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3 TO 100 SCALE MODEL STUDY OF CHUTE SPILLWAY

PENN FOREST DAM

for

Bethlehem Authority

by

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Hydraulic Laboratory
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INTRODUCTION

On April 15th, 1955, Mr. Robert L. Fox, Executive Director of the Bethlehem Authority inquired as to the possibility of conducting the subject model study at Lehigh, with a completion date of 1 September 1955. Laboratory arrangements were cleared by Professor W.J. Eney, Fritz Laboratory Director, and an agreement was drawn up by Dr. H.A. Neville, Director of the Institute of Research.

The final agreement (dated 9 June; original agreement made on 3 May - revised to final form to include change in prototype discharge specifications) included the following qualifications:

"The extent of the model will be from station - 4 + 00 to 12 + 00, using stationing indicated on Bethlehem Authority drawings dated October 1948. The model will be based upon the following specifications for the spillway:

> Maximum discharge 12,000 cfs. with the crest at Elev. 1000 and the Maximum Water level at Elev. 1012.5. The width of the forebay will be 85'; in the intiial tests the width of the chute will be 50', with a 40' width as a final objective. The floor of the stilling basin will not be lower than Elev. 880".

A letter dated 5 May 1955 from the Pennsylvania Department of Forests and Waters to Mr. Fox indicated a recommended spillway capacity of 8,740 cfs. Due to the complexity of operation with the future Penn Forest reservoir as part of the Wild Creek system, as well as other reasons, Mr. Fox specified on May 9th that the maximum design discharge would be set at 12,000 cfs.

The preliminary layout drawings of 1948 included an ogee spillway normal to the forebay, followed by a contracting horizontal curve. Mr. Fox was advised that this combination would result in shock waves at the curve of great height which would require very high walls and would disturb the flow throughout the length of the chute and in the stilling basin. The writers were given complete freedom in arriving at a sound, economical design, under the restrictions specified in the agreement. Location of foundation rock made it necessary to maintain the center line at or near the position shown in the 1948 drawings. The stilling basin T.W. was restricted to somewhere between Elev. 910 to 915, the capacity of a downstream canal.

The report which follows will describe the final, accepted design and then the developments or arrangements studied for each of the components of the overall structure. All dimensions are in terms of the prototype.

FINAL DESIGN

The drawings, photographs and data included in the Appendix of this report are for the final design, only. Details indicated in the accompanying photographs were observed on 22 June 1955 by Mr. Fox during the acceptance inspection. At this time Mr. Fox was accompanied by Mr. M.G. Mansfield of Morris Knowles, Inc., and Mr. Harvey R. Frantz and Mr. J.S. Richards of the Bethlehem Authority.

This design includes a constant slope chute from the crest at Sta. 0+00 and Elev. 1000 to Sta. 8+95 at Elev. 907. Flow is conveyed through a 28° bend in a subcritical (tranquil) state, and delivered to the crest without transverse disturbances. The forebay and horizontal curve floor at Elev. 992 is as high as possible without adversely affecting velocity distribution. The 150' straight forebay walls are optimum to insure rectilinear entrance of flow and to restrict ride-up of waves entering the forebay at any angle. To reduce this length to 130' should not materially reduce the safety of the spillway. The sloping section at the end of the horizontal curve is essential to development of a critical (control) condition at or near the crest. Although a 3' radius was recommended on 22 June, perhaps the best arrangement for maintaining a definite crest would be to use a fabricated steely inlay conforming to the slopes of the two panels; a width of 1' to 2' on each slope should be sufficient.

The straight wall contraction from 85' to 40' is the most economical and simple arrangement which will provide a minimum of shock wave disturbance in the chute, at all rates of flow. The straight walls are dictated by the presence of supercritical (or rapid) flow throughout the contraction.

The 40' chute width is a minimum with regard to chute flow performance and satisfactory stilling pool control.

The chute expansion is necessary to form a satisfactory hydraulic jump. The vertical curve at the end of the chute continues the expansion to the bucket-type dissipator and conveys the water from Elev. 907 in the shortest economical horizontal distance.

Use of a bucket-type dissipator permits use of a natural rock floor from the lip of the bucket to the downstream weir, inasmuch as high velocities are thrown to the water surface and not directed at or along the floor or walls. To accomplish satisfactory dissipation of energy in the short distance available with a horizontal stilling basin would have required a paved and wider channel at the end of the vertical curve with a correspondingly longer expansion. In addition, an extensive system of floor blocks and a heavily reinforced floor sill would no doubt have been necessary. The downstream velocity distribution would not be uniform with such a short horizontal basin; the final design has a very uniform velocity distribution, the only disadvantage being the formation of a wave chain within the area of the sloping floor. The bucket lip will require extensive reinforcing to resist the dynamic and static thrusts imposed by turning the jet through an angle of 45°. The straight edge of the bucket roller, upstream, indicates a good diffusion of the jet from the expansion. The weir (to Elev. 905) was incorporated to protect the stilling basin in the event of failure of the downstream canal (not part of this project) and to serve as a high-level tail-water control. The upstream edge of this sill could be moved upstream to Sta. 11 + 30 without seriously interfering with the stilling basin operation. If this is done, the horizontal distance (75' from the lip of the bucket) should not be reduced but the slope downstream increased accordingly.

During the acceptance inspection on 22 June, small stone was placed on the basin floor to a depth of about 3/4". No movement was noted at 6300 cfs. and 9200 cfs. At 12,000 cfs. the stone in the area extending from 75' to 45' from the lip accumulated about 30' from the lip. Some scour in this same area, with a rock floor, might be expected; however, if footings are placed at or near Elev. 875 undermining of the walls should not occur.

The tapered basin walls are arranged so as to contain the surface "boil" with a minimum of disturbance. The downstream channel width of 90' was selected to provide reasonable entrance velocities to the canal below the stilling basin.

The forebay walls are carried to the crest (Sta. 0+00) at Elev. 1015, the elevation of the top of the dam. All wall heights are measured normal to the floor. A 12' height at Sta. 1+54 (end of contraction) is more than adequate for the maximum discharge; the surplus was provided for wave ride-up in the event that surges are carried from the reservoir through the forebay, and to insure against over-topping since this section is adjacent to the earth dam. The largest shock wave disturbances occur between Sta. 1+54 and Sta. 4+00; therefore the walls taper from a 12' height to a 10' height at Sta. 4+00, continuing at a 10' height to Sta. 8+66. From Sta. 8+66 to the weir at Sta. 11+40 the top of the wall is maintained at Elev. 920. The depth of flow at the walls at Sta. 8+95 (P.C. of vertical curve) according to the model is less than 4' at the design discharge. However, the 10' wall height should be carried to Sta. 8+66 to provide for increased flow depths in the prototype as the result of air entrainment, which would be more pronounced in the lower reaches of the chute.

There is very little splash over the training walls beyond the bucket at 9,200 cfs. The splashing from the "boil" at 12,000 cfs. is not severe, but to protect adjacent fill it might be desirable to provide a narrow rip-rap strip adjacent to each wall, preferably sloping down towards the top of the walls. The walls beyond the bucket, above Elev. 910, are not subject to dynamic loads of significant magnitude, and this section of the walls can be designed as spray walls.

In the event that 12,000 cfs. might represent a discharge near the point where the jet from the bucket would spring free without a roller, in a special test the head was increased to Elev. 1014.6 at a discharge of 15,600 cfs. At this flow the maximum depths were 11', occurring at the crest, Sta. 1 + 54 and Sta. 2 + 20, with water levels below the top of the recommended walls at all points. Roller action was still good, splash was increased and flow to the 90' wide downstream channel was satisfactory. Therefore, with the weir intact (or corresponding tailwater) the bucket jet is controlled well beyond the design discharge of 12,000 cfs. A similar test was demonstrated at the acceptance inspection on 22 June with a reservoir water level of 1014.0 and 14,600 cfs. These tests indicate a safe, stable structure, throughout.

S P I L L W A Y   R A T I N G

The spillway width in the final design is 85'. The following coefficients were obtained for the equation $Q = K\ (85')\ H^{3/2}$, where H is the reservoir pool level above the crest (Elev. 1000) and Q is the discharge in cfs:

Condition	K
Theoretical, Horizontal crest:	3.10
Forebay Floor at Elev. 990, Contraction starting at Sta. 0 + 00:	3.30
Forebay Floor at Elev. 990, 85' width to Sta. 0 + 80:	3.39
Final Design, Forebay Floor at Elev. 992, Contraction commencing at Sta. 0 + 00:	3.25

From the above it may be noted that changing the downstream contraction and/or raising the forebay floor to Elev. 992 has a relatively small effect on the spillway rating. (The 85' width to Sta. 0 + 80 was obtained while experimenting with the contraction geometry).

The original, tentative design had included an ogee spillway which would have had a coefficient as high as 3.9. The final design requires a wider forebay and crest but delivers the flow to the contraction at an easily controlled velocity and at as high an elevation as possible. The increased cost of the wider approach channel is more than offset by the elimination of a massive concrete overflow section and expensive counter-disturbance floor controls in the contraction. In addition, it is possible with the final design to maintain a chute of constant slope throughout, whereas with an ogee spillway construction of a bucket, nappe and vertical curve in the chute would have been involved.

The reservoir pool level at 12,000 cfs., with the final design, is at Elev. 1012.4, providing a 2.6' freeboard, consistent with the 2.5' required by the Bethlehem Authority.

CONTRACTION

A 150' long contraction from the crest (85' width) to a 50' wide chute was used in the exploratory tests.

The final design was for a 40' wide chute. At first a contraction of the same angle as for the 50' chute was used, having a length of 193'. Since this was known to be a maximum length it was not difficult to study shorter lengths by means of insert walls. The length of contraction which produced the least shock wave disturbance in the chute, consistent with satisfactory flow within the contraction, was found to be 154' long. This dimension is incorporated in the final design.

At the suggestion of Mr. Fox, experiments with a variety of straight-wall contractions were made using a central hump within the contraction as a counter-disturbance in an effort to reduce shock waves in the chute. Although better chute conditions at the design discharge were obtained in this way, conditions at lesser rates of flow were not satisfactory.

Later an attempt was made to form an intersecting shock wave within the contraction so as to eliminate shock waves in the chute. It was found that the 85' width would have to be carried down to at least Sta. 1+00, and the contraction walls tapered to about 45° to accomplish this.

Again, flow at discharges less than the maximum would be unsatisfactory.

The disturbance created by the final design contraction is small, too small, in fact to be effectively changed at any but the maximum or design discharge. Hence no counter-disturbance is included in the final design nor is such a device warranted.

CHUTE

A 50' wide chute was tested first since it was known that this width with a 150' long straight wall contraction from the 85' spillway would give very close to a uniform transverse depth of flow all along the chute. The 50' width was carried down to Sta. 8 + 95. Results of this test were as follows:

Discharge, 12,000 cfs.
Reservoir pool, Elev. 1012.2, (and for n = 0.0135)
Depth at end of 150' long contraction, 6.8'
Head loss, reservoir to end of contraction, 1.6'
Calculated normal (uniform flow) depth of chute, 3.3'
Calculated depth at Sta. 8 + 95, 3.8'
Measured depth at Sta. 8 + 50, 4.1'
Head loss in chute, Sta. 1 + 50 to 8 + 95, Calc., 34'
Head loss in chute, Sta. 1 + 50 to 8 + 95, actual, 37'
Velocity at end of chute, calc., 65 ft. per sec.
Velocity at end of chute, actual, 60 ft. per sec.

The above confirmed the accuracy of the model in reproducing prototype head losses. The model was made with a smooth wood finish, painted with two coats of boat paint and waxed since model roughness must be less than the prototype. Note that a uniform flow depth is approached but not reached and that the "backwater" curve from the end of the contraction to the end of the chute precludes a large head loss.

Having confirmed the basic design and model conformance, the walls were narrowed to a 40' width, maintaining the same center line. This phase was approved on 31 May by Mr. Fox. Results of the initial tests with a 40' chute from Sta. 1+54 to Sta. 7+89 were as follows (see also Appendix):

Discharge 12,000 cfs.

Reservoir pool, Elev. 1012.2, (and for n = 0.0135)

Depth at end of 154' contraction, 8.8', ave.

Head loss, reservoir to end of contraction, 1.4'

Calculated normal (uniform flow) depth of chute, 3.9 ft.

Calculated depth at Sta. 7+89, 4.7 ft.

Measured depth (ave.) at Sta. 7+89, 5.1 ft.

Head loss in chute, Sta. 1+54 to 7+89, calc., 26 ft.

Head loss in chute, Sta. 1+54 to 7+89, actual, 34 ft.

Velocity at Sta. 7+89, calc., 64. ft./sec.

Velocity at Sta. 7+89, actual, ave., 59. ft./sec.

Velocity at Sta. 8+95, width = 50', actual,ave., 62 ft./sec.

(Note: for same conditions as above, but with forebay floor at Elev. 990, depth at each wall was the same at Sta. 7+ 89, 3.5', with 5.6' at the center line. Comparison with the data in the Appendix shows that raising the floor to 992 in the forebay tends to upset the depth balance. This does not seriously affect flow, but under no circumstances should forebay floor be raised above Elev. 992).

Head loss in expansion, Sta. 7+ 89 to 8 + 95, about 7' to 10', or about 50% more than in the chute, on the average, for a 106 ft. length.

There is a greater disparity between the calculated and actual losses and velocities with a 40' wide chute. This is due primarily to the fact that the 40' chute shock waves are more pronounced than with the 50' width, and affect the velocity distribution as far as the P.C. of the vertical curve at Sta. 8 + 95.

STILLING POOL

In the initial tests with a 50' wide chute from Sta. 1+ 50 to 8+ 95 a vertical curve was placed beyond Sta. 8 + 95 with walls tapered from a 50' to 85' width, and the stilling basin floor at Elev. 890. With this arrangement and a T.W. at Elev. 920 the jump was repelled at moderate rates of flow. The basin floor was lowered to Elev. 880 with no particular improvement. The flow separated from the walls and an uneven jump was formed for both basin floor levels. The jump might have been controllable at about 9,000 cfs. with floor blocks and a sill. It was obvious that to form a satisfactory, controllable jump an expansion would have to be placed upstream from the vertical curve so that a width of 60'-70' at Sta. 8 + 95 could be obtained, and this latter width carried through the length of the vertical curve and about 90' beyond. Even so, blocks and a sill might have been necessary. The short distance available for getting the flow into the stilling basin, forming a hydraulic jump and attaining a near-uniform velocity distribution for delivery to the downstream canal (245') precluded the use of a horizontal - floor stilling basin in terms of relative cost. With a chute width of 40' the necessary expansion upstream from the vertical curve would have been much longer. To obtain good dispersion in an expansion the chute should change to a lesser slope through the expansion. Because of the shallow depth of rock at Sta. 8 + 95, the elevation there would have to be held at 907, with changes of slope achieved by cutting more rock throughout the 895' of channel.

To reiterate and amplify, in order that a satisfactory jump for a 40' chute could be attained, changing the chute slope and using an expansion about 250' long to Sta. 8 + 95 would have been the minimum changes required. Floor blocks and a floor sill might still have been necessary.

The short length available would not be sufficient to diffuse the flow prior to entry into the canal downstream. With a horizontal stilling pool high velocities would have been obtained at the floor of the basin and been concentrated at the center of the water surface downstream from the basin. With drastic changes elsewhere it might have been possible to use a basin floor level at Elev. 890.

The only way known to the writers to achieve efficient, inexpensive energy dissipation in a short distance was by means of a bucket-type design. A floor at the bucket lip at Elev. 880 was thereby needed with walls as high as 40'. On the other hand, the savings in chute excavation, shorter expansion required, probable elimination of floor paving between the bucket toe and the weir, elimination of any need for floor blocks and a floor sill greatly outweighted the possible added cost of higher walls in the basin and the forming of the bucket.

The bucket dissipator does not yield the most attractive surface configuration because of the mushrooming "boil". However, energy dissipation takes place almost entirely within the fluid, not by partial reaction against obstacles.

RECOMMENDATIONS - FINAL DESIGN

The final design is as economical and sound as the writers could make it in the short time allotted for the study. If more time were available to them it is doubtful if any but minor improvements would be attained. Some components are marginal, but are offset by safety features elsewhere. The more important recommendations for consideration are:

a. The forebay floor should not be any higher than Elev. 992 since some disturbance in the chute flow takes place using this floor level.

b. The crest should probably be shod with steel plate.

c. The straight portion of the forebay walls could probably be shortened to 130' length without seriously disturbing the entrance flow alignment, although a 150' length appears optimum.

d. Extreme care should be exercised in the forming of expansion and construction joints to avoid misalignments, particularly in the floor.

e. The toe of the bucket should be designed to withstand both dynamic and static thrust. Heavy diagonal ties will no doubt be necessary.

f. Excavation for the stilling basin must extend to Elev. 880, adjacent to the lip of the bucket. The floor (particularly if left in rock) can safely be raised to Elev. 885, about 40' downstream from the lip and carried at 885 to a distance 80' downstream from the lip. The floor alignment from the lip to 40' downstream from the lip given above, and otherwise as shown in the accompanying drawings up to the weir, should be approached in the vicinity of the walls. Over-cutting in the area thus bounded will not interfere with, or adversely affect the basin operation.

g. The end sill (shown at station 11+40) could be moved as much as 10' upstream without serious interference to the basin performance. The end sill is provided to protect the stilling basin and control the basin tailwater. If the basin floor is left in natural rock, the end sill should then obviously be well imbedded into the foundation material.

h. The only place where wall height is probably greater than necessary is at the weir crest. The wall could be carried at Elev. 1015 to station 0+00 (crest) and then dropped locally to a 12' wall (making it a constant 12' wall from there Sta. 1+54).

i. A rip-rap parapet adjacent to the walls of the stilling basin would prevent any serious splash erosion behind the walls.

* * * * * * * * * *

The model was constructed, assembled and modified by the Bethlehem Pattern and Model Shop.

Mr. J. Carrol Tobias took the photographs appearing in this report.

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APPENDIX

Table 1

Final Design 9,200 cfs.

Reservoir Pool Water Surface, Elev. 1010.3

Water Surface, Stilling Pool, upstream from Weir, Elev. 913,ave.

Depths, Facing Downstream

Station	Left Wall	Center line	Right Wall	Remarks
Midpoint, Bend	17.6'	17.9'	18.0'	
0 + 00	8.3'	7.9'	8.3'	(crest)
0 + 78.5	5.2'	5.6'	5.3'	
1 + 54	7.0'	6.5'	7.1'	(end contr.)
1 + 70	5.2'	7.0'	5.5'	(trough)*
2 + 40	6.5'	4.6'	6.8'	(peak)*
3 + 00	5.0'	6.8'	5.0'	(trough)*
4 + 15	5.7'	3.7'	5.6'	(peak)*
4 + 92	3.9'	5.2'	3.9'	(trough)*
6 + 00	4.8'	3.6'	4.8'	(peak)*
7 + 89	4.3'	3.4'	4.2'	(P.C.Expans.)
8 + 95	2.9'	3.5'	3.3'	(P.T.Expans.)

- -

* Refers to maximum and minimum water levels at walls, which occurred at stations indicated.

Table 2

Final Design 12,000 cfs.

Reservoir Pool Water Surface, Elev. 1012.4

Water Surface, Stilling Pool, upstream from Weir, Elev. 915, ave.

Depths, Facing Downstream

Station	Left Wall	Center line	Right Wall	Remarks
Midpoint, Bend	19.2'	19.7'	19.8'	
0 + 00	9.8'	9.3'	9.9'	(crest)
0 + 78.5	6.7'	7.2'	6.9'	
1 + 54	8.9'	8.6'	8.9'	(end,contr.)
1 + 70	6.6'	9.2'	7.1'	(trough)*
2 + 40	8.2'	5.9'	8.8'	(peak)*
3 + 15	5.8'	7.9'	5.7'	(trough)*
3 + 95	7.4'	5.3'	7.2'	(peak)*
4 + 72	4.8'	6.5'	4.8'	(trough)*
5 + 80	6.0'	4.3'	5.9'	(peak)*
7 + 89	5.6'	4.2'	5.6'	(P.C.Expans.)
8 + 95	3.2'	4.9'	3.7'	(P.T.Expans.)

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* Refers to maximum and minimum water levels at walls, which occurred at stations indicated.

F I N A L   D E S I G N

3 : 100 Model

No Flow

FINAL DESIGN

3 : 100 Model

6,300 cfs.

F I N A L D E S I G N

3 : 100 Model

9,200 cfs.

F I N A L D E S I G N

3 : 100 Model

12,000 cfs.