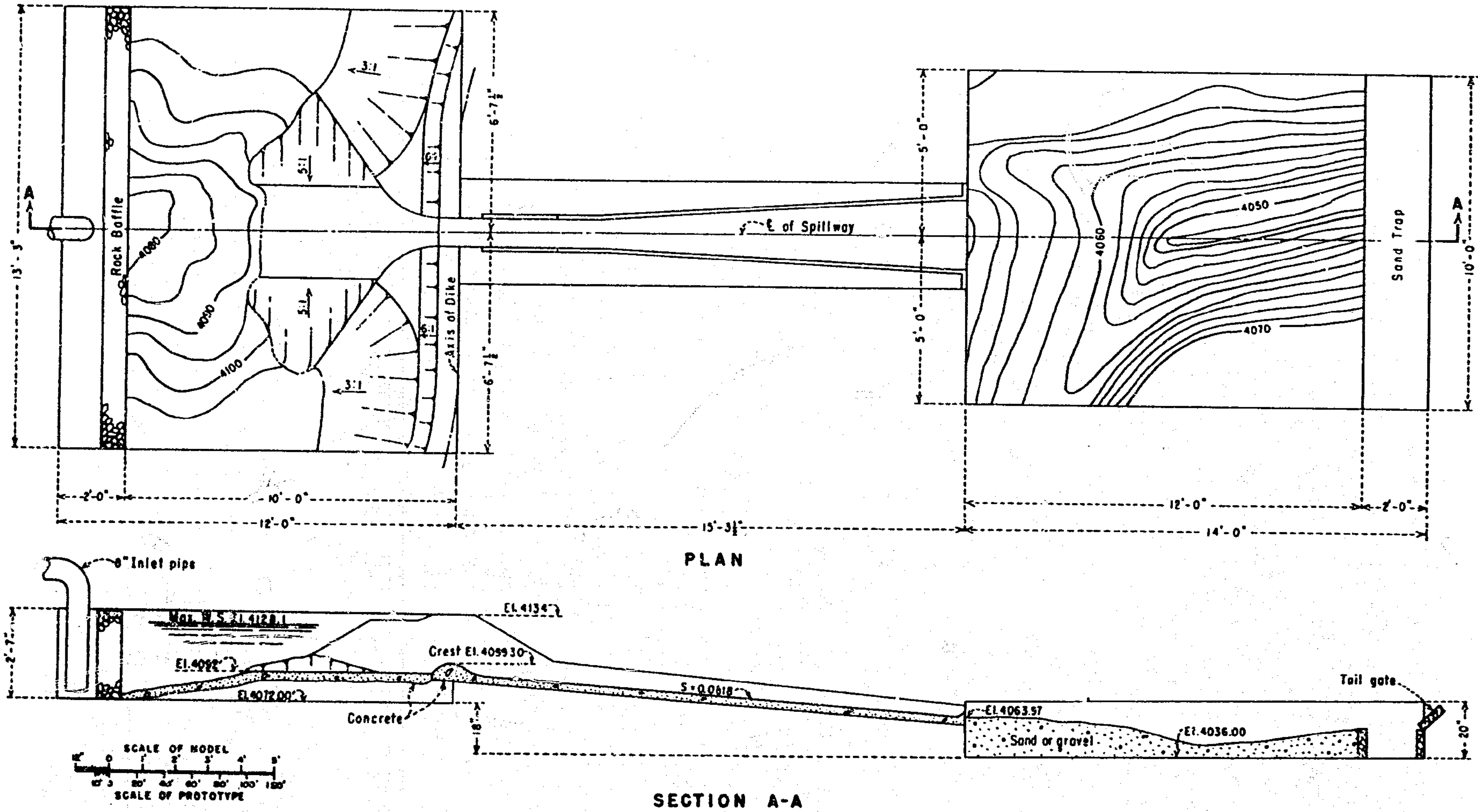

PLAN
ELEVATION A-A
SECTION ON ℄ OF SPILLWAY
SECTION M-M
SECTION L-L
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
SECTION K-K
SECTION F-F
SECTION G-G
SECTION H-H
SECTION J-J
DETAIL Y
DETAIL Z
SPILLWAY BRIDGE
DISCHARGE CURVE
Spillway discharge curve
El. 4099.30
RESERVOIR W.S. ELEV.
DISCHARGE THOUSANDS SEC. FT.
SCALE OF FEET
Spillway crest El. 4099.30
Axis of dam
Dam crest El. 4134.0
Chain link fence
Concrete bridge
Contraction joints with metal seals, type MI.
Dumped riprap
Assumed rock surface
Approach channel El. 4092.0
Cut off
Ground surface
Backfill
Excavated channel
Max. W.S. El. 4128.2
Inlet approach channel El. 4092.00
Origin of curve
Y = -0.049 X^1.695
6" S.P. Drain with uncemented joints
1¼" Ø Anchor bars @ 6' ± crs.
Grout holes @ 10' crs.
Metal seals Type MI
Cut offs
NOTES
Reinforcement not shown.
All concrete will be designed for 3000 lbs. per sq. inch compressive strength at 28 days.
Apply two coats of sealing compound to one face of contraction joints.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
CHEYENNE DIVISION-KEYHOLE UNIT- SO. DAK.-WYO.
KEYHOLE DAM
SPILLWAY
PLAN AND SECTIONS
DRAWN
TRACED
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO, OCT. 17, 1949
486-D-28

FIGURE 4



KEYHOLE DAM SPILLWAY

MODEL LAYOUT - PRELIMIN ... SIGN

1:24 MODEL

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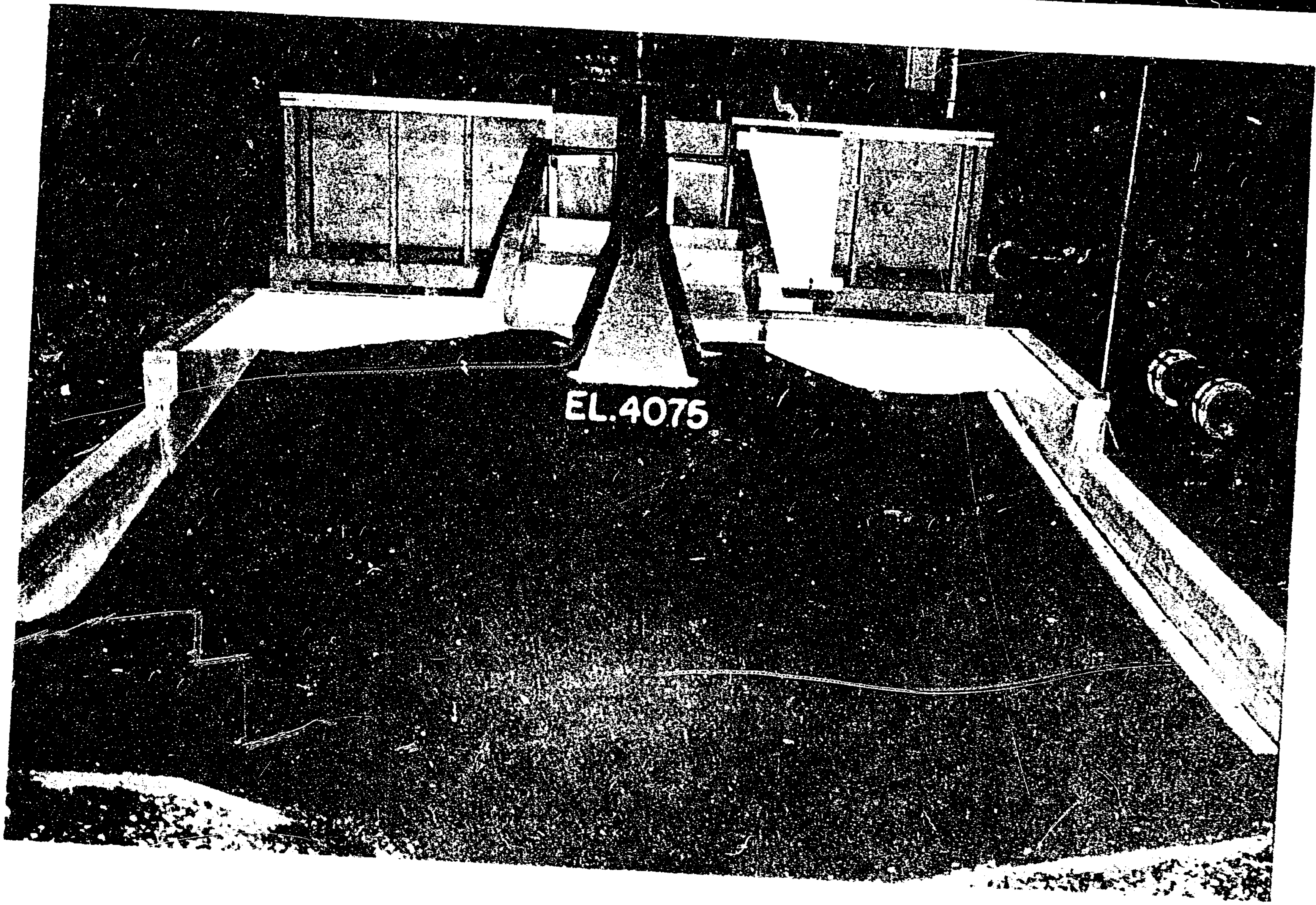
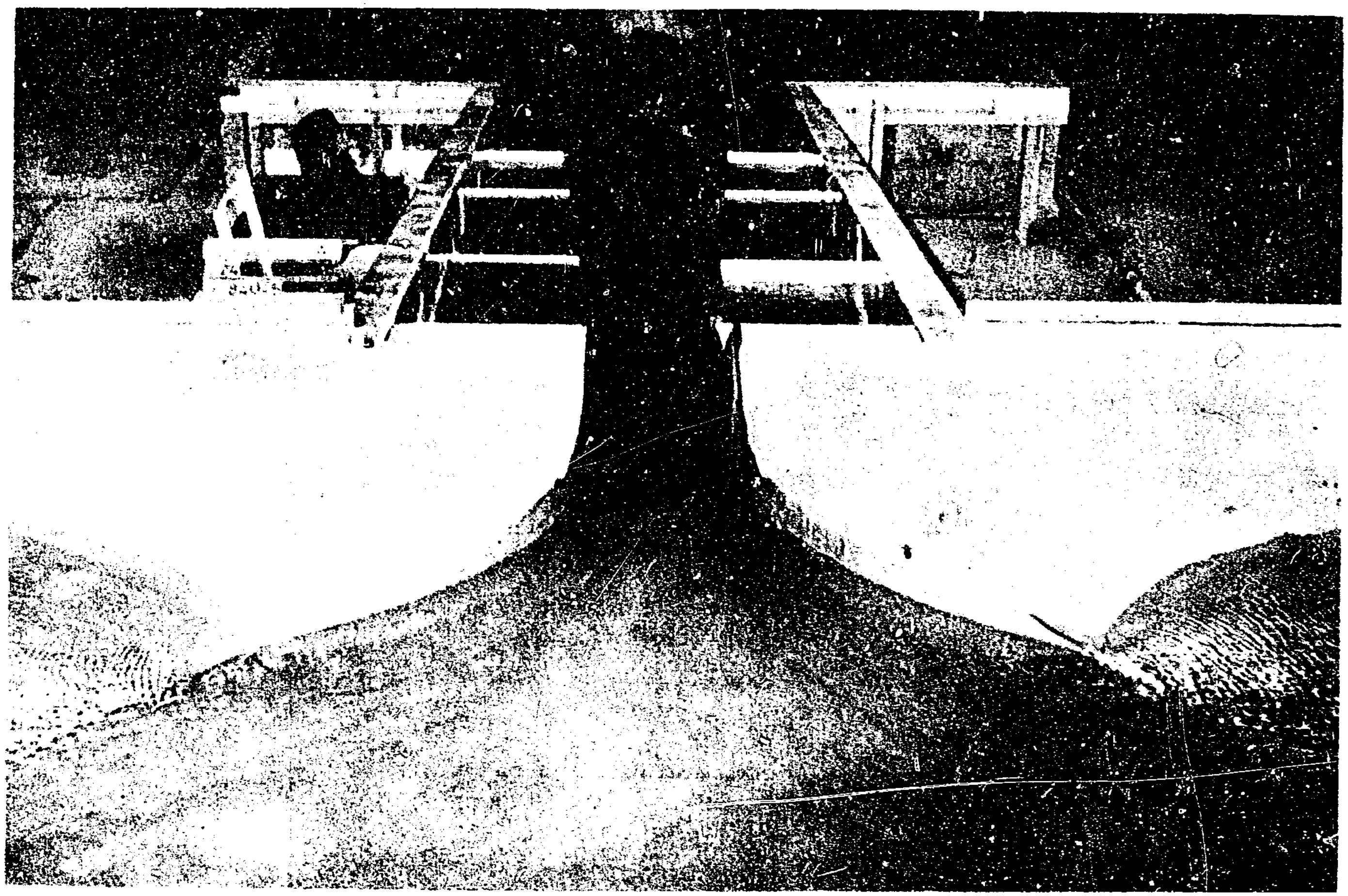
FIGURE 5



KEYHOLE DAM SPILLWAY
MODEL VIEW LOOKING UPSTREAM - RECOMMENDED DESIGN
1:24 MODEL

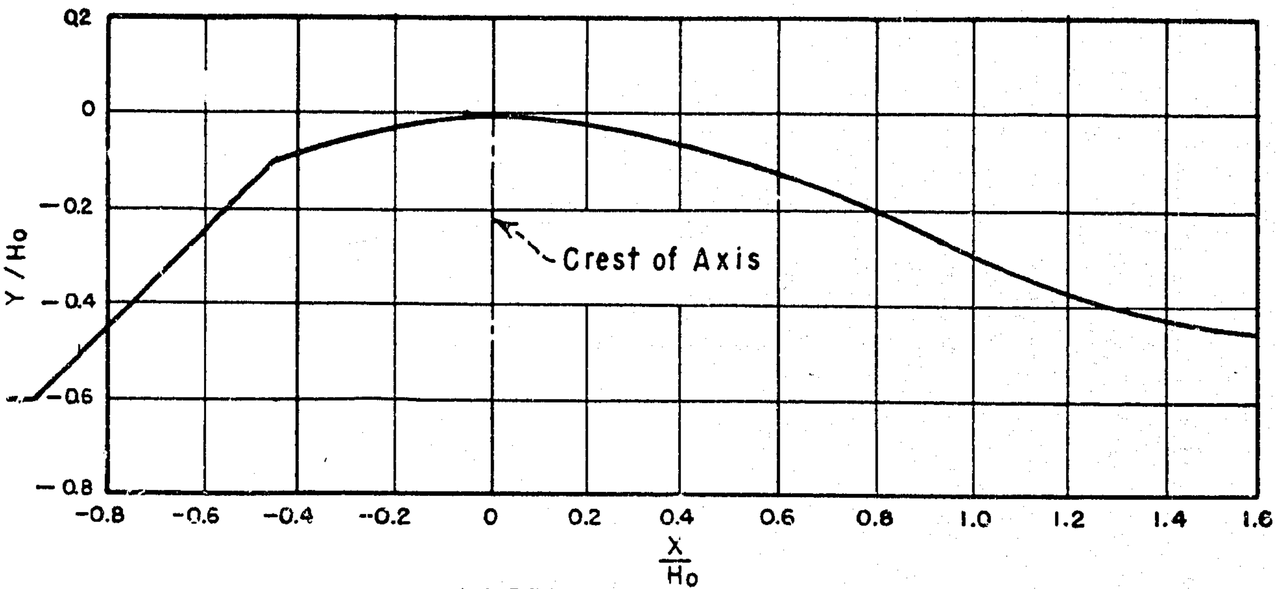
FIGURE 6



Discharge 10,800 second feet
Crest length 21 feet

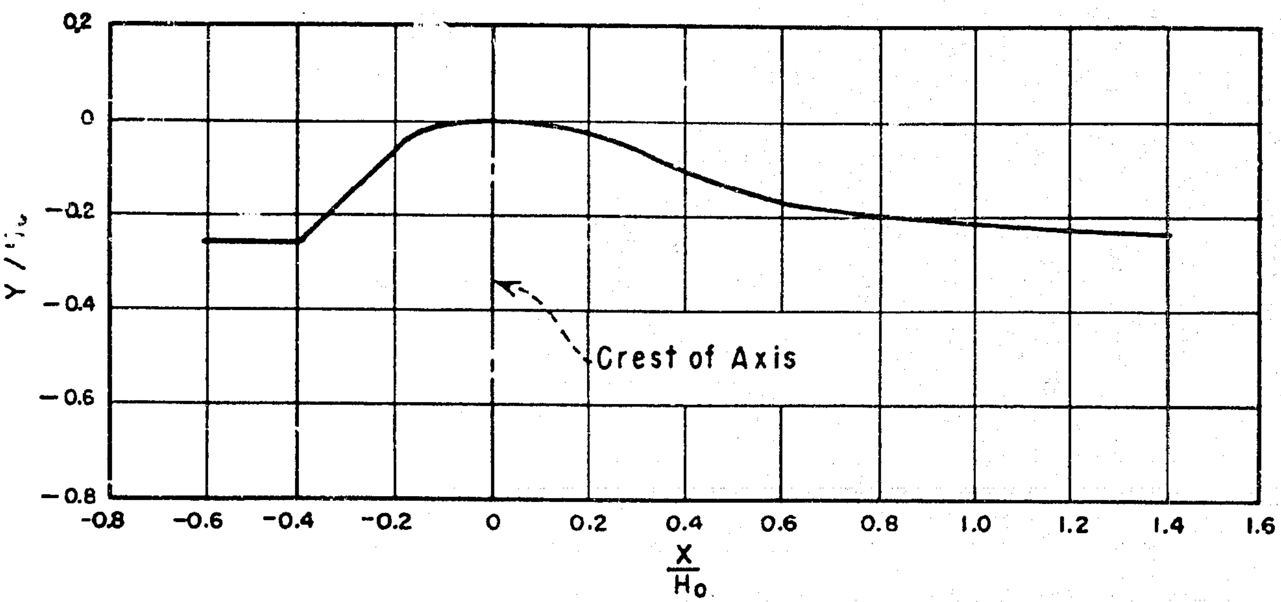
KEYHOLE DAM SPILLWAY
SPILLWAY APPROACH - FLOW CHARACTERISTICS
1:24 MODEL

FIGURE 7



(a) RESERVOIR EL. 4111.5

H_o = 12.20 FT. C_M = 3.65



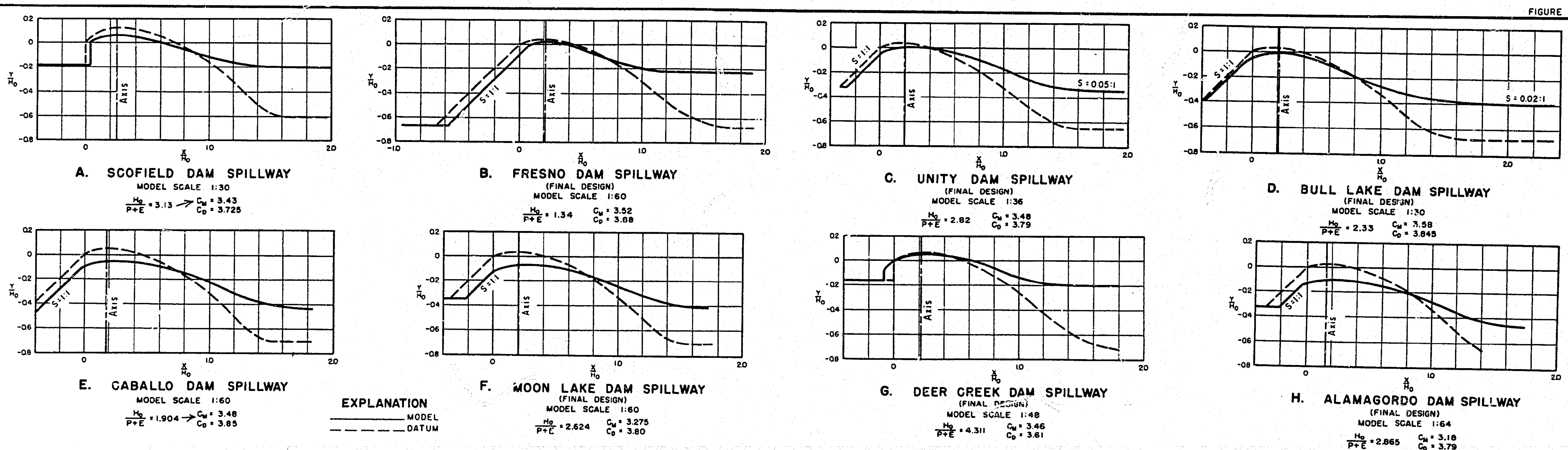
(b) RESERVOIR EL. 4128.2

H_o = 28.90 FT. C_M = 3.54

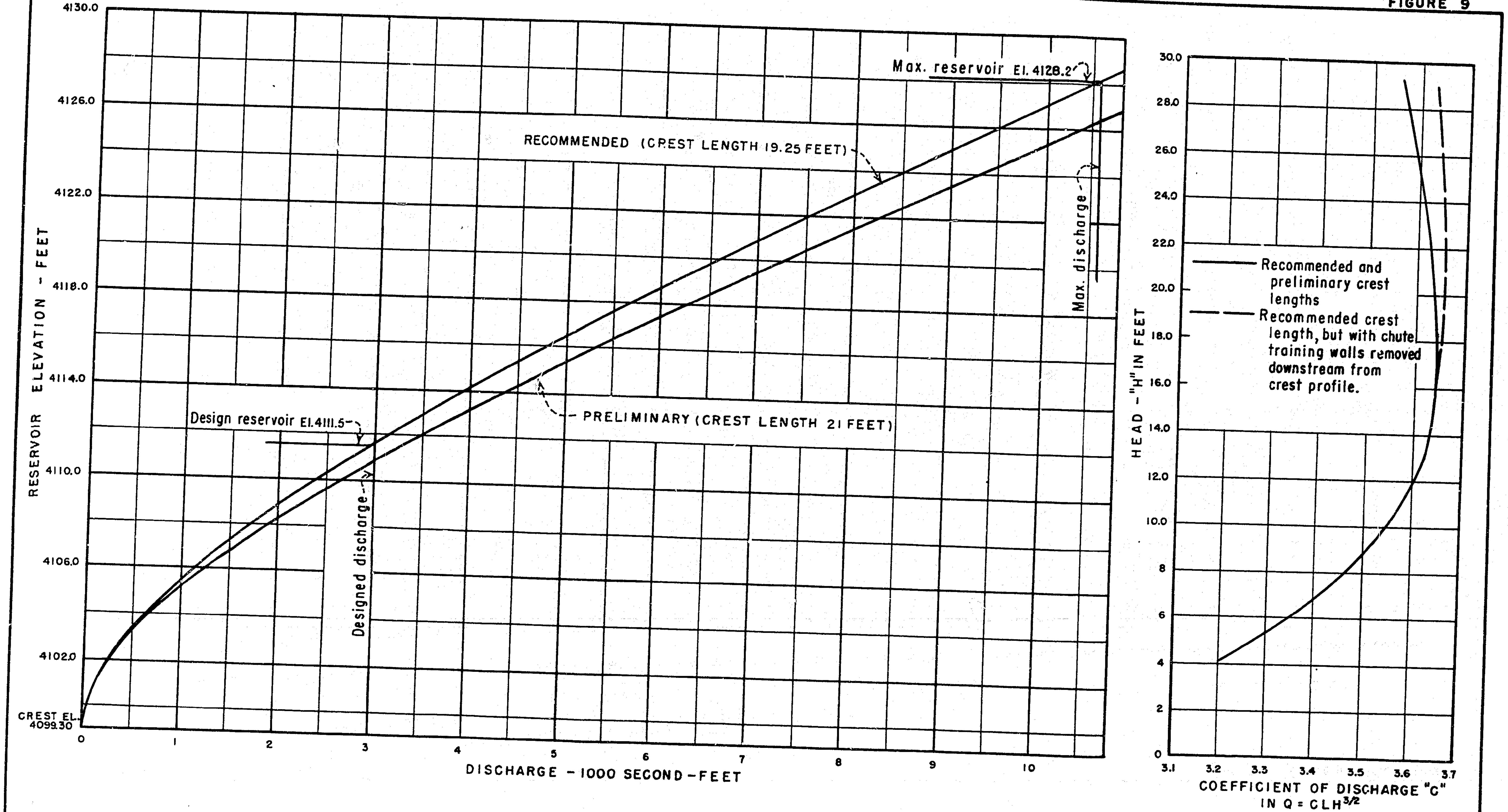
KEYHOLE DAM SPILLWAY

DIMENSIONLESS PLOTS OF THE CREST PROFILE

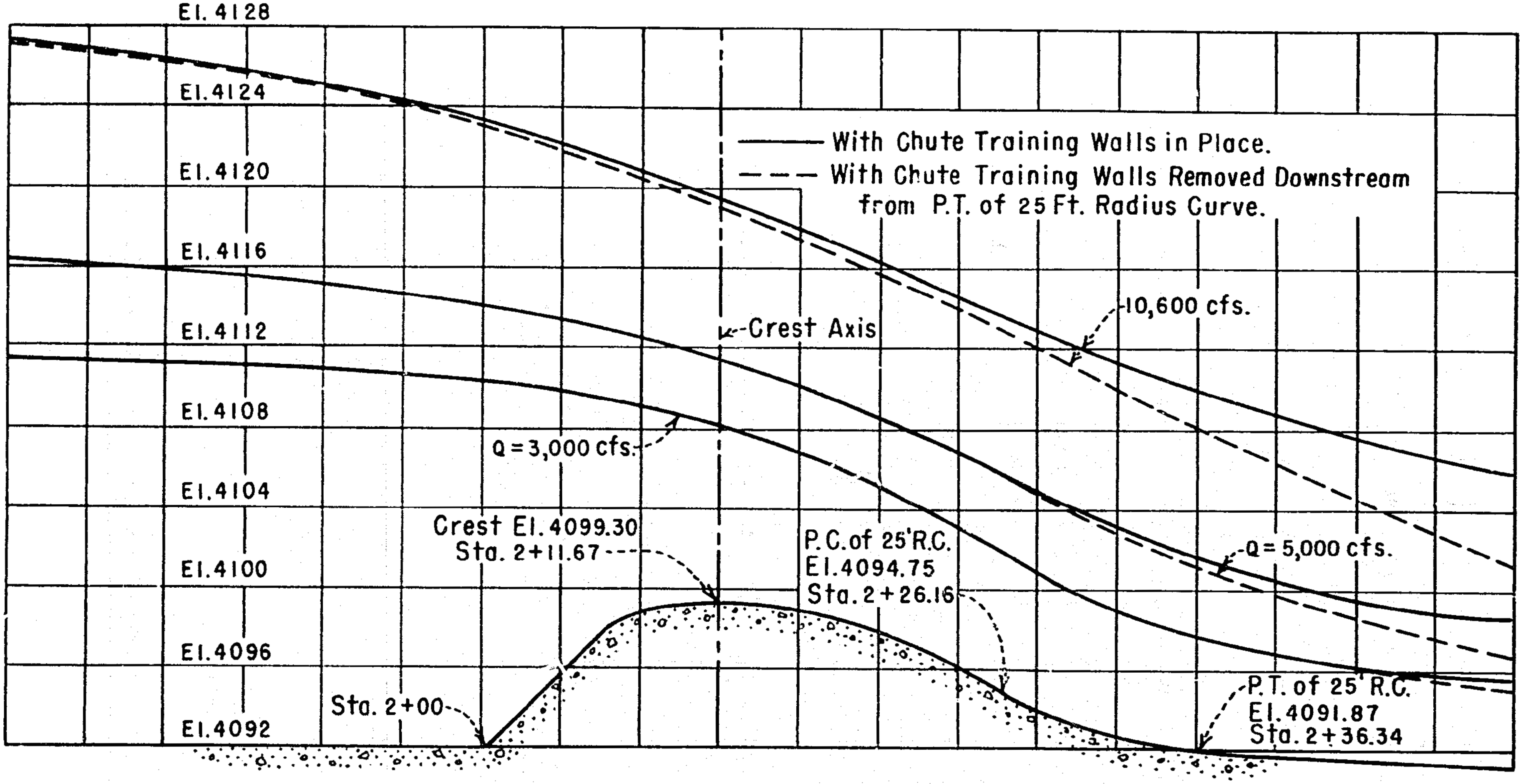
1:24 MODEL



COMPARISON OF DISCHARGE COEFFICIENTS
FOR EARTH DAMS SPILLWAYS WITH SHALLOW APPROACH CHANNEL



KEYHOLE DAM SPILLWAY
SPILLWAY CAPACITY AND COEFFICIENT OF DISCHARGE CURVES
1:24 MODEL



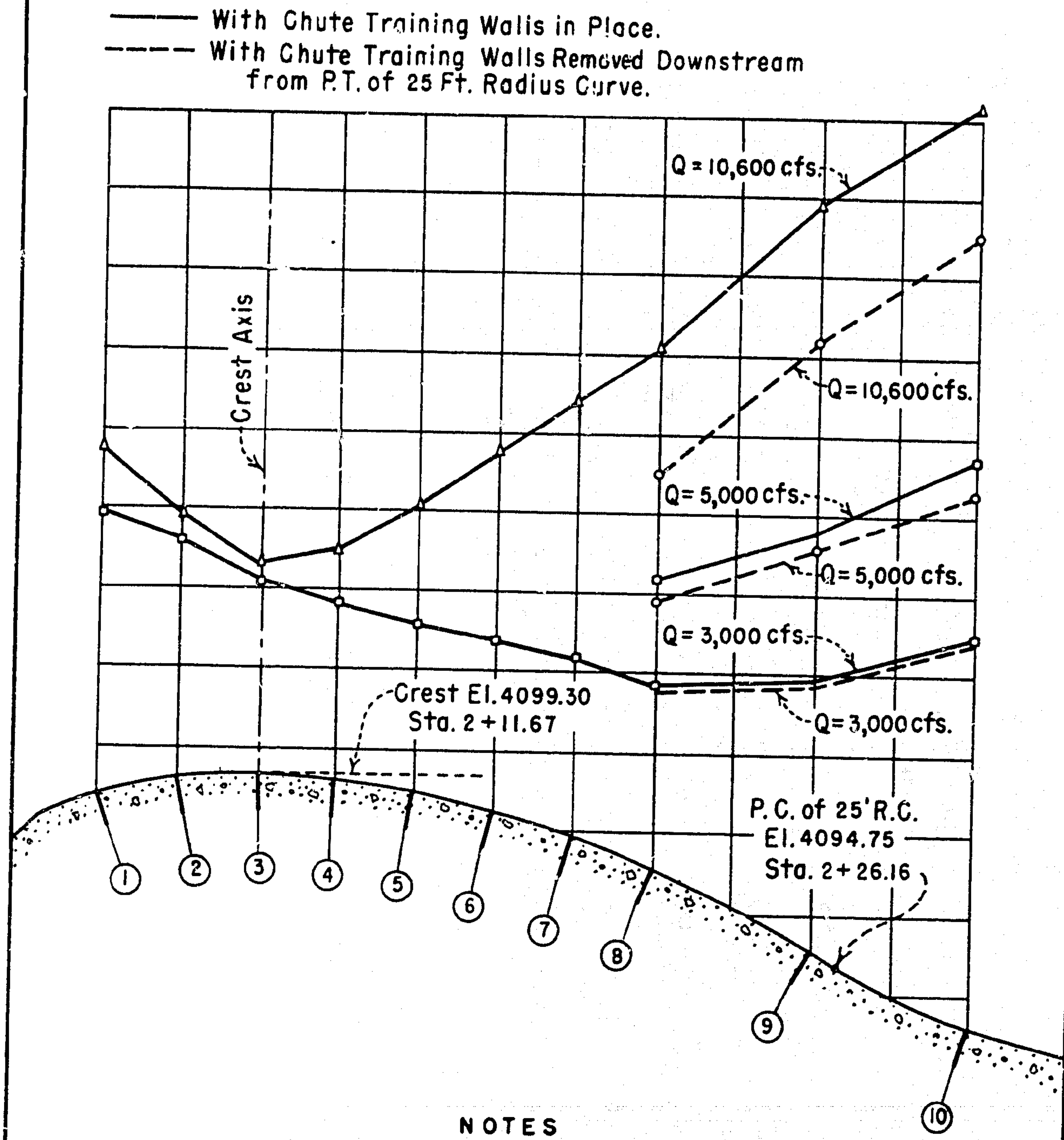
KEYHOLE DAM SPILLWAY

WATER SURFACE PROFILES ON ℄ OF RECOMMENDED CREST

1: 24 MODEL

FIGURE 10

FIGURE 11



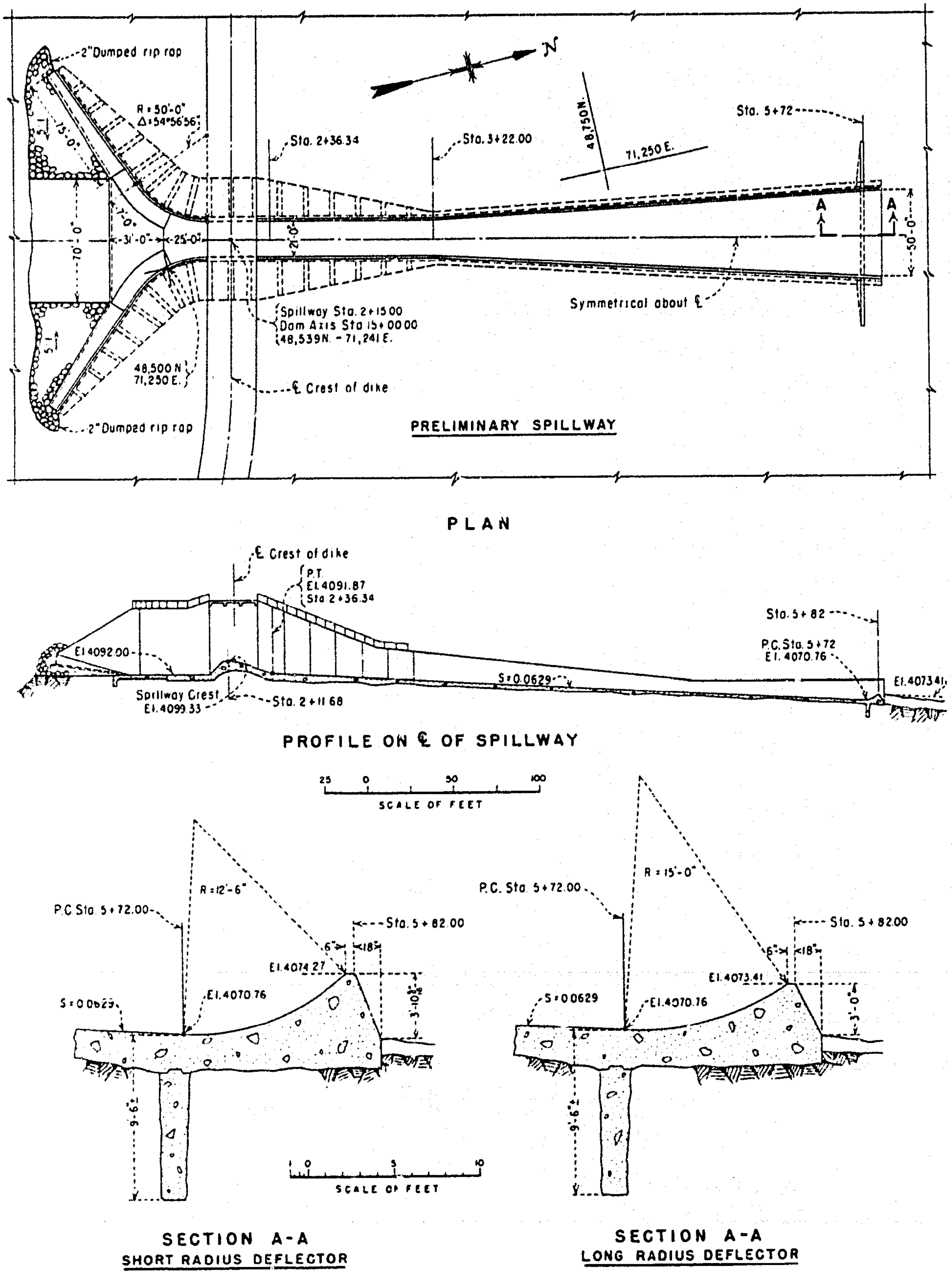
NOTES

Circled numbers indicate piezometers
Crest outline is zero pressure datum.
Positive pressures are measured above the datum.
Pressure scale is 1" = 4 feet of water.
Crest scale is 1" = 4 feet

KEYHOLE DAM SPILLWAY

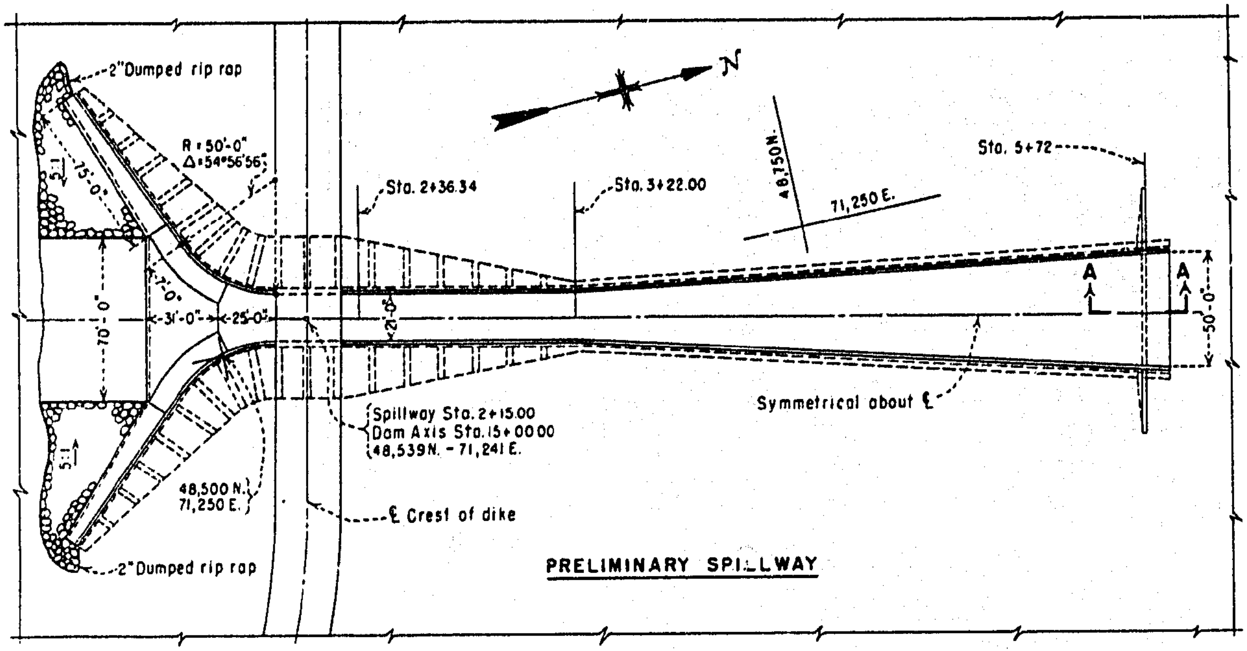
PRESSURES ON ℄ OF RECOMMENDED CREST

1:24 MODEL

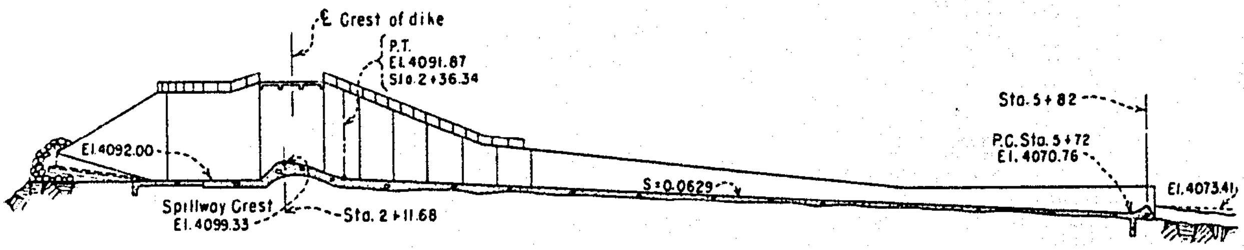


KEYHOLE DAM SPILLWAY

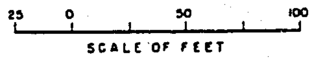
PRELIMINARY SPILLWAY WITH LONG AND SHORT RADIUS DEFLECTORS

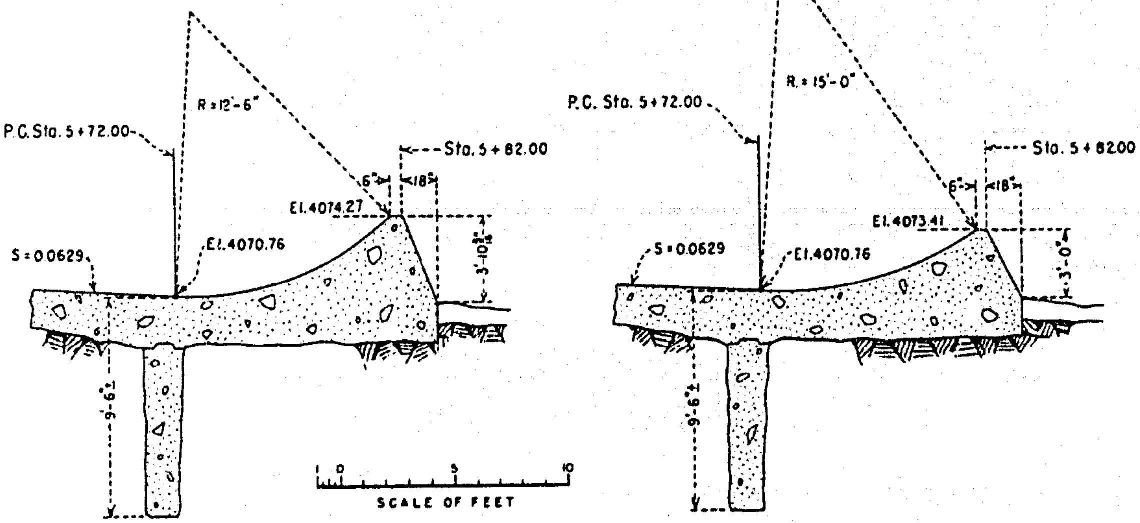


PLAN



PROFILE ON ℄ OF SPILLWAY





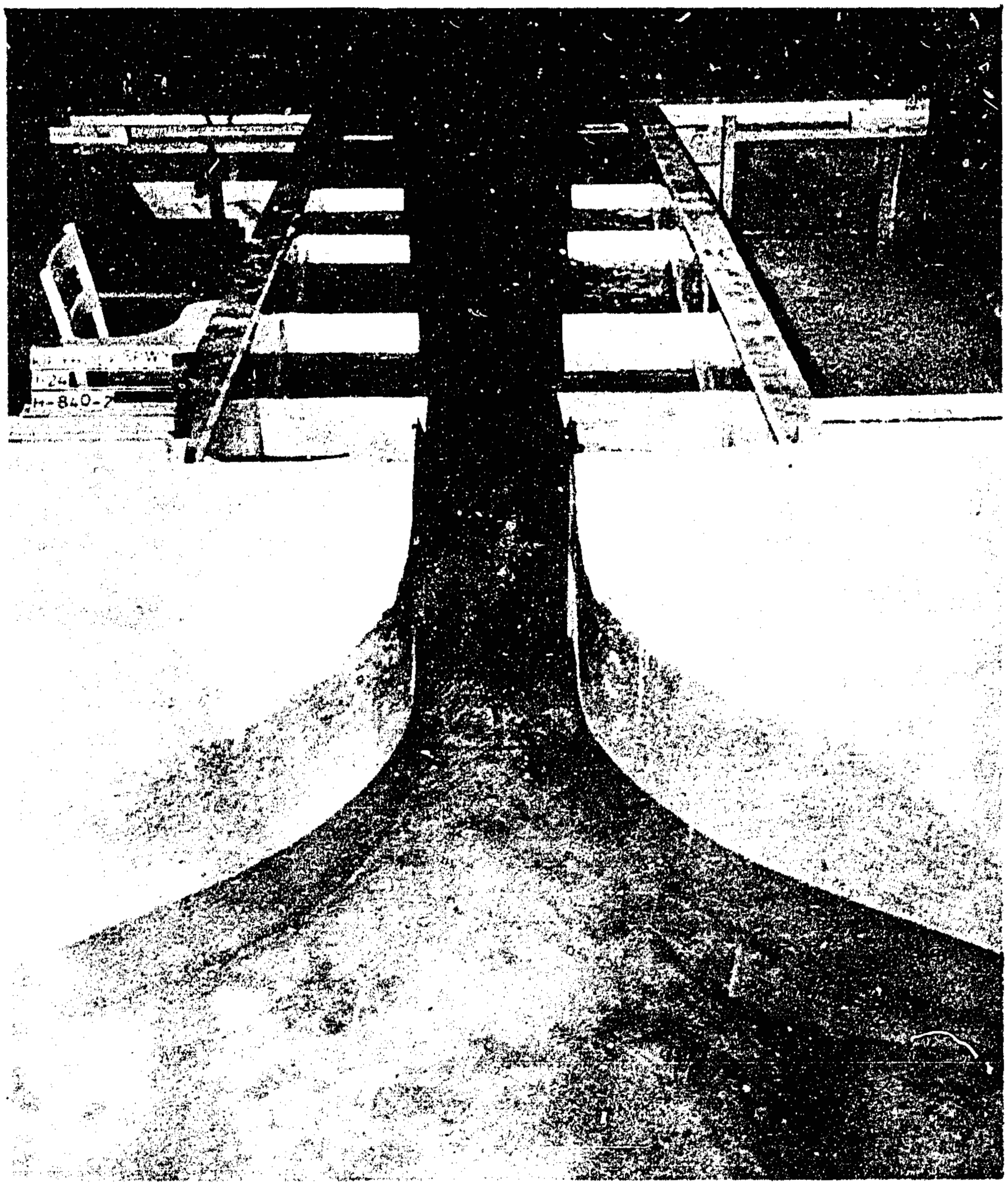
SECTION A-A
SHORT RADIUS DEFLECTOR

SECTION A-A
LONG RADIUS DEFLECTOR

KEYHOLE DAM SPILLWAY

PRELIMINARY SPILLWAY WITH LONG AND SHORT RADIUS DEFLECTORS

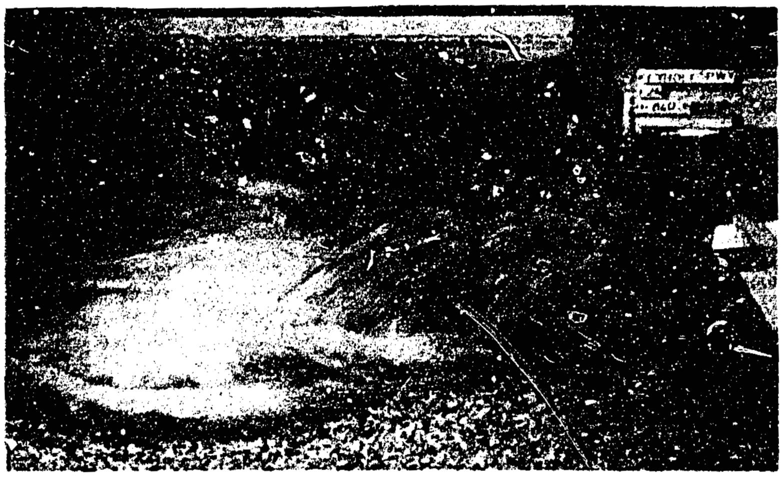
FIGURE 13



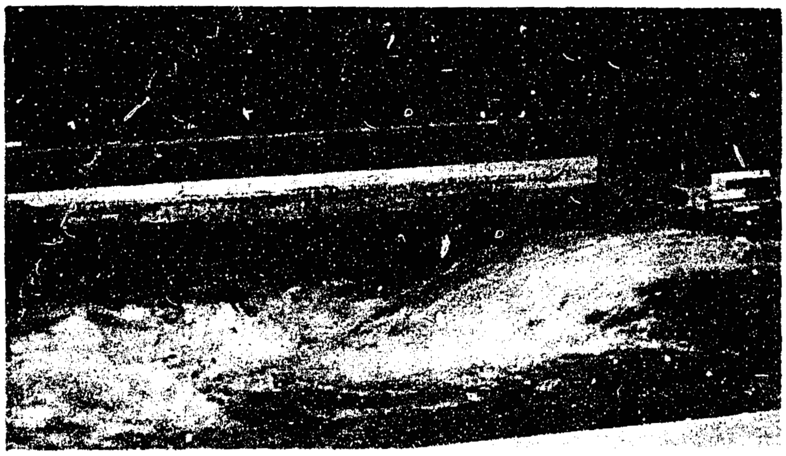
Discharge 3,000 second feet

KEYHOLE DAM SPILLWAY
Flow Pattern Through the Preliminary Chute
1:24 MODEL

(a) Discharge 1,000 second feet



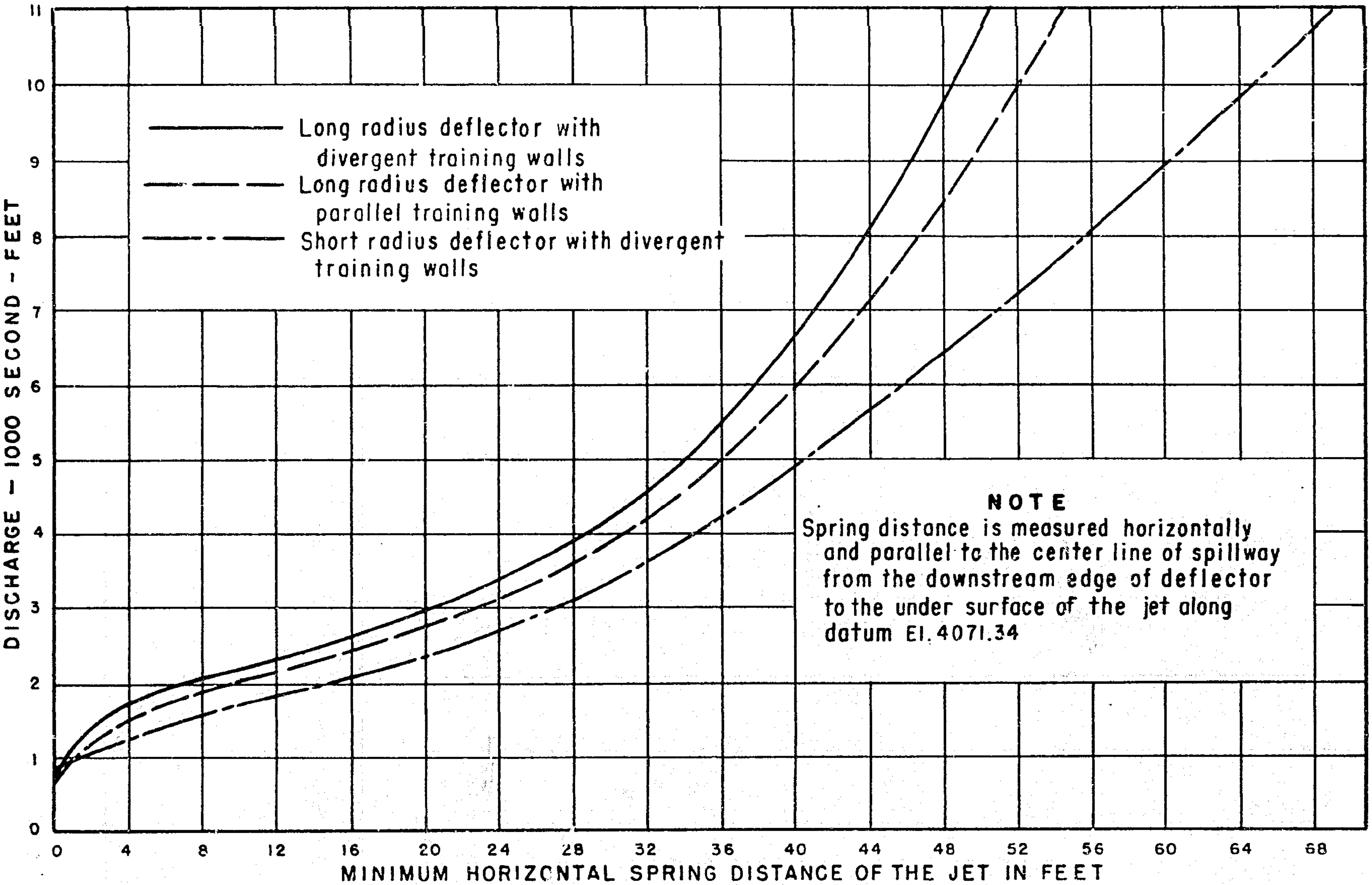
(b) Discharge 3,000 second feet



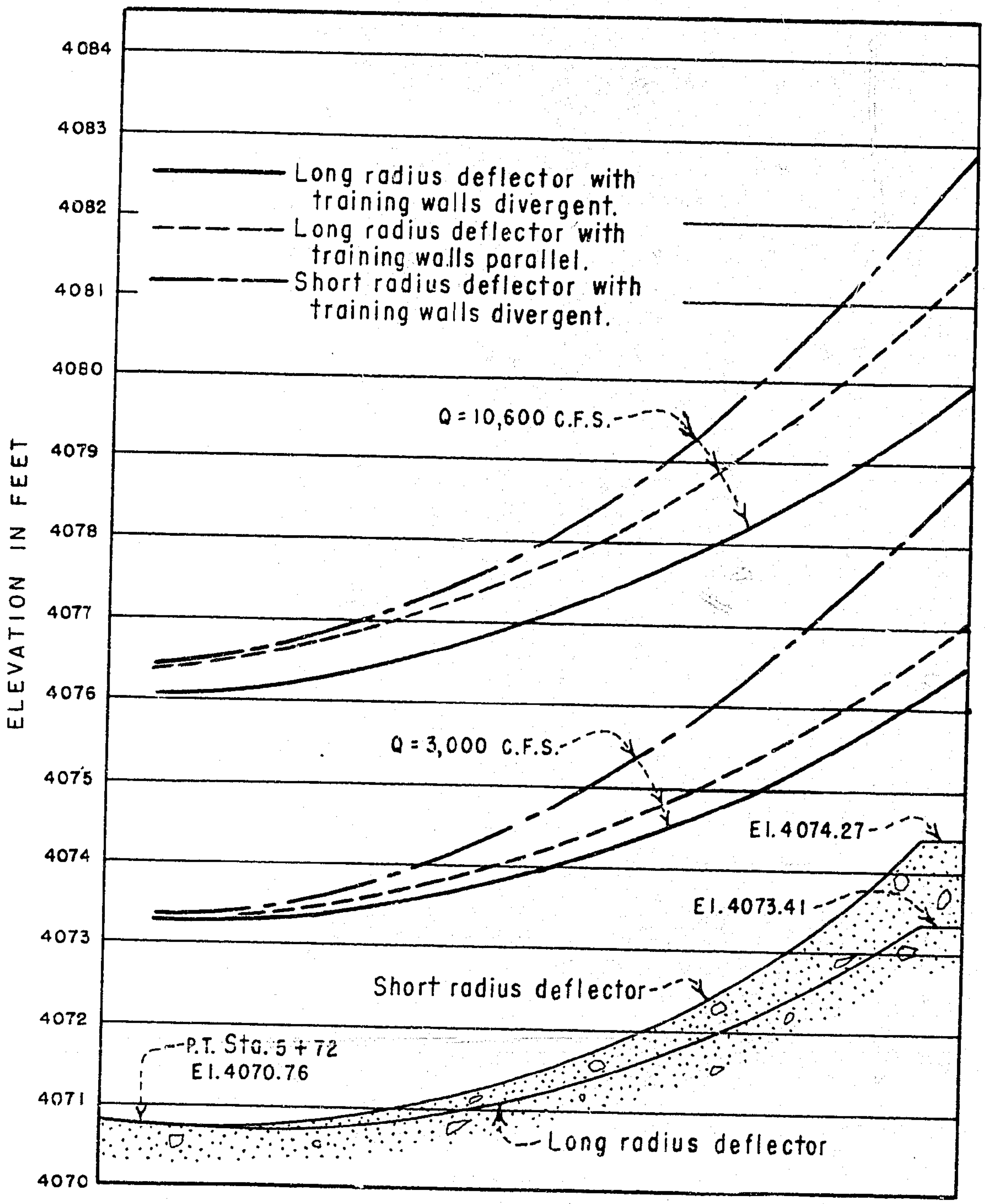
(c) Discharge 10,600 second feet

KEYHOLE DAM SPILLWAY
Performance of the Long Radius Deflector Used With the Preliminary Chute
1:24 MODEL

FIGURE 15



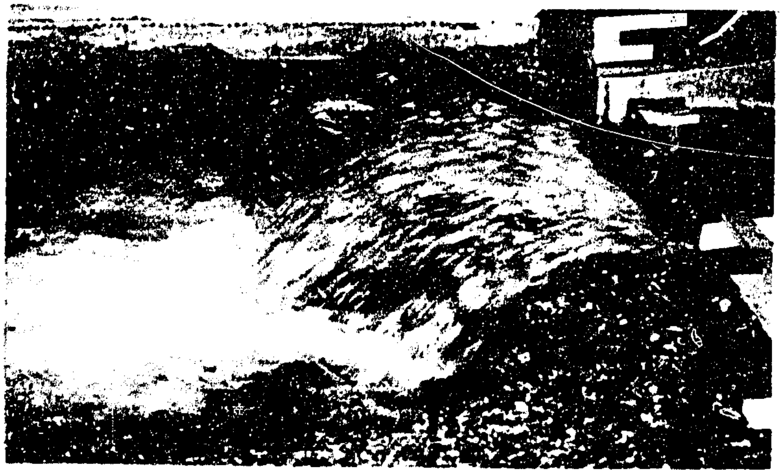
KEYHOLE DAM SPILLWAY
JET SPRING DISTANCE VS DISCHARGE
1:24 MODEL



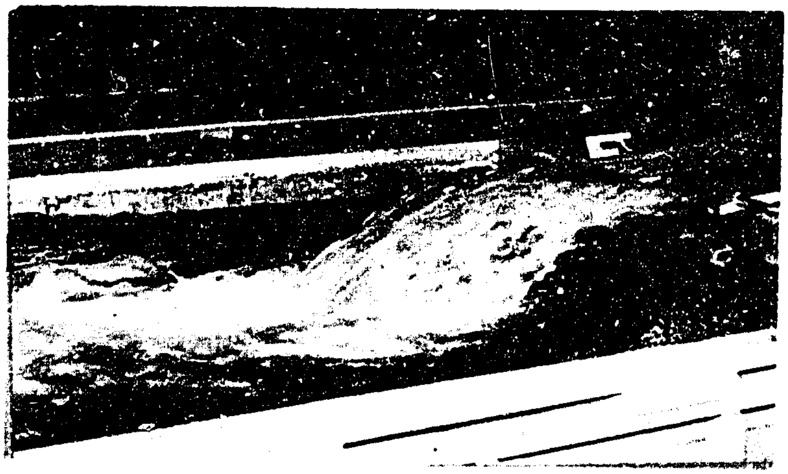
KEYHOLE DAM SPILLWAY
WATER SURFACE PROFILES ALONG TRAINING WALL OF LONG AND SHORT RADIUS DEFLECTORS WITH PRELIMINARY CHUTE DESIGN
1:24 MODEL

FIGURE 17

(a) Discharge 1,000 second feet

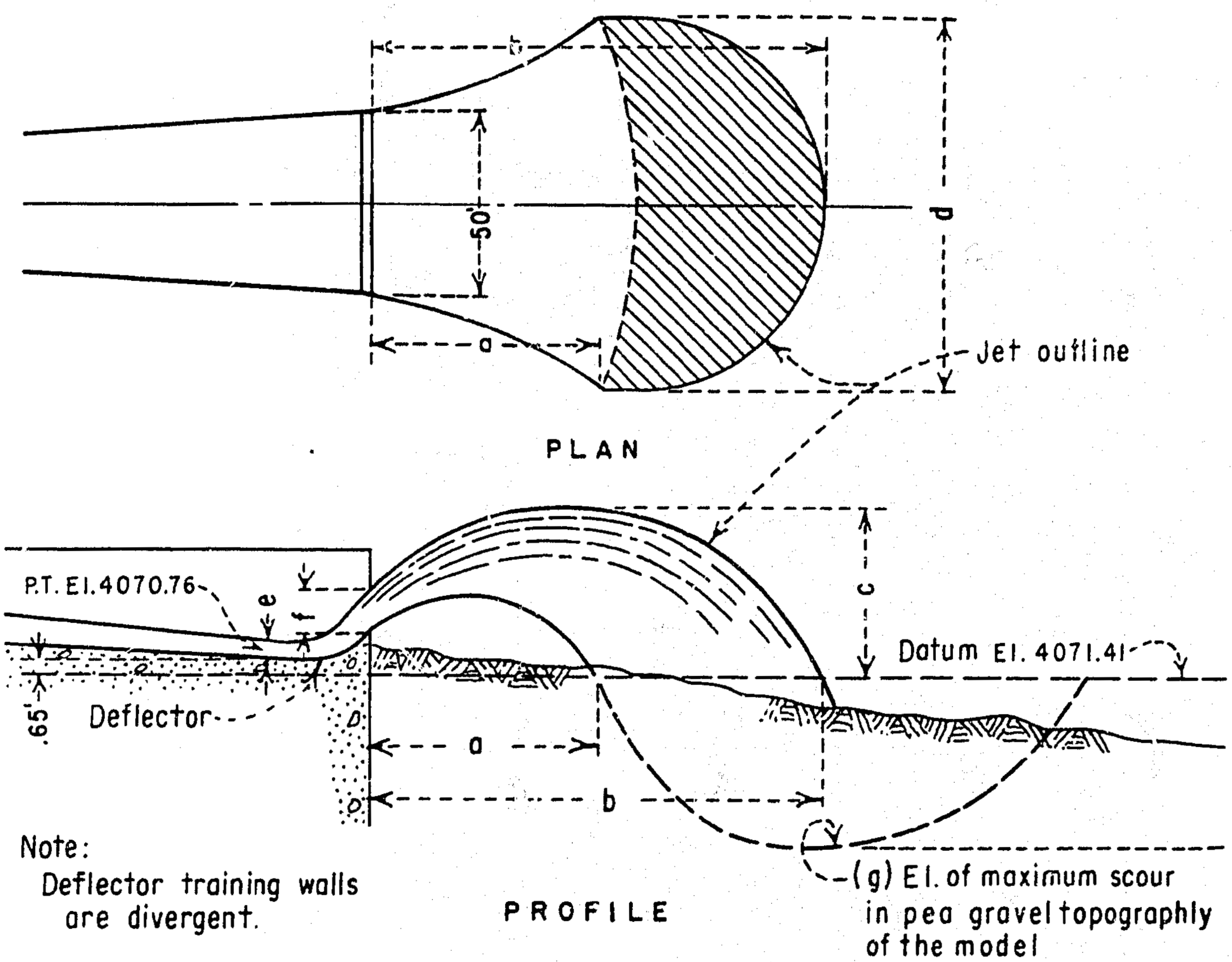


(b) Discharge 3,000 second feet



(c) Discharge 10,600 second feet

KEYHOLE DAM SPILLWAY
Performance of the Short Radius Deflector Used With the Preliminary Chute
1:24 MODEL



		a	b	c	d	e	f	g
Q = 3000 cfs	LONG RADIUS DEFLECTOR	20'	60'	12.5'	60'	2.6'	3.2'	4047
	SHORT RADIUS DEFLECTOR	27'	70'	18'	62'	2.6'	4.5'	4045
Q = 10,600 cfs	LONG RADIUS DEFLECTOR	50'	114'	17'	66'	5.3	7.0	—
	SHORT RADIUS DEFLECTOR	68'	126'	22'	76'	5.7	8.6	—

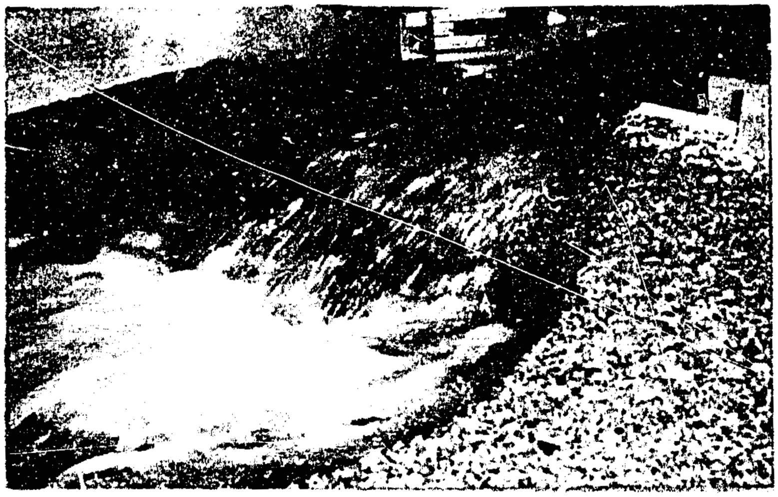
	Q WHEN JET FIRST SPRINGS FROM DEFLECTOR
LONG RADIUS DEFLECTOR	550 cfs
SHORT RADIUS DEFLECTOR	850 cfs

KEYHOLE DAM SPILLWAY

JET MEASUREMENTS – PRELIMINARY CHUTE WITH LONG AND SHORT RADIUS DEFLECTORS 1:24 MODEL

FIGURE 19

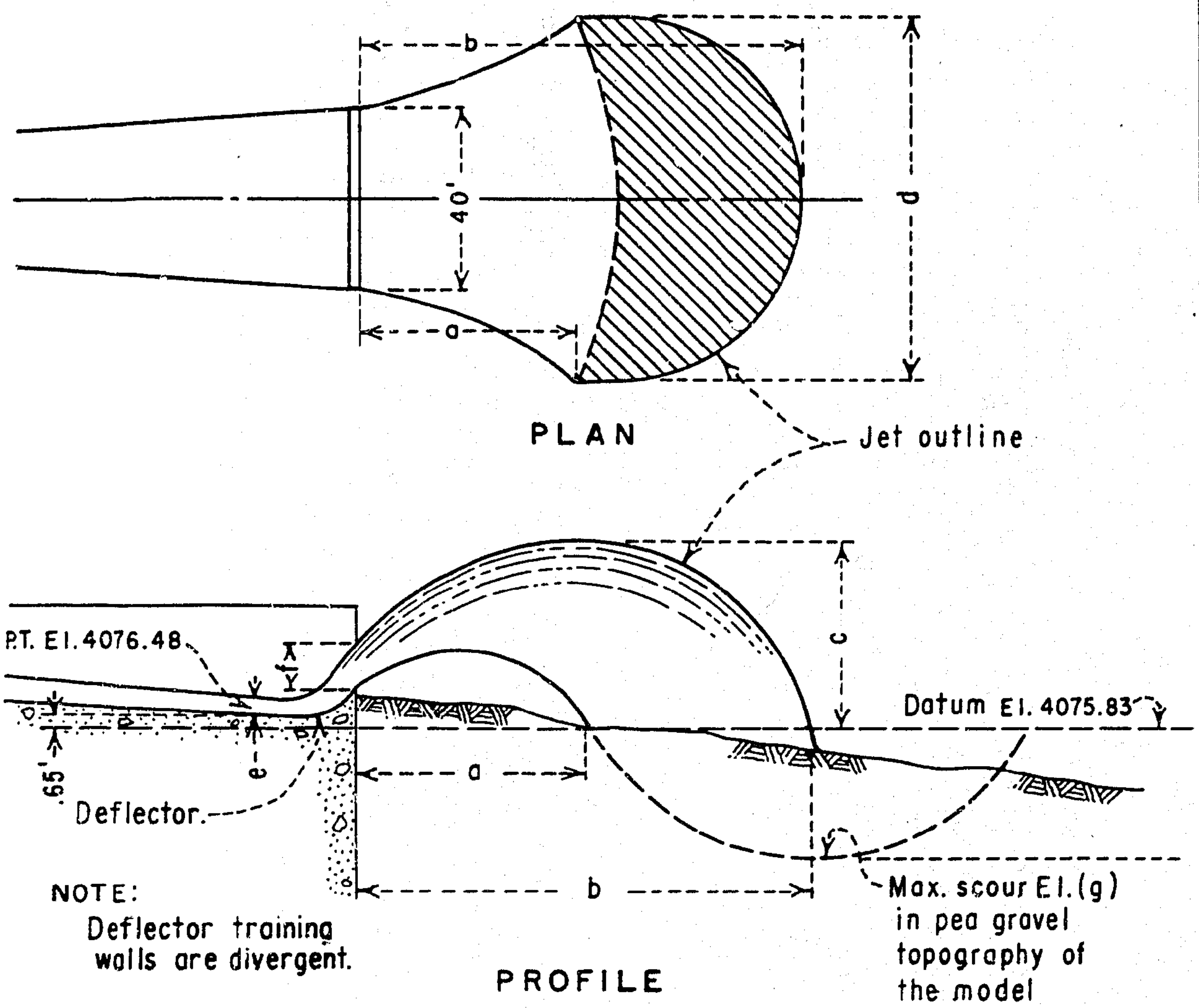
(a) Discharge 1,000 second feet



(b) Discharge 3,000 second feet

(c) Discharge 10,600 second feet

KEYHOLE DAM SPILLWAY
Performance of the Long Radius Deflector Used With the Recommended Chute
1:24 MODEL



	a	b	c	d	e	f	g
Q = 3,000 cfs	18'	55'	11'	54'	3'	3.5'	4050'
Q = 10,600 cfs	40'	100'	14'	60'	6.0'	7.5'	—

KEYHOLE DAM SPILLWAY
JET MEASUREMENTS - RECOMMENDED CHUTE AND LONG RADIUS DEFLECTOR
1:24 MODEL

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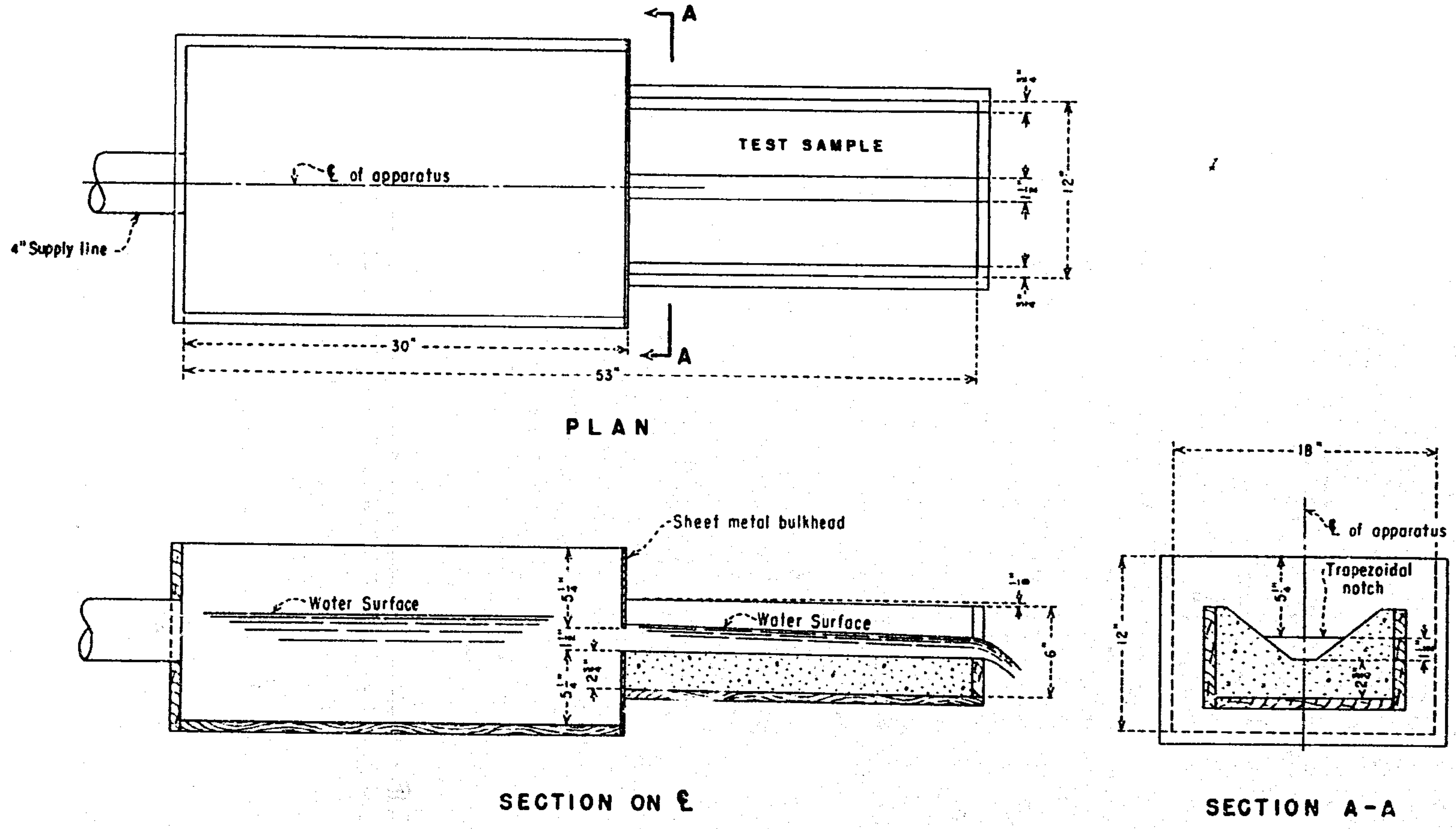
FIGURE 21



KEYHOLE DAM SPILLWAY

APPARATUS FOR TESTING MODEL ERODIBLE BED MATERIAL

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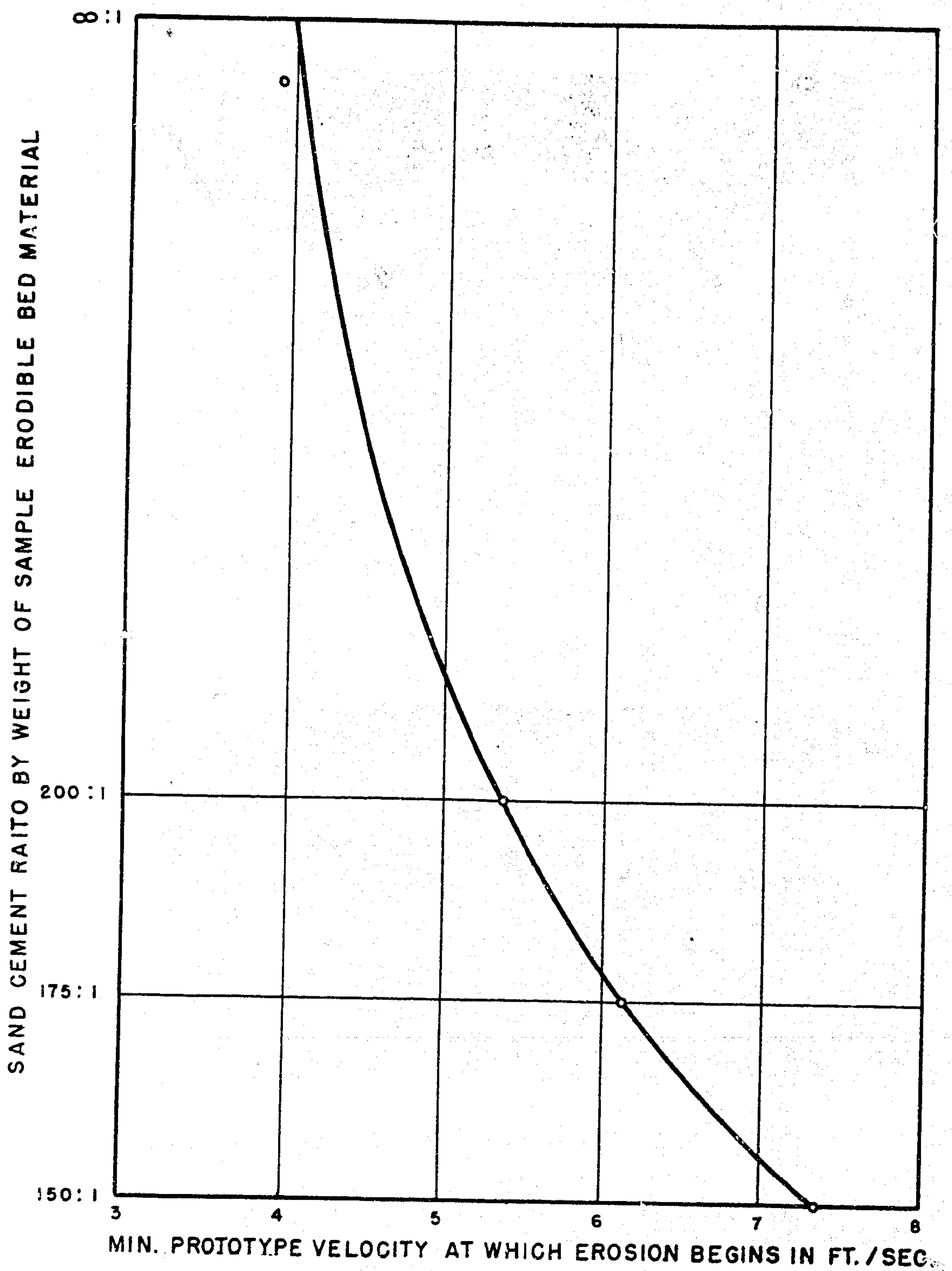
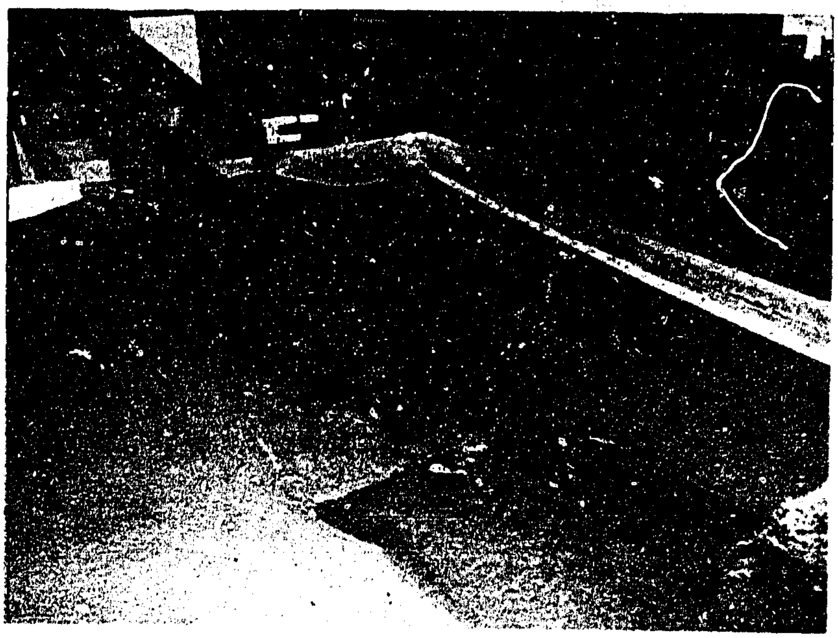
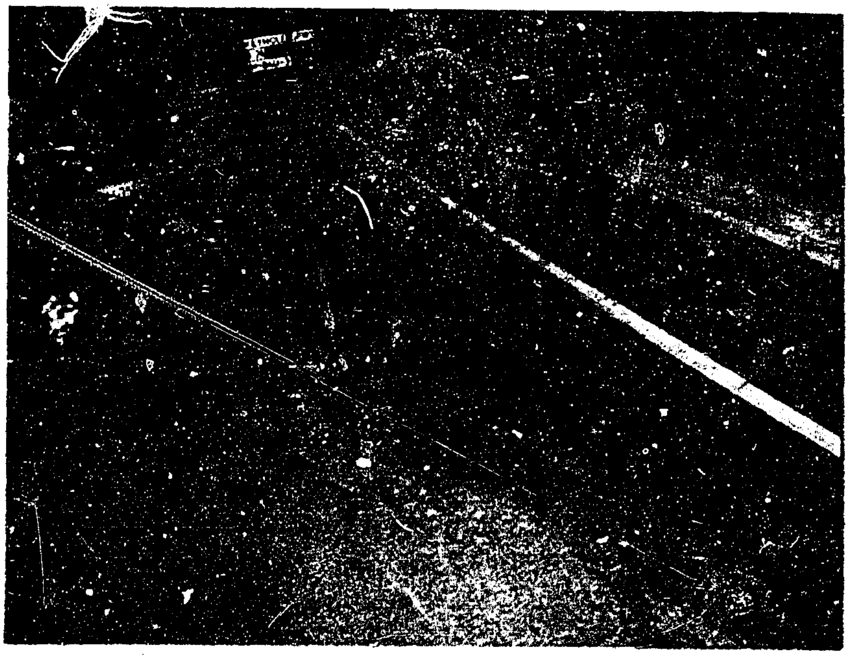


KEYHOLE DAM SPILLWAY
SAND CEMENT RATIO OF SAMPLE ERODIBLE BED MATERIAL
VS VELOCITY AT WHICH EROSION BEGINS
1:24 MODEL

FIGURE 23



a. Test in progress

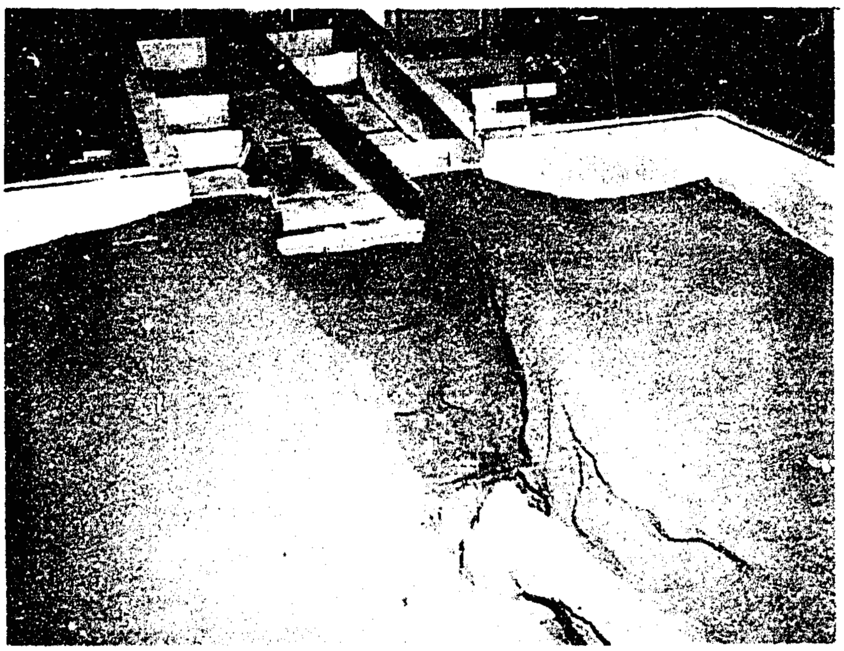


b. Scour pattern after 30 min. model test

KEYHOLE DAM SPILLWAY
Erosion Test - 1,000 Second Feet - Recommended Design
1:24 MODEL

FIGURE 24

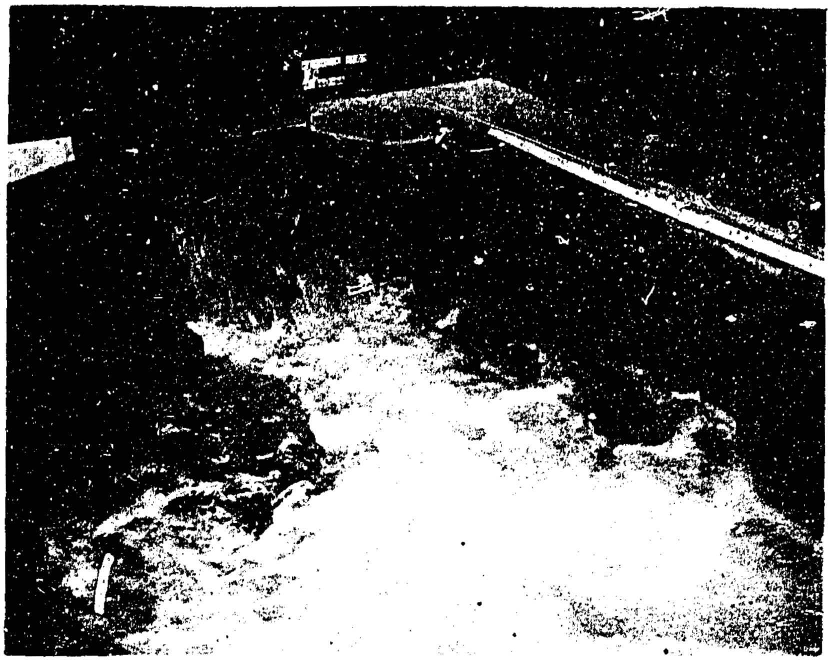
a. Scour test in progress



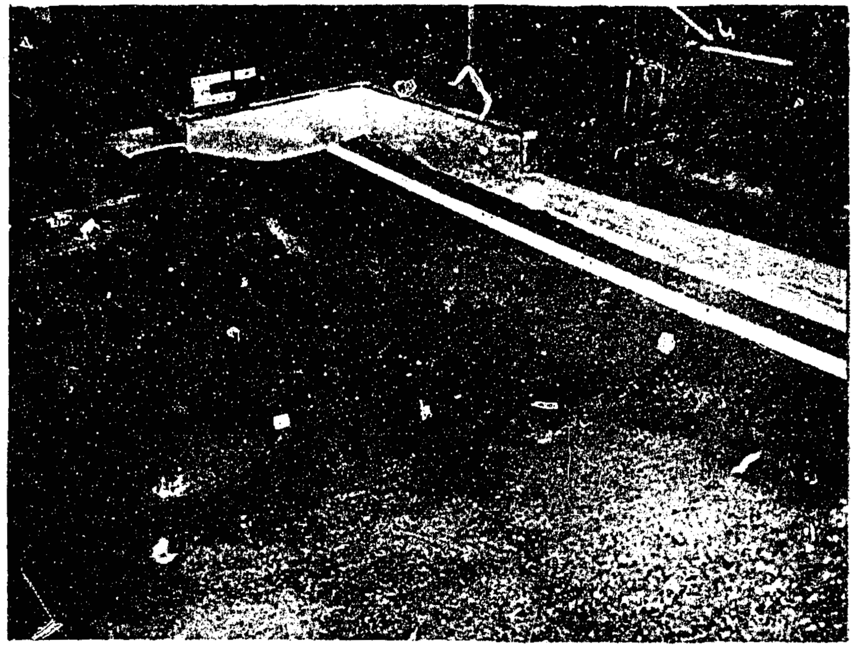
b. Scour pattern after 30 min. model test

KEYHOLE DAM SPILLWAY
Erosion Test - 3,000 Second Feet - Recommended Design
1:24 MODEL

FIGURE 25



a. Test in progress



b. Scour pattern after 30 min. model test

KEYHOLE DAM SPILLWAY
Erosion Test - 10,600 Second Feet - Recommended Design
1:24 MODEL

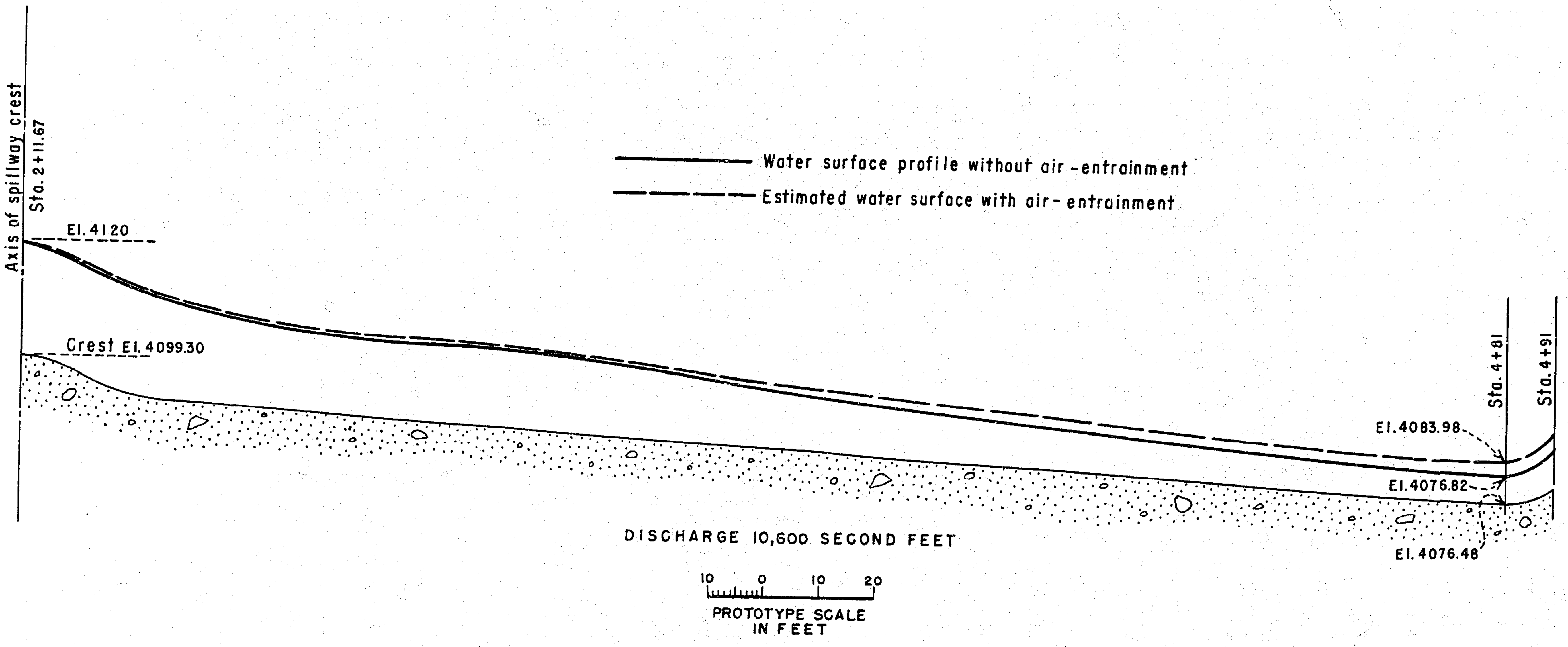
a. Test in progress - Discharge 1,000 second feet

b. Test in progress - Discharge 3,000 second feet

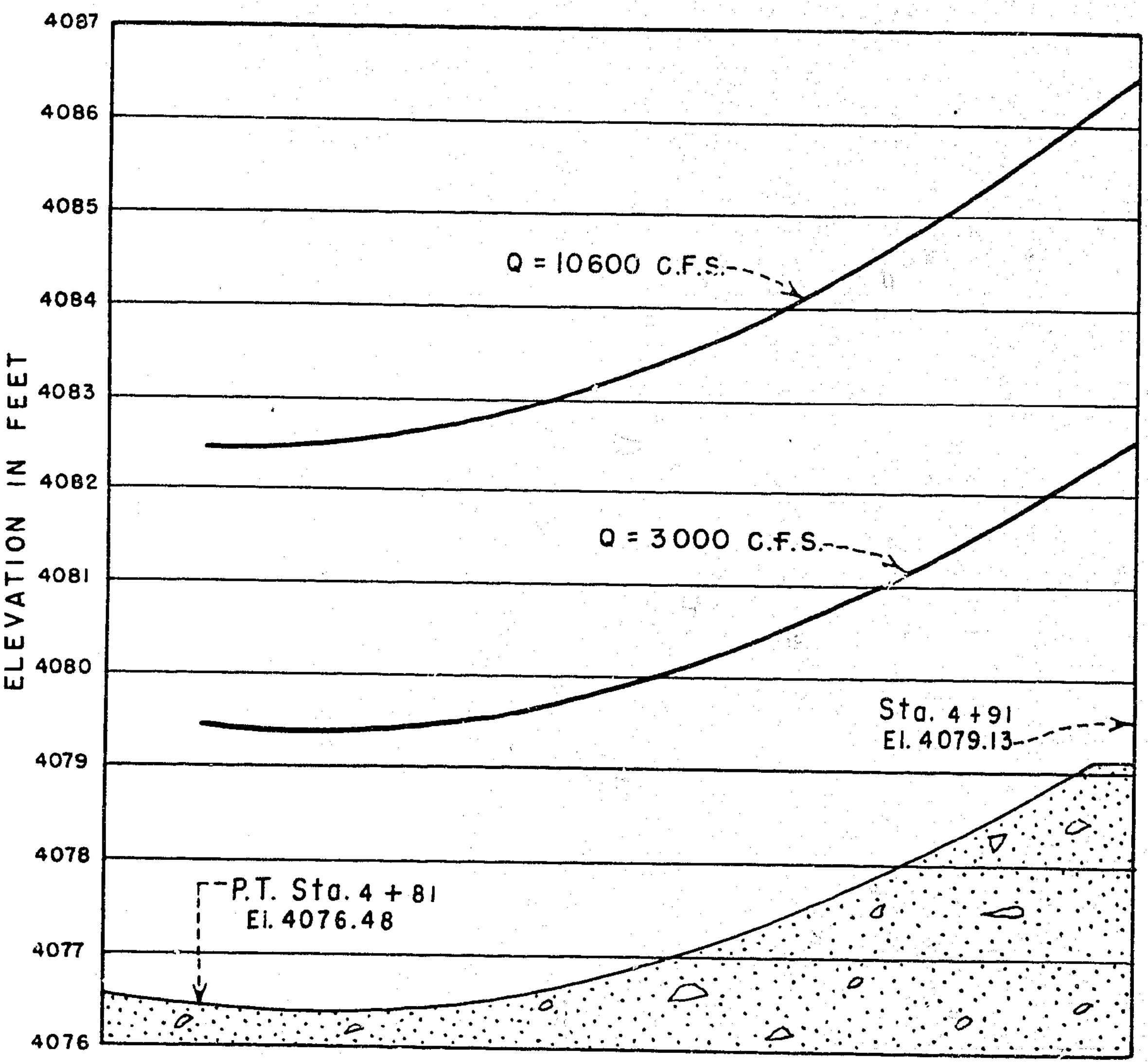
c. Scour pattern after 50 min. test

KEYHOLE DAM SPILLWAY
Erosion Test - 1,000 and 3,000 Second Feet - Respectively
Recommended Design
1:24 MODEL

FIGURE 27



KEYHOLE DAM SPILLWAY
WATER SURFACE PROFILE ALONG SPILLWAY TRAINING WALL
RECOMMENDED DESIGN
1:24 MODEL



KEYHOLE DAM SPILLWAY
WATER SURFACE PROFILES ALONG TRAINING WALL OF LONG RADIUS DEFLECTOR WITH RECOMMENDED CHUTE DESIGN
1:24 MODEL

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