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HYDRAULIC MODEL STUDIES OF THE PUEBLO DAM SPILLWAY AND PLUNGE BASIN

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Engineering and Research Center
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16. ABSTRACT

Studies were performed on a 1:56 scale hydraulic model of Pueblo Dam spillway and plunge basin (stilling basin) to determine if the unusual design could handle the required releases safely. The model contained the flip-type spillway, plunge basin, river outlets, and a section of downstream river channel. Channel erosion, basin impact pressures, nappe oscillations, crest rating, and flow profile studies were made on the model. Flow splitters were added to the spillway to eliminate nappe oscillations. The plunge basin initially containing 2 floor elevations was enlarged to the level of the deeper section to minimize impact pressures. A technique of data collection was used in obtaining impact pressures which provided an electronic statistical analysis. A curve was obtained to relate basin floor effective pressure head to spillway discharge for the normal river tailwater conditions.

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by

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June 1971

Hydraulics Branch
Division of General Research
Engineering and Research Center
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION
Rogers C. B. Morton, Secretary
Ellis L. Armstrong, Commissioner

ACKNOWLEDGMENT

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PURPOSE

The model study was made to evaluate the flow characteristics of the overfall spillway and plunge basin (stilling basin) associated with the concrete buttress portion of Pueblo Dam.

CONCLUSIONS

1. The spillway adequately handled the maximum release of 190,500 cfs (5,394 cu m/sec) resulting from the spillway design flood.

2. Assuming that the concrete stilling basin failed, the buttresses were not undercut by the passage of the spillway design flood. The principal erosion in a graded gravel bed was to elevation 4705, with a small area to elevation 4700.

3. The recommended basin adequately stills a spillway release of 30,000 cfs (850 cu m/sec).

4. By lowering the basin floor 9 feet to elevation 4710 the impact head on the basin floor was greatly reduced. Impact head on the recommended basin floor for a discharge of 190,500 cfs (5,394 cu m/sec) amounted to 83.3 feet (25 meters) of water.

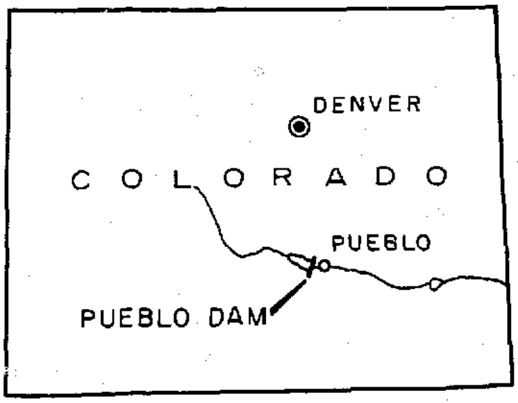
5. The free-falling spillway jet oscillated at two separate frequencies when passing releases up to 10,000 cfs (283 cu m/sec). Seven flow splitters, 18 inches (46 cm) high, placed on the downstream end of the flip bucket effectively eliminated the nappe oscillation.

APPLICATIONS

The report contains information regarding a technique of data collection which will eliminate the time-consuming task of statistically analyzing oscillograph records. Also, the report contains considerable information on plunge basin impact pressures which could be applied to structures with similar heads, basin depths, and unit discharges. Additional studies are required to completely define plunge basin depth requirements for a full range of heads and discharges.

INTRODUCTION

Pueblo Dam will be on the Arkansas River about 6 miles west of Pueblo, Colorado and will be a major feature of the Fryingpan-Arkansas Project. The project involves bringing water from the mountains on the west slope of the Continental Divide through a tunnel to the east side where it will supplement the Arkansas River for irrigation, municipal, and industrial needs.



The 10,200-foot (3.109-meter) long dam will be composed of two earthfill sections separated by a massive head buttress concrete section (Figure 1) approximately 1,750 feet (533 meters) long. The dam will rise approximately 187 feet (57 meters) above the riverbed and will create a reservoir with a capacity of 357,000 acre-feet (440 million cubic meters). An uncontrolled spillway approximately 550 feet long (168 meters) and three spillway outlet works in the spillway and a river outlet works in the river gorge will be included in the concrete portion of the dam. The flow from the spillway will be flipped downstream of the buttresses into a plunge-type stilling basin to dissipate the energy. The three spillway outlet works will also utilize the plunge basin as an energy dissipator. The fourth will be located in the existing river channel and will discharge into a pool created downstream from a large concrete block used to plug the river gorge.

The spillway was designed to pass the spillway design flood of 190,500 cfs (5,394 cu m/sec). The plunge basin was designed to completely still the discharge of 30,000 cfs (850 cu m/sec) resulting from approximately the 400-year frequency flood. The 100-year flood produces a spillway release of 10,400 cfs ((294 cu m/sec).

THE MODEL

A 1:56 scale model of the dam was built to study, the flow characteristics of the proposed spillway-plunge basin (stilling basin) design (Figure 2). The model contained a large head box simulating the reservoir, the entire spillway section with three and one-half nonoverflow buttresses on the right and four nonoverflow buttresses on the left of the spillway.

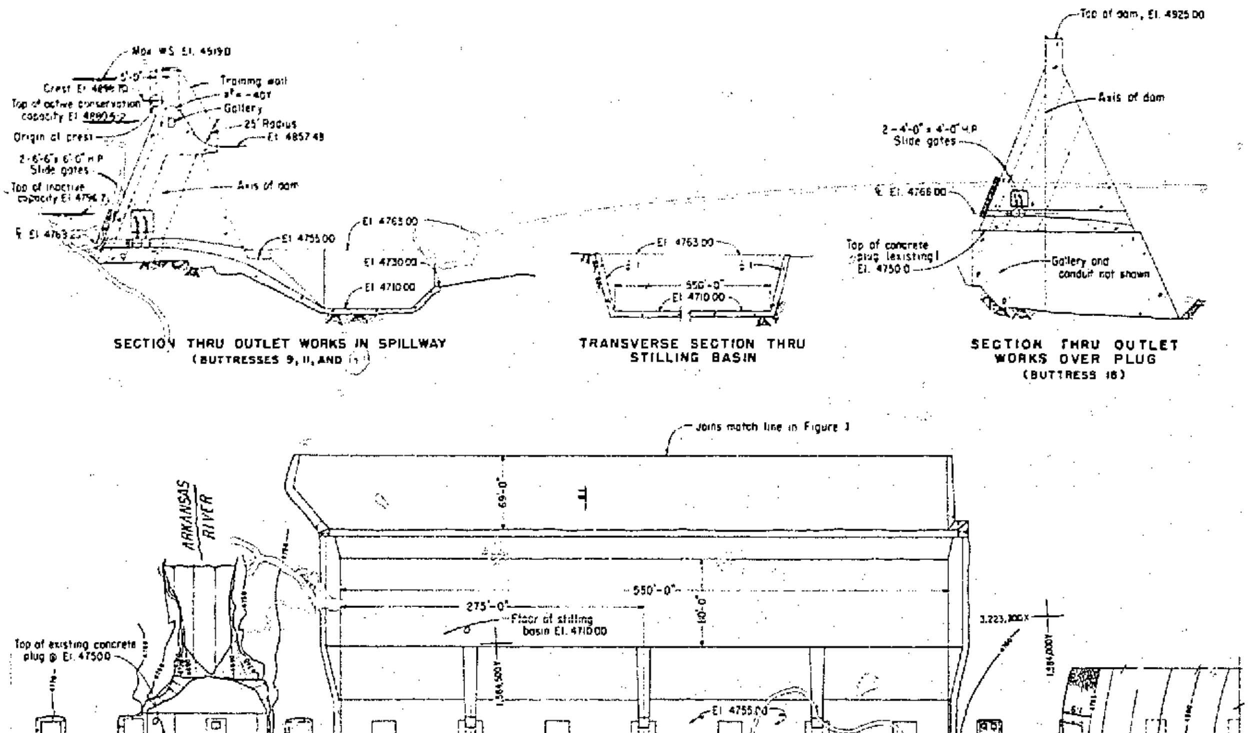


Figure 1. Pueblo Dam spillway and plunge basin—Modeled portion of Pueblo Dam.

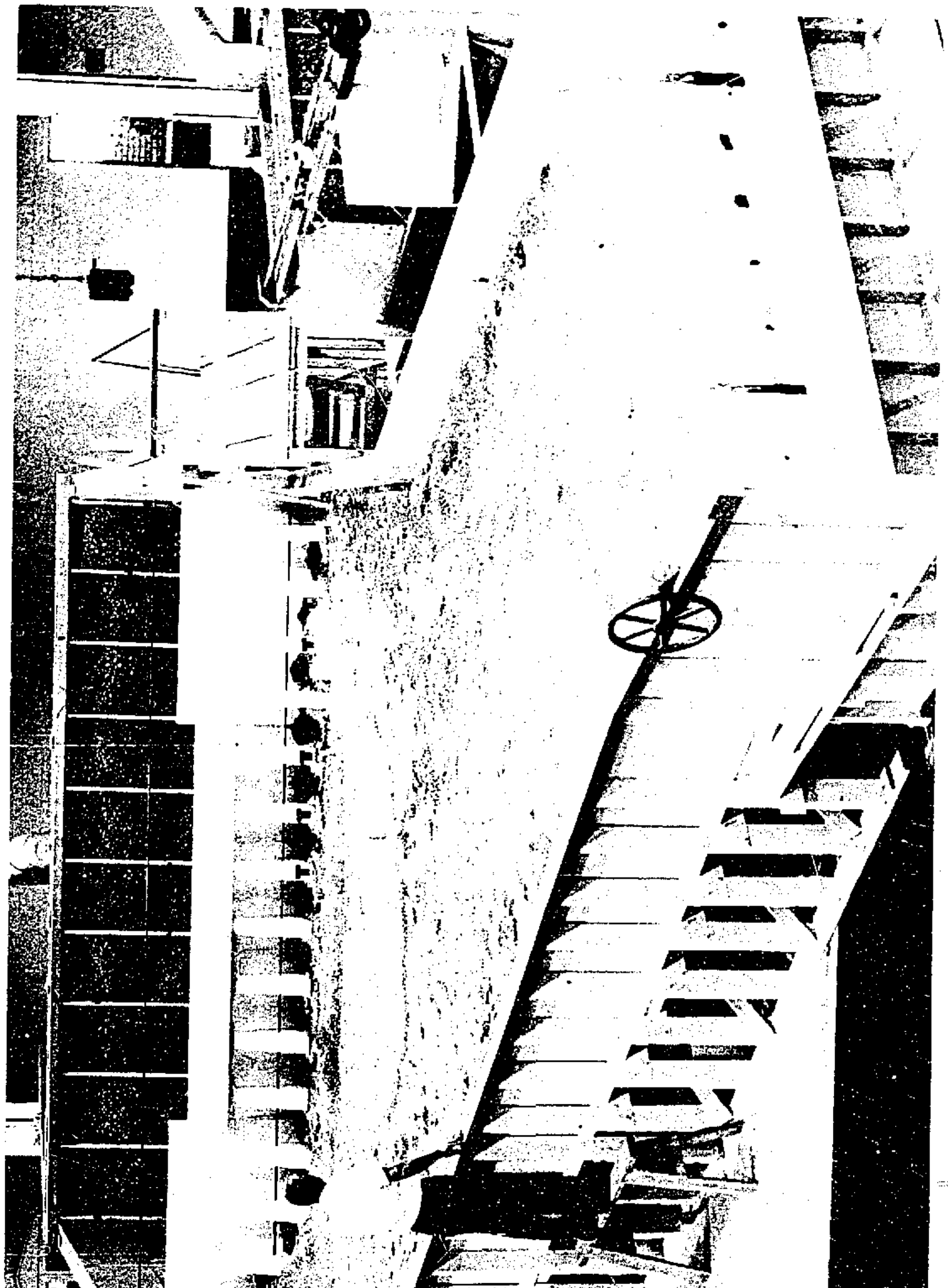


Figure 2. Pueblo Dam spillway and plunge basin—1:56 scale model. Photo P-382-D-63281

Initially the plunge basin was represented with a movable bed material in order to test the possibility of the buttresses being undercut by the free falling spillway jet. After erosion tests, the plunge basin was fabricated of plywood and equipped with piezometers to measure impact pressures. A gravel bed was extended 1,300 feet (396 meters) downstream of the plunge basin to simulate the river channel improvement area. Later two spillway outlet channel improvement schemes were constructed of concrete and tested to determine their effects on the Hamp-Bell Ditch headworks and rockfilled diversion dam (Figure 3).

THE INVESTIGATION

Erosion Tests

Early investigations involved testing spillway operation with a movable bed plunge basin. This was done in order to determine whether the safety of the dam would be affected because of failure of the concrete-lined plunge basin. The bed material in the plunge basin and adjacent to the buttresses represented prototype stone broken into blocks of from 3 to 7 feet (1 to 2 meters); the size estimated to occur with existing fracture planes. The material was placed to conform to the shape of the concrete plunge basin. The entire spillway design flood hydrograph (Table 1), simulating both discharge rate and time was passed through the spillway. The maximum erosion (Figure 4), during the test occurred approximately 120 feet (37 meters) downstream from the buttresses, leaving material adjacent to the buttresses undisturbed. No erosion occurred to the right abutment which was composed of sand simulating material up to 7 inches (18 cm) prototype.

Table 1

PUEBLO DAM
SPILLWAY DESIGN FLOOD
DATA FOR 2-HOUR INTERVALS BEGINNING AT THE
248th HOUR AND EXTENDING TO THE 290th HOUR

Hour	Reservoir elevation	Reservoir inflow		Spillway discharge	
		cfs	cu m/sec	cfs	cu m/sec
248	4898.31				
250	2902.44	151,800	4,299	6,477	183.4
252	4906.80	189,850	5,376	28,315	801.8
254	4910.96	227,000	6,428	64,145	1,816.4
256	4914.62	257,850	7,302	106,989	3,029.6
258	4917.33	265,250	7,511	148,321	4,200.0
260	4918.74	240,250	6,803	177,930	5,038.4
262	4918.88	196,000	5,550	189,572	5,368.1
264	4918.14	152,350	4,314	184,901	5,235.8
266	4916.93	117,650	3,331	170,367	4,824.3
268	4915.52	91,200	2,583	151,368	4,286.3
270	4914.08	71,100	2,013	131,711	3,729.7
272	4912.68	55,800	1,580	113,461	3,212.9
274	4911.37	44,100	1,249	97,063	2,748.5
276	4910.17	35,200	997	82,764	2,343.6
278	4909.10	28,400	804	70,576	1,998.5
280	4908.13	23,100	654	60,332	1,708.4
282	4907.27	19,050	539	51,731	1,464.9
284	4906.51	15,950	452	44,520	1,260.7
286	4905.84	13,600	385	38,482	1,089.7
288	4905.25	11,750	333	33,471	947.8
290	4904.73	10,300	292	29,307	829.9

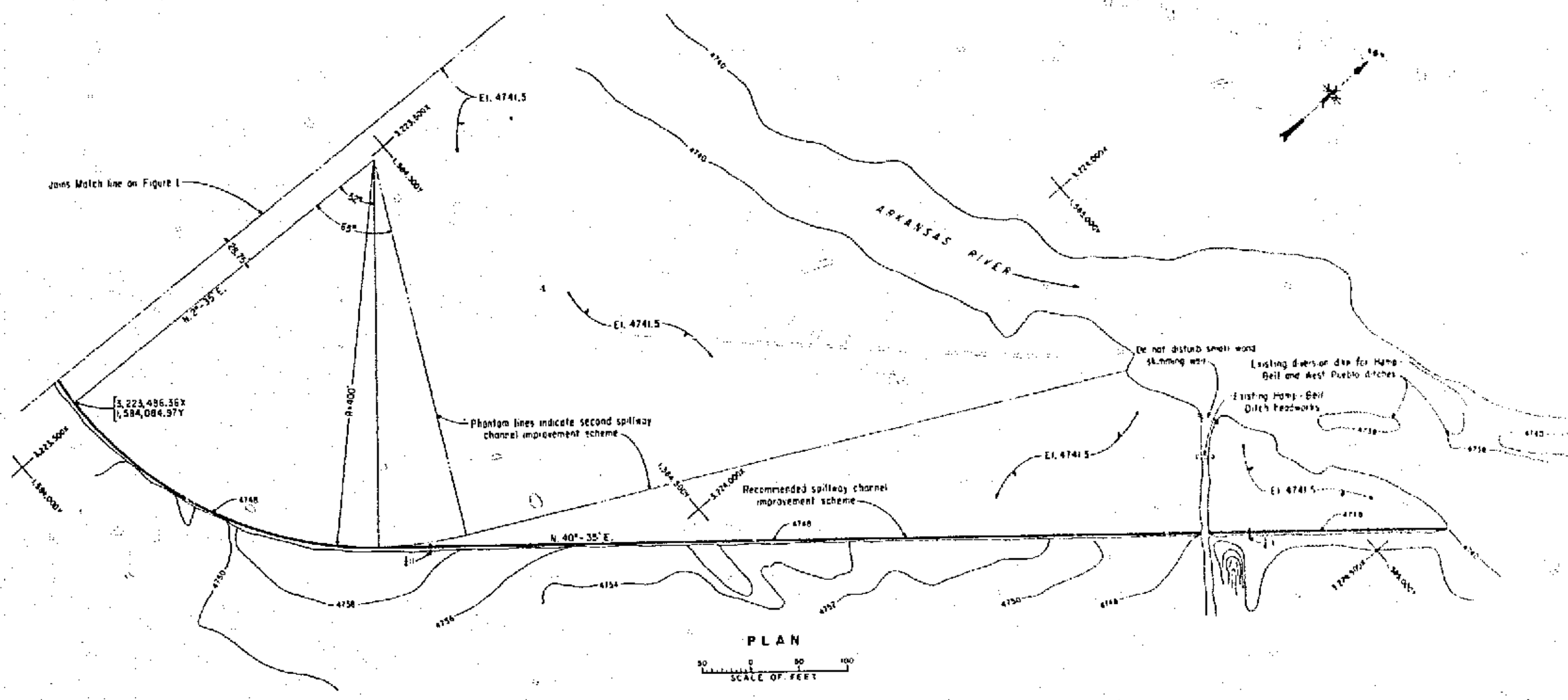
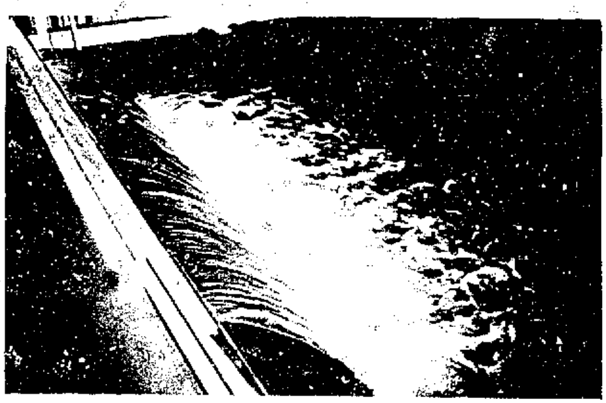


Figure 3. Pueblo Dam spillway and plunge basin--Spillway outlet channel improvement schemes.

A. Erosion from passing spillway design flood. Photo P382-D-69039



B. Spillway design flood of 190,500 cfs (5,390 cu m/sec), released to unlined plunge basin. Note stillness of water surface upstream of impact point. Photo P382-D-69040

Figure 4. Pueblo Dam spillway and plunge basin—Erosion from spillway design flood and spillway design flood maximum release—1:56 model.

Initially the invert of the movable bed plunge basin on the left side was at elevation 4710, and the right side at elevation 4719. At the completion of the test, the major erosion occurred along a contour line at elevation 4705 extending nearly the full width of the jet impact area (Figure 4). Near the middle of this contour was a small area eroded to elevation 4700. The pool between the buttresses and the penetrating jet was relatively quiet for all releases tested (Figure 4B). The major erosion and turbulence occurred downstream of the jet penetration point.

Plunge Basin Impact Heads

The initial basin contained two floor elevations. The floor on the left side was at elevation 4710, and on the right side at elevation 4719. The three spillway outlet works utilized the deeper left side of the basin as an energy dissipator.

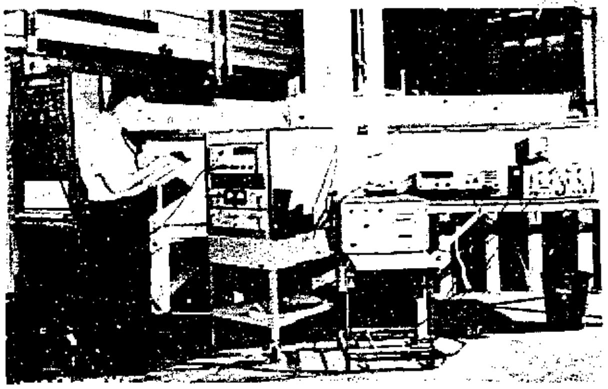
Impact pressure head data from the two level basin showed a considerable advantage was gained from the deeper pool. For maximum discharge, the deeper basin attenuated the impact head nearly 50 percent of the total head, whereas the shallower basin attenuated the impact head only about 10 percent of the total head. These results were obtained by interpreting oscillograph records of pressure sensor responses from piezometers on the inverts of the two level basin.

The improved performance of the deeper pool resulted in the decision to excavate the entire basin to elevation 4710.

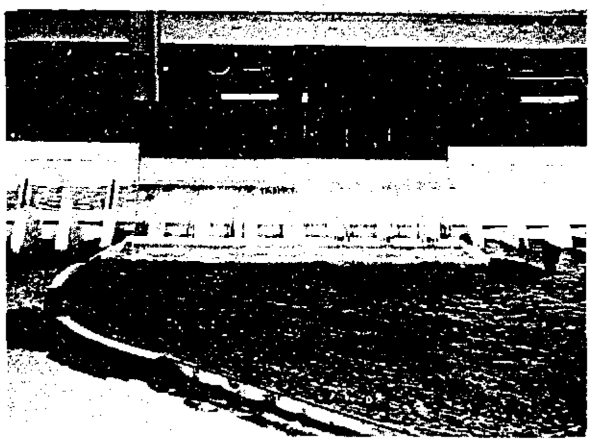
With the deeper pool, more elaborate instrumentation was utilized to obtain impact heads on the floor of the plunge pool (Figure 5A). Pressure sensors were again attached to piezometers on the basin floor. The signal from the sensors was fed to a direct writing oscillograph where it was amplified and recorded. The output of the amplifier was fed to a voltage averaging system, and to a system to measure the effective voltage of the random fluctuations resulting from the turbulent flow in the basin.

The averaging system consisted of an integrating digital voltmeter, an oscillator, and a printer. The oscillator was necessary to adjust integrating time to a larger value than that provided by the internal capability of the voltmeter (200 seconds). The printer recorded the voltmeter reading at the end of integration.

The fluctuating system obtained the signal from the amplifier, fed it thorough a filter to eliminate the 2,400 hz amplifier carrier frequency, to the rms voltmeter to obtain the rms value of the fluctuating



A. Instrumentation for performing statistical analysis of impact forces on the plunge basin floor. Photo PX-D-64078



B. Plunge basin design discharge (30,000 cfs or 850 cu m/sec) totally stilled within the basin. Photo P382-D-69041

Figure 5. Pueblo Dam spillway and plunge basin—Impact instrumentation and plunge basin design discharge—1:56 model.

signal. This value was then integrated for 200 seconds by a second integrating digital voltmeter, and the final reading manually recorded.

Both volt-second values were then changed to volts by dividing by the integrating time. These values relate to the static pool depth (average voltage), and the pressure-head fluctuations on the basin floor (rms voltage).

The total effective voltage was obtained from the equation:

$$V \text{ effective} = \sqrt{V\ avg^2 + V\ rms^2}$$

The effective impact head (EIH) resulted from applying a factor which included the linearity of the amplifier, the amplifier attenuation, and a calibration factor to convert volts to feet of water.

A considerable amount of data was obtained from the model in the hope of relating basin floor impact heads to pool depth, total head, and unit discharge. Model limitations such as a near constant total head for all discharges and a restricted amount of tailwater control resulted in a close grouping of model data points which could not be satisfactorily extended on the existing model. The total head (reservoir water surface to basin invert) varied from 208.6 feet (64 meters) for 190,500 cfs (5,394 cu m/sec) to 188.7 feet (58 meters) with 0 discharge and reservoir surface at crest elevation.

From the model tests, it is expected that future data when obtained will follow curves similar to specific energy curves, with pool depth as the ordinate and effective impact head on the basin floor (EIH) as the abscissa. With a constant discharge and a pool sufficiently deep to prevent the jet from penetrating to the floor, the EIH is essentially the pool depth. As the pool depth decreases, the EIH decreases to a minimum value. A further decrease in pool depth results in a rapid increase in EIH. The point of minimum EIH gives the smallest combined value of static and dynamic head for a given discharge. A greater depth will result in less dynamic head on the pool floor but higher construction costs. From the model data the pool depth for the majority of test discharges was greater than the depth for minimum EIH with the exception of 190,500 cfs (5,394 cu m/sec), which showed a slight increase in EIH with decrease in pool depth. To prevent overextending the data, the only curve included in the report was for pool depth resulting from tailwater values supplied by the design section (Figure 6). The completely stilled 30,000 cfs (850 cu m/sec) release results in an EIH on the basin floor equal to the tailwater depth. This release is shown in Figure 5.

Nappe Oscillations

Two distinct modes of oscillation in the freely falling spillway jet existed when spillway releases of under 10,000 cfs (283 cu m/sec) were made (Figure 7). The lower mode began as soon as a full sheet of water left the lip of the flip bucket and persisted (reservoir rising) until a release of 4,500 cfs (127 cu m/sec) was passing over the spillway (Figure 8). Here an instability occurred and the lower mode shifted into the higher mode. The higher mode continued until a release of approximately 10,000 cfs (283 cu m/sec) was attained. Then the oscillations disappeared and the jet became

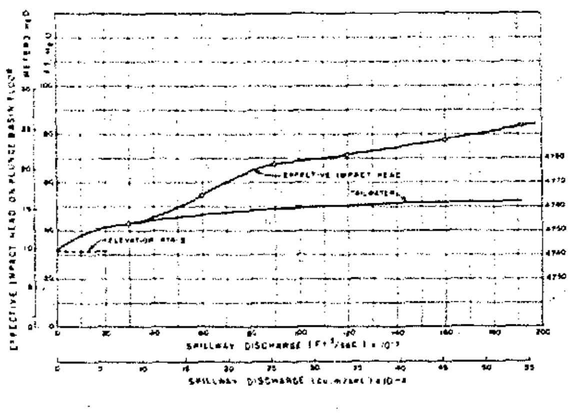


Figure 6. Pueblo Dam spillway and plunge basin—Effective head on plunge basin floor from 1:56 model.

stable (Figure 8). A stable jet would exist (reservoir falling) down to a release of slightly below 7,000 cfs (198 cu m/sec) before the higher mode oscillations were encountered. The higher mode would persist down to 3,400 cfs (96 cu m/sec) before shifting to the lower mode.

Initially the oscillations were thought to occur at constant frequencies; however, subsequent testing revealed slight increases in frequency with increasing discharge within the respective modes (Figure 8).

Some interesting observations were made on the nappe oscillations, while testing the model. A single-flow splitter placed on the centerline at the downstream end of the flip bucket could eliminate the oscillations and produce two stable jets. Also, oscillations could occur to one side of the splitter, while a stable jet existed on the other. Oscillations could be eliminated by allowing the jet to fall into a trough slightly above the water surface which passed the spillway flow to one side and allowed air to circulate through a narrow slot under the trough to the underside of the nappe.

During the course of the model study, the laboratory ceiling was spray painted. A considerable amount of overspray was inadvertently deposited on the spillway face creating excessive roughness. The nappe could not be made to oscillate until this excessive roughness was removed.

To determine if the volume of air under the nappe caused or affected the oscillations, the air space was modified. First, a plywood filler board was placed against the downstream sides of the buttresses to reduce the air quantity available to the free falling jet. This eliminated the lower mode of oscillation and made the higher mode unstable for lower discharges, reverting alternately to smooth flow.

Next plywood wingwalls were added to the left and right sides of the jet between the dam, the jet, and the tailwater, eliminating the possibility of the jet venting from the sides. The only effect noted was that oscillations would continue to a discharge of 12,000 cfs (340 cu m/sec), rather than to 10,000 cfs (283 cu m/sec) as prior to wingwall addition.

Similar oscillations have been observed and reported by many investigators. A comprehensive study by H. Ivan Schwartz* contains information on predicting the frequency of such oscillations and suggests guidelines for eliminating the oscillations.

To prevent the nappe from oscillating, the model was equipped with seven flow splitters, one above each buttress at the downstream end of the flip section (Figure 9). The splitters separate the flow and minimize the chance for a pressure differential to exist between the upper and under surface of the jet. The first blocks were 14 inches (36 cm) high and of triangular-wedge shape with 45° sloping sides. The top line was horizontal and joined the flip bucket curve on the upstream end. The splitters began to submerge at 10,000 cfs (283 cu m/sec) and were totally submerged at about 14,000 cfs (396 cu m/sec).

To increase the margin between releases resulting in oscillations and those resulting in splitter submergence, seven 18-inch (46-cm) high splitters with 60° sloping sides were tested (Figures 9 and 11). These began to submerge at 20,000 cfs (566 cu m/sec) and were totally submerged at 24,000 cfs (680 cu m/sec) providing a 10,000 cfs (283 cu m/sec) margin between nappe oscillation and splitter submergence. As little is known on scaling nappe oscillations to the prototype, this margin was considered necessary and adequate to prevent their occurrence in the prototype.

Crest Characteristics

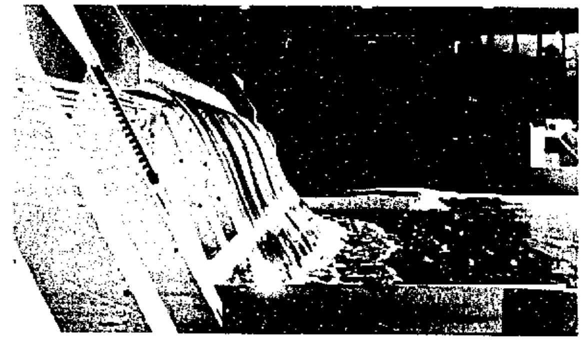
The model was used to obtain crest pressures (Figure 10), water surface profiles (Figure 11) and a head-discharge crest curve (Figure 12).

The crest pressures were obtained from water manometers attached to 14 piezometers located near the spillway centerline.

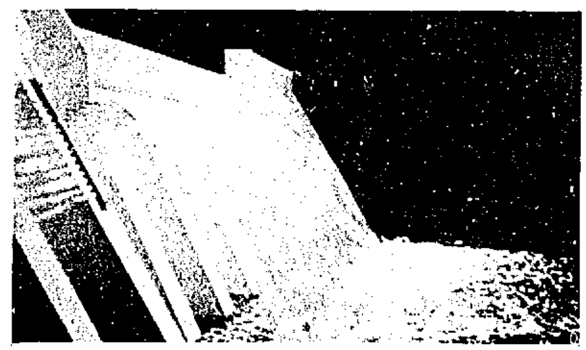
The water-surface profiles were obtained with a point gage at 13 points along the crest and flip bucket.

The crest was rated through the use of calibrated 4-, 6-, 8-, and 12-inch (10-, 15-, 20-, and 30-cm) laboratory

*"Nappe Oscillation," H. Ivan Schwartz, Hydraulics Division, ASCE, November 1964.



A. Lower mode oscillations, frequency approximately 27-1/2 cycles per minute prototype. Left photo P382-D-69042. Right photo P382-D-69043



B. Higher mode oscillations, frequency approximately 52 cycles per minute prototype. Left photo P382-D-69044. Right photo P382-D-69045

Figure 7. Pueblo Dam spillway and plunge basin—Spillway jet nappe oscillations—1:56 model.

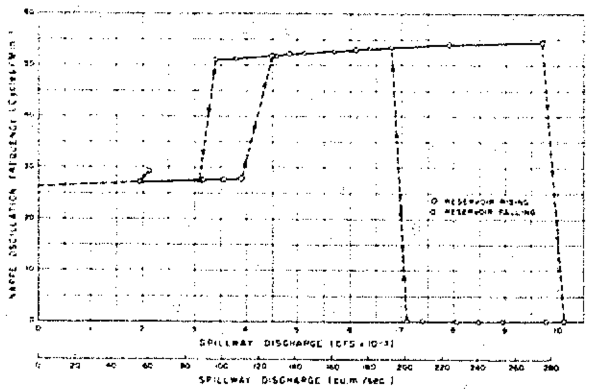


Figure 8. Pueblo Dam spillway and plunge basin—Nappe oscillation frequency versus discharge—From 1:56 model.

venturi meters, and a curve was prepared for the complete range of releases up to 190,500 cfs (5,394 cu m/sec).

Spillway Training Walls

The spillway training walls on the initial design were parallel to the spillway centerline. Large releases spread after leaving the flip bucket and struck the ground outside of the left and right walls of the plunge basin (Figure 13). The training walls were angled inward toward the spillway centerline in the downstream direction to eliminate the condition (Figure 11). Vorticies in the head box (Figure 13) produced an instability in large flows over the spillway. These appear as depressions in the flow over the crest which move laterally back and forth on the spillway face. Occasionally, the instability will reach the sides of the spillway and cause the jet to strike outside of the plunge basin walls. As the entire reservoir was not modeled, the vorticity problem may not occur in the prototype. Also, the basin was designed for approximately the 400-year frequency flood of 30,000 cfs (850 cu m/sec) and the jet struck outside the basin walls only at discharges exceeding 120,000 cfs (3,398 cu m/sec). Therefore, a wider basin was considered unnecessary.

Spillway Outlet Channel Improvement

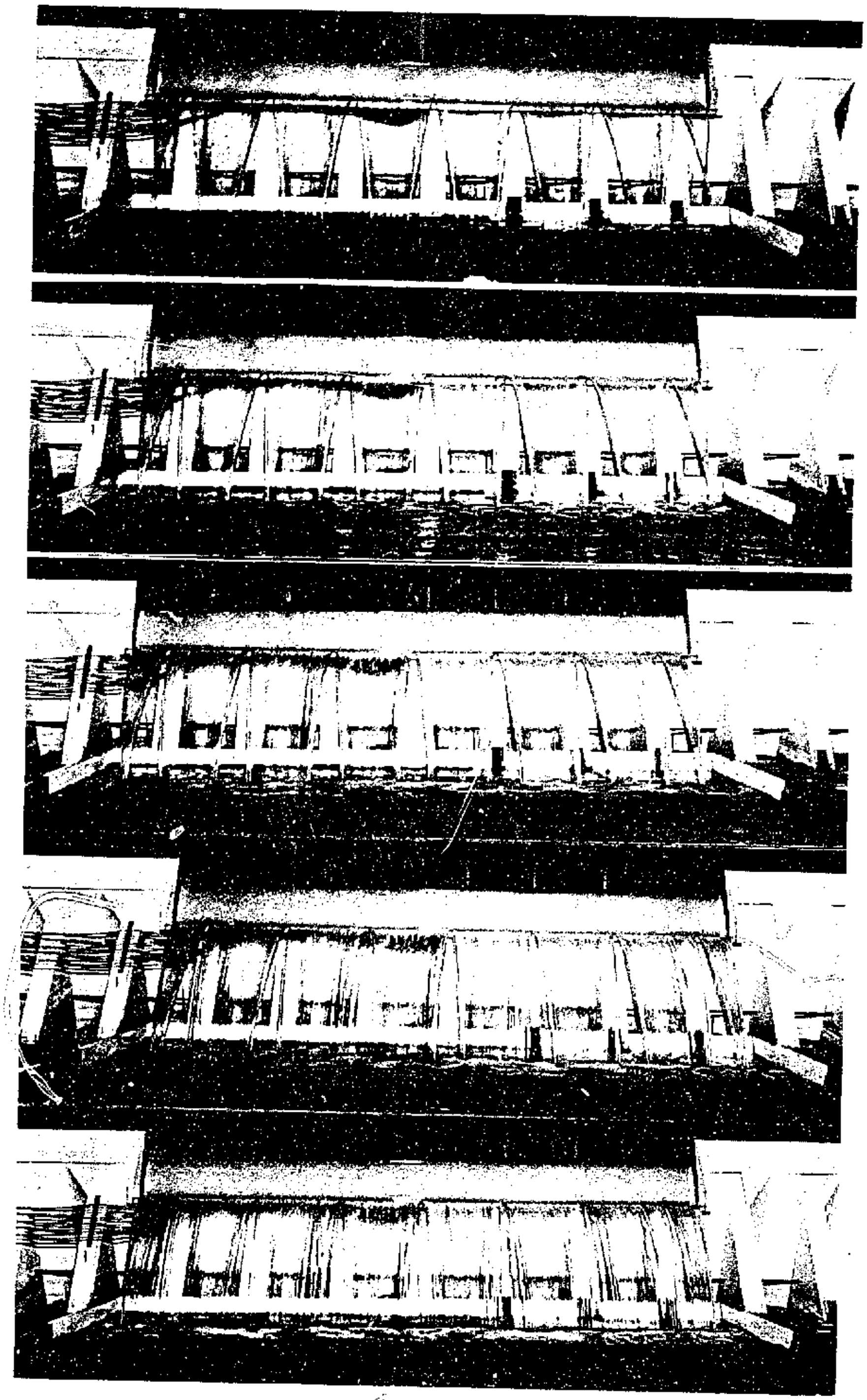
Two spillway outlet channel improvement schemes were tested in the model to determine which scheme would produce the most satisfactory flow conditions in the area of the Hamp-Bell Ditch Headworks, Figure 3. The initial scheme extended from the plunge basin to approximately 260 feet (79 meters) downstream of the ditch headworks, and would require excavation adjacent to the existing headworks and rockfilled diversion dam. Precautions would be required to avoid interfering with diversion. The second scheme ended approximately 70 feet (21 meters) upstream of the headworks, and would minimize excavation and eliminate interference with the diversion operation.

Flow conditions for the second scheme were unacceptable. Local high velocities and a rough-water surface resulted from the restricted flow area immediately downstream of the junction of the second scheme and the existing river channel (Figure 14B). The wave action was apparent at the canal intake and carried downstream to the rockfilled diversion dam area where considerable erosion resulted for flows as low as 5,000 cfs (142 cu m/sec).

The recommended initial scheme produced a more even flow distribution in the vicinity of the intake (Figure 14A), and across the rockfilled diversion dam. The much larger flow area greatly reduced the erosion to the rockfilled diversion dam, and allowed for passage of flows up to 30,000 cfs (850 cu m/sec) with only minor effects.

Plunge Basin Modification

After a decision was made to adopt the deeper stilling basin, the slope of the upstream apron of the stilling basin was changed from 1.5:1 to 1.08:1 to keep the basin floor at approximately the same location and provide adequate foundation for the dam. This bench at the downstream toe of the buttresses will be above the tailwater for all outlet works releases and will provide an access for examining the stilling basin, outlet works, and the downstream faces of the dam. Releases under 3,500 cfs (99 cu m/sec) impinged directly on the horizontal section causing considerable splash (Figure 15A). The splash and lack of tailwater to cushion the impact were undesirable. However, air entrained when the jet free falls over 100 feet (30 meters) should help to reduce the impact head. With the lack of spillway control, no definite means is available to avoid these small flows, although optimum river outlet control could minimize the time in which they are encountered. For higher releases, flow in the basin upstream of the jet impact point remained satisfactory (Figure 15B).



Spillway discharge

5,000 cfs
141 cu m/sec

Photo P382-D-69046

10,000 cfs
283 cu m/sec

Photo P382-D-69047

15,000 cfs
425 cu m/sec

Photo P382-D-69048

20,000 cfs
566 cu m/sec

Photo P382-D-69049

25,000 cfs
708 cu m/sec

Photo P382-D-69050

Figure 9. Pueblo Dam spillway and plunge basin—Flow splitter effectiveness for releases up to 25,000 cfs—1:56 model.

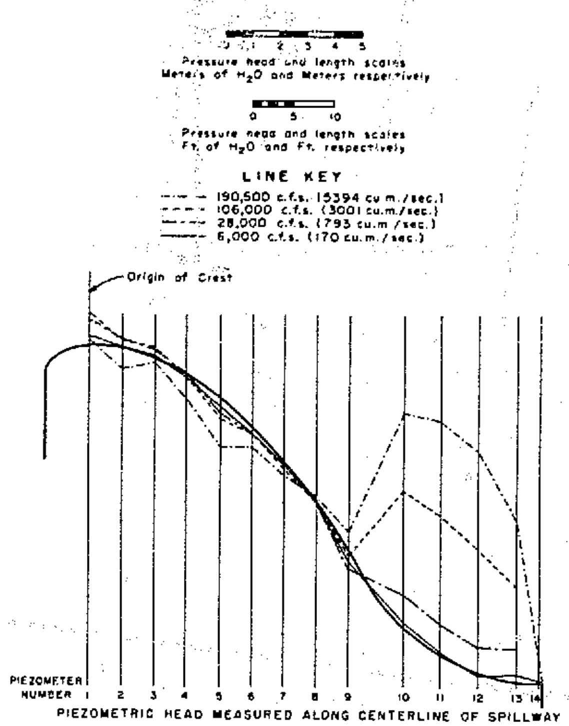


Figure 10. Pueblo Dam spillway and plunge basin—Spillway crest pressures—From 1:56 model.

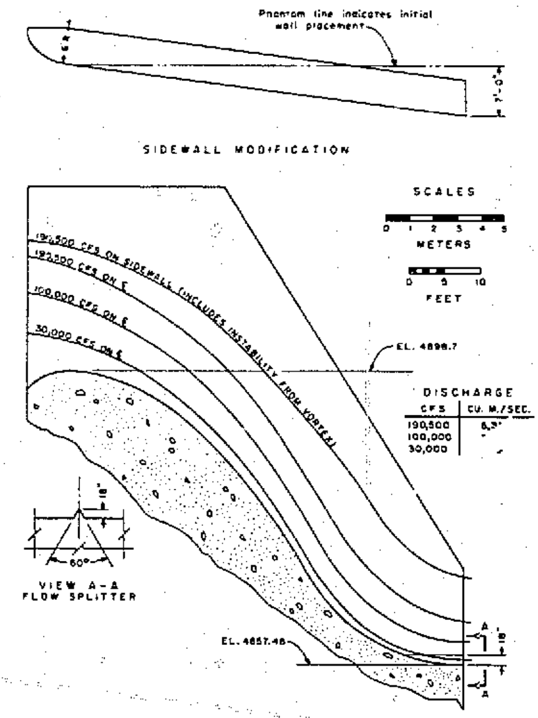


Figure 11. Pueblo Dam spillway and plunge basin—Spillway water surface profiles, wall modification, and flow splitter design—From 1:56 model.

River Outlet Gates

The model scale (1:56) was too small to accurately study the river outlets. Additional studies were performed utilizing model scales of 1:15.2 and 1:10.1 for the gates in the spillway buttresses, and the gate in the river gorge, respectively. These studies were performed by Mr. G. L. Beichley and will be covered in another report.

The spacing between outlets in the spillway was doubled after the decision was made to excavate the entire basin to elevation 4710. The increased spacing, although not modeled, should reduce the severity of circulation in the basin. Figure 16A shows the circulation that results when two outlets in adjacent buttresses were operated. By doubling the spacing between buttresses, flow should appear more as in Figure 16B for a single outlet.

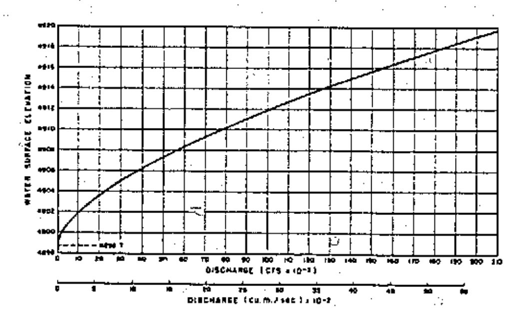
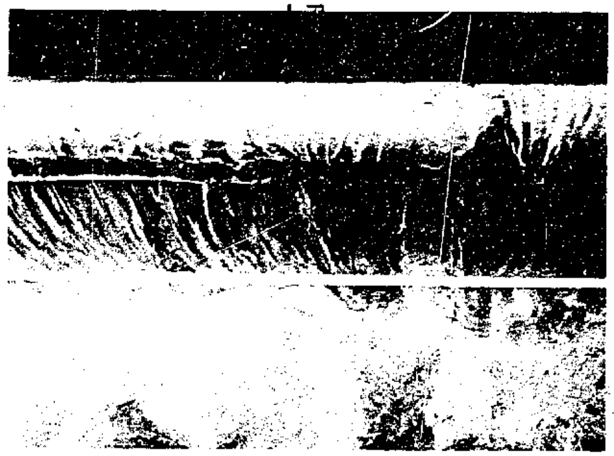
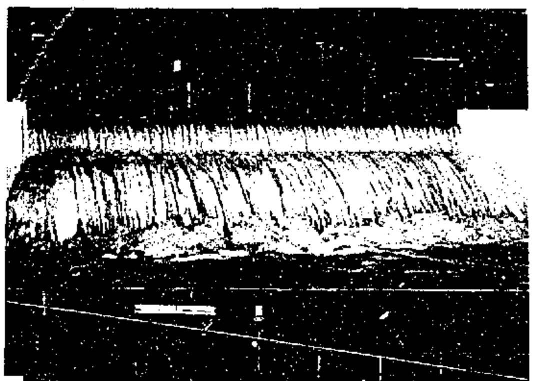


Figure 12. Pueblo Dam spillway and plunge basin—Head-discharge curve—From 1:56 model.

A. Vortices formed in head box move over spillway crest causing large depressions in the flow surface which produce rooster tails when flow rejoins downstream. Discharge 190,500 cfs (5,394 cu m/sec). Left Photo P382-D-69051. Right Photo P382-D-69052



Initial spillway training walls parallel to spillway centerline.

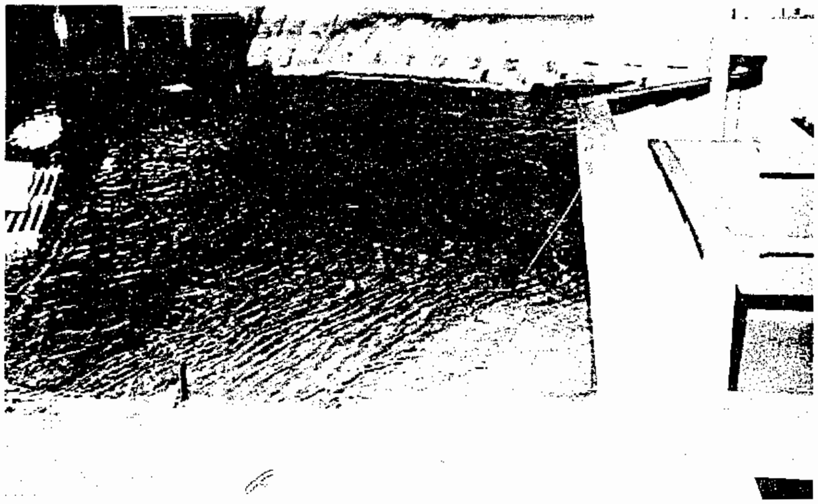
Photo P382-D-69053

Spillway walls angled towards centerline in downstream direction.

Photo P382-D-69054

B. Spillway design discharge. Note reduced spreading of the jet with wall modification.

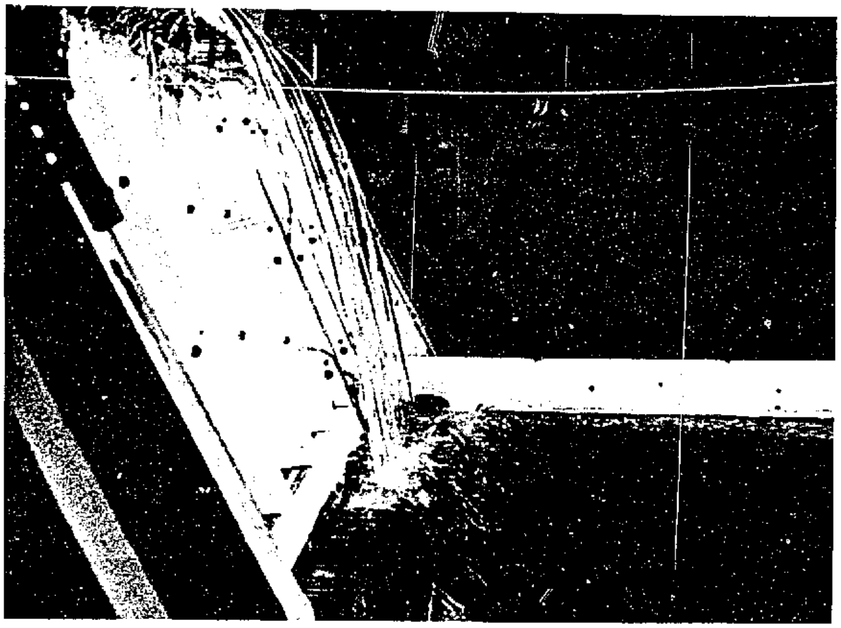
Figure 13. Pueblo Dam spillway and plunge basin—Vortices in flow over spillway and effect of spillway wall modification—1:56 model.



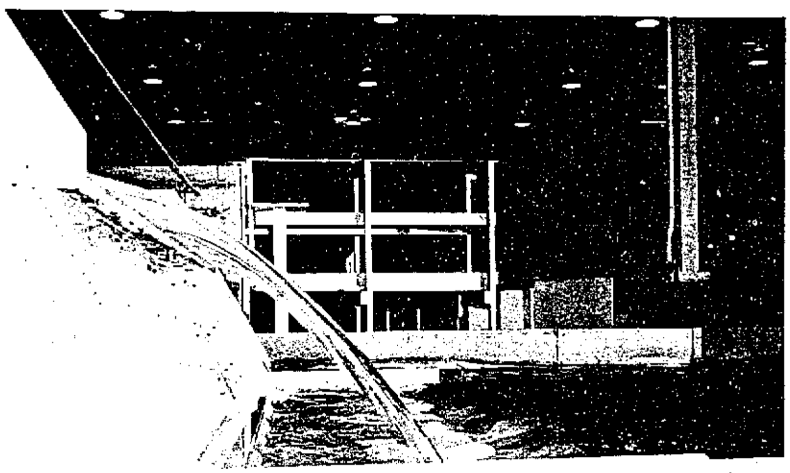
A. Recommended spillway outlet channel improvement. Larger flow area results in lower velocities in the vicinity of the intake. Discharge 15,000 cfs (424 cu m/sec). Photo P382-D-69055

B. Improvement Scheme 2 showing areas of high turbulence near the headworks. Discharge 15,000 cfs (424 cu m/sec). Photo P382-D-69056

Figure 14. Pueblo Dam spillway and plunge basin—Schemes for spillway outlet channel improvement near Hamp-Bell Ditch headworks—1:56 model.

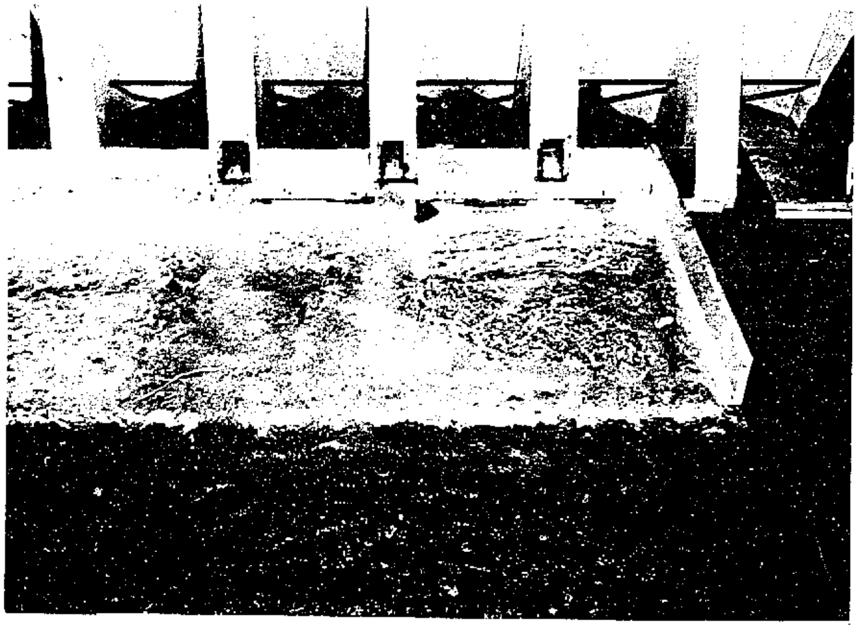


A. Spillway release 3,000 cfs (85 cu m/sec) impinging directly on bench upstream of basin. Note considerable splash. Photo P382-D-69057

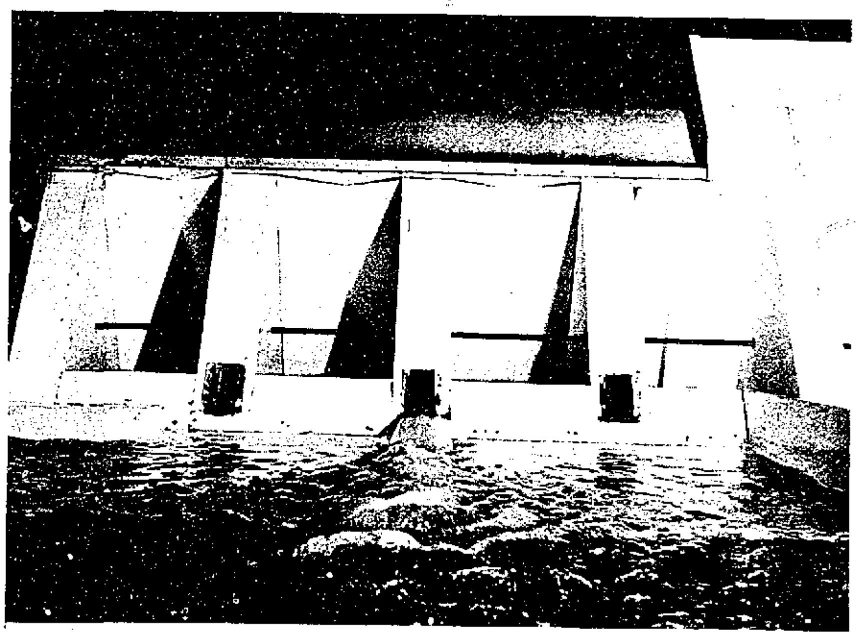


B. Spillway release of 30,000 cfs (850 cu m/sec). When flow exceeds about 3,500 cfs (99 cu m/sec) jet impinged in basin. Photo P382-D-69058

Figure 15. Pueblo Dam spillway and plunge basin—Appearance of small and moderate spillway flows—1:56 model.



A. Heavy circulation resulting when two adjacent outlet works gates operate in narrow, deep basin. Photo P382-D-69059



B. Increased outlet spacing should reduce circulation and more nearly approximate flow from the single outlet. Photo P382-D-69060

Figure 16. Pueblo Dam spillway and plunge basin—Outlet works operation—1:56 model.

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
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*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
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*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
Short tons (2,000 lb)	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
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	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
Pounds per cubic foot	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
Inch-pounds	1.12985 x 10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	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
Feet 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
Miles 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
Pounds	*4.4482	Newtons
Pounds	*4.4482 x 10^5	Dynes

Table II--Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	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 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
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 838-737

ABSTRACT

Studies were performed on a 1:56 scale hydraulic model of Pueblo Dam spillway and plunge basin (stilling basin) to determine if the unusual design could handle the required releases safely. The model contained the flip-type spillway, plunge basin, river outlets, and a section of downstream river channel. Channel erosion, basin impact pressures, nappe oscillations, crest rating, and flow profile studies were made on the model. Flow splitters were added to the spillway to eliminate nappe oscillations. The plunge basin initially containing 2 floor elevations was enlarged to the level of the deeper section to minimize impact pressures. A technique of data collection was used in obtaining impact pressures which provided an electronic statistical analysis. A curve was obtained to relate basin floor effective pressure head to spillway discharge for the normal river tailwater conditions.

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REC-ERC-71-18
Isbester, T J
HYDRAULIC MODEL STUDIES OF THE PUEBLO DAM SPILLWAY AND PLUNGE BASIN
Bur Reclam Rep REC-ERC-71-18, Div Gen Res, June 1971. Bureau of Reclamation, Denver, 16 p, 16 fig, 4 tab, 1 ref

DESCRIPTORS—/ *spillways/ *hydraulic models/ instrumentation/ hydraulic structures/ impact/ *energy dissipation/ fluctuation/ Colorado/ stilling basins/ *plunge basins/ *model tests/ channel erosion/ nappe/ dams/ flow profiles/ model studies/ scour/ oscillations/ turbulence/ *flip buckets
IDENTIFIERS—/ Pueblo Dam, Colo/ Fryingpan-Arkansas Proj, Colo/ flow splitters

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