HYDRAULIC MODEL STUDIES FOR CHIPPEWA RIVER RESERVOIR DAM

by

St. Anthony Falls Hydraulic Laboratory

University of Minnesota

Project Report No. 2

Submitted by
Lorenz G. Straub
Director

Prepared by
Warren W. DeLapp

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REPORT ON
HYDRAULIC MODEL STUDIES FOR CHIPPEWA RIVER RESERVOIR DAM
FOR
NORTHERN STATES POWER COMPANY

INTRODUCTION

The following is a report of tests made on a 1:24 scale model of the Chippewa Reservoir Dam, a property of the Northern States Power Company, and located in the headwaters of the Chippewa River, Wisconsin.

In April 1945, soundings determined that a portion of the apron had been destroyed, and that erosion had taken place as shown in Figure 1 attached. The purpose of the tests was to determine the most satisfactory way to improve the spillway to overcome the deficiency indicated by the apron failure.

Tests were based upon the tailwater curve shown on Figure 2, and were first made upon the basis of a maximum discharge of 12,000 cu ft per sec with a pool elevation of 1313; later upon the basis of a maximum discharge of 24,000 cu ft per sec and a pool elevation of 1315. These criteria were provided by the Power Company.

Hydraulics Model Studies

In order that the results of model studies may be applicable to the prototype, it is essential that the model behave in the same way as the actual structure. This requires not only geometric similarity between model and prototype, but also similarity of all the forces of gravity, fluid viscosity, surface tension, and the like. While it is not generally possible to attain strict similarity of all these forces, it is generally found that the influence of one of them dominates the behavior of the model so that the effects of the others may be entirely neglected. Thus, in the case of flow over a spillway, the force of gravity is predominant; other forces have little effect on the behavior of the model unless the scale ratio is too great.

With gravity the predominant force, similarity is attained by operating the model in accordance with the so-called Froude Model Law. This requires in addition to geometric similarity, that the ratio of the velocities in the model and prototype vary as the square root of the length ratio. Using a model scale of 1:24, the following ratios are thus established.

Quantity	Ratio, Model to Prototype
Lengths	1:24
Areas	1:576
Velocities	1:4.9
Discharges	1:2822
Forces	1:13824
Pressures	1:24

The river bed material is far more difficult to simulate than either the structure or the dynamic forces. Here again, however, true similarity does not prove to be essential to the accuracy of experimental results, particularly in dealing with relatively large dynamic forces such as occur downstream of a spillway. While the actual amount of erosion for given conditions of discharge may vary with the size of the bed material, the erosion pattern--points of maximum scour or deposition--will be similar to that to be expected in the prototype, and the relative effectiveness of various control measures may be determined by using virtually any erodible material to simulate the stream bed.

Tailwater Elevations

If the flow in the model is to simulate accurately that in the prototype, the elevation of the tailwater must be essentially the same in both for similar rates of discharge. Tailwater elevations were determined by the Northern States Power Company at the reservoir on May 8, 1945 for rates of discharge up to about 3750 cu ft per sec. The spillway gates were opened by various amounts from

10 inches to 27 inches and the tailwater elevations measured for each opening. A coefficient of discharge of 0.71 was assumed in computing the rate of discharge. Results of these tests are plotted in Figure 2. Since only approximate data is available for higher rates of flow, considerable extrapolation of the curve is necessary. It appears that the method used for determining the tailwater elevations would be likely to yield results which are too low, since considerable time would normally be required for the tailwater to build up to normal elevation after a given discharge is established. More recent observations, in the spring of 1946, at higher rates of flow indicate that actual elevations are slightly higher than those shown on Figure 2. Since the latter have been used in model tests, it appears that the actual behavior of the prototype will be slightly more favorable than is indicated by the model studies.

Description of Model

The model used in these experiments was constructed of wood and waterproof wallboard and included the outlet works, a supply channel leading to the outlet, and the equivalent of 340 ft of river below the dam. The model was supplied by gravity flow from the Upper Mississippi River pool through a supply channel, and flow from the model passed through weighing tanks permitting an accurate determination of the rate of discharge. Tainter gates could be adjusted independently to any desired setting, the opening being taken as the vertical distance from the spillway sill to the lowermost edge of the face of the gate. Elevations in the model were measured by means of point gages accurate to 0.001 ft corresponding to about 1/4 inch in the actual structure.

For purposes of discussion, the test runs made have been divided into two series. Series A includes Run Nos. 1 to 23 inclusive and were made by the Northern States Power Company. These experiments were concerned primarily with the calibration of the gate discharges and with the effects on downstream erosion of tailwater elevations higher than normal. Series B was made by the writer and was intended primarily to determine the effects of baffle piers placed on the upper apron of the spillway. This series includes Run Nos. 24-76.

TEST SERIES A

Purpose

It was originally believed that the most satisfactory method of preventing further damage to the spillway apron would be to fill the damaged apron with rock and decrease the erosive force of the water by constructing a secondary low dam downstream which would raise the tailwater and cause a hydraulic jump to form on the upper apron. This series of tests was made to determine the effects of increasing the tailwater height.

Tainter Gate Calibration

Although the rate of discharge for any particular run could be determined accurately by weighing, there was no means of reproducing the same discharge other than by using the same tainter gate openings. For this reason, the rate of discharge for various gate settings was determined so that any rate of flow could be readily established. In all tests, the headwater pool was maintained at the normal elevation of 1313. The discharge from three gates was weighed with prototype openings up to 8 ft and from one gate with openings up to 16 ft. The results of the tests for three gates is shown graphically in Figure 2. The coefficient of discharge in the orifice formula, $Q = CA\sqrt{2gh}$ varies from 0.668 to 0.678 for the discharge from three gates, assuming a coefficient of contraction of 0.70 in computing the net head. With only one gate open, the coefficient of discharge is nearly the same as for three gates with the same gate opening, so that the values shown on the graph in Figure 2 may be divided by three to determine the discharge for only one gate.

Erosion Experiments

In determining the effects of the tailwater elevation on erosion, tests were made at various rates of flow both with the tailwater normal and approximately 4 ft above normal. Soft coal screenings were first used for the erodible bed but the rate of erosion proved to be so great that it was found necessary to pave the bed with pea rock up to 3/4 inch in diameter. An effort was made to duplicate the river bed in cross-section at various distances downstream of the apron. Runs of up to 3.5 hours duration were made and the resulting erosion noted at the termination of the run.

With the broken apron filled with pea rock and the tailwater normal, only slight erosion was found for a flow of 6260 cu ft per sec, after one and one-half hours of operation. However, a flow of 9120 cu ft per sec for the same conditions caused erosion which would be the equivalent of up to 7 ft in the prototype. The latter test showed that it would be inadvisable to fill the damaged apron with rock unless additional measures were taken to protect the structure.

Following these tests a rock dam was constructed about 210 ft downstream of the apron to maintain a tailwater elevation about 4 ft higher than normal. This eliminated entirely the erosion at a flow of 6260 cu ft per sec and reduced that at 9120 cu ft per sec to a small amount. However, after a flow of 12,000 cu ft per sec for 3.5 hours, the erosion was found to be as great as 5.4 ft.

The lower apron and endsill were then restored to their condition previous to the damage and test runs made at discharges corresponding to 3420 and 6260 cu ft per sec with the tailwater normal. No erosion resulted at the lower flow and only a small amount at the higher. From these tests it was concluded that erosion in the prototype begins at a flow of about 6000 cu ft per sec. This conclusion assumes that the material in the model simulates accurately that in the river bed as regards erodibility.

TEST SERIES B

Purpose

This series of tests was undertaken to determine the optimum proportions of baffle piers placed on the upper apron of the spillway in order to improve the flow pattern and prevent further damage to the spillway apron.

Experimental Procedure

The first step in making test runs was to level up the stream bed to the desired elevation. The bed downstream was made the same as that of the end-sill, 1275, and the broken apron was filled with material to the floor level of 1269. It was not necessary that these conditions conform exactly to the conditions in the actual river bed, since it was only desired to have a basis for comparison of erosion for various flow conditions. In the preliminary tests the pea rock from the earlier series was used for the stream bed. With improvements in design the scour decreased to such an extent that in order to produce appreciable bed movement in the lower apron, it was necessary to use a more readily erodible material. Sand having a mean grain diameter of about 1 mm was chosen for this purpose.

Discharge in the model was controlled by adjusting the gates to the opening corresponding to the required rate of flow and regulating the supply valve until the headwater pool reached normal elevation. The tailwater was then adjusted by means of a tailgate. A few of the preliminary runs were as much as two hours in length, but later tests showed that most of the erosion occurred in the first 30 minutes of operation and later runs were shortened to this duration. At the conclusion of the run, the bed elevations were measured with a point gage and recorded.

Preliminary Tests

Before attempting to take corrective measures on the spillway apron, a number of preliminary runs were made to determine as nearly as possible the exact cause of the damage and the nature of the existing flow pattern. With the apron restored to its original undamaged condition, a run was made with a discharge corresponding to 8000 cu ft per sec with equal gate openings and tailwater at normal elevation. This was followed by one duplicating conditions at the time of the high water in 1941 when the flow was believed to be about 8000 cu ft per sec, and when the gate openings were unbalanced, gate No. 1 being open 15", gate No. 2 open 117", and gate No. 3 open 35". It was found that although duplicating the gate openings of September 1941 produced a discharge of only 7000 cu ft per sec, the resulting erosion was considerably greater than for a flow of 8000 cu ft per sec with equal gate openings. For the latter case the maximum scour was about 5 ft near the center of the spillway, while with unbalanced openings it was nearly twice this amount and to the left of the centerline in the vicinity of the present break. In the light of these tests there appears to be little doubt that the unequal gate openings at the time of the high water were a contributing factor in the damage. Results of the above tests are shown in Figures 3 and 4.

Observations made with the discharge of 8000 cu ft per sec showed the flow conditions downstream to be far from satisfactory even under the favorable conditions of balanced gate openings and undamaged apron. These conditions were caused by two factors; the small amount of energy dissipation taking place on the upper apron and the failure of the flow to diverge and follow the training walls. Actually, the entire discharge passed over the center 2/3 of the endsill, while near the wingwalls large eddies formed and the flow was in an upstream direction over the endsill. Velocities as high as 7 ft per sec upstream were observed in this region and the total amount of backflow was estimated at 1500 cu ft per sec. Thus with a gate discharge of 8000 cu ft per sec, the total flow over the center portion of the endsill was roughly 9500 cu ft per sec resulting in a maximum velocity in excess of 8 ft per sec. This compares with a mean velocity of 4.4 ft per sec assuming the flow to be uniformly distributed over the full length of the endsill. Evidently, any means of causing a more uniform distribution of flow on the apron would be of benefit in decreasing erosion.

If the lower apron and endsill are not to be restored fully to their original condition, effective means must be provided to prevent further erosion in the existing break, and the solution becomes somewhat more complicated than it would otherwise be. The transverse length of the upper apron along the toe is 142 ft and with a discharge of 12,000 cu ft per sec the elevation of the tailwater is approximately 1265.7. The minimum velocity possible at the end of the apron for this rate of flow is therefore about 10 ft per sec, with a reduction to about half this amount in the stilling pool. On the other hand, the velocity resulting from a difference in elevation of about 27 ft between the headwater and tailwater pools is nearly 40 ft per sec. It thus appears that even with an ideal flow distribution, most of the energy dissipation will take place in the stilling pool and considerable erosion is likely to develop in the damaged portion. Any method of control must therefore provide both for dissipating a large portion of the energy on the upper apron and in spreading out the flow as much as possible over its entire width.

An experimental run at a discharge of 10,500 cu ft per sec with the apron in its present condition showed clearly the nature of the flow pattern and the erosion to be expected at high discharges. The break in the endsill reduces the effectiveness of the stilling pool causing still greater concentration of the flow down the center and deep scour in the break. Figure 6 shows the model in operation during this run and Figures 5 and 7 the resulting scour.

Baffle Pier Experiments

Consideration of the nature of the problems involved led to the conclusion that baffle piers placed on the upper apron would be most likely to prove a satisfactory method of solution. Although no method is known for determining the optimum size and location of such baffles analytically, experience with similar structures serves as a guide in the model experiments. It was at once evident that in order to be effective such baffles would need to be high enough to prevent an appreciable amount of water from passing over them. Preliminary tests indicated this height to be a minimum of about 7 ft for a discharge of 12,000 cu ft per sec. With the height fixed, structural considerations determined at least to some extent the other dimensions, which in turn limited the number which it would be practical to use on the apron.

On the basis of the foregoing, five baffles were constructed corresponding to prototype dimensions of 7 ft in height, 3 ft in width, and a length of 6 ft in the direction of flow conforming to the size of the existing steps on the apron. Tests were then made with these baffles in various locations on the apron to determine the position which resulted in the most favorable flow conditions. These tests were generally made with a discharge corresponding to 12,000 cu ft per sec with balanced gate openings and the tailwater at normal elevation. Runs were usually of 30 minutes duration although with some baffle arrangements the unsatisfactory nature of the flow pattern was at once apparent and the run was not continued. With improvements in design check runs were made of greater duration and at lower rates of flow.

These experiments showed that there was a relatively small area in which baffles might be placed and still be effective at all rates of flow.

placed near the end of the apron, they proved to be unsatisfactory at low discharges because of the high local velocities caused by the concentration of the flow between them. On the other hand, placing them near the gates failed to provide sufficient space for energy dissipation and the flow tended to shoot over the top of the baffles. With the baffles near the center of the apron, a large portion of the energy in the flow is dissipated and after passing the baffles the flow tends to become equalized before passing into the stilling pool.

The most effective arrangement of baffles for both high and low flows appears to be with the baffles in two rows; one in the upstream row approximately in the center of each gate and in the downstream row behind each pier. This arrangement results in an almost uniform distribution of the flow in the stilling pool and over the endsill for a wide range of discharges with uniform gate openings, and only negligible erosion for flows of up to 12,000 cu ft per sec.

Revisions in Baffles

Although the baffles described above appeared to be satisfactory hydrodynamically for flows of up to 12,000 cu ft per sec, their desirability from a structural standpoint appeared open to question. An analytical approximation to the total force on each baffle indicated a possible maximum of nearly 160,000 lbs for a flow of 12,000 cu ft per sec. Owing to the fact that the apron of the spillway is thin and lightly reinforced, it was the opinion of the Power Company that it would not be possible to anchor the proposed baffles securely enough to resist such a force.

In an effort to increase the strength of the baffles without reducing their effectiveness, several alternate designs were tested. The first change consisted in increasing the length of the baffles to 12 feet, maintaining a uniform slope on the downstream face and with the corners of the upstream face rounded to a radius of 9 inches. These changes caused a marked change in the effectiveness of the baffles in spreading out the flow and some increase in downstream erosion. This situation was overcome to a large extent by modifying the shape of the baffle so that it corresponded as nearly as practicable to the original design but maintaining the length at 12 feet. This shape gave results substantially the same as the design first used.

A series of tests was then made to determine the behavior of the design at successive rates of discharge up to 24,000 cu ft per sec. These experiments showed that the baffles should be satisfactory for all flows up to about 15,000 cu ft per sec but that for still higher rates of flow considerable erosion in the stilling pool was likely. This erosion was the result of the jet passing over the baffles and falling directly into the stilling pool without adequate dissipation of energy. At a discharge of 24,000 cu ft per sec the erosion approached in magnitude that found at a flow of 3000 cu ft per sec without the baffles.

The effects of higher baffles on the erosion at these discharges was then investigated, and indicated that if their height were raised by three feet, increasing the baffle height from 7 feet to 10 feet, the design might be considered satisfactory. With the 10 foot baffles the erosion for the 24,000 cu ft per sec flow was quite similar to that for 15,000 cu ft per sec with the lower baffles.

Measurement of Pressure on Baffles

In view of the importance of the magnitude of the force on the baffles and the approximate nature of the computed value, it was decided that the force should be determined by model tests.

The pressure distribution on the upstream face of the baffle directly in front of gate no. 3 was determined, using discharges of 12,000, 17,000 and 24,000 cu ft per sec. respectively. The baffles used had prototype dimensions corresponding to a height of 7 feet and a width of 8 feet, with all upstream corners rounded to a radius of 3 inches, and the arrangement of baffles corresponded to that previously found to be most satisfactory. A total of nine piezometers were installed in the baffle. These consisted in 1/8 inch diameter copper tubing extending through the baffle parallel to the direction of flow with the upstream end of the tubing filed to a smooth surface flush with the face of the baffle. The downstream end of the tubing was connected to open manometers by means of rubber tubing. At the lowest rate of flow the headwater pool was maintained at elevation 1313 and the maximum elevation of 1315 was used at the higher discharges. The tailwater in each case corresponded to that shown on the rating curve.

Results of Pressure Measurements

The distribution of pressure on the upstream face of the baffles as determined above is shown in Figures 8, 9, and 10 for the three discharges. In each case the maximum pressure was found to occur on a vertical section on the centerline of the baffle and at a point approximately 2 feet from the bottom of the baffle. The magnitude of the maximum pressure was found to vary from approximately 81 percent to 92 percent of the theoretical value obtained by neglecting friction losses, and the relative amount of friction loss was found to decrease with the discharge. In each case the indicated pressure in the outside row of piezometers was about 80 percent of that in the center row at corresponding elevations.

Integration of the pressure measurements over the face of the baffles indicates the following total force on each baffle:

Discharge, cu ft per sec	Total force, pounds
12,000	68,500
17,000	75,000
24,000	88,000

The fact that these values are smaller than those computed on the basis of the full dynamic force is apparently due to the lack of a complete 90 degree change in the direction of the jet approaching the baffles and to the effects of frictional resistance.

Final Design

On the basis of the studies of erosion and force on the baffles, a final design was adopted by the Power Company. It consists in baffles 8 feet in height corresponding in shape to those first tested, and placed on the apron in the position found experimentally to be most effective in distributing the flow and reducing the erosion to a minimum. Anchorage for the baffles is provided by a new concrete slab 12 inches thick over the present apron. The essential features of the final design are shown in Figure 16.

Tests of this design indicate that it is somewhat more effective than the design first proposed. Only negligible erosion occurs at discharges up to 16,000 cu ft per sec but the rate of erosion increases at higher discharges, and the flow over the endsill becomes less uniform as the discharge increases. At the maximum flow velocities along the training wall are considerably higher than those in the center of the apron and some scour at the end of the training wall is indicated. Figures 11 to 15, inclusive, best summarize the results of the final series of tests.

Increasing the thickness of the apron as indicated in Figure 16 appears to have an effect similar to that of lowering the tailwater with respect to it and therefore somewhat less energy dissipation occurs in the region upstream of of the baffles. This results in more splash on the training walls but seems to have no adverse effects on the downstream erosion. Model tests indicate that if it proves necessary to carry the increased apron thickness to the end of the present apron that slightly less erosion will occur.

Water Surface Profiles

With baffles on the apron the height of the training walls will need to be substantially increased to prevent their being overtopped by waves and spray at high discharges. The amount of such increase is more or less a matter of arbitrary choice since there is no minimum height of wall which confines all of the spray. Figure 17 shows the approximate profile of the spray and intermittent waves on the training wall for a flow of 24,000 cu ft per sec. Except for the tailwater elevation, results are not greatly different at lower discharges since the velocity of the water striking the baffles is about the same. The profile of the proposed training wall shown in Figure 17 is that selected by the Power Company.

In addition to the profile at flood flow, an investigation was made of conditions likely to be encountered during the period of construction. It is anticipated that this work will be undertaken during the period of low flow and the maximum discharge during the period will not exceed 1000 cu ft per sec. In the initial stages of construction this flow may be discharged through one gate below which there are no baffles. Model tests indicate that a cofferdam 6 feet in height will be required for this condition. In constructing the last of the baffles it will be necessary to discharge water through one of the gates with baffles in position below that gate. This causes a deflection of the jet and a water surface along the wall higher than would otherwise be the case. Figures 18 and 19 show the water surface profiles for two possible positions of the cofferdam, the latter being somewhat more desirable from a hydraulic standpoint since it allows a lower wall and results in less dynamic force on the wall from the jet deflection. Although these studies were made on an intermediate design with baffles 7 ft in height and without the slab on the apron, it is not likely that results for the final design would be noticeably different.

Spillway Operation

Although it is recommended that the gate openings be maintained as nearly equal as practical, model studies indicate that in case of necessity unbalanced openings may be used without fear of serious erosion after the baffles are constructed. Tests made with various combinations of gate openings show that up to 3000 cu ft per sec may be safely passed through either of the outside gates or up to 4000 cu ft per sec through the center gate, with the other gates closed. With any one of the gates closed, up to 8000 cu ft per sec may be safely passed through the remaining two.

Conclusions and Recommendations

The following conclusions and recommendations may be made as a result of the two series of model tests described:

1. The spillway as originally constructed did not operate satisfactorily at high rates of flow because of the small amount of energy dissipated on the upper apron and the concentration of the flow in the center of the stilling pool. This was especially true for flows of 8000 cu ft per sec and above.

2. The unbalanced gate openings at the time of the maximum discharge in September, 1941 resulted in greater erosion than had the openings been equal, and probably contributed to the damage to the lower apron.

3. The present condition of the apron increases the concentration of the flow down the center and the resulting erosion.

4. A secondary dam downstream which would raise the elevation of the tailwater would serve to reduce the erosion to some extent. However, considerable erosion would still be likely at high discharges.

5. Baffles on the upper apron corresponding to the design shown in Figure 16 serve to distribute the flow almost uniformly over the width of the stilling pool for all discharges up to 12,000 cu ft per sec, and reduce erosion to a negligible amount for all flows up to 16,000 cu ft per sec.

6. It is recommended that the present break in the stilling pool be filled with rock up to 1 foot in diameter or larger. No erosion of material of this size is likely for flows up to 16,000 cu ft per sec.

7. For flows above 16,000 cu ft per sec, increasing amounts of erosion must be expected with the baffles adopted. At a discharge of 24,000 cu ft per sec this erosion approaches that for 8000 cu ft per sec without baffles.

8. The dynamic force on each baffle varies with the rate of discharge from approximately 68,500 lbs at 12,000 cu ft per sec to approximately 88,000 lbs at a discharge of 24,000 cu ft per sec.

9. It will be necessary to increase the height of the present training walls to prevent their being overtopped by waves and spray. The proposed increase shown in Figure 17 appears to be adequate to confine virtually all of the spray.

10. The coefficient of discharge of the gate orifice is approximately 0.68.

APPENDIX I
FIGURES ACCOMPANYING REPORT

Figure

1. Plan and section of spillway showing condition of apron in April, 1945

2. Variation of tailwater elevations and spillway discharge with equal gate openings

3. Plan of downstream erosion with original apron after a flow corresponding to 8000 cu ft per sec for a two hour period with equal gate openings

4. Plan of downstream erosion with original apron after a flow corresponding to 7000 cu ft per sec for a two hour period with gate openings of September, 1941

5. Plan of downstream erosion with apron of April, 1945 after a flow corresponding to 10,500 cu ft per sec for a one hour period with equal gate openings

6. Model in operation at a flow corresponding to 10,500 cu ft per sec with equal gate openings and apron of April, 1945

7. Resulting erosion after 30 minutes of operation at flow shown in Figure 6

8. Pressure distribution on the face of a baffle 7 ft high and 8 ft wide at a discharge of 12,000 cu ft per sec

9. Pressure distribution on the face of a baffle 7 ft high and 8 ft wide at a discharge of 17,000 cu ft per sec

10. Pressure distribution on the face of a baffle 7 ft high and 8 ft wide at a discharge of 24,000 cu ft per sec

11. Model in operation at a flow corresponding to 16,000 cu ft per sec with recommended baffles

12. Resulting erosion after 30 minutes of operation at the flow shown in figure 11

13. Stream bed prior to test runs

14. Resulting erosion after 30 minutes of operation at a discharge corresponding to 24,000 cu ft per sec

15. Plan of downstream erosion with recommended apron and baffles after a flow corresponding to 24,000 cu ft per sec for a period of one hour with equal gate openings

16. Details of recommended baffles

17. Approximate profile of spray on training walls for a flow of 24,000 cu ft per sec with recommended baffles on apron

18. Profile of water surface on spillway apron for a flow of 1000 cu ft per sec through gate no. 1 with cofferdam below gate nos 2 and 3, and baffles 7 ft high

19. Profile of water surface on spillway apron for a flow of 1000 cu ft per sec with cofferdam below gate no. 3 and baffles 7 ft high

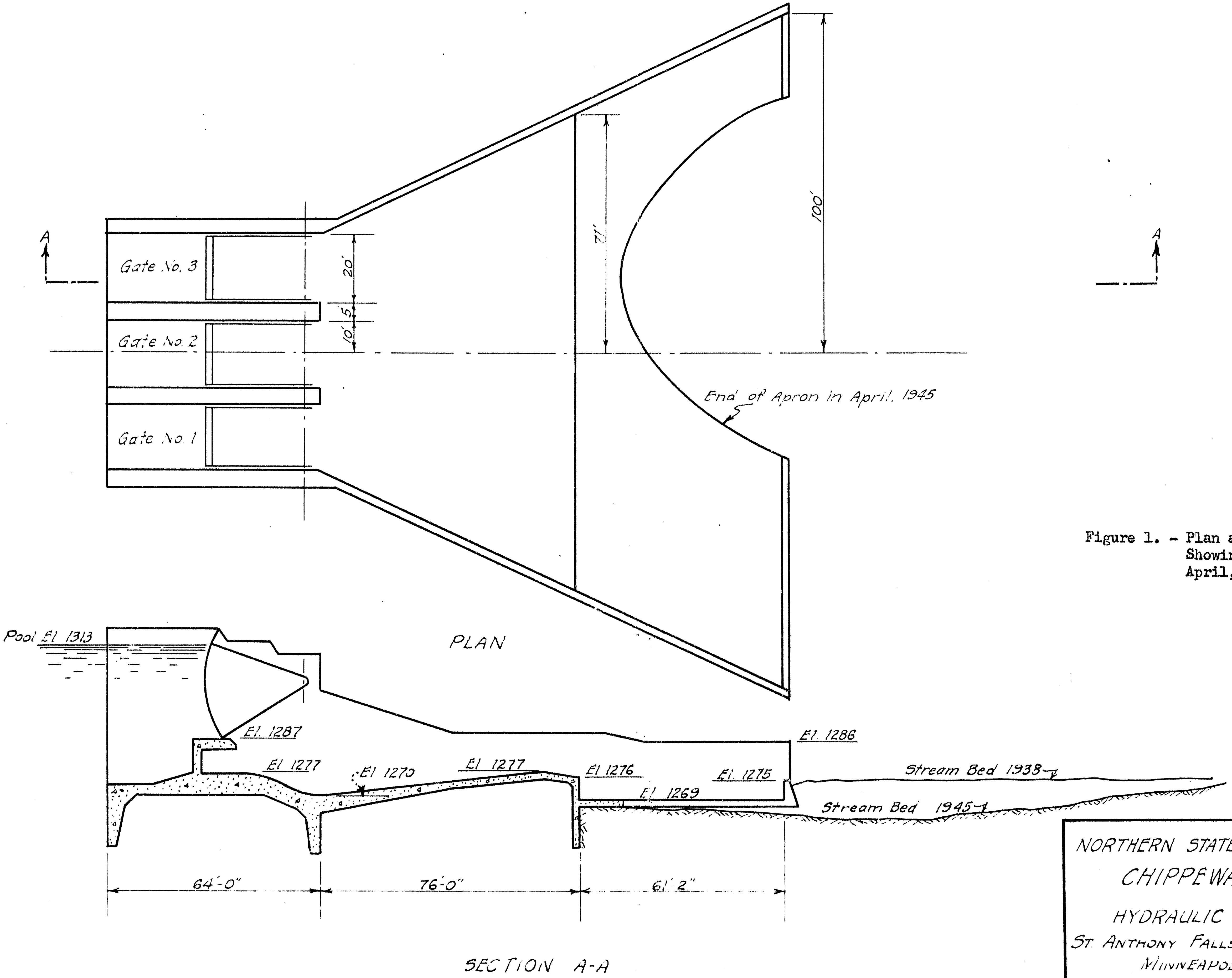

Figure 1. - Plan and Section of Spillway Showing Condition of Apron in April, 1945.

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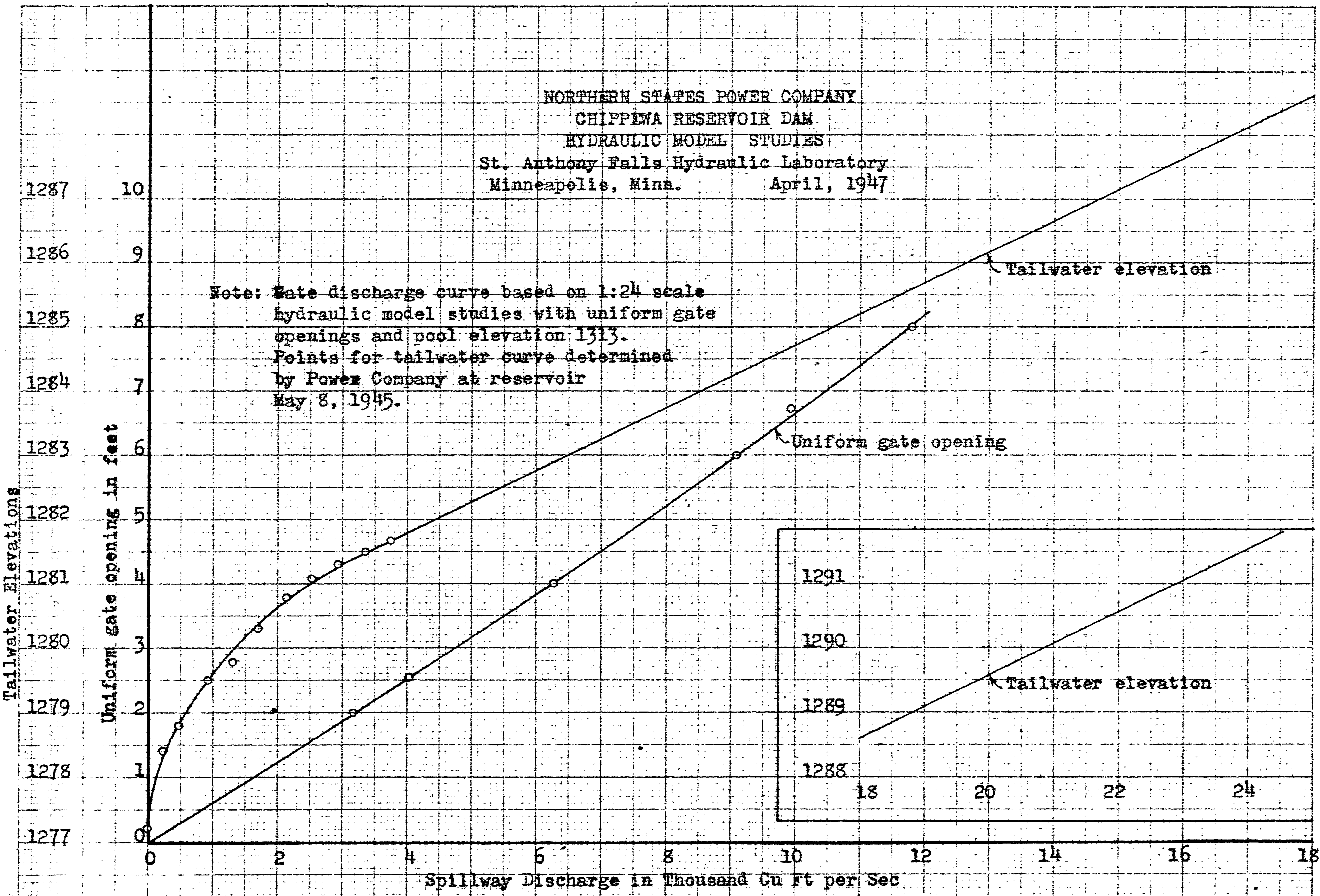
SCALE: 1"=30' AUGUST, 1946



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Note: Gate discharge curve based on 1:24 scale hydraulic model studies with uniform gate openings and pool elevation 1313.
Points for tailwater curve determined by Power Company at reservoir May 8, 1945.

Figure 2.-Variation of Tailwater Elevations and Spillway Discharge with Equal Gate Openings.

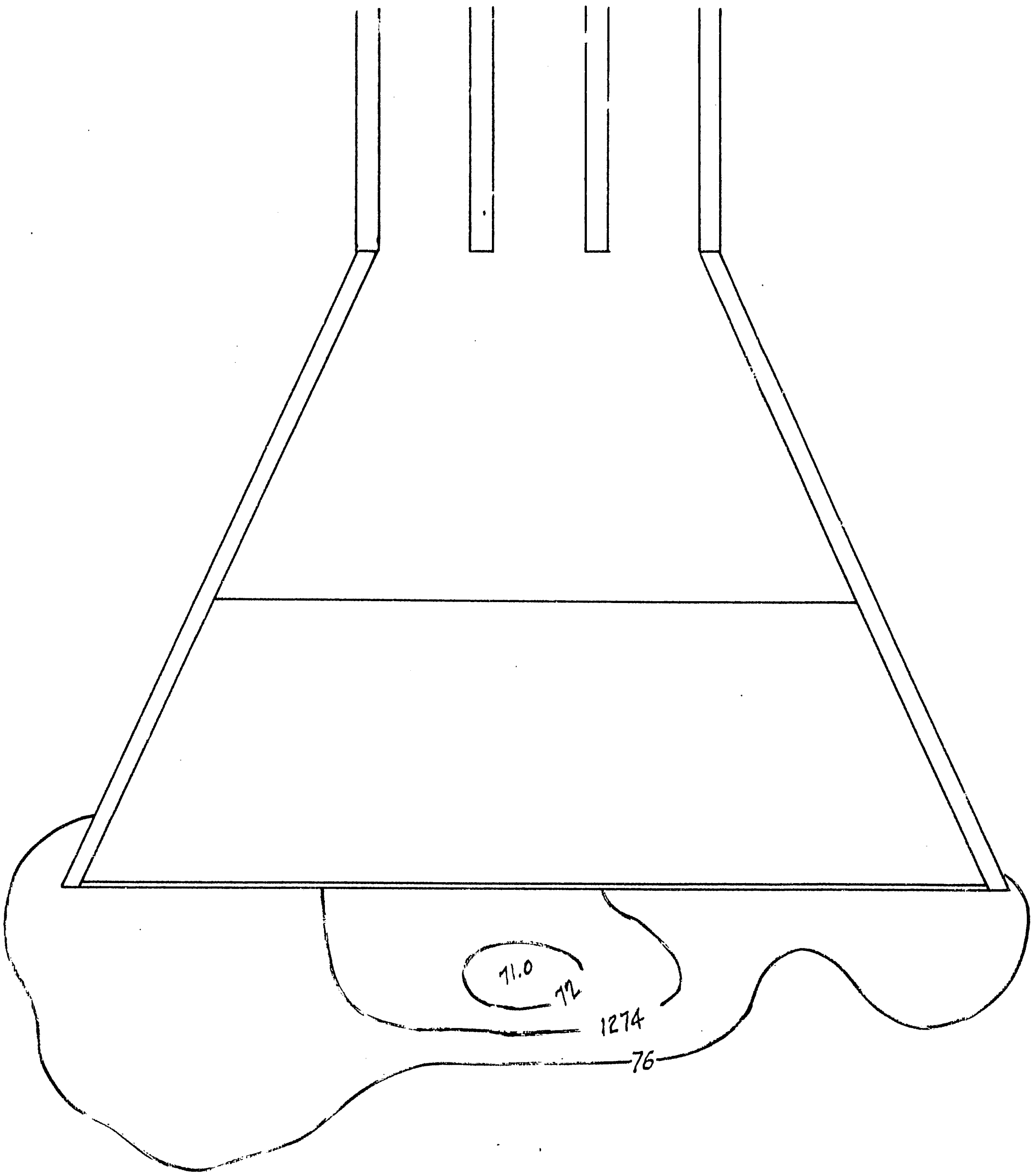

Figure 3.- Plan of Downstream Erosion with Original Apron after a Flow Corresponding to 8000 cu ft per sec for a Two Hour Period with Equal Gate Openings. Original Bed Elevation 1276.

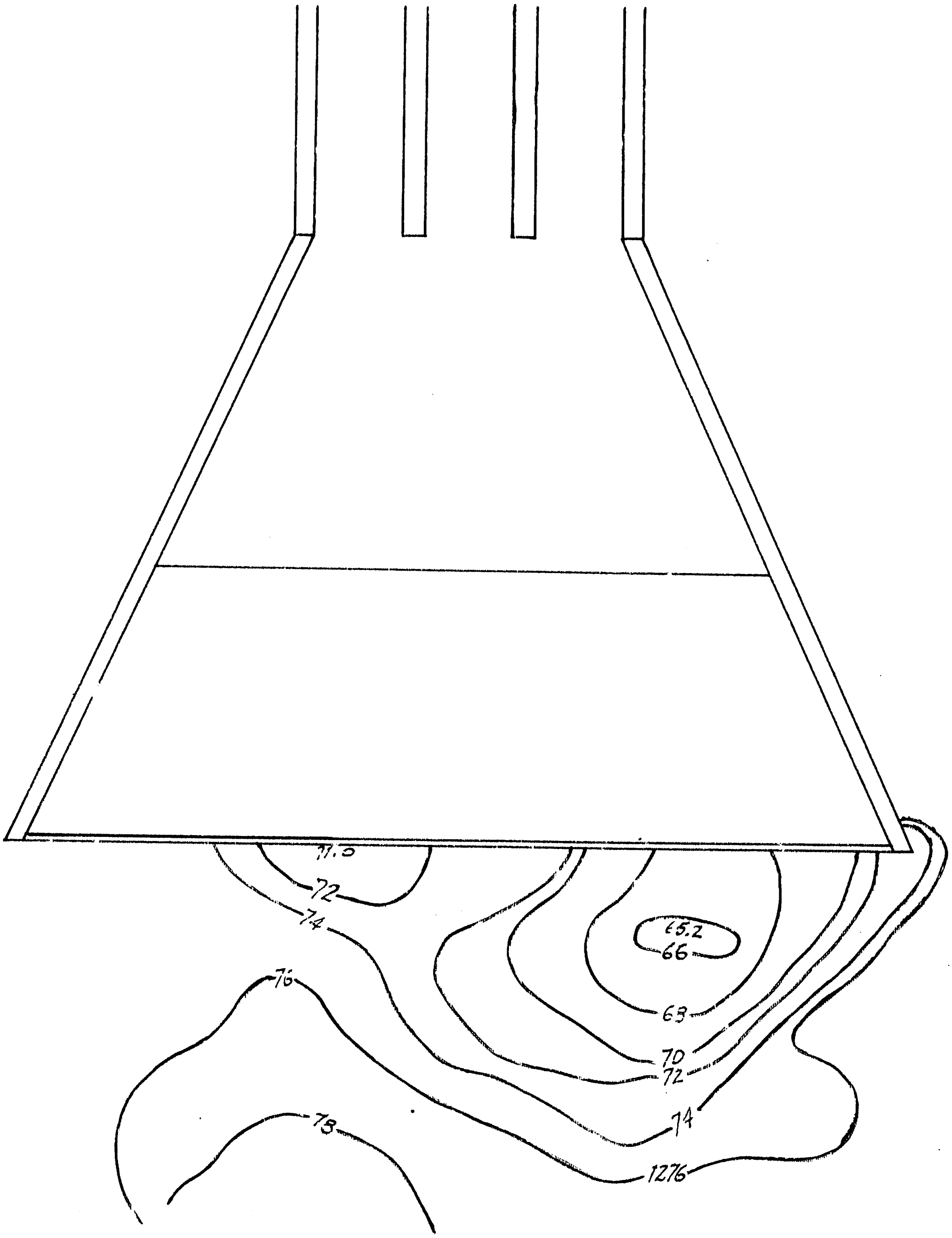

Figure 4.- Plan of Downstream Erosion after a Flow Corresponding to 7000 cu ft per sec for a Two Hour Period with Original Apron and Gate Openings of September , 1941. Original Bed Elevation 1276.

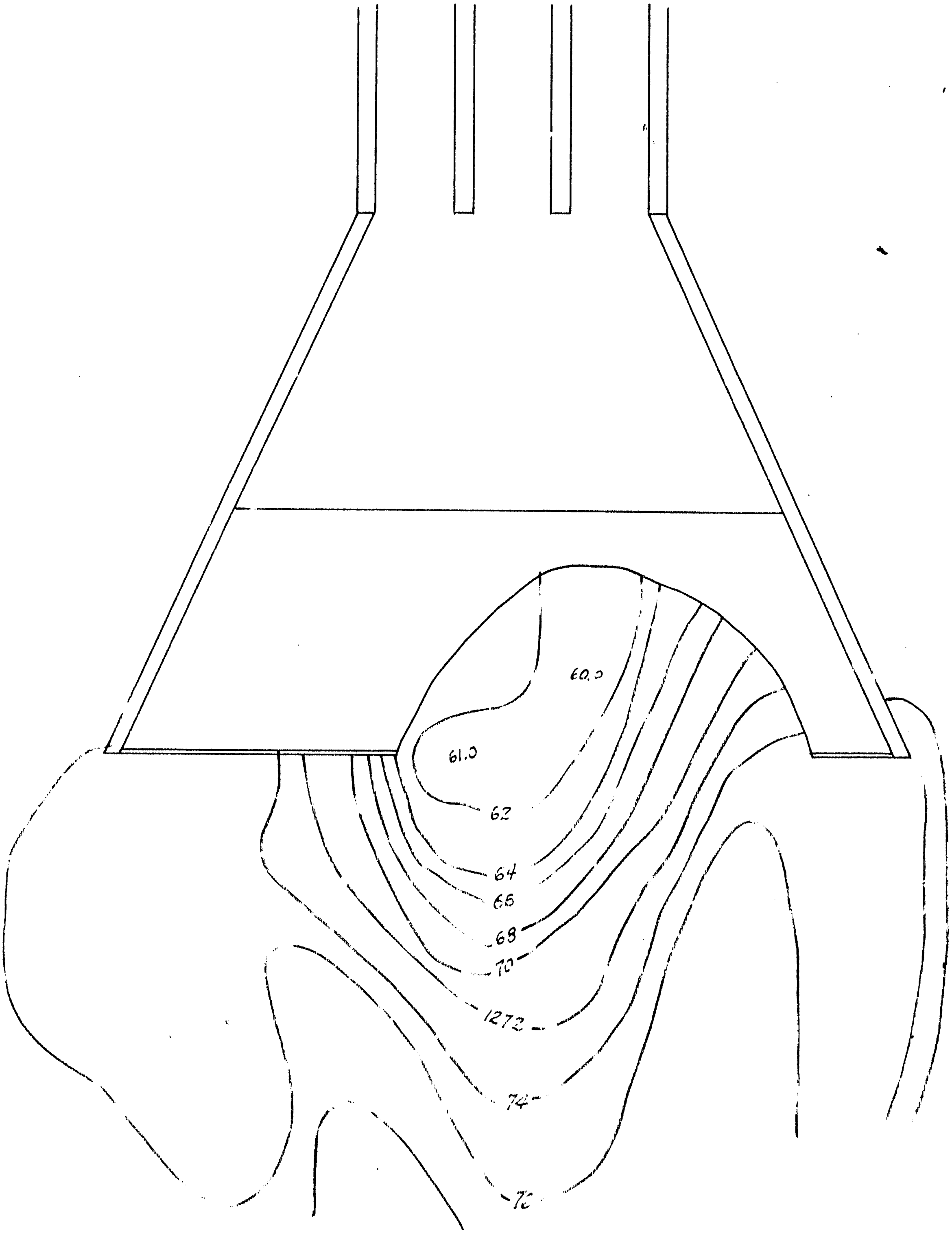

Figure 5.- Plan of Downstream Erosion with Apron of April, 1945 after a Flow Corresponding to 10,500 cu ft per sec for a One Hour Period with Equal Gate Openings. Original Bed Elevation 1276.

Figure 6.-- Model in Operation at a Flow Corresponding to 10,500 cu ft per sec with Equal Gate Openings and Apron of April, 1945.

Figure 7.-- Resulting Erosion after 30 Minutes of Operation at the Flow Shown in Figure 6.

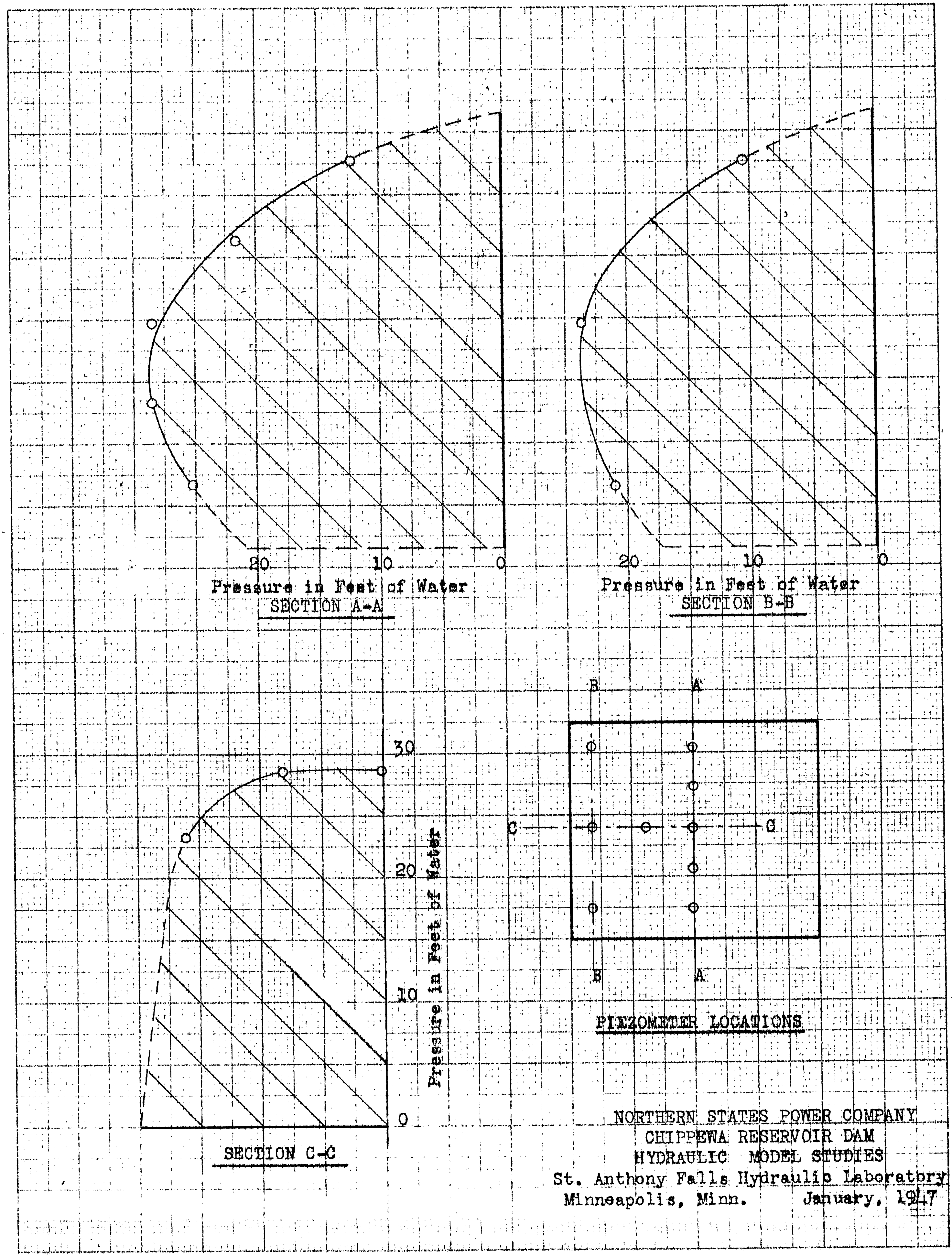

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Figure 8. - Pressure Distribution on the Face of a Baffle 7 ft High and 8 ft wide at a Discharge of 12,000 cu ft per sec.

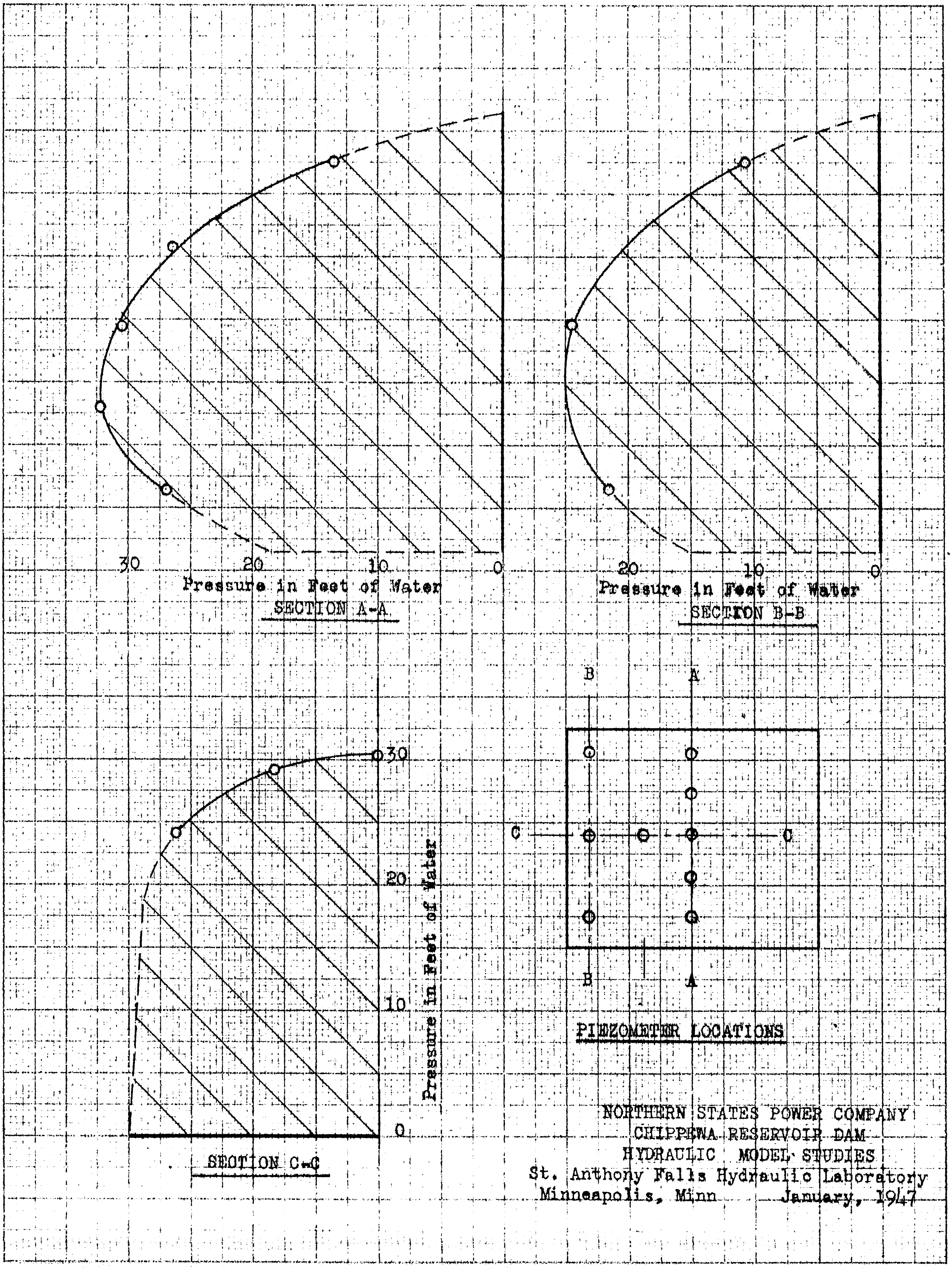

Figure 9.- Pressure Distribution on the Face of a Baffle 7 ft high and 8 ft wide at a Discharge of 17,000 cu ft per sec.

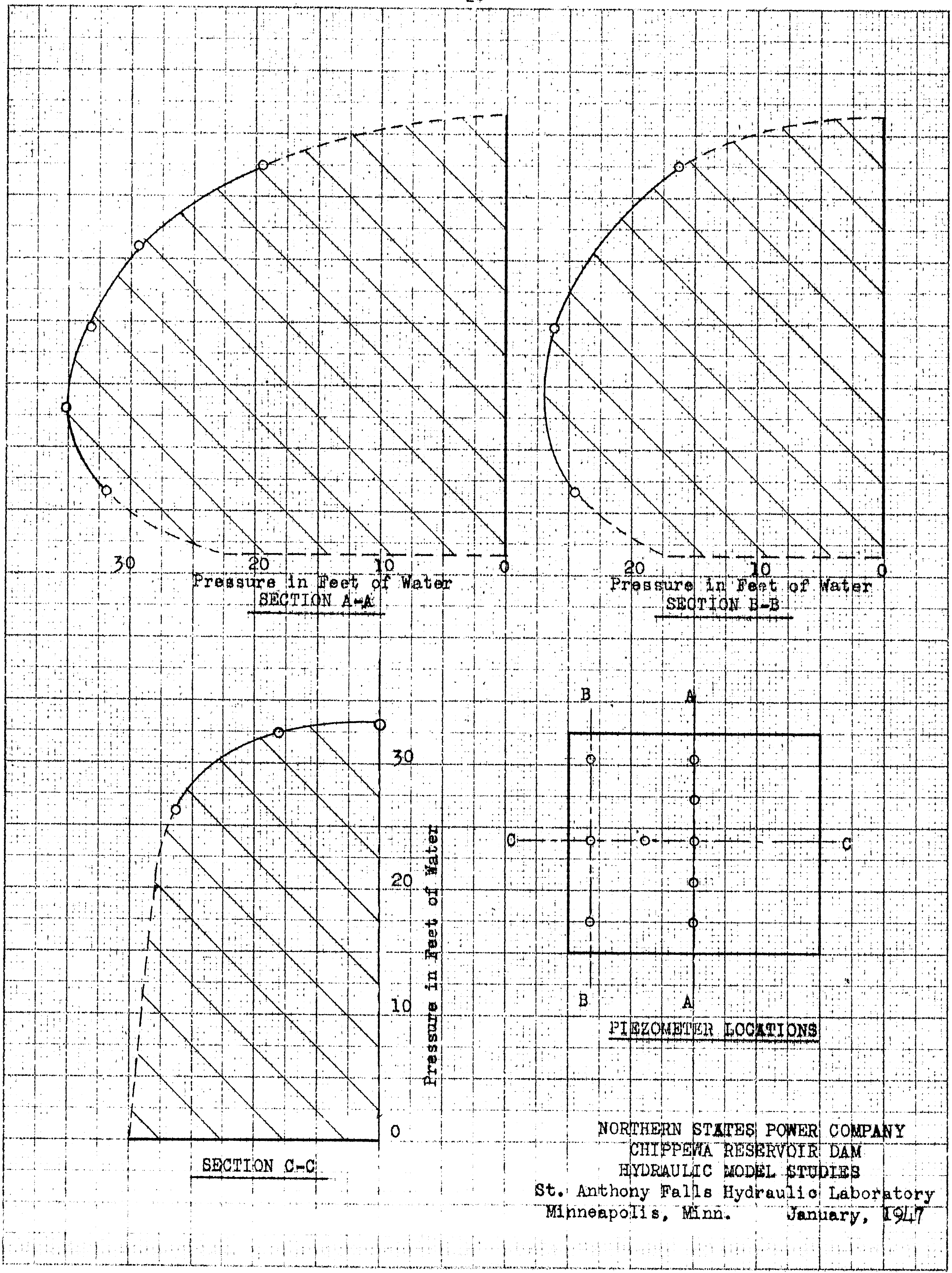

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Figure 10.- Pressure Distribution on the Face of a Baffle 7 ft High and 8 ft Wide at a Discharge of 24,000 cu ft per sec.

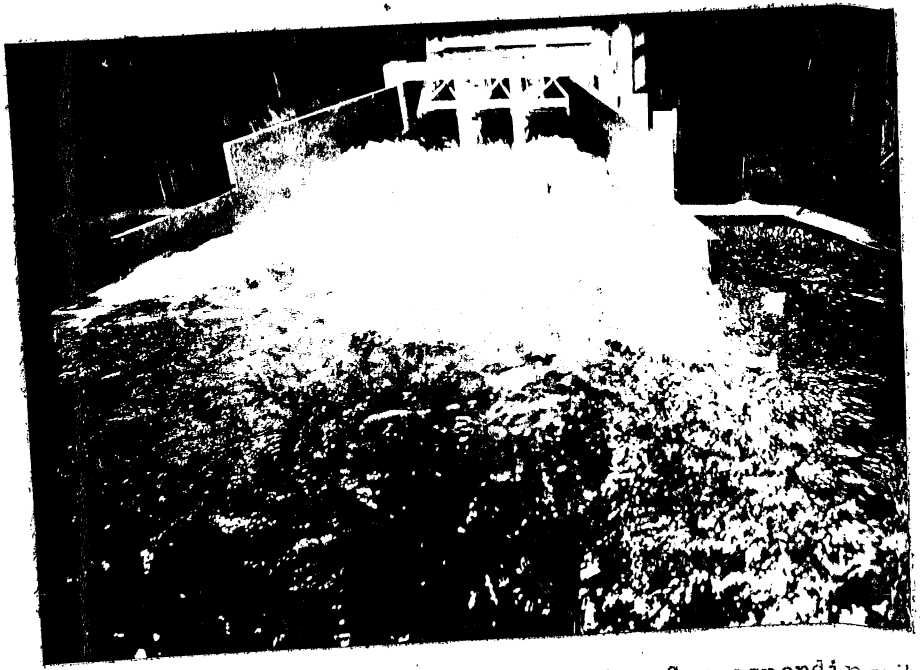


Figure 11.- Model in Operation at a Flow Corresponding to 16,000 cu ft per sec with Recommended Baffles.

Figure 12.-Resulting Erosion after 30 Minutes of Operation at the Flow Shown in Figure 11.

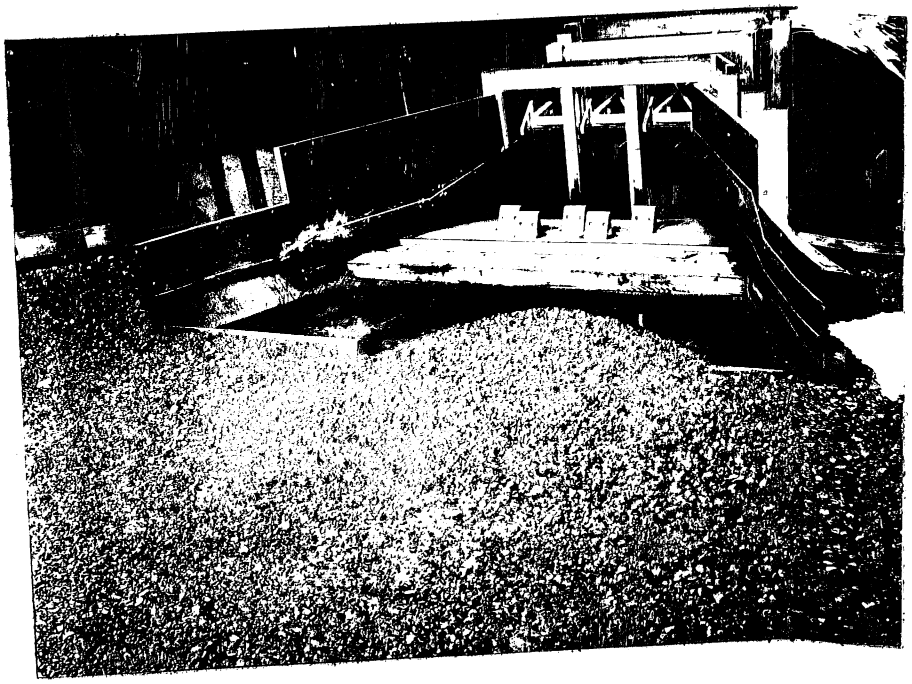


Figure 13. - Stream Bed Prior to Test Runs.

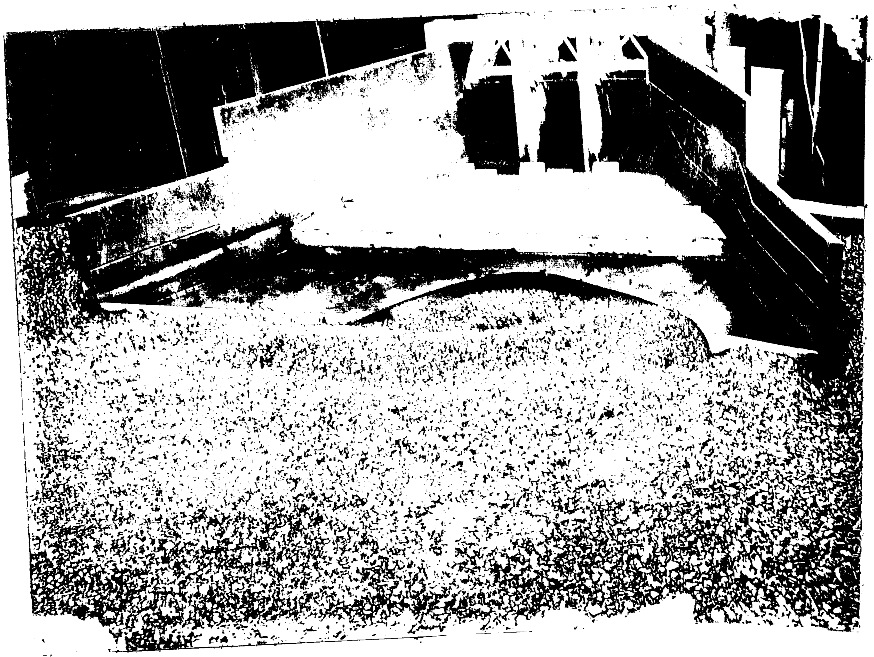


Figure 14. - Resulting Erosion after 30 Minutes of Operation at a Discharge Corresponding to 24,000 cu ft per sec.

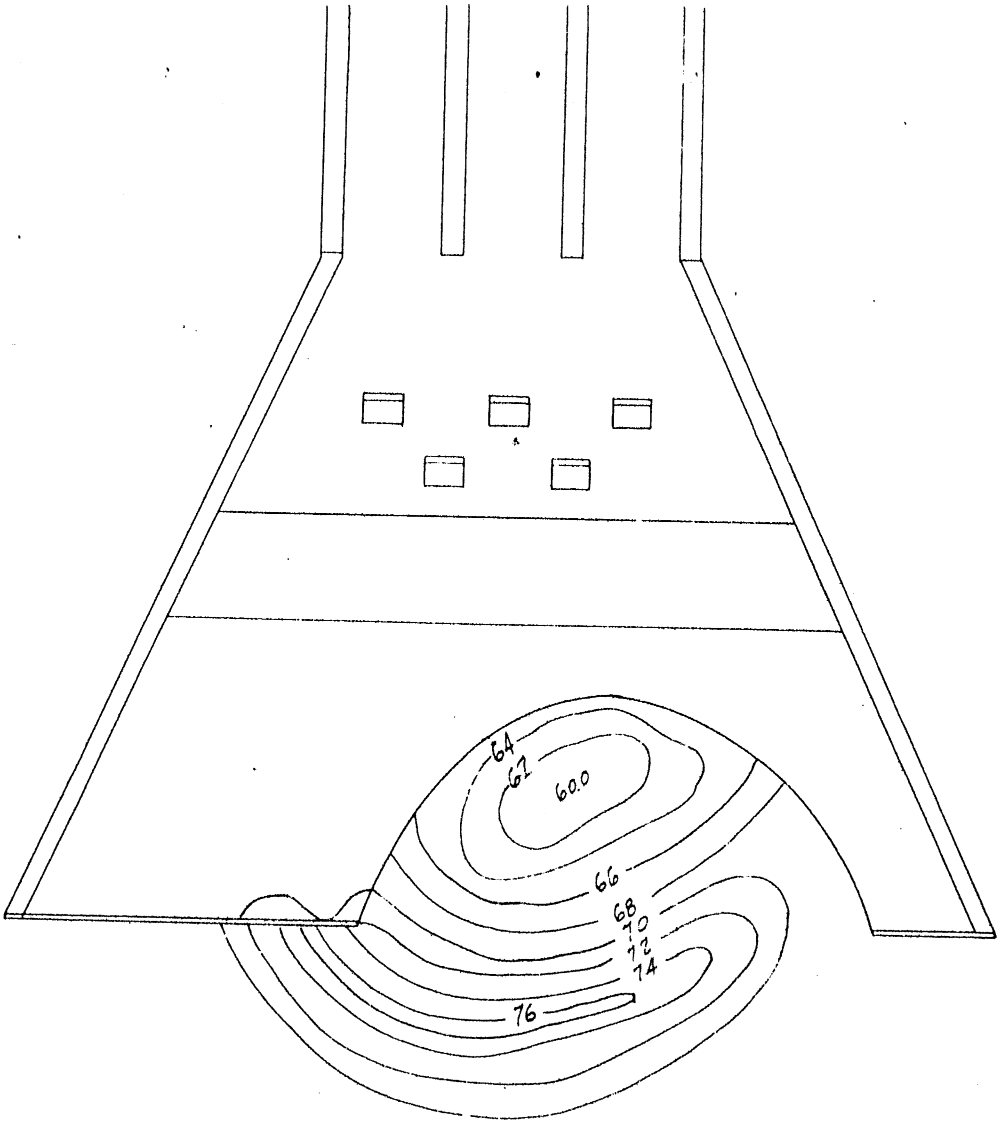
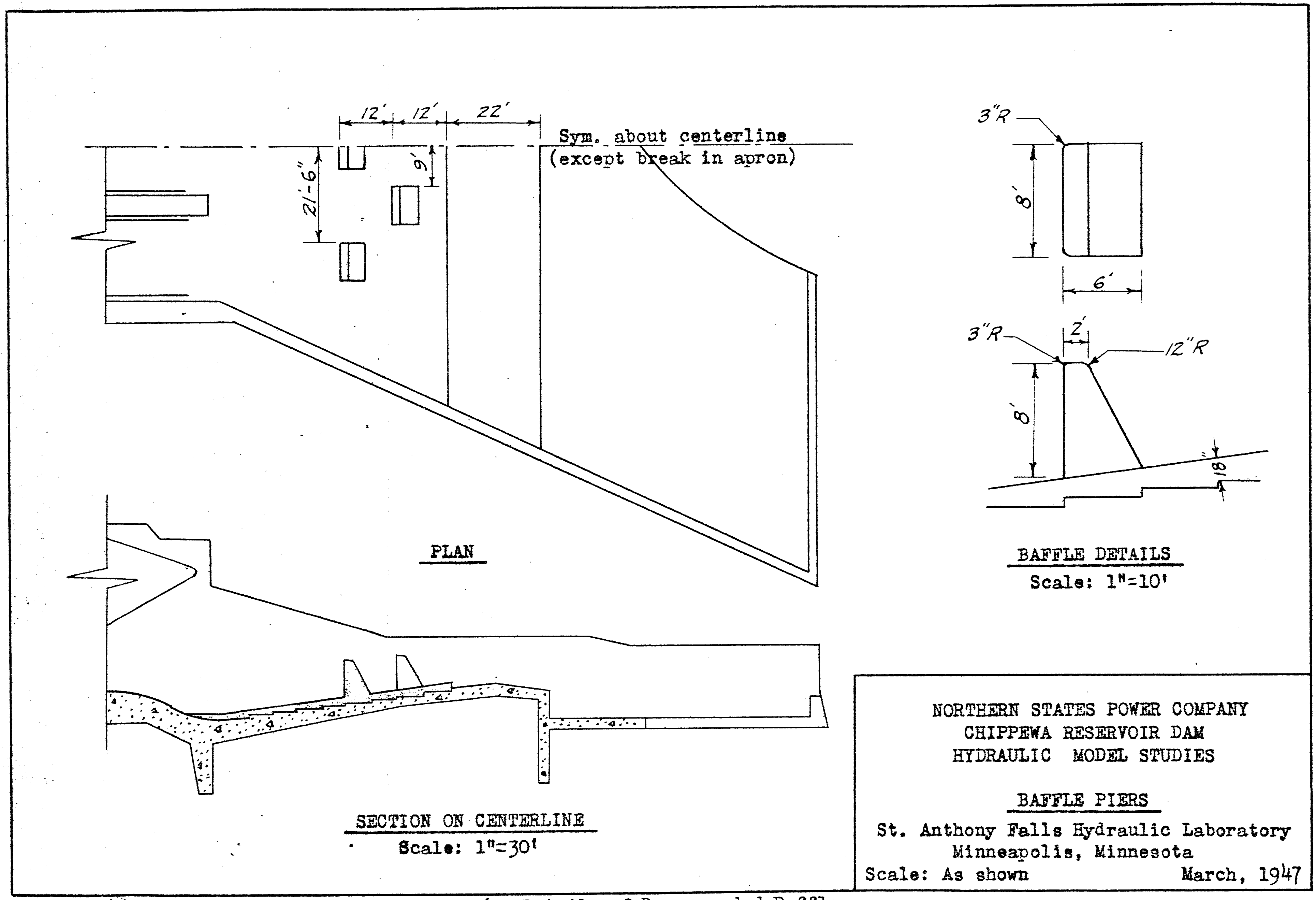


Figure 15.-Plan of Downstream Erosion with Recommended Apron and Baffles after a Flow Corresponding to 24,000 cu ft per sec for a Period of One Hour with Equal Gate Openings. Original Bed Elevation 1269.



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BAFFLE PIERS

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Minneapolis, Minnesota
Scale: As shown March, 1947

Figure 16.- Details of Recommended Baffles

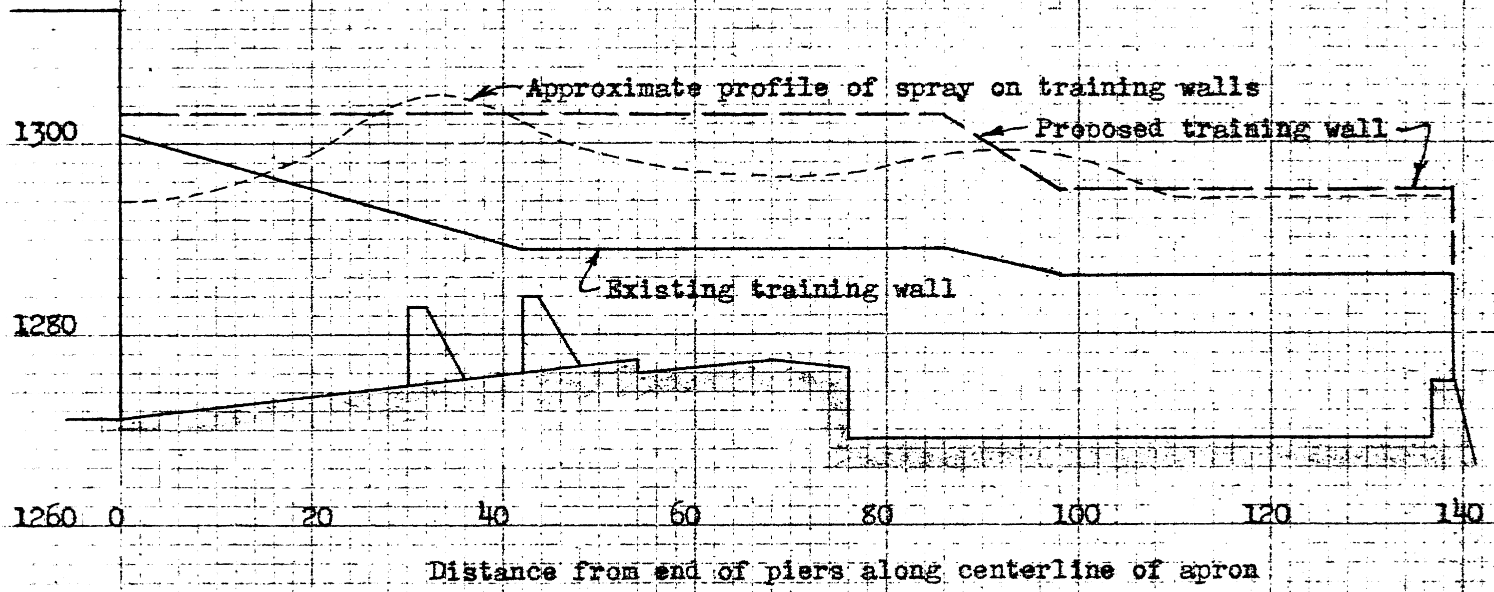

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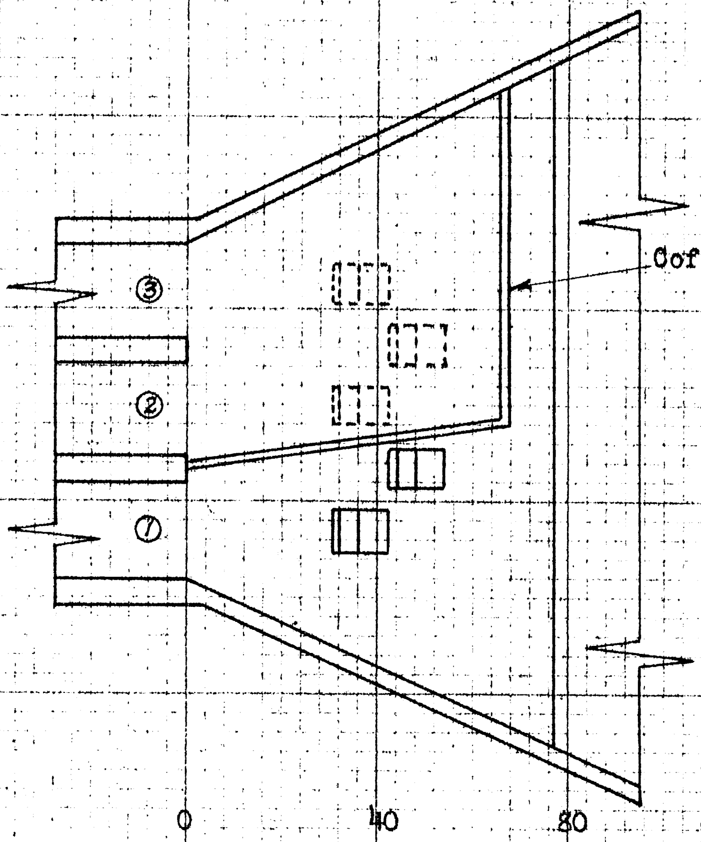
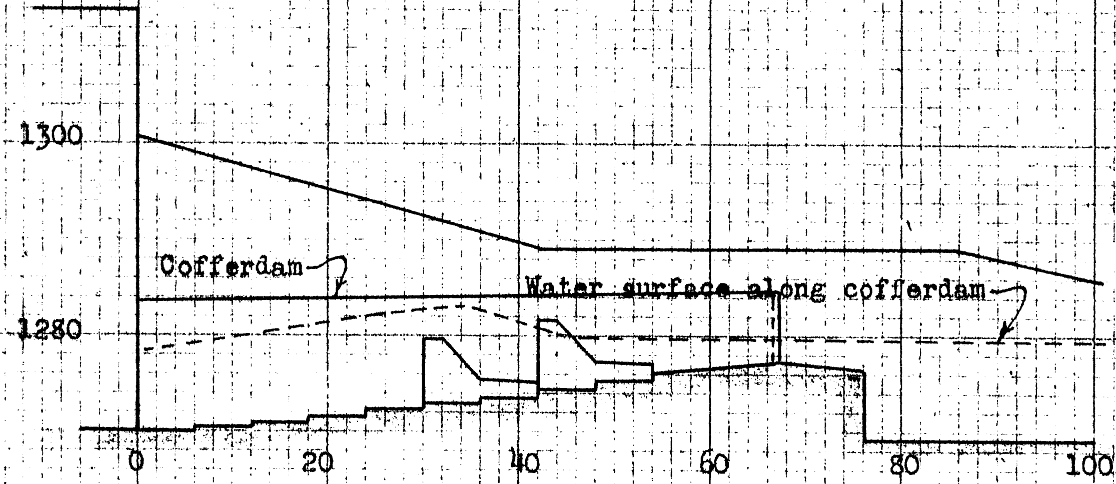
Figure 17.- Approximate Profile of Spray on Training Walls for a Flow of 24,000 cu ft per sec with Recommended Baffles on Apron.



PLAN
Scale: 1"=40'



PROFILE
Scale: 1"=20'

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Figure 18.- Profile of Water Surface for a Flow of 1000 cu ft per sec with Cofferdam below Gate Nos. 2 and 3, and 7-ft Baffles.

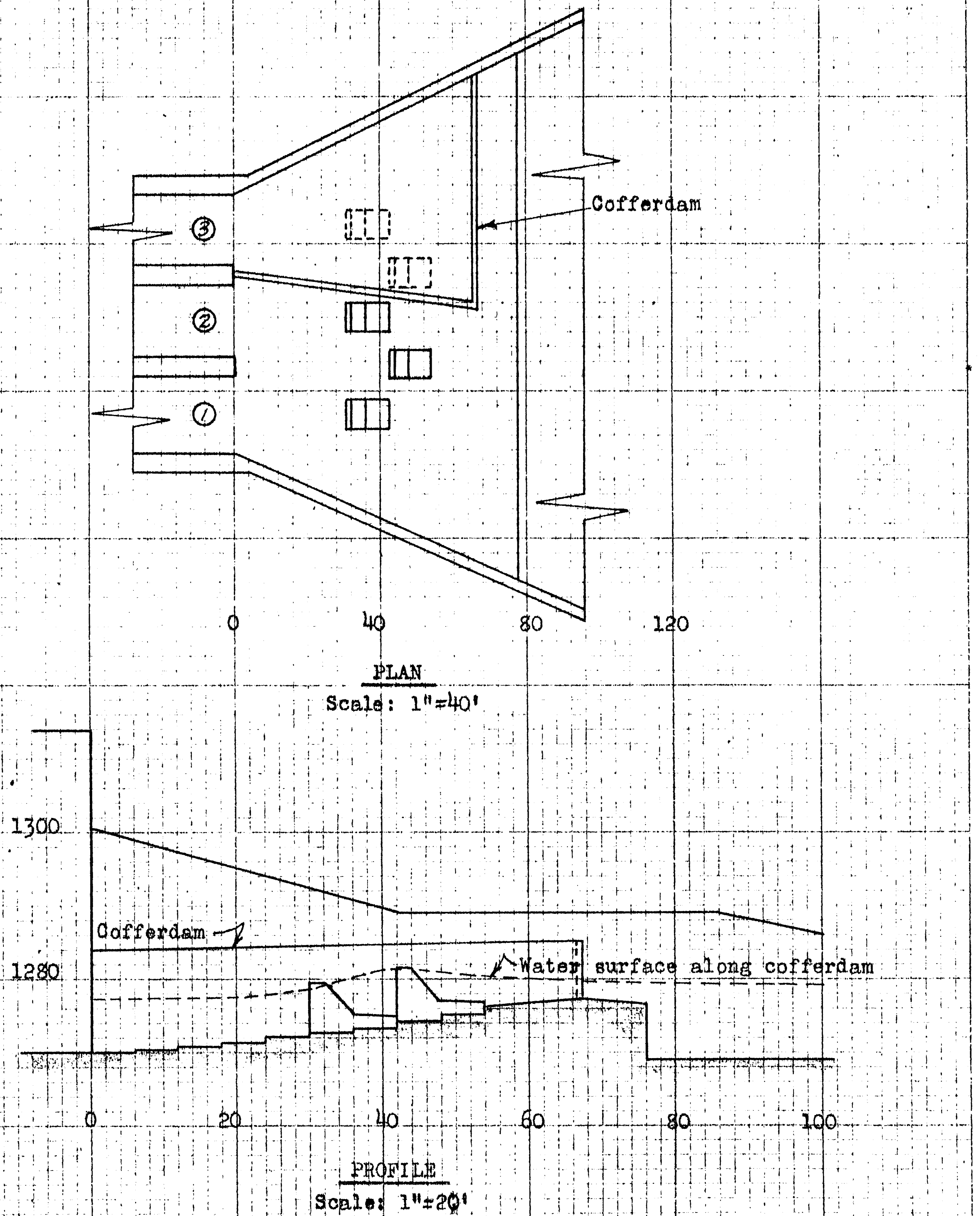

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Figure 19.- Water Surface Profile for a Flow of 1000 cu ft per sec through Gate 1 with Cofferdam below Gate No. 3, and Baffles 7 ft High.

APPENDIX II: CONDENSED SUMMARY OF TEST RUNS

Report on Hydraulic Model Studies for Chippewa Reservoir Dam

Test Series A

Run No.	Discharge*	Description	Results
1	-	Calibration of gate discharge; all gates open 2 ft*	Discarded; wrong gate position
2	-	" all gates open 4 ft	"
3	9000	" all gates open 6 ft	
4	9100	" "	
5	11,800	" all gates open 8 ft	
6	11,850	" "	
7	3200	" all gates open 2 ft	
8	6260	" all gates open 4 ft	
9	2100	" center gate open 4 ft	
10	4020	" center gate open 8 ft	
11	5800	" center gate open 12 ft	
12	7400	" center gate open 16 ft	
13	9450	" center gate wide open	
14	8500	Tailwater 2.5' below normal; gate openings 2.5',10',4'	Up to 9' of erosion in lower basin
15	8080	Tailwater 2.5' below normal; "	Similar to Run No. 14
16	6260	All gates open 4 ft; tailwater normal	Slight erosion in lower basin
17	9120	All gates open 6 ft; tailwater normal	Up to 7' of erosion in lower basin
18	9120	All gates open 6 ft; tailwater 4' above normal	Run not completed
19	6260	All gates open 4 ft; tailwater 4.5' above normal	No Erosion
20	9120	Same as Run No. 18	Maximum of 1' of erosion
21	11,800	All gates open 8 ft; tailwater 4' above normal	Maximum of 5.4' of erosion
22	3240	All gates open 2 ft; tailwater normal; apron repaired	No erosion below endsill
23	6260	All gates open 4 ft; " "	Some movement of bed below endsill

* All discharges and dimensions correspond to those in the prototype.

APPENDIX II: CONDENSED SUMMARY OF TEST RUNS

(Continued)

Test Series B

Run No.	Discharge	Description	Results
24	3000	Investigation of flow conditions with equal gate openings	Moderate erosion below endsill
25	7020	Duplication of conditions of September 1, 1941	Up to 10' of erosion below endsill
26	9920	Equal gate openings; coarse material in damaged apron	Up to 9' of erosion in basin
27	10,000	Equal gate openings; baffles on upper apron	Moderate erosion
28	10,000	" baffles rearranged	No erosion in basin
29-37	10,000	" various baffle arrangements; fine material in damaged apron	Varying degrees of erosion
37A	10,000	Continuation of Run No. 37 to determine time effect	Results similar to Run No. 37
38	4030	Equal gate openings; baffles of Run No. 37	Moderate erosion
39	6000	" "	Very slight erosion
40	10,000	" baffle arrangement revised	Slight erosion
41	4000	" baffles of Run No. 40	"
42	6000	" "	"
43	8000	" "	"
44	7000	All flow through Gate 4; "	Excessive erosion
45	7000	All flow through Gate 2; "	Excessive erosion along wall; moderate erosion in basin
46	4000	All flow through Gate 2; "	Slight erosion
47	4000	All flow through Gate 3; "	Considerable erosion in basin
48	8000	All flow through Gates 2 and 3; "	Slight erosion
49	10,500	Equal gate openings; coarser material in apron	Very little erosion
50	4000	All flow through Gate 3	Moderate erosion
51	10,000	Baffle length increased to 12' (Wehner design)	Slight increase in erosion
52	1000	All flow through one gate with cofferdam below two gates	Profile plotted
53	1000	All flow through one gate with cofferdam below one gate	"
54	1000	Same as Run No. 52 without baffles on apron	"
55	10,000	Same as Run No. 51 with compromise baffles	Similar to Run No. 49
56	1000	Same as Run No. 52	Profile Plotted
57	1000	Same as Run No. 53	"
58	11,500	Equal gate openings, normal tailwater, final baffle design	Very slight erosion

CONDENSED SUMMARY OF TEST RUNS

(Continued)

Test Series B

Run No.	Discharge	Description	Results
59	15,000	Calibration of Gate Orifice, H W Elev 1315	
60	20,200	Baffles of Run No. 58	Up to 9 ft of erosion
61	16,600	"	Up to 7 ft of erosion
62	14,600	"	Slight erosion
63	24,100	"	Similar to Run No. 60
64	24,100	Baffle height increased to 10 ft	Slight erosion
65	20,200	Baffles of Run No. 64	Very slight erosion
66	12,000	Determination of force on baffles	
67	17,000	"	
68	24,000	"	
69	16,600	Baffles of Run No. 61 with portion of apron raised 18"	Slightly more erosion than Run 61
70	16,600	" with entire apron raised 18"	Similar to Run No. 61
71	13,700	Same as Run No. 70	No erosion
72	16,000	Similar to Run No. 70 with 8' baffles	Very slight scour
73	17,700	Same as Run No. 72	Moderate erosion
74	16,000	Same as Run No. 69 with 8' high baffles	Slightly more scour than Run 72
75	8,000	Same as Run No. 74	No erosion
76	24,000	Same as Run No. 74	Excessive scour