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HYDRAULIC MODEL STUDIES OF THE SPILLWAY BUCKET ENERGY DISSIPATOR, PA MONG DAM, PA MONG PROJECT, LAOS AND THAILAND

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Office of Chief Engineer
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16. Abstract

Model studies were made to determine the most efficient means of energy dissipation for the Pa Mong Dam spillway. The spillway has a design discharge of 36,150 cu m/sec. Solid and slotted buckets were tested. The slotted bucket design resulted in excellent energy dissipation with minimum surface wave action and bed erosion. Various tooth width-to-spacing ratios were tested in an attempt to achieve as large a tooth width and spacing as possible. Several lengths of apron placed at bucket lip elevation were tested to determine optimum length. Tests of an offset on the spillway surface indicated a method of entraining air in the high-velocity flow entering the bucket energy dissipator.

17. Key Words

DESCRIPTORS--/ *hydraulic models/ *energy dissipation/ *buckets/ aprons/ spillways/ *erosion/ laboratory tests/ riprap/ discharges/ velocity/ air entrainment/ offsets/ hydraulic structures/ waves (water)/ *pulsating flow

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by
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Hydraulics Branch
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Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION
Walter J. Hickel, Secretary
Ellis L. Armstrong, Commissioner

ACKNOWLEDGMENTS

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PURPOSE

The purpose of this investigation was to test various spillway bucket energy dissipators to determine the most efficient and economical means of dissipating the energy at the toe of Pa Mong Dam spillway. This investigation was a preliminary study related to the feasibility design for Pa Mong Dam.

INTRODUCTION

The Pa Mong Project area lies on both sides of the Mekong River, where the river forms the boundaries between northeast Thailand and northwest Laos (Figures 1 and 2). Pa Mong damsite is located about 20 kilometers upstream from Vientiane, Laos, and about 1,600 kilometers above the mouth of the Mekong. One abutment will be in Laos and the other in Thailand.

The Pa Mong Project will include a concrete dam on the Mekong River, plus two additional major dams with a number of dikes on the adjacent watersheds to the north and south which form a large, single reservoir for multipurpose development, plus associated power and irrigation facilities. The reservoir will impound 100 billion cubic meters.

The main hydraulic structure consists of a gated, ogee-crest spillway section 375 meters long (including piers) and a maximum pool height of 110 meters above the bucket invert and 90 meters above the existing riverbed (Figure 2). The spillway is designed to carry a maximum discharge of 39,750 m^3/sec (cubic meters per second), including 3,600 m^3/sec release from the powerplant. The stilling basin is designed to still a flow of 30,000 m^3/sec. Dissipation of the high energy flow is achieved by the use of a submerged bucket. Flood routing criteria call for an annual regulated maximum discharge of 17,000 m^3/sec.

RESULTS

1. The various solid bucket designs proved to be unacceptable for the tailwater conditions at the Pa Mong damsite. Boil height above tailwater was excessive; pulsating surges occurred at degraded tailwater conditions; and ground roller action caused severe erosion.

2. The 13.5-meter slotted bucket dissipated the energy very well. The boil height above tailwater was less than 5 meters at design spillway discharge. The bed erosion was negligible (Figure 12B).

3. The 1.69-meter tooth width and 0.48-meter spacing yielded the smoothest bucket performance. However, a tooth width of 4.25- and 1.00-meter spacing resulted in approximately the same bucket performance with half the number of teeth and twice as wide a spacing (Figure 12B). Therefore, the 13.5-meter-radius slotted bucket with 4.25-meter tooth width and 1.00-meter spacing is recommended.

4. A 21-meter-long apron at lip elevation with 2- by 1-meter sloping end sill resulted in the optimum apron design. The ground roller extended horizontally approximately 80 meters downstream from the end sill; therefore, the bed should extend horizontally a distance of 80 meters and then rise at a 6:1 slope to the existing riverbed.

5. One to 3-ton riprap will be needed for a distance of 5 meters immediately downstream of the apron. Smaller riprap will be required for a distance of 30 meters downstream of the large riprap.

6. Due to the size and uniqueness of Pa Mong Dam, more thorough studies will be required for the final design.

An investigation of pressures on the teeth and apron lip immediately downstream of the teeth should be included in these studies.

APPLICATION

The material in this report applies primarily to the specific structure under investigation. This report confirms the conclusions of Monograph No. 25 with regard to the improved performance of the slotted bucket over the solid bucket for lower ranges of tailwater depths.

THE MODEL

The model was a 1:55.117 scale sectional model of the overflow spillway. It included 2 of the 18 bays, 1 full intermediate pier, 2 half-piers, a detachable bucket assembly, 200 meters of the reservoir, and 400 meters of the downstream channel, Figure 3A. The radial gates were not included in the model. The model was built of wood with a galvanized sheet metal spillway and a plexiglass wall on one side. The test flume was 10.97 meters long and 76.20 centimeters wide. The head bay was 2.29 meters deep and the tail bay was 0.76 meter deep. The downstream channel consisted of various combinations of false floors (representing concrete aprons) followed by pea gravel. Flow was supplied to the flume through a 12-inch centrifugal pump and was measured by one of a bank of venturi meters permanently installed in the laboratory. The tailwater elevation was controlled by an adjustable gate.

THE INVESTIGATION

An efficient method of dissipating the tremendous amount of energy generated by the vertical drop at Pa Mong was required. It was felt that a bucket energy dissipator would yield a more economical design than a hydraulic jump stilling basin.

In considering the general performance of a bucket dissipator, there are generally two critical zones of energy dissipation, namely: the surface boil and the ground roller. Generally speaking, energy dissipation in one zone can be reduced resulting in an increase of energy dissipation in the other zone. The criterion for a good bucket design is therefore based on arriving at an equilibrium of energy dissipation in the two zones or a design favoring one zone where more protection is assured.

Several bucket designs were tested. The effectiveness of each design was based on the efficiency of energy dissipation. Visual observation as well as data taken of the water surface profile were used to evaluate the energy dissipation in the two zones. Four spillway discharges were tested for each bucket design; 15,000, 20,000, 25,000, and 30,000 m^3/sec. Degradation of 6 to 10 meters is expected in the downstream channel. Therefore, two tailwater conditions, existing and degraded, were tested for each spillway discharge. The degraded tailwater was 6 meters lower than the existing.

Solid Bucket Investigations

Initial Solid Bucket Design.—The initial bucket design was a 13.5-meter-radius solid bucket with an invert elevation of 144.5 meters. The bucket had a 45° tangent exit similar to the Grand Coulee bucket. This bucket provided inadequate energy dissipation. Figure 3B illustrates the general performance with 15,000 m^3/sec and existing tailwater conditions. The surface boil was too high resulting in a large scour hole downstream from the bucket where the flow impinged on the pea gravel bed.

Other Solid Bucket Designs.—The short radius of the 13.5-meter bucket turned the spillway flow too sharply (Figure 3B), therefore a 15-meter radius solid bucket was constructed with the invert at elevation 140.00 meters (Figure 4). The invert was placed as low as possible in the flume to increase the tailwater depth at degraded tailwater conditions. Although there was still a large ground roller in the channel bed, the surface boil and wave action looked fairly good at existing tailwater conditions (Figure 4A). When the degraded tailwater conditions were tested, the surface boil began to pulsate in an upstream-downstream orientation (Figure 4B). At the 30,000 m^3/sec discharge, the pulsating action became quite intense resulting in 7-meter-high waves 400 meters downstream from the bucket.

Some investigators[1] have suggested that a pulsating surge will appear when the h_1/R ratio exceeds a specific value related to the parameter $q/[\sqrt{g}(h_1)^{3/2}]$ where h_1 is defined as the difference in elevation between the maximum reservoir elevation and the bucket invert elevation and R is the bucket radius. A range in h_1/R values of 3 to 6 was suggested for the $q/[\sqrt{g}(h_1)^{3/2}]$ parameters associated with this investigation. The 13.5- and 15-meter radius buckets had h_1/R values exceeding 6. Eighteen- and 28-meter-radius buckets were tested having h_1/R values of 6.1 and 3.9, respectively. These large radius buckets with h_1/R ratios within or near the suggested limits pulsated in the same manner as the smaller radius buckets (Figures 5B, 6B, and 7B). The 13.5- and 15-meter-radius buckets were as stable, if not more stable, than the 18- and 28-meter-radius buckets. The 15-meter-radius bucket produced the best general performance of the solid buckets.

Tailwater Considerations.—Since at least 6 meters of degradation is expected downstream of Pa Mong Dam, the range of tailwater conditions for a given spillway discharge is fairly broad. The solid buckets tested were placed as low as possible in the test flume, 140.00-meter invert elevation, which is 20 meters below the existing channel bed. With the invert elevation at 140.00 meters, most of the solid buckets tested had just enough tailwater to dampen the tendency for a pulsating surge at existing tailwater. At the degraded tailwater, the surge pulsated in an upstream-downstream orientation creating large waves in the channel downstream from the bucket (Figures 4B, 5B, 6B, and 7B). With sufficient tailwater the pulsating surge was completely eliminated. To achieve more efficient dissipation of energy in the bucket as well as eliminating the pulsating surge, an invert elevation of 130 meters would be required.

It is interesting to note the occurrence of a similar phenomena in the model testing of the Grand Coulee bucket[2]. A transverse wave action occurred in the

[1] Numbers refer to items in bibliography.

bucket, and it was effectively eliminated by lowering the bucket invert 20 feet. Although the lower elevation resulted in a negligible increase in excavation in the Grand Coulee design, the bucket invert elevation required for Pa Mong Dam would result in a considerable increase in excavation since the existing riverbed elevation is 160 meters.

Various Exit Designs.—Tests were conducted to determine the effect of various bucket exit configurations on the flow pattern. The 15-meter-radius bucket was used for these tests. The first exit configuration was a radial exit, the bucket curve terminated at the 45° slope (Figure 8). The second and third configurations consisted of tangent exits extending out from the radial exit on a 45° slope. The lip elevation was raised to 0.6R and 0.8R above the invert, respectively (Figure 8).

Water surface data are recorded in Table 1 for all three exit designs. The radial exit and 0.6R tangent exit water surface data had essentially the same boil height and water depth in the bucket for corresponding spillway discharge and tailwater conditions. The 0.8R tangent exit yielded a higher boil elevation and lower water depth in the bucket than the radial or 0.6R tangent exits (Figures 4B and 9).

The various solid bucket investigations did not produce a satisfactory energy dissipator for the proposed Pa Mong Dam. Investigations conducted by the Bureau of Reclamation[3] have shown that a slotted bucket is an improvement over the solid bucket for low ranges of tailwater depth; therefore, the tests were continued using slotted buckets.

Slotted Bucket (Recommended)

Initial Slotted Bucket Design.—A 13.5-meter slotted bucket (Figure 10) was designed using the design criteria presented in Monograph No. 25[3]. The bucket invert was placed at elevation 140 meters. The tooth width was 1.69 meters with a 0.48-meter space between teeth.

The slotted bucket performance showed quite an improvement over the solid bucket design. The maximum boil height above the tailwater elevation was approximately 5 meters whereas a 12-meter boil height was recorded for the 15-meter solid bucket. The maximum height for the surface waves downstream of the bucket was 4 meters, relatively tranquil compared to the 9-meter waves in the solid bucket tests. A false floor representing a concrete apron was placed at lip elevation and extended downstream 110 meters. This produced flow currents along the apron for some distance before rising to the surface (Figure 11A).

There were two major areas of concern with the slotted bucket: The problem of cavitation damage on the teeth and apron lip behind the teeth, and the proper design of a concrete apron downstream from the bucket.

Tooth Modifications.—Subsequent protective work on the teeth could be substantially economized by increased tooth width and spacing which would reduce the surface area exposed to low pressures and possible cavitation damage. While retaining the tooth profile, a tooth width-to-spacing ratio of approximately 2:1 was tested using a 2.75-meter tooth width with a 1.40-meter spacing.

Although a smooth surface resulted, there was considerable agitation of the bed downstream of the apron (Figure 11C).

A tooth width to spacing ratio of 3.2:1 was next tested using a 4-meter-width tooth and 1.25-meter spacing. There was a notable improvement in the bucket performance (Figure 12A). The jet flowing along the apron was somewhat unstable at the end sill when lower spillway discharges were tested (15,000 and 20,000 m^3/sec). This instability at times pulled pea gravel over the end sill and onto the apron.

A tooth width-to-spacing ratio of 4.25:1 was tested using a 4.25-meter tooth width and 1.00-meter spacing. This tooth configuration yielded almost as good a general performance as the initial small teeth (Figures 11B and 12B), with the added advantage of half the number of teeth with twice the spacing. Data for buckets with an invert elevation of 140.0 meters are presented in Table 1.

Spillway Offset.—In an effort to entrain air in the jet impinging on the teeth, a 1.27-cm offset was constructed on the spillway face above maximum water level in the bucket (Figure 13). The high velocity jet flowing over the offset created a reduced pressure and drew air under the jet immediately downstream from the offset. The difference in the width of the light strip next to the spillway surface in Figures 14A and 14B illustrates the air entrainment produced by the offset. This test indicated that it might be advantageous to include an offset in the spillway design.

Downstream Apron.—The second area of concern was the required length of the apron downstream of the bucket. Since the geological conditions at the Pa Mong damsite require the use of a concrete apron, various lengths were tested to see which would be less exposed to the abrasive action of riprap. Flow leaving the bucket had a tendency to concentrate near the apron surface and cause a backflow along the apron, when it was placed at lip elevation, as shown in Figure 15B. The apron shown in Figure 11A was 110 meters long and as can be seen in the figure, pea gravel was drawn upstream on the apron where it circulated and tended to abrade the apron downstream of where the flow rose off the apron.

Various lengths of apron were tested for 15,000 and 30,000 m^3/sec spillway discharges. A 21-meter-long apron with a 2- by 1-meter sloping end sill proved to be the optimum length for the various discharges. At the 30,000 m^3/sec spillway discharge, no bed material was drawn back on the apron and there was no severe erosion of the channel bed downstream of the end sill (Figure 12B). The surface boil rose about 1 meter higher than it had with the initial tooth design due to the end sill. Flow patterns for three bed configurations are illustrated in Figure 15.

Riprap Protection.—The ground roller extends horizontally approximately 80 meters downstream from the end sill at the 30,000 m^3/sec spillway discharge and proposed tailwater. The channel bed should therefore extend 80 meters horizontally from the end sill and then rise at a 6:1 slope to the existing riverbed. One- to 3-ton riprap should be placed for a distance of 5 meters downstream from the end sill to withstand the lifting force exerted on the bed by the jet leaving the end sill. Smaller riprap should be placed for an additional 30 meters immediately downstream from the large riprap.

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Table 1

COMPARISON OF WATER SURFACE PROFILES FOR VARIOUS BUCKET DESIGNS

Bucket type	Radius m	Exit type	Bed configuration and elevation	Tooth width m	Discharge 15,000 m^3/sec TW*	C*	A*	D*	B*	Discharge 30,000 m^3/sec TW	C	A	D	B
Solid	15	Radial	Conc. Mat. 138.5	–	173.0	67.2	182.5	19.7	168.2	179.0	71.7	192.0	29.7	173.5
					167.0	51.6	178.0	16.8	163.5	173.0	72.6	186.7	30.6	167.1
Solid	15	0.6R Tan.	Conc. Mat. 138.5	–	173.0	53.3	182.5	23.9	170.4	179.0	–	192.0	–	173.5
					167.0	50.4	178.1	23.0	164.0	173.0	–	186.7	–	167.1
Solid	15	0.8R Tan.	Conc. Mat. 138.5	–	173.0	54.9	183.5	24.7	169.9	179.0	73.4	194.6	31.4	173.3
					167.0	58.3	179.8	24.7	161.7	173.0	–	191.7	34.8	165.8
Solid	28	Radial	Pea Gravel	–	173.0	57.1	181.1	28.6	169.8	179.0	79.0	191.9	33.6	175.0
					167.0	55.5	178.1	26.9	166.3	173.0	–	187.5	–	172.0
Slotted	13.5	–	Pea Gravel	1.69	173.0	45.4	176.3	28.6	170.0	179.0	87.0	184.0	38.6	173.7
					167.0	45.4	170.0	26.9	163.5	173.0	87.0	177.6	38.6	165.5
Slotted	13.5	–	110 m Conc. Mat. 143.24	1.69	173.0	67.1	176.3	33.6	170.0	179.0	105.5	181.1	60.1	172.7
					167.0	67.1	169.2	33.6	163.0	173.0	105.5	175.3	57.6	164.8
Slotted	13.5	–	21 m Conc. Mat. 143.24	1.69	173.0	80.6	173.4	42.0	169.7	179.0	102.5	182.1	48.7	172.4
					167.0	73.9	169.1	36.6	163.5	173.0	101.0	176.4	49.5	165.3
Slotted	13.5	–	21 m Conc. Mat. 143.24	2.75	173.0	–	174.2	61.8	169.2	179.0	–	180.8	84.0	171.7
					167.0	–	167.4	56.7	161.6	173.0	–	174.6	81.0	165.7
Slotted	13.5	–	21 m Conc. Mat. 143.24	4.00	173.0	81.0	174.6	45.8	169.5	179.0	106.2	182.6	52.5	172.2
					167.0	81.0	168.7	45.0	163.2	173.0	106.2	177.3	52.5	165.5
Slotted	13.5	–	21 m Conc. Mat. 143.24	4.25	173.0	91.3	175.6	49.2	170.4	179.0	107.5	183.3	51.8	173.4
					167.0	91.3	169.7	47.6	163.3	173.0	107.5	177.9	52.2	165.2

*All dimensions in meters
TW—Tailwater elevation
A—Surface boil elevation
B—Elevation of water in bucket
C—Horizontal distance from bucket invert to normal tailwater downstream of surface boil
D—Horizontal distance from bucket invert to maximum surface boil elevation

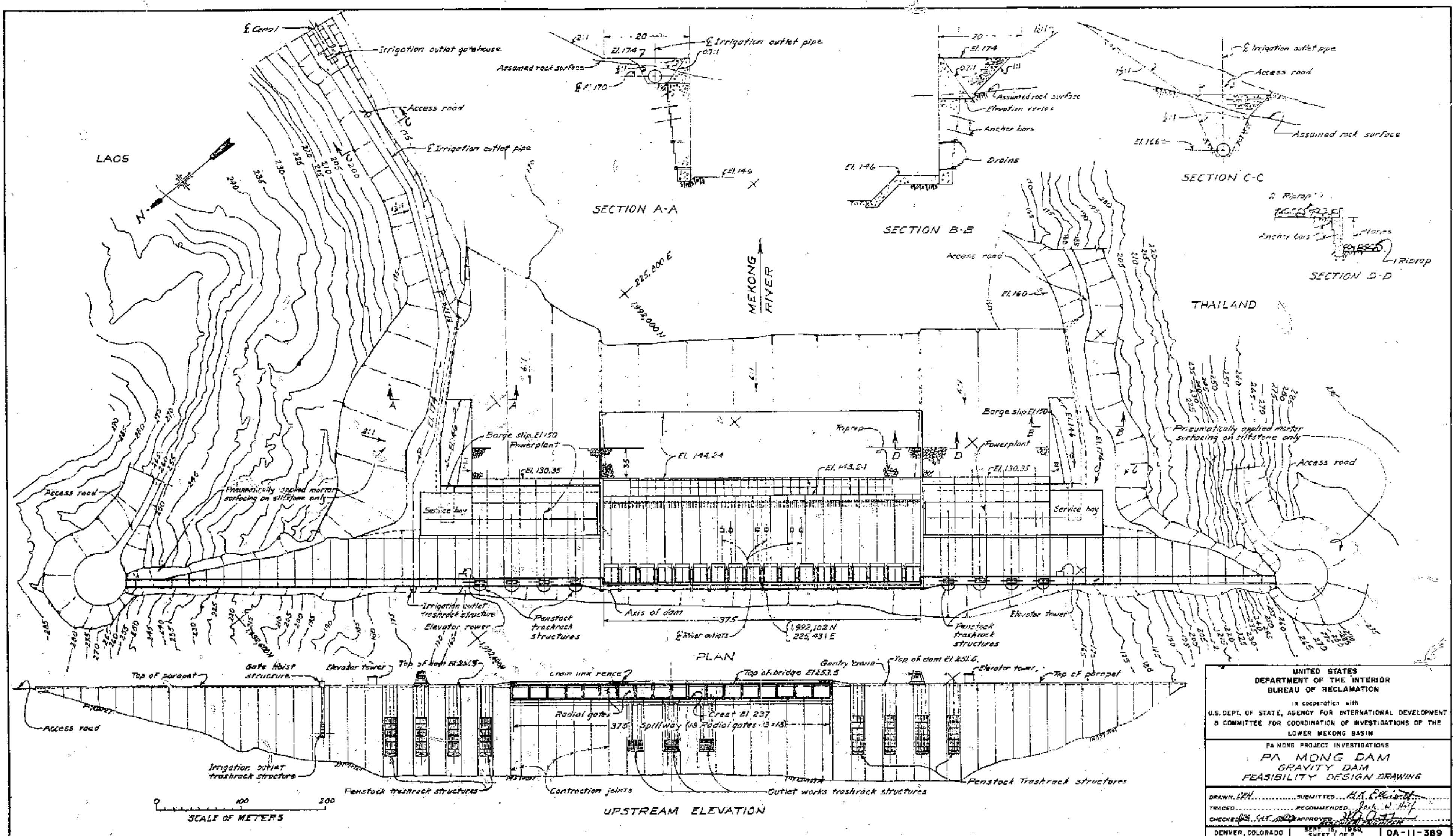


Figure 1. Pa Mong Dam—gravity dam—feasibility design drawing

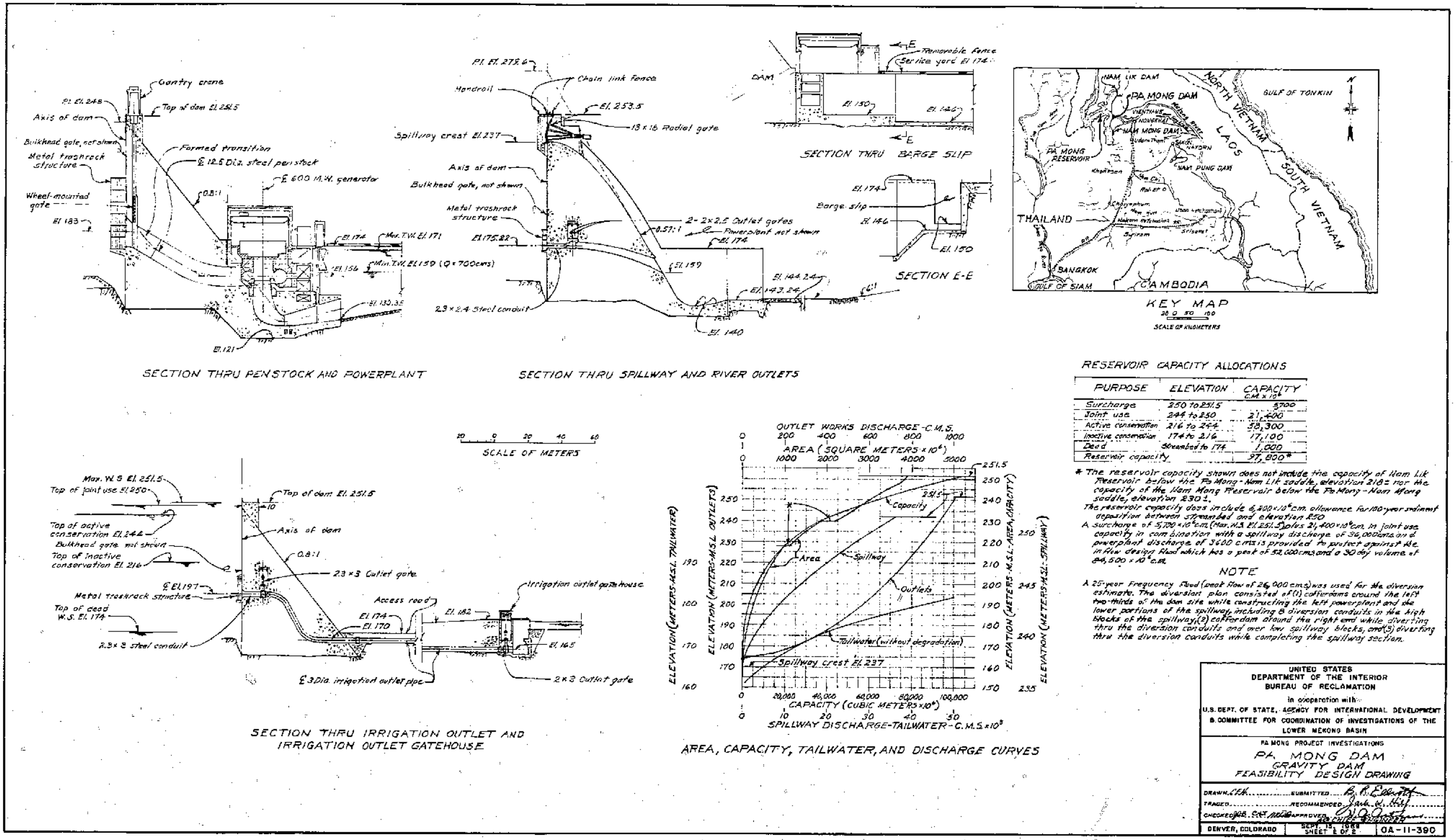
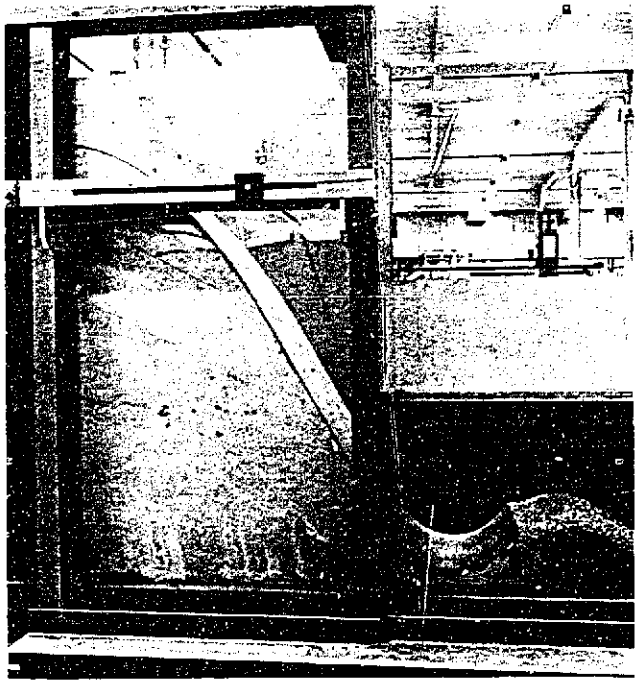
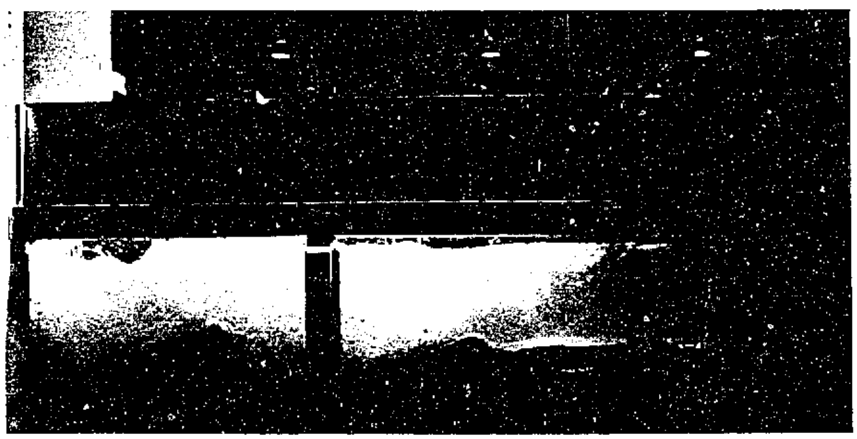


Figure 2. Pa Mong Dam—gravity dam—feasibility design drawing.



A. Spillway with 13.5 m radius solid bucket, invert elevation 144.50. Photo POA28-D-66383



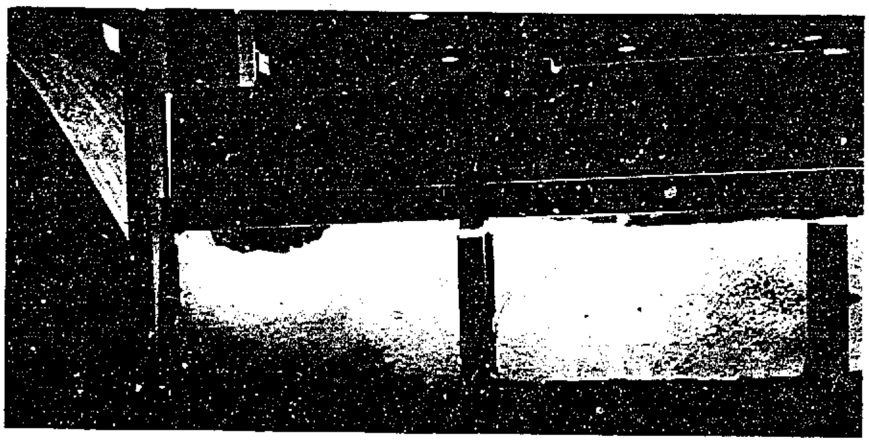
B. Flow in initial design bucket. Q = 15,000 cu m/sec existing tailwater elevation. Photo POA28-D-66384

Pa Mong Dam
Spillway Bucket Energy Dissipator

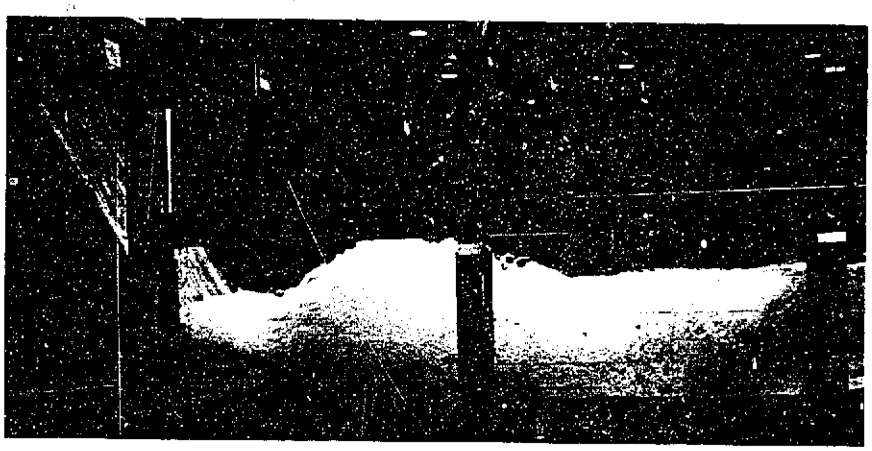
1:55.12 Scale Model

Initial Design Bucket

Figure 4



A. Existing tailwater. Photo POA28-D-66385



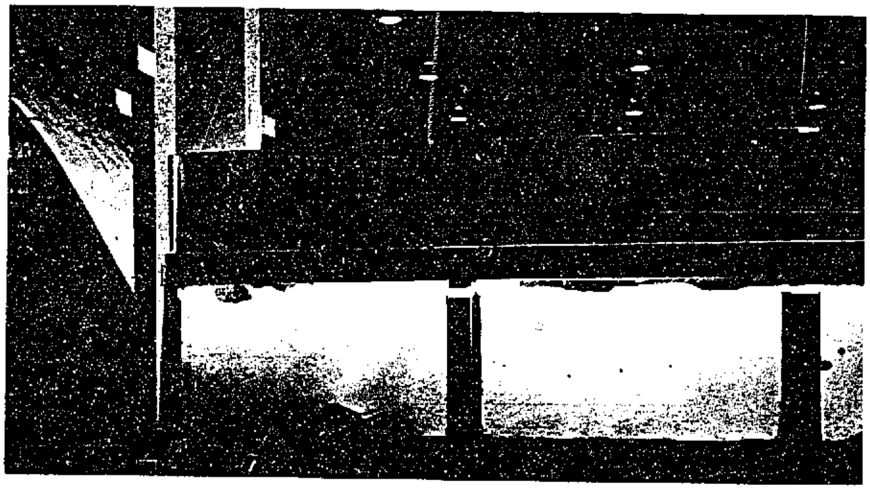
B. Degraded tailwater. Photo POA28-D-66386

Invert elevation 140.0 m, apron elevation 138.5 m

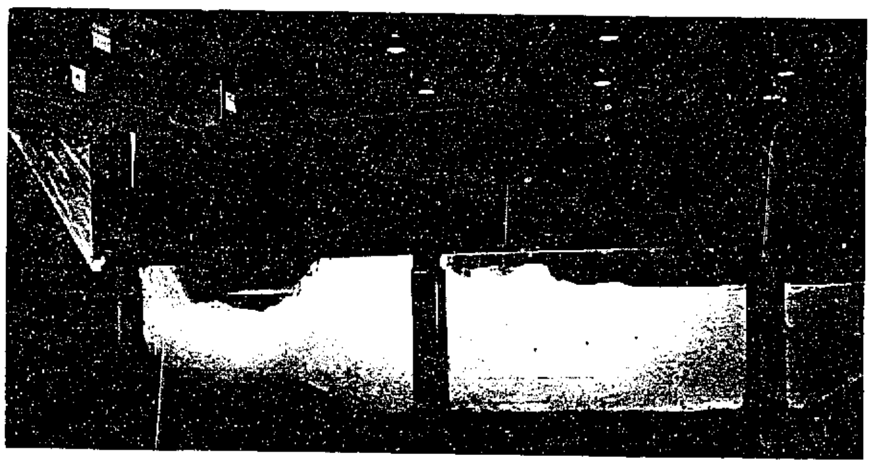
Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

15 Meter Radius Solid Bucket with
Radial Exit, Q = 15,000 cu m/sec



A. Existing tailwater. Photo POA28-D-66387



B. Degraded tailwater. Photo POA28-D-66388

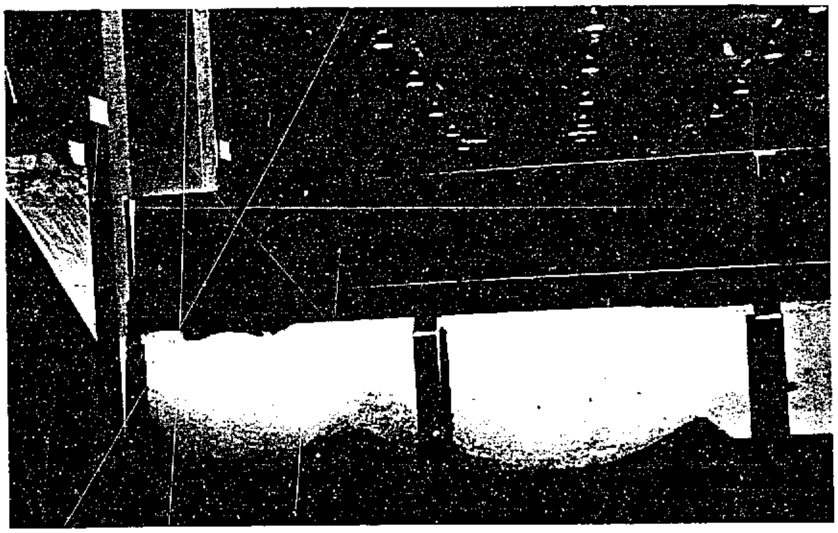
Invert elevation 140.0 m, apron elevation 138.5 m

Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

18 Meter Radius Bucket with
Tangential Exit, Q = 15,000 cu m/sec

Figure 6



A. Existing tailwater. Photo POA28-D-66389

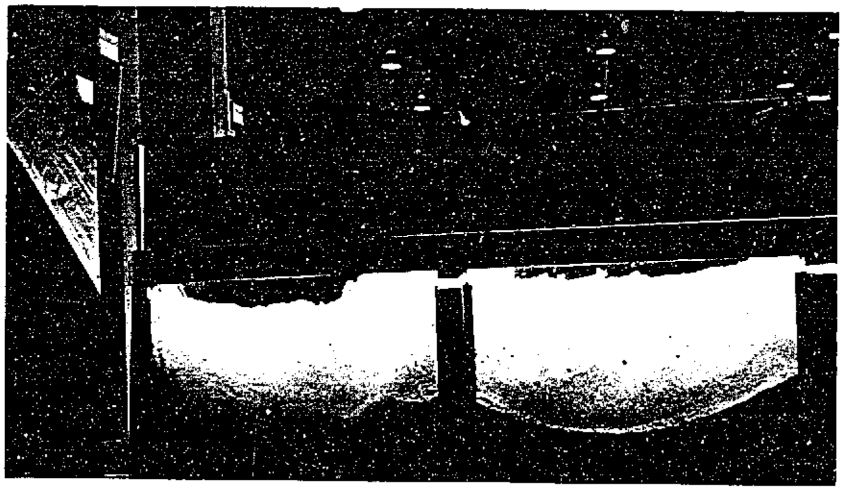
B. Degraded tailwater. Photo POA28-D-66390

Invert elevation 140.0 m
Pea gravel bed at bucket lip elevation

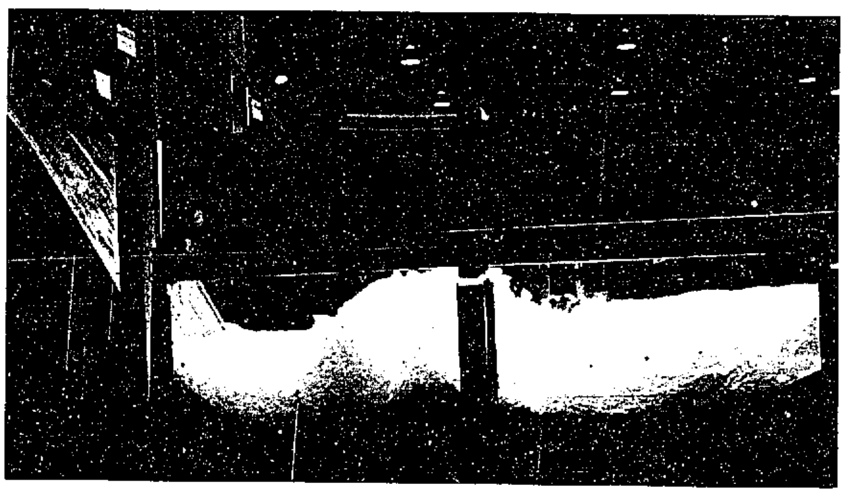
Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

13 Meter Radius Solid Bucket with
Tangential Exit, Q = 15,000 cu m/sec



A. Existing tailwater. Photo POA28-D-66391



B. Degraded tailwater. Photo POA28-D-66392

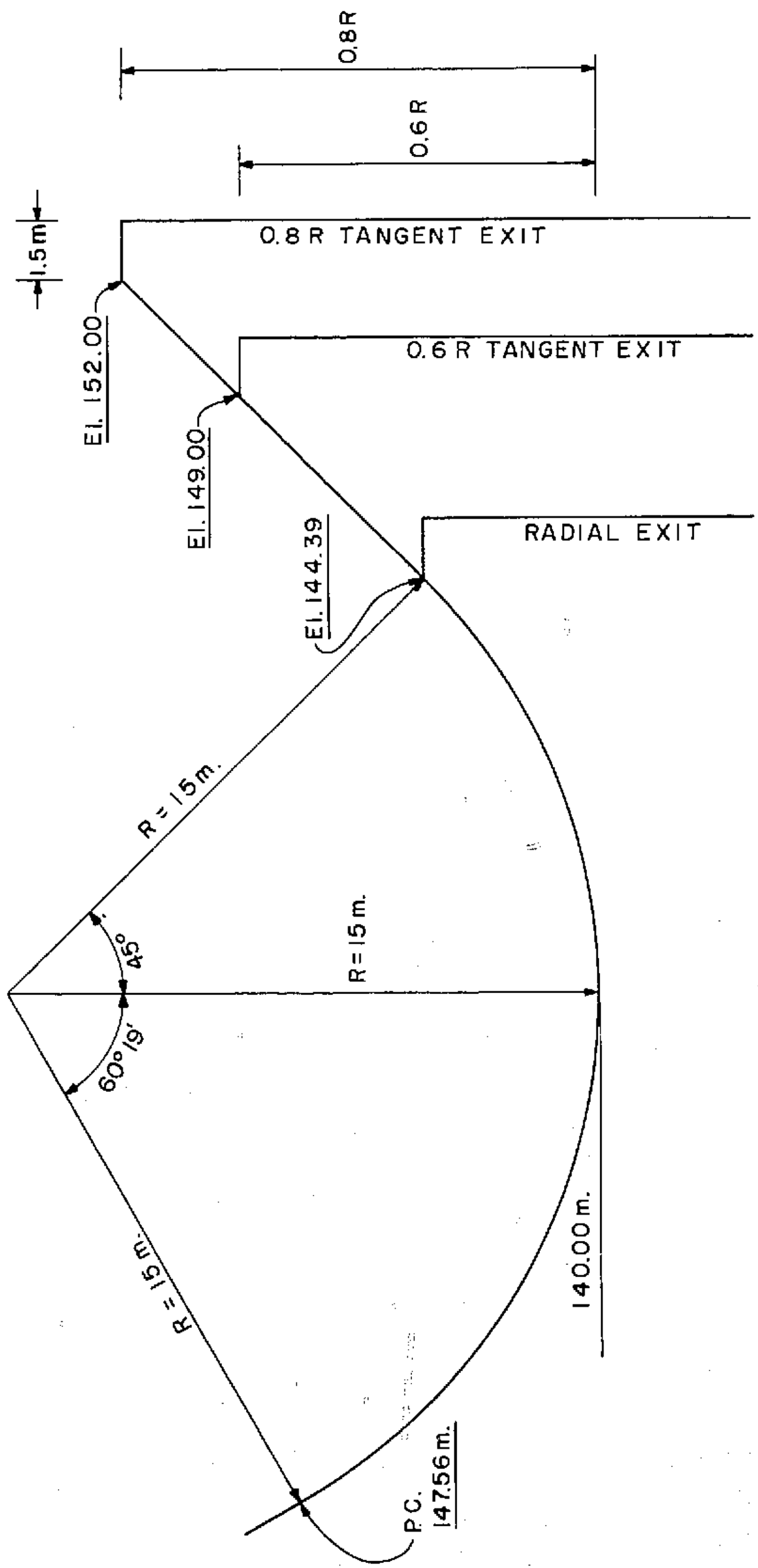
Invert elevation 140.0 m
Pea gravel bed at bucket lip elevation

Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

28 Meter Radius Solid Bucket with
Radial Exit. Q = 15,000 cu m/sec

Figure 8



Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

Various Spillway Solid Bucket Exits

745

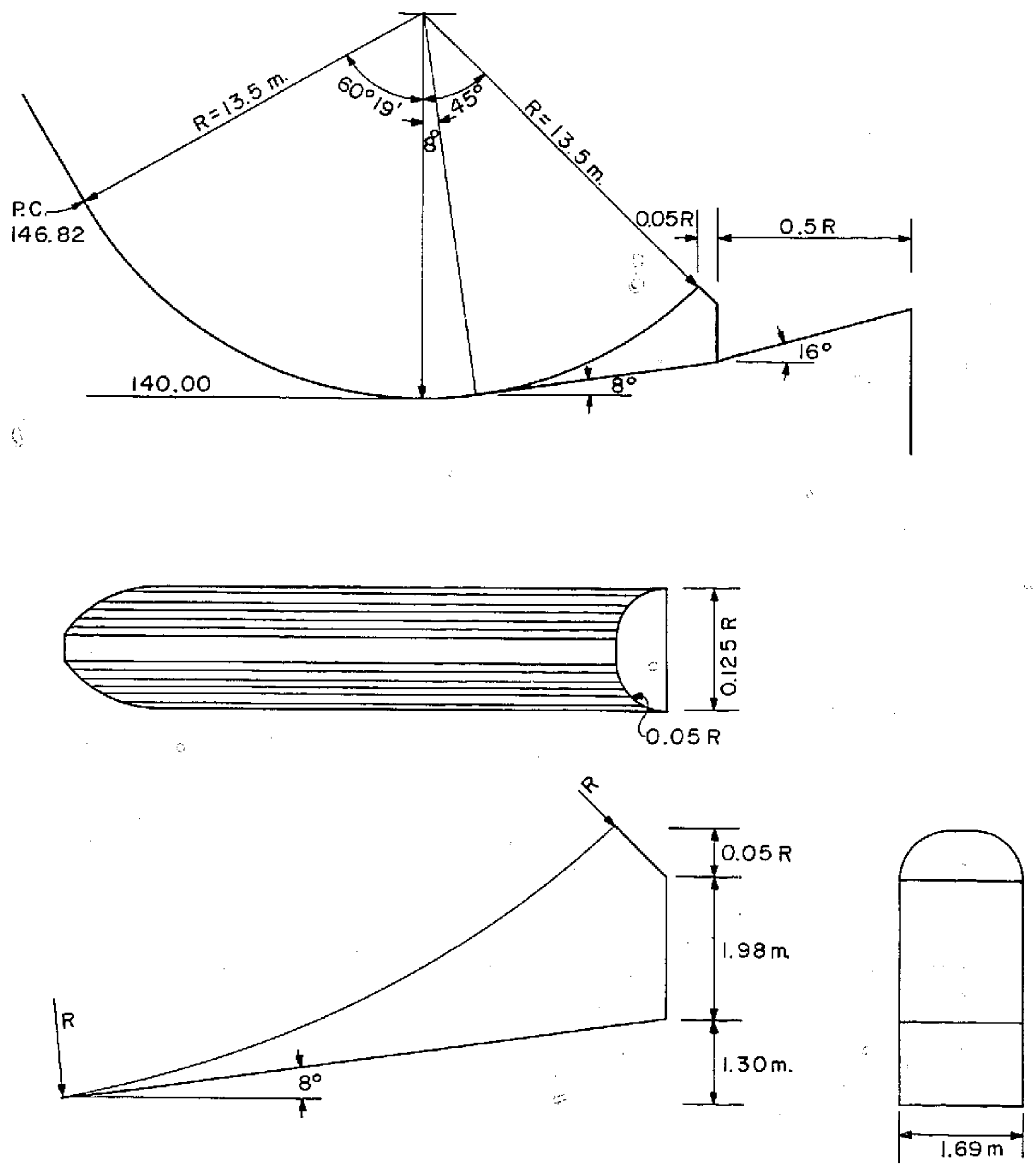
Q = 15,000 cu m/sec, 0.8R tangent exit, degraded tailwater. Photo POA28-D-66393

Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

15 Meter Radius Solid Bucket

Figure 10



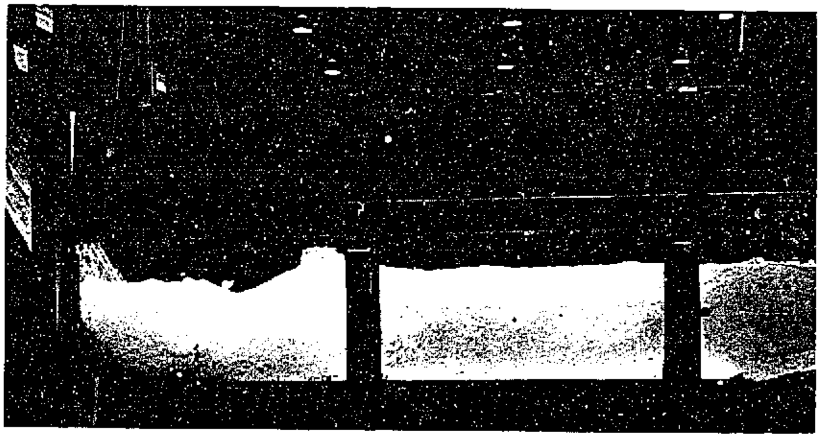
Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

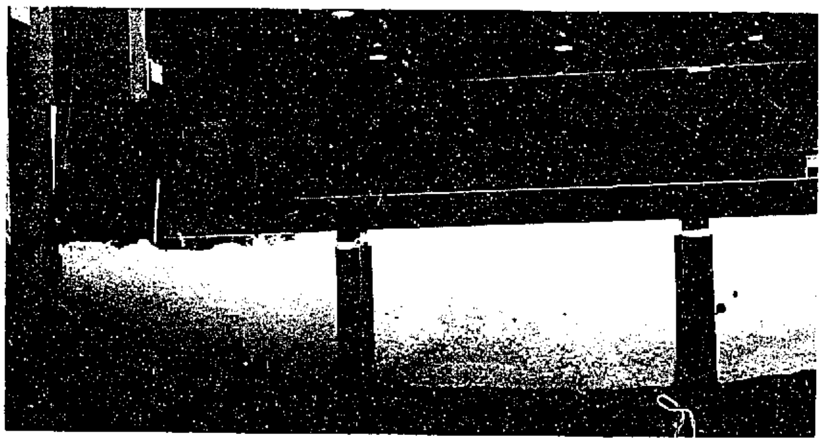
Slotted Bucket Design

745

Figure 11



A. Tooth width 1.69 m, spacing 0.48 m, 110-m-long apron at bucket lip elevation, Q = 15,000 cu m/sec degraded tailwater. Photo POA28-D-66394



B. Tooth width 1.69 m, spacing 0.48 m, 21-m-long apron, Q = 30,000 cu m/sec existing tailwater. Photo POA28-D-66395

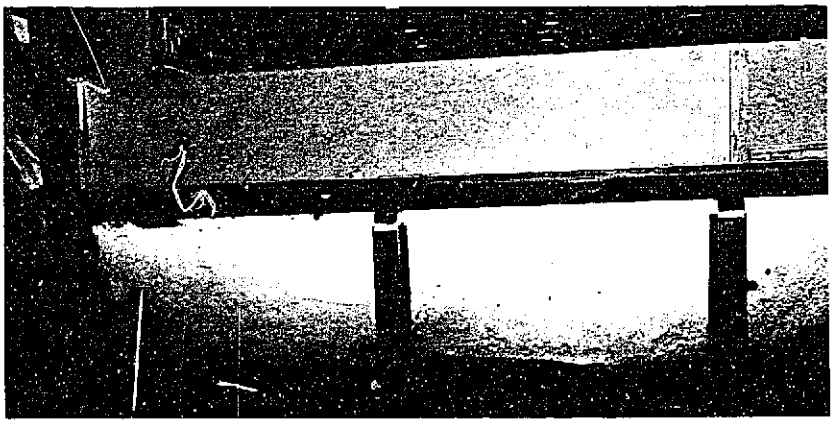
C. Tooth width 2.75 m, spacing 1.40 m, 50-m-long apron, Q = 30,000 cu m/sec, existing tailwater. Photo POA28-D-66396

Pa Mong Dam
Spillway Bucket Energy Dissipator

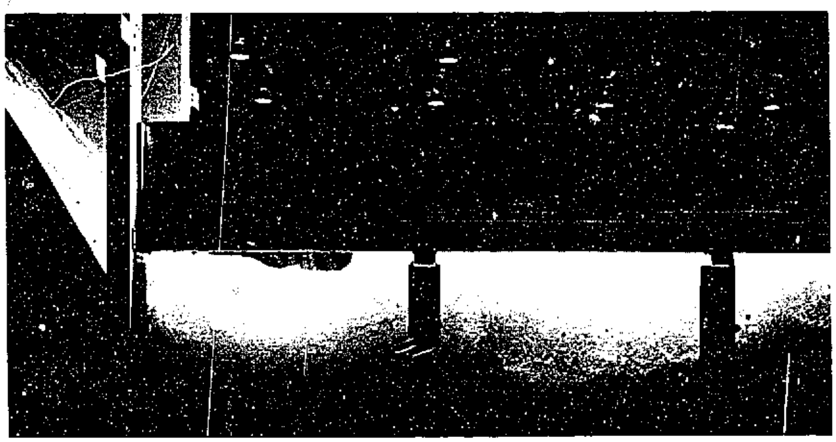
1:55.12 Scale Model

Various Tooth Width—Spacing Ratios
for 13.5 Meter Radius Slotted Bucket

Figure 12



A. Tooth width 4 m, spacing 1.25 m, 21-m-long apron. Photo POA28-D-66397



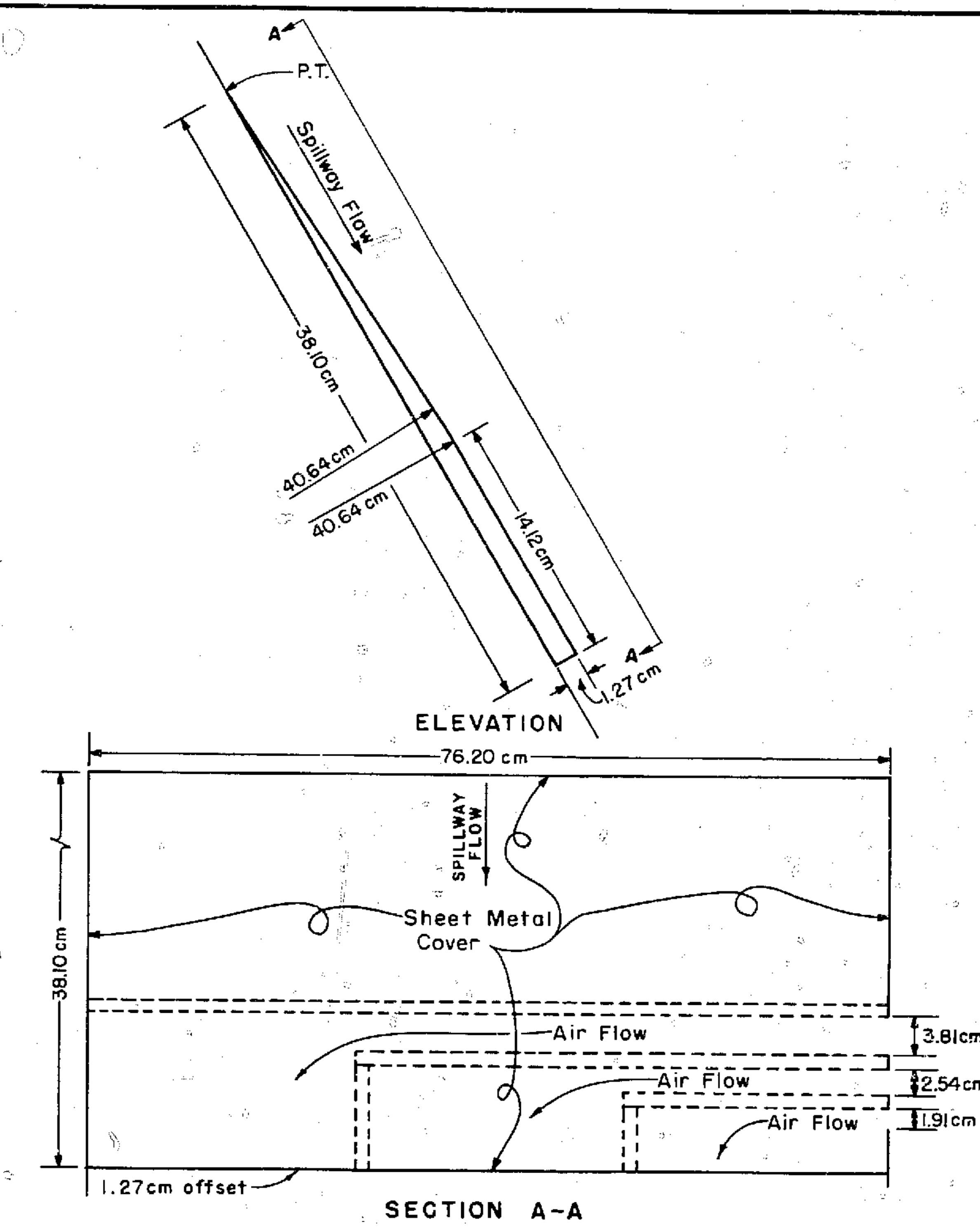
B. Tooth width 4.25 m, spacing 1.0 m, 21-m-long apron. Photo POA28-D-66398

Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

Various Tooth Width–Spacing Ratios
for 13.5 Meter Slotted Bucket
Q = 30,000 cu m/sec, Existing Tailwater

Figure 13



Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

Air Slot Modification Detail

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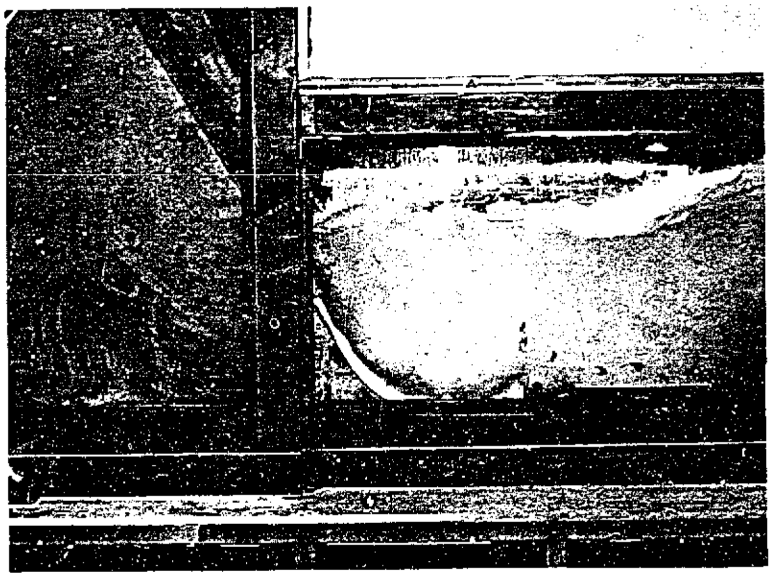
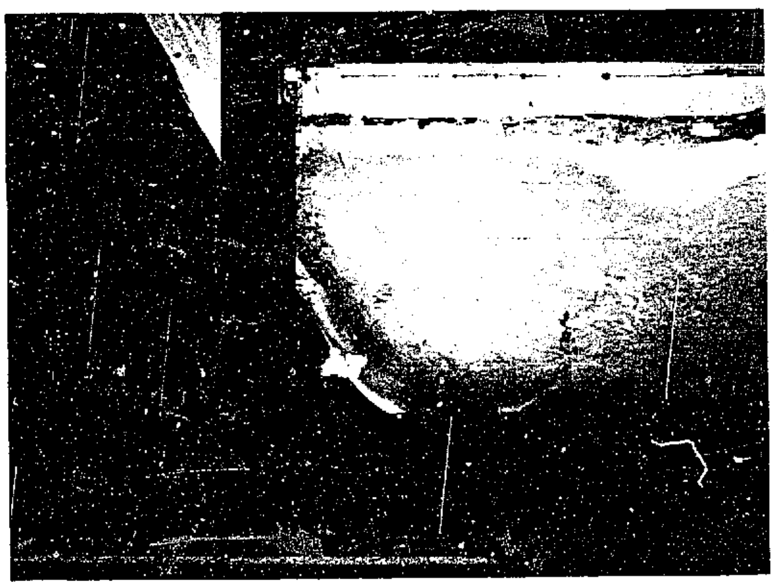
Figure 14



A. Without air slot. Photo POA28-D-66399



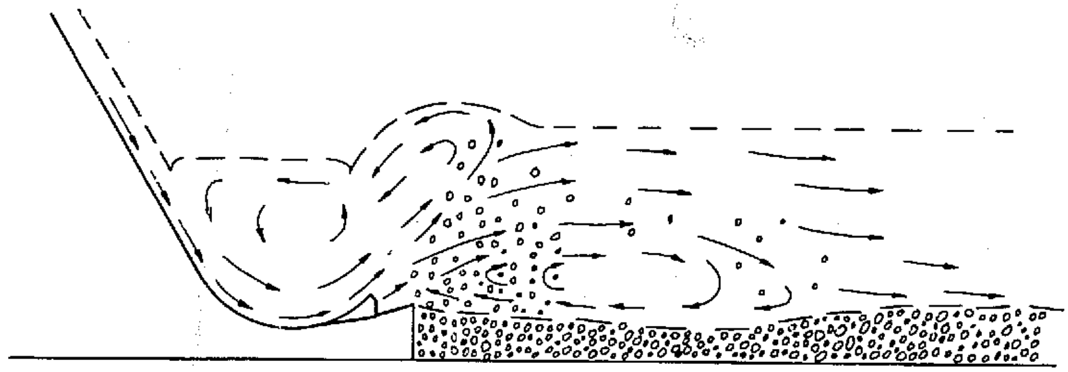
B. With air slot. Photo POA28-D-66400

Pa Mong Dam
Spillway Bucket Energy Dissipator

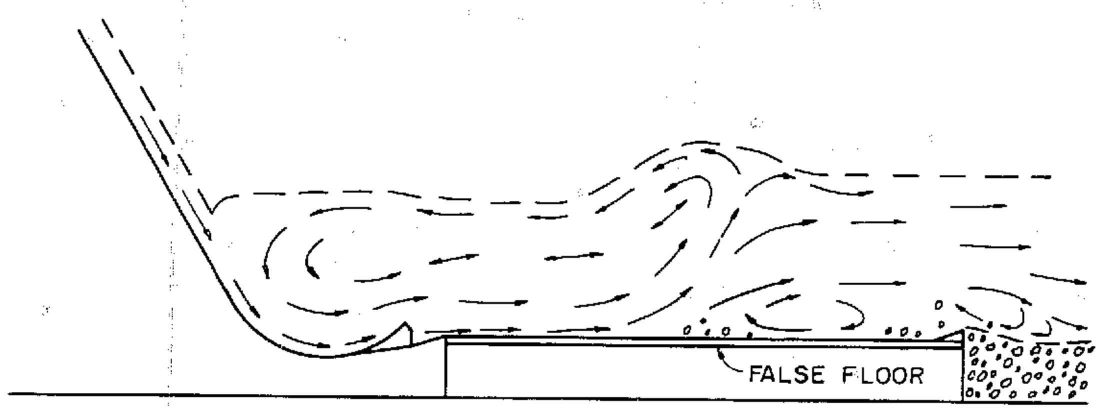
1:55.12 Scale Model

Light Slit Indicating Solid Jet at
Bucket Wall, Q = 30,000 cu m/sec
Proposed Tailwater

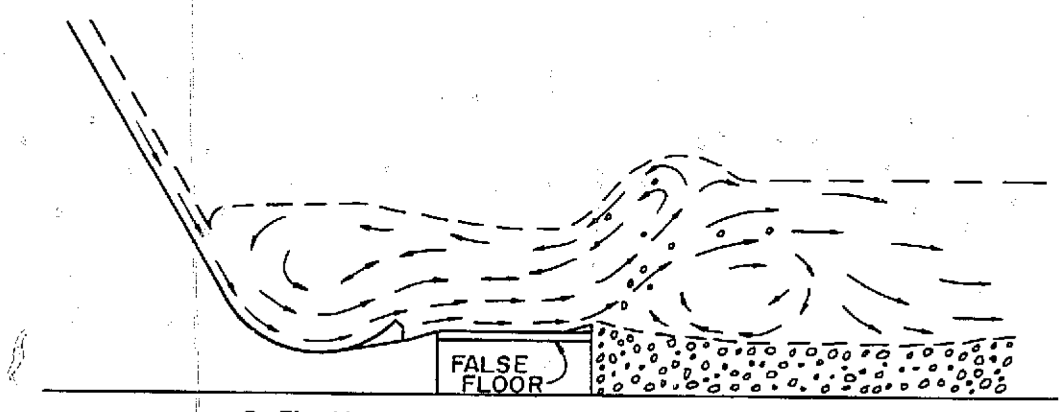
Figure 15



A. Pea gravel bed.



B. Fixed bed at apron lip elevation—too long.



C. Fixed bed at apron lip elevation—optimum length.

Pa Mong Dam
Spillway Bucket Energy Dissipator

1:55.12 Scale Model

Various Downstream Bed Configurations

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CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units **is the newton (N), which is defined as** that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil.	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03*	Square centimeters
	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	946.358*	Cubic centimeters
	0.946331*	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985 x 10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582 x 10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873 x 10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482 x 10^{-5}*	Dynes

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	[illegible]
	0.09290*	M^2
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.092903*	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

GPO 830-798

ABSTRACT

Model studies were made to determine the most efficient means of energy dissipation for the Pa Mong Dam spillway. The spillway has a design discharge of 36,150 cu m/sec. Solid and slotted buckets were tested. The slotted bucket design resulted in excellent energy dissipation with minimum surface wave action and bed erosion. Various tooth width-to-spacing ratios were tested in an attempt to achieve as large a tooth width and spacing as possible. Several lengths of apron placed at bucket lip elevation were tested to determine optimum length. Tests of an offset on the spillway surface indicated a method of entraining air in the high-velocity flow entering the bucket energy dissipator.

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REC-OCE-70-17
Burgi, P H
HYDRAULIC MODEL STUDIES OF THE SPILLWAY BUCKET ENERGY DISSIPATOR, PA MONG DAM, PA MONG PROJECT, LAOS AND THAILAND
Bur Reclam Lab Rep REC-OCE-70-17, Hydraul Br, May 1970. Bureau of Reclamation, Denver, 23 p, 15 fig, 4 tab, 3 ref

DESCRIPTORS—/ *hydraulic models/ *energy dissipation/ *buckets/ aprons/ spillways/ *erosion/ laboratory tests/ riprap/ discharges/ velocity/ air entrainment/ offsets/ hydraulic structures/ waves (water)/ *pulsating flow
IDENTIFIERS—/ *slotted buckets/ Pa Mong Dam/ Pa Mong Project

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