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HYDRAULIC MODEL STUDIES FOR PALMETTO BEND DAM SPILLWAY

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16. ABSTRACT

Hydraulic model studies were made to help design the spillway for the Palmetto Bend Dam in Texas. The 141-m (464-ft) wide spillway, with the flow controlled by 12 radial gates, was designed to pass a maximum flood of 6230 m^3/s (220 000 ft^3/s). The approach channel, spillway, and exit channel were flow features studied in the 1:100 scale model. A dike placed on the left side of the approach channel greatly improved flow entering the spillway; a dike on each side of the exit channel decreased eddy size and scouring action occurring at each downstream corner of the stilling basin. Floor block appurtenances had the most significant effect for increasing basin energy dissipation. Because of the low Froude number (3.5) for the stilling basin, further studies were made with a 1:30 scale sectional model to obtain optimum appurtenance dimensions. Spillway discharge curves were obtained and pressure measurements made which showed a very small likelihood that cavitation will occur on the floor blocks. The report gives a detailed description of the investigation.

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Denver, Colorado

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PURPOSE

Hydraulic studies were made of the Palmetto Bend Dam spillway on 1:100 and 1:30 scale models to aid in designing the prototype structure.

INTRODUCTION

Palmetto Bend Dam is an earthfill dam under construction in Texas near the Gulf of Mexico, on the Navidad River, just upstream from the confluence of the Navidad and Lavaca Rivers (fig. 1). The damsite is upstream from a river bend, and the spillway is located on the right side where the topography rises 12 m (40 ft) above the river. Hydraulic features studied in the model were: the approach channel to the spillway, the spillway, and the exit channel from the spillway (fig. 1). Detailed dimensions of these hydraulic features are given on figures 2 and 3.

Special emphasis was given to the stilling basin because of the high discharge and low-head flow. The Bureau of Reclamation has relatively little experience with low Froude number (3.5) basins of 27.9 to 46.5 $(m^3/s)/m$ [300 to 500 $(ft^3/s)/ft$] unit discharges. Therefore, two different scale models (a 1:100 scale overall model and a 1:30 scale sectional model) were used.

CONCLUSIONS

1. A curved dike, placed on the left side of the approach channel upstream from the dam and extending into the reservoir, greatly improved flow at the spillway (fig. 5d).

Note: The data presented in this report were measured and computed using U.S. customary units and converted to SI metric units.

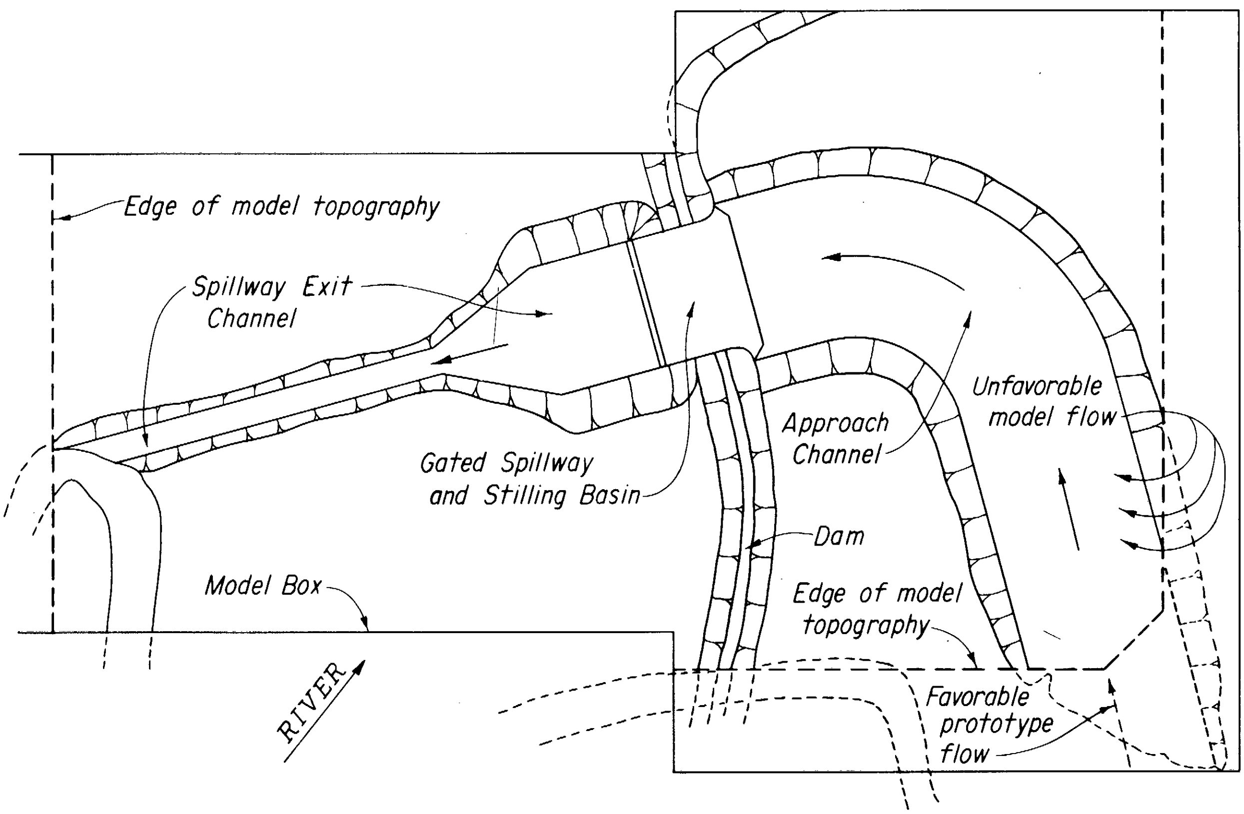

Figure 1.–Plan view of the 1:100 scale model.

2. For this low Froude number stilling basin, floor blocks had the most significant effect in increasing the energy dissipation (fig. 8e).

3. A dentated end sill reduced the erosive force downstream from the stilling basin better than a solid triangular end sill.

4. Model tests showed that a stilling basin floor elevation 1.2 m (4 ft) higher than the initial design elevation still provided satisfactory energy dissipation.

5. Dikes 122 m (400 ft) long, one on each side of the spillway exit channel, improved flow conditions at the downstream corners of the stilling basin. The size of the eddy on the right and the strength of the lateral undercurrent at the corner side of the stilling basin were substantially reduced by the dikes (fig. 12).

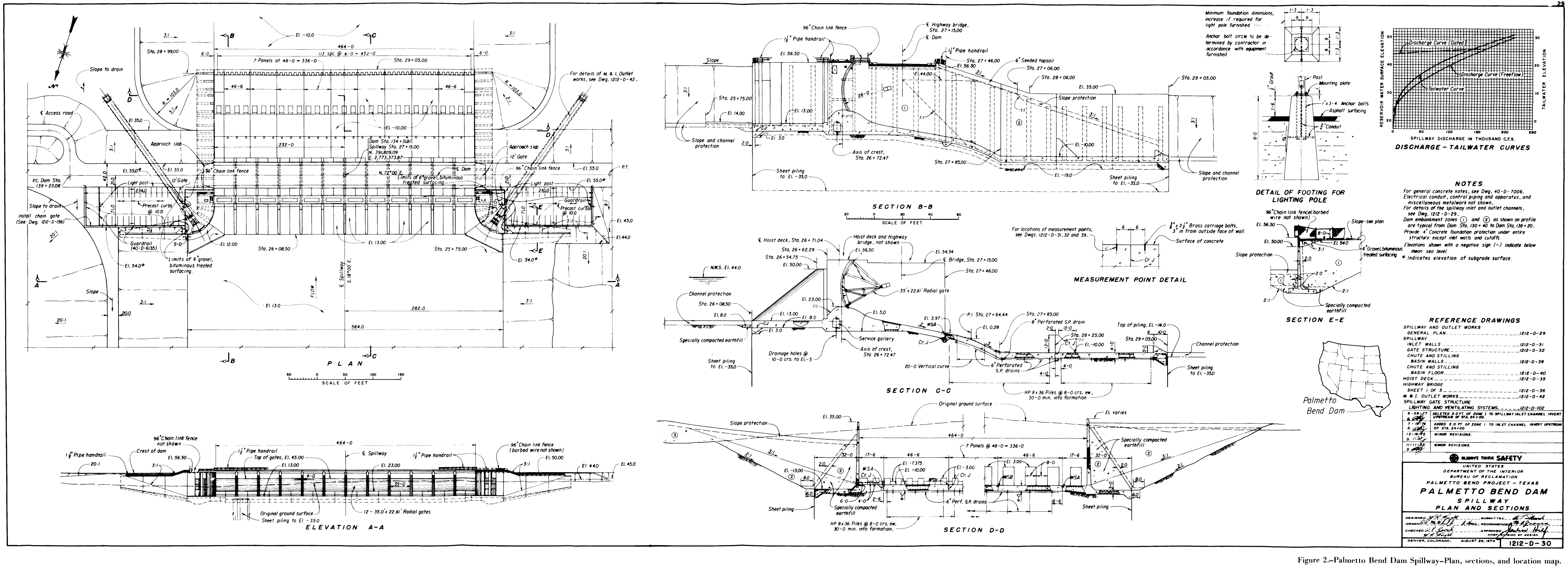

Figure 2.–Palmetto Bend Dam Spillway–Plan, sections, and location map.

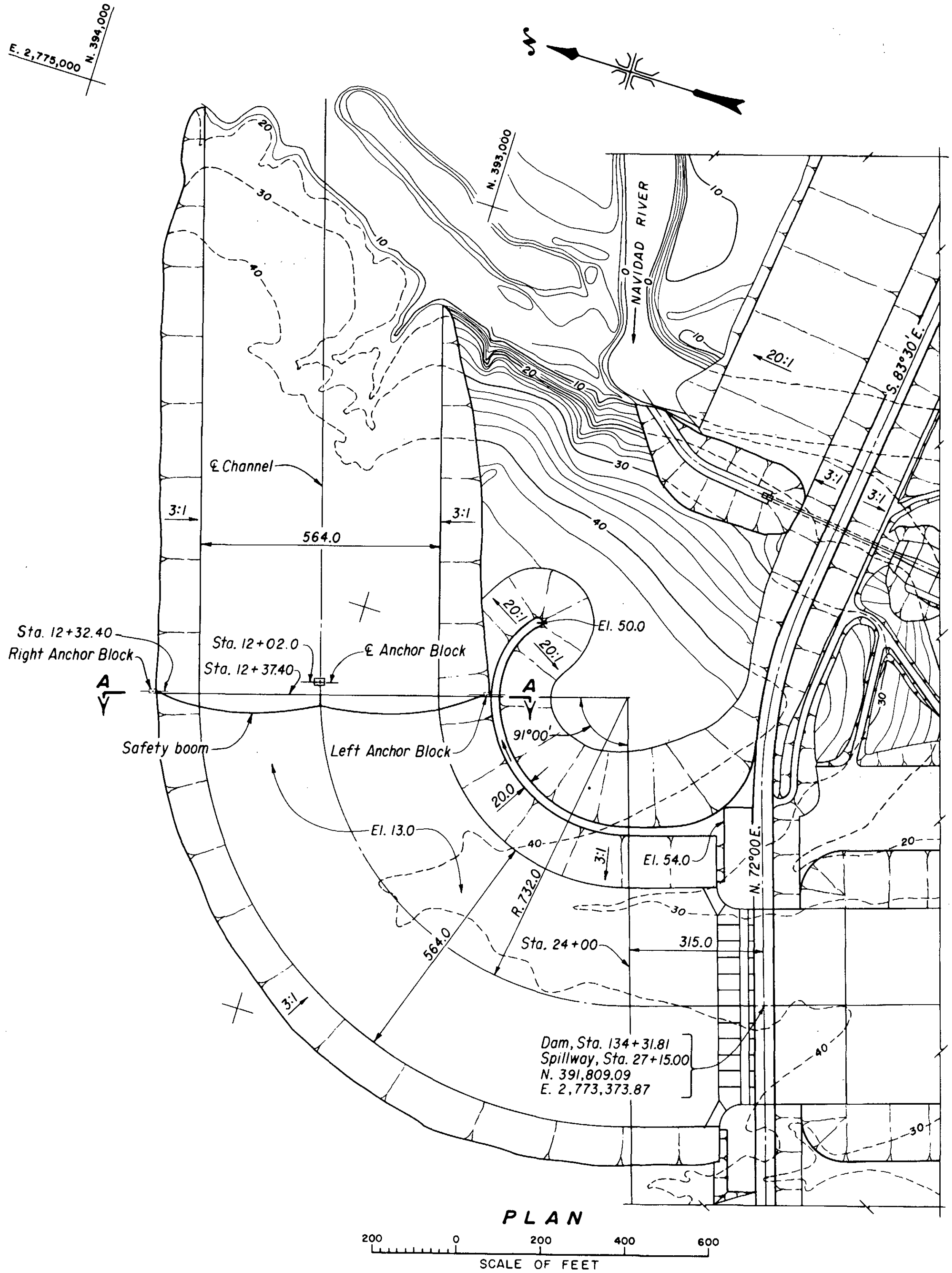

Figure 3.–The spillway approach channel.

6. Analysis of the model pressure measurements indicated that the floor blocks are safe from cavitation damage.

APPLICATION

Spillway features recommended for Palmetto Dam may be used for design of similar structures in the future. The stilling basin model studies were for the specific flow geometry of Palmetto Bend Dam spillway. However, this low Froude number (3.5) design should be applicable to other spillway structures having similar flow conditions. These studies provided a stimulus for conducting more intensive model research investigations of low Froude number stilling basins,[1] and was helpful in providing background information for that research.

THE 1:100 SCALE MODEL

Location of the hydraulic features relative to the 1:100 scale model box is shown on figure 1 and in the photograph of the model on figure 4. Some of the approach channel could not be included in the model box because of size limitations. In the initial model, there was a small channel on the right side of the approach channel in the reservoir (fig. 4). Later, this channel was excluded from the design and was filled with sand for the remainder of the test program.

The shape of the model dam was formed using metal lath covered with cement-sand mortar. A watertight barrier was constucted along the dam axis to prevent leakage from the reservoir to the exit channel section of the model. The model topography was formed with sand having the following size analysis:

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[1] George, Robert L., "Low Froude Number Stilling Basin Design," REC-ERC-78-8, Bureau of Reclamation, August 1978.

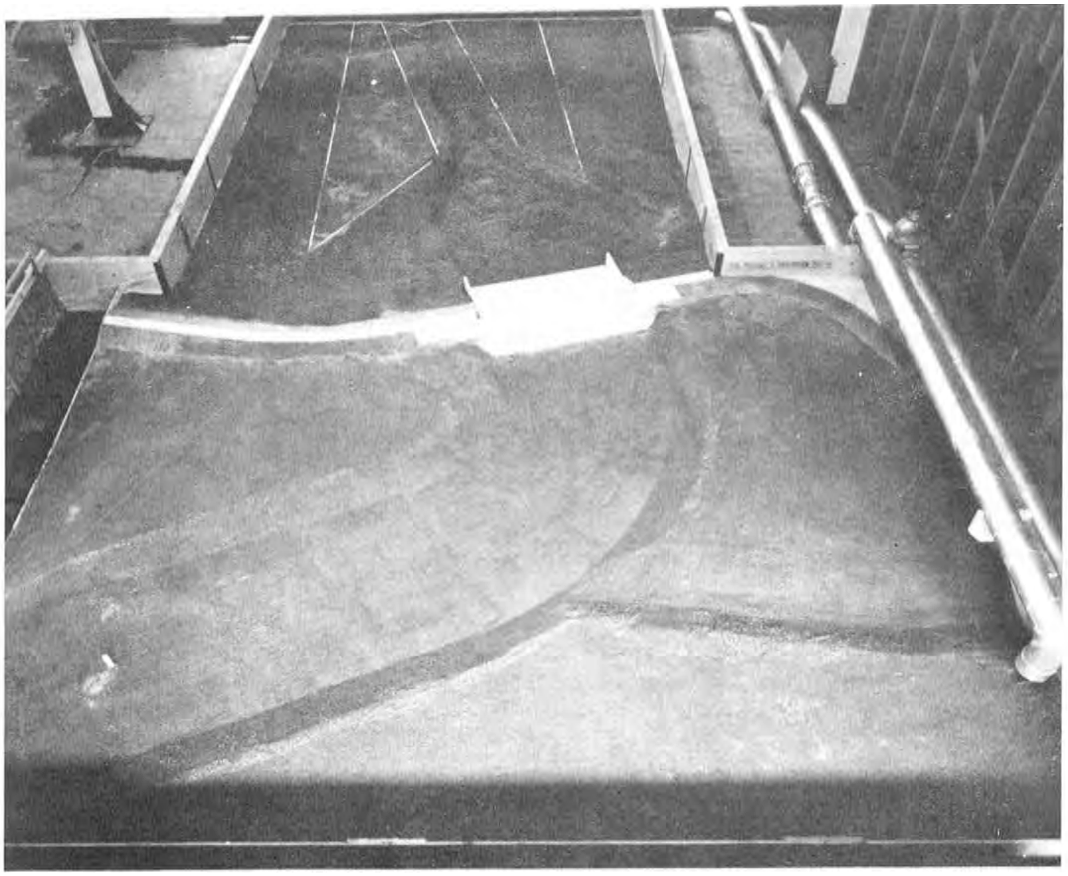


Figure 4.–The 1:100 scale model of reservoir, approach channel, spillway, and exit channel. Photo P801-D-79033

Sieve designation size		Percent passing
SI metric	U.S. customary	
4.75 mm	4	100
2.36 mm	8	93
1.18 mm	16	65
600 μm	30	39
300 μm	50	18
150 μm	100	5
75 μm	200	3

Templates were used to help mold the sand to correct elevations in the model. During initial tests, fines were flushed from the sand surface; thereafter, the sand topography generally held its shape.

Some sand was added and remolded during the test program. Extensive erosion occurred downstream from the stilling basin. After each model test, the eroded topography was reshaped. For this study, it is emphasized that erosion was not modeled. The model used could not accurately scale the prototype erosion. Instead, the area and depth of erosion were used as guides to judge hydraulic performance for a given set of features tested in the model. If in the exit channel there was less erosion for modification B than for modification A, then B was judged better than A.

Water was supplied to the model from the permanent hydraulic laboratory pipe system and entered the model through a vertical pipe behind a rock-filled baffle. The rock-filled baffle calmed turbulence and wave action of the pipe flow and provided a smooth flow of water into the model. Venturi meters and mercury manometers were used to measure model discharges. Tailwater elevation in the model was controlled with an adjustable flap at the downstream end of the model. The tailwater elevation curve for the prototype is shown in the upper right-hand corner of figure 2.

DISCUSSION OF THE 1:100 SCALE MODEL TEST PROGRAM

Introduction

Flood discharges of 2710, 4250, 4980, and 6230 m^3/s (95 600, 150 000, 176 000, and 220 000 ft^3/s) were observed for beginning operation of the model. The 2710-m^3/s discharge is the maximum recorded flood, the 4250- and 4980-m^3/s discharges were computed from flood hydrology studies representing 500- and 1,000-year frequencies, and the 6230-m^3/s discharge was the computed maximum design flood. The maximum design flood was mathematically obtained by centering the most severe hurricane storm ever recorded in southern Texas (which also had the greatest intensity of rainfall ever recorded in the United States) over the Navidad River drainage basin. In viewing the model operation, the 2690- and 4250-m^3/s flood flow conditions appeared tranquil when compared to the 6230-m^3/s flood. Therefore, the 6230-m^3/s flood was used in making most of the model tests because the corresponding model flows provided larger forces and a better means of making qualitative judgments of features tested in the model.

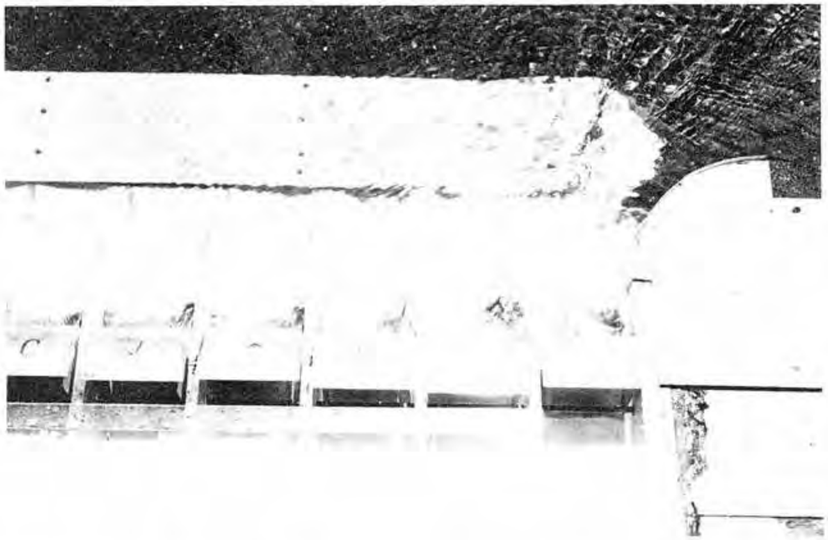
Twenty-six erosion tests were performed in the model (app. A). As a result of these tests, modifications were made to the approach channel, stilling basin, and the exit channel. The water surface of the spillway flow was below the elevation of the gate trunnions. No modifications were made to the spillway crest or chute because the model showed satisfactory operation. Modifications to the approach and exit channels were made within the first seven tests, and thereafter only modifications which influenced the stilling basin design were tested. Erosion tests using a finer sand than described above are discussed later in this report.

Approach Channel

Initially the approach channel had a 141-m (464-ft) bottom width and an 83° curve with a 198-m (650-ft) radius to the channel centerline. A straight channel approaching the crest was tangent to the curve 66 m (215 ft) upstream from the dam axis (fig. 3).

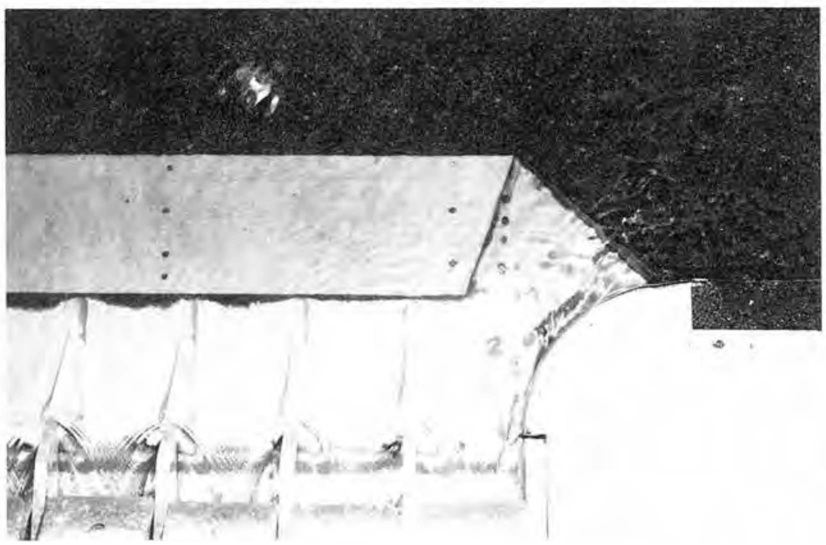
Flow conditions at the left side of the spillway were poor (fig. 5a). Water flowed along the dam and perpendicular to the approach channel at the spillway, disturbing flow through the two side bays and influencing flow as far as the fifth bay.

To prevent undesirable perpendicular flow, a spur dike was placed normal to the dam 61 m (200 ft) left of the spillway (fig. 5b). The spur dike extended 107 m (350 ft) into the reservoir, with the upstream edge near the inner bank of the curve. Flow conditions at the spillway entrance were greatly improved. However, at the reservoir end of the dike, there was an acceleration of flow around the dike into the approach channel. Sand eroded from the end of the dike and moved into the spillway entrance. This configuration of the dike, without adequate riprap protection, appeared potentially susceptible to erosion.

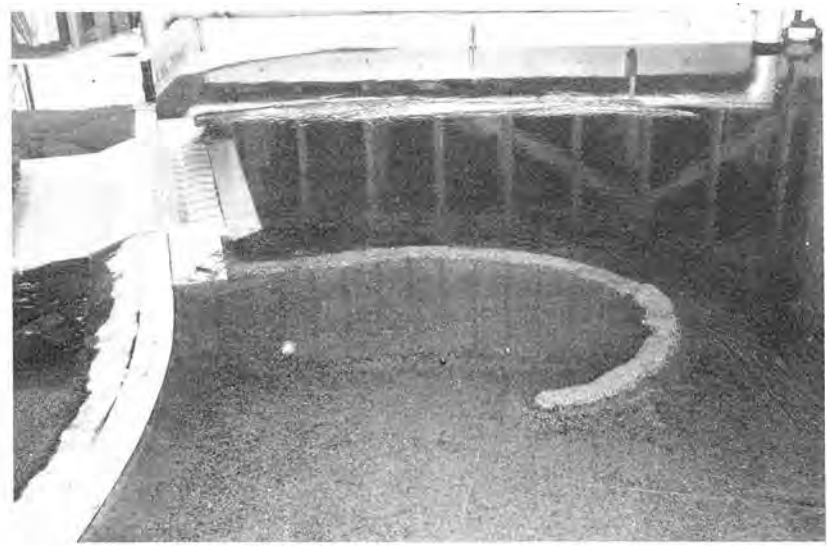


a. Flow at spillway entrance without a spur dike.

b. First trial spur dike.



c. Flow at spillway entrance with recommended dike.



d. The recommended dike.

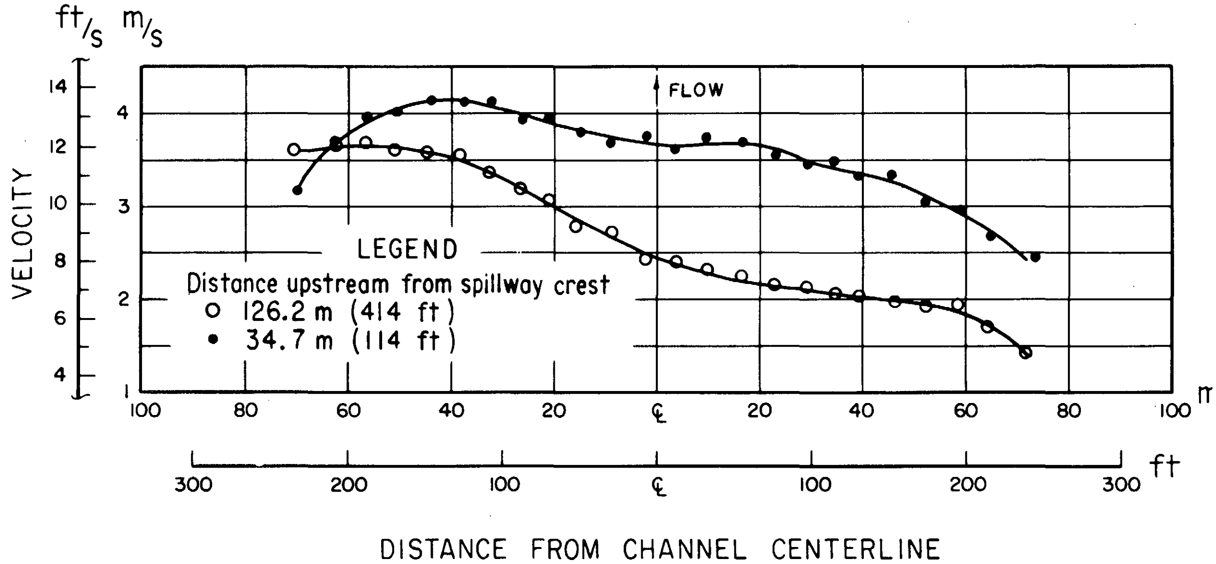
Figure 5.–Flow conditions of the approach channel. Photo P801-D-79034

Because the reservoir topography near the inner curve of the approach channel was generally 12 m (40 ft) above sea level, and near normal water surface, a relatively small quanitity of fill was required for a longer curved dike. The dike was placed on the inner curve of the approach channel as an extension of the 3:1 side slope (fig. 5d). Although there were high-velocity currents along the inner curve, flow conditions were considerably improved at the left spillway entrance and in the channel (see figs. 5a and 5c). Slight changes were made to the dike of figure 5d to conform to that shown on figure 3. These changes included the addition of 20:1 side slopes outside of the approach channel where the dike was not formed by the 3:1 approach channel slope. The 20:1 slope blended better with the landscape.

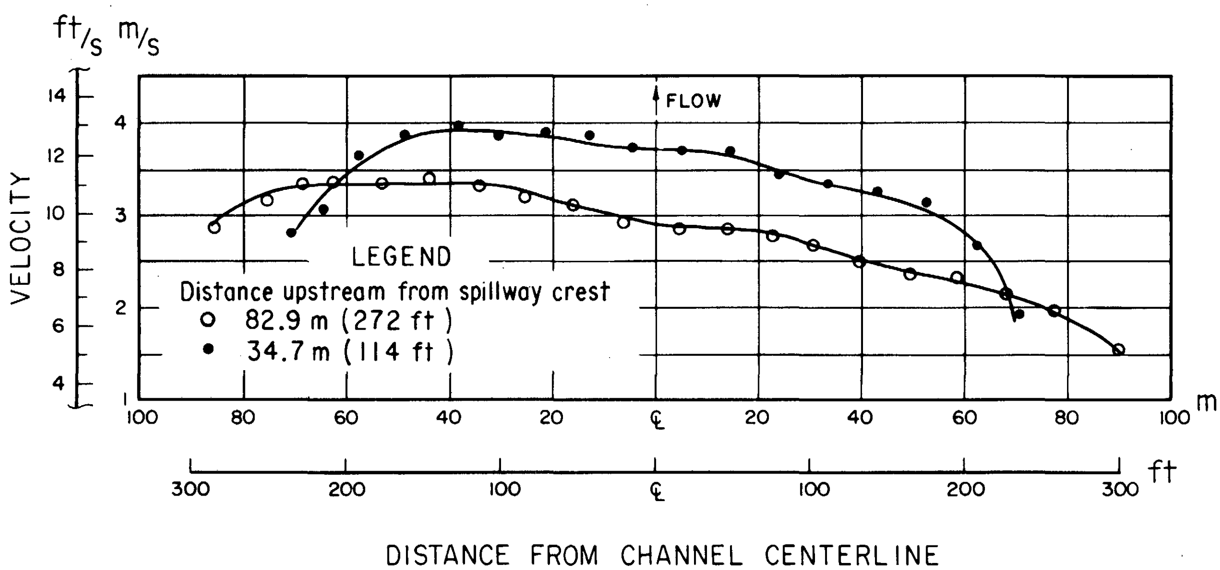
Velocity measurements were made in the approach channel for the 6230-m^3/s discharge. A pygmy current meter was used to make measurements normal to the channel centerline. The center of the bucket wheel was positioned 30 mm (0.1 ft) below the water surface to obtain velocities representative of the channel flow. Velocities were higher on the inside of the bend than on the outside (fig. 6a).

Channel modifications were made in an attempt to provide a uniform approach velocity in the channel immediately upstream from the spillway crest. It was desireable to move the channel curve further upstream from the spillway and to increase the radius. However, because of topography near the channel, major changes of the location and alinement were expensive and only minor modifications could be made. The downstream tangent of the curve was increased to 96 m (315 ft) to provide additional straight approach channel, the curve radius was increased to 223 m (732 ft), the curve angle was increased to 91°, and the bottom width was increased to 172 m (564 ft) (fig. 3). Velocity measurements (fig. 6b) showed very little improvement, but, the general flow appearance was improved with the modified curve in the 172-m channel.

The prototype channel flow can be expected to be better than that in the model. Model inflow to the 172-m channel was less favorable than for the 141-m channel. Widening the



a. Bottom width 141 m (464 ft)



b. Bottom width 172 m (564 ft)

Figure 6.–Velocity measurements–approach channel. Discharge [6230 m³/s (220 000 ft³/s)].

model channel and placing the curve further upstream allowed a side flow at the entrance of the channel near the edge of the model topography. In the prototype there will be a better flow distribution approaching the channel curve from the reservoir (fig. 1, lower right corner).

An approach wall at a 45° angle was tested in the model (fig. 7), but observations indicated no improvement in spillway flow.

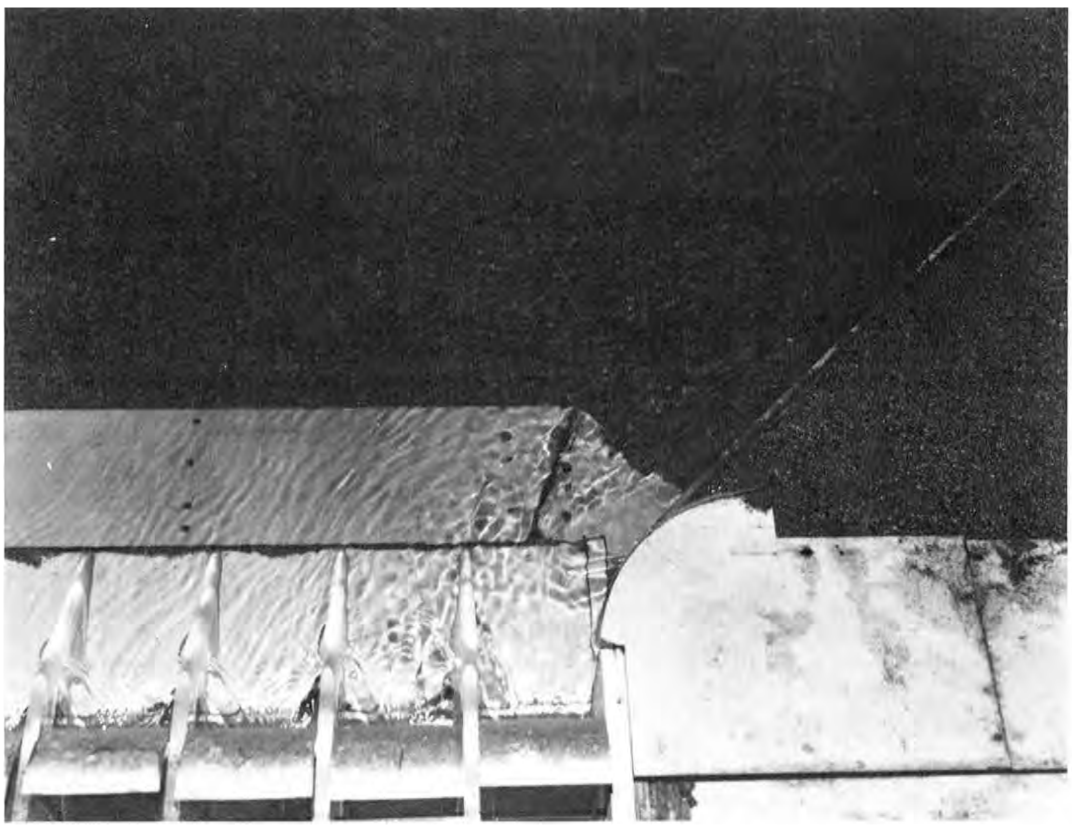


Figure 7.–Approach wall at 45°. Photo P801-D-79035

Stilling Basin

Stilling basins with Froude numbers less than 3.5, dissipating energy from 27.9 to 46.5 $(m^3/s)/m$ [300 to 500 $(ft^3/s)/ft$] unit discharge are not covered in Engineering Monograph

No. 25.[2] Design guidelines are not well established for required basin appurtenances and dimensions. Thus, the general program of testing the model stilling basin was to start with a hydraulic jump on a horizontal apron, add appurtenances to the apron, and then economize basin demensions.

In test 1T (No. 1), the basin was 141 m (464 ft) wide, 46 m (150 ft) long, and the floor elevation was minus 4.3 m (minus 14 ft) below sea level (basin 1).

The model was operated at a discharge at 6230-m^3/s (220 000-ft^3/s) for an erosion test lasting 3 hours and 15 minutes (fig. 8a). Considerable erosion occurred at the end of the stilling basin with the material being carried downstream and deposited on the exit channel. The deepest point in the eroded hole was 10 m (33 ft) below the basin apron.

While the depth of erosion in later model tests was not the same, it was found that most of the erosion occurred within the first hour's operation, increasing slightly during the second. However, since the first erosion test lasted for 3 hours and 15 minutes, all other erosion tests with this size sand were made for the longer time interval.

Erosion was reduced by placing a triangular sill across the end of the stilling basin (test 2T). The end sill was 6.10 m long by 3.05 m high (20 ft by 10 ft). For test 3T, the stilling basin remained the same but a dike was placed along the spillway approach channel; erosion was very similar to that of test 2T (fig. 8b). Widening the approach channel, test 4T, reduced erosion near the left corner of the stilling basin (compare figs. 8b and 8c). The high-velocity flow, along the inside curve of the narrow approach channel and passing through the spillway, was believed responsible for the erosion hole near the left corner of the basin shown in figure 8b.

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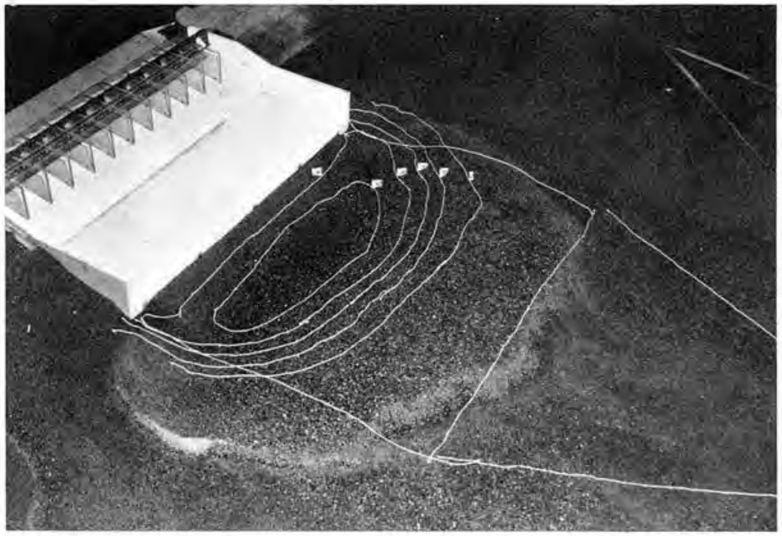
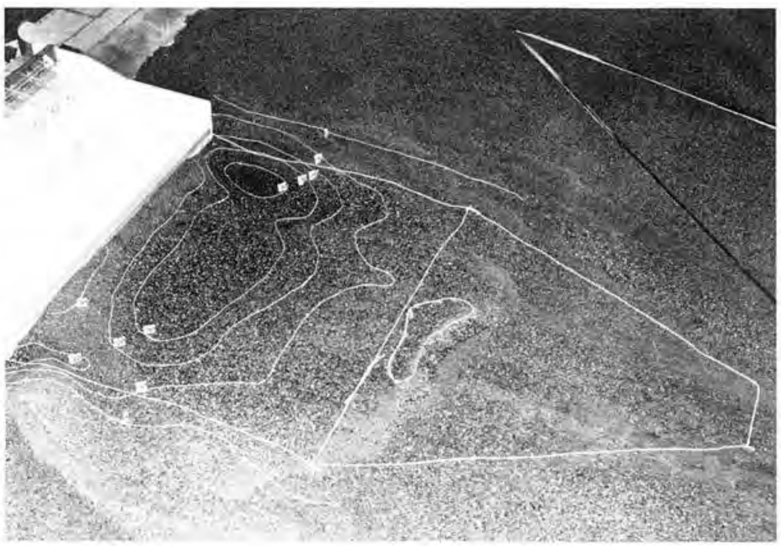
[2] Peterka, A. J., "Hydraulic Design of Stilling Basins and Energy Dissipators," Engineering Monograph No. 25, Bureau of Reclamation, July 1963.

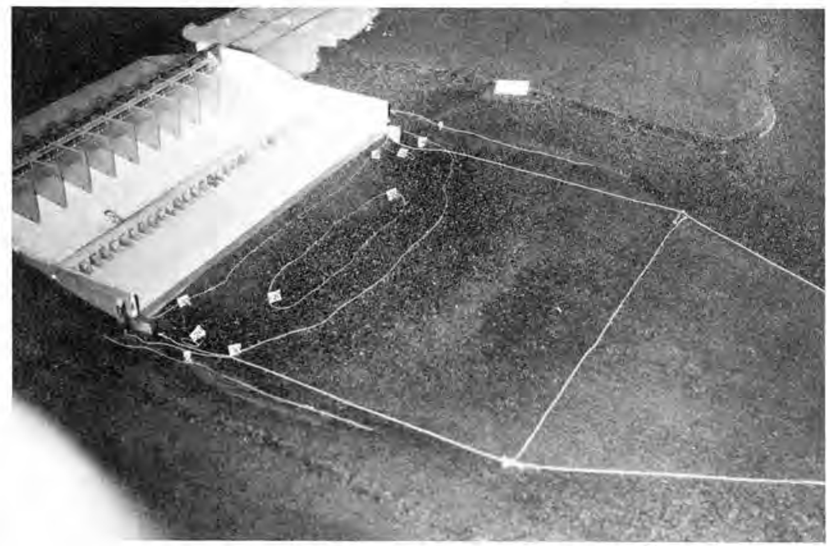


a. Plain floor with no appurtenances (1T).

c. Triangular end sill and 172-m (564-ft) bottom width approach channel (4T).



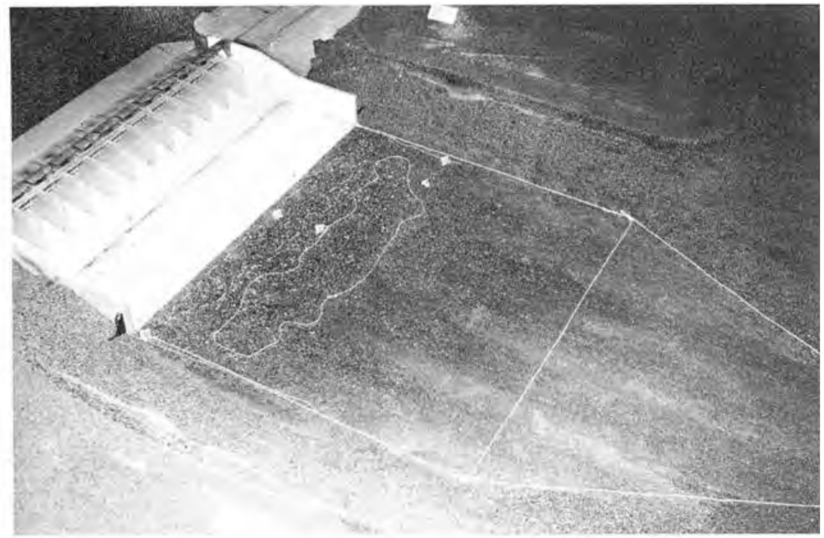
b. Triangular end sill and 141-m (464-ft) bottom width approach channel (3T).



d. Triangular end sill and floor blocks (8T).

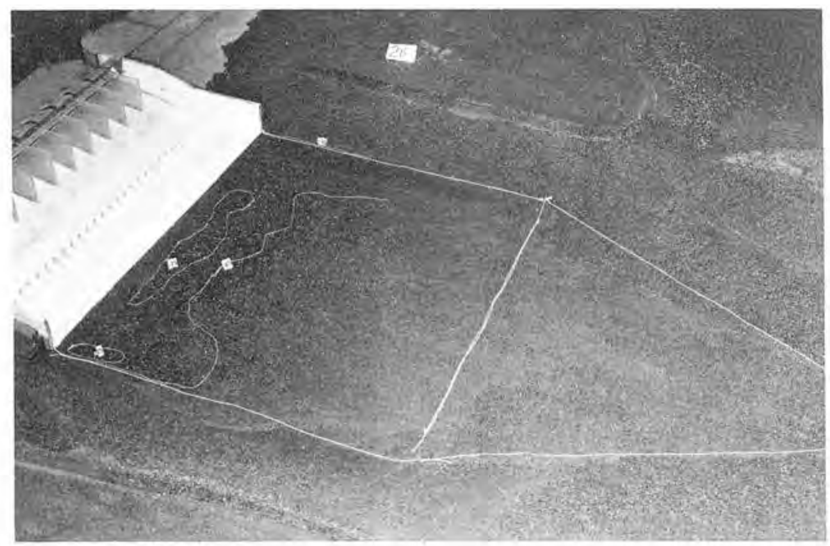
Figure 8.–Erosion tests of 1:100 scale model. Photo P801-D-79036

e. Floor blocks only and floor EL –4.3 m (–14 ft) [11T].



g. Floor blocks only, floor EL –3.0 m (–10 ft), and stilling basin length reduced by 11.6 m (38 ft) [18T].

f. Floor blocks and dentated end sill, floor EL –4.3 m (–14 ft) [12T].



h. Recommended stilling basin [26T].

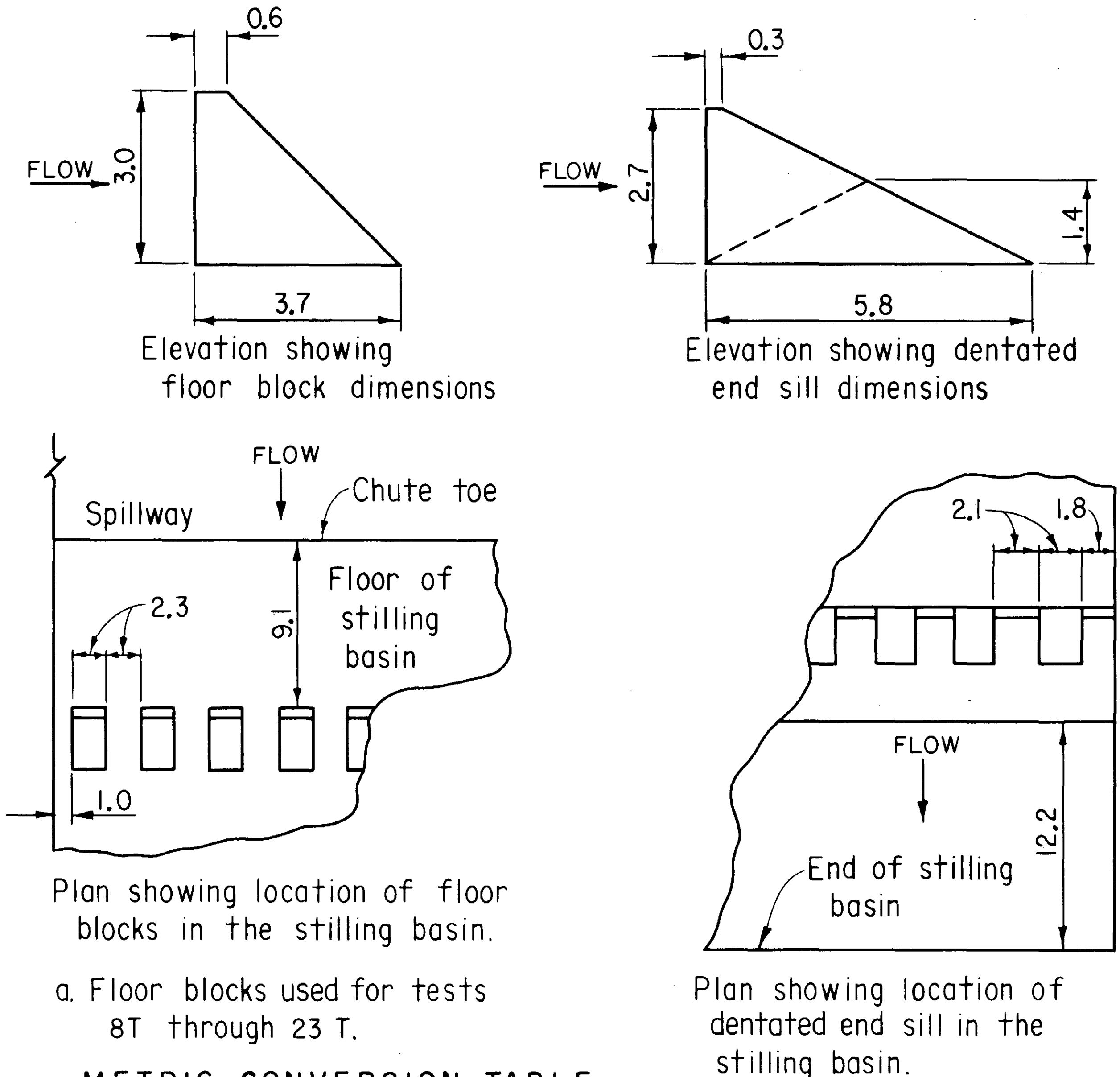
Figure 8.–Erosion tests of 1:100 scale model.–Continued. Photo P801-D-79037

Floor blocks were added to the stilling basin before erosion test 8T (fig. 9a). The hydraulic jump was better contained in the stilling basin than before. A boiling motion of the water surface ocurred slightly downstream from the floor blocks, where in previous tests there was a boil above the end sill. Erosion was noticeably reduced and the sandbar of eroded material was closer to the basin (fig. 8d). Thus, the floor blocks were considered very beneficial to energy dissipation in the stilling basin.

Up to this point, all erosion tests had been made with a 9.4-m (31-ft) tailwater elevation and a discharge of 6230 m^3/s (220 000 ft^3/s) (fig. 2). In the event that the prototype tailwater elevation could be less, the model was operated at a 7.9-m (26-ft) tailwater elevation for a discharge of 6230 m^3/s (test 9T). The hydraulic jump was contained in the stilling basin; however, the water surface downstream from the basin had heavy waves. There were standing waves on the water surface for a 122- to 183-m (400- to 600-ft) distance downstream from the basin. Because of the decrease in flow depth at the exit of the basin, velocities were greater, and the eroded hole was 0.6 to 0.9 m (2 to 3 ft) deeper for test 9T than for 8T. Coarser sand grains were carried further downstream and the sandbar deposit of eroded material was not as evident as in previous tests. After test 9T, erosion tests were performed at 9.4- and 7.9-m tailwater elevations for most modifications made to the spillway basin.

Up to this point in the test program, the floor block appurtenances made the most significant reduction in erosion. The triangular end sill had been in place since 2T. Thus, for 11T, the triangular end sill was removed to determine how effective the floor blocks alone were in dissipating the energy. There was less erosion without the sill than with the sill (figs. 8d and 8e). The solid triangular end sill did not appear to be a very effective appurtenance. Flow conditions at 9.4- and 7.9-m tailwater elevations for the stilling basin configuration are shown in figures 10a and 10b.

A dentated end sill (dimensions shown in fig. 9) was tested next. A sheet metal strip attached at each side of the dentated sill provided handles for moving the sill within the



a. Floor blocks used for tests 8T through 23 T.

b. Dentated end sill used for 12 T.

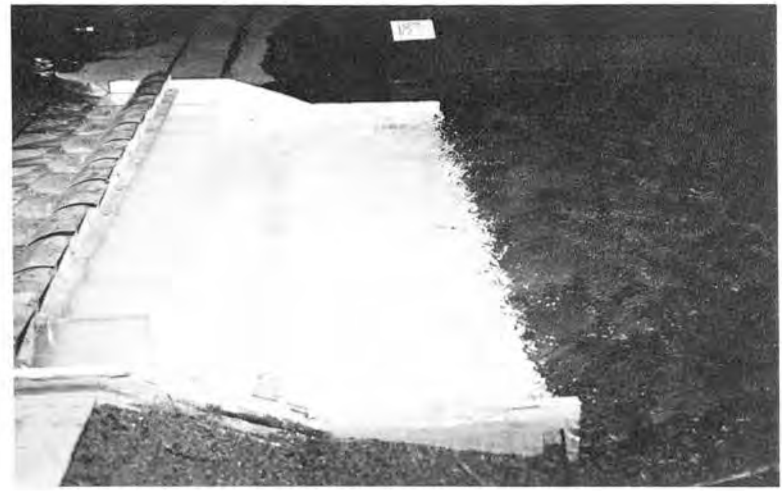
METRIC CONVERSION TABLE

mm	ft	mm	ft	mm	ft
0.30	1 – 0	2.10	6 – 9	5.80	19 – 0
0.60	2 – 0	2.30	7 – 6	9.10	30 – 0
1.00	3 – 3	2.70	9 – 0	12.20	40 – 0
1.40	4 – 9	3.00	10 – 0		
1.80	5 – $10\frac{1}{2}$	3.70	12 – 0		

Figure 9.–Appurtenance dimensions for 1:100 scale model.

a. Floor EL –4.3 m (–14 ft) and tailwater EL 9.4 m (31 ft).

b. Floor EL –4.3 m (–14 ft) and tailwater EL 7.9 m (26 ft).



c. Floor EL –3.0 m (–10 ft) and tailwater EL 9.4 m (31 ft).

d. Floor EL –3.0 m (–10 ft) and tailwater EL 7.9 m (26 ft).

Figure 10.–Flow in stilling basin with floor blocks. Photo P801-D-79038

stilling basin while the model was operating. Not much difference in basin flow conditions was detected, but the best operation appeared when the sill was located about 12 m (40 ft) upstream from the basin end. Erosion test 12T indicated that the dentated sill at this location was not an appreciable improvement (figs. 8e and 8f).

At this point in the investigation, the floor blocks had significantly improved the stilling basin action and an end sill was of questionable value. Chute blocks were believed inconsequential for the stilling basin, and if tested in the 1:100 scale model, would not provide definite results for proving their effectiveness. Also at this time, a sectional model was being considered as a more effective means of studying the basin. Therefore, the next series of tests concentrated on reducing the cost of the stilling basin construction.

For test 14T, the stilling basin floor elevation was raised to 3.0 m (10 ft) below sea level. Operation of the stilling basin appeared satisfactory, with erosion being similar to that in figure 8f. Next, the 45.7-m (150-ft) long stilling basin was shortened by 6.1 m (20 ft). Operation remained satisfactory, so an additional 5.5 m (18 ft) were removed–a total of 11.6 m. Operation still appeared satisfactory; however, there was slightly more erosion for test 18T (fig. 8g). The eroded hole was 0.3 to 0.6 m (1 to 2 ft) deeper than that shown in figure 8f. Thus, reducing the stilling basin length to 34.1 m (112 ft) allowed slightly greater erosive forces to act on the spillway exit channel. Flow conditions at the 9.4- and 7.9-m (31- and 26-ft) tailwater elevations for this stilling basin configuration are shown in figures 10c and d. No additional basin shortening was tried.

Further studies of the stilling basin were later made with a 1:30 sectional model. Afterwards, the recommended stilling basin design obtained from this study was placed in the 1:100 scale model. Results of the erosion test are shown in figure 8h. At the 6230-m^3/s (220 000-ft^3/s) discharge, there was an occasional overtopping of flow across the stilling basin walls near the floor blocks, similar to that seen on the far wall of figure 10d. However, there was water outside the walls and thus no potential for damage to the embankment from overtopping.

Tests With Fine Sand

A box with prototype dimensions of 141 by 125 m (464 by 410 ft) was placed immediately downstream from the spillway and filled with a fine, uniform (0.2-mm-average-diameter) sand. Possibly, the fine sand would show erosion characteristics which were undetectable with the coarser sand. For this test, the stilling basin was 34.1 m (112 ft) long with floor blocks and the floor elevation was 3.05 m (10 ft) below sea level. There was more erosion with the fine sand (compare figs. 11a and 8g). Also, the fine sand revealed a pattern of eroded furrows downstream from the stilling basin that appeared as a periodic erosion pattern across the width of the exit channel (fig. 11a).

Secondary currents, of a periodic nature, were surmised to be from flow through the spillway bays interacting with the floor blocks. Although the floor blocks were evenly spaced across the basin, the blocks had a different spacing arranement with each spillway bay. Thus, the secondary currents could have produced an erosion pattern of alternate furrows and humps in the sand across the exit channel.

In the prototype, either soil-cement or riprap protection against channel erosion will be provided upstream from the spillway and downstream from the stilling basin. Erosion tests 21T and 22T were made on the model with a 61-m (200-ft) length of protection downstream from the basin without a dentated end sill. After test 21T, the box constructed to hold the fine sand in the exit channel was removed because of possible influence on the movement of sand. The model showed erosive forces acting 61 m downstream from the protected area (test 22T, fig. 11b).

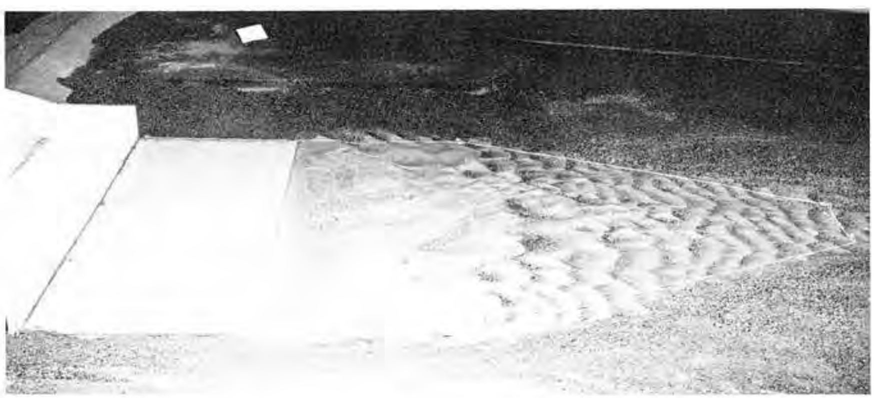
Figures 11c through 11e show results of tests made to help interpret results from the 1:30 sectional model and are discussed in a subsequent section of the report.

Erosion tests using fine sand were of a limited nature, and the results did not indicate that the fine sand was any better than coarse sand in the model. Possibly if additional tests had been made in the 1:100 scale model to optimize the size and location of floor blocks

a. Stilling basin floor EL –3.0 m (–10 ft) with floor blocks.

c. Sidewalls with dentated end sill.

d. Sidewalls without dentated end sill.



b. Simulated 61-m (200-ft) length of soil-cement.

Figure 11.–Tests with fine sand. Photo P801-D-79039

e. Representation of the 1:30 scale sectional model in the 1:100 scale model.

and sills, the fine sand would have proved more beneficial. While the fine sand was more erodible, the sand dunes tended to obscure erosion levels in the model.

Erosion Tendencies Near the Sidewalls of the Stilling Basin

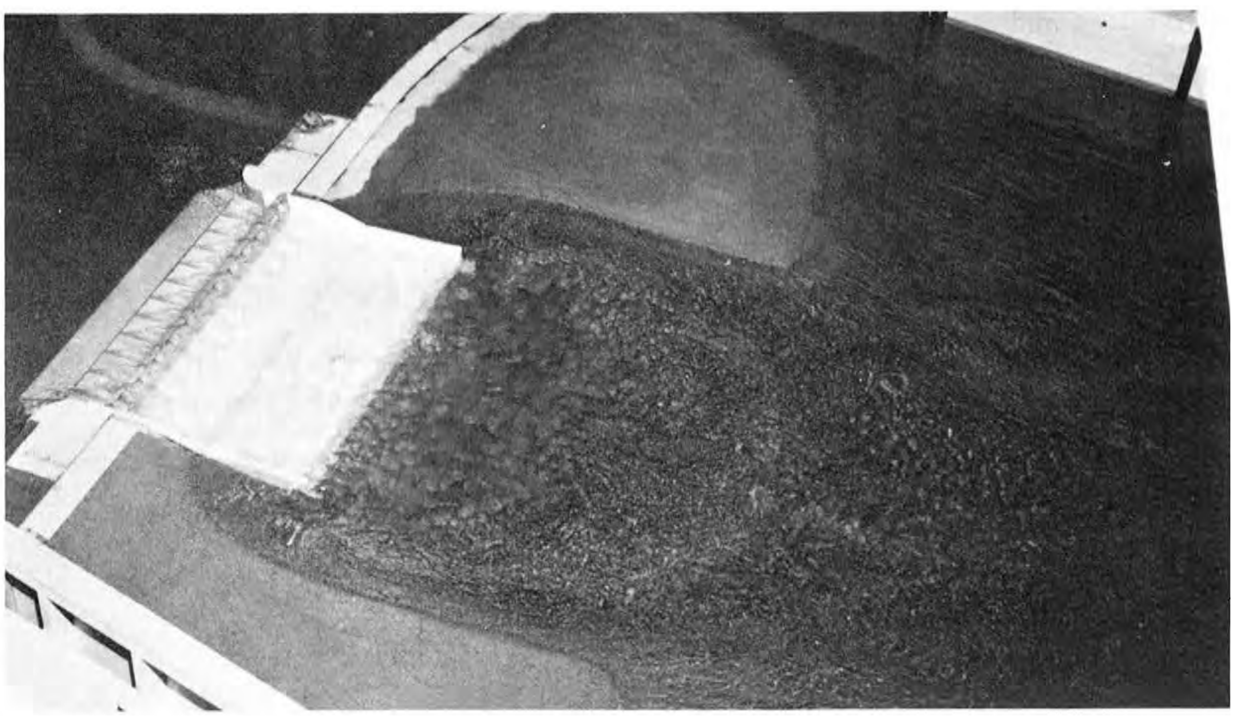
For many of the tests there was a tendency for greater erosion to occur downstream from the sidewalls of the stilling basin (figs. 8b through 8d). Two stilling basin modifications were made in an attempt to reduce this erosion. A rectangular end sill 3.0 m high by 6.1 m long (10 by 20 ft) extending 9.1 m (30 ft) in from each sidewall was added to the triangular end sill (test 5T). Erosion with these blocks in place was similar to that shown in figure 8b, except that at the left side there was more erosion at the end of the basin. The minus 12.2-m (minus 40-ft) contour touched the basin end.

For test 7T, the endmost counterforts of the stilling basin sidewalls were added to the model to better simulate prototype construction in this area. Also, a 6.1-m (20-ft) extension of the sidewall, with the top at a 1.8-m (6-ft) elevation, was added. These end wall extensions and counterfort additions did not decrease the channel erosion near the downstream corners of the stilling basin. The sidewall extensions were in place for tests 7T through 9T and are shown in figure 8d. The counterforts were in place for all tests after 7T.

During initial tests, a large eddy was present at each corner of the basin outlet. To constrain the flow, dikes were placed along a 119-m (390-ft) downstream distance on each side of the exit channel. The bottom toe of the dikes was in line with the basin sidewalls, and extended 13.7 m (45 ft) upward at a 3:1 slope. The eddies were considerably reduced (fig. 12). Excavated material from the exit channel is a waste-type fill which could not be used for constructing the dam. This excess fill may be placed in back of the dikes and the dikes blended into the natural topography (fig. 12b).

Waves issuing from the stilling basin will act on the dikes; thus, the designers planned to provide wave protection with either riprap or soil cement. Waves leaving the diked channel

a. Exit channel flow before dikes.



b. Exit channel flow confined by dikes.

Figure 12.–Exit channel downstream from the stilling basin. Photo P801-D-79040

enter a large flood plain (fig. 12b) and should attenuate in the lake-like area. Therefore, in evaluating the stilling basin modifications, more consideration was given to erosion of the exit channel by flow velocities than to waves.

Dye was used in the model for observing flow currents near ends of the stilling basin sidewalls. There was an undercurrent or return flow that moved laterally below the flow deflected upward from the end sill. This undercurrent was larger on the left side of the exit channel. Placement of the exit channel dikes partially restricted water supplied to the undercurrents, reducing the undercurrent size. The solid triangular end sill tended to increase the undercurrent by lifting the flow and causing a reduced pressure on the downstream side of the sill. With the triangular end sill in place, erosion was greater near the ends of the stilling basin sidewalls (figs. 8b through 8d), while without the end sill, the erosion was less (figs. 8e through 8h).

DISCUSSION OF THE 1:30 SCALE MODEL TEST PROGRAM

Introduction

During the 1:100 scale model tests, additional tests with a sectional model appeared advantageous. The model discharge and physical size of the spillway and stilling basin were larger than that of the 1:100 scale model and allowed for better study of energy dissipation of the appurtenances in the low Froude number stilling basin. A 1:30 scale sectional model was installed in a 0.76-m-wide by 0.76-m-deep (2-1/2- by 2-1/2-ft) flume.

The spillway dimensions of the model were the same as shown in figure 2, with exception of the stilling basin appurtenances. For the erosion tests the same sand size distribution was used as in the 1:100 scale model. There was the equivalent of a 4.6-m (15-ft) erodible depth of sand that extended 122 m (400 ft) downstream from the stilling basin. A 22.9-m (75-ft) spillway crest length was placed symmetrically in the model (fig 13). The center gate was full width, 10.7 m (35 ft), and the side gates were approximately half width, 4.9 m

(16 ft). The stilling basin portion of the model was located between the transparent sides of the flume to better observe the profiles of the flow action.

Figure 13.–The 1:30 scale sectional model, test R2 in progress.
Photo P801-D-79041

The first phase of the test program was to determine what appurtenances should be used in the stilling basin. During this phase some modeling problems were resolved, and then model tests were directed toward obtaining optimum appurtenance dimensions. Twenty-five erosion tests were performed in the model (app. B). Afterwards, pressure measurements on a floor block were made to check for possible occurrence of cavitation.

Stilling Basin Appurtenances

The 1:100 scale model definitely showed that floor blocks should be used to force energy dissipation to occur within the stilling basin. Thus, the initial floor block size and location were similar to the 1:100 scale model, except the blocks were 2.4 m (8 ft) wide instead of 2.3 m (7.5 ft) wide. However, deciding which of the 12 spillway bays should be represented in the sectional model was difficult because each bay had a slightly different block spacing with respect to the bay centerline. Block configuration of bay No. 7 was chosen because of the advantage that none of the model floor blocks had to be reduced in width. However, one block was against the left wall of the model (tests R1 through R10, fig. 14b).

The three appurtenances tested (with the floor blocks in place) were chute blocks, a solid triangular end sill, and a dentated end sill (figs. 15 and 16). Sand bed erosion depths again were used in judging effects of the different appurtenances and tests were of 2-hour duration.

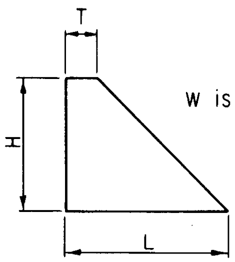
The triangular sill 3.0 m high by 6.1 m long (10 by 20 ft) was placed upstream from the end of the stilling basin (fig. 15b) to observe flow effects of a shorter basin. There was severe turbulence generated by flow passing over the sill, and erosion was greater than when using only floor blocks (compare figs. 16a and 16b). Thus, the decision was made not to use a solid triangular end sill.

Chute blocks (dimensions shown in fig. 14b) reduced erosion slightly (figs. 16a and c). However, the chute blocks did not show a significant advantage to justify the expense of their construction in the stilling basin.

With the dentated end sill in place (dimensions shown in fig. 14d), there was less erosion (figs. 16a and d). This was especially noticeable in the central portion of the model. Of the three appurtenances tested, the best improvement in energy dissipation appeared to occur with the dentated end sill.

Model Test Problems

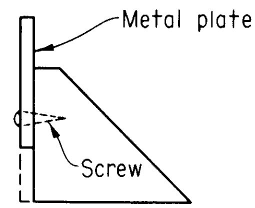
During the initial tests, two modeling problems were encountered: (1) providing symmetrical flow to the model spillway and stilling basin and (2) using the erosion criterion for judging appurtenance effectiveness.



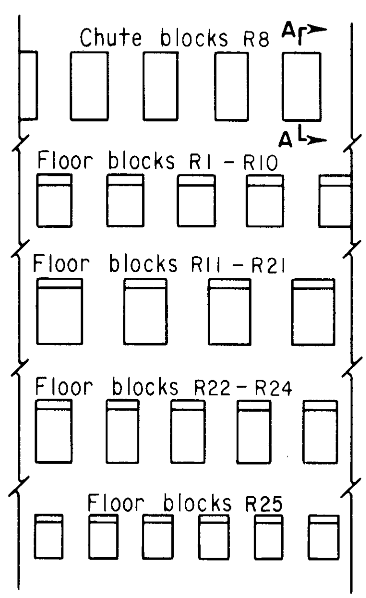
Definition sketch

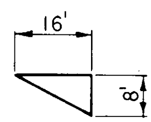
Test No.	H		L		T		W	
	m	ft	m	ft	m	ft	m	ft
R1 - R10	3.0	10.0	3.7	12.0	0.6	2.0	2.4	8.0
R11 - R20	4.0	13.0	4.6	15.0	0.6	2.0	2.9	9.5
R21	3.0	10.0	3.7	12.0	0.6	2.0	2.9	9.5
R22-R24	4.0	13.0	4.6	15.0	0.6	2.0	2.3	7.5
R25	2.4	8.0	2.9	9.5	0.5	1.5	1.9	6.25

a. Dimensions of floor blocks tested in the model.



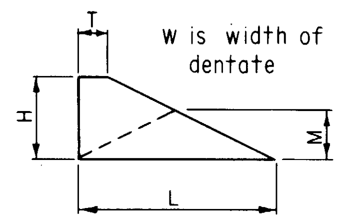
c. Metal plate that could be moved up and down, and secured in position with the screw.





SECTION A-A

b. Lateral location of blocks in the flume.

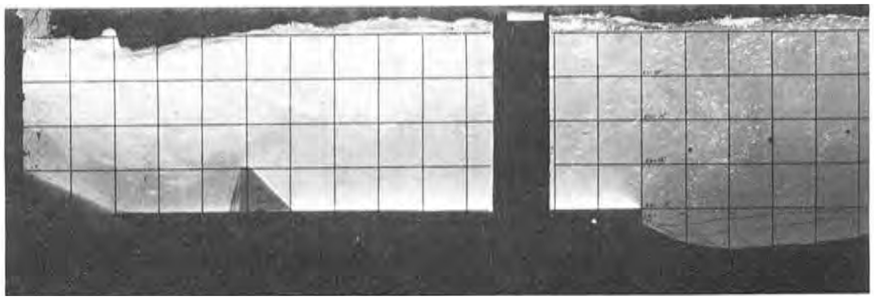


Definition sketch

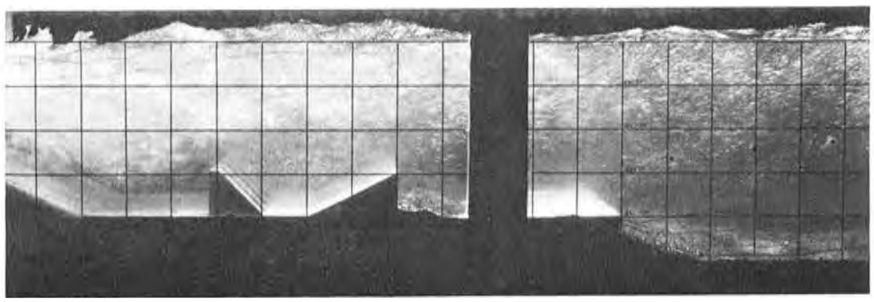
Test No.	H		L		T		W		M	
	m	ft	m	ft	m	ft	m	ft	m	ft
R9, R10, R18 and R19	2.1	7	4.5	14.75	0.2	0.75	1.6	5.25	1.1	3.70
R15-R17 R21-R25	1.5	5	3.4	11	0.3	1	1.1	3.75	0.8	2.75

d. Dimensions of the dentated end sills used in the model. The sills were placed symmetrically to the model centerline and partial width dentates placed against the flume walls.

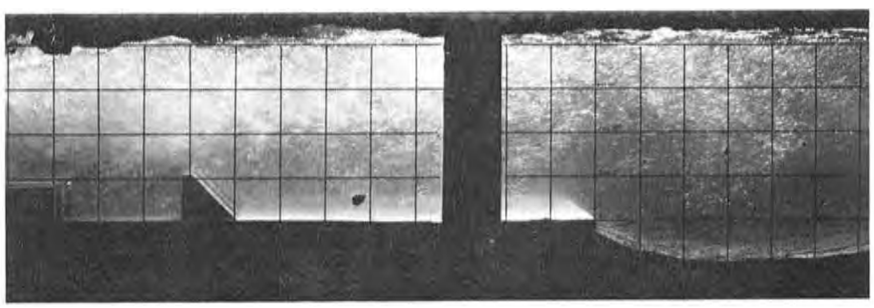
Figure 14.–Appurtenance dimensions for 1:30 scale model.



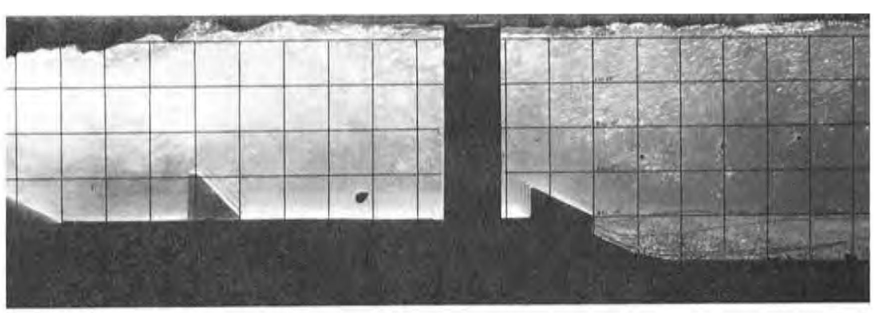
a. Floor blocks only (R4).



b. Floor blocks and triangular end sill (R7).



c. Chute blocks and floor blocks (R8).

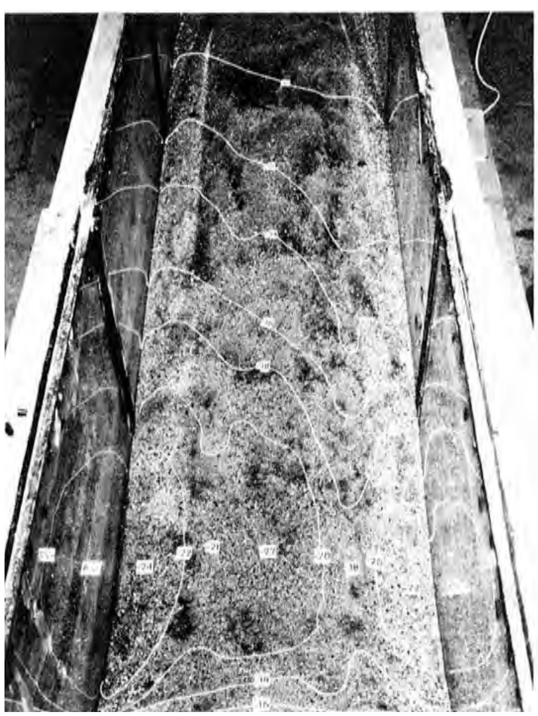


d. Floor blocks and dentated end sill (R9).

Figure 15.–Stilling basin flow with different appurtenances. Grid size is 3 by 3 m (10 by 10 ft). Photo P801-D-79042

a. Floor blocks only (R4).

b. Floor blocks and triangular end sill (R7).



c. Floor blocks and chute blocks (R8).

d. Floor blocks and dentated end sill (R9).

Figure 16.–Erosion tests of 1:30 scale model. Stilling basin flow conditions are shown in figure 15. Photo P801-D-79043

A nonsymmetrical flow was observed during test R1. A shifting of the inlet pipe, addition of baffle slats, and placing a small mesh screen 0.5 m (1-3/4 ft) downstream from the rock baffle produced an acceptable velocity distribution. With the model modifications, the velocity at the right gate was 0.90 m/s (2.95 ft/s); at the center gate, 1.00 m/s (3.29 ft/s); and at the left gate, 0.86 m/s (2.82 ft/s). Also, sealing strips, placed vertically along the panel joints of the flume, created a disturbance in the flow immediately downstream from the gate. The left side seal protruded into the flow, causing turbulence which produced extensive erosion in the sand on the left side of the flume. After removing the strip, the erosion pattern was greatly changed and nearly symmetrical (test R4, fig. 16a). Results from tests R1 through R3 were disregarded because of these difficulties.

The second modeling problem encountered was the erosion criterion. Deeper erosion was expected to occur near the channel walls; thus, a decision had been made to judge the appurtenance effectiveness on the erosion in the central part of the model channel. Because of the observed extent of the erosion near the wall, it was questionable whether erosion at the sidewalls should be entirely disregarded.

Two tests were made in the 1:100 scale model to study sidewall effects. Each spillway wall was extended 122 m (400 ft), and erosion tests were made with fine sand. Tests were made with and without a dentated end sill, and with floor blocks in the stilling basin. The wall erosion was very noticeable with the end sill and barely noticeable without the sill (figs. 11c and d). Turbulence from the sill confined by the sidewalls produced erosion next to the wall. Without the sill, the turbulence generated by the floor blocks upstream probably dissipated on the stilling basin floor and wall before reaching the erodible sand.

Another feature of the tests was the variation of erosion across the exit channel. There were eroded furrows, distinguished by the darkened areas of the larger sand grains across the channel (fig. 11e). The two parallel lines scratched in the sand surface show the lateral location of the sidewalls of the 1:30 scale sectional model.

Note that the sectional model sidewalls were located in eroded furrows. If model similitude of the eroded furrows did carry over to the sectional model, then additional erosion caused by the presence of the wall would deepen the furrow erosion. However, there was no way to determine the amount. Because erosion near the walls in the 1:100 scale model could correspond to furrow erosion, figures 11a and e, the amount of wall erosion in the 1:30 scale model was considered with the central erosion in evaluating the appurtenances.

In figures 16a, b, and c, there appeared to be slightly more erosion on the left side of the flume. The floor block against the left wall (tests R1 through R10, fig. 14b) was suspected of contributing to excessive erosion on the left side. This suspicion was confirmed after observing some flow tests with floor blocks located 13 m (44 ft) downstream from the chute toe having a height representing 4.6 m (15 ft). During the first 15 minutes of operation, the scour hole on the left side of the flume was observed to be 2 m (7 ft) deep and on the right 1 m (3.3 ft) deep. Turbulence generated from the left floor block was believed to be acting similarly to that generated by the end sill of test 23T (fig. 11c), because the floor block was 13 m (44 ft) downstream from the tow of the spillway chute. Therefore, the decision was made to place the floor blocks symmetrically with respect to the model centerline with none against the model wall. This change was in effect for all erosion tests after R10 in an attempt to alleviate the nonsymmetrical erosion of sand near the wall caused by the floor blocks.

Optimum Appurtenance Dimensions

The objectives for this stage of the test program were to: (1) determine the best floor block location downstream from the chute toe, (2) determine the type or need of an end sill, and (3) optimize the appurtenance dimensions. Flow observation tests were made to help define what block location and dimensions appeared optimum, which thus decreased the number of erosion tests required. Floor blocks were attached to a thin metal strip that could be moved readily upstream and downstream in the model stilling basin. Metal plates of the same block width (fig. 14c) were attachd to the blocks. The plates could be adjusted upward to change the effective block height and area exposed to the flowing water.

Flow observation tests were made for 3.0-, 4.0-, and 4.6-m (10-, 13-, and 15-ft) block heights and at 6.1-, 8.5-, 11.0-, and 13.4-m (20-, 28-, 36-, and 44-ft) distances from the toe of the spillway chute. The 4.0-m block height was believed better than the 3.0-m height because erosive swirls downstream from the basin did not appear as violent. Raising the plates to the 4.6-m block height produced no improvement. When varying the block location downstream from the chute toe, the 11.0-m distance appeared best, but only slightly better than the 8.5- and 13.4-m locations.

Because of the difficulty of mentally retaining differences in the observed flow patterns, 12 tests were repeated and recorded on videotape. The tests were viewed and replayed for comparative observations. After observing these tapes, the 4.6-m block height was considered too high because the water was overly deflected upward in the basin. Also the 6.1-m block location was suspected of being too close to the chute tow. A conclusion from the tests was that 4.0-m-high floor blocks should be used, but further tests should be made to determine the block location along the apron.

Solid floor blocks, without the metal plates, were used for the remaining tests. The blocks were placed symmetrically about the model centerline, and as nearly as possible one-half block width away from the sidewalls. Observations of previous tests disclosed most of the erosion had occurred within an hour after starting the model. Model velocities for the 6230-m^3/s (220 000-ft^3/s) test discharge were sufficient to produce sand movement 3.7 m (12 ft) downstream from the basin without the turbulence of the stilling basin. There was some erosion during the second hour of operation but farther downstream from the stilling basin. Therefore, the time duration of the erosion tests was changed from 2 hours to 1 hour to be more representative of erosion caused by turbulence from the stilling basin. Photographs did not provide the desired detail for comparing erosion of the different appurtenance tests. To better define erosion, a reference grid with 3.0-m (10-ft) openings was placed in the model. Sketches were made of the erosion contours, previously formed with strings, by observation through the reference grid (fig. 17).

Tests R11 through R14 were performed without an end sill, with floor blocks 4.0 m high by 2.9 m wide (13 by 9.5 ft), and at 6.1-, 8.5-, 11.0-, and 13.4-m (20-, 28-, 36-, and 44-ft) locations. Floor block spacing is shown in figure 14b and the erosion contours in figures 17a to 17d. There was slightly greater erosion at the 6.1- and 8.5-m locations than at the 11.0- and 13.4-m locations. However, this erosion difference was not great enough to decide conclusively on a floor block location. Extensive flow observations of the 6.1-m location showed that the jet flowing down the spillway chute did not penetrate to the stilling basin floor at this point. Dye placed at the junction of the chute and stilling basin floor (chute toe) readily moved a short distance upstream on the spillway chute. Thus, there was separation of the flow from the chute surface before the flow reached the chute toe. The floor blocks were shown to be too close to the spillway chute and were crowding the flow exiting from the chute. Therefore, the 6.1-m location was not studied further.

Previous tests had not determined whether the stilling basin performed best with or without a dentated end sill. In the earlier tests with end sills there was considerable erosion of bed material along the wall, indicating the end sill structures were too large. Possibly with a smaller sill and dentates, the eddies generated from the dentates would be smaller and produce smaller velocity fluctuations acting on the channel bed. Tests R15 through R17 included a 1.5-m-high dentated end sill and the same floor blocks at the 8.5-, 11.0-, and 13.4-m locations. Again, the erosion tests did not conclusively show the best block location. However, comparisons of the erosion tests with and without the end sill showed that the stilling basin performed best with the dentated end sill. For each block location there was less erosion with the end sill than without. (Compare figs. 17e, f, and g to 17b, c, and d.)

The final choice for the floor block location was not based entirely on the results of the erosion tests. Visual observations showed the 8.5-m (28-ft) location to be unsatisfactory because: (1) water surface downstream from the stilling basin had the greatest wave action, (2) water surface roughness from the flow boiling upwards from the floor blocks was the

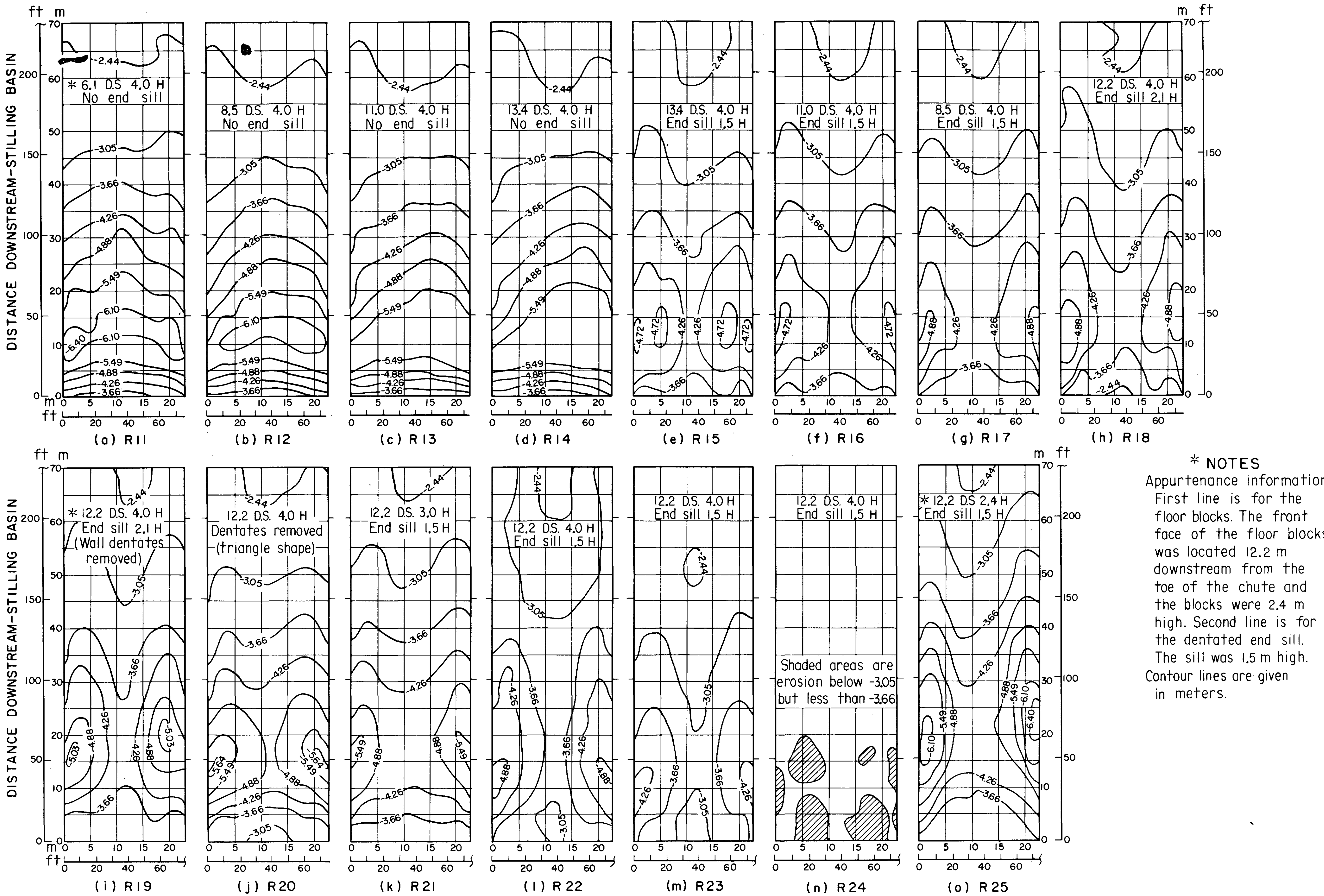


Figure 17.–Erosion tests R11 through R25.

greatest, and (3) pulsations of water near the toe of the hydraulic jump were the most violent.

The visual observations or erosion tests did not show a distinct advantage for the 11.0- or 13.4-m (36- or 44-ft) locations, and the final choice was made because of structural reasons. In the prototype structure design there was a joint in the concrete floor slab at the 12.19-m (40-ft) location. If the downstream end of the floor blocks were at the 12.19-m location, then the upstream faces of the blocks would be at 7.62 m (25 ft)–too close to the chute toe. Because it was undesirable for the blocks to extend over the floor joint, placing the upstream face of the blocks at the 12.2-m location was considered optimum. Evidence from model erosion tests and flow observations indicated there was no need to change the floor joint location.

For test R18, the 2.1-m (7-ft) high dentated end sill was reinstalled in the model. Erosion was similar to that of a 1.5-m (5-ft) high sill. (Compare fig. 17h to figs. 17e and f.) Because erosion depth was not decreased by the higher sill, the 1.5-m sill was considered satisfactory. The smaller sill also had the advantage of less concrete.

In R19 the partial width dentates against each sidewall on the 2.1-m-high sill were removed to study wall effects. There was more erosion for test R19 than for R18 (figs. 17i and h). Thus, the small partial dentates against the sidewalls did not appear detrimental in the model. For test R20, all the dentates were removed to simulate effects of a 1.1-m (3.7-ft) high triangular end sill. The shape of the remaining sill was a triangle of base L and height M (fig. 14d), which was different than a normal solid triangular end sill. However, the erosion test gave an indication that the dentated end sill was better than a solid triangular end sill. Erosion for the triangular end sill for test R20 was greater than either the 2.1- or 1.5-m-high dentated end sills (figs. 17g, h, and j). Thus, test R20 was considered to confirm the test results of R7: that the solid triangular end sill was less beneficial to the stilling basin than a dentated sill.

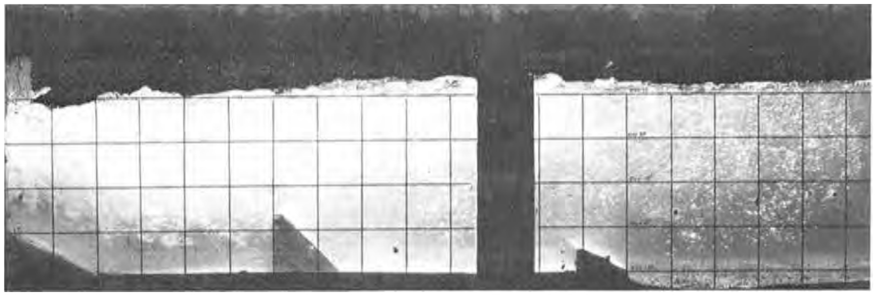
The remaining tests R21 through R25 were to optimize size of the floor blocks and make tests for the recommended stilling basin. In test R21, the floor block height was reduced and the blocks were 3.0 m (10 ft) high, but still 2.9 m (9.5 ft) wide. The erosion increased (figs. 17k and g) and, thus, the 4.0-m (13-ft) height was believed optimum. In test R22, the width of the 4.0-m-high floor blocks was reduced from 2.9 to 2.3 m (9.5 to 7.5 ft). Erosion was slightly less than that of the 2.9-m (9.5-ft) wide blocks (figs. 17l and g). Thus, the 4.0-m-high by 2.3-m-wide blocks were considered optimum for the recommended stilling basin. Test R23, with the recommended design and a 4980-m^3/s (176 000 ft^3/s) flood, produced less erosion than the 6230-m^3/s flood (figs. 17m and l); and a 2710-m^3/s flood passing through a 3.05-m (10-ft) uniform opening of the gates produced comparatively insignificant erosion (fig. 17n). Stilling basin flow conditions for tests R22, R23, and R24 are shown in figure 18.

Test R25 was made with floor blocks 2.4 m high and 1.9 m wide (8 ft and 6.25 ft). This test provided a positive check against decreasing floor block size, since there was significantly more erosion (figs. 17l and o). Test R25 was interpreted to mean that this block size was substantially smaller than an optimum block size for the low Froude number stilling basin.

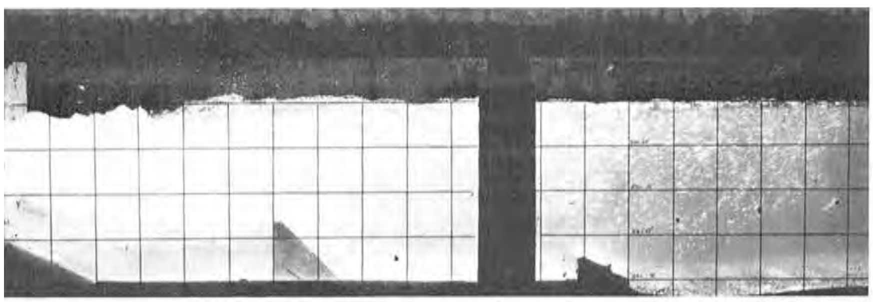
The recommended design stilling basin appurtenances were 4.0-m high by 2.3-m wide (13- by 7.5-ft) floor blocks, 12.2 m (40 ft) downstream from the chute toe, and a 1.5-m (5-ft) high dentated end sill.

Pressure Measurements

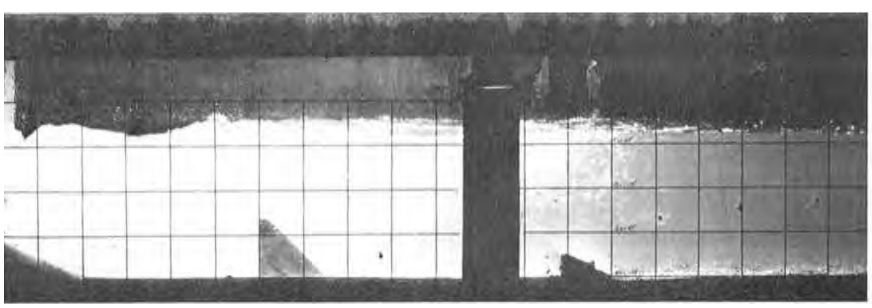
Cavitation erosion can occur on floor blocks and on the stilling basin floor near the blocks (fig. 19). Therefore, measurements were made on a model floor block to check for cavitation pressures. The erosion locations shown in figure 19 were used as guides for locating piezometer taps in the model. Piezometer taps were placed within and upstream from the damaged areas and along the centerline of the floor block (figs. 20b and c). Also, piezometer taps were placed along the centerline upstream and downstream from the floor



a. Test R22–6230 m³/s (220 000 ft³/s) and 9.45-m (31-ft) tailwater elevation.



b. Test R23–4980 m³/s (176 000 ft³/s) and 8.60-m (28.2-ft) tailwater elevation.



c. Test R24–Gate opening 3.05 m (10 ft), 2710 m³/s (95 600 ft³/s), and 6.71-m (22-ft) tailwater elevation.

Figure 18.–Flow in the recommended stilling basin. Photo P801-D-79044

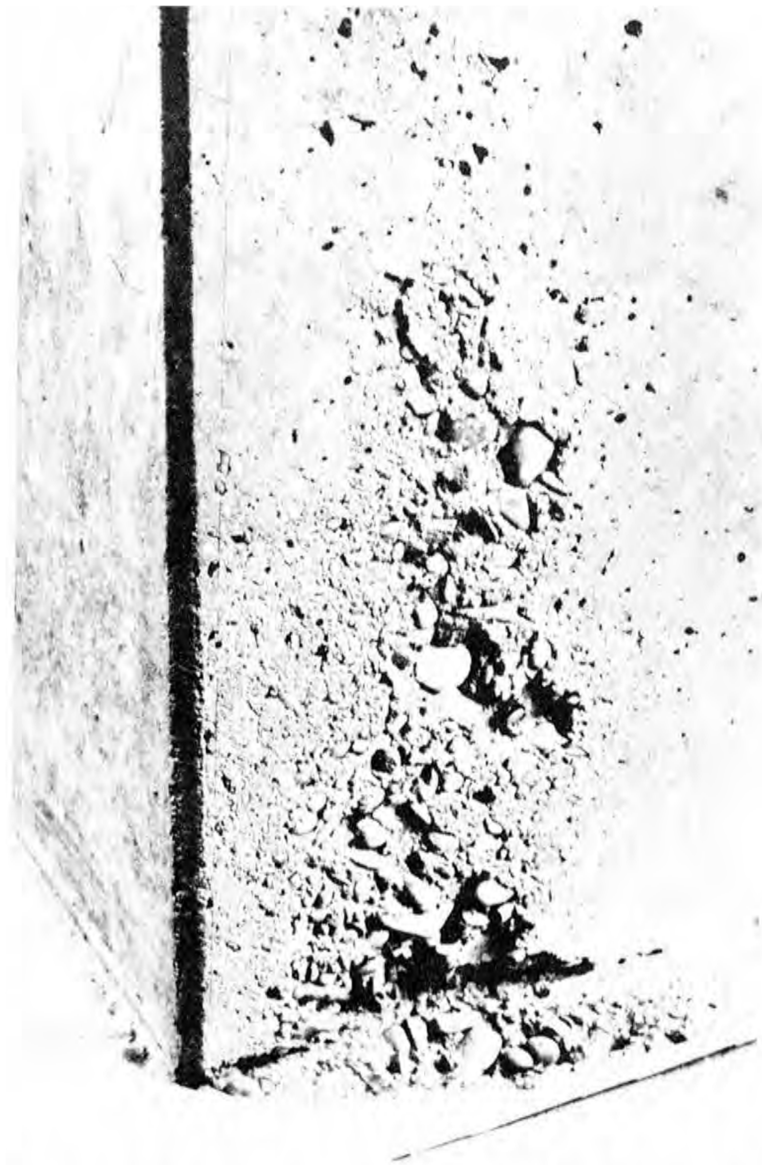
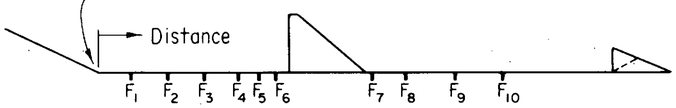
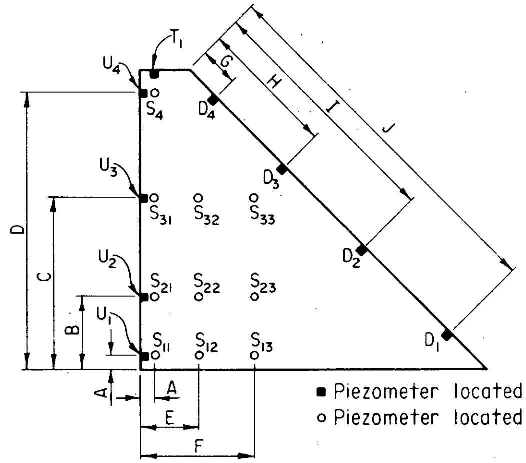


Figure 19.–Cavitation erosion of a floor block, in a prototype structure having a head and basin velocity approximately the same as Palmetto Bend at maximum design flow. View looking at the side of the floor block, flow from left to right. Photo P801-D-79046

Floor Piezometer	Distance, meters	Distance, feet
F_1	2.3	7.5
F_2	4.6	15.0
F_3	6.9	22.5
F_4	9.1	30.0
F_5	10.3	33.75
F_6	11.4	37.5
F_7	17.5	57.5
F_8	19.8	65.0
F_9	22.9	75.0
F_{10}	25.9	85.0



a. Location of floor piezometers on centerline of the model stilling basin floor.

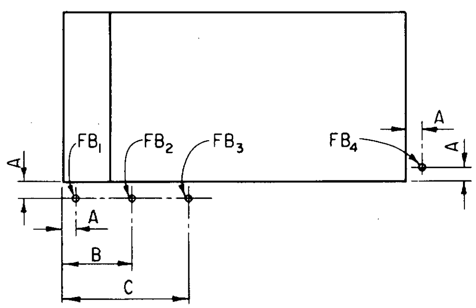


Dimension	Distance, meters	Distance, feet
A	0.15	0.5
B	0.98	3.2
C	2.29	7.5
D	3.63	11.9
E	0.76	2.5
F	1.52	5.0
G	0.55	1.8
H	1.83	6.0
I	3.35	11.0
J	4.88	16.0

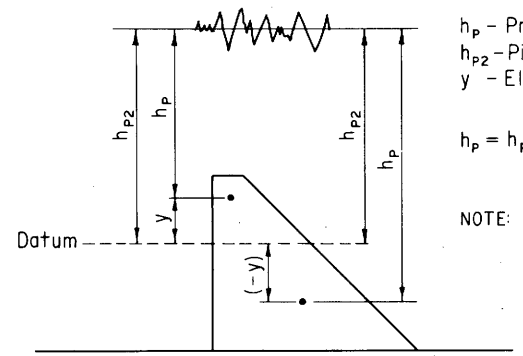
■ Piezometer located on centerline of the floor block.
○ Piezometer located on side of the floor block.

c. Side view of floor block showing piezometer locations on the block.

Dimension	Distance, meters	Distance, feet
A	0.15	0.5
B	0.91	3.0
C	1.65	5.4



b. Plan view of floor block showing piezometer locations on stilling basin floor near the block.



h_p - Pressure head
h_{p2} - Piezometric head
y - Elevation

$h_p = h_{p2} - y$

NOTE: When the piezometer tap is below the datum, values of "y" are negative in the above equation.

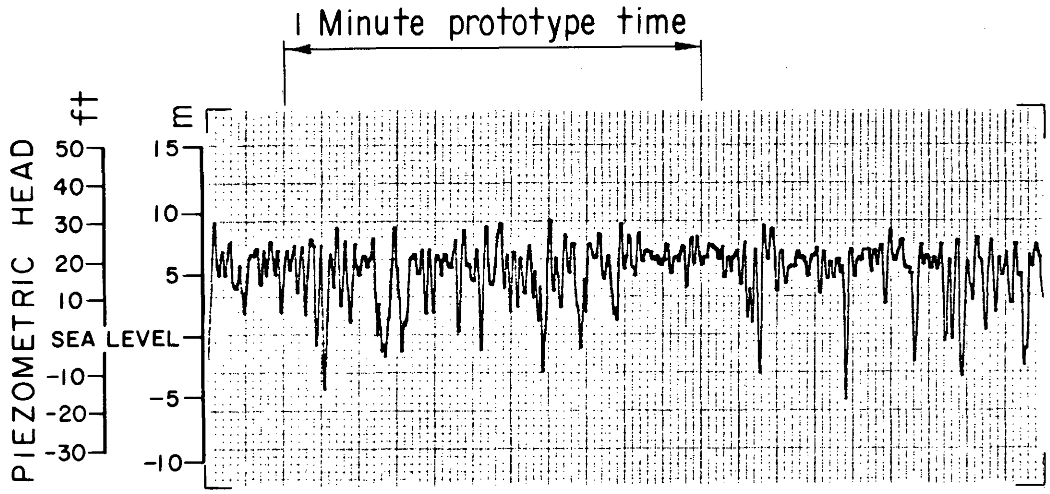
d. Definition sketch for pressure head and piezometric head. Sea level (zero elevation) was the reference datum for the piezometric head measurements.

Figure 20.–Location and identification of piezometer taps.

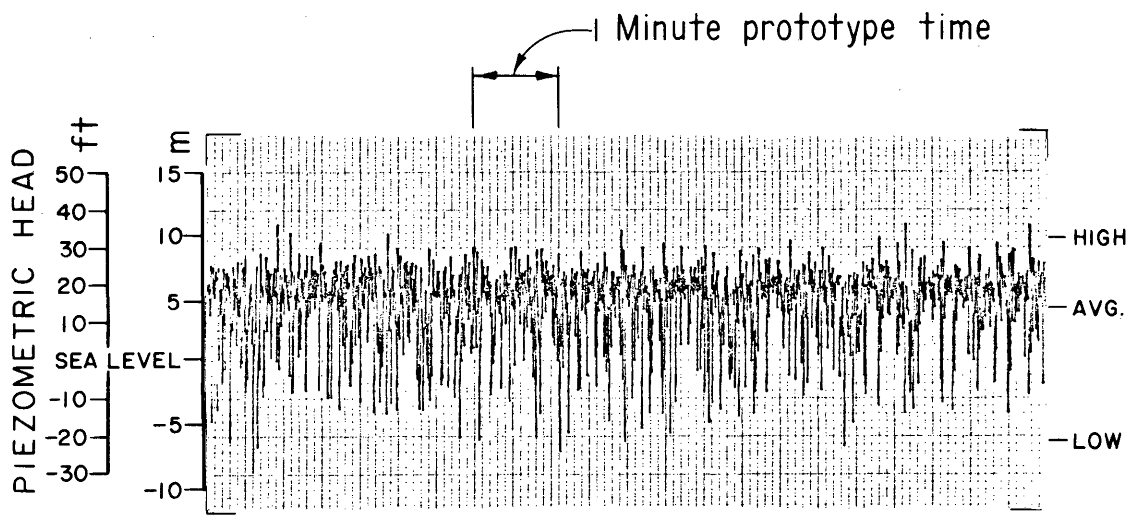
block on the stilling basin floor to obtain design information (fig. 20a). The floor block was installed on the model centerline and was exposed to flow from the full width bay. Oscillograph records of the piezometric head fluctuations were taken using a pressure transducer for free crest flow conditions of 6230 and 4980 m^3/s (220 000 and 176 000 ft^3/s), and for 2710 m^3/s (95 600 ft^3/s) with a 3.0-m (10-ft) gate opening.

Pressure fluctuations were severe for many of the piezometer taps (fig. 21). The 5-mm/s paper speed of figure 21a shows numerous pressure fluctuations occurring within a minute of prototype time and also the random nature of the occurrence. The 1-mm/s paper speed used for figure 21b gives a longer record for showing the peak high and low pressures. Thus, the 1-mm/s paper speed oscillograph records were used for making a pressure analysis. An average and a high and a low head were determined for each piezometer tap in the following manner: A clear plastic rectangle with a straight scribed line was placed over the oscillograph. Then the plastic was positioned until fluctuations above and below the line were balanced to obtain the average. The most extreme value was not used for the high and low, but instead, an arbitrary method was used which selected the two maximum and minimum pulses for a given minute. For example, when obtaining the high value, the scribed line was moved upward until only two fluctuations for any given prototype-minute time interval exceeded this value. Then, at this position on the graph the piezometric head beneath the scribed line was recorded. Low heads were obtained in a similar manner. The high, average, and low heads are shown on figure 21b.

Average, high, and low piezometric heads are given in table 1, along with the piezometer tap elevation. Thus, the pressure head, in feet of water, acting at a given piezometer is the piezometric head minus the piezometer tap elevation (fig. 20d). These high and low heads indicate maximum and minimum pressure surges that may occur and the fact that two high and low pressure surges of this magnitude can occur in 1 minute. There will be many surges smaller than these values and very few of greater value (fig. 21b).



a. Paper speed 5 mm per second for model tests.



b. Paper speed 1 mm per second for model tests.

Figure 21.–Oscillographs for piezometer S4. The test condition was 6230 m^3/s (220 000 ft^3/s) at 9.45-m (31-ft) tailwater elevation.

Table 1.–*Piezometric head measurements made on the stilling basin floor and floor block in the 1:30 scale Palmetto Bend Dam Spillway sectional model**

SI Metric

Piezometer identification	Piezometer EL in prototype (meters)	PIEZOMETRIC HEADS											
		Q = 6230 m^3/s Tailwater EL 9.45 m			Q = 6230 m^3/s Tailwater EL 7.92 m			Q = 4980 m^3/s Tailwater EL 8.60 m			Q = 2710 m^3/s Tailwater EL 6.71 m (3.0-m gate opening)		
		High	Avg.	Low	High	Avg.	Low	High	Avg.	Low	High	Avg.	Low
F_1	-3.0	10.4	9.8	9.1	8.8	8.5	8.2	9.8	9.1	8.5	7.3	6.4	5.5
F_2	-3.0	10.1	9.4	8.8	7.6	7.3	7.0	9.1	8.5	7.9	6.7	6.1	5.5
F_3	-3.0	10.1	9.4	9.1	8.2	7.9	7.6	9.1	8.8	8.5	6.7	6.1	5.5
F_4	-3.0	11.3	11.0	10.4	10.4	9.8	9.1	10.4	10.1	9.8	7.6	6.4	6.1
F_5	-3.0	12.5	11.9	11.0	11.9	11.3	10.4	11.6	11.0	10.4	8.5	7.3	6.7
F_6	-3.0	15.2	12.2	9.1	14.6	11.6	7.9	14.0	11.3	7.9	10.4	7.9	4.9
F_7	-3.0	10.4	8.2	5.5	8.5	6.4	3.7	9.1	8.2	6.1	6.7	6.1	5.5
F_8	-3.0	10.4	9.4	7.3	8.8	7.6	6.4	9.8	8.8	7.3	6.7	6.4	6.1
F_9	-3.0	9.8	9.4	9.1	8.5	7.9	7.3	9.1	8.8	8.5	6.7	6.4	6.1
F_{10}	-3.0	9.8	9.4	9.1	8.5	7.9	7.3	9.1	8.8	8.5	6.7	6.4	6.1
U_1	-2.9	16.5	14.6	12.2	17.7	14.6	12.2	16.5	13.4	10.4	12.2	9.1	7.0
U_2	-1.9	17.1	14.6	12.2	17.7	14.6	11.6	16.5	14.0	11.6	13.4	9.1	6.7
U_3	-0.8	17.1	14.9	10.4	17.1	14.6	12.2	15.8	13.7	9.8	8.5	7.9	6.1
U_4	0.6	15.8	12.8	9.1	14.6	11.6	7.9	14.0	11.6	8.5	8.5	6.7	5.5
T_1	0.9	7.6	6.7	4.9	5.5	4.3	2.4	7.3	6.4	4.9	6.4	5.8	5.2
D_4	0.6	7.9	6.4	4.3	5.5	4.3	2.4	7.3	6.1	5.5	6.4	5.8	5.2
D_3	-0.4	8.5	7.0	4.9	6.1	4.9	3.7	7.9	6.7	5.5	6.4	6.1	5.8
D_2	-1.5	9.8	7.3	4.3	7.3	5.5	3.7	8.5	7.3	6.1	6.4	6.1	5.8
D_1	-2.5	9.8	7.9	6.1	7.3	6.1	4.3	8.5	7.9	6.7	6.4	6.1	5.8
S_{11}	-2.9	9.1	4.9	-0.9	6.1	2.4	-6.7	7.9	4.9	-3.7	6.7	4.3	-2.4
S_{12}	-2.9	9.8	4.9	-1.5	6.1	1.8	-7.0	8.5	4.9	-1.8	7.3	4.9	0
S_{13}	-2.9	11.6	5.5	2.7	8.5	3.7	-3.0	9.1	6.1	-0.3	7.3	4.9	2.1
S_{21}	-1.9	8.5	4.9	-0.6	4.9	1.8	-3.4	7.3	4.9	-0.3	6.1	4.3	-0.3
S_{22}	-1.9	9.1	4.3	-1.2	5.5	1.8	-5.5	7.9	4.3	-2.4	6.7	4.3	-0.9
S_{23}	-1.9	10.4	4.9	0.6	6.1	2.4	-3.7	9.1	4.9	-0.9	7.3	5.5	1.8
S_{31}	-0.8	9.1	5.2	-1.2	5.5	2.4	-4.0	7.3	4.9	-0.3	6.7	4.3	-1.2
S_{32}	-0.8	9.8	4.3	-1.2	6.7	1.8	-6.4	8.5	4.3	-2.4	7.3	4.9	-0.6
S_{33}	-0.8	12.2	5.5	-1.8	8.5	2.4	-5.8	10.4	4.9	-1.5	7.9	5.8	1.5
S_4	0.6	9.8	4.3	-6.7	7.9	3.0	-10.4	8.5	5.5	-5.8	7.3	4.3	-2.1
FB_1	-3.0	11.6	4.3	-1.2	7.3	2.4	-6.1	9.1	4.9	-3.0	7.9	4.3	-3.4
FB_2	-3.0	11.0	4.9	0	6.1	2.4	-7.6	9.1	4.9	-3.0	7.3	4.7	-1.2
FB_3	-3.0	11.0	5.5	1.8	8.5	3.7	-4.3	9.8	6.1	-1.2	7.3	5.8	1.2
FB_4	-3.0	16.5	7.9	0	12.2	6.1	-5.2	12.8	7.9	-1.2	6.1	4.6	3.7

* Measurements given in meters of water with the datum at sea level. (See fig. 20 for piezometer location and definition sketch.)

Table 1.—*Piezometric head measurements made on the stilling basin floor and floor block in the 1:30 scale Palmetto Bend Dam Spillway sectional model**

U. S. Customary

Piezometer identification	Piezometer el. in prototype (feet)	PIEZOMETRIC HEADS: Q = 220 000 ft^3/s Tailwater El. 31 ft			Q = 220 000 ft^3/s Tailwater El. 26 ft			Q = 176 000 ft^3/s Tailwater El. 28.2 ft			Q = 95 600 ft^3/s Tailwater El. 22 ft (10-ft gate opening)		
		High	Avg.	Low	High	Avg.	Low	High	Avg.	Low	High	Avg.	Low
F_1	-10	34	32	30	29	28	27	32	30	28	24	21	18
F_2	-10	33	31	29	25	24	23	30	28	26	22	20	18
F_3	-10	33	31	30	27	26	25	30	29	28	22	20	18
F_4	-10	37	36	34	34	32	30	34	33	32	25	21	20
F_5	-10	41	39	36	39	37	34	38	36	34	28	24	22
F_6	-10	50	40	30	48	38	26	46	37	26	34	26	16
F_7	-10	34	27	18	28	21	12	30	27	20	22	20	18
F_8	-10	34	31	24	29	25	21	32	29	24	22	21	20
F_9	-10	32	31	30	28	26	24	30	29	28	22	21	20
F_{10}	-10	32	31	30	28	26	24	30	29	28	22	21	20
U_1	-9.6	54	48	40	58	48	40	54	44	34	40	30	23
U_2	-6.2	56	48	40	58	48	38	54	46	38	44	30	22
U_3	-2.5	56	49	34	56	48	40	52	45	32	28	26	20
U_4	1.9	52	42	30	48	38	26	46	38	28	28	22	18
T_1	3	25	22	16	18	14	8	24	21	16	21	19	17
D_4	1.8	26	21	14	18	14	8	24	20	18	21	19	17
D_3	-1.2	28	23	16	20	16	12	26	22	18	21	20	19
D_2	-4.8	32	24	14	24	18	12	28	24	20	21	20	19
D_1	-8.3	32	26	20	24	20	14	28	26	22	21	20	19
S_{11}	-9.6	30	16	-3	20	8	-22	26	16	-12	22	14	-8
S_{12}	-9.6	32	16	-5	20	6	-23	28	16	-6	24	16	0
S_{13}	-9.6	38	18	9	28	12	-10	30	20	-1	24	19	7
S_{21}	-6.2	28	16	-2	16	6	-11	24	16	-1	20	14	-1
S_{22}	-6.2	30	14	-4	18	6	-18	26	14	-8	22	14	-3
S_{23}	-6.2	34	16	2	20	8	-12	30	16	-3	24	18	6
S_{31}	-2.5	30	17	-4	18	8	-13	24	16	-1	22	14	-4
S_{32}	-2.5	32	14	-4	22	6	-21	28	14	-8	24	16	-2
S_{33}	-2.5	40	18	-6	28	8	-19	34	16	-5	26	19	5
S_4	1.9	32	14	-22	26	10	-34	28	18	-19	24	14	-7
FB_1	-10	38	14	-4	24	8	-20	30	16	-10	26	14	-11
FB_2	-10	36	16	0	20	8	-25	30	16	-10	24	16	-4
FB_3	-10	36	18	6	28	12	-14	32	20	-4	24	19	4
FB_4	-10	54	26	0	40	20	-17	42	26	-4	20	15	12

* Measurements given in feet of water with the datum at sea level. (See fig. 20 for piezometer location and definition sketch.)

The model cannot correctly scale the cavitation phenomenon. A minus 10-m (minus 34-ft) water pressure head at sea level is sufficient for formation of a cavitation vapor pocket in water. If there is cavitating flow in a prototype structure, a vapor pocket forms and changes the waterflow geometry near the structure boundary. At the 1:30 scale model velocities no vapor pocket forms, but the tendency for separation of flow causes a decrease in the pressure along the boundary. Although the cavitation phenomenon is not accurately scaled, the model is a very valuable tool for detecting locations of potential cavitation erosion in the prototype structure by the measurement of pressures on the boundaries. The model indicates low pressure areas in the prototype where vapor pockets may form and points out the potential vapor pocket formation and implosion associated with cavitation damage.

The pressure analysis was directed mainly at detecting cavitation potential for the stilling basin floor blocks. For minimum piezometric heads in table 1 (indicating possible incipient cavitation pressures), there is the implication that two vapor pocket implosions per minute could occur on the prototype structure, based on the arbitrary pressure analysis. Only at piezometer S4 and for one flow condition was there an indication that cavitation pressures could occur. At this location, the minimum pressure head, (-10.4)-(0.6) = -11.0 m [(-34 ft)-(2 ft) = -36 ft], was less than the minus 10-m (minus 34-ft) pressure head that is associated with incipient cavitation. Thus, the S4 oscillograph was again examined for the number of times the scaled prototype piezometric head was indicated to be minus 9.8 m (minus 32 ft) or lower. During the 15-minute prototype time of record there were 29 occurrences on an average of two pulses every minute. The extreme minimum was minus 12.8 m (minus 42 ft) and there were 16 pulses between minus 11.3 to minus 12.8 m (minus 37 to minus 42 ft). These measurements indicated the potential of cavitation occurring on the upper sides of the floor blocks for this one flow condition.

A literature search was made for hydraulic model studies relating to prototype cavitation of floor blocks. One applicable report by the Corps of Engineers was found.[3] The report describes a 1:36 scale model-prototype study of Clayton Dam stilling basin in Virginia. The prototype basin experienced a 4-day duration flood. There was superficial pitting on the side surface of some of the concrete baffle blocks. Afterwards, pressure transducer measurements were made in a model study of the blocks. In the critical areas, instantaneous pressures scaled from the model were lower than cavitation pressures about 25 to 30 percent of the time. A figure in the report of the model oscillograph showed a scaled minimum pressure pulse of minus 19.8 m (minus 65 ft) and for a selected 1-minute period 12 pressure pulses between minus 15.2 and minus 19.8 m (minus 50 and minus 65 ft).

The measured low pressure at S4 appeared mild compared to the Clayton model measurements. These low S4 pressures occurred for the maximum design flood and at a 1.5-m (5-ft) lower tailwater elevation than given by the tailwater rating curve (fig. 2). There appeared to be little likelihood this event will occur, and if so, the flood peak will pass in a matter of hours. For all other piezometers and at all the tested flow conditions, there was no indication of cavitation pressures. Therefore, the floor blocks were judged safe from cavitation erosion.

SPILLWAY CREST AND GATES

Discharge Capacity

The 1:30 scale sectional model allowed more precise measurements of the spillway capacity than the 1:100 scale model. However, an excellent opportunity existed for comparing results from the two models and, therefore, measurements were made for both scales. Water surface elevation measurements were made 43 m (140 ft) upstream from the spillway crest,

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[3] "A Laboratory Development of Cavitation-free Baffle Piers, Bluestone Dam, New River, West Virginia," Technical Memorandum No. 2-243, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Miss., March 1948.

both on the centerline of the approach channel for the 1:100 scale model and on the model centerline for the 1:30 scale model. This 43-m distance was a four-bay-width distance and upstream from major drawdown effects of flow approaching the spillway. Also, water surface elevation measurements were made in the 1:100 scale model reservoir for freeflow over the spillway crest.

The two models showed essentially the same discharge capacity for the 0.3- to 1.5-m (1- to 5-ft) gate openings (fig. 22), but diverged for the 3.0- and 4.6-m (10- and 15-ft) gate openings. Also, for flows larger than the 5665-m^3/s (200 000-ft^3/s) freeflow discharge, the test results increasingly diverged.

Discharge rating curves (solid lines) were obtained from the 1:30 scale model data and include the velocity head $V^2/2g$ of the approach flow computed from the discharge and flow area (fig. 22). With inclusion of velocity head, the freeflow discharge curve for the 1:30 scale falls slightly below the 1:100 scale model reservoir water surface elevations. This difference resulted from head losses, both as an entrance loss from the model reservoir into the approach channel and from channel surface resistance to the water flowing through the channel in the 1:100 scale model. Thus, the discharge curves do not represent the reservoir water surface elevation, but rather, the energy head (depth plus velocity head) at the point in the model channel where the measurements were made. The discharge curves of figure 22 were converted to those for an individual gate (fig. 23).

Gate Operation

Observations of spillway flow were made for different modes of gate operation in the 1:100 scale model. Initial tests were made with 1.5-m (5-ft) gate openings. Operating one or more gates only on one side of the spillway produced a large eddy in the stilling basin adjacent to the opened gates. Fine sand, placed in the eddy, circulated within the eddy on the stilling basin floor. The eddy was of sufficient size to extend downstream beyond the end of the apron and the return flow moved fine sand into the model basin. Another undesirable flow

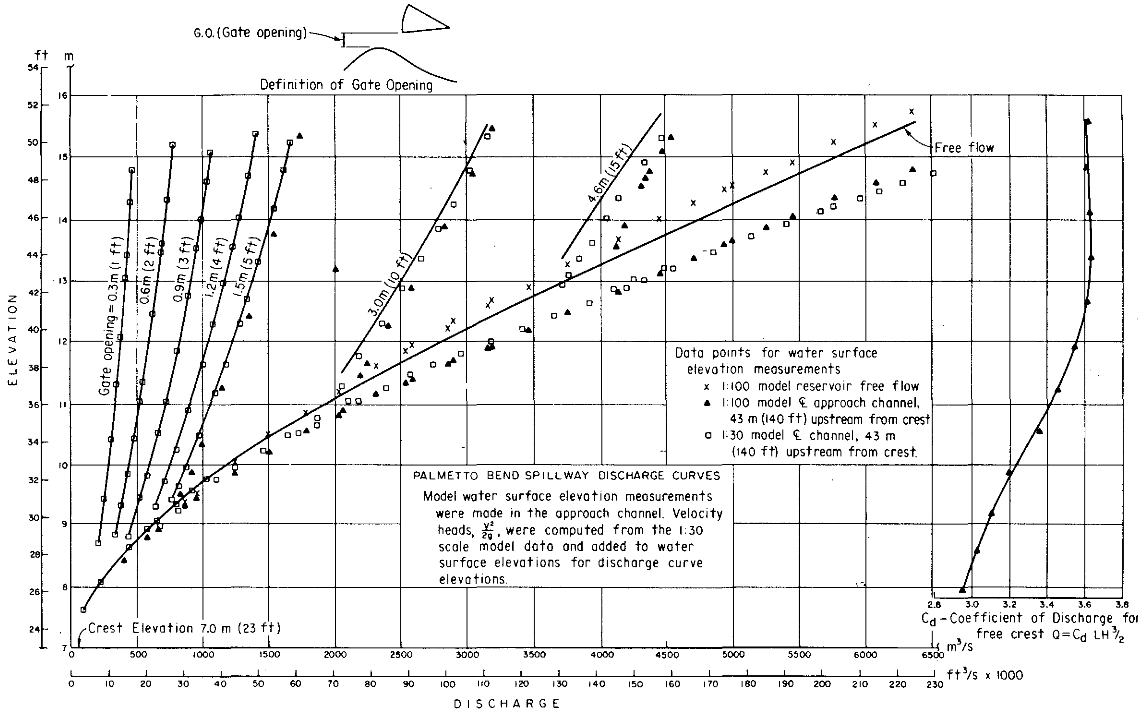

Figure 22.–Spillway discharge curves.

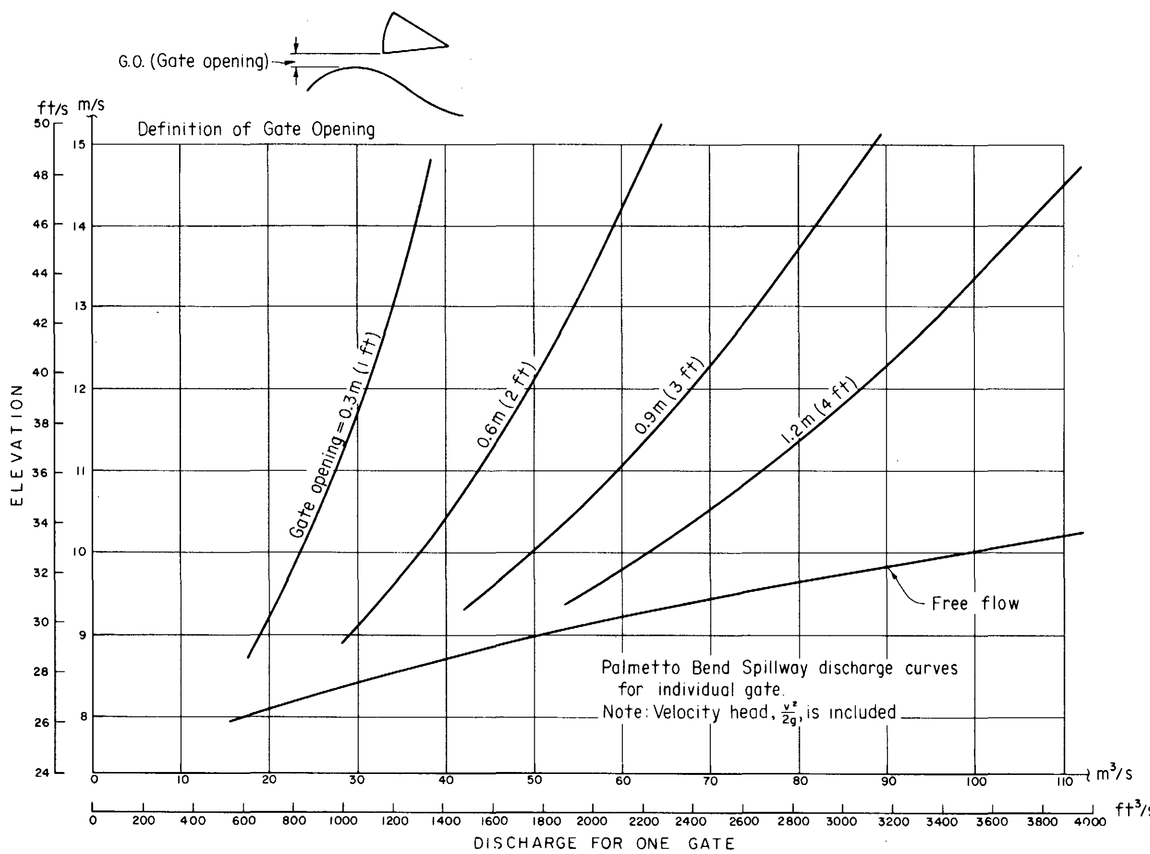

Figure 23.–Spillway discharge curves for one gate.

condition resulted when every other gate was opened: There were eddies in the stilling basin downstream from the unopened gates.

From the above model observations, judgments were made concerning spillway operation to prevent adverse eddy conditions in the stilling basin. For small discharge through the spillway, small gate openings and sequential (for example, gate 1, then 2, etc.) operation of adjacent gates are recommended. Preferably a small gate opening of 0.15 m (0.5 ft) should be used, but if this is not possible, an opening not greater than 0.3 m (1 ft) will minimize the eddy intensity in the stilling basin.

APPENDIXES

APPENDIX A

LOG OF TESTS WITH THE OVERALL 1:100 SCALE MODEL

In the notes which follow, TW designates the tailwater elevation and DS designates the front face of the floor blocks which are located a given distance downstream from the toe of the spillway chute.

Test No.	Notes
1T	Approach channel 141 m (464 ft) wide, 83° bend, smooth floor stilling basin, 46 m (150 ft) long, at minus 4.3 m (minus 14 ft) below sea level.
2T	Added spur dike near approach channel and a 3.0-m (10-ft) high by 6.1-m (20-ft) long triangular end sill.
3T	Added a dike on inside bank of approach channel. Upstream of curve tangent the dike extended back toward the dam.
4T	Installed a new approach channel 172 m (564 ft) wide and 91° bend.
5T	Installed 45° spillway entrance walls and a 3.0-m-high by 6.1-m-long rectangular end sill shape that extended 9.1 m (30 ft) in from each spillway side.
6T	Installed 118-m (387-ft) long dikes along each side of exit channel and removed rectangular end sill shape.
7T	Installed downstream-most counterfort end extensions on spillway end wall and removed 45° spillway entrance walls.

Test No.	Notes
8T	Installed floor blocks 9.1 m downstream from chute toe of spillway, blocks 3.0 m high, 3.7 m (12 ft) long, and 2.3 m (7.5 ft) wide.
9T	Same as 8T except TW 7.9 m (26 ft) [TW 7.9 m (26 ft)].
10T	Removed end extensions and same as 9T.
11T	Repeat of 10T, but TW 9.4 m (31 ft).
12T	Installed dentated end sill 12.2 m (40 ft) upstream from end of stilling basin, sill with dentates 2.7 m (9 ft) high, 5.8 m (19 ft) long, and 2.1 m (6.75 ft) wide.
13T	Same as 11T, but TW 7.9 m (26 ft).
14T	Raised stilling basin floor 1.2 m (4 ft), up to minus 3.0-m (minus 10-ft) elevation below sea level.
15T	Same as 14T, but TW 7.9 m.
16T	Removed 6.1-m (20-ft) length from stilling basin, TW 9.4 m (31 ft).
17T	Same as 16T, but TW 7.9 m.
18T	Removed another 5.5-m (18-ft) length from stilling basin [basin 34.1 m (112 ft) long], TW 9.4 m (31 ft).
19T	Same as 18T, but TW 7.9 m (26 ft).

Test No.	Notes
20T	Installed fine sand in exit channel downstream from stilling basin, then same as 18T.
21T	Two-foot plywood board to simulate soil-cement protection for 61-m (200-ft) bottom length of exit channel.
22T	Same as 21T, except removed box that contained fine sand.
23T	Wall effect test to better understand wall erosion in sectional model. Extended stilling basin sidewalls 4 model feet into exit channel.
24T	Same as 23T, except removed dentated end sill and made tests.
25T	Installed floor blocks and dentated end sill of the design prototype. Removed the extended stilling basin sidewalls. This was the design stilling basin except the basin was 2.4 m (8 ft) shorter than the design 36.6-m (120-ft) length. TW 9.4 m (31 ft).
26T	Removed fine sand and replaced with original sand, same as 24T.

APPENDIX B

LOG OF TESTS WITH THE SECTIONAL 1:30 SCALE MODEL

In the notes which follow, TW designates the tailwater elevation and DS designates the front face of the floor blocks which are located a given distance downstream from the toe of the spillway chute.

Test No.	Notes
R1	Floor blocks only in stilling basin, located 8.5 m (2.8 ft) DS, 3.0 m (10 ft) high, 2.4 m (8.0 ft) wide, discharge 6230 m^3/s (220 000 ft^3/s), and 9.45 m (31 ft) TW. Bad inflow conditions.
R2	Same as R1, but made adjustments to inflow.
R3	Same as R1 except discharge 4980 m^3/s (176 000 ft^3/s and 8.60 m (28.2 ft) TW. Discovered side seal projecting into flow.
R4	Same as R1.
R5	Same as R3.
R6	Gated flow, 3.0-m (10-ft) gate opening discharge 2710 m^3/s (95 600 ft^3/s) and 6.71 m (22 ft) TW.
R7	Same as R1, but added a 3.0-m-high by 6.1-m-long (10- by 20-ft) triangular end sill with the back face located 21.3 m (70 ft) downstream from the chute toe of the spillway.
R8	Same as R7, but added chute blocks 2.4 m high and 2.4 m wide (8 by 8 ft) and removed triangular sill.

Test No.	Notes
R9	Removed chute blocks and installed dentated end sill at the end of the stilling basin, dentates 2.1 m high and 1.6 m wide (7 by 5.25 ft).
R10	Same as R9 except 7.3-m (24-ft) TW. Checked if there was more favorable hydraulic jump action with less depth; there was not.
R11	Removed dentated end sill and installed new floor blocks, located 6.1 m (20 ft) DS, 4.0 m high, and 2.9 m wide (13 by 9.5 ft).
R12	Same as R11 except floor blocks located 8.5 m (28 ft) DS.
R13	Same as R11 except floor blocks located 11.0 m (36 ft) DS.
R14	Same as R11 except floor blocks located 13.4 m (44 ft) DS.
R15	Installed new dentated end sill, dentates 1.5 m high and 1.1 m wide (5 by 3.75 ft), floor blocks located 13.4 m (44 ft) DS.
R16	Same as R15 except floor blocks located 11.0 m (36 ft) DS.
R17	Same as R15 except floor blocks located 8.5 m (28 ft) DS.
R18	Reinstalled the 2.1-m (7-ft) high by 1.6-m (5.25-ft) wide dentated end sill to test with R11 floor blocks. The floor blocks were located 12.2 m (40 ft) DS.
R19	Same as R18 except removed each dentate tooth adjoining the wall.

Test No.	Notes
R20	Same as R18 except removed all dentate teeth to simulate flow action of a smaller size (than R7) triangular end sill.
R21	Reinstalled the 1.5-m high by 1.1-m wide (5- by 3.75-ft) dentated end sill; and smaller height floor blocks, located 12.2 m (40 ft) DS, 3.0 m high, and 2.9 m wide (10 by 9.5 ft). The width was similar to the height of the floor blocks.
R22	Installed new floor blocks, located 12.2 m (40 ft) DS, 4.0 m high, and 2.3 m wide (13 by 7.5 ft).
R23	Same as R22, but discharge 4980 m^3/s (176 000 ft^3/s) and 8.60 m (28.2 ft) TW.
R24	Same as R22, but gated flow, 3.0-m (10-ft) gate opening, discharge 2710 m^3/s (95 600 ft^3/s), and 6.71 m TW.
R25	Installed smallest size floor blocks, located 12.2 m (40 ft) DS, 2.4 m high, 1.9 m wide (8 by 6.25 ft), discharge 6230 m^3/s (220 000 ft^3/s) and 9.45 m (31 ft) TW.

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