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NAVAJO

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES OF NAVAJO DAM SPILLWAY AND AUXILIARY OUTLET WORKS JUNCTION WITH THE SPILLWAY

Hydraulic Laboratory Report No. HYD-458

DIVISION OF ENGINEERING LABORATORIES

OFFICE OF ASSISTANT COMMISSIONER AND CHIEF ENGINEER
DENVER, COLORADO

November 14, 1961

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Office of Assistant Commissioner
and Chief Engineer
Division of Engineering
Laboratories
Hydraulic Structures and
Equipment Section
Denver, Colorado
November 14, 1961

Laboratory Report No. HYD-458
Compiled by: G. L. Beichley
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Subject: Hydraulic model studies of Navajo Dam Spillway and Auxiliary Outlet Works Junction with the Spillway

SUMMARY

Hydraulic model studies of the Navajo Dam Spillway and the junction of the auxiliary outlet works with the spillway chute were conducted on a 1- to 48-scale model to develop the hydraulic design.

Data and notes taken on the flow in the model showed the general concept of the preliminary structure to be satisfactory, but that certain modifications in the approach channel, the chute, and the stilling basin would be desirable. A simpler and more economical approach channel was developed, the stilling basin performance was improved by placing a hump in the upstream portion of the spillway chute floor, and scour tendencies at the downstream corners of the stilling basin were reduced by modifying the end sill at the corners of the basin.

Motion pictures were made of the spillway discharging both large and small flows.

ACKNOWLEDGEMENT

The final plans evolved from this study were developed through the cooperation of the staffs of the Spillway and Outlet Works Section and the Hydraulic Laboratory during the period December 1957 to April 1959.

INTRODUCTION

Navajo Dam is a part of the Upper Colorado River Storage Project. It is located on the San Juan River in northwestern New Mexico about 39 miles east of Farmington (Figure 1). The dam (Figure 2) is an earthfill structure approximately 3,800 feet long at the crest, 388 feet high above the riverbed, 2,600 feet wide at the base, and 30 feet wide at the crest. It will be the Bureau's second largest earthfill dam with a volume of more than 26 million cubic yards. Water releases are made through a spillway, an outlet works, and an auxiliary outlet works.

The spillway (Figures 3 through 8) is designed to discharge 34,000 cubic feet per second through an open-channel chute on the right abutment into a stilling basin. The ungated spillway crest is 138 feet long and has two bridge supporting piers each 3 feet thick which divide the spillway into 3 bays. The drop from the spillway crest to the stilling basin apron is 410 feet over a horizontal distance of 1,126.5 feet. The apron is horizontal at elevation 5675, and is 195 feet wide by 163 feet long. Thirty-two chute blocks 3 feet high are placed at the upstream end of the basin and a dentated sill having 16 dentils 8 feet high is placed at the downstream end (Figure 7).

Materials for the dam are to be excavated from a 3-mile length of river channel extending downstream from the dam. If the maximum amount of material is excavated from the channel, the tailwater elevation for the design spillway discharge is expected to be about elevation 5715.5 feet, 40 feet above the basin apron (Figure 3). However, if the excavated discharge channel for the spillway and outlet works is limited to a width of 600 feet, the tailwater in the channel is expected to be at about elevation 5719.5, 44.5 feet above the apron; and if a minimum amount of material is excavated from the channel the tailwater would be at elevation 5725, 50 feet above the apron.

An auxiliary outlet works structure is located in the right abutment beneath the centerline of the spillway and discharges through the downstream end of the spillway chute floor into the spillway stilling basin from a tunnel 6 feet wide by 8 feet high (Figure 6). This outlet works is designed to discharge about 2,000 cubic feet per second. It will operate during the time the diversion works are being converted to the permanent outlet works (Figure 2), and also whenever the outlet works is shut down for repairs.

The permanent outlet works is designed to discharge 4,860 cubic feet per second through two 72-inch hollow-jet valves into a stilling basin which is adjacent to and parallel to the spillway stilling basin. The two basins discharge into the same channel, which empties into the San Juan River some 1,000 feet downstream.

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THE MODEL

A 1:48 scale reproduction of the prototype spillway and stilling basin, including the junction of the auxiliary outlet works with the spillway chute (Figures 9 and 10) was constructed and tested in the U. S. Bureau of Reclamation Hydraulic Laboratory at Denver, Colorado. A portion of the reservoir adjacent to the spillway crest and a reach of river channel downstream from the stilling basin were included.

The reservoir area and the spillway approach were contained in the head box. These features were molded in concrete mortar placed on metal lathe which had been nailed over wooden templates shaped to the ground surface contours. The surface was given a rough finish to simulate the natural topography of the prototype. The excavated surfaces of the approach channel were given a smooth finish.

The spillway crest was molded in cement mortar using sheet metal templates accurately cut and placed as guides. Piezometers consisting of 1/16-inch-inside-diameter brass tubes were soldered at right angles to the template profile and filed flush. The template containing the piezometers was placed on the spillway centerline.

The spillway chute, extending from the spillway crest to the stilling basin was constructed of plywood. To provide a smooth surface and prevent warping, the chute was coated with resin and then painted. Piezometers were installed along the centerline of the spillway where the chute changes from a relatively flat slope to a steep one.

The auxiliary outlet works junction with the chute floor was constructed of transparent plastic. Fifteen piezometers were placed in the floor and walls of the junction. Upstream from the plastic section a 16-foot length of prototype tunnel was modeled and connected to a water supply from the model head box. The tunnel was constructed of sheet metal and the tunnel flow was controlled by use of two slide gates, one to control the discharge and one to control the depth of flow.

The stilling basin was constructed of plywood. The plywood was coated with resin and painted to resist warping. The fillets at the base of the training walls and end sill were constructed of sheet metal; the sill dentils and chute blocks were made of wood. Piezometers were placed in two of the chute blocks and in the floor of the basin immediately downstream from one of the chute blocks near the center of the basin. The stilling basin and the discharge channel were contained in the tail box. The discharge channel was molded in sand to elevation 5728; the channel banks in concrete.

Water was supplied to the model through an 8-inch line from the laboratory's supply system. The quantity of water was measured by use of a venturi meter in the supply system. The flow through the auxiliary outlet works was supplied through a 6-inch pipe from the head box and was controlled by two slide gates mounted in tandem at the upstream end of the auxiliary outlet works tunnel section. The water surface elevation in the reservoir was measured about 50 feet upstream from the approach channel by means of a hook gage operating in a transparent stilling well. The water surface in the discharge channel was controlled by means of a hinged tailgate and its elevation was measured by means of a staff gage placed on the spillway centerline about 200 feet downstream from the stilling basin.

THE INVESTIGATION

The primary purpose of the investigation was to develop the hydraulic design of the spillway structure, stilling basin, and the junction of the auxiliary outlet works with the spillway chute. To accomplish this it was necessary to study, (1) the characteristics of the spillway flows as they approached and passed through the spillway and stilling basin, and (2) the characteristics of the auxiliary outlet works flows discharging from the auxiliary outlet works portal into the spillway chute and stilling basin, both with and without the spillway discharging. The spillway is designed to discharge 34,000 cubic feet per second, and the auxiliary outlet works about 2,000 cubic feet per second.

Preliminary Spillway Approach Channel

The preliminary approach channel approached the spillway crest from the left, as shown in Figure 10A. The toe of the left bank was on a curve having a 200-foot radius. The toe of the right bank was on a curve having a 600-foot radius. From the upstream end of the channel to the approach training walls, the banks sloped 2:1. At the approach training walls the banks sloped 2-1/2:1 and were riprraped. The top of the approach walls sloped 2-1/2:1, flush with the channel banks, and the walls were vertical. The approach training walls extended upstream from the crest and flared to provide a channel width of 162 feet at approach channel floor elevation 6070.

The channel was adequate to discharge all flows up to and including the designed flow as shown in Figure 11; however, for all discharges an eddy occurred along the left bank as shown by the confetti paths on the water surface. For discharges near the designed flow, a small water surface disturbance occurred along the right approach wall just upstream from the spillway crest (Figure 10C).

As a result of the flow approaching the spillway crest from the left, the flow was deeper over the center and righthand bays than over the lefthand bay (Figure 12). This uneven distribution persisted throughout the entire length of chute and into the stilling basin, as shown in Figures 12, 13 and 14. The distribution of white water in the stilling basin (Figure 14) indicates the degree of uneven lateral distribution of flow entering the stilling basin. Scour in the discharge channel was considerably more extensive downstream from the righthand side of the basin than the left (Figure 15). This indicated also that an unsymmetrical flow pattern existed.

Spillway Approach Schemes

Several approach schemes to improve the distribution of flow across the spillway crest and across the spillway chute and stilling basin were investigated. One of the best schemes tested provided a straight approach bank on the right bank and a parabolically curved bank on the left. The slope of the left bank varied from 2:1 at the left approach training wall to 3:1 at the upstream end of the bank to form a warped surface. The purpose of the warp was to provide an approach channel of minimum width for small discharges having a sufficiently wide entrance for the larger discharges. This scheme produced a smooth water surface in the approach and reduced the magnitude of the eddy along the left bank (Figure 16). However, little, if any, improvement occurred in the flow distribution or in the disturbance at the right approach wall.

An approach training wall shaped as shown in Figure 17A was developed to smooth out the disturbance along the right wall. The modified wall was an addition to the preliminary wall that extended it vertically upward to elevation 6105. At elevation 6105 the addition extended upstream to the end of the original preliminary approach wall, then undercut downstream on a 1:1 slope to meet the top of the preliminary wall. This wall functioned very well in smoothing the water surface along the right training wall (compare Figure 17B with 17C). However, this more costly wall was not recommended for use in the prototype because improvement was largely in flow appearance and not in flow distribution.

Other alinement curves in the left bank of the approach channel were tested but none improved the flow distribution at the stilling basin. The most extreme curvature tested had a 90° turn at the upstream end of the left training wall, placing the left bank at right angles to the spillway centerline. This caused the water surface to be drawn down considerably as the flow passed around the 90° corner. It was found that the drawdown decreased as the radius of curvature was increased.

The right bank of the approach channel was tested with various curvatures. It was found that the degree of curvature had very little effect on the flow distribution in the stilling basin. It was not possible to curve the right bank in the opposite direction from that of the left bank without considerably lengthening the approach channel; a straight bank line was, therefore, considered to be a practical limit.

Recommended Spillway Approach Channel

The recommended approach channel shown in Figure 3 utilizes a straight bank line on both sides of the approach channel. This channel was recommended because of its simplicity and economy of construction, and because it performed about as well as the curved approaches (compare Figures 11 and 18). For all flows in the recommended approach channel, an eddy occurred along the left bank and a water surface disturbance occurred at the entrance to the approach channel. However, these conditions did not appear to be overly objectionable and it was believed that flow conditions in the prototype will be better than those shown in the model. This is because the prototype will provide a larger area of the reservoir from which the approach channel will draw its water than was possible to represent in the model. Also, tests made concurrently with the spillway approach tests indicated that the problem of flow distribution at the stilling basin, caused by the unsymmetrical approach, could be solved by using a distributing device in the spillway chute. This is described later.

Recommended Spillway Crest

The preliminary crest shape (Figure 4) was tested and found to be satisfactory. For the design flow of 34,000 cubic feet per second, all pressures measured on the crest section were above atmospheric (Figure 19). Immediately downstream from the high point of the crest, pressures were very close to atmospheric. The fact that no high pressures were found in the vicinity of the crest indicates that the crest design is efficient with respect to discharge capacity.

The discharge capacity of the spillway crest was determined using the preliminary approach channel. This preliminary calibration curve was found to agree very closely with the discharge quantities predicted during the design studies (Figure 20). For the design flow, the model showed the reservoir surface to be about 0.25 foot below the expected reservoir elevation. The difference could be accounted for by the velocity head of the approaching flow at the reservoir elevation gage in the model (Figure 11). The prototype coordinates of this location are approximately N 20,650 and E 53,350. From the measured length of the confetti streaks in Figure 11 and the exposure

time of the picture, the surface velocity in the prototype at the location of the head gage was computed to be 5.5 feet per second for the design flow. The average velocity is approximately three-fourths of this, or about 4.0 feet per second; the corresponding velocity head is about 0.25 foot.

Using the recommended approach channel, the spillway crest was again calibrated to determine the effect of the modifications on the reservoir elevation. The calibration curve (Figure 21) showed the reservoir water surface at the gage to be higher than in the preliminary design, but the velocity head was negligible so that the model calibration still agreed with the design curve. The coefficient of discharge was computed from the discharge calibration data points and plotted versus head (Figure 21). The crest shape was considered to be very efficient in that the coefficient of discharge ranged from about 3.4 for 5,000 cubic feet per second to about 3.78 for the design flow of 34,000 cubic feet per second.

Crest pressures, using the recommended approach channel, were found to be the same as those measured using the preliminary channel (Figure 19) and were satisfactory. The preliminary crest shape is therefore recommended for the prototype.

General Considerations Related to Spillway Chute and Stilling Basin

A roughness coefficient n = 0.013 had been used in the Manning equation in calculating the depth of the design flow on the chute to obtain proper training wall heights. However, to determine the maximum velocity at which the design flow might enter the stilling basin, a roughness coefficient of n = 0.008 had been used.

The design discharge per foot of width on the Navajo spillway is 175 cubic feet per second at the downstream end of the spillway chute, considerably lower than the usual design discharge for a spillway of these overall dimensions; therefore, the spillway discharge is a relatively high velocity shallow depth flow. Hydraulic losses in shallow depths of flow moving at high velocity are believed to be somewhat greater than those which occur in deeper flows. Because optimum performance of the stilling basin depends primarily on the velocity and depth of the incoming flow, it is imperative that the model represent as closely as possible the flow conditions as they will occur in the prototype; however, little is known regarding losses in shallow prototype flows moving at high velocity. If quantitative prototype data were available, it might be possible to show that the hydraulic losses are so great that a considerably shorter and shallower stilling basin would suffice for the maximum discharge. Without this proof, it is necessary to provide a basin of

the usual proportions, as determined by the model, even though it contains an unnecessarily large factor of safety.

To determine the effect of different velocities on the performance of the proposed stilling basin, two arrangements of the model (Figure 22) were tested. The first was an undistorted model, geometrically similar to the prototype, and the second a distorted model having a higher fall from headwater to tail water, designed to produce higher velocities at the entrance to the stilling basin. Results of tests on these two arrangements are discussed separately.

Preliminary Spillway Chute and Stilling Basin

The Undistorted Model--The undistorted model (Figure 9) was constructed geometrically similar to the prototype except for the roughness of the spillway chute. It is not always physically possible to construct a model surface sufficiently smooth to represent the expected prototype concrete surface. The painted surface of the model in this case had an estimated roughness coefficient "n" in the Manning equation of 0.007 to 0.008. Using scale relationships for roughness, this corresponds to a prototype surface having a roughness coefficient of n = 0.0133 to 0.0152. Since a design value of n = 0.013 was used for the prototype, flow velocities in the model would be equal to or slightly less than those required to represent the prototype. and the flow depths would be equal or slightly greater.

Water surface cross sections were measured and plotted at several stations along the spillway chute for the preliminary chute, and again later for the recommended chute (Figures 12 and 23 respectively). From these profiles the average velocity was computed at each station and plotted in Figure 24 for comparison with the velocities used in the design of the prototype structure and for verification of the estimated model roughness.

The profiles were measured, using a point gage mounted to operate normal to the flow surface. In the tests on the preliminary chute the point was set visually; in the recommended chute tests the point was set by means of an electronic circuit and neon light. For the electronic method, a positive electrode was placed in the flow along the training wall near the station at which the measurement was being made. The negative electrode was attached to the point gage. When the point gage contacted the water surface, a red light in the circuit flickered, indicating that the point was in contact with the water part of the time. If was difficult with either method to find the average water surface, because many particles of water were

actually separated from the main mass. However, based on these water surface measurements, it was estimated that the roughness coefficient of the model was between 0.007 and 0.008, which agrees with the preliminary estimate and corresponds to a prototype roughness coefficient ranging from 0.0133 to 0.0152 (Figure 24). Therefore, these values are close enough to the design value of 0.013 to make predictions of the necessary training wall heights, the pressure on the vertical curve in the chute, and the flow pattern.

Chute Training Wall Heights--The water surface cross-section profiles measured in the chute of the geometrically similar model (Figure 12) indicate that the proposed training walls are more than twice as high as the flow depth at most points in the chute. No high waves occurred anywhere along the chute walls (Figure 9). At Station 11+51.1 where the average velocity computed from the model data in Figure 12 is 50.3 feet per second, the freeboard is approximately 1.4 times the flow depth. Downstream from Station 11+51.1, the freeboard increases as the velocity increases. At Station 20+96 where the average velocity is 105.3 feet per second, the freeboard is approximately 3 times the flow depth.

From past experience, these freeboard values are judged to be sufficient to allow for the deeper flow that will result from air entrainment which occurs in the prototype, but does not occur in the model.

Chute Pressures--Pressures on the vertical bend in the chute were measured along the centerline of the spillway. Pressures were found to be above atmospheric and almost equal to the depth of flow above each piezometer (Figure 25). At Station 16+30, the pressure was approximately 2.25 feet of water for the design flow which produced an average velocity of approximately 72 feet per second. The pressures should change very little even if the prototype velocities are higher than those represented by the model.

Chute Roll Waves--For small flows of thin, shallow depth, roll waves are apt to develop in the prototype chute. In the model, these waves occurred for discharges representing approximately 3,400 cubic feet per second and less (Figure 26), and were most evident for spillway discharges approximately 2,000 cubic feet per second. The waves were developed in the upstream portion of the chute, due to the very shallow depth of flow, and were magnified as they passed over the vertical bend because the flow depth became even shallower as the velocity increased. As the waves entered the stilling basin, they caused splashing and

surging in the tail water pool. The surges continued out into the discharge tunnel. However, it is believed that the riprap protection for the discharge channel shown in Figures 2 and 3 will be sufficient for protection of the channel banks.

Exact scale relationships for roll waves are not known and it is therefore difficult to predict the upper discharge limit at which roll waves will cease to exist in the prototype structure. It is believed, however, that the roughness of the model chute has little effect on roll waves occurrence and that the prototype waves will occur approximately in the range predicted by the model.

Stilling Basin Performance--The stilling basin had been designed for a chute roughness coefficient of n = 0.008. This provides an entrance velocity and depth at the chute blocks of 139 feet per second and 1.25 feet, respectively, which produces a Froude Number of 21.8 and a conjugate tail water depth of 38 feet. From measurements in the undistorted model it was determined that the velocity was 110 feet per second, with a depth of 1.58 feet, which provides a Froude Number of 15.4 and a conjugate tail water depth of 34 feet. However, stilling basin tests were continued in the undistorted model because there is a good possibility that the prototype velocity will be no more than 116 feet per second, which is the velocity computed for a chute design roughness coefficient of n = 0.013. In addition, the prototype losses in the chute may be even greater than anticipated due to the high velocity shallow depth of flow, as discussed earlier in this report.

The stilling basin in the preliminary undistorted model performed very well. However, the basin was not utilized to its fullest extent because of the uneven lateral distribution of the flow entering the basin (Figure 14) and because the basin was designed for a higher entrance flow velocity than was produced by the undistorted model. The uneven distribution was caused by the unsymmetrical flow conditions in the spillway approach and has been discussed earlier in the spillway approach sections of this report. The distribution was improved by changes made to the recommended chute as is described later in the recommended spillway chute and stilling basin section of this report.

Water surface profiles were measured in the stilling basin along each training wall to aid in the structural design of the walls. The profiles were recorded along each training wall because of the uneven lateral distribution of the entrance flow. The profiles were recorded for design flow of 34,000 cubic feet per second, at both the minimum and maximum possible tail water elevations, and show the average water surface location

for each of these limits (Figure 27). For maximum tail water elevation 5725, waves sometimes overtopped the training walls from Station 22+24 to the downstream end of the basin along the left wall, and from Station 21+63.5 to the downstream end of the basin along the right wall. For minimum tail water elevation 5715, waves came to within 4 feet of the top of the training wall. Overtopping of the training wall was not considered objectionable since the tail water pool extends to the back side of the training walls, as shown in Figure 9.

For design discharge at maximum tail water elevation 5725, the average location of the toe of the jump occurred 75 feet up the slope of the chute from the intersection of the chute and the apron (Figure 27). For minimum expected tail water elevation 5715, the toe of the jump occurred 50 feet up the slope. The fact that the toe of the jump formed so far upstream indicated that the tail water depth was greater than need be for the entrance velocity in the undistorted model. The maximum tail water depth at design flow is 50 feet, 1.47 times the conjugate depth of 34 feet for Froude Number 15.4. The minimum tail water depth at design flow is 39 feet, 1.15 times conjugate depth. The length of the basin apron is 163 feet, 4.8 times conjugate depth.

Pressures were measured on one of the chute blocks near the centerline of spillway and on the basin floor downstream from the block. At Piezometer 26 on the side of the block and Piezometer 28 on the floor downstream from the block, the pressures measured were about equal to the depth of flow for the design discharge (Figure 28). At Piezometer 27 on the downstream end of the chute block (where low pressures sometimes exist in other installations) the pressure was above atmospheric, but less than half of that measured at the other two piezometers. Lowering the tail water reduced the pressures and increased the effectiveness of the blocks. This was another indication that the basin was deeper than necessary for an entrance velocity of 110 feet per second.

Erosion tests were made using a movable bed in the discharge channel. The design discharge of 34,000 cubic feet per second produced some erosion at each of the downstream corners of the basin for both high and low tail water elevations (Figure 15). The erosion depths were practically the same for either high or low tail water. However, for low tail water, erosion in the discharge channel was more extensive than for high tail water because of less depth and higher velocity. Additional erosion tests conducted after the installation of the recommended chute are discussed in the recommended spillway chute and stilling basin section of this report.

Modified Spillway Chute and Stilling Basin

The Distorted Model--To more nearly represent the design entrance velocity of 139 feet per second at the chute blocks, the model was distorted by increasing the height of fall and reducing the length of the chute, as shown in Figures 22 and 29. The steep slope of the downstream portion of the chute was extended upward to elevation 6204 and the head box was extended to meet the shorter chute. The length of the chute was thereby decreased about 25 percent and the height of fall from crest to stilling basin floor was increased 29 percent.

The average velocity for the maximum discharge at Station 20+96 computed from the electronic depth measurements recorded in Figure 30, was 131.5 feet per second for the design flow of 34,000 second feet, which when projected to Station 21+63.5 showed the entrance velocity to be about 135 feet per second (Figure 24). A roughness coefficient of about n = 0.0085 in the computations would produce this velocity in the prototype.

Spillway Chute Performance--In the distorted model, the flow did not spread to the sides of the chute as well as in the undistorted model, because of the more rapid acceleration of the flow. Also, the uneven distribution of the flow approaching the spillway crest still affected the lateral distribution of flow in the chute. This was demonstrated by placing confetti on the water surface in the spillway approach area. More water was flowing down the right side of the chute than down the left as shown in Figure 30 and indicated by the turbulent white water in the stilling basin (Figure 31).

In an attempt to improve the lateral distribution, a hump was installed on the chute floor just upstream from the auxiliary outlet works entrance into the chute (Figure 32). The hump consisted of a rise in the chute floor which extended nearly the full width of the chute. It was 176 feet wide by 216 feet long and gradually rose from the sides and ends to a height of 4 feet at the center.

In operation, the hump had very little effect in altering the course of the high velocity flow (compare Figures 31 and 32). Therefore, it was concluded that if a hump in the chute floor was to be successful it should be installed farther upstream and in the flatter portion of the undistorted model where it could exert a greater effect on the slower moving water.

Stilling Basin Performance--The performance of the stilling basin using the distorted chute is shown in Figure 31 (compare with

Figure 14). In Figure 31 the entrance flow velocity as determined from the electronic depth measurements was 135 feet per second (Figure 24). In Figure 14 the entrance velocity as determined from the visual depth measurements was 110 feet per second (Figure 24). For the higher velocity the hydraulic jump extended farther beyond the end of the basin than for the lower velocity, and the toe of the jump formed approximately 10 feet farther down the slope of the chute (Figure 27) but the basin length was still adequate. The flow depths in the basin were very close to the same as for the lower entrance velocity. Chute block pressures were only slightly lower than those shown in Figure 28 for the lower entrance velocity in the undistorted model.

Erosion of the discharge channel at the downstream corners of the basin was less than for the lower entrance velocity, but was greater toward the center of the channel along the end sill. This was a result of the uneven entrance flow conditions. Compare Figure 31D with Figure 15B.

As a result of these tests it was determined that the basin dimensions were satisfactory for the design flow but that the basin depth was greater than need be since the chute block pressures were well above atmospheric and the toe of the jump formed well upstream from the chute blocks. However, it was not feasible to raise the basin floor above design elevation 5675 because of the low elevation of the foundation rock. The excess tail water depth did not appear to affect the stilling action of the hydraulic jump sufficiently to be of concern. As a matter of general interest, it appeared that the 3:2 slope of the entrance chute (usually 2:1) benefited the stilling action.

Recommended Spillway Chute and Stilling Basin

Spillway Chute Performance--The undistorted model was again used to develop the recommended spillway chute and to improve the lateral flow distribution at the entrance to the stilling basin. Several humps were tested in the flat upstream portion of the chute, varying the height and shape for each test.

Humps 240 feet long by 120 feet wide, pointed at both ends, and from 1 to 2 feet high, as shown in Figure 33, improved the flow distribution better than shorter humps or those having square upstream or downstream ends. The pointed humps were effective in diverting more of the flow toward the sides of the chute to improve the flow distribution at the stilling basin entrance for all discharges (Figure 34). At times the flow filaments appeared to be unstable, but in general the flow was quite evenly distributed.

(as shown in Figure 35 and indicated by the scour patterns in Figures 36 and 37). Compare Figure 14 with Figure 35, and Figure 15 with Figure 36, to see the improvement.

Piezometers were installed in three of the humps as shown in Figure 33, to determine the severity of the possible subatmospheric pressures downstream from the high point of the hump. For the 2-foot-high hump subatmospheric pressures were most severe for the design flow of 34,000 cubic feet per second along the downstream slope change, particularly toward the outer edges. Piezometer 8 in Figure 33 indicated a pressure equivalent to 13 feet of water below atmospheric. No subatmospheric pressures occurred along the centerline of the hump.

In the 1-foot-high hump, only the piezometers along the downstream slope change were installed, since this was found to be the area of greatest subatmospheric pressure. Again, the piezometers toward the outer edges showed the greatest subatmospheric pressure; however, the largest value was only 3 feet of water below atmospheric pressure and this occurred for 34,000 cubic feet per second. Since the 1-foot hump was not sufficiently effective in changing the course of the flow, a hump 1-1/2 feet high was installed with both the upstream and downstream slope changes joined by 20-foot-radius curves (Figure 8). The upstream end of the hump was placed at Station 13+84. The largest subatmospheric pressure measured on this hump was 2.8 feet of water at Piezometer 1 (Figure 33). Since this hump was quite effective in redistributing the flow at the toe of the jump for all discharges, it was recommended for the prototype. The recommended chute then is the preliminary chute with the addition of the recommended hump.

Flow discharged through the recommended chute very satisfactorily (Figure 33). Cross-section profiles measured at several stations along the chute are shown in Figure 23. No excessively high waves occurred along the training walls and it was judged that there was ample freeboard to allow for air entrainment in the prototype. Training wall heights, roll waves, and chute pressures were the same as discussed in the preliminary design, pages 8 and 9.

Stilling Basin Performance--The basin performed very much as described for the preliminary basin tests since the basin itself had not been changed. However, the basin was utilized more effectively across its width because of the better lateral distribution of the entrance flow provided by the hump in the recommended chute (Figure 35). Chute block pressures were the same as shown in Figure 28 and water surface profiles were the same as shown in Figure 27.

As a result of the better lateral distribution the erosion pattern in the discharge channel was improved; however, the deepest scour still occurred near the corners of the basin. The presence of the counterfort walls behind the basin training walls did not affect the scour pattern to any measurable degree.

The erosion test was repeated using a 3/4-inch layer of gravel over a sand bed (Figure 37). This represented a 3-foot-thick layer in the prototype. The gravel had maximum length dimensions of between 1/2 inch and 3/4 inch, which represented 2- to 3-foot lengths in the prototype. After a 4-1/2-hour model test with either high or low tail water, minor erosion occurred at the downstream corners of the stilling basin and along the top of the right bank of the discharge channel (Figures 37B and 37C).

Another erosion test was made to determine whether deeper scour would occur at the right corner of the basin if the right bank was stabilized to prevent material from sloughing into the eroded area. Larger stones were placed on the bank near the right-hand corner of the basin and a 3-inch-wide board was placed on edge in the bank, as shown in Figure 38. After a 4-1/2-hour model test, the eroded hole at the right-hand corner was 2 feet deeper than in the previous test (compare Figures 37B and 38). Because of the increased erosion depth, it was decided that the preliminary design should be improved.

The first step to obtain improvement was to place larger stones (up to 4 feet in prototype) near the corners of the stilling basin and at the downstream curve in the right bank where scour was observed to begin before progressing upstream. After 4-1/2 hours of operation at 34,000 cubic feet per second with the tail water at elevation 5715, the extent and depth of erosion at the corners were about the same as in the preliminary arrangement (Figures 37C and 39B). Nevertheless, it was logical to believe that heavier stones would better resist movement by larger flows than would smaller stones; therefore, the use of larger stones at the corners of the basin was recommended (Figure 40). It was interesting to note that the stones at the corners of the basin were carried downstream and then upstream toward the center of the basin end sill, as shown by the location of the large dark colored stones in Figure 39B.

In addition to using the larger stones at the corners of the basin, it is believed necessary to change the end sill such that the erosion at the corners of the basin would be reduced. The first end

sill modification was taken from HYD-399 1/, which recommends a 2:1 slope for the upstream face of the sill. After a 2-1/2-hour test, the erosion pattern for 34,000 cubic feet per second with high tail water was found to be improved. The erosion along the end sill, particularly at the corners of the basin, was reduced (compare Figures 37B and 41A). However, since scour was a problem only at the basin corners it was not recommended to change the slope of the sill; instead, it was recommended to test the preliminary sill modified only at the ends. Because of the training wall fillets and the manner in which they intersected the upstream slope of the sill (Figure 38), water passing over the ends of the sill was not given sufficient lift to prevent scour of the channel bed. It was reasoned that less scour would result if the slope of the upstream face of the sill at the ends of the sill was increased.

First, the upstream face of the sill at the corners of the basin was increased to a 6:1 slope rising from the training wall fillets. This modification improved the scour pattern from that which occurred with the preliminary sill (compare Figures 37B and 41B). However, the erosion pattern was not as good as for the standard sill design in Figure 41A. In the next trial, the slope of the end sill in the end slot and in one-half of the next slot was increased to 2:1 by raising the top of the sill to elevation 5681.75. The top of the new portion of the sill was level (Figure 41C). For this modification there was no scour at the apron corners. To further simplify the sill, only that portion of the sill in the one end slot adjacent to the training wall at each end of the sill was modified to a 2:1 slope (Figure 42). Four- and one-half-hour scour tests at two different tail water elevations showed that no measurable erosion occurred at the apron corners (Figure 43). This modification did not alter the performance of the basin in other respects from that shown in Figure 35, and therefore, was recommended for use in the prototype.

Recommended Auxiliary Outlet Works Junction with Spillway Chute

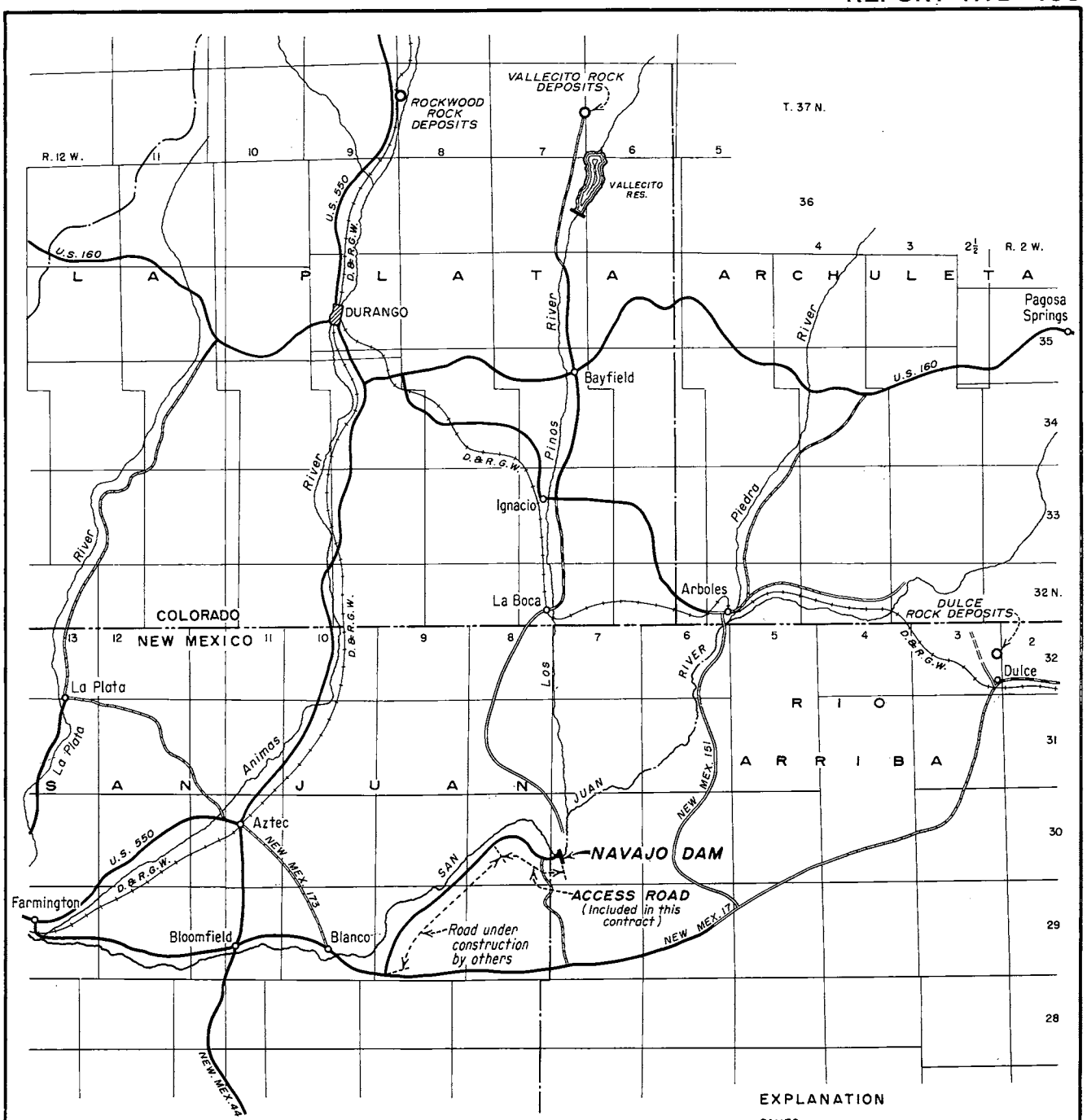
The preliminary junction of the auxiliary outlet works with the spillway chute shown in Figures 3 and 6, was tested and found to be satisfactory. It was, therefore, recommended for the final prototype design.

1/HYD-399, "Progress Report II--Research Study on Stilling Basin, Energy Dissipators and Associated Appurtenances," by J. N. Bradley and A. J. Peterka.

The auxiliary outlet works is designed to discharge 2,010 cubic feet per second at a velocity of 83 feet per second, flowing 4-feet deep at Station 19+54; and 1,850 cubic feet per second at a velocity of 45 feet per second flowing approximately 7.1 feet deep. The hydraulic characterisitics of the flow for these operating conditions were very satisfactory (Figures 44 and 45). The spillway flow passed over the auxiliary junction outlet works quite smoothly when the auxiliary outlet works was not operating (Figure 44A), but some splash occurred as a result of the spillway flow striking the trajectory curve of the outlet works tunnel floor. The flow passing over the outlet works junction acted as an ejector to draw a considerable amount of air from the auxiliary outlet works tunnel which was vented to the atmosphere immediately downstream from the control gate. When the vent was closed, the lowered pressure in the tunnel caused water from the spillway flow to partially fill the tunnel portal. Therefore, it is recommended that the auxiliary outlet works be vented during spillway operation, as well as during operation of the outlet works.

When the spillway and auxiliary outlet works were both discharging, whether spillway flows were large or small, the two discharges merged in a very satisfactory manner (Figures 44B, 45A, and 45B). When the auxiliary outlet works was operated alone, at either the 4- or 6-foot portal depth, corresponding to low or high head respectively (Figures 45C and 45D), no hydraulic performance problems were apparent. The water flowed down the spillway face and entered the stilling basin without creating objectionable eddys. To determine whether pressure problems existed in the junction area of the auxiliary outlet works, pressures were measured at the piezometers shown in Figure 46 for several combinations of spillway and outlet works flows. The largest subatmospheric pressure recorded was at Piezometer 14, located on the edge of the slot in the spillway chute. For 34,000 cubic feet per second discharge over the spillway and no flow from the auxiliary outlet works, the pressure was 4.2 feet of water below atmospheric pressure. Downstream at Piezometer 15, the subatmospheric pressure was 0.8 feet of water. Upstream from Piezometer 14 the edge of the slot is out of the flow. Since the pressure measurements indicated that no cavitation would occur and since the visual appraisal indicated satisfactory performance, the preliminary design is recommended for prototype use.

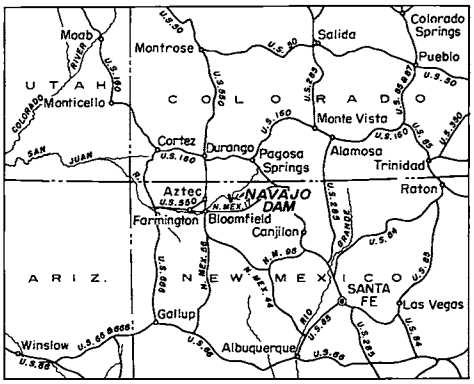
FIGURE I
REPORT HYD 458



EXPLANATION

PAVED
GRAVELED, GRADED
DIRT, GRADED
UNIMPROVED
Approx. location of rock deposits from which samples have been tested for riprap

5 0 5 10 15
SCALE OF MILES



KEY MAP

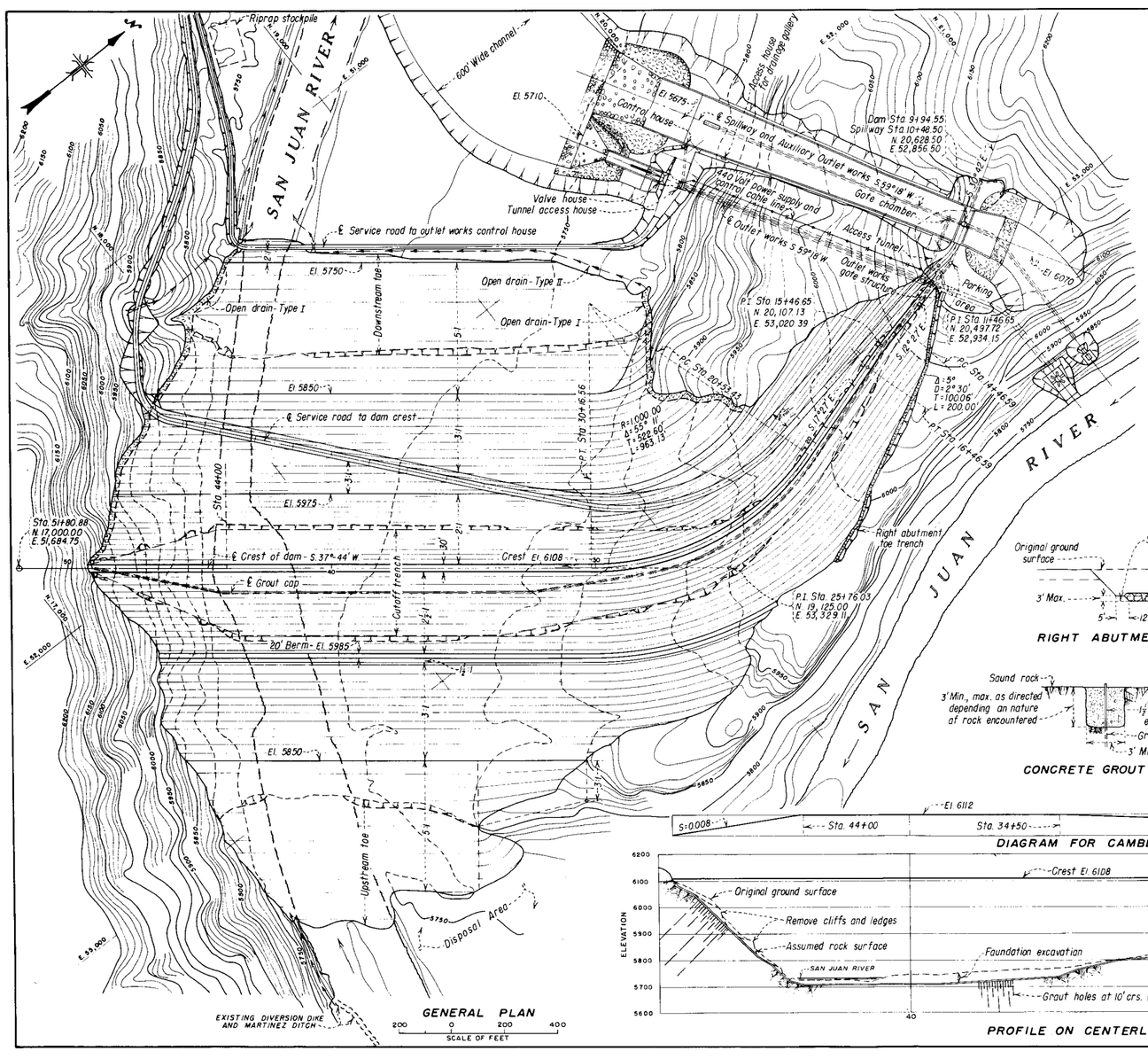
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV.-NAVAJO UNIT--COLORADO-NEW MEXICO

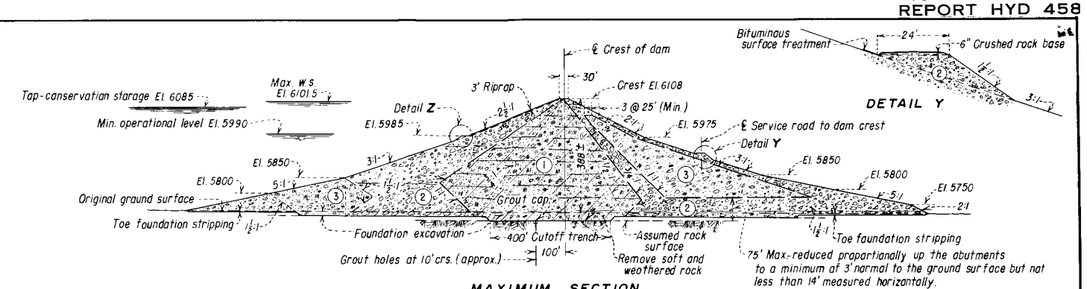
NAVAJO DAM
LOCATION MAP

DRAWN D.D.C. SUBMITTED R. J. Larsen
TRACED D.D.C. RECOMMENDED C. B. Duke
CHECKED W.S.H.Jr.W. APPROVED E. Grinstein
ACTING ASST. COMM. AND CHIEF ENGINEER

DENVER, COLORADO, APRIL 22, 1958 | 711-D-35

FIGURE 2
REPORT HYD 458

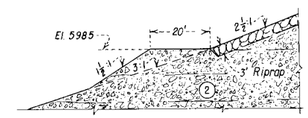




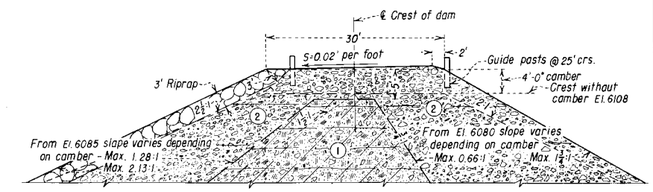
EMBANKMENT EXPLANATION

1. Selected clay, silt, sand, and gravel compacted by tamping rollers to 6-inch layers
2. Selected sand, gravel, cobbles and boulders compacted by crawler type tractors to 18-inch layers.
3. Miscellaneous material compacted to 12-inch layers.

Note: Slopes at the division lines between zones are tentative and subject to variation.



DETAIL Z

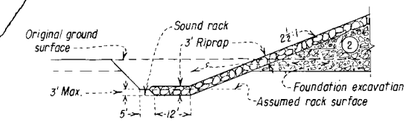


CREST DETAIL AT MAXIMUM CAMBER

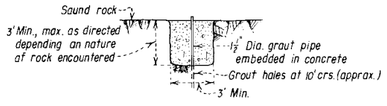
RESERVOIR ALLOCATION

PURPOSE	ELEVATION	STORAGE ACRE FEET
Conservation	5990 to 6085	1,037,000
Inactive	5882.5 to 5990	500,000
Dead	5720 to 58825	175,000
Total storage capacity		1,712,000

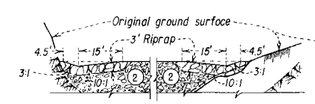
A surcharge of 273,000 a.f. (Max. W.S. El. 6101.5) in combination with a spillway discharge of 34,000 c.f.s. and an outlet works discharge of 4,100 c.f.s. protects against the spring design flood (peak-107,000 c.f.s., 30 day volume-1,037,700 a.f.)



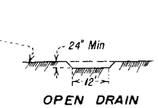
RIGHT ABUTMENT TOE TRENCH



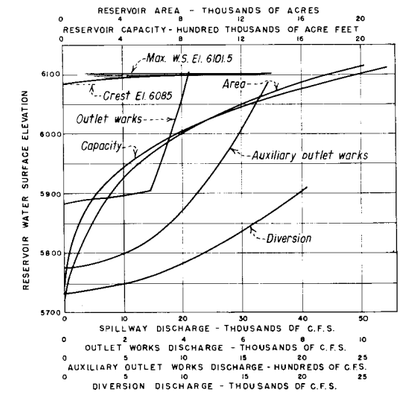
CONCRETE GROUT CAP



OPEN DRAIN-TYPE I



OPEN DRAIN TYPE II



AREA - CAPACITY - DISCHARGE CURVES

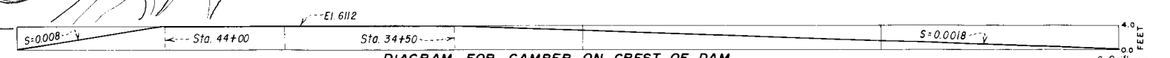
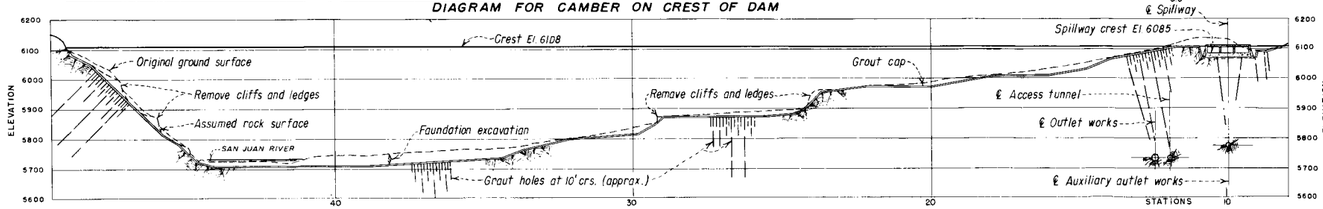


DIAGRAM FOR CAMBER ON CREST OF DAM



PROFILE ON CENTERLINE OF CREST OF DAM

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV.-NAVAJO UNIT--COLORADO-NEW MEXICO

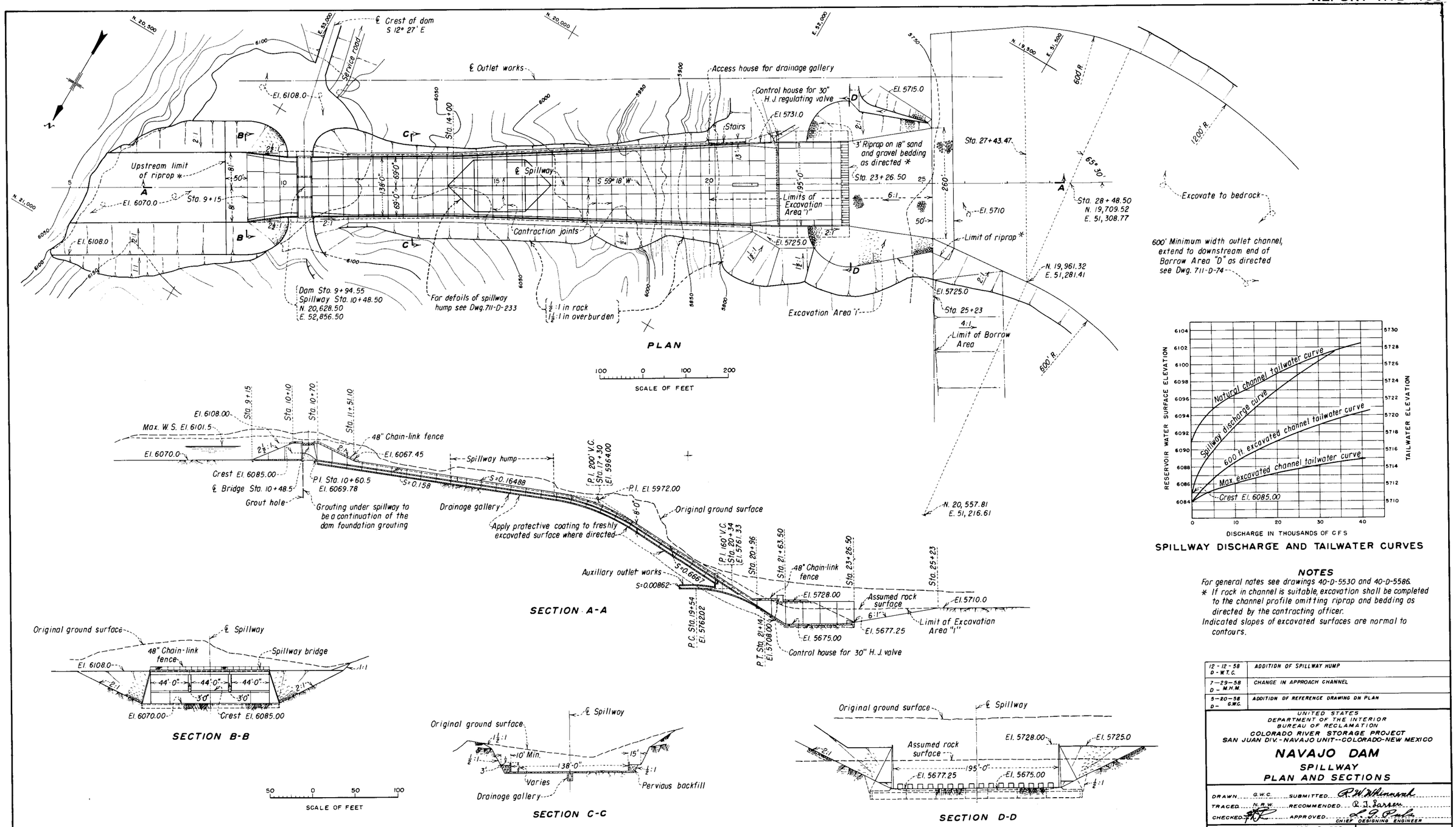
NAVAJO DAM

GENERAL PLAN AND SECTIONS

DRAWN W.G.H. SUBMITTED R. J. Larsen
TRACED J.F.M. RECOMMENDED L. G. Rubin
CHECKED W.K.C. APPROVED E. Nielsen
ACTING ASSISTANT COMM. AND CHIEF ENGINEER
DENVER, COLORADO, APRIL 22, 1958

711-D-37

FIGURE 3
REPORT HYD 458



SPILLWAY DISCHARGE AND TAILWATER CURVES

NOTES

For general notes see drawings 40-D-5530 and 40-D-5586.

* If rock in channel is suitable, excavation shall be completed to the channel profile omitting riprap and bedding as directed by the contracting officer.

Indicated slopes of excavated surfaces are normal to contours.

12-12-58 D-W.T.C.	ADDITION OF SPILLWAY HUMP
7-29-58 D-M.H.M.	CHANGE IN APPROACH CHANNEL
5-20-58 D-G.W.C.	ADDITION OF REFERENCE DRAWING ON PLAN

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV.-NAVAJO UNIT--COLORADO-NEW MEXICO

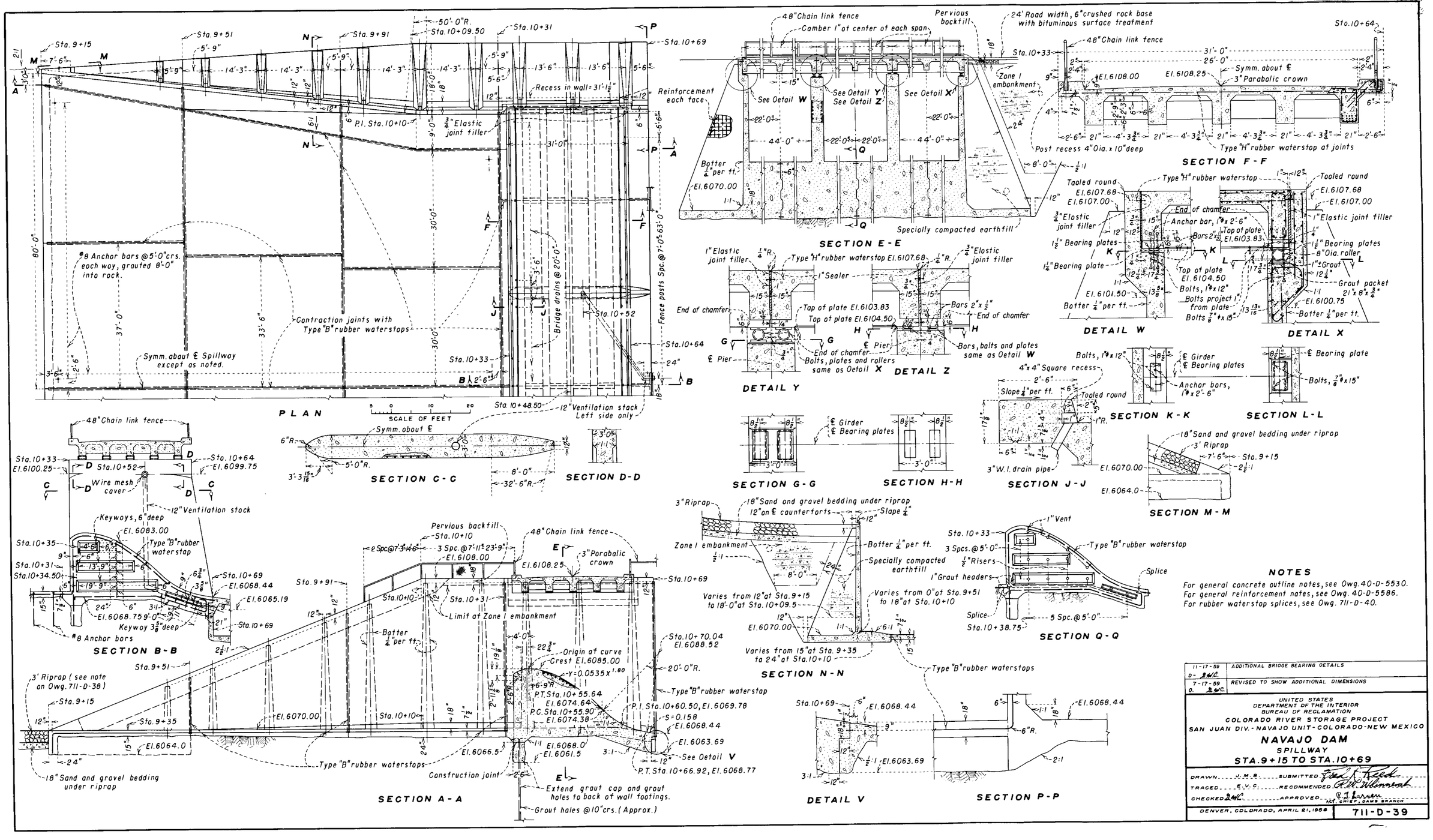
NAVAJO DAM

SPILLWAY
PLAN AND SECTIONS

DRAWN G.W.C. SUBMITTED R.W. Whitwell
TRACED N.R.W. RECOMMENDED R. J. Larsen
CHECKED APPROVED L. F. Pals
CHIEF DESIGNING ENGINEER

DENVER, COLORADO, APRIL 21, 1958 — 711-D-38

FIGURE 4
REPORT HYD 458



NOTES

For general concrete outline notes, see Owg. 40-D-5530.
For general reinforcement notes, see Owg. 40-D-5586.
For rubber waterstop splices, see Owg. 711-D-40.

11-17-59 D-RWC	ADDITIONAL BRIDGE BEARING DETAILS
7-17-59 D. RWC	REVISED TO SHOW ADDITIONAL DIMENSIONS

UNITED STATES
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BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV. - NAVAJO UNIT - COLORADO-NEW MEXICO

NAVAJO DAM
SPILLWAY
STA. 9+15 TO STA. 10+69

DRAWN J.M.B. SUBMITTED Fred L. Reed
TRACED E.V.C. RECOMMENDED A. H. Wilmanns
CHECKED RWC APPROVED R. J. Larsen, ACT. CHIEF, DAMS BRANCH

DENVER, COLORADO, APRIL 21, 1958 — 711-D-39

FIGURE 5
REPORT HYD 458

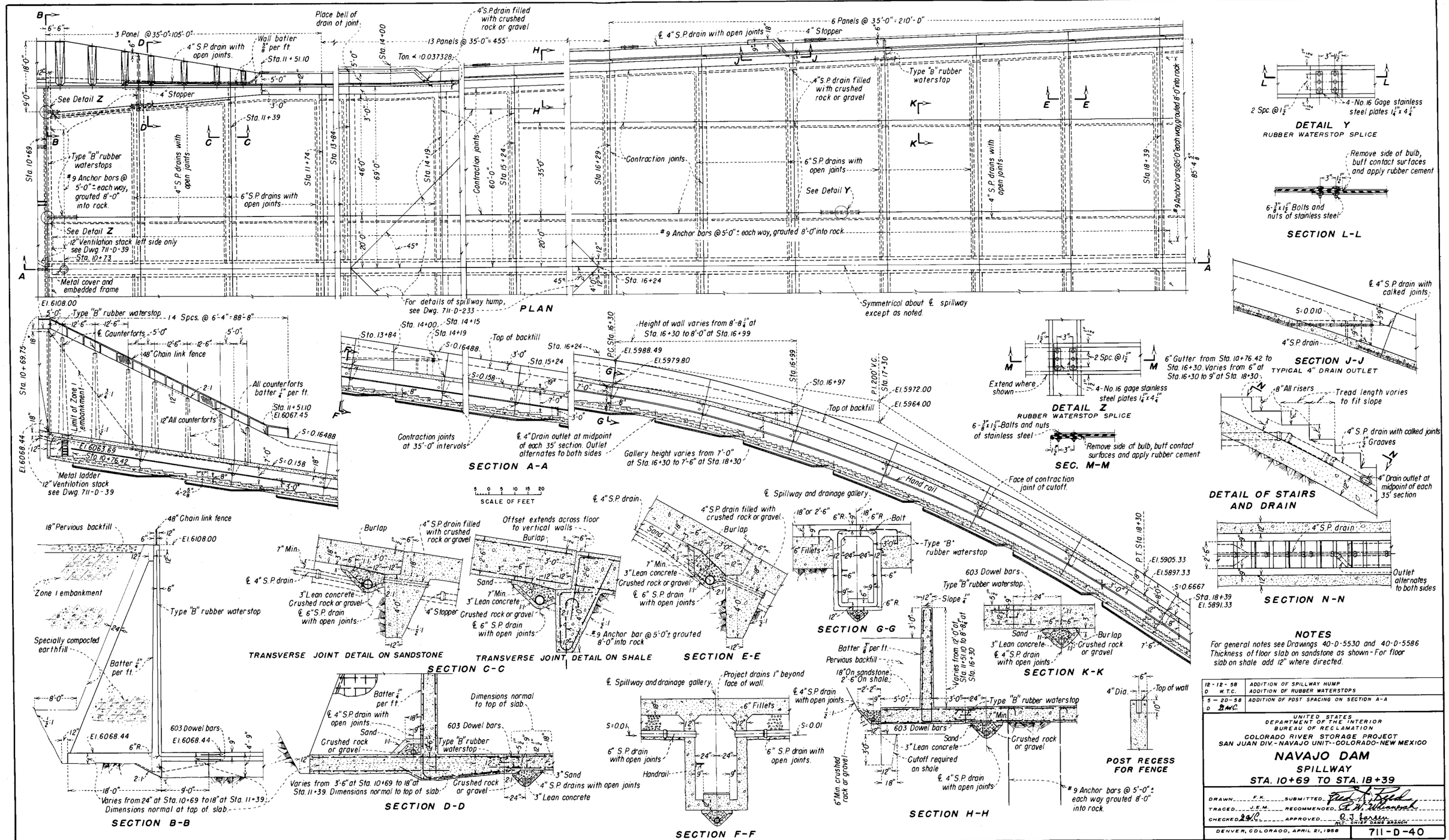
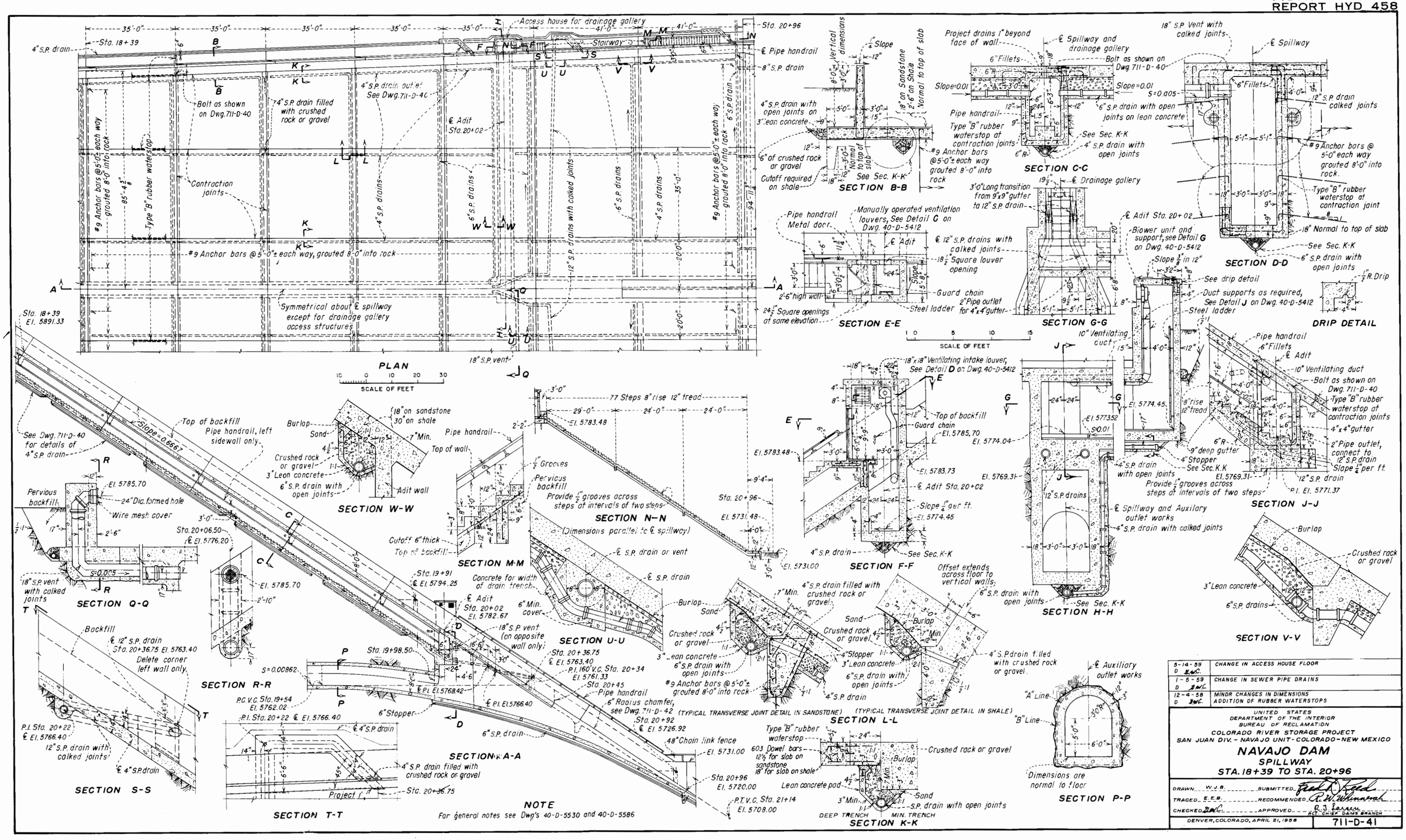


FIGURE 6
REPORT HYD 458



5-14-59 D W.W.C.	CHANGE IN ACCESS HOUSE FLOOR
1-5-59 D W.W.C.	CHANGE IN SEWER PIPE DRAINS
12-4-58 D W.W.C.	MINOR CHANGES IN DIMENSIONS ADDITION OF RUBBER WATERSTOPS

UNITED STATES
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COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV. - NAVAJO UNIT - COLORADO - NEW MEXICO

NAVAJO DAM
SPILLWAY
STA. 18+39 TO STA. 20+96

DRAWN W.J.B. SUBMITTED Fred D. Reed
TRACED E.E.B. RECOMMENDED R. W. Wilmanns
CHECKED W.W.C. APPROVED R. J. Lawrence ACT. CHIEF DAMS BRANCH
DENVER, COLORADO, APRIL 21, 1958 — 711-D-41

FIGURE 7
REPORT HYD 458

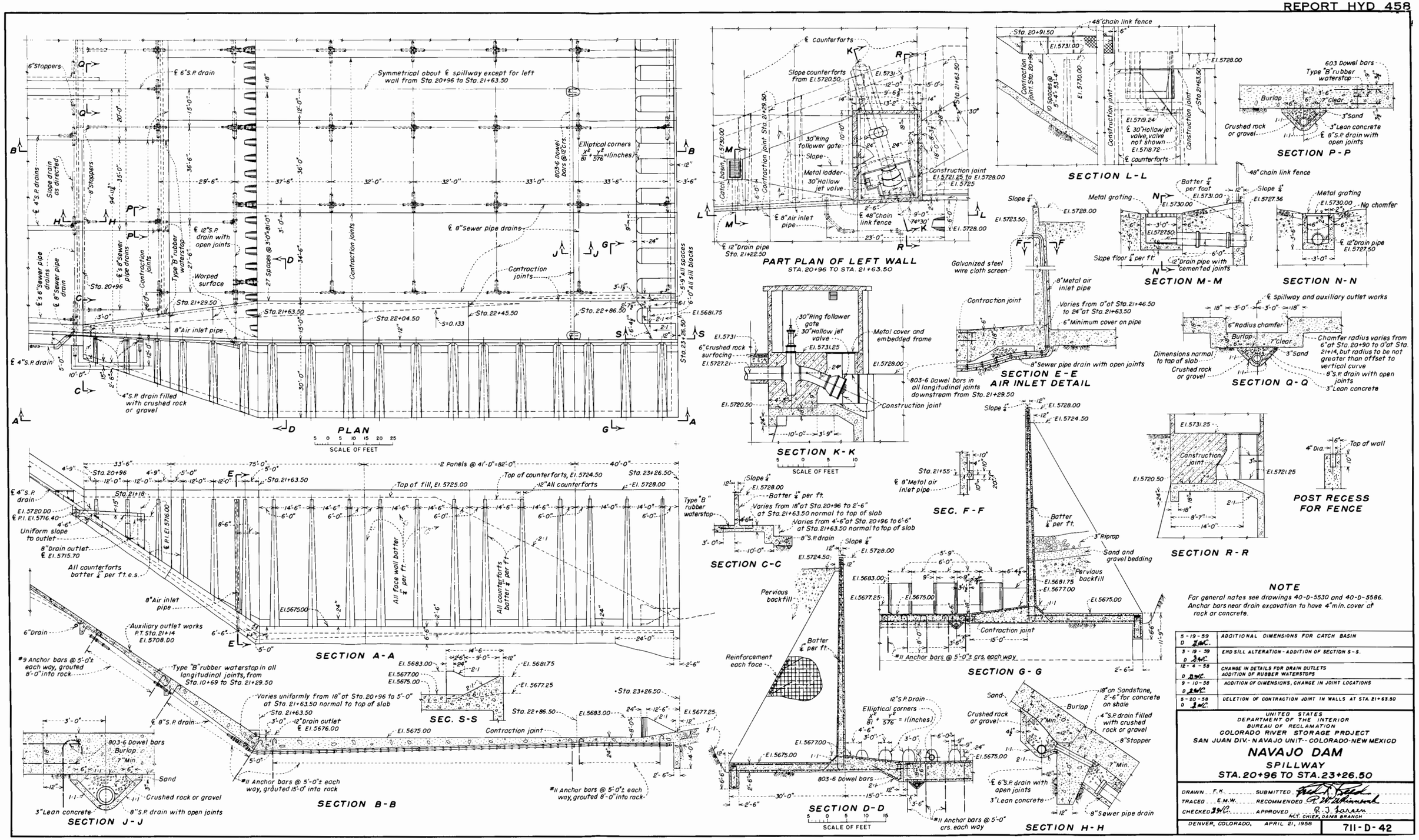
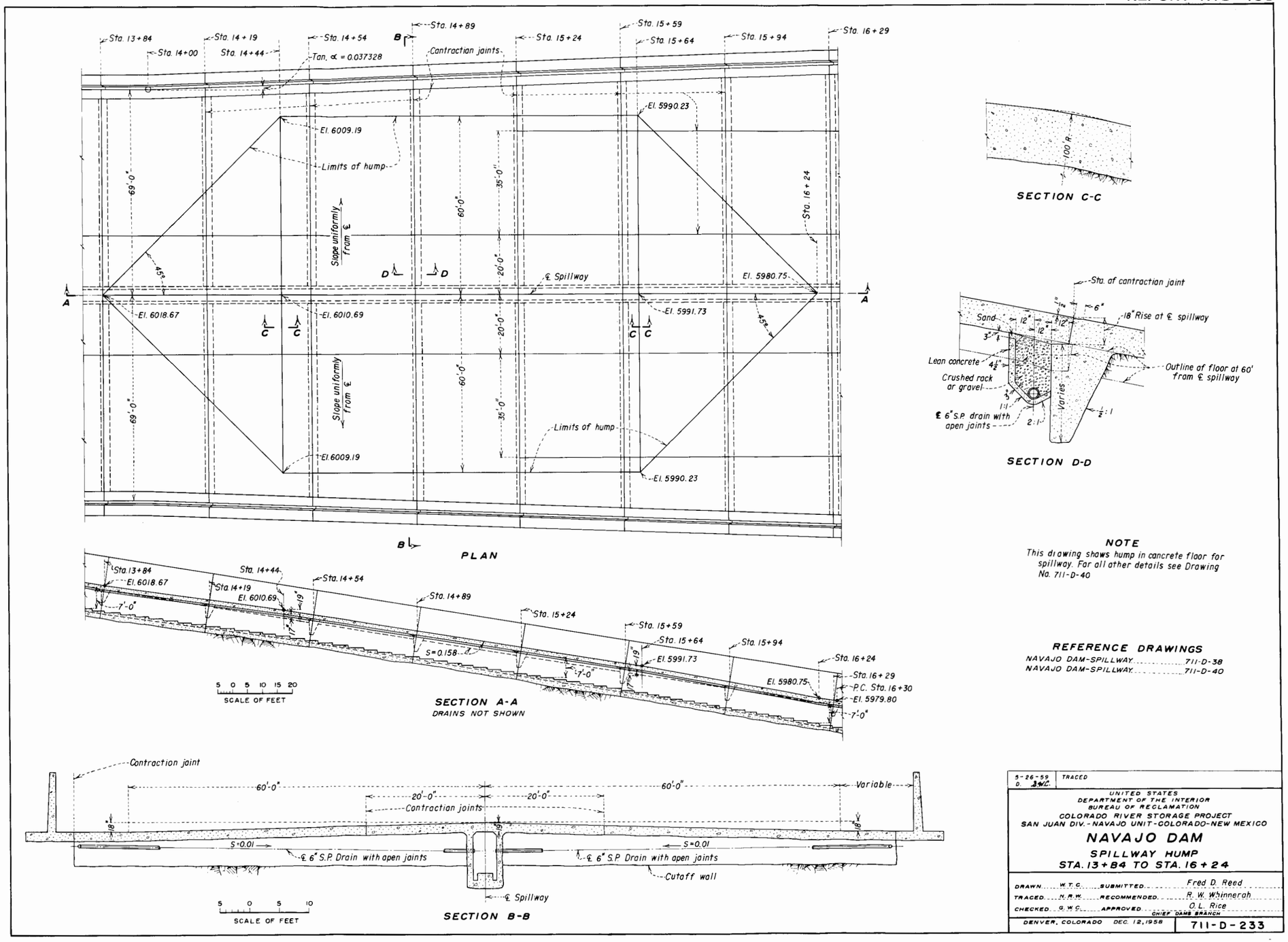


FIGURE 8
REPORT HYD 458



NOTE

This drawing shows hump in concrete floor for spillway. For all other details see Drawing No. 711-D-40

REFERENCE DRAWINGS

NAVAJO DAM-SPILLWAY 711-D-38
NAVAJO DAM-SPILLWAY 711-D-40

5-26-59 D. J.W.C.	TRACED

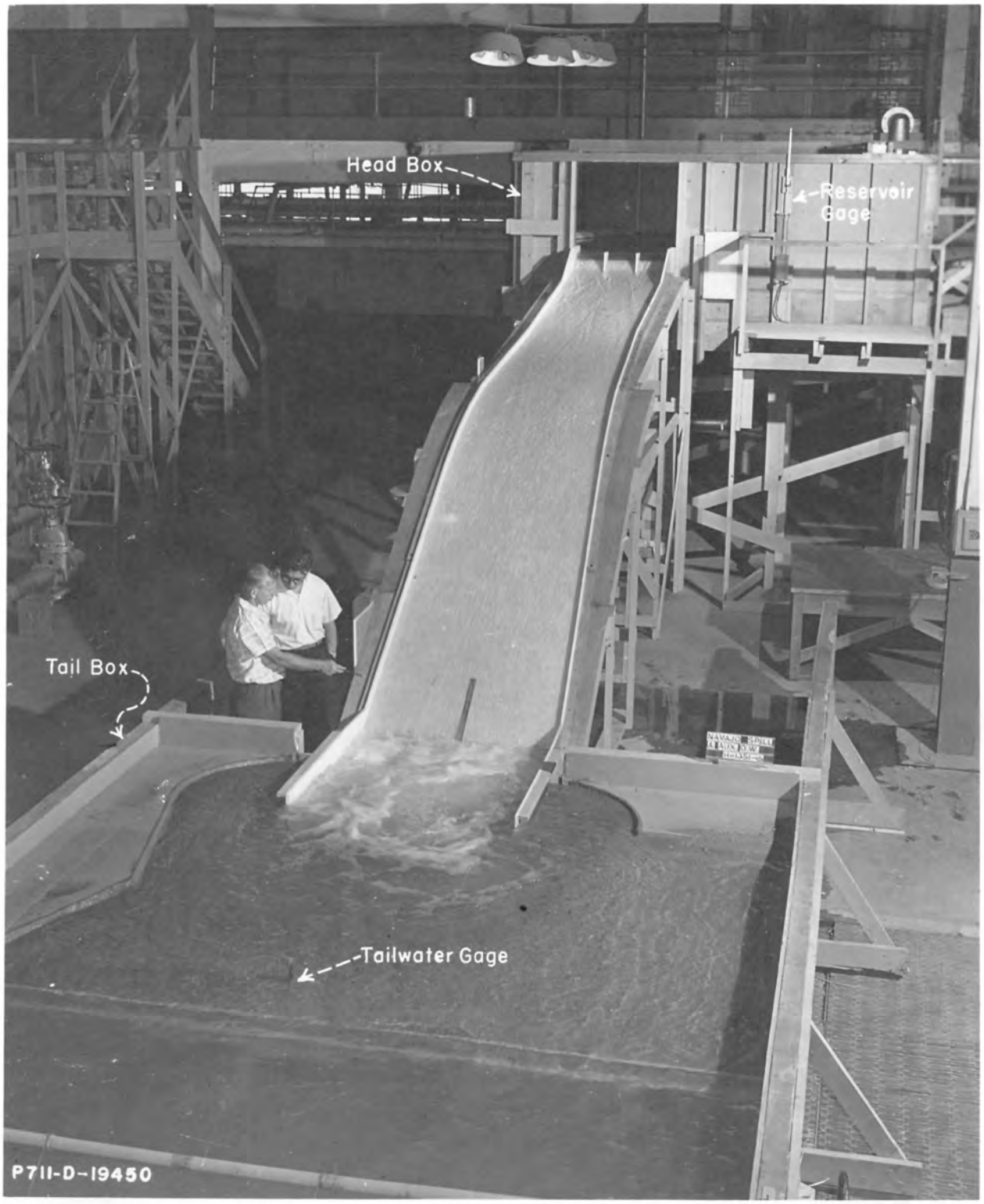
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV.-NAVAJO UNIT-COLORADO-NEW MEXICO

NAVAJO DAM

SPILLWAY HUMP
STA. 13+84 TO STA. 16+24

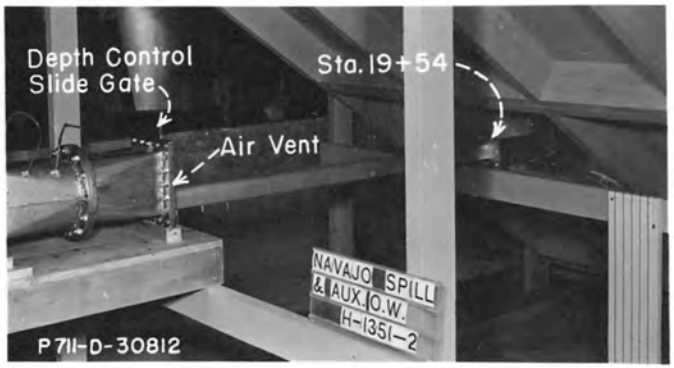
DRAWN W.T.C. SUBMITTED Fred D. Reed
TRACED N.R.W. RECOMMENDED R. W. Whinnerah
CHECKED G.W.C. APPROVED O. L. Rice
CHIEF DAMS BRANCH

DENVER, COLORADO DEC. 12, 1958 | 711-D-233

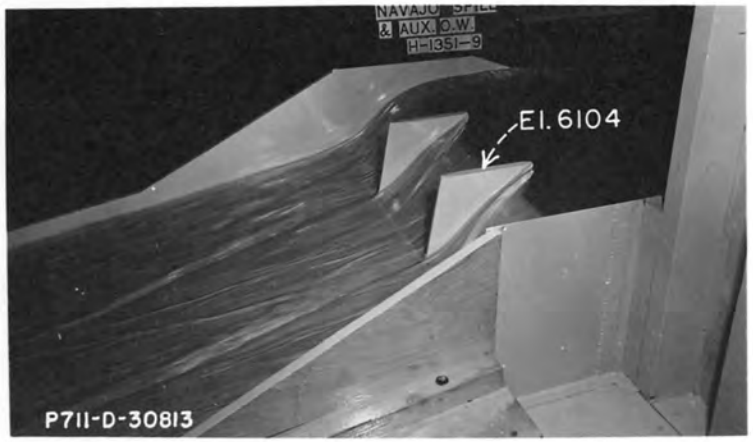


NAVAJO DAM SPILLWAY
Preliminary Spillway Discharging 34,000 cfs--
Tailwater Elevation 5719
1:48 Scale Model

A. Crest section, bridge piers, and approach channel.



B. Auxiliary outlet works.

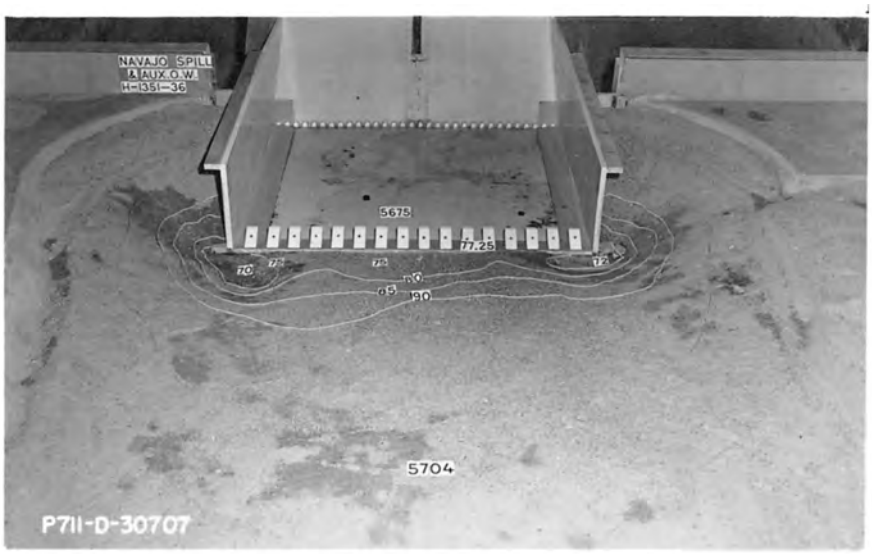


C. Spillway discharging 34,000 cfs. Note the water surface disturbance at right wall.

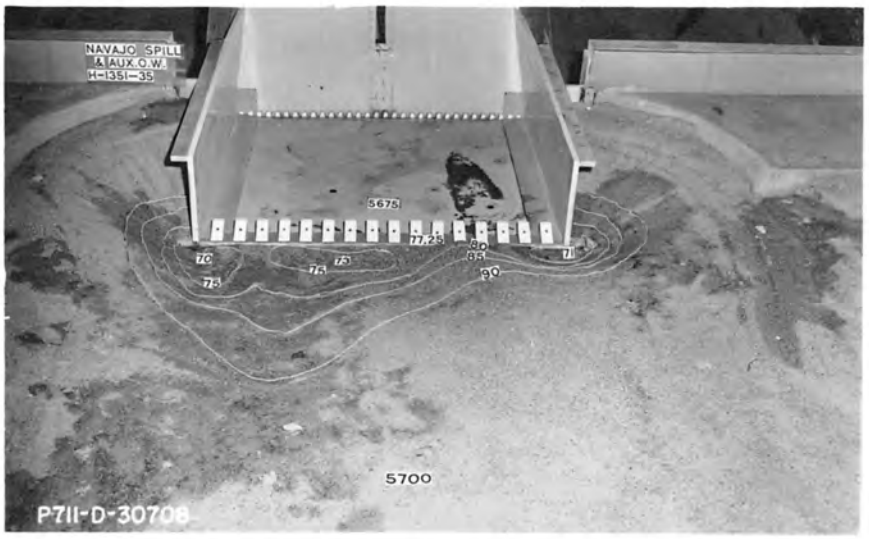
D. Stilling basin and discharge channel.

NAVAJO DAM SPILLWAY
Model Views
1:48 Scale Model

Figure 10
Report HYD 458

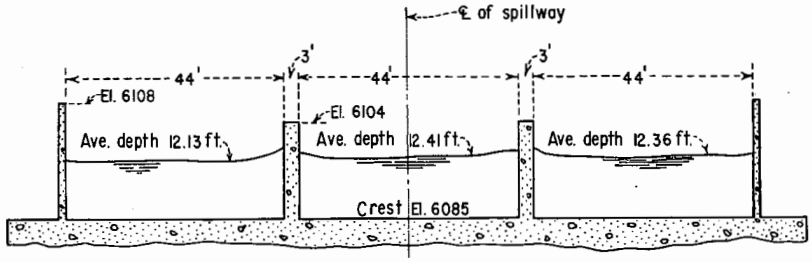


A. 17,000 cfs, reservoir elevation 6095.5 at gage surface velocity at head gage approximately 3-1/2 ft/sec.

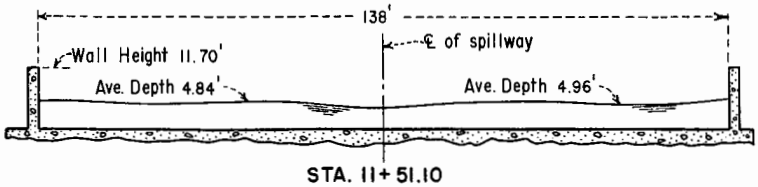


B. 34,000 cfs, reservoir elevation 6101.2 at gage surface velocity at head gage approximately 5-1/2 ft/sec.

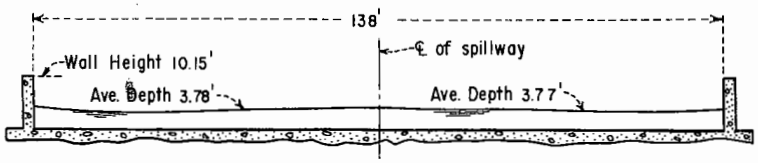
NAVAJO DAM SPILLWAY
Flow in Preliminary Spillway Approach Channel
1:48 Scale Model



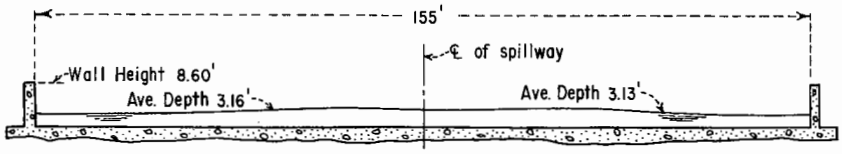
STA. 10+37



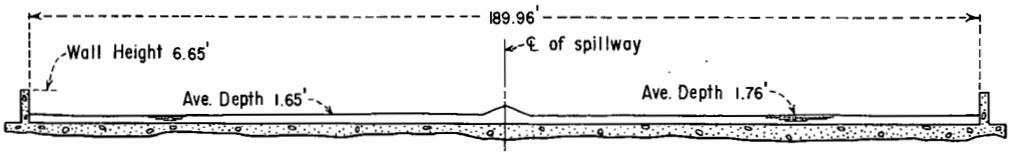
STA. 11+51.10
AVERAGE VELOCITY= 50.30 FEET PER SECOND



STA. 14+00
AVERAGE VELOCITY= 65.13 FEET PER SECOND

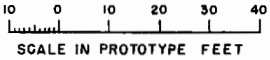


STA. 16+25
AVERAGE VELOCITY = 69.82 FEET PER SECOND



STA. 20+96
AVERAGE VELOCITY = 105.26 FEET PER SECOND

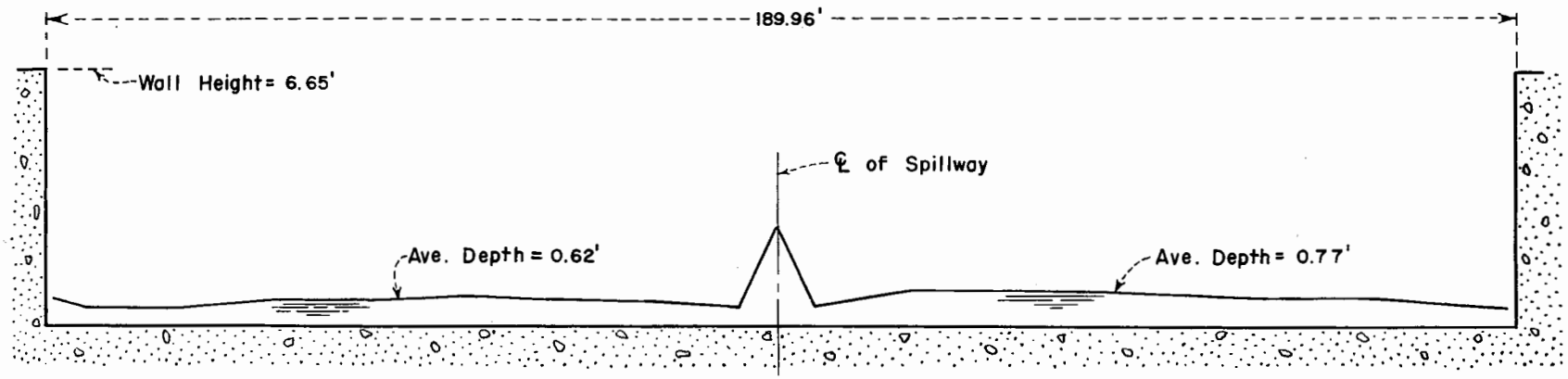
NOTE: Sections are shown looking downstream. Depths are measured visually by means of a point gage mounted normal to the chute floor. See figure 24 for plotted velocities.



NAVAJO DAM SPILLWAY

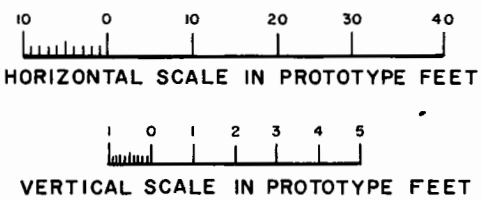
WATER SURFACE PROFILES IN CHUTE-34,000 C.F.S.
PRELIMINARY DESIGN

1:48 SCALE MODEL



STATION 20+96 — LOOKING DOWNSTREAM
AVERAGE VELOCITY = 64.89 FEET PER SECOND

Note: Depths measured normal to chute floor.

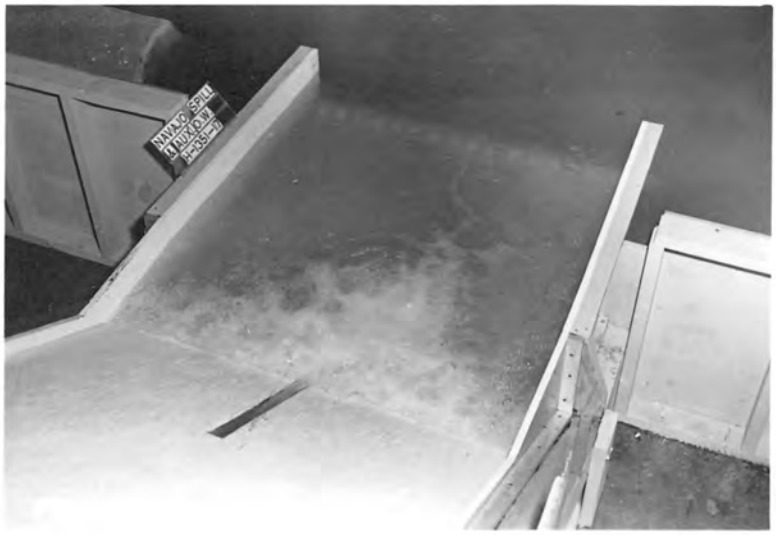


NAVAJO DAM SPILLWAY

WATER SURFACE PROFILE IN THE CHUTE - 8,500 C.F.S.
PRELIMINARY DESIGN

1:48 SCALE MODEL

FIGURE 13
REPORT HYD. 458



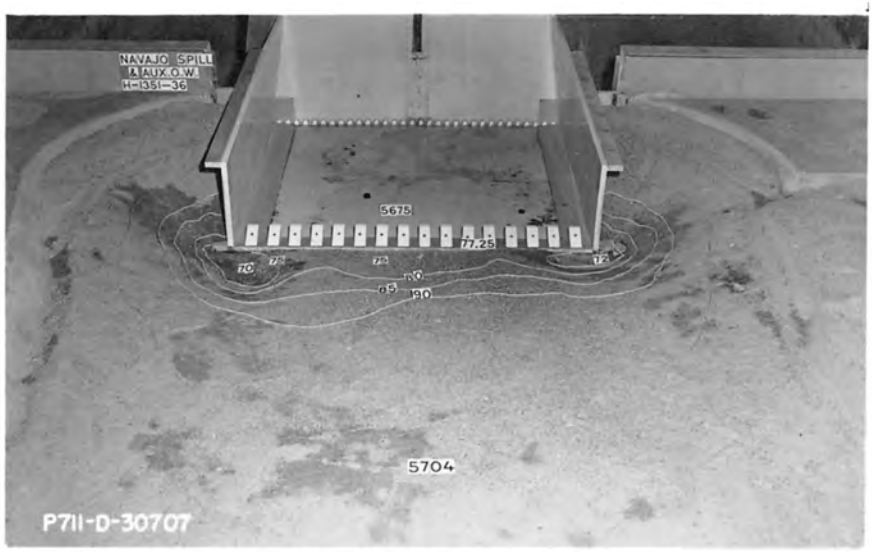
A. 8,500 cfs T.W. elevation 5713.

B. 17,000 cfs T.W. elevation 5714

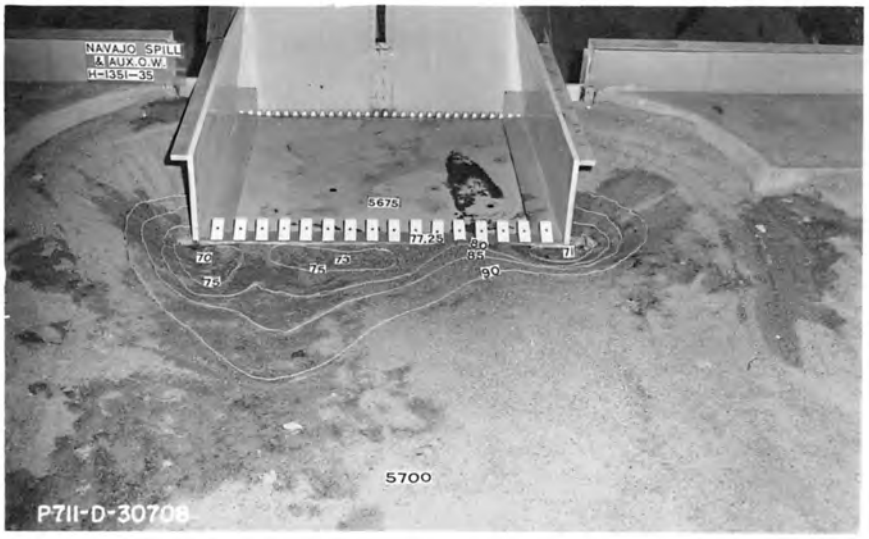
C. 34,000 cfs T.W. elevation 5715. Dotted line is the water surface profile for T.W. elevation 5725.

NOTE: The uneven lateral distribution of flow entering the basin is indicated by the white water.

NAVAJO DAM SPILLWAY
Preliminary Stilling Basin Performance
1:48 Scale Model



Tailwater elevation 5725.



Tailwater elevation 5715.

Erosion after 1 hour operation of the model.

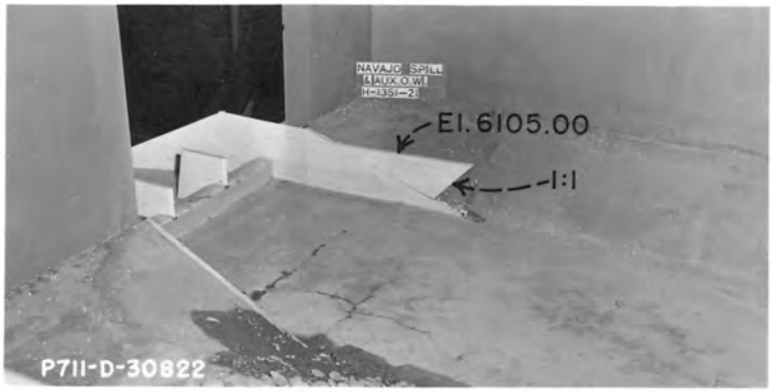
NAVAJO DAM SPILLWAY
Erosion For 34,000 cfs--Preliminary Chute and Stilling Basin
1:48 Scale Model

A. 17,000 cfs.

B. 34,000 cfs.

NOTE: Toe of left bank is parabolic in plan. Right bank is straight. Slope of left bank varies from 3:1, upstream, to 2:1 at training wall. Slope of right bank 2:1.

NAVAJO DAM SPILLWAY
Flow in Modified Spillway Approach Channel
1:48 Scale Model



A. Improved right training wall.

B. Minimum disturbance at right wall with 34,000 cfs discharging.

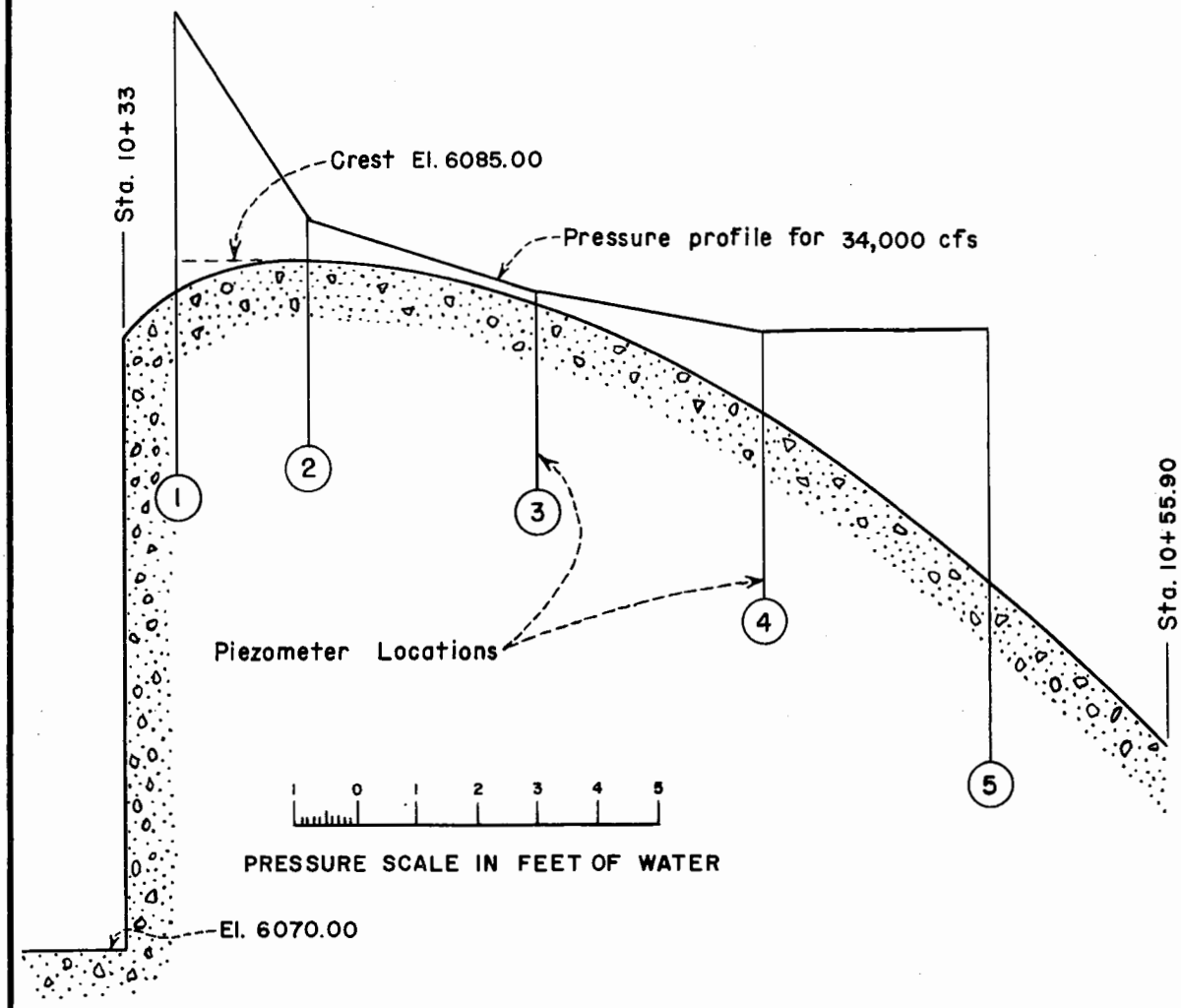
C. Preliminary approach training wall 34,000 cfs discharging.

NAVAJO DAM SPILLWAY
Flow at Right Training Wall
1:48 Scale Model

A. 17,000 cfs.
Surface velocity at head gage 1-1/2 ft/sec.

B. 34,000 cfs.
Surface velocity of head gage 2 ft/sec.

NAVAJO DAM SPILLWAY
Flow in Recommended Spillway Approach Channel
1:48 Scale Model



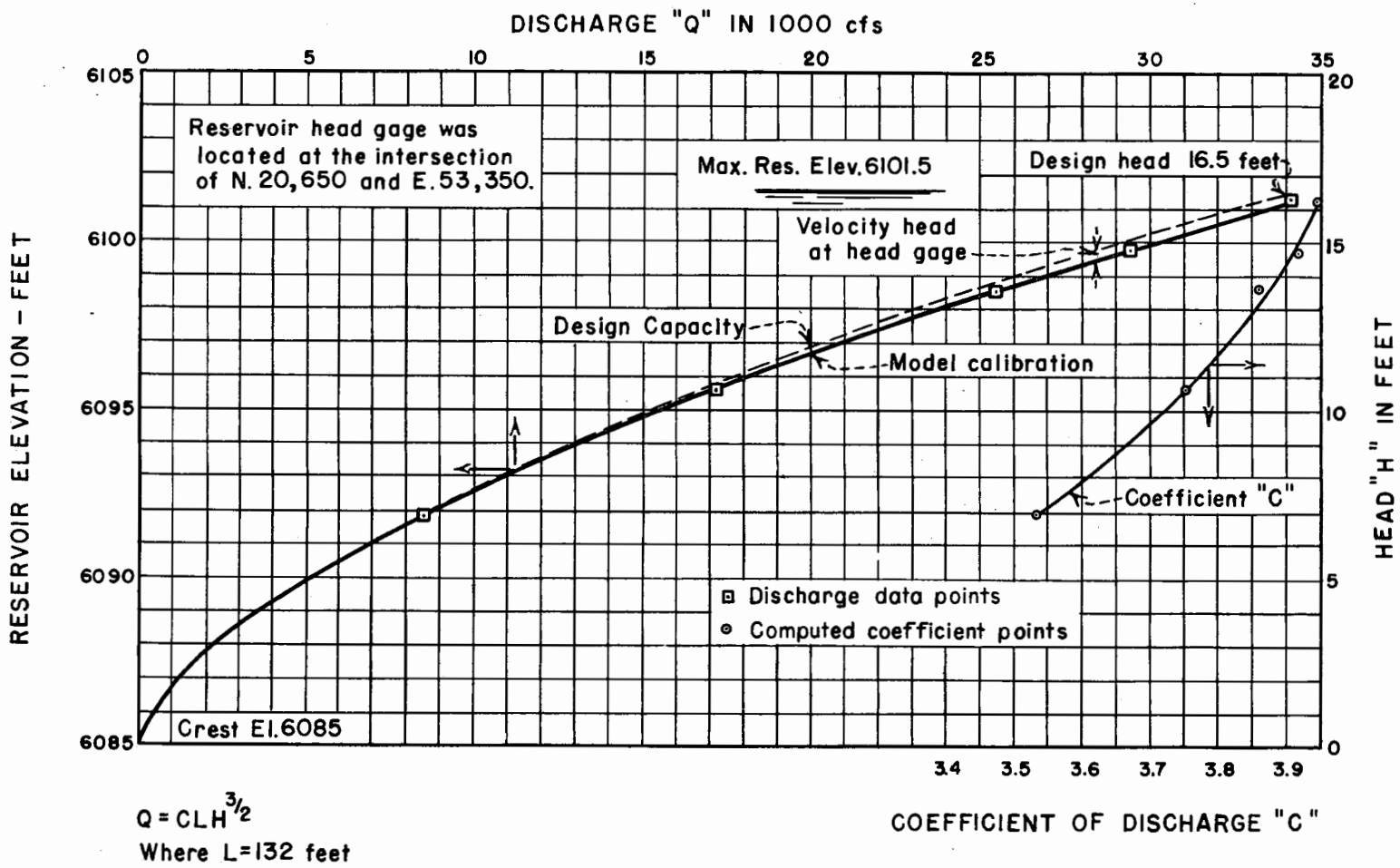
Pressures are above atmospheric and are plotted vertically upward using spillway profile as the datum.

SECTION ON ℄ OF SPILLWAY

NAVAJO DAM SPILLWAY

CREST PRESSURES ON CENTERLINE OF SPILLWAY

1:48 SCALE MODEL



$Q = CLH^{3/2}$

Where L=132 feet

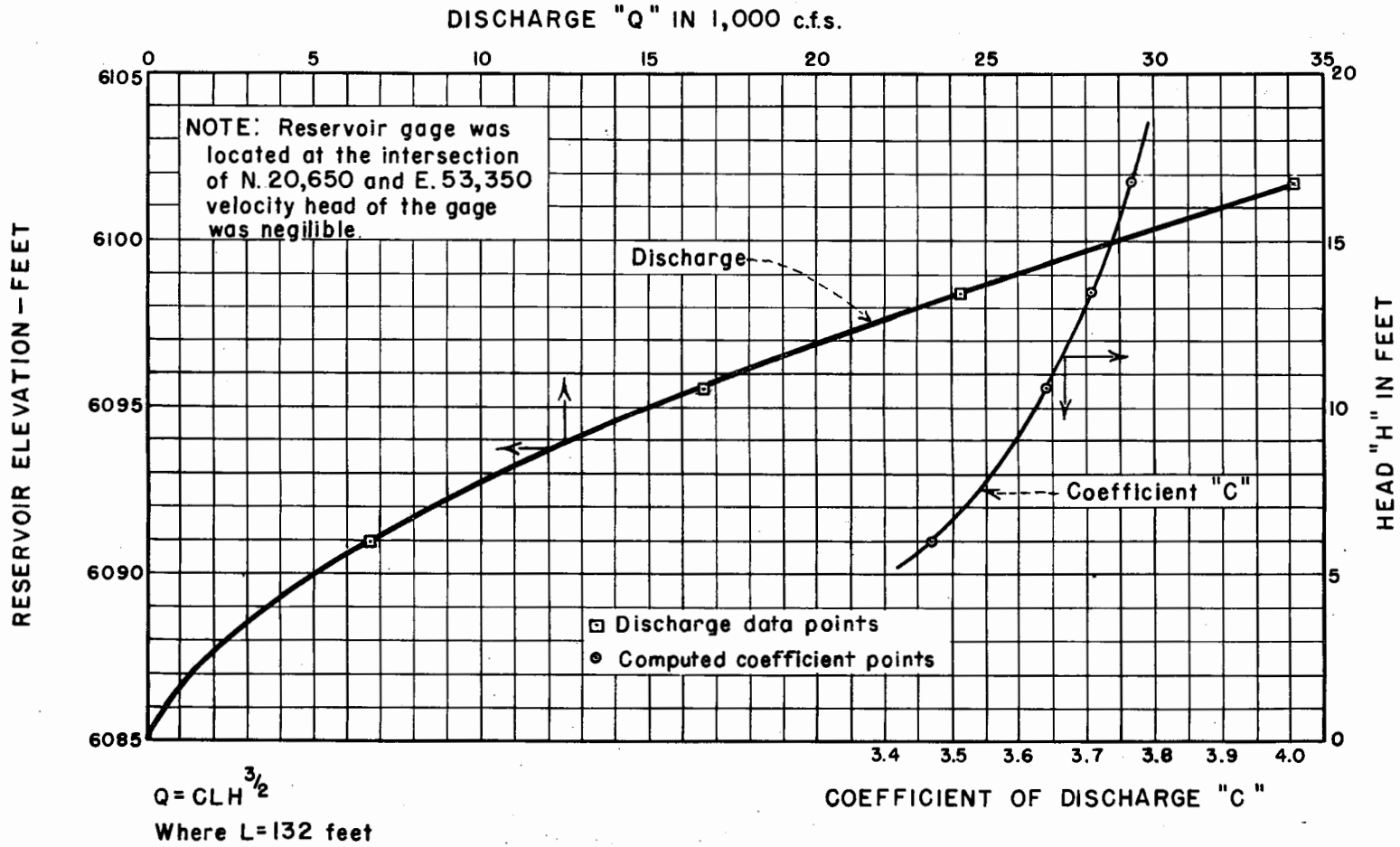
NAVAJO DAM SPILLWAY

SPILLWAY CAPACITY AND DISCHARGE COEFFICIENT CURVES

PRELIMINARY DESIGN

1:48 SCALE MODEL

FIGURE 20
REPORT HYD. 458



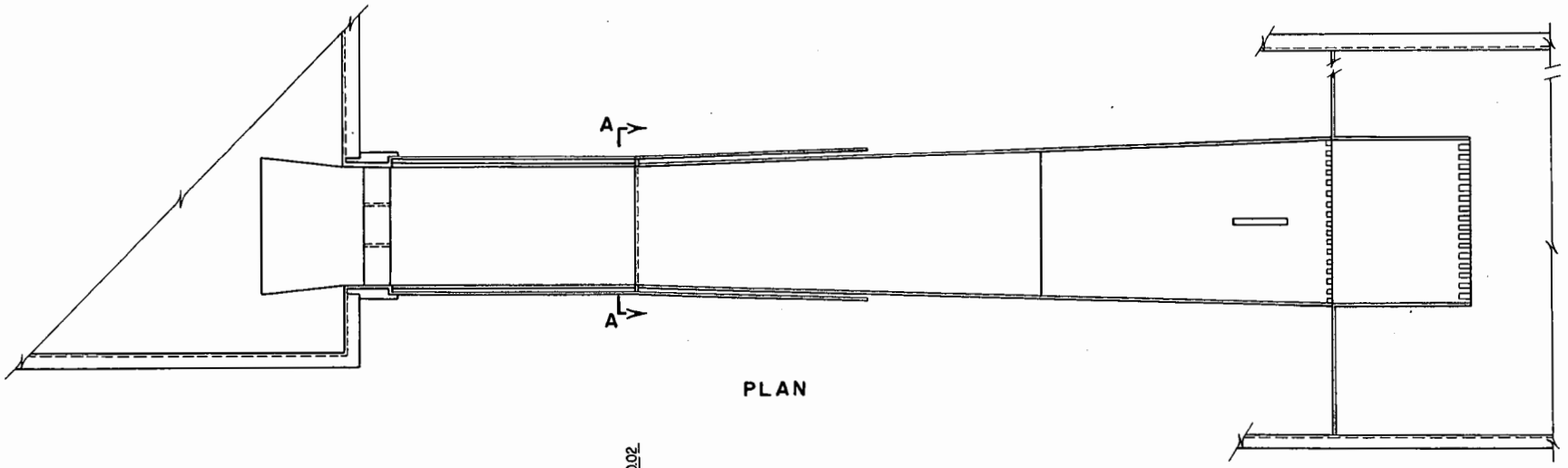
NAVAJO DAM SPILLWAY

SPILLWAY CAPACITY AND DISCHARGE COEFFICIENT CURVES

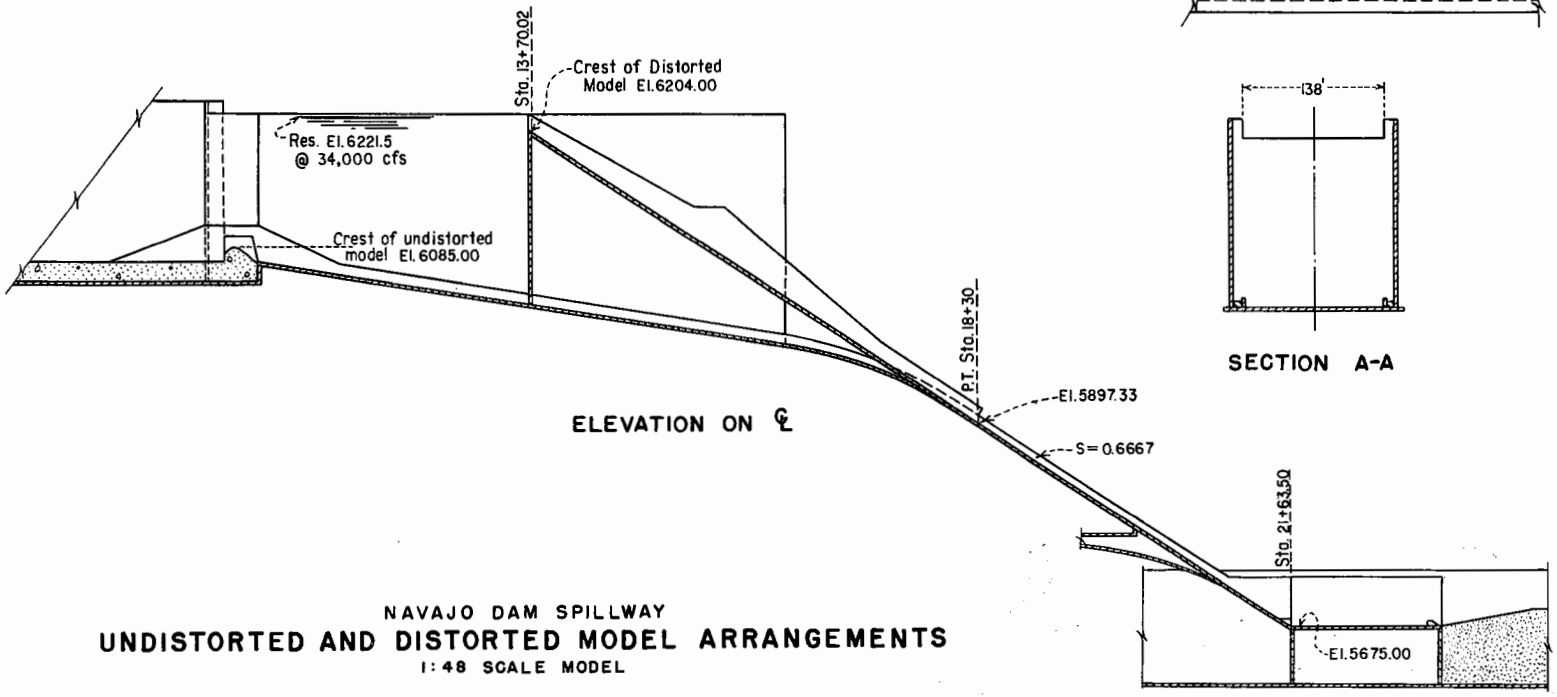
RECOMMENDED DESIGN

1 : 48 SCALE MODEL

FIGURE 21
REPORT HYD. 458



PLAN



ELEVATION ON ℄

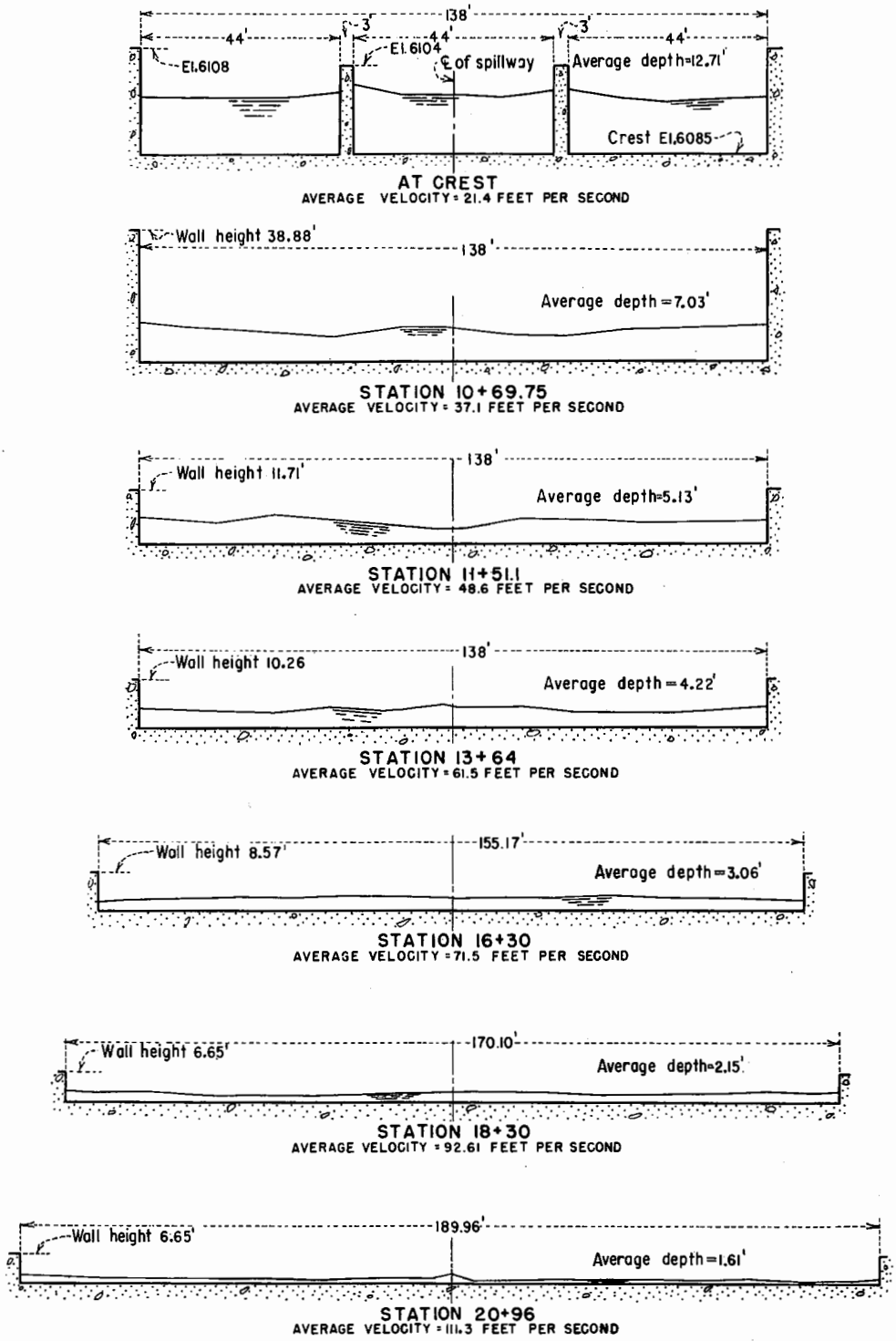
SECTION A-A

NAVAJO DAM SPILLWAY

UNDISTORTED AND DISTORTED MODEL ARRANGEMENTS

1:48 SCALE MODEL

FIGURE 22
REPORT HYD. 458



NOTE: Sections are shown looking downstream. Depths are normal to the chute floor. At sta. 13 + 64 and continuing downstream the depths were measured by use of an electronic circuit. See figure 24 for plotted velocities.

10 0 10 20 30 40
SCALE IN PROTOTYPE FEET

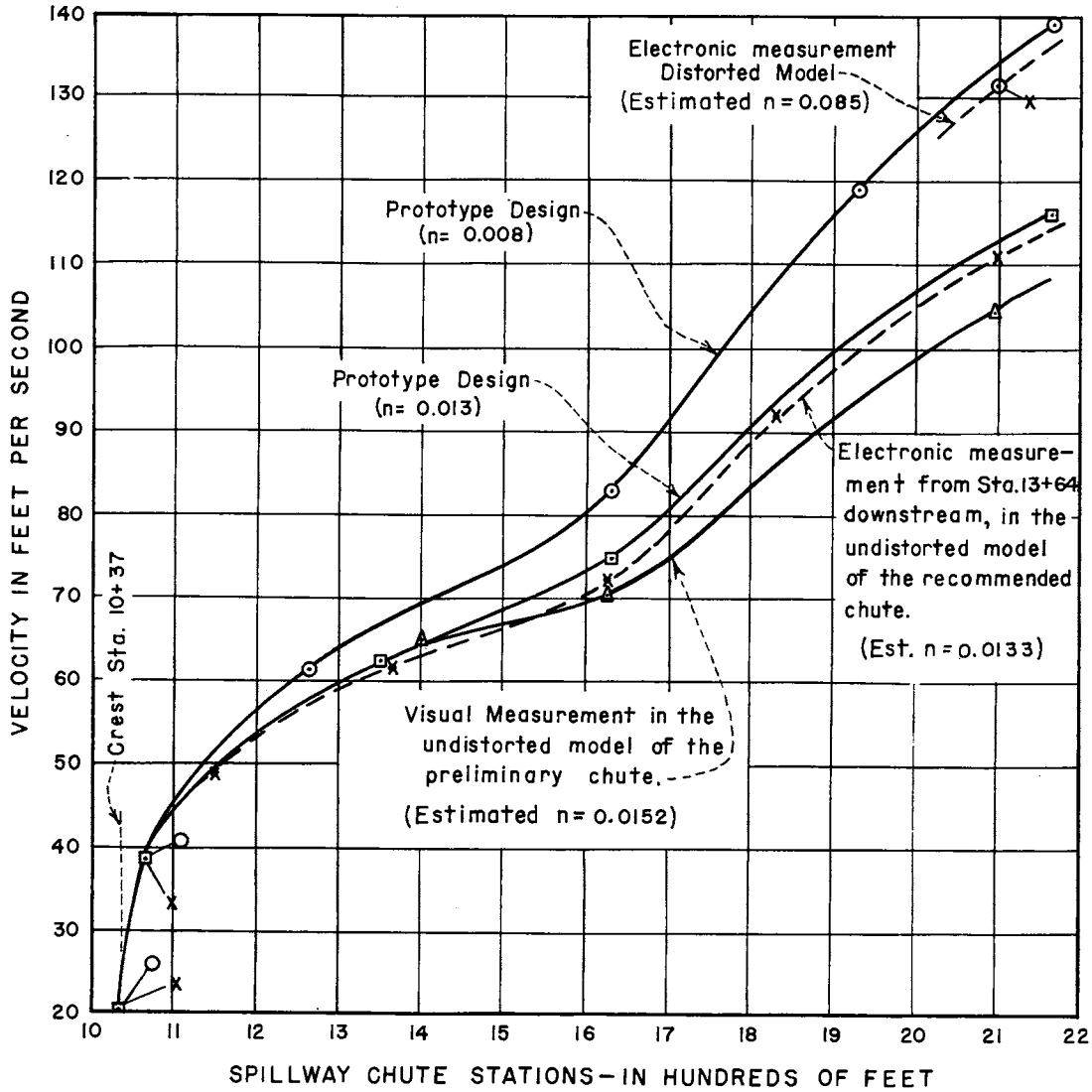
NAVAJO DAM SPILLWAY

WATER SURFACE PROFILES IN CHUTE-34,000 C.F.S.

RECOMMENDED DESIGN

1:48 SCALE MODEL

596

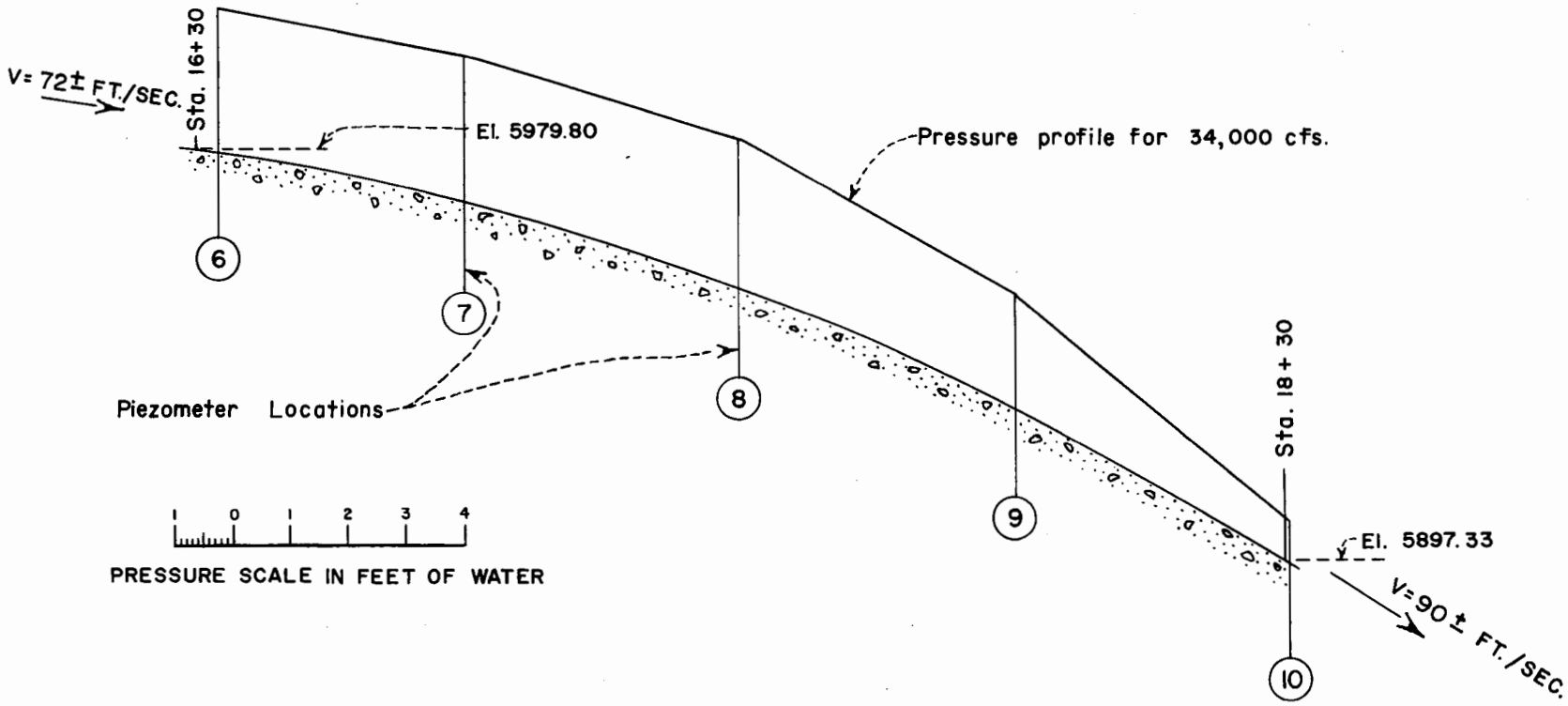


NAVAJO DAM SPILLWAY

DESIGN VELOCITIES VS MEASURED VELOCITIES IN CHUTE

34,000 C.F.S.

1 : 48 SCALE MODEL



Pressures are above atmospheric and are plotted vertically upward using chute profile as the datum.

SECTION ON ℄ OF SPILLWAY
IN UNDISTORTED MODEL OF PRELIMINARY CHUTE

NAVAJO DAM SPILLWAY

PRESSURES ON VERTICAL BEND IN CHUTE

1:48 SCALE MODEL

FIGURE 25
REPORT HYD. 458

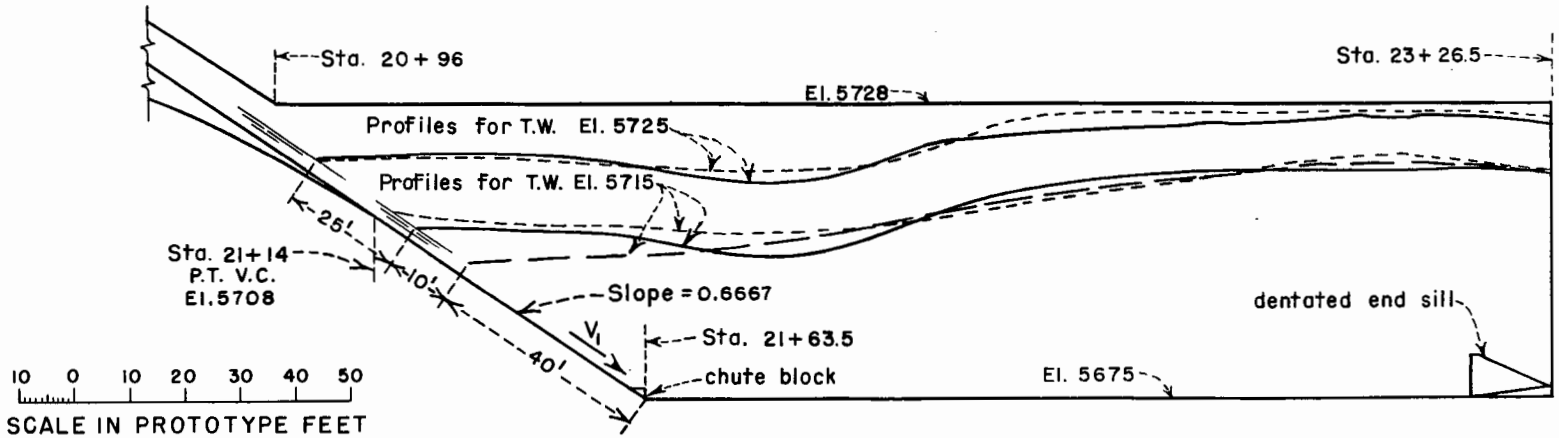
A. Spillway--2,000 cfs.
Auxiliary O.W.--2,000 cfs.
T.W. elevation 5711.

B. Spillway--3,400 cfs.
Auxiliary O.W.--2,000 cfs.
T.W. elevation 5711.

C. Same as in A.

NOTE: Recommended straight approach channel used with preliminary chute.

NAVAJO DAM SPILLWAY
Roll Waves in Chute and Stilling Basin
1:48 Scale Model



LONGITUDINAL SECTION THROUGH BASIN

——— PROFILE ALONG LEFT WALL FOR UNDISTORTED MODEL (V_1 = 110 FEET PER SECOND)
- - - - PROFILE ALONG RIGHT WALL FOR UNDISTORTED MODEL (V_1 = 110 FEET PER SECOND)
— — — AVERAGE CENTER LINE PROFILE FOR DISTORTED MODEL (V_1 = 135 FEET PER SECOND)

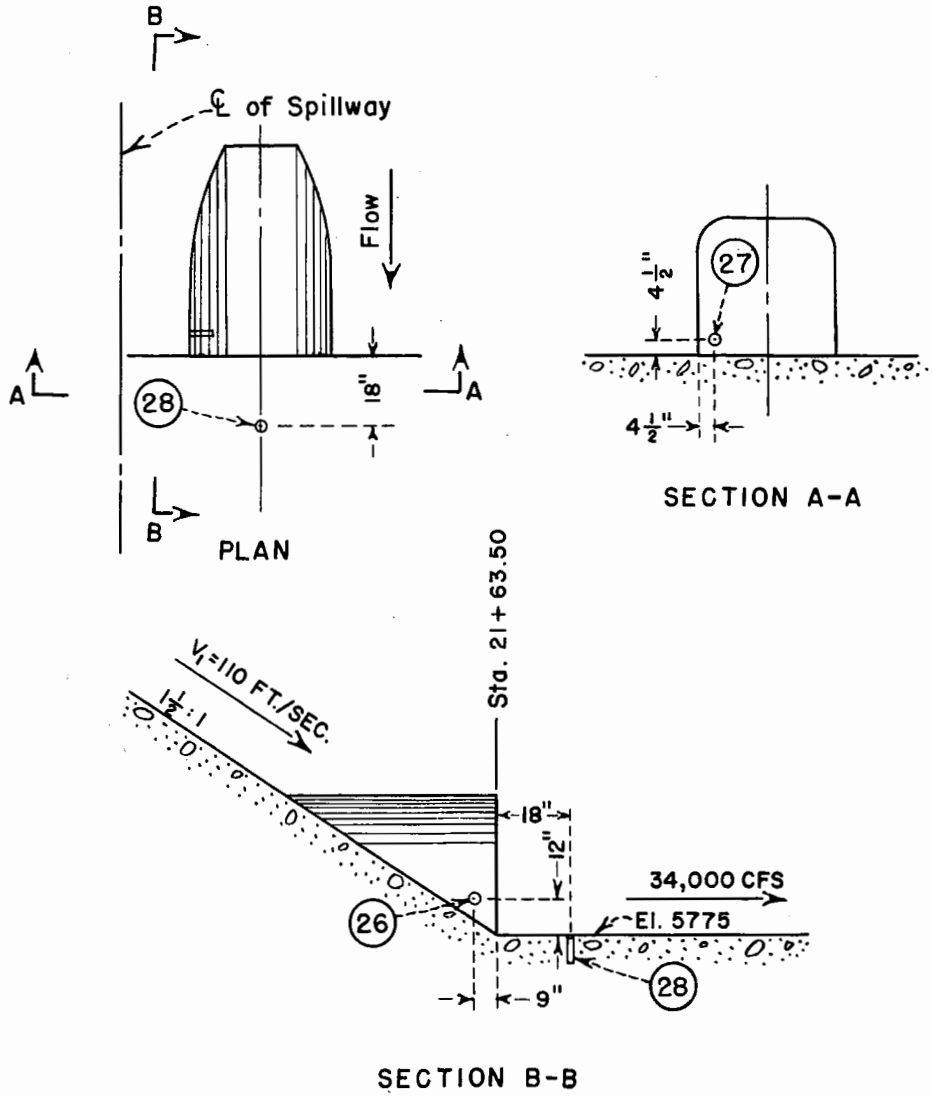
For tailwater elevation 5725 waves sometimes overtop left training wall from Sta. 22 + 24 to downstream end and right wall from Sta. 23 + 63.5 to downstream end. For tailwater elevation 5715 waves come to within four feet of top of walls.

NAVAJO DAM SPILLWAY

WATER SURFACE PROFILES IN RECOMMENDED STILLING BASIN
34,000 C.F.S.

1:48 SCALE MODEL

FIGURE 27
REPORT HYD. 458



PIEZOMETER	PRESSURES IN FT. OF WATER	
	T.W. El. 5711	T.W. El. 5723
26	+32.6	+40.5
27	+14.3	+16.0
28	+34.0	+41.0

NAVAJO DAM SPILLWAY

CHUTE BLOCK PRESSURES

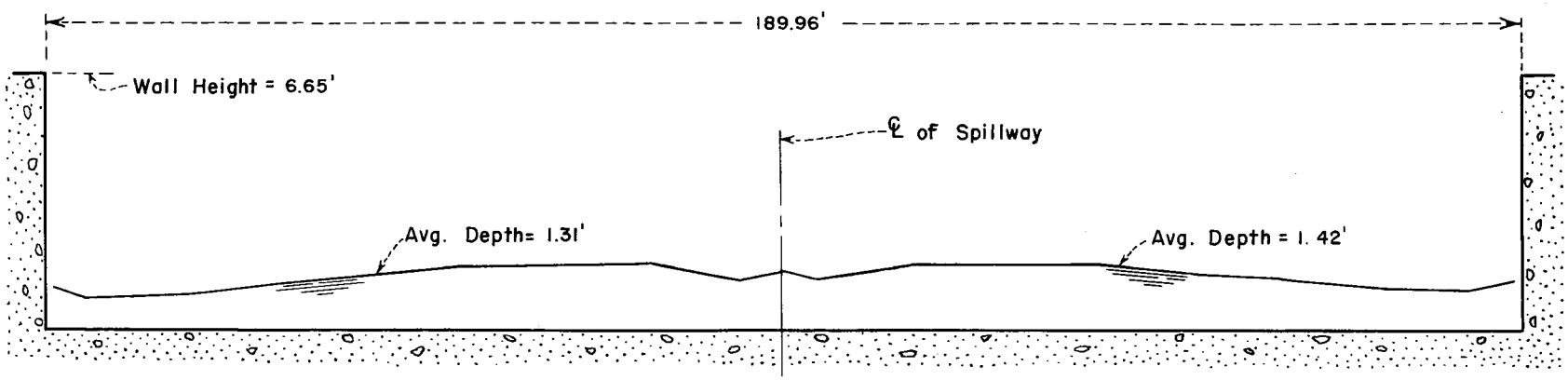
1 : 48 SCALE MODEL

A. Spillway crest raised 119 feet to increase velocity entering basin.

B. 34,000 cfs, T.W. elevation 5714.5
Crest elevation 6204, Res elevation 6221.5
Crest length 138 feet

NOTE: Counterforts are installed behind stilling basin training walls.

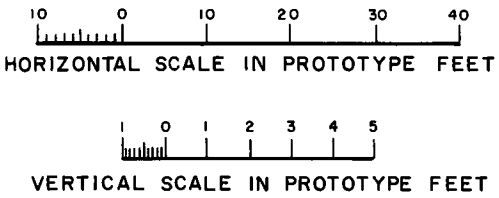
NAVAJO DAM SPILLWAY
Distorted Model Views
1:48 Scale Model



STATION 20+96

AVERAGE VELOCITY = 131.48 FEET PER SECOND

Note: Section is shown looking downstream. Depths measured normal to chute floor.

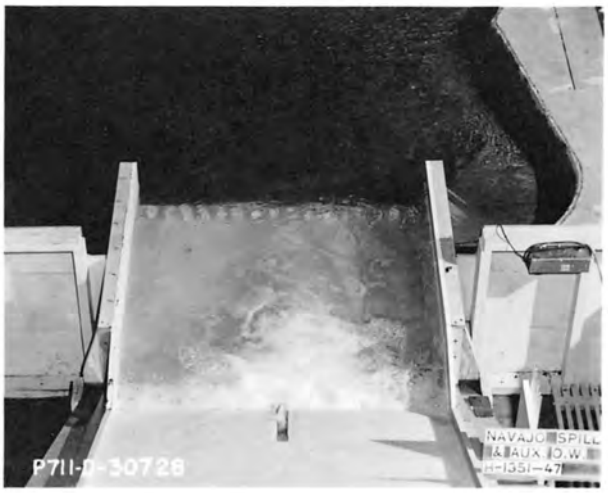


NAVAJO DAM SPILLWAY

WATER SURFACE CROSS SECTION PROFILE -34,000 C.F.S.

DISTORTED MODEL

1:48 SCALE MODEL



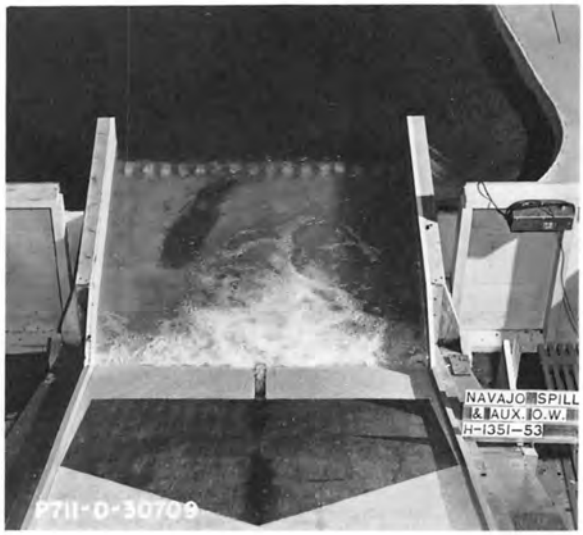
A. 8,500 cfs, T.W. elevation 5714.

B. 17,000 cfs, T.W. elevation 5716.5.

C. 34,000 cfs, T.W. elevation 5719.5.

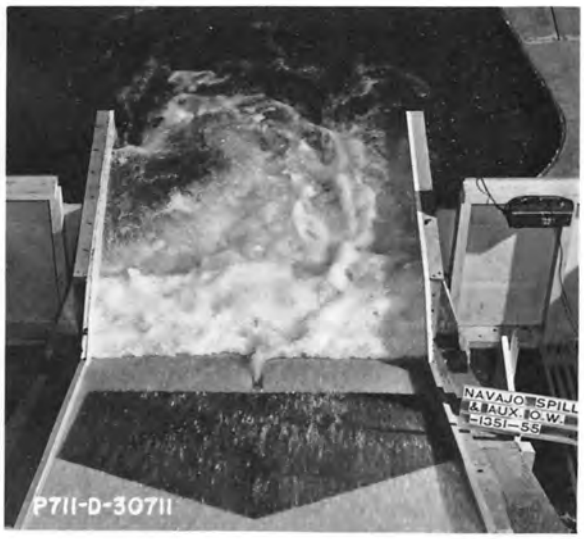
D. Erosion after 1 hour operation of the model at 34,000 cfs.

NAVAJO DAM SPILLWAY
Stilling Basin Performance for Distorted Model
1:48 Scale Model



A. 8,500 cfs, T.W. elevation 5714.

B. 17,000 cfs, T.W. elevation 5716.5.

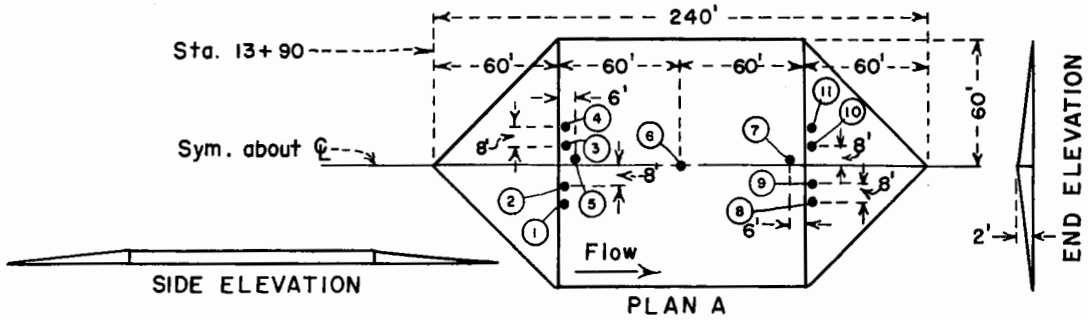


C. 34,000 cfs, T.W. elevation 5719.5.

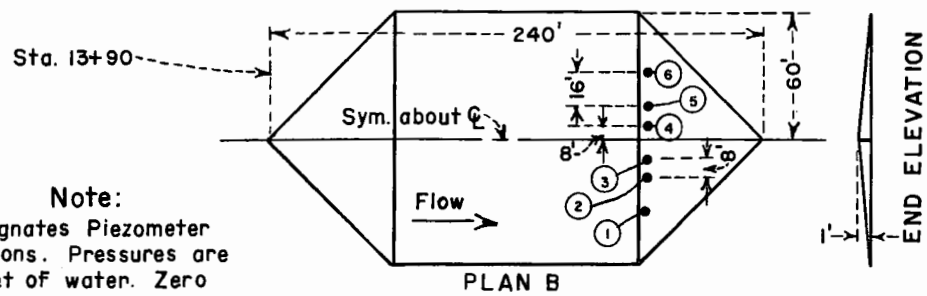
D. Erosion after 1 hour operation of the model at 34,000 cfs.

Hump is 4 ft High by 176 ft Wide by 216 ft Long

NAVAJO DAM SPILLWAY
Stilling Basin Performance for Distorted Model With Hump
1:48 Scale Model

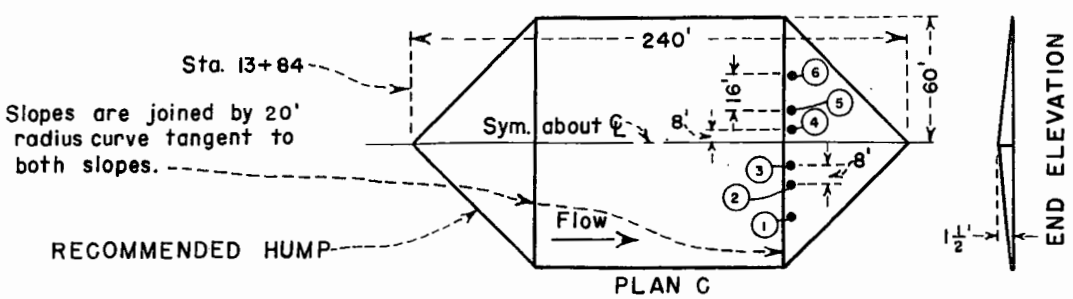


DISCHARGE CFS	PIEZOMETER PRESSURES										
	1	2	3	4	5	6	7	8	9	10	11
34,000	-5.8	-6.7	-4.8	-4.3	+2.9	+3.8	+4.3	-13.0	-8.6	-7.4	-7.7
17,000	-3.8	-5.3	-4.1	-2.9	+2.2	+2.5	+3.6	-8.6	-6.0	-5.5	-5.4



Note:
(NO) Designates Piezometer locations. Pressures are in feet of water. Zero pressure is atmospheric.

DISCHARGE CFS	PIEZOMETER PRESSURES					
	1	2	3	4	5	6
34,000	-2.0	-2.5	+3.5	+2.0	0.0	-3.0
17,000	1.0	-1.5	+2.0	+1.5	0.0	-2.5
8,500	-0.3	-1.0	+1.5	+1.3	-0.3	-1.5



DISCHARGE CFS	PIEZOMETER PRESSURES					
	1	2	3	4	5	6
34,000	-2.8	-0.3	+1.3	+3.5	+1.3	-1.5
17,000	-2.3	-0.3	+1.0	+2.5	+0.8	-1.5
8,500	-1.0	0.0	+0.8	+1.8	+0.8	-0.8

NAVAJO DAM SPILLWAY

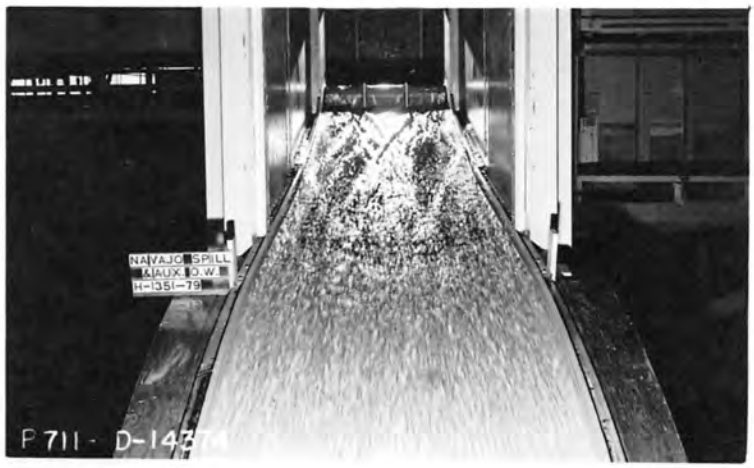
PRESSURES ON TESTED HUMPS

1:48 SCALE MODEL

Figure 34
Report HYD 458

A. Hump 1-1/2 feet high by 120 feet wide by 240 feet long installed in undistorted model.

B. 34,000 cfs.



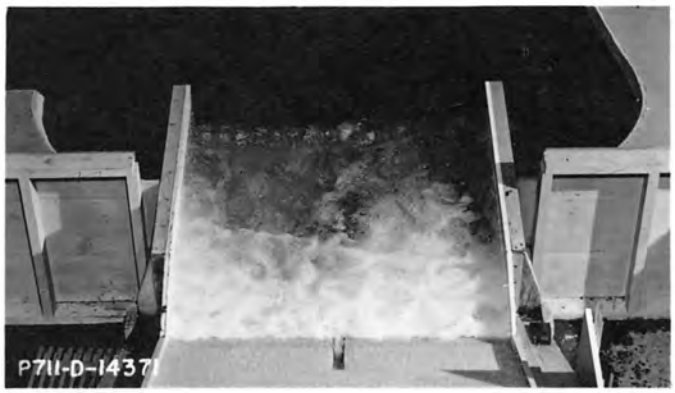
C. 34,000 cfs.

NAVAJO DAM SPILLWAY
Flow in Recommended Chute
1:48 Scale Model

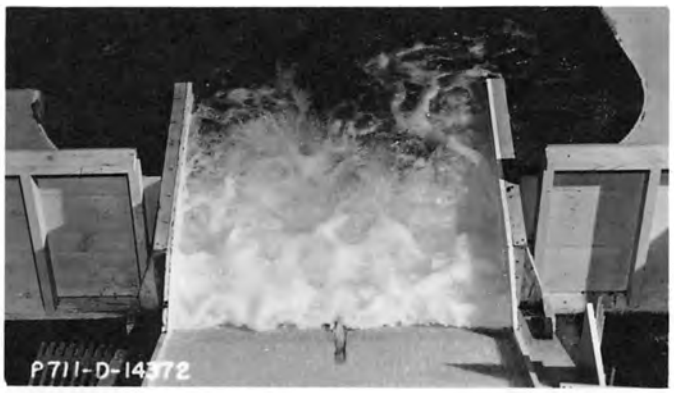
Figure 35
Report HYD 458

A. Recommended hump 1-1/2 ft high by 60 ft by 240 ft.

B. 8,500 cfs
T.W. elevation 5708.

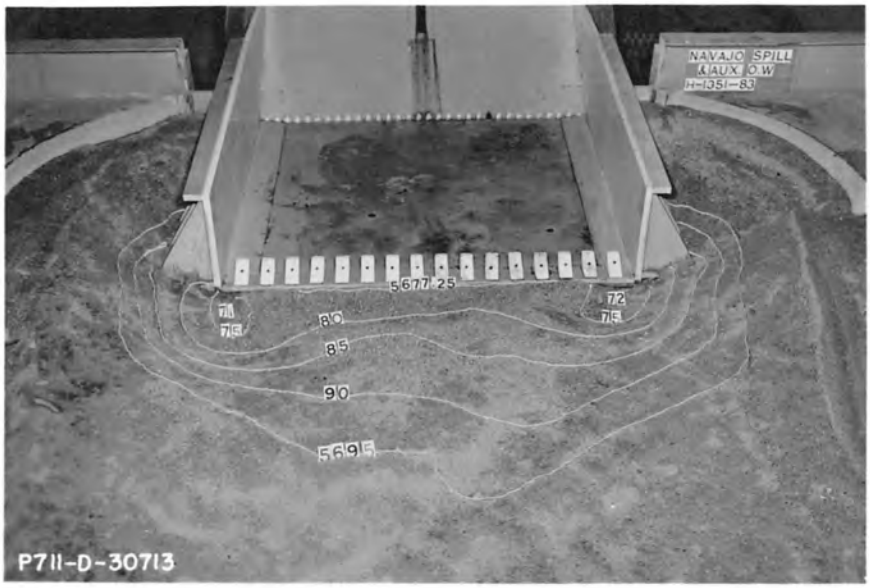


C. 17,000 cfs
T.W. elevation 5716.

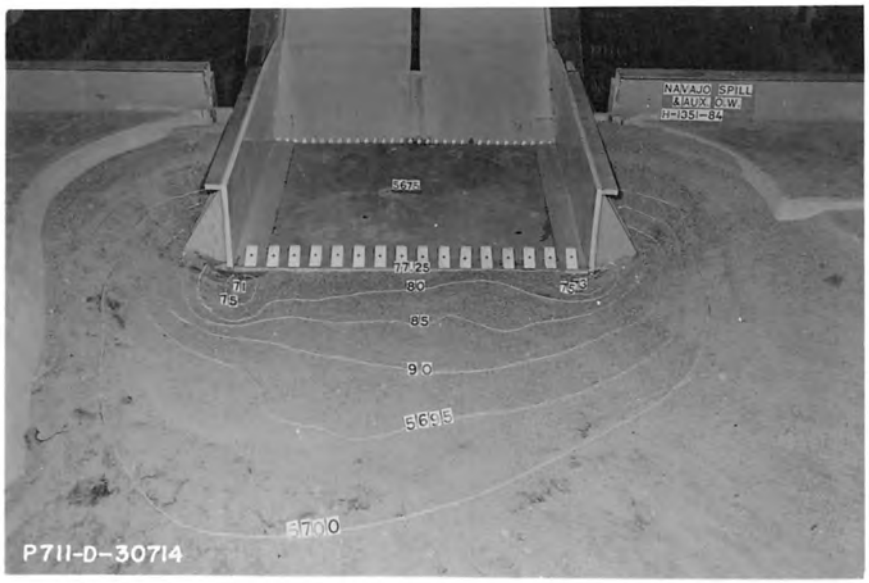


D. 34,000 cfs
T.W. elevation 5719.

NAVAJO DAM SPILLWAY
Stilling Basin Performance--Recommended Chute and Basin
1:48 Scale Model



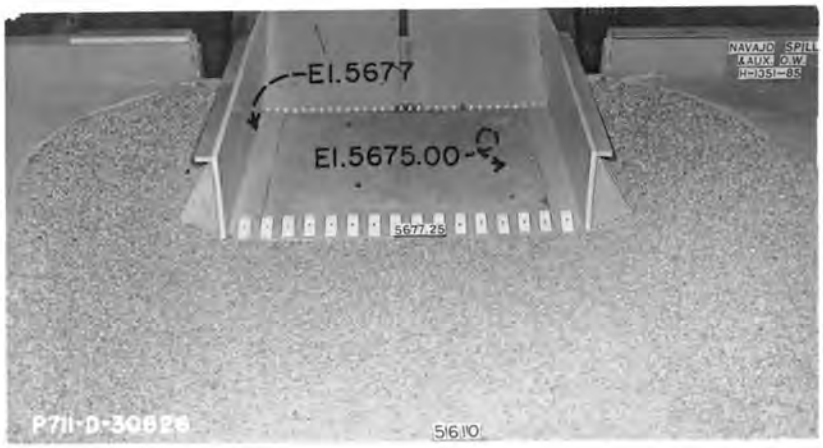
Erosion for tailwater elevation 5723.



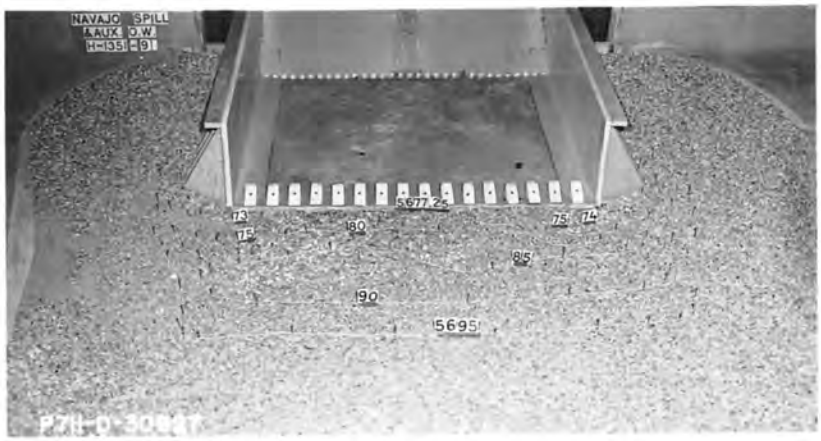
Erosion for tailwater elevation 5715.

NOTE: Discharge 34,000 cfs; erosion test duration 1 hour model time recommended spillway approach channel and chute; counterforts on basin walls.

NAVAJO DAM SPILLWAY
Erosion Tests--Preliminary Basin Without Riprap
1:48 Scale Model



A. Erodible bed before each test.

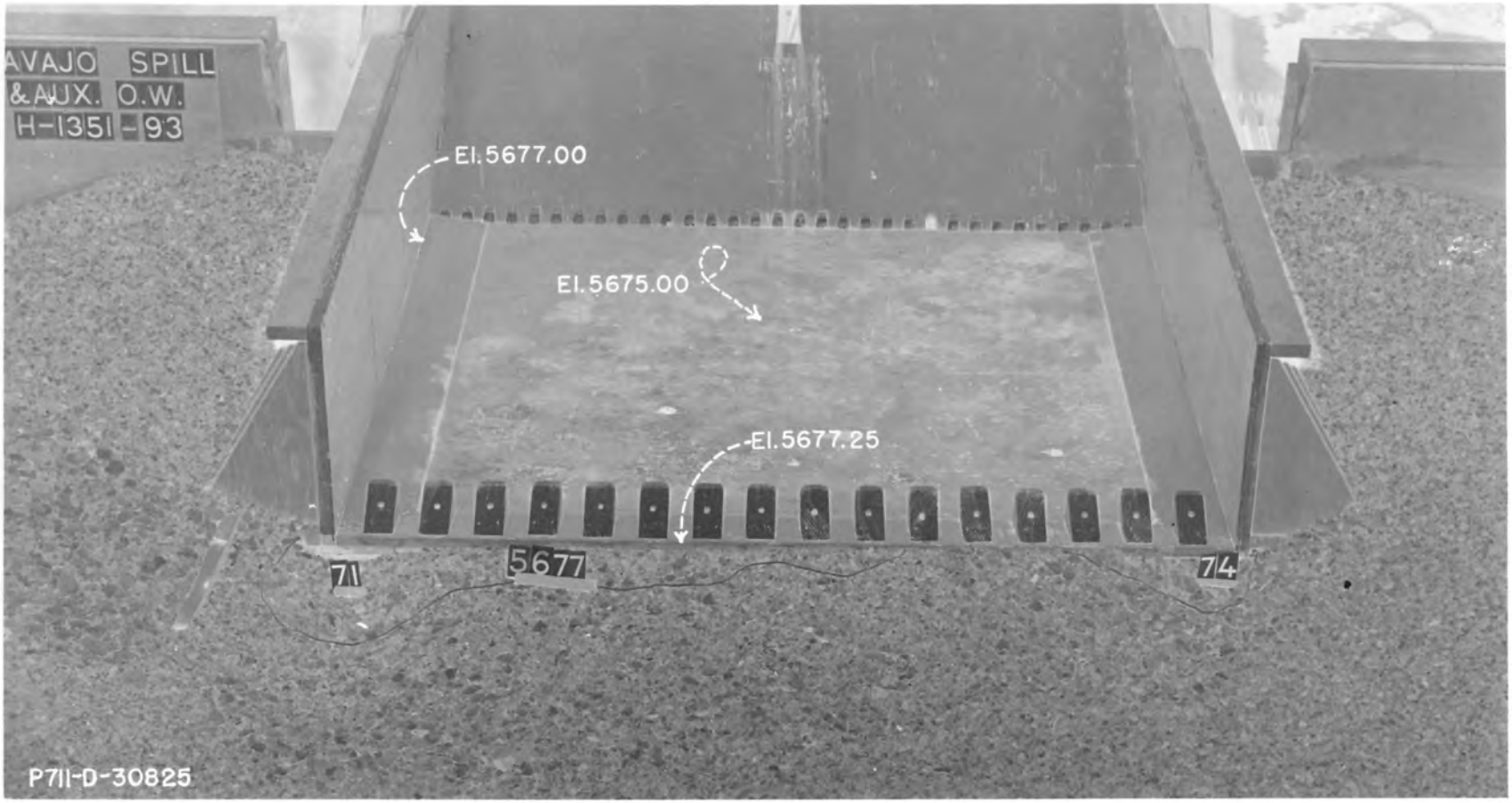


B. 4-1/2-hour test
34,000 cfs
tailwater elevation 5723

C. 4-1/2-hour test
34,000 cfs
tailwater elevation 5715

NOTE: Erodible bed was a sand bed riprapped with a 3/4-inch layer of 1/2-inch gravel to represent the proposed 3-foot layer of riprap composed of 24-inch stones.

NAVAJO DAM SPILLWAY
Erosion Tests--Preliminary Basin With Riprap
1:48 Scale Model



Scour after 4-1/2 hour test, 34,000 cfs, tailwater elevation 5723.

NOTE: Test conditions as described in Figure 37.

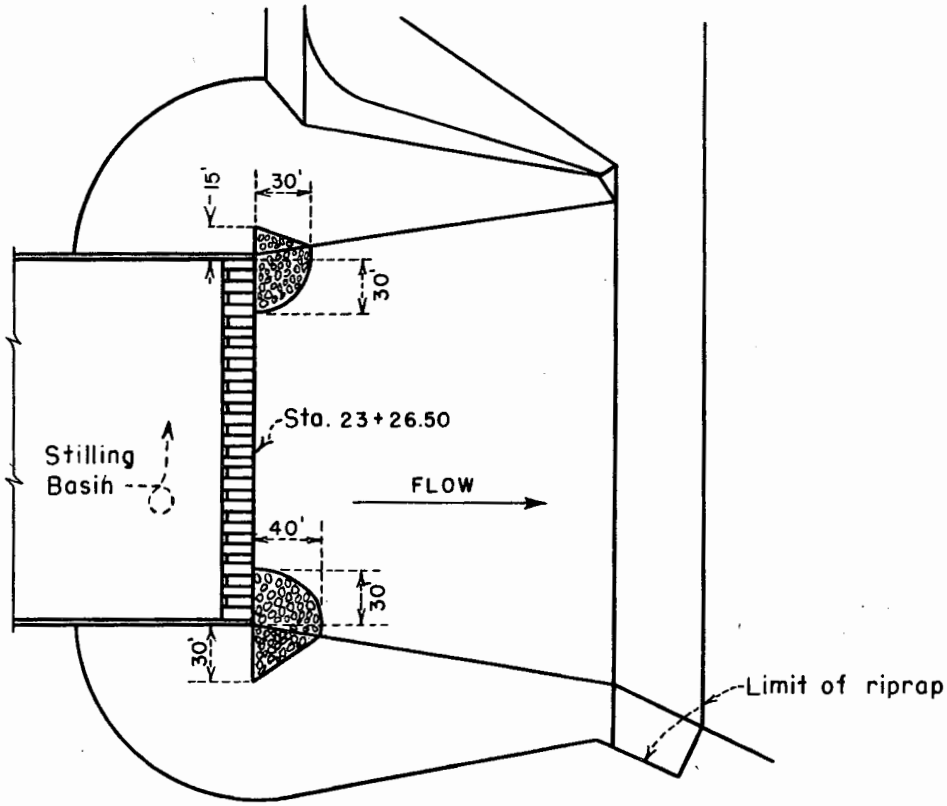
NAVAJO DAM SPILLWAY
Erosion Test--Preliminary Basin
With Riprap and Stabilized Right Bank
1:48 Scale Model

A. Before test.

B. Scour after 4-1/2-hour test 34,000 cfs, tailwater elevation 5715.

NOTE: Test conditions as described in Figure 37. Dark areas are larger stones up to 4 feet prototype size.

NAVAJO DAM SPILLWAY
Erosion Test Using Larger Riprap
1:48 Scale Model



In the areas indicated at the corners of the stilling basin, it is recommended that extra heavy riprap be used. The size of the stones used should be from 2 to 4 feet in dia. or larger.

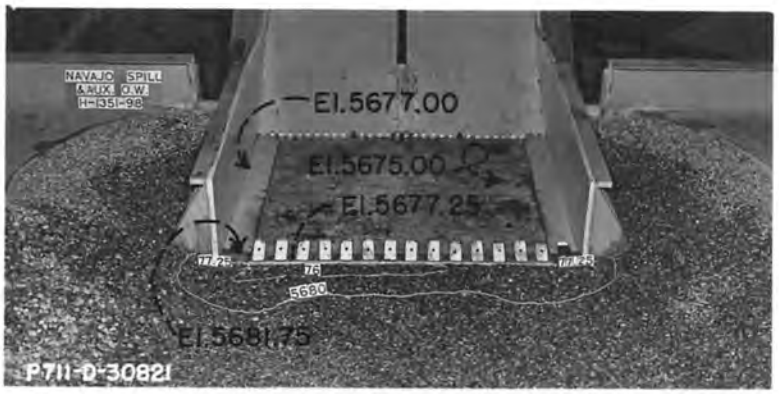
NAVAJO DAM SPILLWAY

RECOMMENDED RIPRAP ARRANGEMENT

1:48 SCALE MODEL

A. Standard 2:1 end sill (see HYD 399) except 4.48:1 at walls of basin.

B. Preliminary end sill modified at basin walls to provide 6:1 slope.

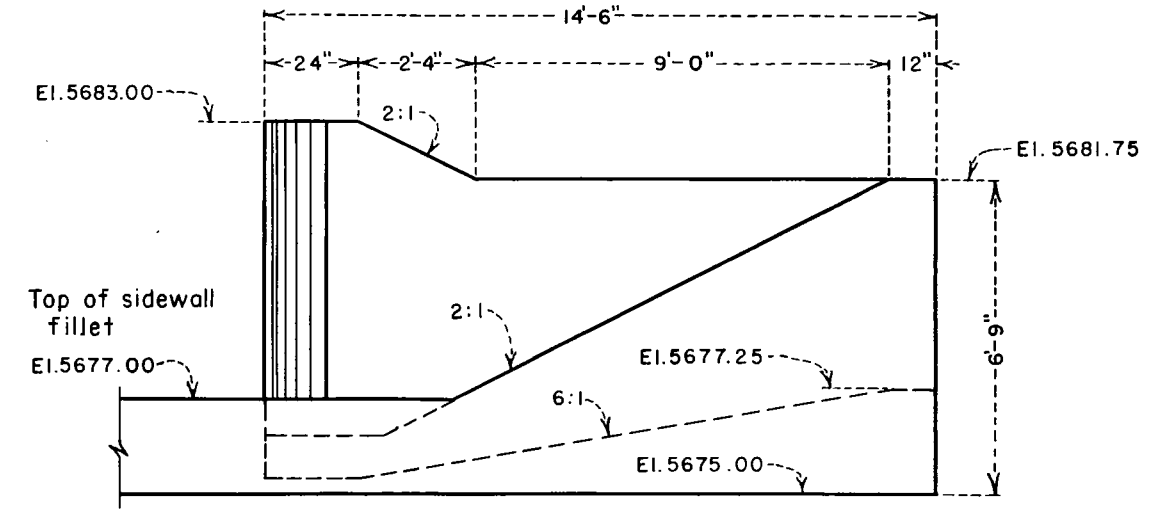


C. Preliminary end sill modified at the basin walls to provide 2:1 slope.

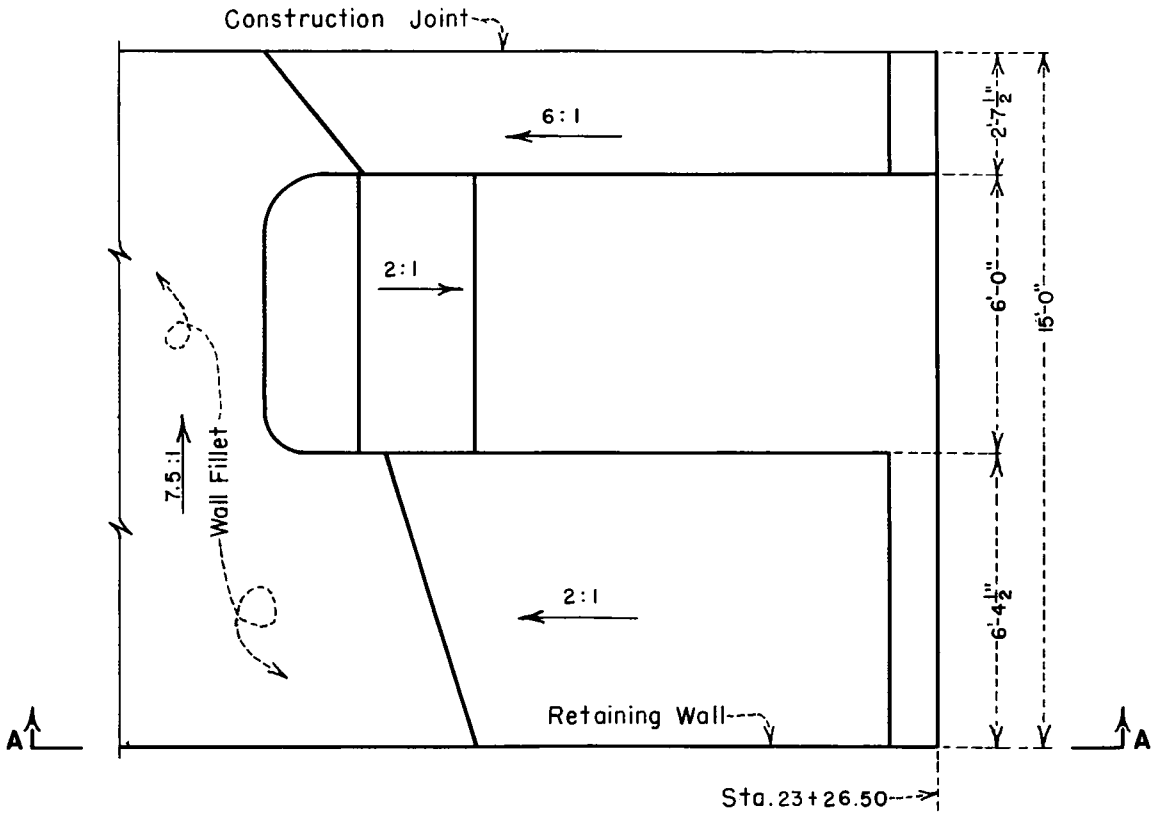
NOTE: 4-1/2-hour tests, 34,000 cfs, T.W. elevation 5723. Test conditions described in Figure 37.

NAVAJO DAM
Erosion Tests With Modified End Sill
1:48 Scale Model

FIGURE 42
REPORT HYD. 458



ELEVATION A-A



PLAN

NAVAJO DAM SPILLWAY

RECOMMENDED END SILL MODIFICATION

1:48 SCALE MODEL

596

A. Tailwater elevation 5723.

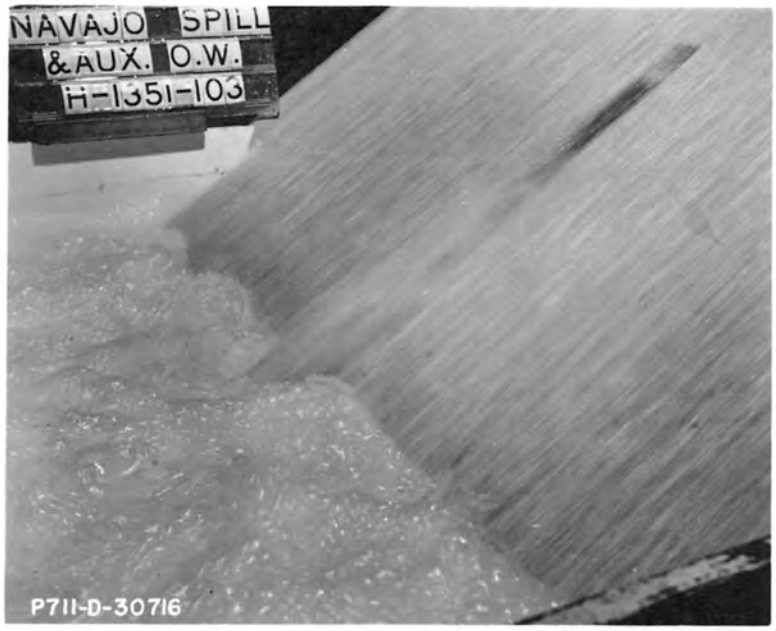
B. Tailwater elevation 5715.

NOTE: Recommended sill is the preliminary 6:1 sloping sill with the slope in each end slot increased to 2:1.

4-1/2-hour tests, 34,000 cfs

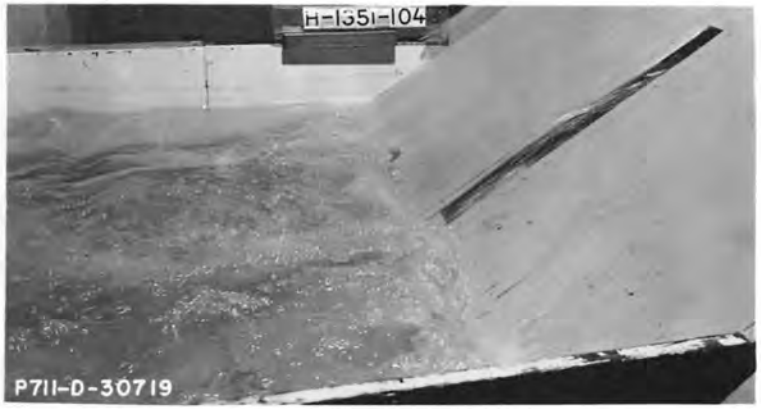
NAVAJO DAM SPILLWAY
Erosion Tests With Recommended End Sill
1:48 Scale Model

A. Spillway 34,000 cfs.
Auxiliary outlet works no flow.
Tailwater elevation 5719.



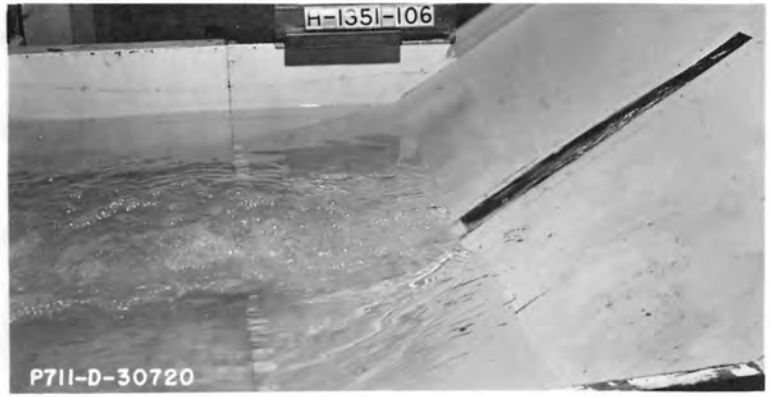
B. Spillway 32,000 cfs.
Auxiliary outlet works 2,000 cfs.
Tailwater elevation 5719.

NAVAJO DAM SPILLWAY
Spillway Discharging Over Auxiliary Outlet Works Junction
1:48 Scale Model



A. Auxiliary outlet works 2,000 cfs.
Spillway 2,000 cfs, T.W. elevation 5710.

B. Same as A.

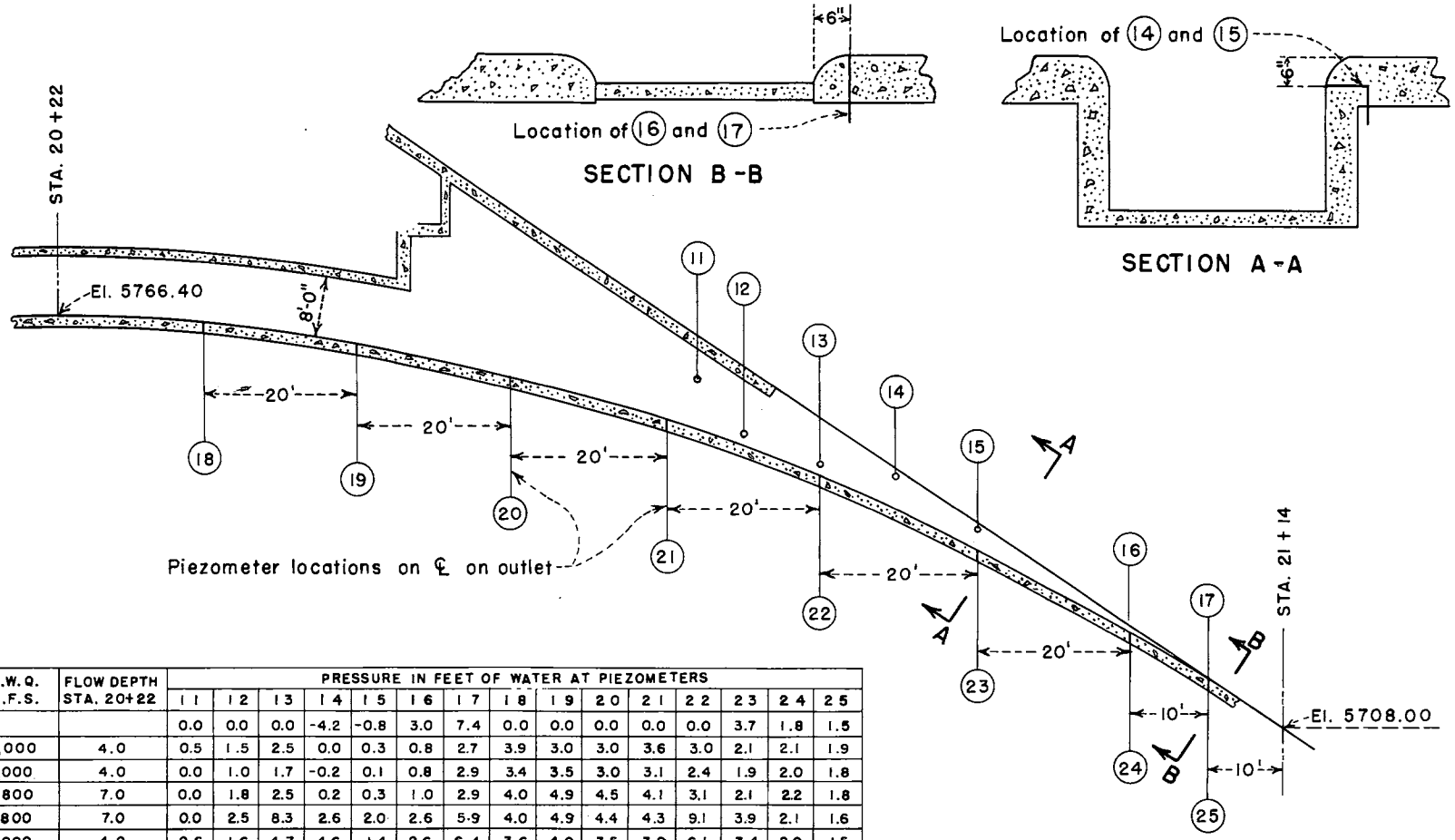


C. Auxiliary outlet works 1,800 cfs.
Portal depth 7 ft 0 in.
Spillway no flow, T.W. elevation 5709.

D. Auxiliary outlet works 2,000 cfs.
Portal depth 4 ft 0 in.
Spillway no flow, T.W. elevation 5709.

NAVAJO DAM SPILLWAY
Auxiliary Outlet Works Discharging
1:48 Scale Model

Figure 45
Report HYD 458



SPILLWAY Q C.F.S.	O.W.Q. C.F.S.	FLOW DEPTH STA. 20+22	PRESSURE IN FEET OF WATER AT PIEZOMETERS														
			11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
34,000			0.0	0.0	0.0	-4.2	-0.8	3.0	7.4	0.0	0.0	0.0	0.0	0.0	3.7	1.8	1.5
2,000	2,000	4.0	0.5	1.5	2.5	0.0	0.3	0.8	2.7	3.9	3.0	3.0	3.6	3.0	2.1	2.1	1.9
	2,000	4.0	0.0	1.0	1.7	-0.2	0.1	0.8	2.9	3.4	3.5	3.0	3.1	2.4	1.9	2.0	1.8
	1,800	7.0	0.0	1.8	2.5	0.2	0.3	1.0	2.9	4.0	4.9	4.5	4.1	3.1	2.1	2.2	1.8
32,200	1,800	7.0	0.0	2.5	8.3	2.6	2.0	2.6	5.9	4.0	4.9	4.4	4.3	9.1	3.9	2.1	1.6
32,000	2,000	4.0	0.6	1.6	4.7	4.6	1.4	2.6	6.4	3.6	4.0	3.5	3.9	6.1	3.4	2.0	1.5

All Pressures are atmospheric unless noted.
Zero pressure is atmospheric pressure.

Note: Recomended hump in chute

NAVAJO DAM SPILLWAY

SPILLWAY AND OUTLET WORKS JUNCTION PRESSURES

1: 48 SCALE MODEL

FIGURE 46
REPORT 458

GPO 852355