HYDRAULIC MODEL STUDIES ON THE SPILLWAY FOR THE ANGOSTURA DAM
ANGOSTURA UNIT - MISSOURI BASIN PROJECT

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BRANCH OF DESIGN AND CONSTRUCTION
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Subject: Hydraulic model studies of the spillway for Angostura Dam--Angostura Project--Missouri River Basin--South Dakota.

Summary: A hydraulic model investigation was requested to check the adequacy of the proposed spillway for Angostura Dam for releasing water during floods. The main portion of the investigation was centered on the energy dissipation as the tailwater depth was not sufficient for the proposed type bucket or a conventional stilling pool.

The original design consisted of a 100-foot radius solid bucket. Prevailing conditions made it necessary to develop a new type bucket for this particular dam. A slotted-type energy dissipator with a 40-foot radius produced the desired results, and a saving of approximately $500,000 was realized over a sloping apron design which would have been necessary were it not for the development of the new device.

The experimentation was carried on with two models: One a 1:42 scale sectional model for the detailed studies of the bucket proper, and the other a 1:72 scale model of the complete spillway. The latter model was used to study side effects and to observe the action of the bucket as a whole. The final design of the downstream wing-walls were determined in the 1:72 scale model.

The Prototype. The Angostura Dam will be an earth-fill structure, located on the Cheyenne River in Fall River and Custer Counties, near Hot Springs in the southwestern corner of South Dakota (Figure 1). The principal hydraulic feature involved in its construction is an overfall concrete spillway with a special design of bucket serving as an energy dissipator (Figures 2 and 3).

The concrete spillway and bucket will serve to convey flood waters safely past the dam. The designed capacity of the spillway is 277,000
second-feet. Other means for releasing water downstream will be through the river outlet works, controlled by a 4- by 4-foot high pressure slide gate and through a canal headworks which will be controlled by two 3.5- by 3.5-foot high-pressure slide gates.

The drainage basin above the reservoir covers an area of 9,100 square miles located in eastern Wyoming, northwestern Nebraska, and southwestern South Dakota. The rate of runoff is highly variable, ranging from negligible amounts in the dry season to the largest recorded flow of 114,000 second-feet. The average annual precipitation over the area is 19.12 inches.

The plan of development includes the construction of a reservoir, an earth-fill dam with gravity concrete spillway, powerplant, outlet conduit, canal headworks, and laterals. The reservoir will have a capacity of 316,000 acre-feet of which 100,000 acre-feet will constitute dead storage below the irrigation level. The powerplant, which will have two 1,500-kilowatt units, will be located about four miles downstream from the dam. The headworks to the main irrigation canal will be located in the reservoir about 100 feet above the riverbed. The main canal will have a length of 25 miles.

The Models. Two models were used in the hydraulic studies for Angostura Dam. One, a sectional model, was placed in a long flume, and the other consisted of the complete spillway and downstream river channel. The sectional model was on a scale ratio of 1:42. It was of wood construction, lined with sheet metal (Figure 4). The overflow shape was formed of sheet metal permanently soldered to the metal side walls of the flume. The bucket was installed in a manner such that it could be readily replaced by other shapes and sizes. A large glass window was installed in one side of the flume to observe flow conditions over the spillway and the action in the bucket. Pea gravel was placed in the downstream portion of the flume to show the action of loose material in the riverbed and to indicate the scour pattern to be expected in the prototype.

The model for the complete spillway and downstream river channel was constructed using a 1:72 scale ratio. The head and tail boxes were
Sheet metal lined wood channel.

PLAN

11'-0"   1'-0"

18'-0"

SECTION

ANGOSTURA DAM SPILLWAY
HYDRAULIC MODEL STUDIES
SCALE 1:42 SECTIONAL MODEL
of wood construction lined with sheet metal (Figure 5). The overflow section and bucket were formed of sheet metal and soldered to the lining of the box. The solid portions of the channel walls were constructed of concrete backed with wood and metal lath for false work. The gate piers on the crest were constructed of oiled redwood. The 50- by 30-foot radial gates on the crest were constructed of sheet metal and hinged to the piers. The riverbed and downstream channel were filled with fine sand to observe scour patterns after various flows over the spillway. The tailwater was controlled by a variable-height weir-type gate hinged at the bottom and raised and lowered by cables fastened to a pipe windlass which was located near the downstream end of the tail box.

The flow of water to the model was supplied by a 12-inch pump through a 12-inch inlet pipe. The quantity of water was measured through 8- and 12-inch venturi meters. The water leaving the model over the variable-height weir spilled into the sump under the floor of the laboratory from which it was recirculated.

Preliminary Investigations on the 1:42 Scale Models. The preliminary investigation on Angostura Dam Spillway was to determine a suitable as well as an economical stilling basin design. These investigations were carried out in the 1:42 scale sectional model. The original dissipating device consisted of a solid bucket with a 100-foot radius as shown in Design 1, Figure 6. The downstream portion of the lip ended on a 45-degree tangent. This bucket produced undesirable flow conditions, in that the water surface was extremely rough and the scour downstream was excessive (Figure 7A) for the limited tailwater depth available. The action in the bucket was violent, and the ground roller, which continually moved material upstream against the end of the bucket, was strong. The model showed the bucket to be unnecessarily large for the flows anticipated.

Next a solid bucket having a 63-foot radius was installed in the model (Design 2, Figure 6). This bucket produced even more unsatisfactory flow and erosion than the previous design, as can be observed from Figure 7B. The scour was excessive in this case.
A - Flow of 277,000 second-feet.

100 FOOT RADIUS BUCKET WITH DOWNSTREAM LIP ON 45° TANGENT

B - Flow of 277,000 second-feet

63 FOOT RADIUS BUCKET WITH DOWNSTREAM LIP ON 45° TANGENT

SECTIONAL MODEL ON 1:42 SCALE
A 42-foot radius solid bucket was used for the third trial (Design 3, Figure 6). This bucket handled the maximum flow as well as the previous designs as far as dissipation of energy was concerned, but the violent movement of the riverbed material was objectionable and erosion downstream was excessive (Figure 8A). Alteration of the downstream lip of the bucket appeared a probable solution for decreasing the erosion and improving flow conditions.

A 42-foot radius solid bucket with the downstream lip tangent to a 15-degree angle, referred to the horizontal and bottom of bucket raised, was next tried in an effort to reduce the erosion of the river channel (Design 4, Figure 6). In this case, the invert of the bucket was raised to elevation 3,070. The result was a trajectory jet on the surface as shown in Figure 8B. Erosion was excessive and the water surface was extremely rough. This bucket demonstrated no particularly desirable features.

The next bucket had a 42-foot radius with the downstream lip tangent to a 25-degree angle, and invert at elevation 3,070 (Design 5, Figure 6). The operation was somewhat improved with this installation for the dissipation of the energy appeared satisfactory and the erosion of the river channel was decreased principally because the former violent ground roller was diminished. The next step was to install this bucket in the 1:72 scale model and study the action of the bucket in connection with the spillway as a whole.

Development of a Bucket with Slots. Experience along the line of the roller bucket has been limited in the past to a few installations of which the Grand Coulee Dam Spillway is one. At Grand Coulee Dam considerable difficulty has been experienced with erosion of the concrete in the bucket because of large boulders and rock rolling around in it, especially for unsymmetrical flow conditions. It was undesirable to make another similar installation until this objectionable feature was corrected.

It was thought that some inexpensive and effective means could be provided to keep the loose rock away from the lip of the bucket. The first idea along this line was to install tubes in the lip of the
A - Flow of 277,000 second-feet 42 foot radius bucket.

42 FOOT RADIUS BUCKETS WITH DOWNSTREAM LIP ON 45° TANGENT

B - Flow of 277,000 second-feet.

42 FOOT RADIUS BUCKET WITH DOWNSTREAM LIP ON 15° TANGENT

SECTIONAL MODEL ON 1:42 SCALE
bucket through which, it was contemplated, jets of water would flow sweeping the loose material away from the downstream edge of the bucket. This was tried and the results were satisfactory at low discharges, but at the higher flows, the ground roller piled the loose rock over the jet openings virtually closing them. Larger tubes seemed necessary if this scheme was to work satisfactorily.

It was suggested that slots be placed in the bucket instead of tubes through the lip. The first design (Design I, Figure 9), was encouraging, except for the fact that the gravel crept up the downstream face of the teeth producing an abrasive action. The action downstream from the slots, however, was entirely satisfactory. An apron was then installed downstream from the teeth to spread the jets issuing through the slots in an effort to keep the gravel away from the bucket. Pressures were observed on the teeth at critical points in the bucket to detect subatmospheric conditions. In general, the pressures proved satisfactory although several areas of negative pressure existed. These were registered by piezometers 1 and 3, Design I, Figures 9 and 10.

The radius of the bucket was next continued throughout the length of the teeth, Design II, Figure 9. The floor of the slots between the teeth was a plane on an angle of 8 degrees with the horizontal, starting at the point of tangency with the bucket radius. The apron downstream was also a plane but on an angle of 16 degrees with the horizontal. The curved teeth proved more satisfactory than those in Design I, as the energy was dissipated more readily and a smoother water surface resulted downstream. The pressures on the teeth were negative for piezometers 1, 2, 3, 4, 6, 7, and 8, Design II, Figure 10, the majority of which were on the downstream face. The rounding of the edges of the teeth was determined by the use of radii ranging from 0.1 inch- to 0.3-inch radius on the model. The larger radius (about 15 inches prototype) was the most desirable for the pressures on the teeth were higher.

The downstream portions of the teeth were shaped differently for the next design in an attempt to improve pressure conditions. The third design was similar to the previous one except that the teeth were shortened, the sloping ends were on a 45-degree angle, and the sides were
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SHAPE OF TEETH AND LOCATION OF PIEZOMETERS
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PRESSURES ON BUCKET TEETH

FIGURE 10
tapered 2 degrees in plan to increase the pressures in the slots (Design III, Figure 9). This design was quite satisfactory in all respects as the dissipation was excellent and the negative pressures were few and above the critical range in which cavitation would occur. Negative pressures were present at piezometers 3, 4, and 5 (Design III, Figure 10). The next step was to determine the most desirable spacing of these teeth.

**Spacing of the Teeth.** The spacing of the teeth was an important factor in the design of the bucket. It was desired not to let any more water through the slots than would be required to keep the downstream apron free of gravel. Spacings tried on the model for the Designs shown as I or II on Figure 9, were: (1) teeth three times the width of the slot, (2) teeth twice as wide as the slot, and (3) teeth the same width as the slot (Designs I, II, & III, Figure 11). Photographs of the model operating at a maximum discharge are shown for the tooth spacing in the same order on Figure 12.

When it became desirable to increase the pressures on the inside faces of the teeth as in Design III, Figure 9, it was again necessary to experiment with the spacing. The 1-foot, 2.7-inch spaces between the teeth, Design IV, Figure 11, were rather small, for rocks and debris could easily be caught between the teeth. The 2-foot, 7½-inch spacing was then tried (Design V, Figure 11), but this spacing was too great and the pressures on the teeth dropped considerably. An intermediate value of 2 feet proved the more satisfactory spacing, shown as Design VI, Figure 11. With the latter spacing, the pressures were reasonably high and operation was satisfactory. Dissipation was principally a spreading action rather than roller action and in no case did bed material come in contact with the teeth.

**Downstream Apron.** The slope and length of the downstream apron was another important requirement for satisfactory operation. The apron served to spread the jets flowing through the slots and the stability of the bucket action was dependent on the vertical angle of the apron. Of the three shown on Figure 12A, the 16-degree sloping apron was the most satisfactory. For the 12-degree slope, the jet became unstable intermittently diving and scouring the riverbed downstream. For the
FIGURE 11

TOOTH SPACING 3 TO 1
DESIGN I

TOOTH SPACING 2 TO 1
DESIGN II

TOOTH SPACING 1 TO 1
DESIGN III

BEVELED TOOTH SPACING
DESIGN IV

BEVELED TOOTH SPACING
DESIGN V

BEVELED TOOTH SPACING
FINAL DESIGN

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VARIOUS SPILLWAY BUCKET TOOTH ARRANGEMENTS
FIGURE 12

A - Flow of 277,000 second-feet.
3 TO 1 TOOTH SPACING

B - Flow of 277,000 second-feet.
2 TO 1 TOOTH SPACING

C - Flow of 277,000 second-feet.
1 TO 1 TOOTH SPACING

SECTIONAL MODEL ON 1:42 SCALE
FIGURE 13

DESIGN I

DESIGN II

DESIGN III

A - DEGREE OF SLOPING APRON
DOWNSTREAM FROM TEETH

B - LENGTH OF SLOPING APRON
DOWNSTREAM FROM TEETH

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ANGOSTURA DAM SPILLWAY
20-degree slope, the spreading of the jet was less effective. Photographs of the three aprons for maximum discharge are shown on Figure 14.

After arriving at the best slope for the apron, it was then necessary to determine the minimum length required for satisfactory operation. Two apron lengths were tried as shown on Figure 13B. The longer of the two was necessary to provide length for the jets to spread, thus producing a more uniform jet leaving the apron. The bucket operated satisfactorily over a wide range of tailwater and discharge conditions. An expanded study as to ranges of flexibility of the different sizes of this type of bucket will be reported on in the future.

Reviewing the development of the new roller type bucket, three factors were involved: (1) the radius of the bucket for a given flow condition; (2) the shaping and spacing of the teeth; and (3) the degree of slope of the apron downstream from the teeth. All of these factors are important in the design of a bucket that will produce the desired dissipation of energy, a smooth water surface, and a minimum amount of erosion of the river channel.

Original Design 1:72 Scale Model. Operation of the 1:72 scale model of Angostura Dam using the solid trajectory bucket indicated objectionable features. This corresponded to the test on the 1:42 scale model for which a plain solid bucket was used with invert placed at elevation 3,070, Design 5, Figure 6. A flow of 277,000 second-feet over the spillway produced a jet action which caused excessive erosion of the riverbed (Figures 15A and B). At the lower discharges sand from the riverbed circulated in and out of the bucket which indicated that considerable erosion of the concrete in the prototype would result from this design. There was also violent motion of the sand at the downstream lip of the bucket which, if permitted to exist for a period of time, would damage the lip of the bucket.

Final Investigation on the 1:72 Scale Model. The new bucket design was now installed in the 1:72 complete model of Angostura Dam Spillway to study side effects which were absent in the sectional model. The bucket design with the sloping apron and the straight teeth (Design I, Figure 9) was first tried in the 1:72 scale model. A photograph of this model is shown on Figure 16. The operation was
A - Flow of 277,000 second-feet.
DOWNSTREAM APRON ON 16° ANGLE

B - Flow of 277,000 second-feet.
DOWNSTREAM APRON ON 12° ANGLE

C - Flow of 277,000 second-feet.
DOWNSTREAM APRON ON 20° ANGLE
SECTIONAL MODEL ON 1:42 SCALE
A - Flow of 277,000 second-feet over spillway

B - Erosion of river channel after flow of 277,000 second-feet.

ANGOSTURA DAM SPILLWAY MODEL (scale 1:72)

ORIGINAL DESIGN
A - Model dam and river channel

ANGOSTURA DAM SPILLWAY MODEL (scale 1:72)

REVISED DESIGN 1
satisfactory in that the erosion was a minimum and the resulting water surface was quite smooth. The teeth were then replaced by the curved teeth with tapered sides (Design III, Figure 9) as the latter proved the better in the 1:42 sectional model. These teeth were also an improvement in the 1:72 model, for erosion was decreased over the former design and a smoother water surface resulted. Figure 17A shows the model in operation for a maximum discharge and Figure 17B shows the resulting scour after a 20-minute run (model). This arrangement was considered the final design for the bucket proper.

**Downstream Wing-walls.** It was desired to have wing-walls adjacent to the bucket which would be economical to construct and at the same time produce no undesirable end effects. The first design, Design I, Figures 17 and 18, resulted in satisfactory operation but the amount of concrete needed to construct the walls was excessive.

A curved wall on the left side (Design II, Figures 18 and 19A) was the next design tried. This arrangement produced no undesirable flow condition but there was an objection to the cost of constructing a curved wall.

In the next design the curved wall was replaced by a wall on a 45-degree angle (Design III, Figures 18 and 19B). This design was undesirable as an eddy formed at each end of the wall. Water from the river, which was at a higher elevation than that in the bucket, flowed into the bucket along the wing-walls.

A square-cornered wall (Design IV, Figures 18 and 19C) eliminated the previous objections. The top of this wall was lowered 10 feet to elevation 3100 to save concrete.

Finally a cutoff wall was constructed at a point 15 feet downstream from the end of the bucket and bonded riprap was placed on a 2:1 slope upstream from this wall (Design V, Figure 18). The purpose of the bonded riprap was to reduce the possibility of loose rock falling into the bucket at the higher discharges. This arrangement was considered the final wing-wall design.

**The Final Design.** Summing up the results of the model studies for Angostura Dam, it is recommended that the final design have incorporated in it a 40-foot radius bucket with teeth, at elevation 3040, and
A - Flow of 277,000 second-feet over spillway.

B - Erosion of river channel after flow of 277,000 second-feet. (Duration 20 minutes, model time).

ANGOSTURA DAM SPILLWAY MODEL (scale 1:72)

REVISED DESIGN I
WING WALLS
DESIGN I

LEFT WING WALL
DESIGN II

LEFT WING WALL
DESIGN III

LEFT WING WALL
DESIGN IV

LEFT WING WALL
DESIGN V
RECOMMENDED DESIGN

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DOWNSTREAM WING WALL DESIGN
**ANGOSTURA DAM DOWNSTREAM WING WAIL DESIGN (1:72 SCALE MODEL)**

**A - 30-foot radius wingwall**

**B - 45 degree angle wingwall.**

**C - Square cornered wingwall.**
wing-walls according to Design V, Figure 18. The final prototype design of the spillway dissipator is shown on Figures 2 and 3. Photographs of the model constructed according to the final design are shown on Figures 20, 21, and 22. Figure 20A shows the model discharging at the maximum flow of 277,000 second-feet and 20B shows the erosion after a 20-minute run (model). Figure 20C shows the erosion after a flow of 1½ hours of continuous operation at maximum discharge. The difference in the erosion between photographs 20B and 20C is small. Figure 21A shows a flow of 50,000 second-feet and 21B, the erosion after 20 minutes of operation at this discharge. Closeup views of the spillway and bucket are shown in Figure 22. The space between the last tooth and side wall of bucket on each end is necessary to prevent a small eddy from forming in the corner of the bucket.

Profiles of the water surfaces at discharges of 235,000, 130,000, and 50,000 second-feet are shown on Figure 23. The curves were used mainly to determine the height of the spillway walls and the necessary freeboard for the maximum discharge.

**Spillway Calibration Curves.** The head-discharge curve obtained from the model is plotted on Figure 24. This curve shows that for the maximum reservoir elevation, corresponding to a head of 44 feet over the crest, a discharge of 277,000 second-feet can be passed over the spillway. The coefficient of discharge curve on the same figure shows a coefficient of 3.87 for the maximum designed head. This was obtained from the expression \( Q = CLH^{3/2} \) in which \( L \) is the net length of crest (excluding the width of the piers) and \( H \) is the total head including velocity head of approach.
A - Flow of 277,000 second-feet over spillway.

B - Erosion after flow of 277,000 second-feet for 20 minutes.

C - Erosion after flow of 277,000 second-feet for 1.5 hours.

ANGOSTURA DAM SPILLWAY MODEL (scale 1:72)
RECOMMENDED DESIGN
A - Flow of 50,000 second-feet over spillway.

B - Erosion after flow of 50,000 second-feet.

ANGOSTURA DAM SPILLWAY MODEL (scale 1:72)
RECOMMENDED DESIGN
A - Model dam and river channel.

B - Model dam from left bank.

C - Model dam closeup.

ANGOSTURA DAM SPILLWAY MODEL (scale 1:72) RECOMMENDED DESIGN
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WATER SURFACE PROFILES
COEFF. OF DISCHARGE

3.2 3.4 3.6 3.8 4.0

HEAD - FEET - PROTOTYPE

DISCHARGE IN THOUSANDS OF CUBIC FEET PER SECOND

\[ Q = C L H^{\frac{3}{2}} \]

when

\( L \) = Net Length of Crest
\( H \) = Total Head

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