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HYDRAULIC MODELS AS AN AID IN DESIGN AND CONSTRUCTION

HYDRAULIC MODEL EXPERIMENTS FOR DESIGN OF GRAND COULEE DAM

By

Jacob E. Warnock
Assoc. M. Am. Soc. C. E.
Hydraulic Research Engineer,
U. S. Bureau of Reclamation,
Denver, Colorado

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By the time the design and construction of the Grand Coulee Dam had been assigned to the Bureau of Reclamation, the practice of using hydraulic models as an aid in the design of large hydraulic structures had been well established. Models were first used extensively by the Bureau in 1930 in the design of the spillway for the Cle Elum Dam of the Yakima Project in Washington. The design of the spillways for the Boulder Dam, the Madden Dam in the Panama Canal Zone, and the Norris and Wheeler Dams for the Tennessee Valley Authority, served as stepping-stones in further developing the technique and improving the methods.

DESIGN OF THE SPILLWAY APRON

The first and the major problem in connection with the design of the proposed overfall spillway for the ultimate development of the Grand Coulee Dam was that of protection against scour at the toe. With a designed maximum capacity of one million cubic feet per second and a difference in head of 280 feet, the energy to be dissipated will be 31,800,000 horsepower or 19,300 horsepower per foot of gross spillway crest length.

Four different models were tested in an attempt to develop a method of protection that would satisfy this unprecedented requirement. Each was constructed with definite limitations and for a definite purpose.

The first model was built to a scale ratio of 1:184 and was tested in the hydraulic laboratory of the Colorado Agricultural Experiment Station at Fort Collins, Colorado. Extensive experiments were then in progress in that laboratory on similar problems for the Norris and Wheeler Dams so that very little space was available for any models of the Grand Coulee Dam. Furthermore, no funds had been appropriated for the design of the ultimate development of the Grand Coulee Dam even though it was proposed that certain of its features would be included in the initial stage of construction. Those two factors led to the selection of the scale ratio of 1:184 for the first model.

It is to be granted that the scale of the model may have been so small as to throw doubt upon the accuracy of the quantitative results when transferred from the model to the prototype. However, this model did serve admirably in a qualitative way for the study of suggested designs and for the elimination of undesirable ones quickly and economically.

An analysis of the data on the 1:184 model indicated that the topogtaphy of the site, the tailwater-discharge relationship, and the condition of the river bed were such as to dictate the use of an apron curved in section and placed at a very low elevation. This apron will be referred to hereafter as the bucket.

A further refinement of this design resulted in the addition of a dentated lip on the downstream edge of the bucket which produced excellent results. The modified design eliminated both the impingement of the jet directly on the river bed and the scouring effect of the turbulent flow. However, the behavior of the water in and around the teeth of the dentated lip led to the belief that partial vacuums existed. That condition would be serious because of the possibility of cavitation and its consequent destruction of the teeth.

Since the 1:184 model was too small to allow detailed studies of those pressure donditions, a second model was constructed to a scale of 1:40. This model consisted of one gate with a half of a pier on each end, and the downstream face of the spillway including the bucket at the toe. A glass panel, six feet long by 3½ feet high, was built into one side of the flume to permit visual study of the flow conditions in the bucket. Piezometers were installed in the faces of two teeth as a means of measuring the pressures.

Inasmuch as the principal interest in this model was focussed on the region at the toe of the dam, the glass panel was invaluable in that it made possible a visual concept of the action in the bucket. It has been found that regardless of the amount of data which may be obtained by other devices, none is as effective in affording a mental image of the true behavior of the water as that obtained through a glass panel.

The pressure studies on the 1:40 model substantiated the belief that partial vacuums did exist around the teeth of the lip and extensive efforts were made either to reduce or to eliminate that condition.

Since very little is known concerning the effect of the dissimilarity between the vacuum conditions in model and prototype, it was believed advisable to construct a third and larger model. Accordingly, a model to a scale ratio of 1:15 was constructed and studied at the Bureau's laboratory on the south canal of the Uncompahgre Irrigation Project near Montrose, Colorado.

From this point and until the completion of the experiments on the final design, the testing was carried on simultaneously on the two large models. This permitted direct comparison of data. Every effort was made to find a modification of the dentated lip which would not have the objectionable vacuum condition. In no case could a solution be found in which the vacuum could be avoided without impairing the effectiveness of the dentated lip. An incidental test was made to determine the extent of the battering effect of ice or other solid materials which might be carried into the bucket during the operation of the spillway gates. The use of cakes of paraffin and short lengths of weighted dowel rods simulating ice and water-soaked logs disclosed that the sharp edges of the teeth were rapidly abraded.

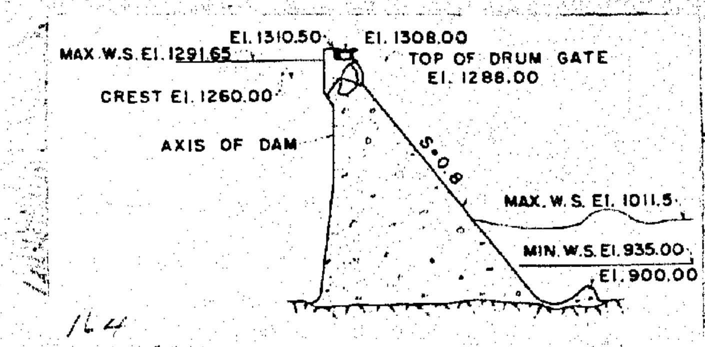


FIGURE 1 - SECTION THROUGH SPILLWAY
SHOWING POSITION OF BUCKET

As a result of the foregoing observations, it was decided that the dentated lip should be eliminated. The design of the bucket as finally adopted (figures 1 and 2), therefore, comprised

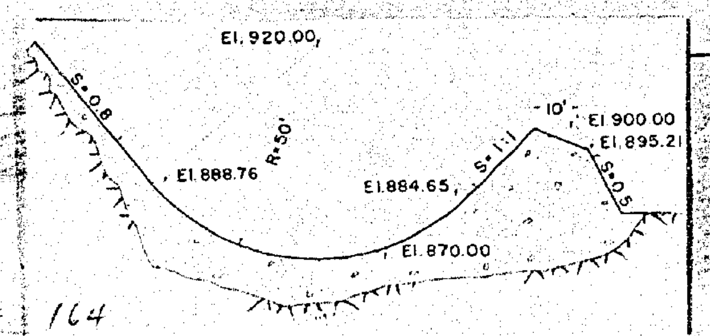


FIGURE 2 - DETAILS OF FINAL DESIGN OF BUCKET

a semi-circular apron with a 50-foot radius tangent to the 0.8 slope of the spillway at elevation 888.76

and terminated in a tangent with a 1:1 upward slope followed by a 2.59 slope toward the stream bed, broken at elevation 895.21 for structural reasons. The crest of the lip was at elevation 900.0, 35 feet below minimum tailwater elevation and 110 feet below the maximum.

After the selection had been made, an additional program of testing was undertaken to obtain more detailed information concerning the pressures and velocities in the bucket and concerning the extent of scour in the river bed. Piezometers were installed in the bucket and on the faces of the lip at such intervals that there was no possibility of a change of pressure conditionoccurring unobserved. Pitot tube traverses were made at representative sections.

The pressure measurements served to supply data for the structural design of the downstream portion of the bucket and to relieve the concern expressed regarding the possibility of the formation of negative pressures directly downstream from the crest of the bucket lip. The pressure data obtained are illustrated in figure 3. As may be seen, the anticipated negative pressures did not appear.

A very clear picture of the behavior of the internal mechanism by means of which the roller accomplishes the dissipation of energy was obtained from the velocity traverses. The descending sheet of water plunged into the tailwater and was diverged. This divergence can best be described as a process of raveling under the influence of the contact with the roller. After the stream enters the bucket, it is diverted with a practically constant velocity to the crest of the lip at elevation 900.0. The effect of the lip is to

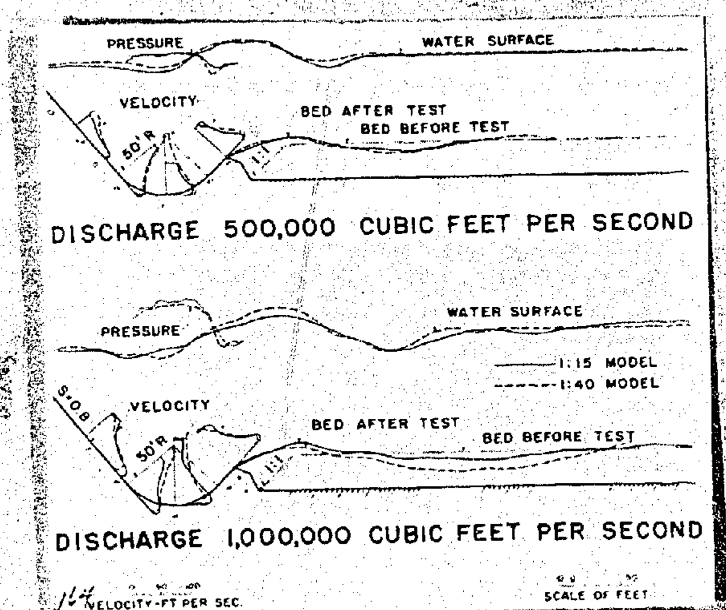


FIGURE 3 - COMPARISON OF FLOW CHARACTERISTICS IN SECTIONAL MODELS OF FINAL DESIGN OF SPILLWAY BUCKET

divide the jet into two parts, one of which is deflected upward to form the elliptical surface roller with its major axis in a horizontal plane above the bucket and the other which bends downstream and forms the so-called "ground roller".

These two rollers are the fundamental factors which govern the dissipation of energy and the prevention of scour. It is the upstream surface roller which is primarily effective in dissipating the energy which might otherwise prove destructive to the river bed, and it is the ground roller whose direction and intensity control the extent of the erosion immediately below the bucket. It was found that a slope steeper than 1:1 on the upstream face of the lip produced a too nearly vertical deflection of the jet with the result that the ground roller dipped sharply and produced excessive scour and the surface roller was rendered ineffective. For slopes flatter than 1:1, the surface roller tended to "sweep" out of the bucket and the ground roller was obliterated by a downstreamward current which again produced excessive scour.

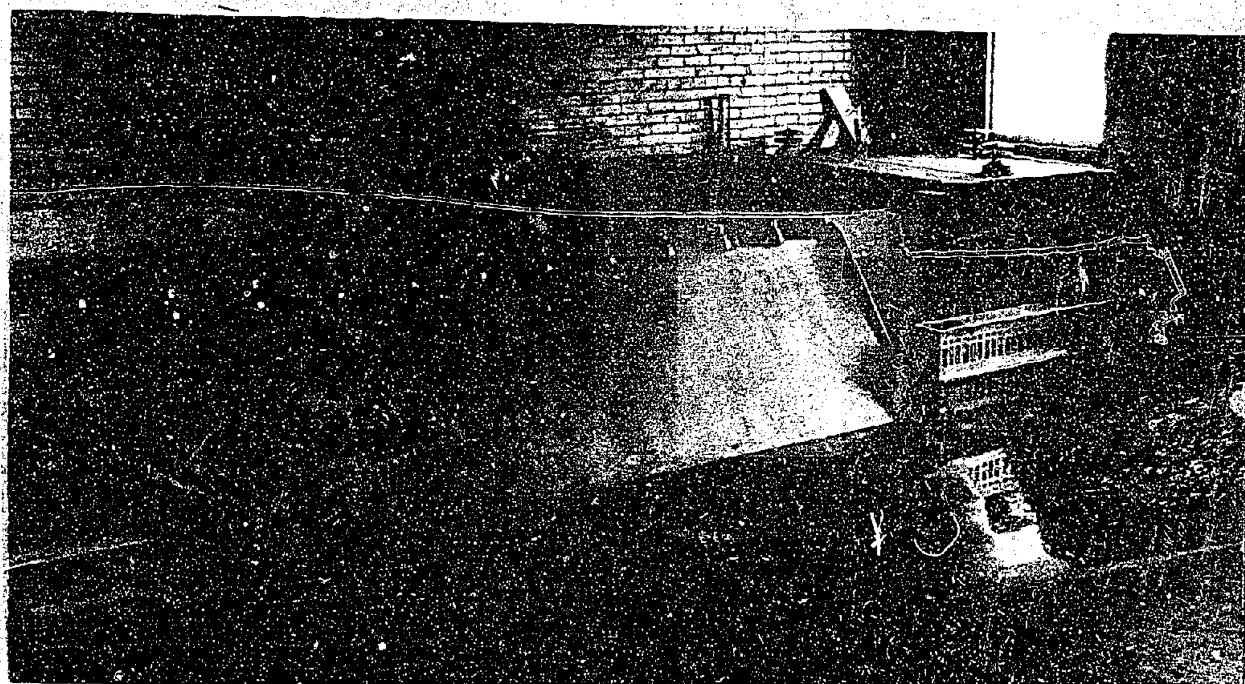
A very significant feature brought out by the pitot tube traverses was the fact that the actual maximum velocities in the curved portion of the bucket are materially less than might have been expected from theoretical considerations. As an example, it was found that for the condition in which the spillway discharge was 500,000 second-feet, the maximum measured velocity at the point of tangency was 55.0 feet per second in contrast to the velocity of 133.0 feet per second measured at the point where the descending sheet enters the pool. This latter velocity was found to be in excellent agreement with the calculated velocity of 141.0 feet per second.

In making the observations on the bed erosion below the bucket, care was exercised before each run to restore the surface of the bed to a predetermined profile selected to facilitate comparison. From the downstream toe, of the bucket, the bed material was carried up on a 1:1 slope to simulate the condition that will probably exist following the construction activities. It was found that, as the discharge gradually was raised to capacity, the river bed material was carried back against the bucket completely filling the trench and forming a deposit parallel to the lip and roughly parabolic in section. This deposit thus formed proved to be quite stable and was not materially effected by subsequent variation of the discharge.

Model buckets with thirty-, fifty-, seventy-five-, and one-hundred-foot radii were tested during the course of these studies. The circular roller of the 30-foot bucket was much less effective than the elliptical roller of the 50-foot bucket. The use of a 75- or 100-foot radius resulted in only slight further improvement which was considered insufficient to justify the additional cost.

During the tests on the 1:184 model a curious transverse wave phenomenon was observed. Starting with a swell which formed midway between the side-walls, the wave divided, travelled laterally to the sides, and was reflected back to the center. This action was contimuously repeated. As characterized in this model, the wave threatened a condition which in the prototype would have seriously battered the spillway training walls and the ends of the power-houses. It was at first thought that this condition in the model might have been caused by the fact that the 1:184 model represented only a portion of the total length of the spillway. Experiments with the dentated sills demonstrated that the wave could be eliminated by this means, but as has been previously observed, other considerations caused the rejection of this solution.

The same phenomenon was observed on both the 1:15 and 1:40 scale models. In no case could it be avoided without the use of the dentated bucket lip. Partly for this reason and partly because it was desired to demonstrate the action of the proposed bucket in its entirety and its proper relation to the riprapped slopes of the tailraces, a complete model on a scale of 1:120 was decided upon. It was felt that such amodel would obviate uncertainties introduced by the artificial conditions of the sectional models. A model representing the complete ultimate development was therefore constructed to a scale of 1:120 in the Fort Collins laboratory. Included in this model was the spillway, powerhouses, tailraces, and a half mile of the river bed below the dam.



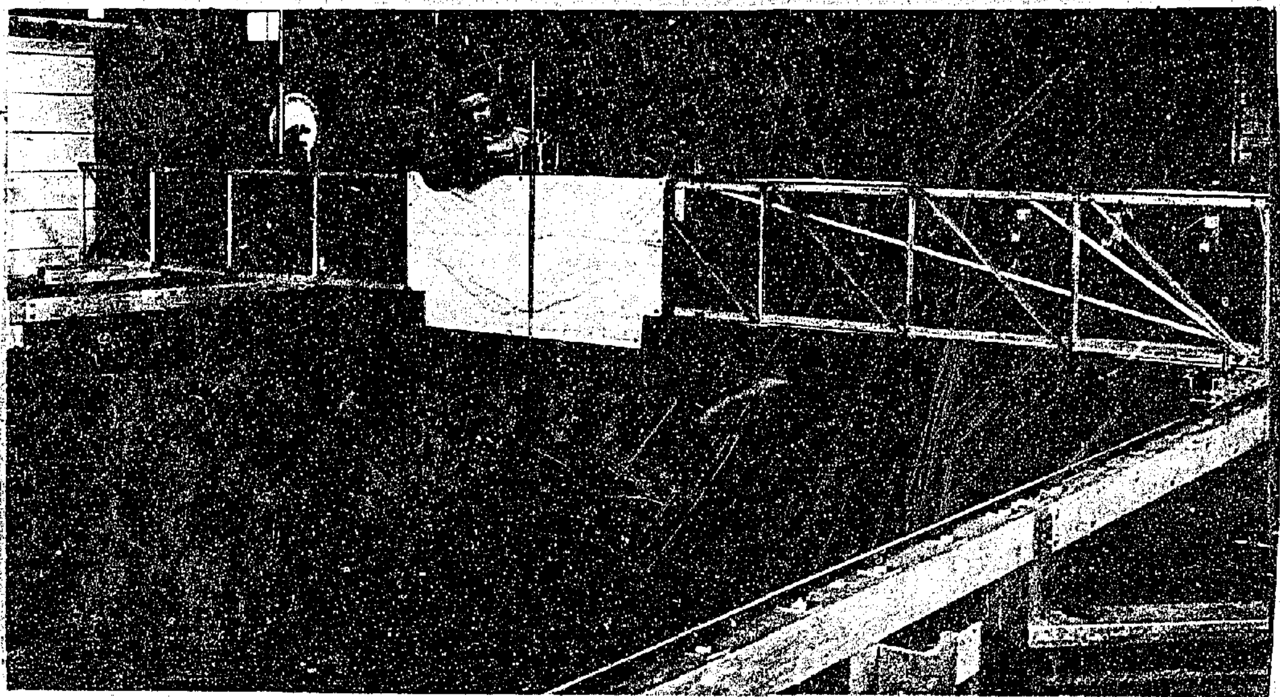
MODEL OF ULTIMATE DEVELOPMENT TO 1:120 SCALE

The presence of this transverse wave was confirmed by the first observations made on the new model. By a process of trial and error, it was discovered that the action could be eliminated by increasing the effective tailwater depth. As a result of this finding, the design of the bucket was altered by lowering it until the crest of the lip was at elevation 900.0. The results were completely satisfactory.

Simultaneously with the study of the transverse wave problem, it was observed that the pool action in the vidinity of the tailraces was much less violent than had been anticipated. It was noted, furthermore, that the removal of one gate on the extreme left end of the spillway would result in a very material improvement in the behavior of the tailrace. As a consequence, the spillway was shortened from a gross length of 1800 feet to 1650 feet. The resulting increase in effective head on the spillway crest fortunately had no adverse effect. This change permitted the shifting of the left powerhouse 150 feet toward the river to a more favorable location which will effect an appreciable construction economy.

In preparation for the studies of the erosion of the river bed, it became necessary both to determine a material which would suitably represent the natural alluvium and to determine a method by means of which the river bed profile could be expeditiously reproduced.

The bed material of the Columbia River at the Grand Coulee damsite is a combination of clay, sand and gravel closely interspersed with larger rock fragments, all intimately associated in a cohesive mass. To find an accurately analogous material was quickly seen to be a practical impossibility. It was felt, however, that satisfactory qualitative results would be obtained by using a cohesionless, and, therefore, much less stable sand. This con-



PROFILOGRAPH AND 1:120 MODEL

clusion was further justified by the fact that comparative rather than absolute data were desired; that is, the comparison of the local erosion produced by numerous proposed designs was sought rather than the quantitative determination of the permanent retrogression. It was believed that a design based upon conditions found to be satisfactory in this sand would be amply conservative when constructed in the tenacious material actually present at the site.

To facilitate the reproduction and recording of the river bed topography, a profilograph was developed similar to those in use in other laboratories, but equipped with certain novel modifications. One of the principal features of this instrument was the substitution of a simple horizontal and vertical gear ratio for the more cumbersome pantograph. The instrument is shown in use in the accompanying photograph. Field data was plotted in prototype dimensions on the profilograph sheets and automatically transferred in proper proportions to the model bed. Similarly, the measurement ofthe model bed after the erosion had occurred was automatically recorded on the profilograph sheets in prototype terms.

SPILLWAY TRAINING WALLS

Upon completion of the foregoing erosion studies, a further series of experiments was initiated on the 1:120 model of the ultimate development for the purpose of improving the design of the spillway training walls. First consideration was given to the hydraulic properties of the walls. As originally proposed, they were of such length that considerable scour was produced by the eddies around their downstream ends. A small number of tests sufficed to establish a length of wall for which the amount of scour was reduced to a satisfactory minimum.

When the detailed structural designs of those walls were undertaken, it was found that no adequate data, either theoretical or experimental, were available as to the intensities of the unbalanced hydrostatic pressures to be expected.

To provide the required information, one of the walls of the model was equipped with 64 piezometers so located as to give the vertical pressure distribution at six different sections. The tests showed that pressure differences were much less than had been assumed. The consequent re-design resulted in a material saving of both concrete and reinforcing steel.

SPILLWAY CREST STUDIES

An entirely separate set of tests were made to assist in the design of the spillway crest and drum gates. The 28-foot by 125-foot drum gates necessitated the use of the unusually heavy vertical cantilever section shown in figure 4. It was desired to determine a crest shape which would coincide as nearly as possible to the natural trajectory of a freely falling jet. A tentative design was based upon data obtained from the Bazin experiments for a 2:3 approach slope. To check these assumptions, a model of the upstream portion of the crest with a sharp-crested weir at elevation 1256.18 was constructed to a scale of 1:30. The lower nappe of the jet was then measured with a coordinometer.

The result of those measurements proved in excellent accord with the theoretical design. The trajectory thus measured was approximated by a compound curve with three radii as shown in figure 4. This new crest was then incorporated in the model and pressure measurements made with various discharges.

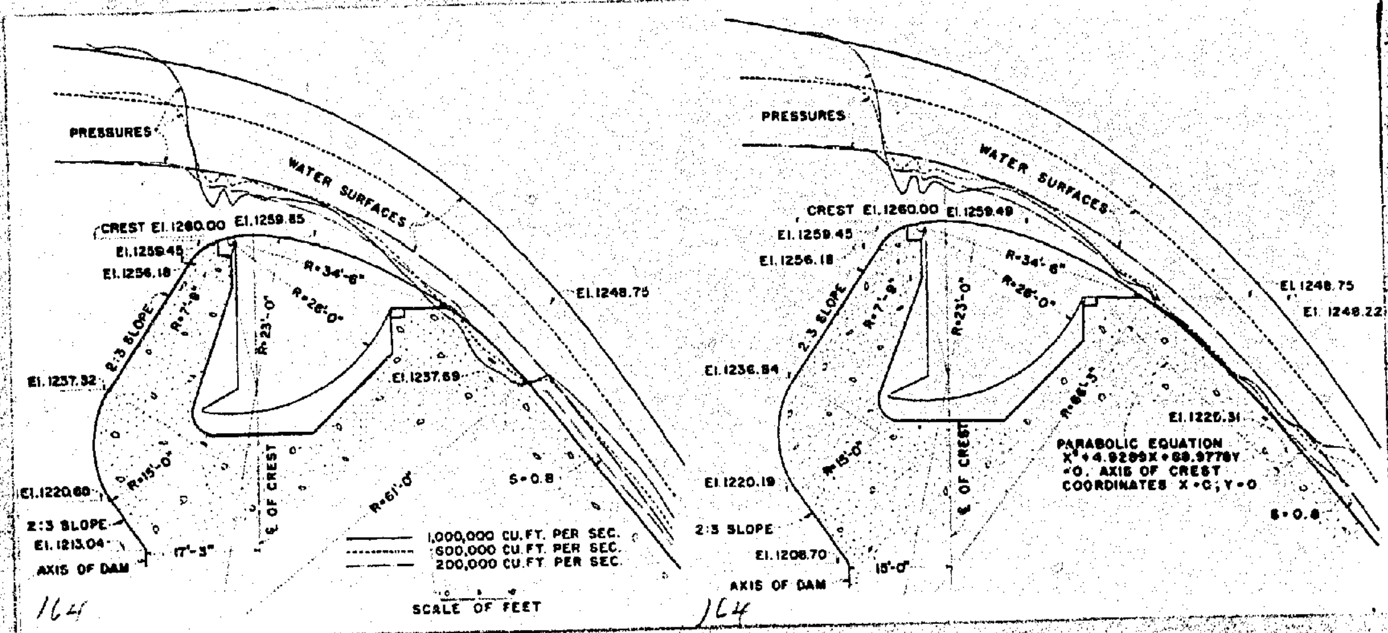


FIGURE 4 - ORIGINAL AND FINAL DESIGN
OF SPILLWAY CREST

Examination of the pressure curves shown in figure 4 will show that a region of negative pressure was produced under all conditions of flow. The indications were that the curvature of the crest was too sudden near the downstream edge of the drum gate.

To eliminate this low pressure region, the radius of the large curve was lengthened, the axis of the crest moved upstream, and a parabolic curve introduced to connect the 66.25-foot curve to the 0.8 downstream slope of the spillway (figure 4). Subsequent installation and testing of the revised section showed that the low pressure zone no longer existed.

After the revised design had been found to be satisfactory with the drum gate in the lowered position, additional measurements were made with the gate raised to provide pressure data for the structural design of the drum gates.

CONSTRUCTION DIVERSION STUDIES

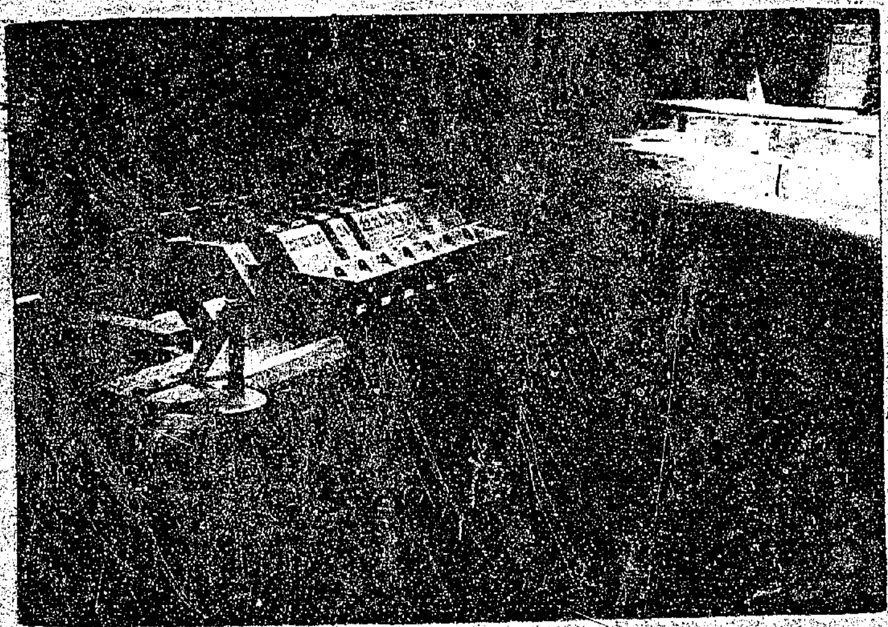
The most recently completed model studies were those made to assist in the preparation of the diversion plans. These plans contemplated two major stages in the construction of the initial development of the dam. In the first, which is now in progress, a cofferdam along the left bank confines the river to its normal channel and protects the construction in the west cofferdam area. After the completion of the initial construction in this area, it is proposed to shift the flow of the river into floodways provided across the newly completed work. This will be accomplished by removing the present cofferdams and constructing others across the present river channel.

MODEL OF WEST COFFERDAM AREA
SHOWING FLOOD PASSAGES

The problem presented for solution was the determination of a combination of flood passages through the west cofferdam area which would carry a maximum flood flow with the least menace to the riprapped slope at the downstream side of the powerhouse tailrace.

For this purpose, a technique was adopted on the diversion model, to a scale of 1:120, which would provide the utmost flexibility and thus permit rapid changes in the combination of flood passages. This was accomplished by the use of concrete blocks cast to simulate the actual prototype blocks but provided with horizontal joints to facilitate removal. The photographs show the combination of flood passages finally adopted.

In the course of these studies, velocity and scour traverses were made for comparing the merits of the different plans. In addition, the head and tailwater elevations were recorded during each test as a possible aid to the construction engineer in determining the discharge during a flood.



MODEL OF WEST COFFERDAM AREA SHOWING RIPRAPPED SLOPE AND POWERHOUSE FOUNDATION

In addition to the studies previously described, other experiments are either contemplated or actually in progress. Efficiency tests are now being made on a model of a turbine complete with penstock, scroll case and draft tube.

In addition, studies are contemplated to assist in the design of the sluiceways and their control gates. Additional studies are planned on the 1:120 model of the ultimate development to determine the necessity for additional riprapping below the left tailrace. The present 1:120 model of the west cofferdam area will be extended to represent the entire initial development for further studies of flow conditions.

The hydraulic model studies for the design of the Grand Coulee Dam by the U. S. Bureau of Reclamation were initiated under the immediate supervision of E. W. Lane, M. Am. Soc. C. E., Research Engineer, and are being continued under the immediate supervision of the author. All the design studies and investigations are under the direction of J. L. Savage, M. Am. Soc. C. E., Chief Designing Engineer. All the engineering and construction work is under the general direction of R. F. Walter, M. Am. Soc. C. E., Chief Engineer, and all the activities of the Bureau are under the general charge of John C. Page, Acting Commissioner.

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