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FEASIBILITY STUDY OF A STEPPED SPILLWAY

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BY

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ABSTRACT

A model study was conducted to investigate the feasibility of a stepped spillway for Upper Stillwater Dam.

The model findings indicate that the energy contained in the jet is minimal due to the tumbling action induced by the steps. Maximum velocity encountered on the 61-m (200-ft) high spillway is about 11 m/s (36 ft/s). The energy reduction is 75 percent greater than a conventional spillway. The low velocity at the bottom of the dam requires only a 7.6-m (25-ft) long stilling basin to dissipate the remaining energy.

Stepped spillways can be used with dams where the unit discharge is low and stilling basin construction is to be limited or where the use of roller-compacted concrete is considered.

INTRODUCTION

Upper Stillwater Dam will include two firsts for the Bureau of Reclamation when it is completed in 1986. It will be the first roller-compacted concrete dam constructed by the Bureau and also the first stairstepped spillway of its size in the United States.

The Upper Stillwater damsite is located 120 km (75 mi) east of Salt Lake City, Utah, on the Bonneville Unit of the Central Utah Project. The dam will help regulate the flows of Rock Creek and South Fork of Rock Creek for release into the Strawberry Aqueduct through the 13-km (8.1-mi) long Stillwater Tunnel. The reservoir will be kept full during the summer recreation months. Fluctuations in the reservoir water level will occur only during the winter months.

Techniques used on roller-compacted concrete are similar to those used in highway construction and, according to researchers, could reduce the cost and construction time of mass concrete gravity dams substantially over conventional methods. These techniques involve the use of extruded concrete on upstream and downstream faces retaining a rolled concrete hearting. Roller-compacted concrete has a zero slump and, at Upper Stillwater, will be placed in 300-mm (1-ft) lifts. The concrete used

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has a low cement and high fly ash content, and the dam is built up in thin layers (with a large surface area) across the full width of the valley and continuously compacted by a vibrating roller. In this way, the dam can be raised rapidly without the usual problems of heat generation and differential shrinkage. The facing elements are constructed slightly in advance of the hearting, using a laser-controlled slip form shown on Fig. 1. A test section for Upper Stillwater Dam was constructed during the summer of 1981 to test bonding between lifts and the techniques involved in placing roller-compacted concrete. This test section is shown in Fig. 2. The maximum height of the dam will be 84 m (275 ft), and the crest length 792 m (2600 ft). The initial configuration had a 0.6 to 1 downstream slope along the entire height. The ungated spillway will be 183 m (600 ft) long and 61 m (200 ft) high. The spillway must pass a design flood of 425 m^3/s (15 000 ft^3/s). The first phase of the model study was for the dam to these specifications.

However, for construction purposes, the top width of the dam was increased from 4.6 to 9.2 m (15 to 30 ft). To accomplish this, the slope of the upper 22 m (72 ft) of the dam was increased to 0.32 to 1 (Fig. 3). Acceptable crest designs were developed for both slopes.

INVESTIGATION

The purpose of the model study was to determine if the design was feasible and to what degree the stepped spillway affected the energy dissipation.

Two models were constructed to conduct the study. Both were sectional models representing only a small portion of the 183-m (600-ft) crest. One model was built to study only the top few meters of the crest to optimize the tumbling action in the flow as early as possible. A discharge curve was also developed using this model. The second was a 1 to 15 scale sectional model of the entire spillway - from crest to stilling basin. This model was used to size the stilling basin.

Crest Model

The 1:5 model was set up in a 760-mm (2.5-ft) wide flume. The first crest design tested was for the 0.6 to 1 downstream spillway slope. The crest acted basically as a broad-crested weir. The flow passed through critical depth at the upstream end of the crest and accelerated as it passed downstream. As the flow negotiated the downstream curve and encountered the first step, the underside of the jet impinged on the upstream end of the step and deflected outward, away from the spillway face (Fig. 4). After further experimentation, it was determined that the point where the underside of the nappe was directed was very critical. By adding one additional step with an angled configuration, the location of the impingement was changed and the tumbling action as shown on Fig. 5 was developed. The final dimensions for the 0.6 to 1 crest are shown on Fig. 6.

After the decision was made to widen the crest and steepen the top slope of the spillway face, it was apparent that getting the flow to cling to a 0.32 to 1 slope would be difficult in light of the earlier studies. It appeared necessary to reduce the substantial velocities developed by the crest acting as a broad-crested weir. This was done by dropping the approach to the crest by 1.82 m (6 ft). A nappe-shaped crest was designed to match the undernappe of the jet. This shape continued down to the point where the slope of the curve met the 0.32 to 1 slope. Using the equation for crest profiles found in Design of Small Dams 1/:

$$y/H_o = -K\ (x/H_o)^n$$

where y and x designate a point on the curve, Ho = design head, K and n = inch-pound unit constants found on design curves which are based on approach velocity and design head. Because, from previous experience, the design seems to work well even beyond the design head, the crest shape was designed using 0.9 m (3 ft) as H_o, while the actual design head was 1.07 m (3.5 ft). This was done to ensure that at the middle range discharges good flow conditions would be developed where previously only marginally acceptable conditions in the crest area had been encountered.

The nappe-shaped crest is approximated by a series of 0.3- and 0.6-m (1- and 2-ft) high steps. Near the crest, the downstream tips of the steps correspond to the theoretical curve and gradually, the downstream tips impinge into the theoretical jet nappe until the upstream end of the steps fall on the theoretical curve. The detail shown on Fig. 3 displays this orientation. The curved portion of the spillway ends 6.1 m (20 ft) below the crest. At this point, the slope of the curve is 0.32 to 1 and this slope continues another 15.8 m (52 ft) vertically. At elevation 2468.9 m (8100 ft), the slope changes abruptly to 0.6 to 1, which continues the remaining 39.6 m (130 ft) to the stilling basin.

The crest model simulating this new design was constructed in the same flume as the previous 0.6 to 1 crest, but at a 1 to 10 scale to permit study of the crest down to the point where the slope of the nappe-shape becomes 0.32 to 1.

The design worked well; turbulence was developed near the crest and the jet clung to the extremely steep 0.32 to 1 slope. Fig. 7 shows the final design operating at the maximum reservoir head. The maximum unit discharge is 2.39 m^2/s (25.7 ft^2/s), which is sufficient to pass the maximum spillway discharge. The developed discharge curve appears on Fig. 8.

Little splash developed with this design except between heads of 150 and 300 mm (0.5 and 1 ft) when the thin jet springs off the first step and comes back to the concrete surface at the sixth step. There is no practical way to alleviate this problem. The tolerances specified in

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1/ Design of Small Dams, Bureau of Reclamation, pp. 374-75.

the construction of the prototype spillway crest and top 3 m (10 ft) must be fairly tight because a 25-mm (1-in) prototype variation from the specified dimensions will cause the jet to spring clear of the concrete surface. In this instance, the laser-controlled slip form will be able to work to close tolerances, although it would not prove critical to the design unless a very substantial portion of the spillway step was either below or above the designated curve. Most likely the step will weave slightly under and over the specified dimension along the 183-m (600-ft) wide spillway; therefore, no problem is anticipated.

Spillway Model

Once the crest shape was optimized, the 1 to 15 scale model from crest to stilling basin was constructed in another, taller flume. The sectional model represented 18.3 m (60 ft) of the 183 m (600 ft) wide crest. The main purpose of this model was to size the stilling basin. Velocities along the length of the spillway were measured and pressures on both the areas exposed to the flow and those where negative pressures might be expected were taken. Also of interest were the flow patterns and pressures where the spillway abruptly changed slope. Necessary wall heights along the sides of the spillway were also determined. At all discharges, the flow down the spillway is well mixed with air and the jet is broken up. At small discharges (0.25 to 0.75 m^2/s), the flow strikes each step and loses nearly all of its velocity before accelerating to the next step where the pattern is continued. At larger discharges, the flow appears to speed up near the crest of the spillway until the steps begin to take affect and slow the jet. The velocity appears to remain constant for the remainder of the fall. Two types of velocity measurements were taken to verify these observations.

A high-speed movie was made of the model operating at the maximum discharge with paper squares introduced into the flow. The camera indexed the side of the film at a specific time interval. In this way, a distance-time relationship was established and the velocity of the jet at various points along the spillway could be determined. The velocity measurements made by the high-speed film were spot checked for accuracy by using a pitot tube. Close agreement was found between the two methods.

At the maximum discharge, the flow becomes fully turbulent within 3 m (10 ft) of the crest and begins to slow down. After falling 8 m (26 ft), the velocity is between 8 and 11 m/s (26 and 36 ft/s). The velocity generally stays within this range for the remaining 53 m (175 ft) of fall distance. The energy reduction achieved by the stepped spillway over a conventional smooth spillway of the same height is approximately 75 percent.

The major benefit of the stepped spillway is that flow velocities on the spillway face are kept low due to the tumbling action caused by the steps. This energy reduction over a conventional smooth spillway with a 61-m (200-ft) drop also eliminates the need for a long stilling basin. In this case, with a 183-m (600-ft) wide spillway, this results in an enormous savings in concrete and excavation along with reducing the area over which uplift pressures can develop. Because of the reduced velocities associated with the stepped spillway over those developed by a conventional smooth spillway, the stilling basin for the new design need be only half as long as one for a conventional 61-m (200-ft) high dam. The stilling basin for the Upper Stillwater spillway is 7.6 m (25 ft) in length and quiets the flow beyond the endsill for all discharges.

CONCLUSIONS

The stepped spillway works well in conjunction with the use of roller-compacted concrete. Because of the energy dissipation produced by the steps, the stilling basin size is minimal. It has specific application to spillways with low unit discharges. Further research will hopefully relate step height versus jet thickness in order to develop more generalized design criteria.

ACKNOWLEDGMENTS

R. J. Quint and A. T. Richardson, Division of Design, Bureau of Reclamation, are acknowledged for their technical input and helpful suggestions during the course of the model studies.

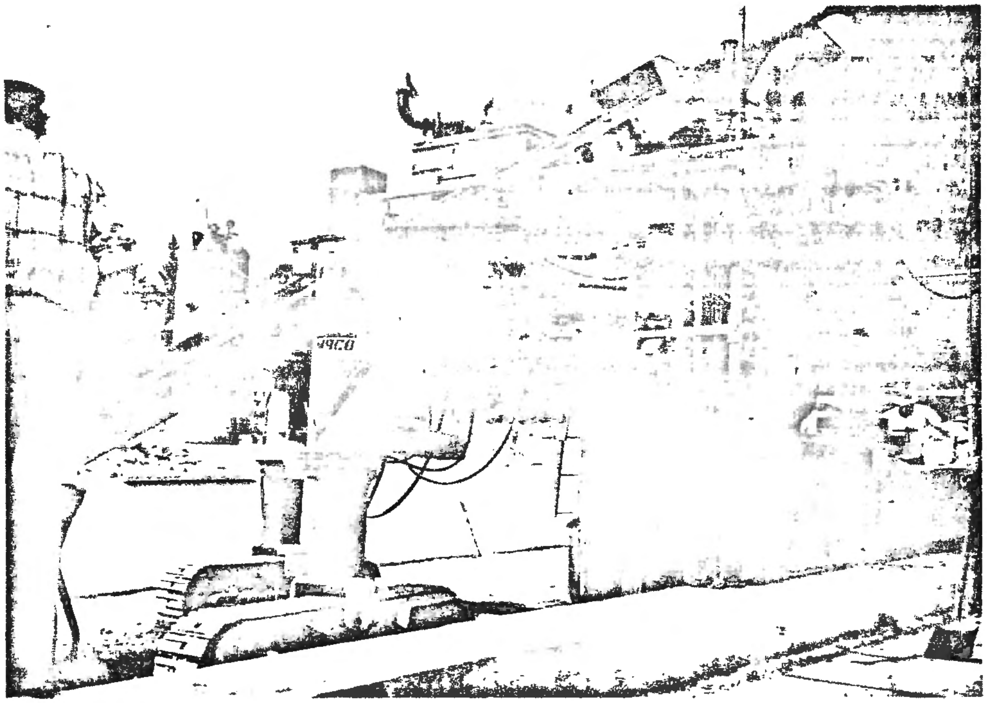

FIG. 1. - Laser-controlled slip form.

FIG. 2. - Upper Stillwater spillway test section.

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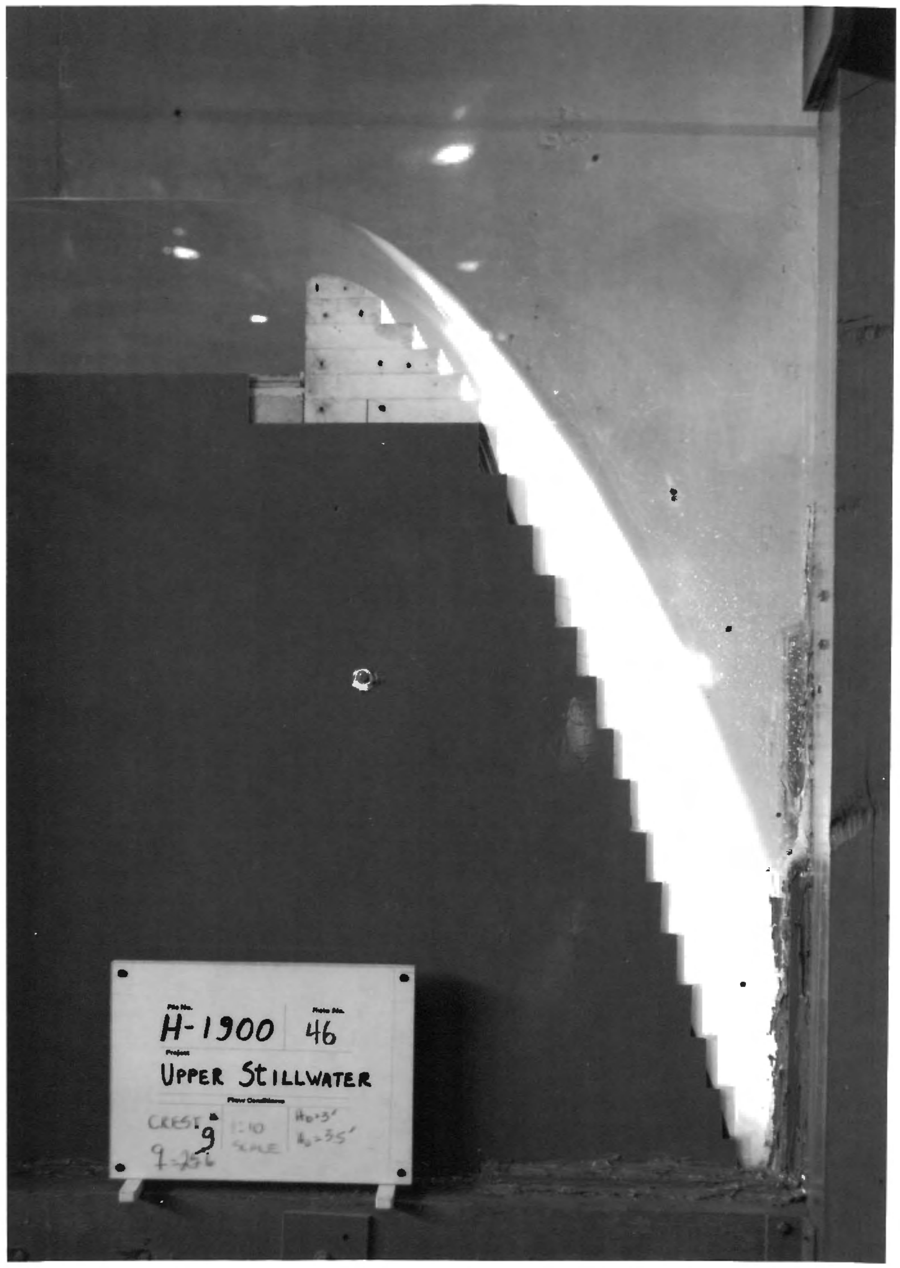
Project
UPPER STILLWATER
Flow Conditions
UNIT Q= 20.7 cfs/ft
1:5 SCALE Model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UPPER STILLWATER
Flow Conditions
UNIT Q= 20.7 cfs/ft

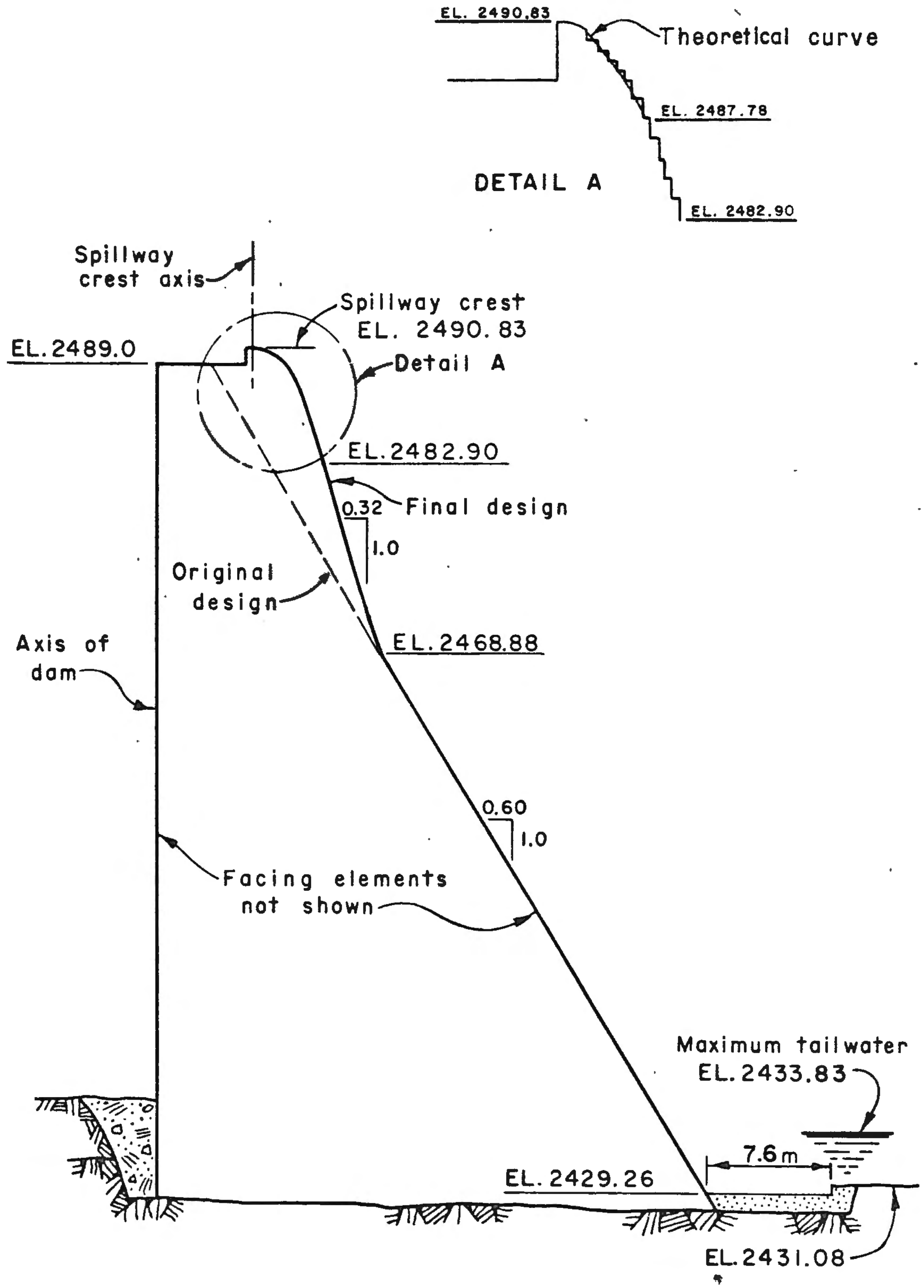

FIG. 3. - Final design - Upper Stillwater Dam section.
(Elevations in meters)

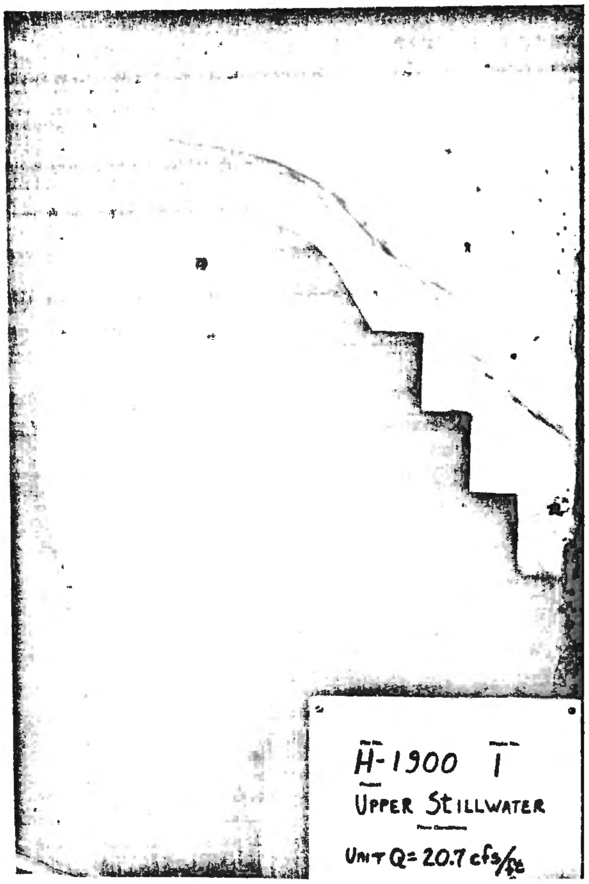

FIG. 4. - 0.6 to 1 spillway crest - original design Q = 1.92 m^2/s (20.7 ft^2/s).

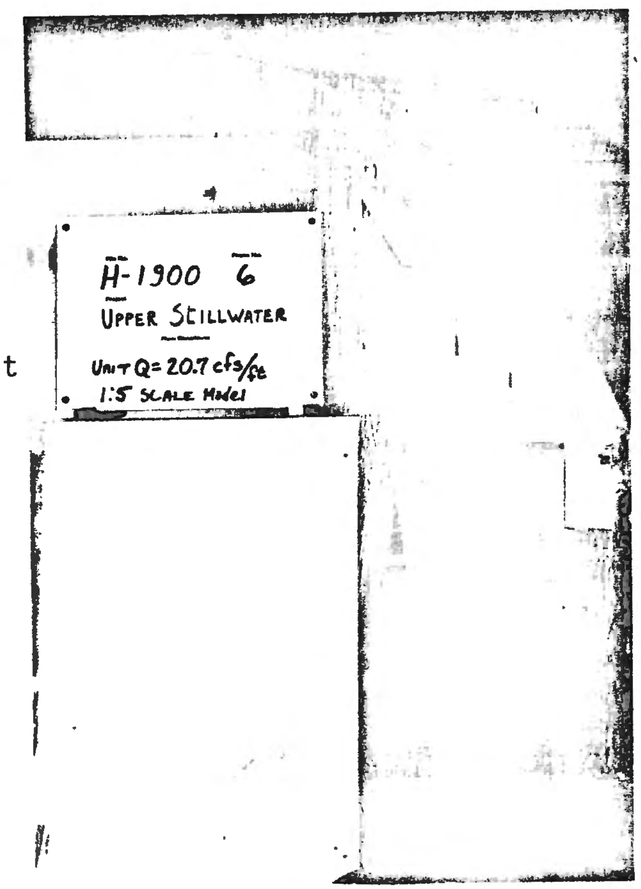

FIG. 5. - 0.6 to 1 spillway crest modified design Q = 1.92 m^2/s (20.7 ft^2/s).

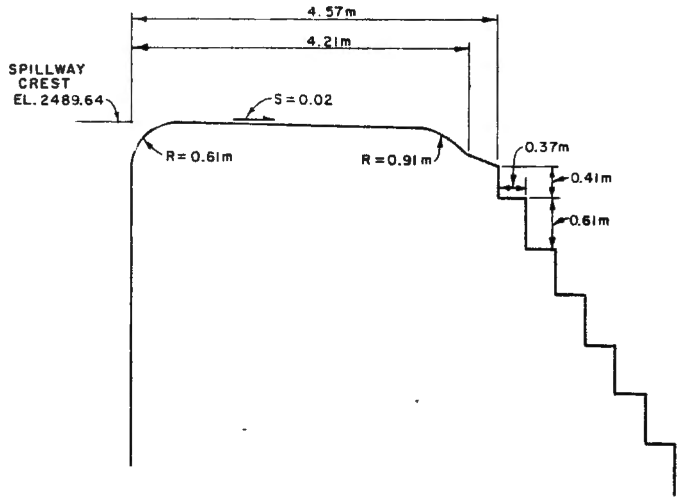

FIG. 6. - Spillway crest dimensions - modified design.

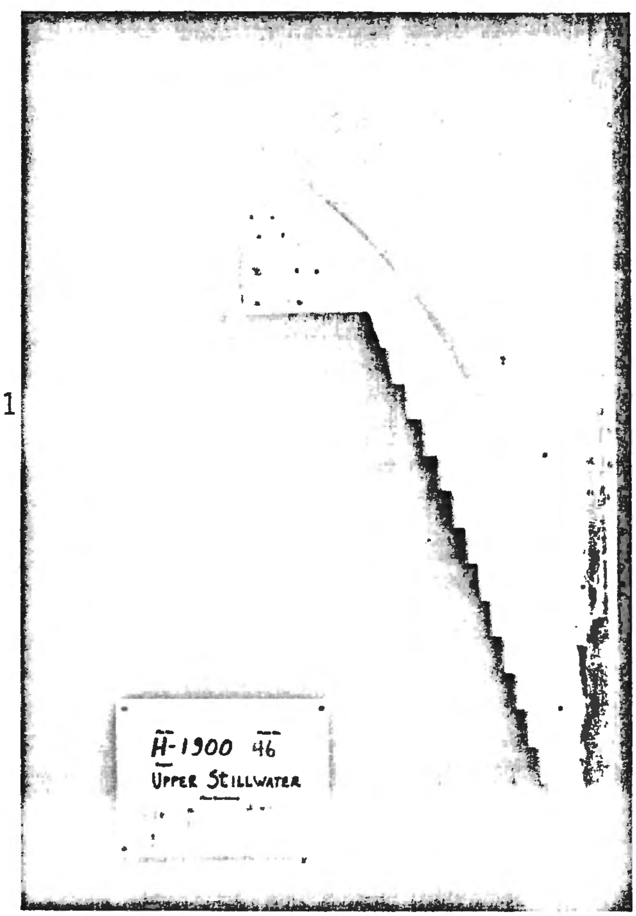

FIG. 7 - Final design - 0.32 to 1 spillway crest - Q = 2.39 m^2/s (25.7 ft^2/s).

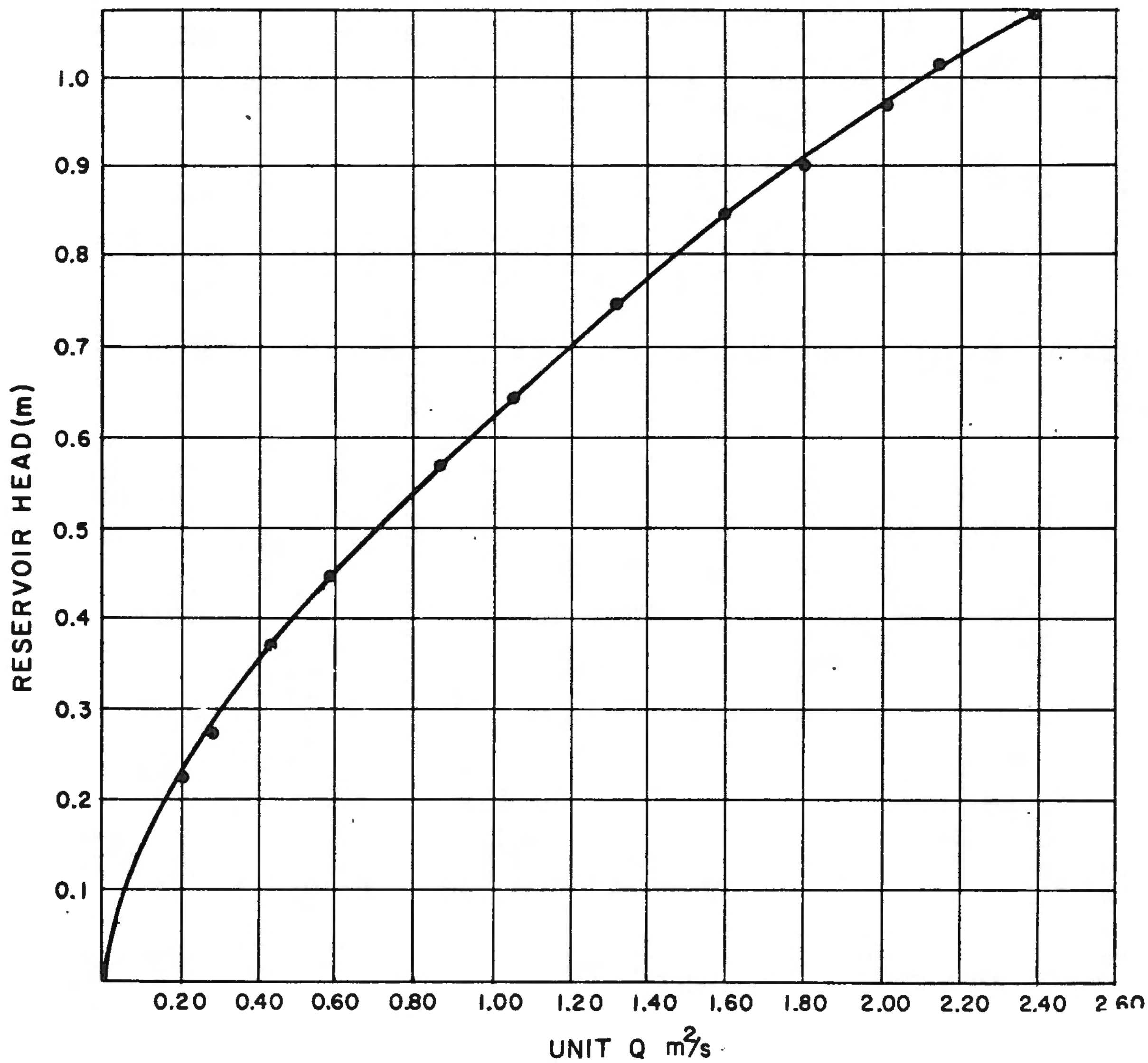

FIG. 8. - Discharge curve - Upper Stillwater spillway final design.