R-90-07

HYDRAULIC MODEL STUDY OF CHILI BAR DAM SPILLWAY MODIFICATIONS

April 1990

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Denver Office
Research and Laboratory Services Division
Hydraulics Branch

7-2090 (4-81)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	R-90-07
2. GOVERNMENT ACCESSION NO.	
3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE	HYDRAULIC MODEL STUDY OF CHILI BAR DAM SPILLWAY MODIFICATIONS
5. REPORT DATE	April 1990
6. PERFORMING ORGANIZATION CODE	D-3750
7. AUTHOR(S)	R. A. Dodge B. W. Mefford
8. PERFORMING ORGANIZATION REPORT NO.	R-90-07
9. PERFORMING ORGANIZATION NAME AND ADDRESS	Bureau of Reclamation Denver Office Denver CO 80225
10. WORK UNIT NO.	
11. CONTRACT OR GRANT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS	Same
13. TYPE OF REPORT AND PERIOD COVERED	
14. SPONSORING AGENCY CODE	DIBR

15. SUPPLEMENTARY NOTES

Microfiche and hard copy available at the Denver Office, Denver, Colorado.

16. ABSTRACT

A physical model study of Chili Bar Dam, located on the South Fork of the American River in northern California, was conducted to compare relative channel bed scour downstream of the spillway for different flip bucket elevations and geometries. The dam is owned by Pacific Gas and Electric Company, San Francisco, California. The prototype spillway consists of an ungated ogee crest with a three-level nonsymmetric ski jump on the downstream spillway face. Movable bed scour tests were conducted for the prototype spillway and for modifications to the three-level ski-jump design. The ski-jump design was modified to a short radius flip bucket. Bed scour tests were then conducted for different bucket elevations. These consisted of testing a single high elevation flip bucket, two-level flip bucket, and three-level flip bucket geometries. Limited testing of slotted and slit-type flip buckets were also conducted.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. *DESCRIPTORS*-- spillway/ channel scour/ flip bucket/ ski jump/ hydraulic model study/ slotted bucket/ slit-type bucket

b. *IDENTIFIERS*-- Chili Bar Dam/ Pacific Gas and Electric

c. *COSATI Field/Group* *COWRR:* *SRIM:*

18. DISTRIBUTION STATEMENT	
19. SECURITY CLASS (THIS REPORT)	UNCLASSIFIED
20. SECURITY CLASS (THIS PAGE)	UNCLASSIFIED
21. NO. OF PAGES	53
22. PRICE	

R-90-07

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Denver Office
Denver, Colorado

April 1990

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

Pete Julius, Hydraulics Branch civil engineering technician, and Art Striefel, ACRM - General Engineering Branch (rotation engineer), were instrumental in model data collection and filming. Wallace English, Pacific Gas and Electric, and Thomas Rhone, Hydraulics Branch Technical Specialist, provided technical review and guidance.

This study was conducted by the Hydraulics Branch, Research and Laboratory Services, U.S. Bureau of Reclamation, in cooperation with Pacific Gas and Electric Company under Cooperative Agreement No. 8-FC-81-12800.

The research covered by this report was funded under the Bureau of Reclamation PRESS (Program Related Engineering and Scientific Studies) allocation No. SO-1, Stilling Basin Drainage.

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BACKGROUND

Chili Bar Dam, owned by PG&E (Pacific Gas and Electric) Company, is a concrete gravity dam on the South Fork of the American River near Placerville, California. The dam and adjacent powerhouse were completed in 1965. The dam is approximately 120 feet high and 375 feet wide. The structure contains an uncontrolled ogee crest spillway 170 feet wide located 31 feet below the top of the dam (fig. 1). The downstream side of the spillway follows a 7 on 10 slope until intersecting the ski jump radii. The spillway currently has three 45-foot-radius ski jumps terminating at the horizontal. All ski jumps are located at different elevations and span different widths of the spillway. Looking downstream from right to left, the ski jumps are as follows:

Toe elevation (ft)	Width (ft)
940	27.5
930	100.0
950	42.5

The spillway exits into an unlined natural rock basin. The downstream channel near the dam has, in general, had all overburden removed to bedrock from previous spillway operation. Since the dam was built in 1965, the maximum daily average spillway discharge has been about 42,000 ft^3/s. The spillway design capacity was 100,000 ft^3/s. The PMF (probable maximum flood) is currently estimated to be 250,000 ft^3/s. The dam must be overtopped by approximately 15 feet to pass this new PMF. Since the dam was completed in 1965, PG&E has reported a small amount of erosion at the toe of the dam due to spillway operation. Although this erosion is not currently serious, PG&E is concerned about continued erosion. Several alternatives that were investigated by PG&E to repair the present erosion damage and prevent future erosion were:

1. To place tremie concrete to fill in the existing erosion holes. The bonding between the aquatic-vegetation-covered bedrock and the concrete was questionable for this alternative.

2. To build a cofferdam and dry up the dam toe to ensure a proper bond between the placed concrete and bedrock. The cofferdam would have to allow for powerplant operation.

3. To not repair the existing erosion and install a flip bucket on the existing spillway structure which would halt further erosion.

PG&E investigated alternative 3 because alternatives 1 and 2, while repairing erosion, would not prevent future erosion from taking place. Alternative 3 was also estimated to be less expensive than alternative 2 because the construction could be conducted without dewatering the dam's toe. A physical model study was necessary because the flip bucket design required did not fit into existing design criteria bounds for roller bucket radius or tailwater conditions. PG&E and the Bureau of Reclamation were interested in research information that would allow for expanding the available design criteria for spillways similar to Chili Bar Dam. Therefore, PG&E and Reclamation entered into a cooperative research agreement to model study the proposed small radius flip bucket spillway.

OBJECTIVES

A 1:45 scale model was designed and tested to investigate flip bucket modifications in order to reduce stilling basin scour near the toe of the dam. A model of the structure was tested to:

1. Define relative scour patterns, particularly at the dam's toe, as a function of flip bucket geometry and bucket elevation. Relative scour patterns were measured after passing discharges of 10, 25, 50, 75, and 100 percent of the PMF. For the final bucket design, tests using flows of 2 and 4 percent of the PMF were also conducted.

2. Determine if a deflector wall placed on the bucket adjacent to the powerhouse would reduce local scour near the end of the tailrace wall. The deflector wall studies were conducted only on the final bucket geometry. A maximum design flow corresponding to the 65-year flood, 62,500 ft^3/s (25 percent of the PMF), was used in evaluating scour along the tailrace wall. Protecting the wall from bed scour was not considered economically practical for larger flows because of their low frequency. The present cost of repairing damage every 65 years is considered to be less than the cost to ensure that the wall is not damaged by major floods. Damage to the wall does not endanger the dam. Relative bed scour tests were conducted with and without the deflector on the bucket.

3. Measure reservoir elevation versus spillway/dam discharge capacity, spillway crest pressures, and pressures in the flip bucket.

4. Conduct basic research on the hydraulic performance of slotted and slit-type flip bucket designs. Use the model results from the standard solid bucket design as a basis of comparison to evaluate the performance of the nonstandard slotted and slit-type bucket designs.

CONCLUSIONS

- Overall, the modified flip bucket spillways tested produced less bed scour within the reach from the toe of the spillway to the end of the tailrace wall when compared to the prototype spillway design.

- Of the three modified spillway geometries tested, the three-level arrangement produced the greatest deposition of fine bed material within the channel reach immediately downstream of the spillway and along the tailrace wall. Significant movement of bed material upstream to the spillway toe occurred in the model for flows 25 percent of PMF and greater. Due to the large flows the spillway/dam is required to pass, moving material toward the toe of the dam is considered desirable. Although some abrasion to the concrete on the downstream face of the lower flip buckets could occur for the higher flows, the abrasion action is not expected to be significant. Visual observations made of the movement of bed material in the model indicated the tailwater velocities beneath the jet and next to the bucket faces were generally low. The deposition of very fine material along the toe in the model also suggests the hydraulic action next to the spillway is not extremely violent.

- The implementation of the deflector wall in the right side bucket did not produce an overall improvement in the local scour along the tailrace wall. Scour at several locations along the wall increased slightly with the addition of the flow deflector. The deflector did force the edge of the jet out from the wall thus preventing the edge of the jet from impinging directly above the wall.

DESCRIPTION OF THE PHYSICAL MODEL

A 1:45 scale model of Chili Bar Dam including reservoir approach topography, dam, spillway, powerhouse, abutments, and about 500 feet (prototype) of downstream channel topography was built for the study. The downstream channel was modeled using an erodible bed material. The bed material was contoured in the model by matching reverse templates representing channel cross sections spaced at about 40-foot intervals down the river channel. In the model, the dam abutments and the downstream canyon walls were considered nonerodible. They were geometrically modeled using a wire mesh molded over plywood forms. A concrete mortar was placed over the wire to give a finished surface. The spillway crest and the ski-jump spillway were milled out of high-density urethane. Six piezometer taps were placed in the crest to measure pressures. The taps were positioned down the crest along the spillway centerline (fig. 2).

MODEL SIMILITUDE

General

For a model to truly represent actual conditions, it must be geometrically, kinematically, and dynamically similar to the prototype. If the model deviates from the prototype in any one of these three areas of similitude, then care must be taken to properly interpret the model results. However, if any one deviation is too large, or there are too many deviations, the model will not represent the prototype and no amount of interpretation will yield the correct results or conclusions.

Flow Similitude

Similitude analysis and model design are best started by finding valid homogeneous equations and dimensionless functional relationships that apply to both the model and prototype. Selection of a set of equations and functions includes the requirement that they be checked for their model and prototype application range and limits. Normalizing complete hydrodynamic equations for open channel flow opposed to tractive shear or friction and then extracting dimensionless parameters result in a Froude number squared (F^2) or ($V^2/R_h g$) and a product of the Darcy-Weisbach friction coefficient (f) times Froude number squared as the required parameters for scaling flow. The friction coefficient is a function of relative roughness (K_s) and Reynolds number (R) expressed as:

$$f = \Phi\ (K_s, R)$$

where:

$$K_s = (k_s/4R_h)$$
$$R = (4R_h V/\upsilon)$$

f	=	friction factor
R_h	=	hydraulic radius
V	=	velocity
g	=	gravitational constant
Φ	=	function operator
k_s	=	rugosity
υ	=	kinematic viscosity

A geometric or length scale ratio (L_r) of 45 was selected because of limited laboratory pump capacity. Based on Froude law alone,

Length ratio	L_r	= 45
Velocity ratio	V_r	= 6.71
Time ratio	T_r	= 6.71
Discharge ratio	Q_r	= 13,584
Unit discharge ratio	q_r	= 302
Tractive shear ratio	t_r	= 45
Pressure ratio	P_r	= 45

Having selected the Darcy-Weisbach equation to normalize friction loss in the complete flow equation, the ratio of friction factors in model and prototype (f_r) must be made equal to 1 to produce similar vertical velocity distributions and secondary flows. The Darcy-Weisbach equation for open channel flow in slope (S) form is expressed as:

$$S = f\,(1/4R_h)\,(V^2/2g)$$

Since the friction factor (f) is a function of Reynolds number ($4R_hV/\upsilon$) and relative roughness ($k_s/4R_h$), the modeler must work within Moody-type friction curves. Reynolds number cannot be made the same for both a model and a prototype river. The model must be made to flow at water surface elevations according to a tailwater curve and produce the proper corresponding velocity. The modeler must find the rugosity that produces an equal (f) for both the model and prototype. Putting the previous scale relations into the Reynolds number results in a measure of Reynolds number distortion (R_{dr}) based on the selected model scale ratio expressed as:

$$R_{dr} = L_r^{3/2} = 302$$

A friction, Reynolds number, and relative roughness model to prototype comparison was done using the prototype tailwater curve and a Moody-type friction function for discharges from 5,000 to 250,000 ft^3/s. These comparisons showed that Reynolds number was sufficiently large for both model and prototype to be on the flat part of the friction function. Thus, model and prototype (f) are expected to be equal. It was also shown that relative roughness was sufficiently small (less than 1/10) so that Darcy-Weisbach equation applies to both the model and prototype. Because Reynolds numbers are large and model and prototype friction coefficients can be made the same, vertical geometric distortion of the model was not necessary. For example, for a prototype discharge of 125,000 ft^3/s, the Reynolds number is 2.5×10^8 prototype and 8.3×10^5 model.

Bed Material Similitude

In general, attempts to scale the structural integrity properties of bedrock were unsatisfactory. Therefore, it was decided that the grain distribution analyses would be used to provide friction scaling, indicate sizes that move and armor, and determine a qualitative comparison of the scouring potential for flip bucket modifications relative to the existing spillway. Fluid shear at the bed, lift, drag, secondary flow, and turbulence are considered the main factors that initiate and maintain the transport of bed material. Particle settling velocity, shape, packing, and submerged weight govern resistance to motion. Simple Froude law and frictional scaling do not ensure that model sediment will similarly transport to the prototype sediment. Thus, further sediment entrainment and transport parameters should to be considered. If transport rate needs to be scaled, a homogeneous transport equation must be selected or a dimensionless transport function must be used. Reclamation uses Taylor's dimensionless sediment discharge parameter (q_s/U^*d_s) denoted by (q_s^*) that produces a set of curves approximately parallel to Shields' entrainment curve for constant values of (q_s^*). Thus (q_s^*) is a function of Shields' parameters for grain diameter-shear velocity Reynolds number R_g^* or (U^*d_s/ν) and dimensionless shear T* or ($\tau/(\gamma_s-\gamma_w)d_s$) expressed functionally as

$$q_s^* = \Phi\ (R_g^*\ ,\ T^*)$$

where:

q_s^*	=	sediment discharge volume per unit width per second
d_s	=	sediment diameter
γ_s	=	specific weight of sediment
γ_w	=	specific weight of water
τ	=	tractive shear
ν	=	kinematic viscosity
U^*	=	shear velocity = $(\tau/\rho)^{1/2}$ = $(SR_h g)^{1/2}$ = $V(f/8)^{1/2}$
ρ	=	water density
S	=	slope

Transport scaling is accomplished by finding a model sediment diameter and specific gravity combination by trial and error that produces a model (q_s^*) equal to prototype (q_s^*). Analyses of Taylor's function and homogeneous transport equations show that noncohesive transport scales by $(L_r)^{3/2}$. Using cohesive sediment transport equations, transport scales by (L_r). Some model and prototype checks were done of Taylor's parameters and compared to existing velocity-diameter data. These checks and comparisons indicated that scaling the river part of the model could be done. Since the prototype material at the plunge area is bedrock, detailed transport analyses were not done. Reclamation experience indicates that scaling by settling velocity alone produces near (q_s^*) scaling, especially for large diameters. Scour in the plunge region is not expected to scale close to Taylor's relationship. Plunging jets scale closer according to pure Froude law for large particles geometrically scaled. Settling velocity is an important sediment parameter since it relates to when sediment will remain at rest and how long it will travel once lifted into flow. To size model sediment, settling velocity is scaled by Froude law velocity scale ratio ($L_r^{1/2}$). Settling velocity for 1-millimeter particles and larger are proportional to diameter to the one-half power. Therefore, these sediment model sizes scale settling velocity by Froude law and prototype diameters of 45 millimeters and greater scale both geometrically and by settling velocity. Settling velocity scaling has been successfully used for most of Reclamation's diversion dam model studies for relative comparisons of different test arrangements.

Model Performance

The following are brief statements of the major results of the similitude and scaling analyses:

- In general, attempts to scale the structural integrity properties of bedrock are unsatisfactory. Therefore, the grain distribution analyses was used to provide friction scaling, indicate sizes that move and armor, and provide a qualitative comparison of the scouring potential for flip bucket modifications relative to the existing spillway.

- Because of the large Reynolds number, model and sediment diameter, it was possible to make the dimensionless parameters, Froude number, Darcy-Weisbach friction coefficient, and relative roughness the same for model and prototype. Therefore, an undistorted model was used for the river part of the model.

- Relative roughness ($k_s/4R_h$) was less than 1/10, thus the Darcy-Weisbach equation applied to both the model and prototype.

- Since the friction coefficient ratio (f_r) could be made equal to 1, vertical velocity distributions and secondary flow scaled.

- Some Taylor-Shields scaling checks were made and indicated good sediment scaling of river part of the model.

- Settling velocity scaling of sediment diameter generally produced close Taylor-Shields scaling.

- Settling velocity scaling and geometric scaling produced the same diameter distribution down to 1-millimeter material in the model, thus geometric scaling was good down to the 20 percent passing size or the 45-millimeter prototype size.

- Verifying good riverflow and sediment scaling without vertical geometric scale distortion also provided confidence in scaling parts of the model where Darcy-Weisbach equation did not apply such as in the jet plunge region. Here, although scale effects were significant, scour scaled by Froude law. Thus sediment material too large to be transported by the normal riverflow was scoured by the impinging jet.

- Quantitative scour comparisons could not be made because loose bed material was used to represent bedrock regions of the prototype, and scour of the loose bed material would be affected by the more resistant exposed bedrock. It is believed that the model scour is conservative as compared to the prototype.

- The model is expected to provide good qualitative and relative comparisons of scouring potential of flip bucket modifications because the scour form did not vary much in shape and mainly changes of flip elevations were tested.

MODEL BED MATERIAL

PG&E provided four grain diameter distribution analyses of the river bottom material. The four samples came from an area of deposited transport material 100 yards downstream of the spillway plunge region. A field contour map of bars and sparsely distributed material remaining on bedrock near the plunge area was also provided (fig. 3). The material on the bedrock near the plunge area consisted of 1- to 15-foot boulders.

Figure 4 shows the cumulative distributions of prototype sediment provided by PG&E. On this figure, samples and distribution curves are identified by circled numbers. Divers obtained four distribution samples by measuring and counting individual boulders within four sample areas. Samples 1 and 2 were combined into a single curve and samples 3 and 4 were plotted separately. Curve 1-2 was then weighted by two and averaged with curves 3 and 4. The average, plotted as curve 5, represented the target sediment distribution to be modeled. Curve 6 defines the estimated grain distribution for isolated individual boulders near the spillway.

Prototype particle distributions were converted to model by geometric scaling and are plotted on figure 5. Distribution curve 5, long dashed line, is considered the upper boundary for permissible geometrically scaled sediment for the model. The lower distribution curve 1-2, long dashed line, is considered the lower boundary. The mean or target distribution is shown as the light solid line curve. The target distribution for settling velocity scaling plots on top of the curve for geometric scaling down to the 1-millimeter model size then deviates as shown. Thus geometric scaling is valid down to the 80-percent retained size. The heavy solid lined curve indicates distribution of a pit run material with some minor sieve separation used in the model.

MODEL TEST PROCEDURE

Prior to each new geometry tested, new bed material was placed in the downstream channel and the bed was contoured based on a prototype channel survey conducted in March 1988 (fig. 6). For each spillway geometry, the model bed was allowed to progressively scour as increased flows were tested. To prevent scouring of the bed during model startup, the model tailwater was slowly raised before each test by filling the model tailbox downstream of the dam. Each spillway geometry was tested for the same sequence of flows and for the same time of operation. After each flow the bed scour was contour mapped with string to show the scour pattern for photographs. In addition to the qualitative string contours, the templates used to form the initial bed were reinstalled and quantitative measurements of changes in the bed elevation were made. The measurements were made in the same location for each test based on a preestablished grid pattern.

TAILWATER ELEVATIONS

The tailwater in the model was established for each test based on figure 7. The tailwater was set in the model artificially by adjusting the height of a downstream overflow weir.

TESTS

Bed Scour Tests of Prototype Ski-Jump Spillway

The prototype spillway geometry was placed in the model to determine the scour patterns developed for flows up to the PMF. Scour tests of the prototype geometry established a comparative base for evaluating future scour patterns created with modified spillway geometries. The three ski-jump levels on the spillway face often cause different flow conditions to occur below each level in the plunge basin. The 930-foot elevation ski jump generally operates in a tailwater sweep-out condition. Flow leaving the higher ski jumps to either side may fall as free jets or, if submerged by tailwater, sweep out similar to the 930-foot elevation ski jump. The prototype ski-jump spillway geometry generally created a scour pattern with scour holes downstream of the 940- and 950-foot elevation ski jumps starting about midway down the tailrace wall (figs. 8-12). During 10 percent PMF flows, fine bed material deposited against the spillway face. The material was drawn toward the spillway toe by return flow along the bed. Along the spillway face, material generally moved from left to right (looking downstream). The flow moved the fines parallel to the face of the 930-foot elevation bucket, forming a deposition peak in front of the 940-foot elevation bucket. Flows larger than 25 percent of PMF progressively eroded the bed at the toe of the spillway (fig. 13).

Flip Bucket Modifications

The basic bucket designs tested in the model were developed by PG&E. The prototype ski jumps were modified by reducing the radius to 35 feet and extending the arc 30° beyond the horizontal (fig. 14). The same bucket radius and arc length were used to modify the prototype geometry for all modified spillway tests. Using the set bucket geometry, model tests were then conducted for three different spillway designs. Spillway modifications tested were limited to designs which could be adapted to the prototype without requiring major concrete excavation of the existing spillway (fig. 15A). First, a single-level bucket at invert elevation 952.6 feet was tested in the model (fig. 15B). The 952.6-foot elevation was the lowest elevation at which a single-level bucket could be constructed due to the 950-foot elevation of the existing ski jump on the left side. For the second series of tests, the spillway was modified by lowering the right 127.5 feet of the bucket to elevation 942.6 feet (fig. 15C). Following testing on the two-level flip bucket spillway geometry, the spillway was changed to a three-level flip bucket design. The invert elevation for the middle portion of the bucket lying above the existing 930-foot elevation ski jump was lowered to elevation 932.6 feet (fig. 15D).

Model Tests of Single-Level Bucket Spillway

The model spillway was changed to a single-level bucket 170 feet wide located on the spillway face at invert elevation 952.6 feet. The lip of the single bucket (elevation 957.25 feet) was above the tailwater for flows less than about 25 percent of PMF. For these flows the jet leaves the spillway bucket as a free jet (fig. 16). At higher spillway discharges the jet sweeps out with a partially aerated undernappe up to about 75 percent of PMF. At 100 percent of PMF the jet was fully suppressed. Scour patterns produced were in general evenly distributed across the channel (figs. 17-21). The channel bed for the first 60 feet downstream of the bucket face showed only small changes in elevation from 10 percent PMF to 100 percent PMF. Just downstream of the toe of the spillway the steep portions of the bed below the old 940- and 950-foot elevation ski jumps eroded to a near level profile (fig. 22).

Model Tests of the Two-Level Flip Bicket Spillway

The two-level flip bucket spillway was tested for discharges of 10 percent PMF (fig. 23) and 50 percent PMF. Scour patterns from flow over the two-level bucket were similar to the scour developed by the single, higher elevation configuration (figs. 24-25). After the 50 percent PMF test, an increase in the scour was noted along the tailrace wall accompanied by greater deposition on the opposite side of the channel as compared to the single-bucket test results. Greater scour also occurred below the toe of the higher bucket (fig. 26).

Model Tests of the Three-Level Flip Bucket Spillway

Bed scour tests were run for the three-level flip bucket spillway at flows of 10, 25, and 50 percent of PMF. At 10 percent PMF, the outside buckets produce free impinging jets into the tailwater. The jet from the center flip bucket was partly suppressed (fig. 27). After the 10-percent PMF test, less scour had occurred along the tailrace wall as compared to the previous geometries tested (fig. 28). At higher discharges deposition of fine bed material increased downstream of the two lower buckets (figs. 29-30). Near the toe of the spillway the flows created only minor scour of the channel bed on the steep slope below the high bucket (fig. 31). Fine material was carried from the downstream scour holes upstream to the toe of the spillway by the action of secondary return flows. The eddies moving material upstream along the bed are driven by the overlying high velocity surface jet. The material deposited in the model at the spillway toe was predominately very fine material.

Model Tests of the Three-Level Flip Bucket Spillway With Flow Deflector Wall

A wedge-shaped deflector wall was placed in the model along the powerhouse wall (figs. 32A-32B). The deflector was tested to determine if it would protect the tailrace training wall from scour for flows up to 25 percent of PMF. The wall was designed to divert the jet from the 942-foot elevation flip bucket away from the tailrace wall. Without the deflector wall, the outer edge of the jet impinges on the wall. Model tests with the deflector were conducted with 2, 4, 10, 25, 50, 75, and 100 percent of PMF. A comparison of scour depths at several points near the tailrace wall shows the deflector wall had little influence on scour in these locations (figs. 33-35). Near the toe of the spillway, material was generally deposited against the center bucket and small amounts removed from the steep slopes in front of the two outside buckets (fig. 36).

After 2 percent of the PMF, no definable scour of the bed was apparent in the model. A discharge of 4 percent of PMF caused a small amount of scour across the channel near the end of the tailrace (fig. 37). The scour was local to the area directly beneath the point of jet impingement. Some of the eroded material was deposited in the upstream river channel area. Overall river channel scour was nearly the same for model tests with and without the deflector wall (figs. 38-40). At 75 and 100 percent of PMF, the three-level flip bucket spillway developed much less scour in the river channel between the toe of the dam and the end of the tailrace as compared to the prototype spillway (figs. 41-42).

Spillway and Overtopping Discharge Capacity

Reservoir elevation versus discharge was measured in the model (fig. 43). Although no attempt was made to directly determine the maximum capacity of the spillway before overtopping of the dam occurred, overtopping was estimated to occur at 115,000 ft^3/s based on the model data. To pass the PMF required a reservoir elevation of 1043.5 feet. Flow overtopped the dam by 15 feet.

Crest Pressures

Hydraulic pressures were measured on the spillway crest for discharges of 10, 25, 50, 75, and 100 percent of the PMF (fig. 44). The pressures are listed in table 1. The pressures given are time averaged values. For the PMF a maximum negative pressure of 30.9 feet below atmospheric pressure was measured on the top of the crest. Pressures remained positive for all flows tested at piezometer location 6. The high negative pressures measured for 75 and 100 percent of PMF are at levels where intermittent cavitation may occur. Due to the very low frequency of the flood events considered and the relatively short peak flow durations, severe cavitation damage is not probable.

Table 1. - Spillway crest pressures

Pressure tap (ft. of water)	Discharge in percent of PMF				
	10	25	50	75	100
1	13.5	18.5	22.1	24.4	24.2
2	3.9	0.3	-8.1	-19.0	-30.9
3	2.5	-2.4	-7.2	-14.3	-21.3
4	1.8	0.4	-5.1	-9.6	-13.8
5	1.8	1.6	-0.1	-1.9	-3.3
6	2.6	1.5	1.4	2.9	4.5

Flip Bucket Pressures - Three-Level Flip Bicket Spillway

Seven piezometer taps were installed in the model to measure hydraulic pressures at selected points on the flip buckets and adjacent walls (fig. 45). These locations were selected to provide hydraulic load data for the structural design. Pressures were measured on the model during flows corresponding to 25, 50, and 100 percent of the PMF. Pressures measured at each location and for each of the flows are listed in table 2.

Table 2. - Flip bucket pressures

Pressure tap (ft of water)	Discharge in percent of PMF		
	25	50	100
1	22.8	27.9	59.6
2	25.4	47.6	74.7
3	23.9	33.5	56.0
4	21.8	14.5	19.2
5	24.2	12.0	18.7
6	23.6	35.6	62.9
7	15.7	44.1	80.5

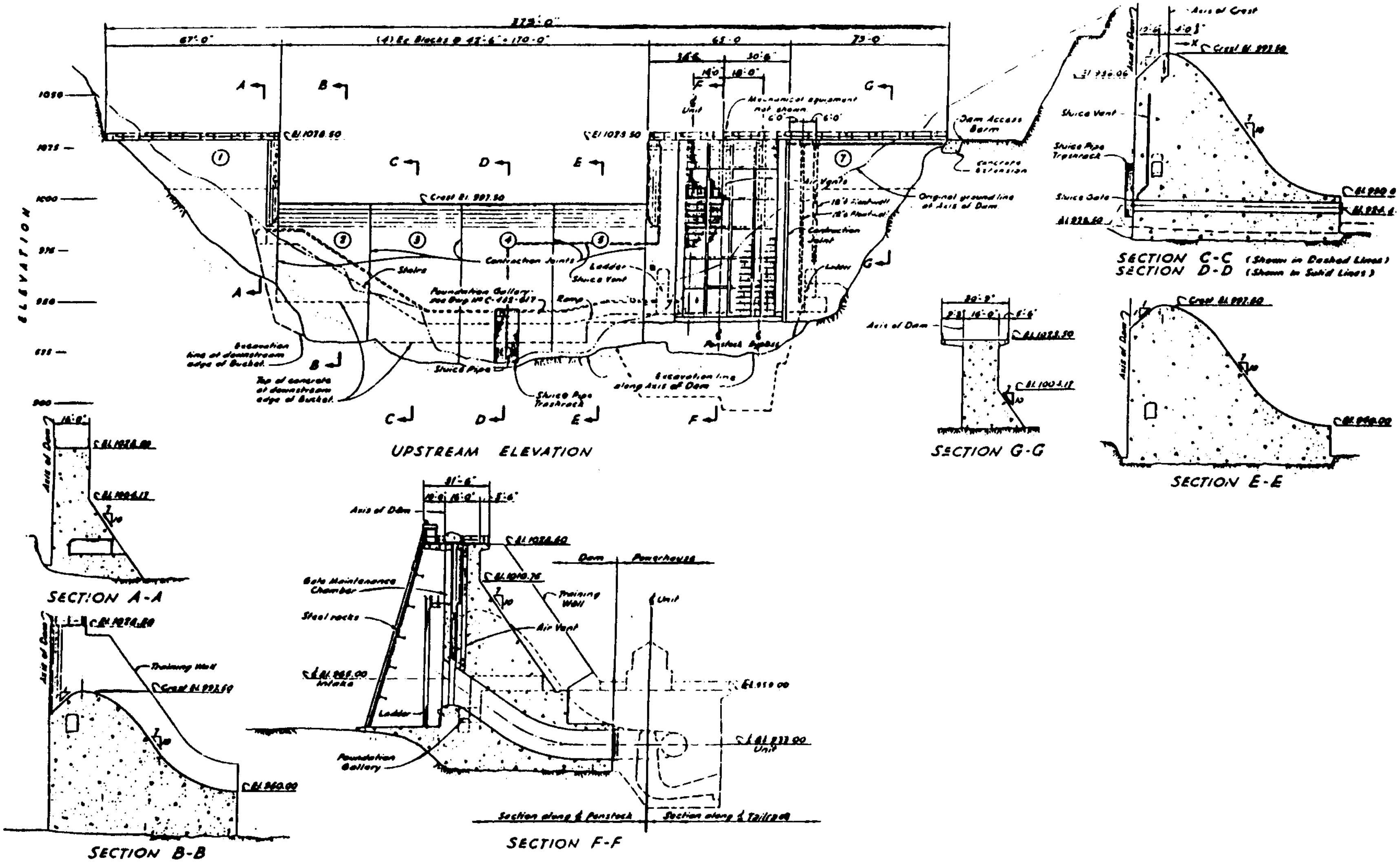


Figure 1. - Dam elevations.

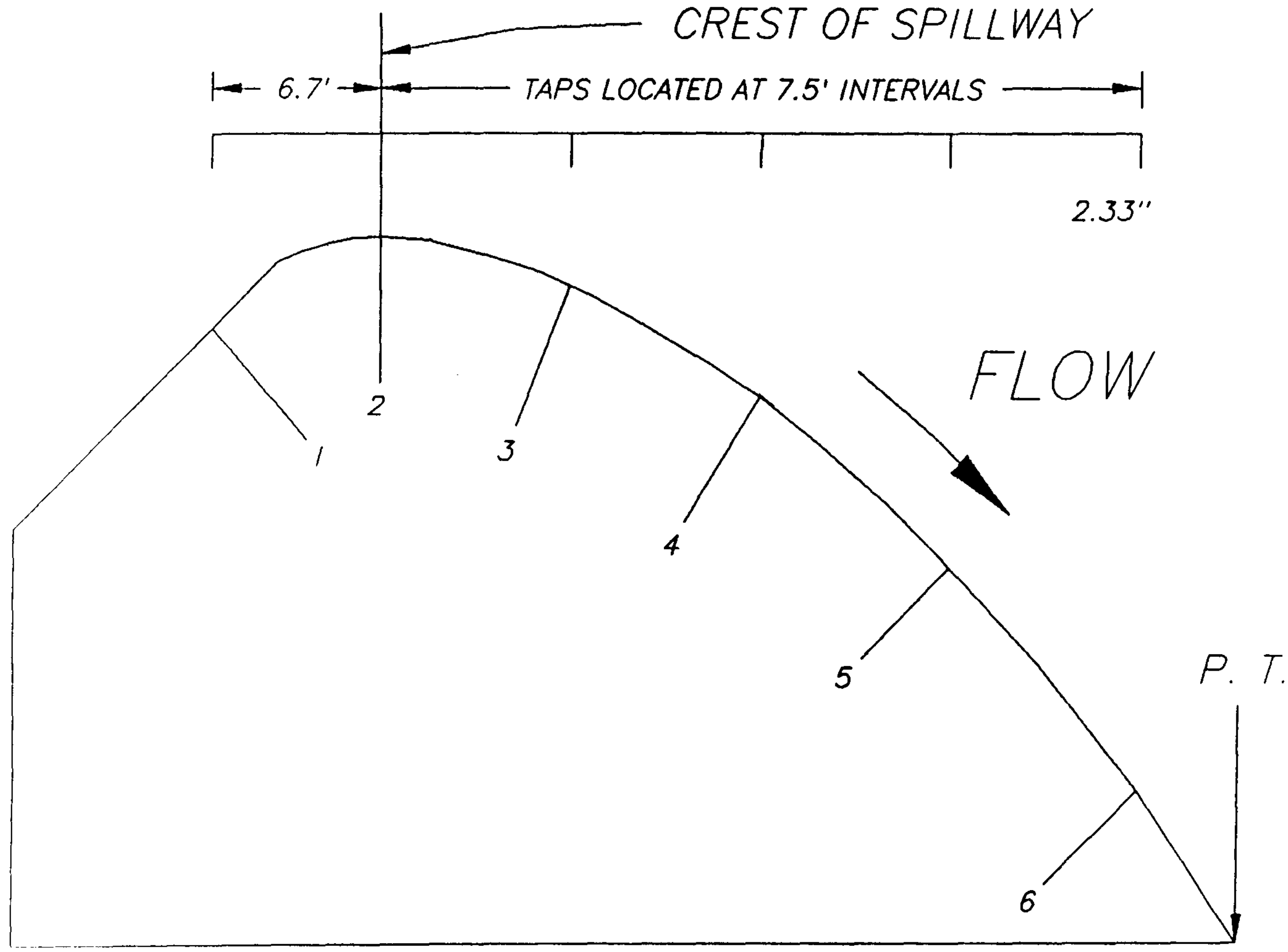


Figure 2. - Chili Bar Dam spillway crest pressure tap locations.

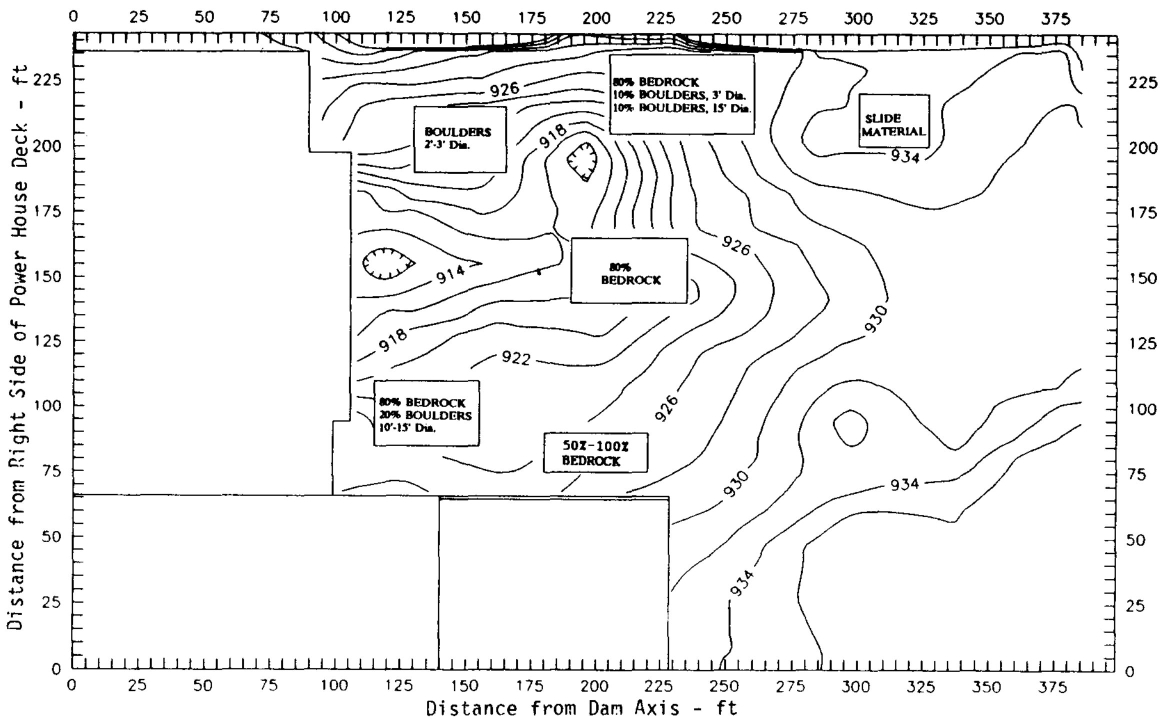


Figure 3. - Prototype bed material survey.

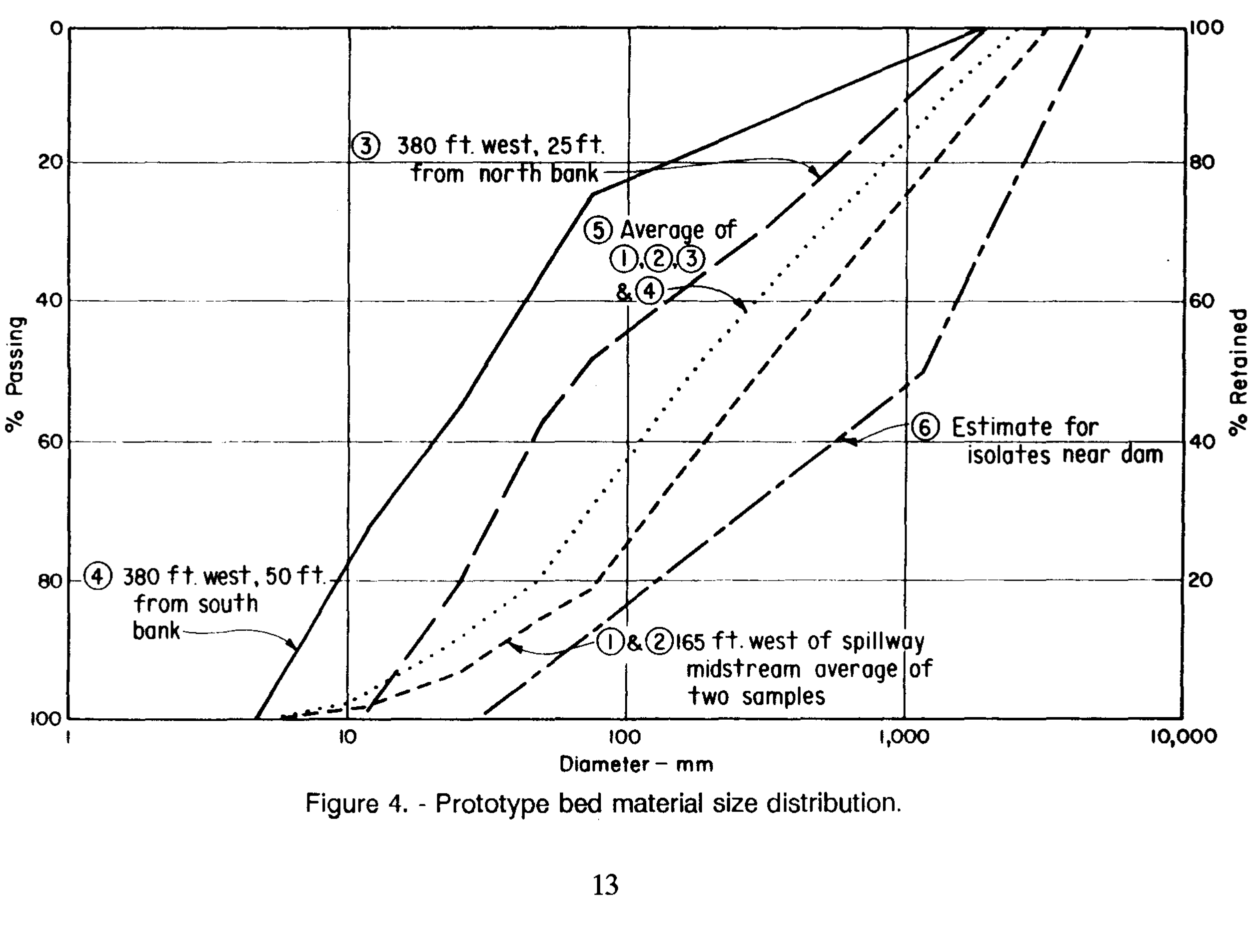


Figure 4. - Prototype bed material size distribution.

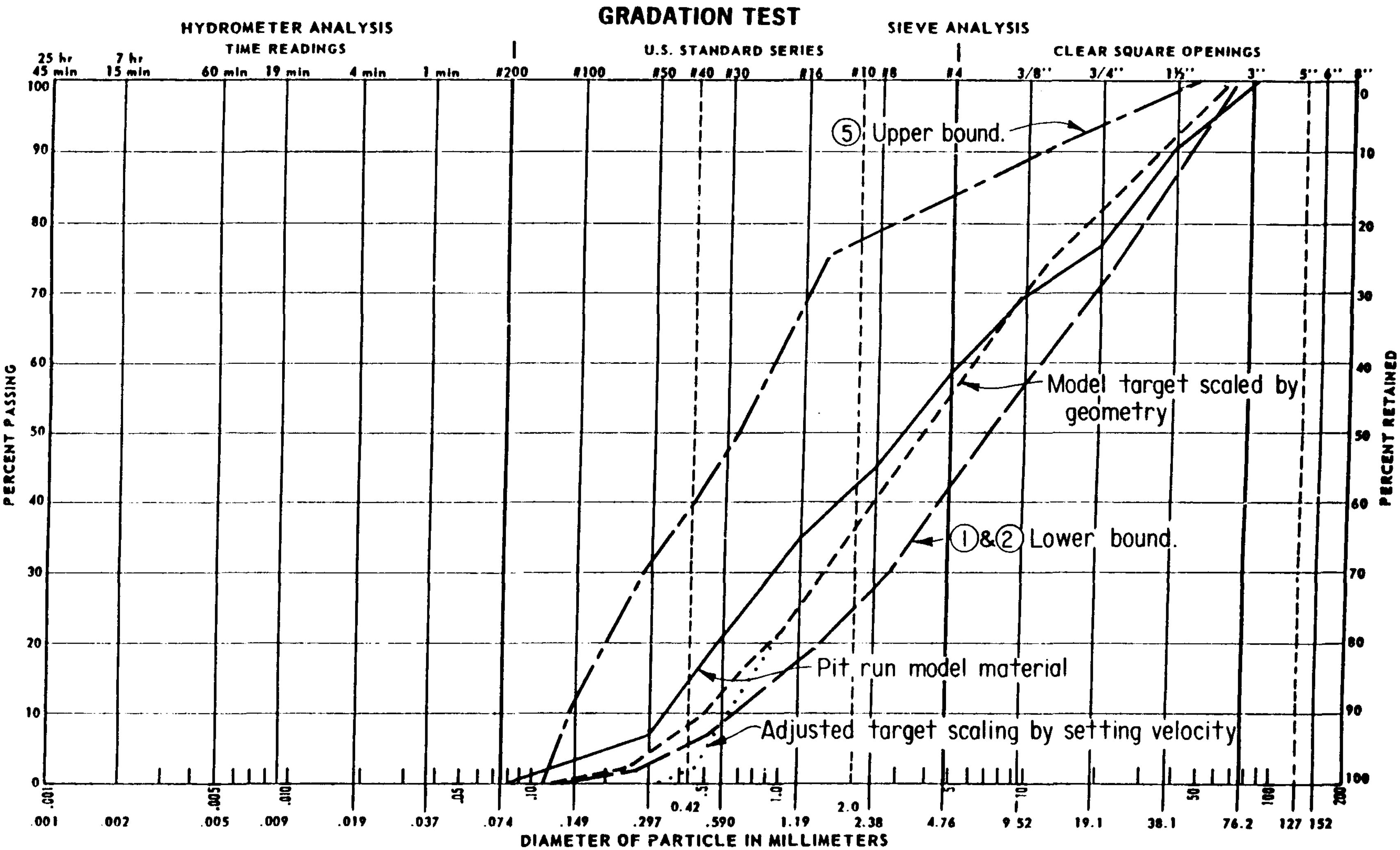


Figure 5. - Model bed size distributions.

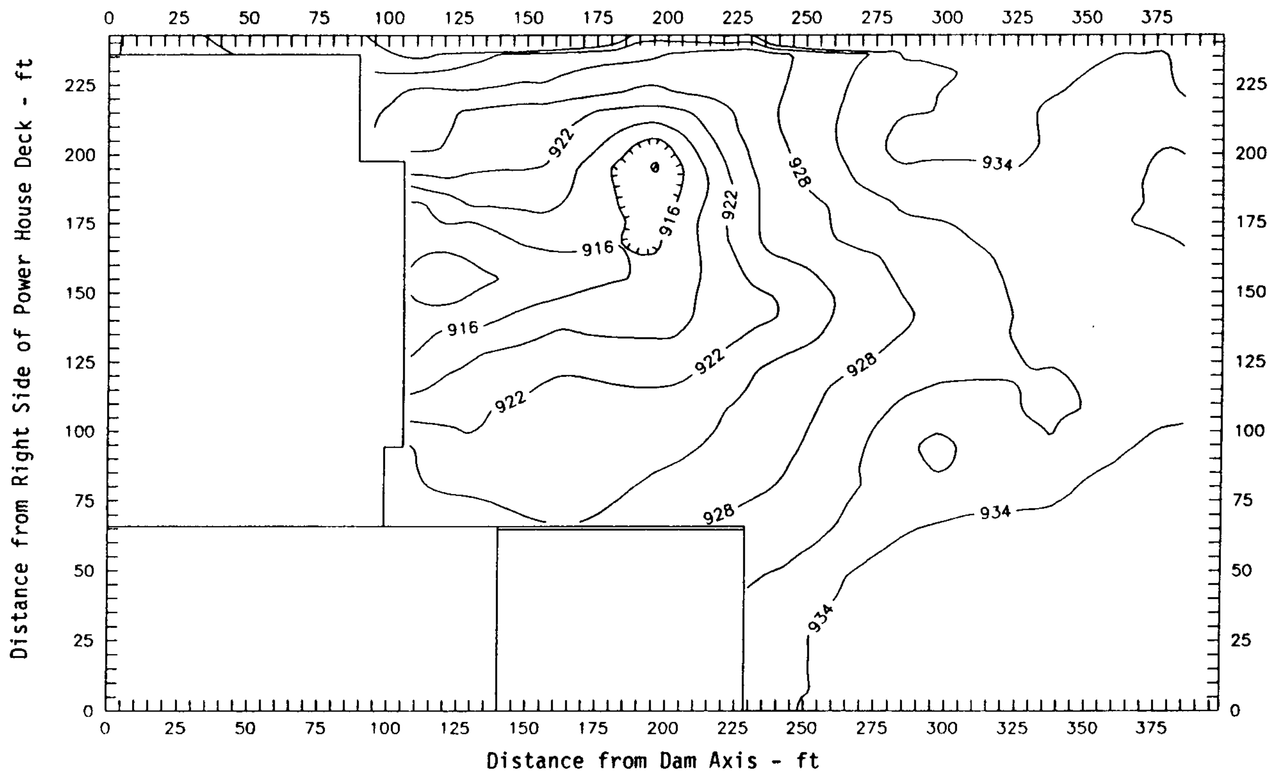


Figure 6. - Prototype channel bed contours.

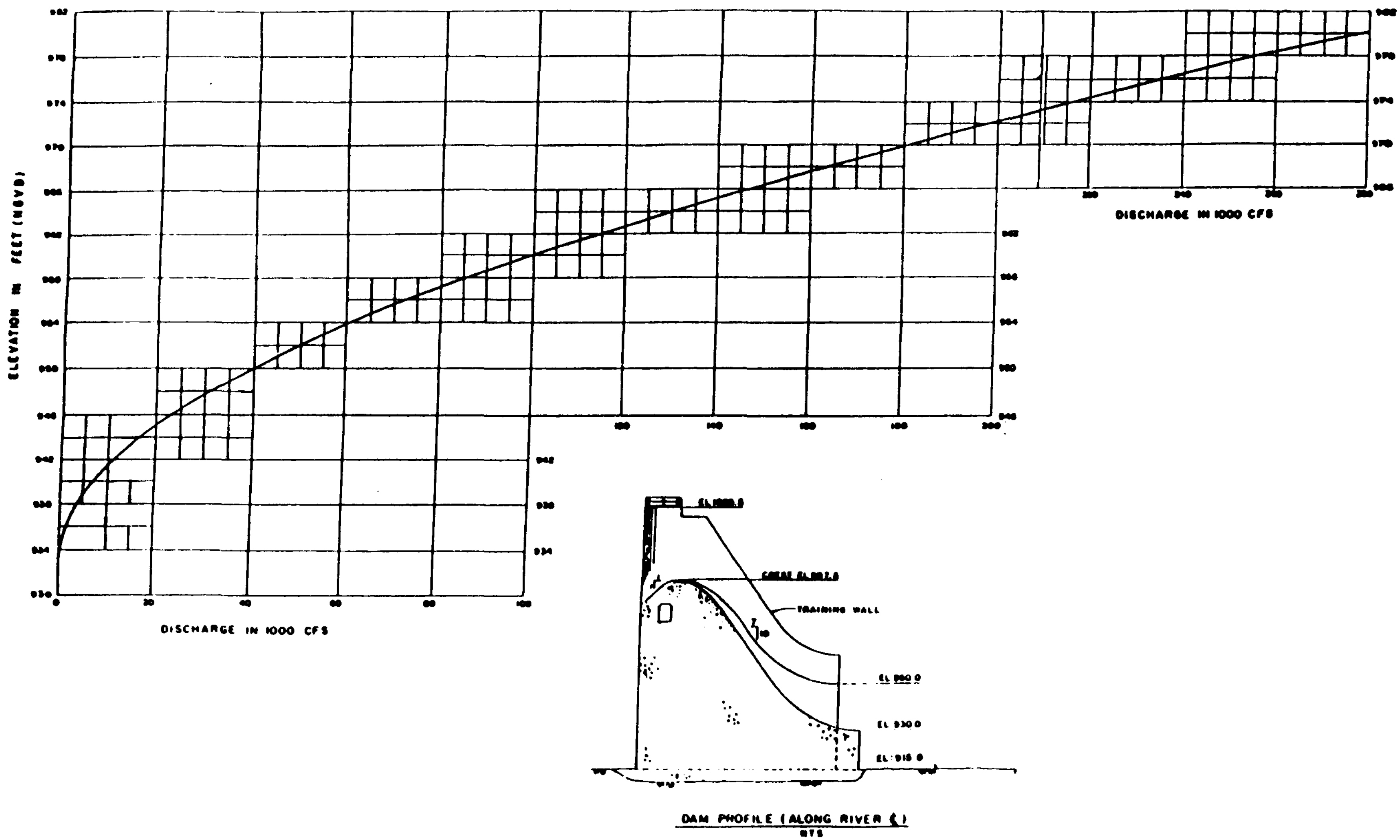


Figure 7. - Tailwater rating curve.

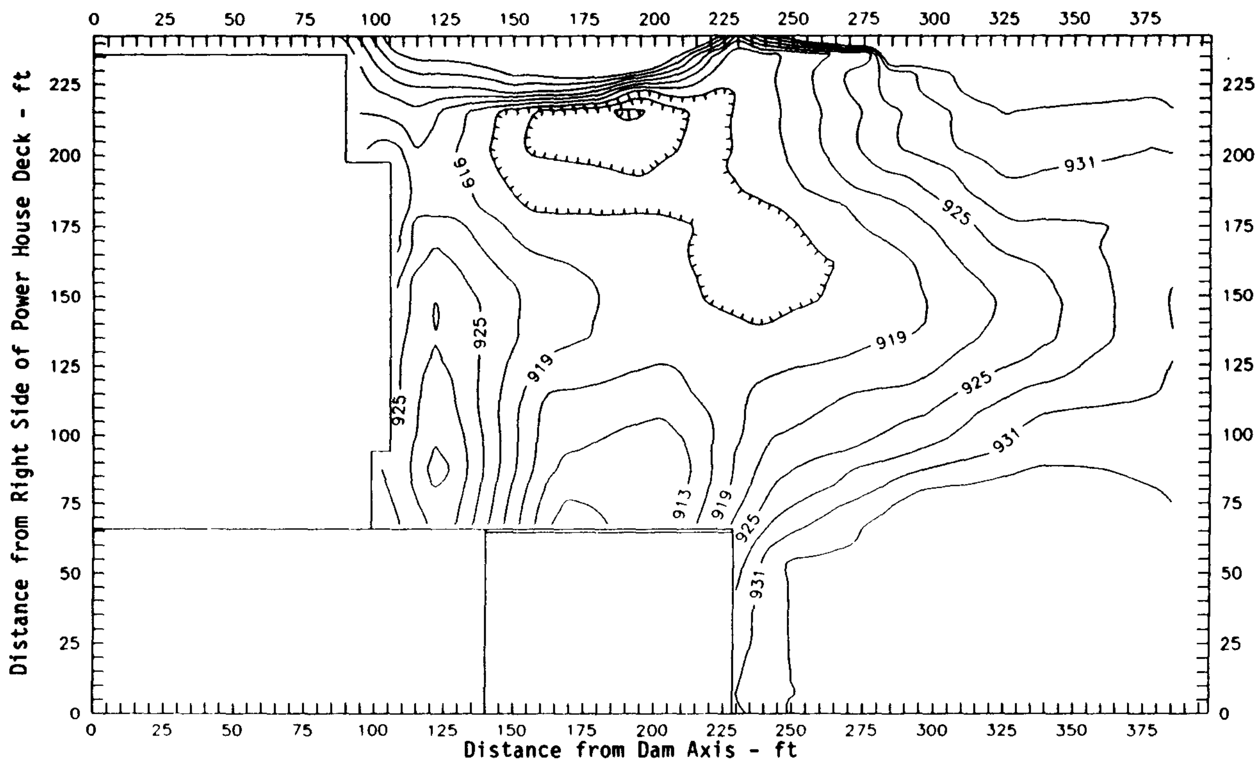


Figure 8. - Prototype bed scour after 10 percent of PMF.

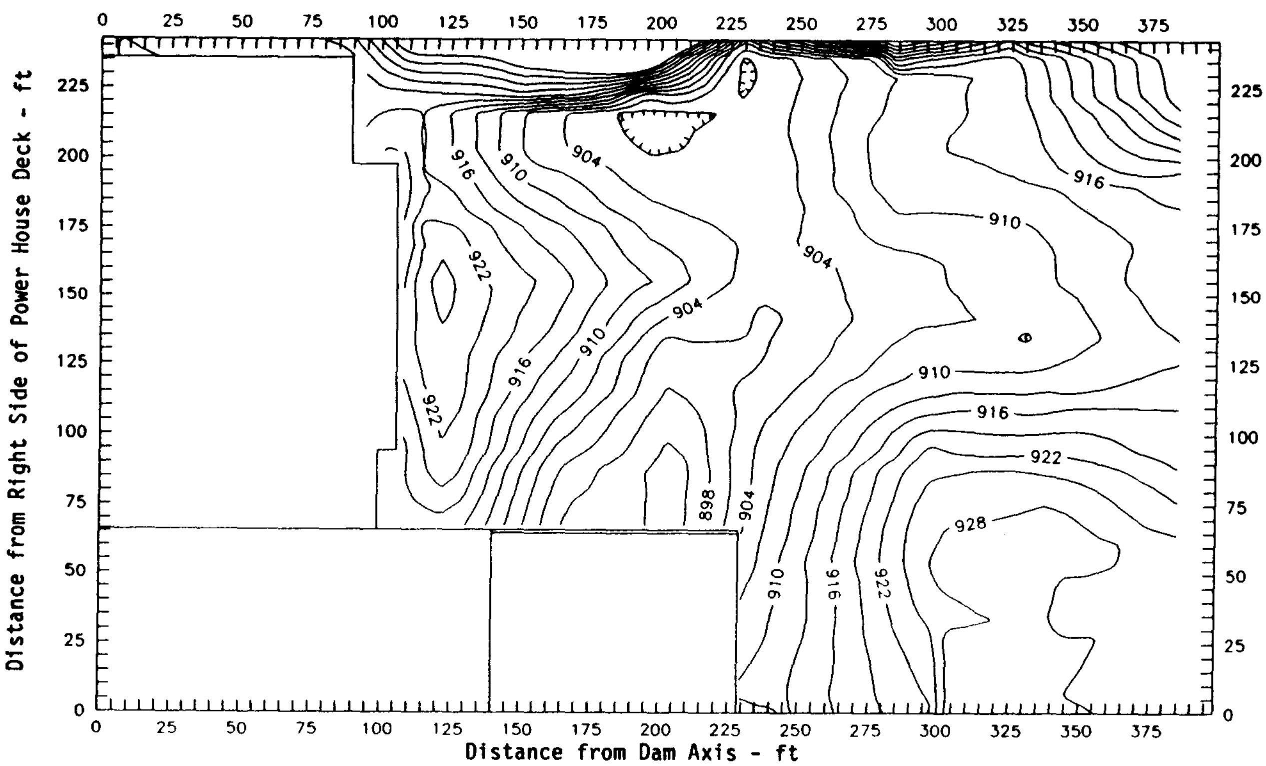


Figure 9. - Prototype bed scour after 25 percent of PMF.

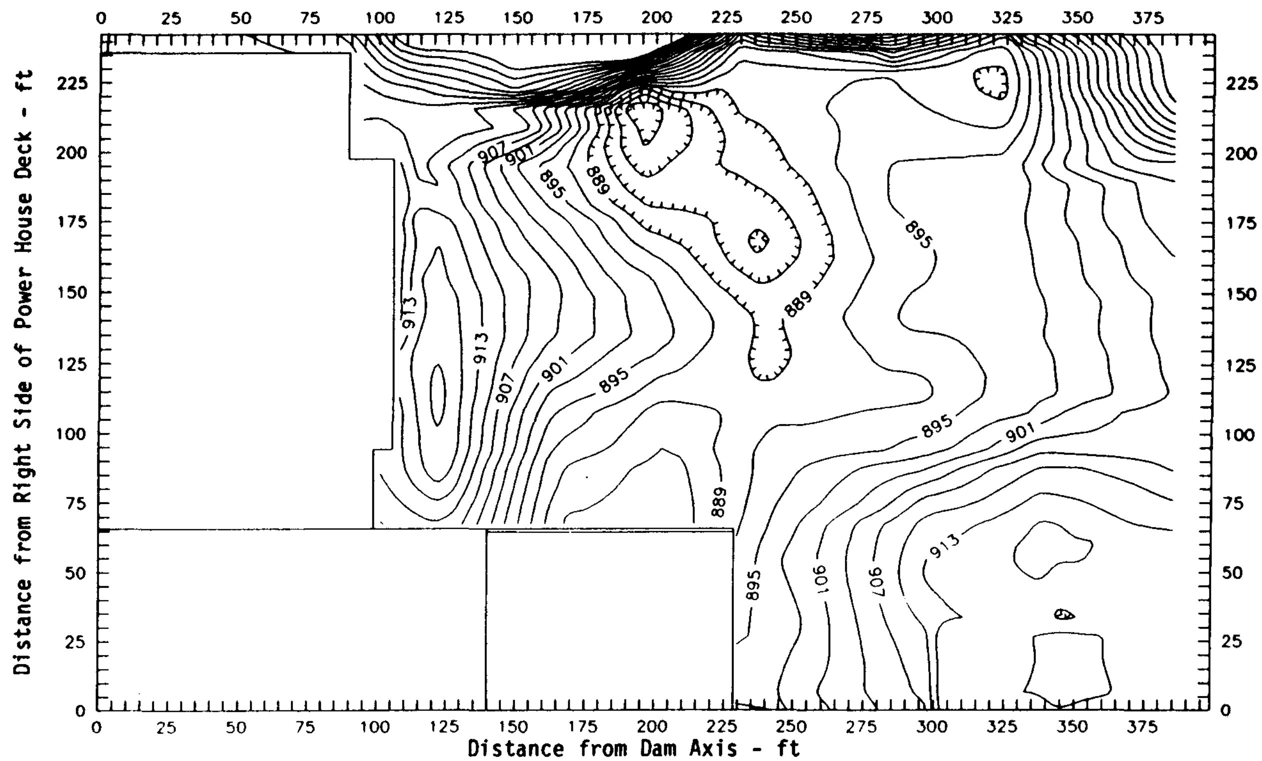


Figure 10. - Prototype bed scour after 50 percent of PMF.

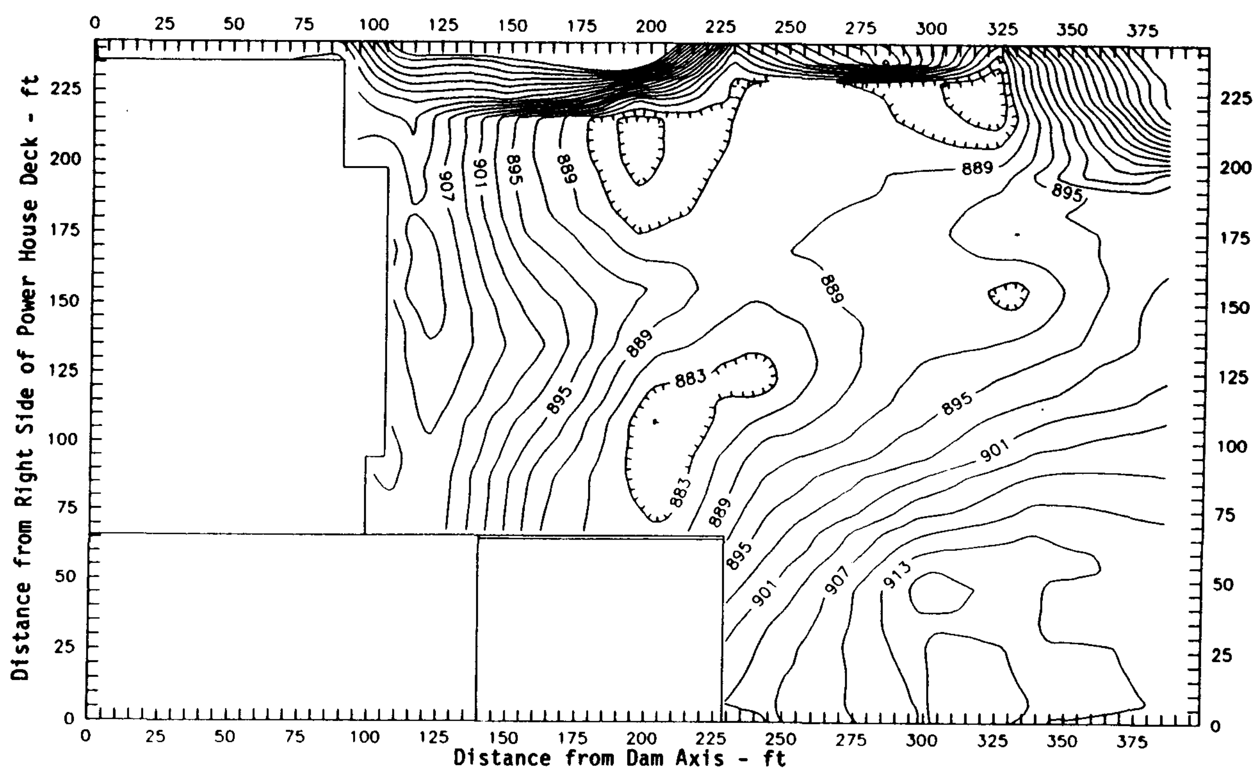


Figure 11. - Prototype bed scour after 75 percent of PMF.

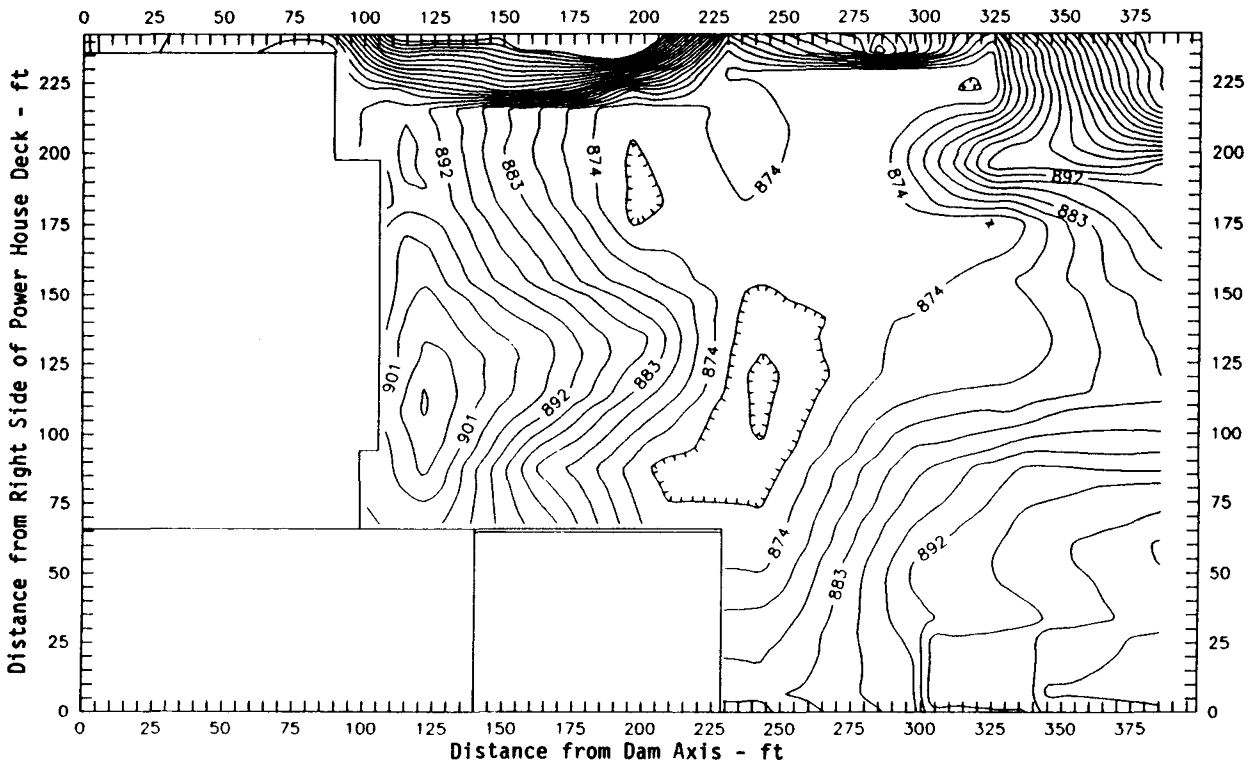


Figure 12. - Prototype bed scour after 100 percent of PMF.

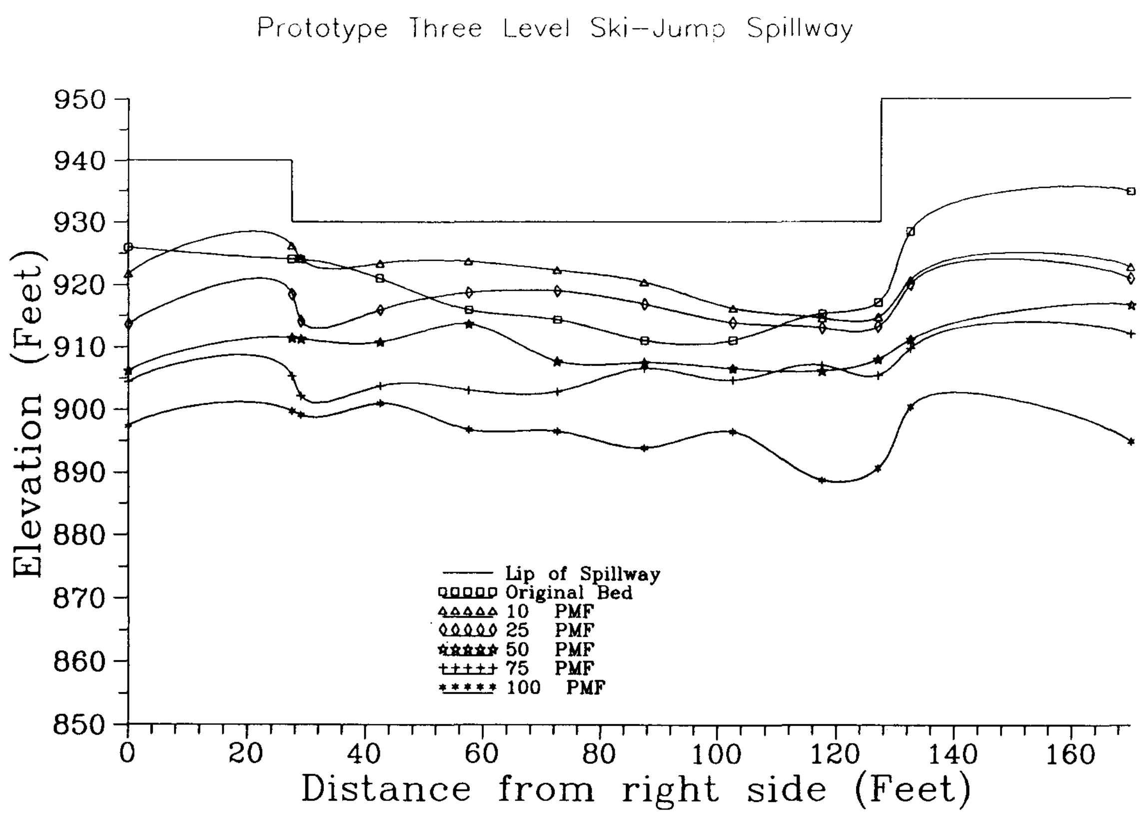


Figure 13. - Prototype spillway bed profiles at toe of spillway.

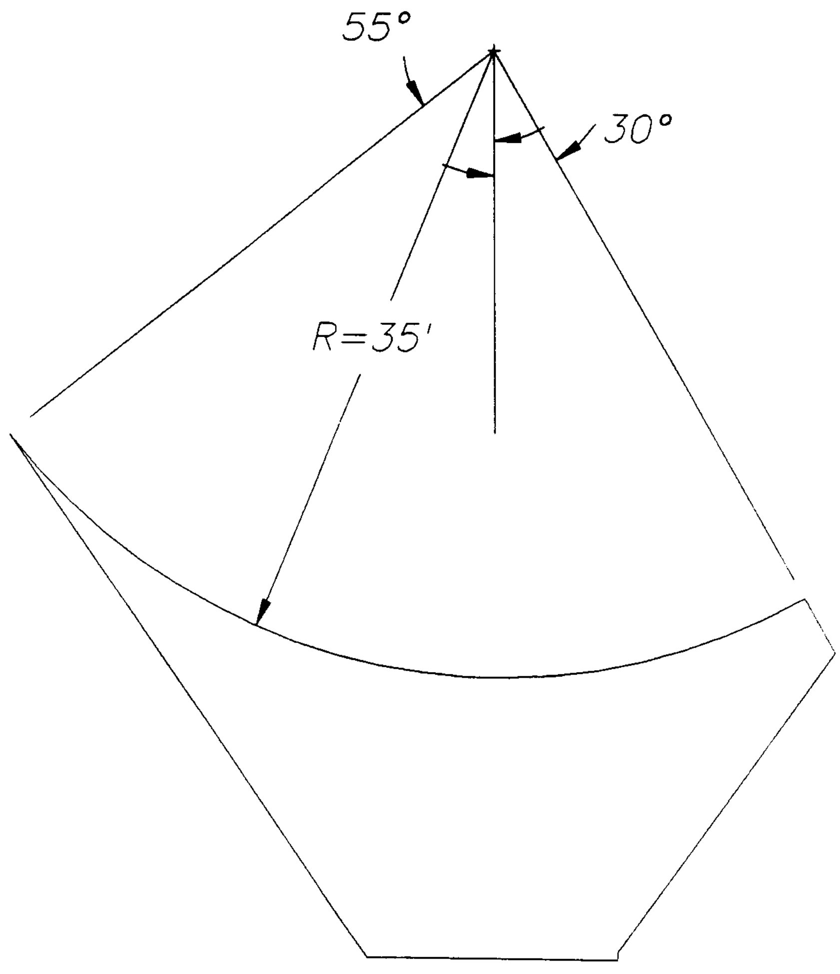


Figure 14. - Modified flip bucket geometry.

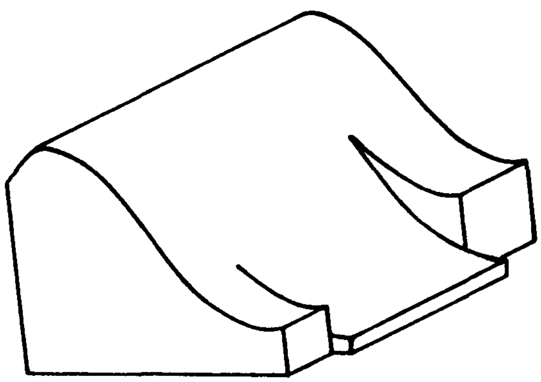


Figure 15A. - Prototype spillway.

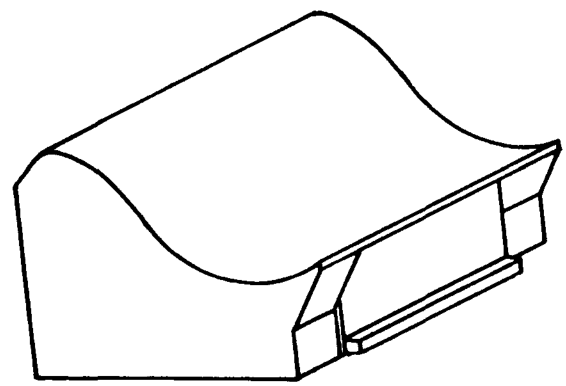


Figure 15B. - Single-level flip bucket spillway.

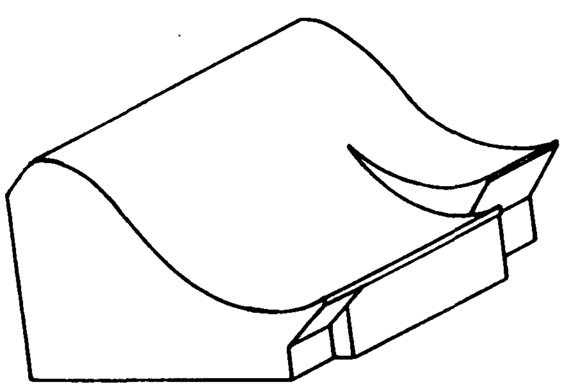


Figure 15C. - Two-level flip bucket spillway.

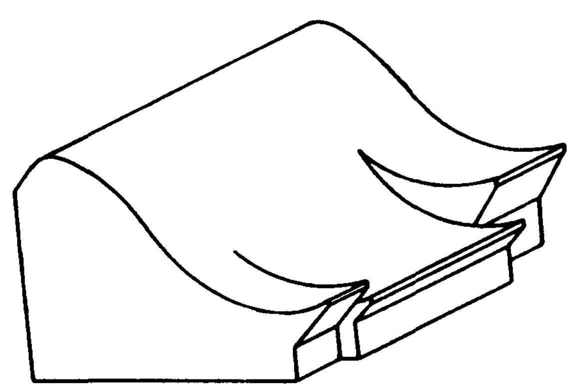


Figure 15D. - Three-level flip bucket spillway.

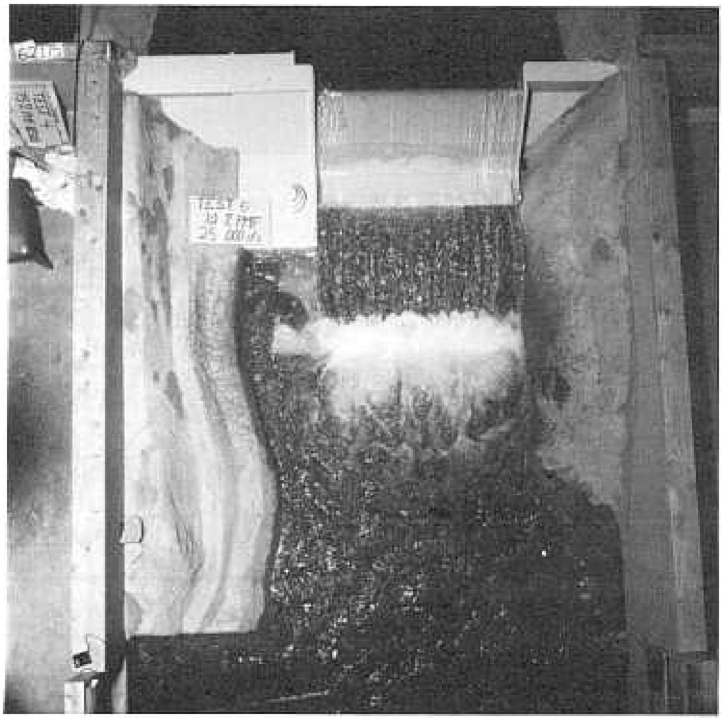


Figure 16. - Single-level flip bucket, 25,000 ft^3/s (10 percent of PMF).

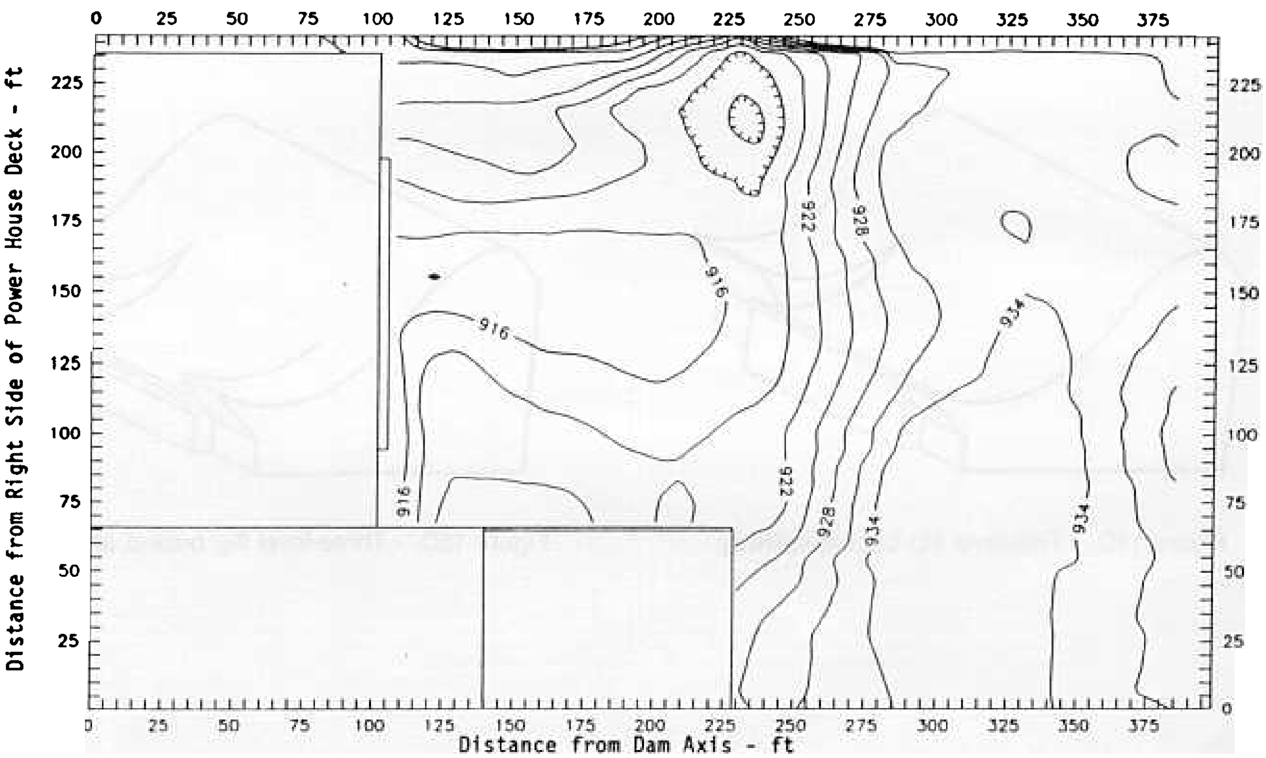


Figure 17. - Single-level flip bucket spillway - bed contours after 10 percent of PMF.

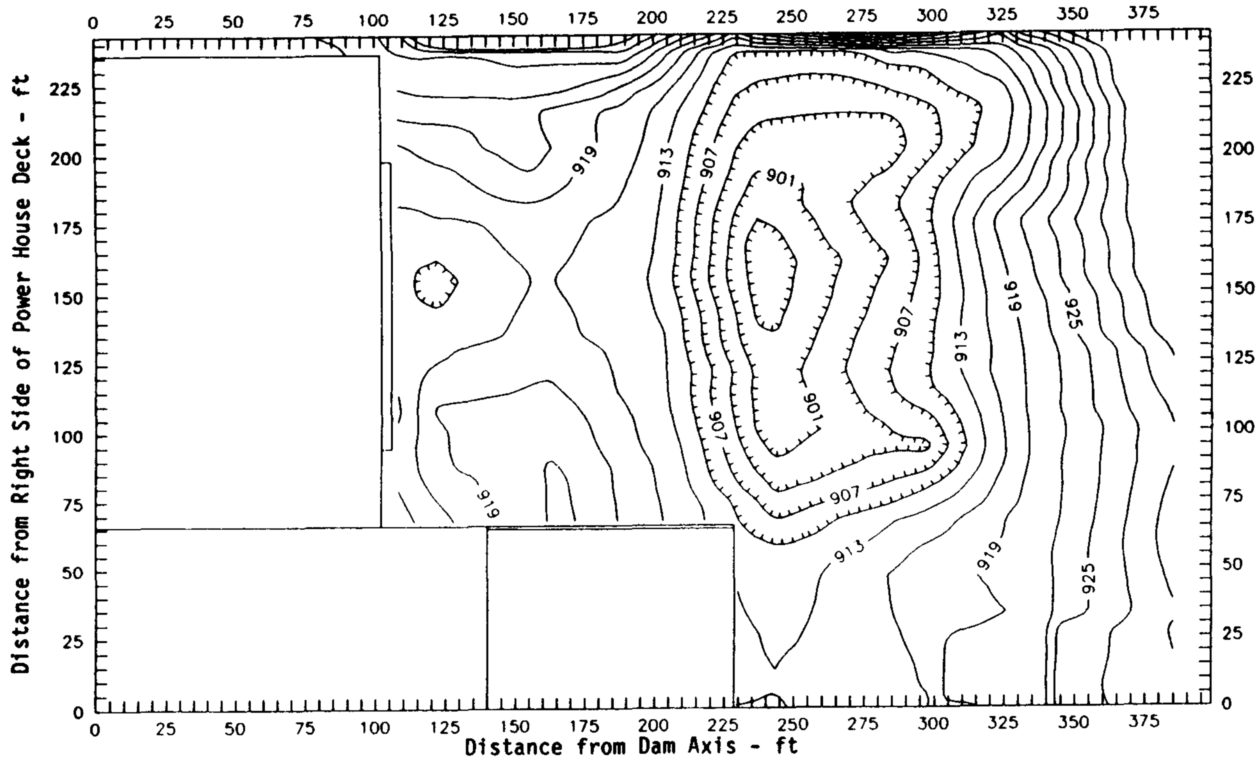


Figure 18. - Single-level flip bucket spillway - bed contours after 25 percent of PMF.

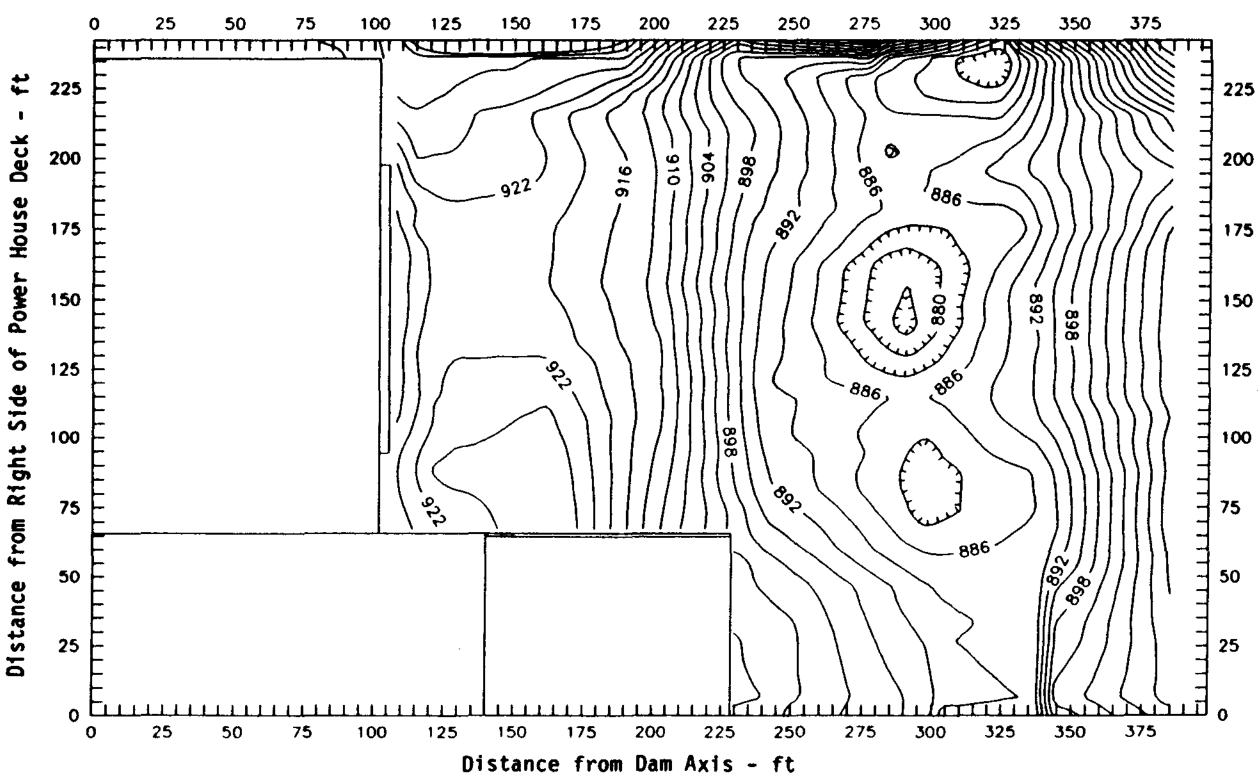


Figure 19. - Single-level flip bucket spillway - bed contours after 50 percent of PMF.

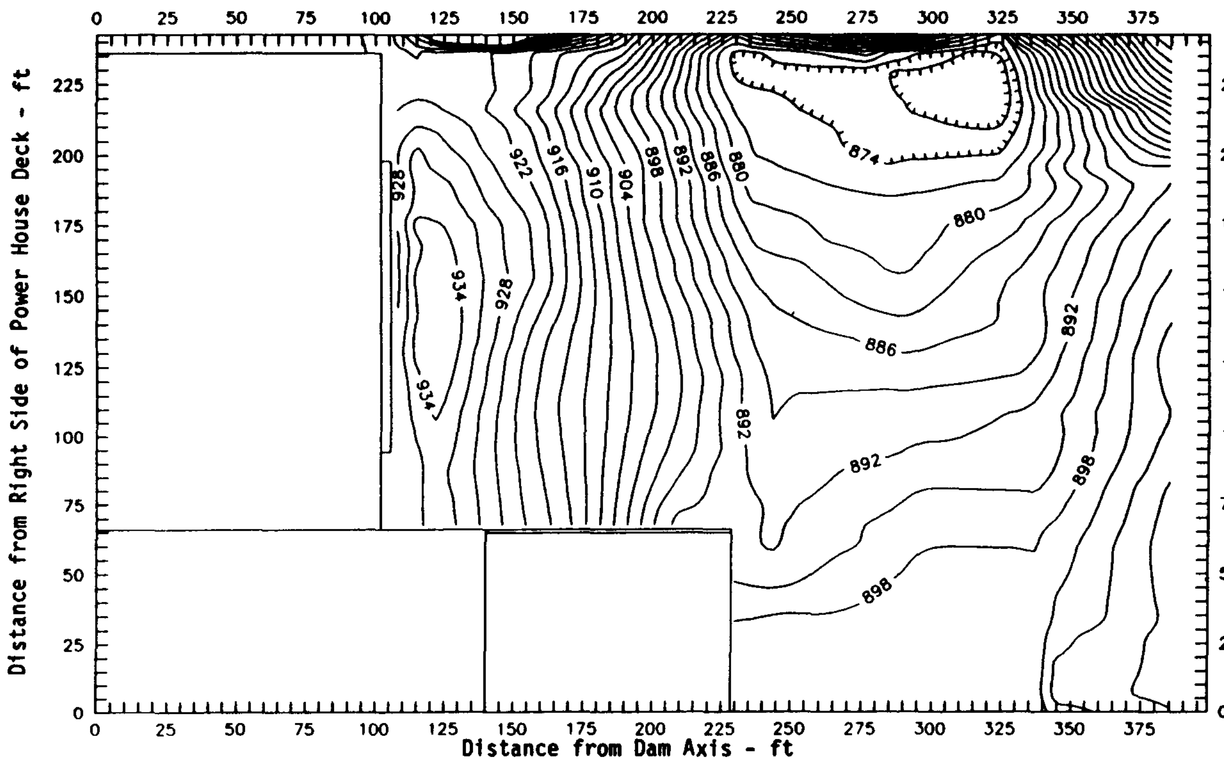


Figure 20. - Single-level flip bucket spillway - bed contours after 75 percent of PMF.

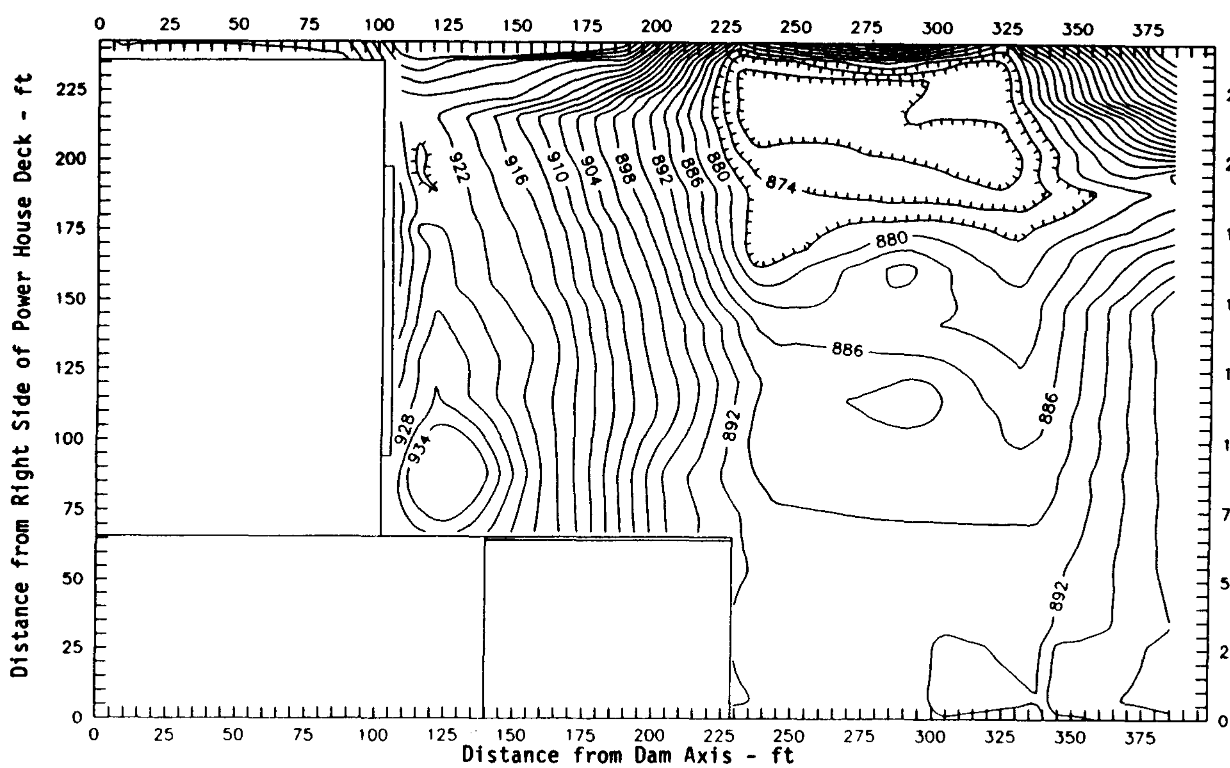


Figure 21. - Single-level flip bucket spillway - bed contours after 100 percent of PMF.

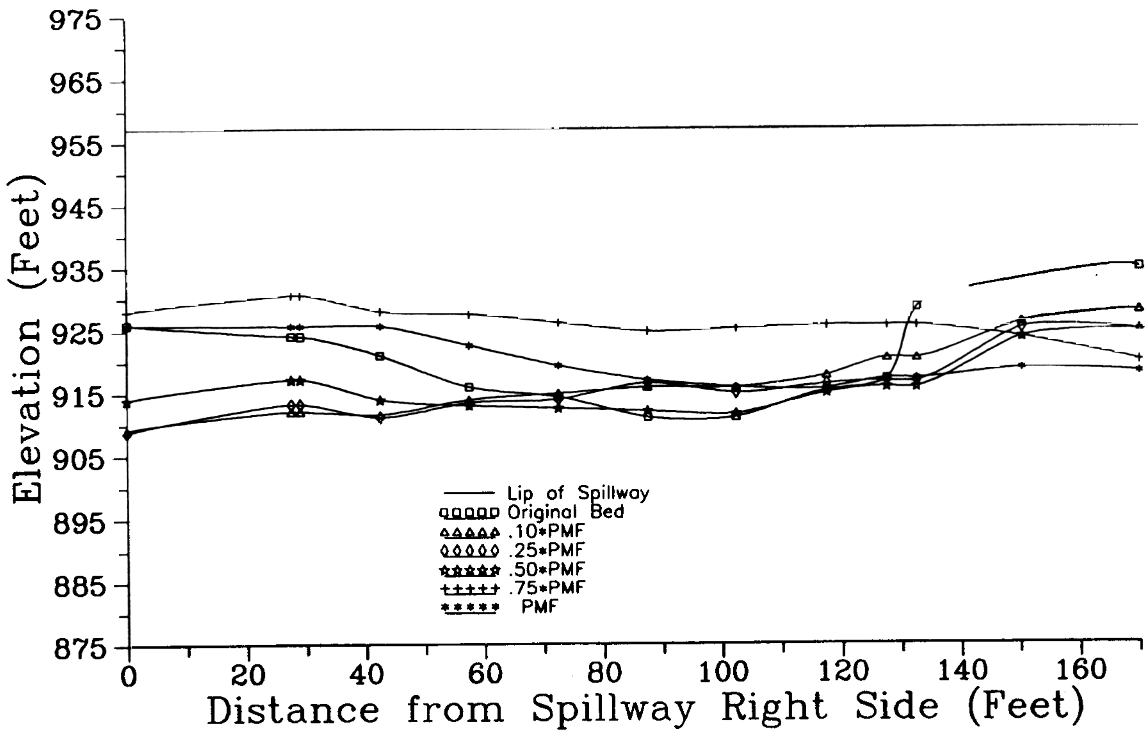


Figure 22. - Single-level flip bucket - bed profiles at toe of spillway.

Figure 23. - Two-level flip bucket - 25,000 ft^3/s (10 percent of PMF).

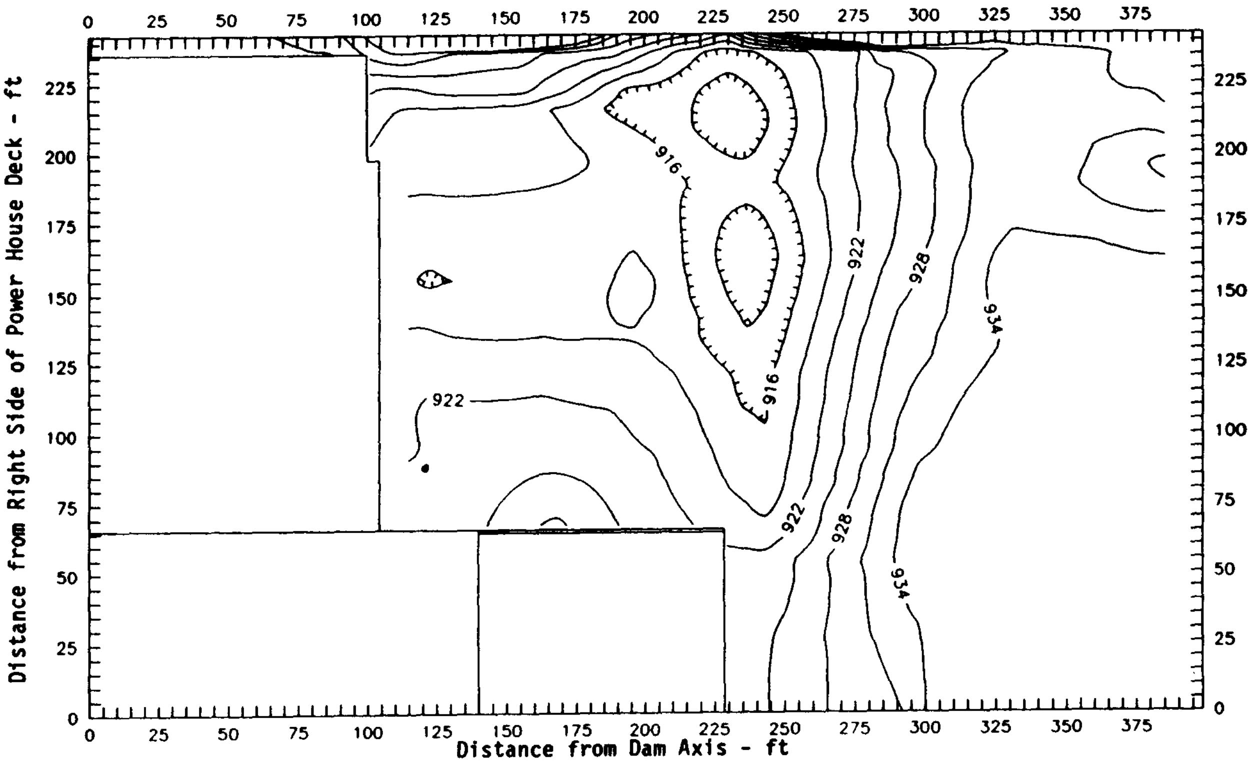


Figure 24. - Two-level flip bucket - bed contours after 10 percent of PMF.

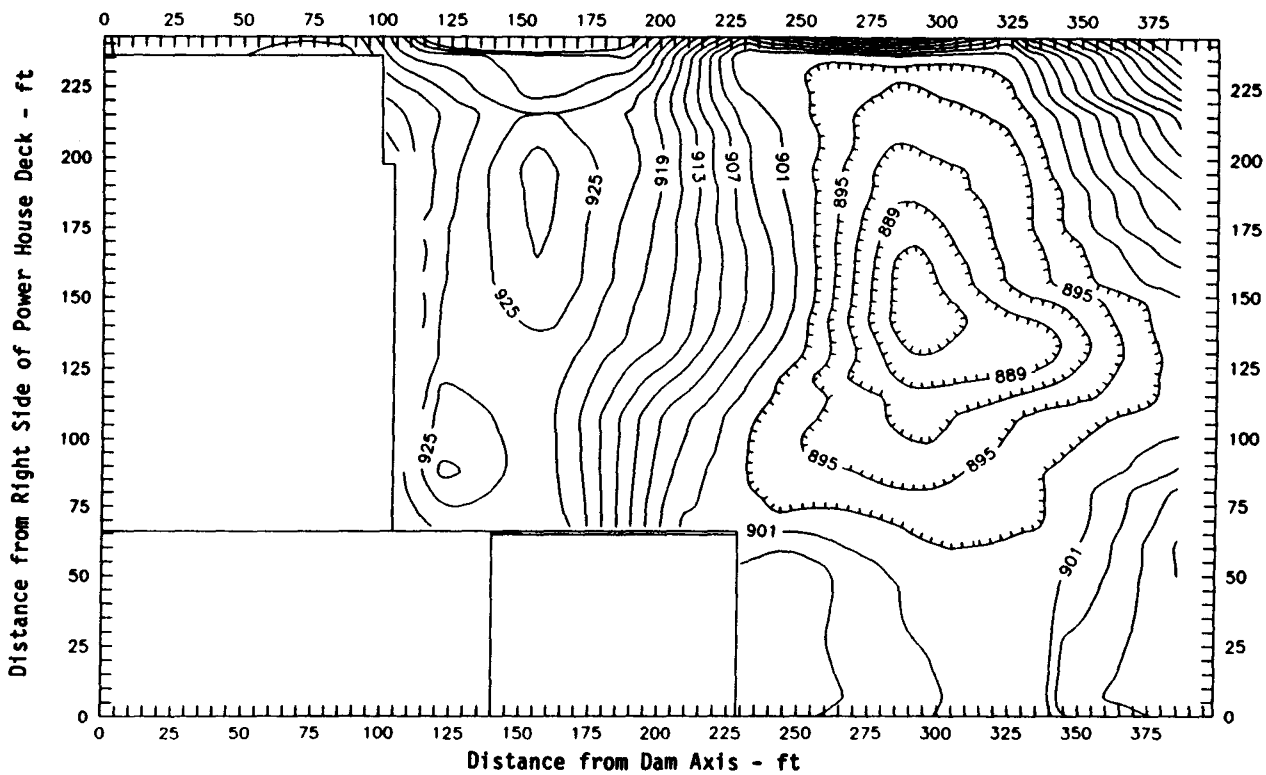


Figure 25. - Two-level flip bucket - bed contours after 50 percent of PMF.

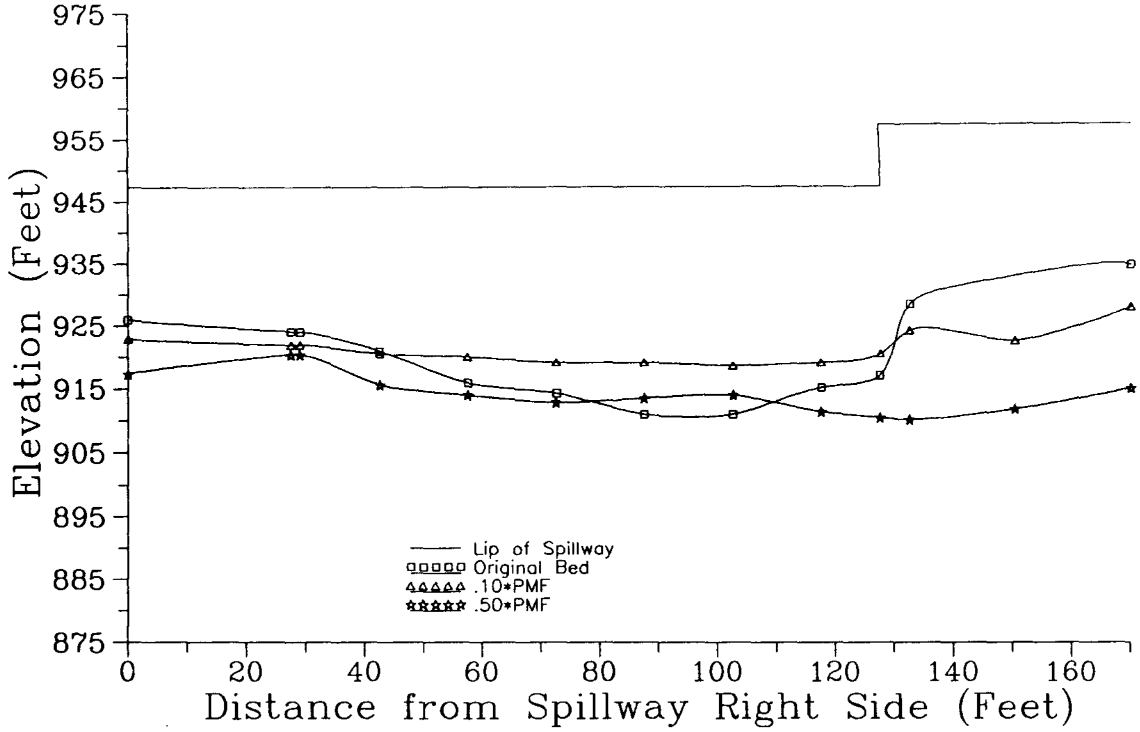


Figure 26. - Two-level flip bucket - bed profiles at toe of spillway.

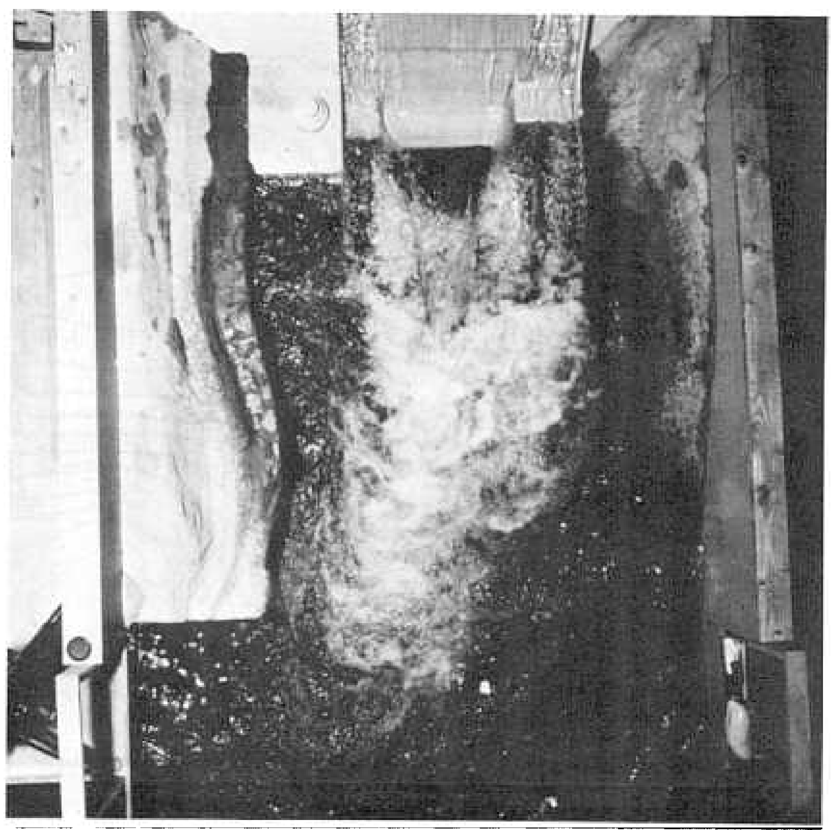


Figure 27. - Three-level flip bucket, 25,000 ft^3/s (10 percent of PMF).

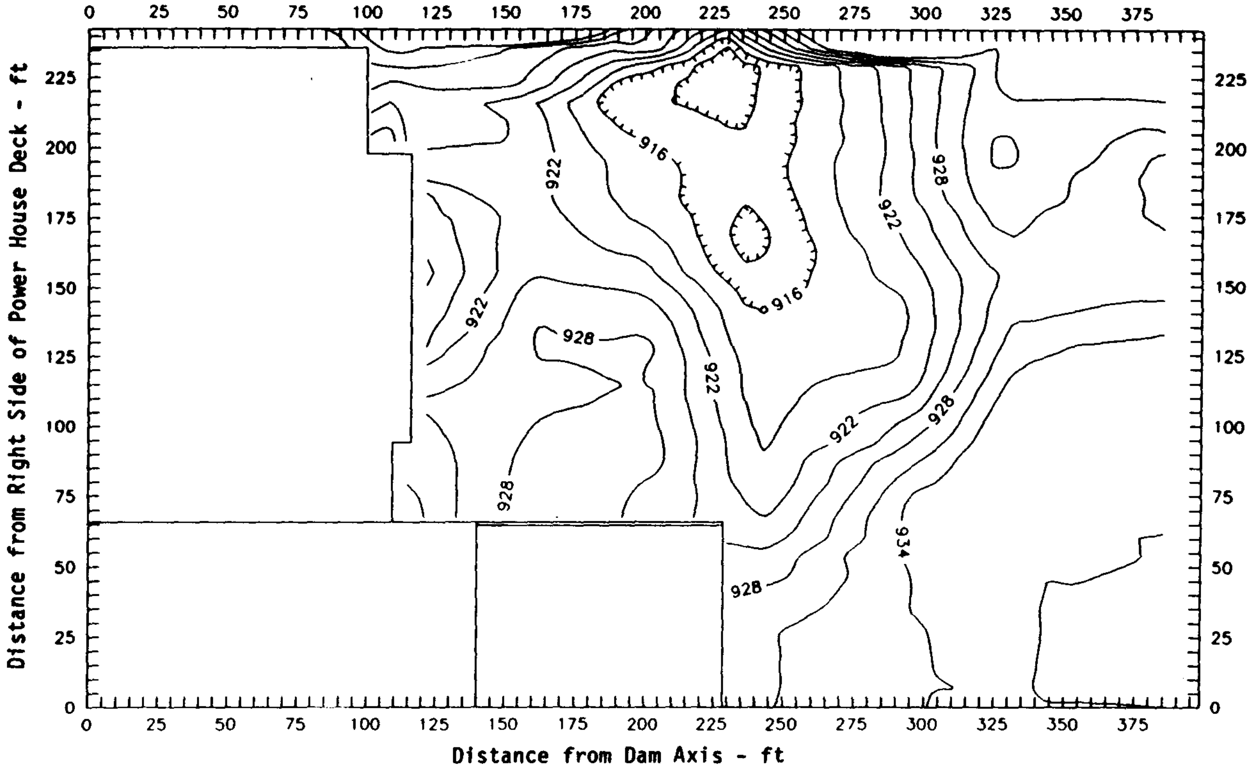


Figure 28. - Three-level flip bucket - bed contours after 10 percent of PMF.

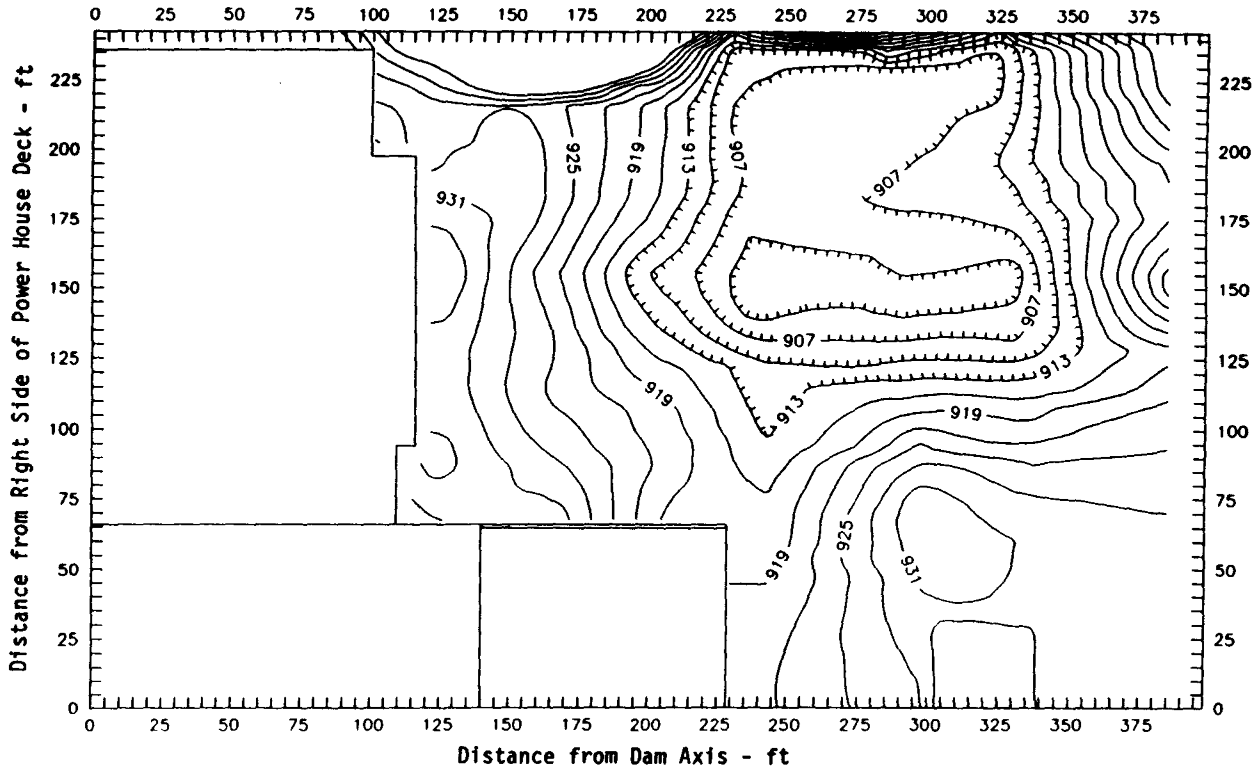


Figure 29. - Three-level flip bucket - bed contours after 25 percent of PMF.

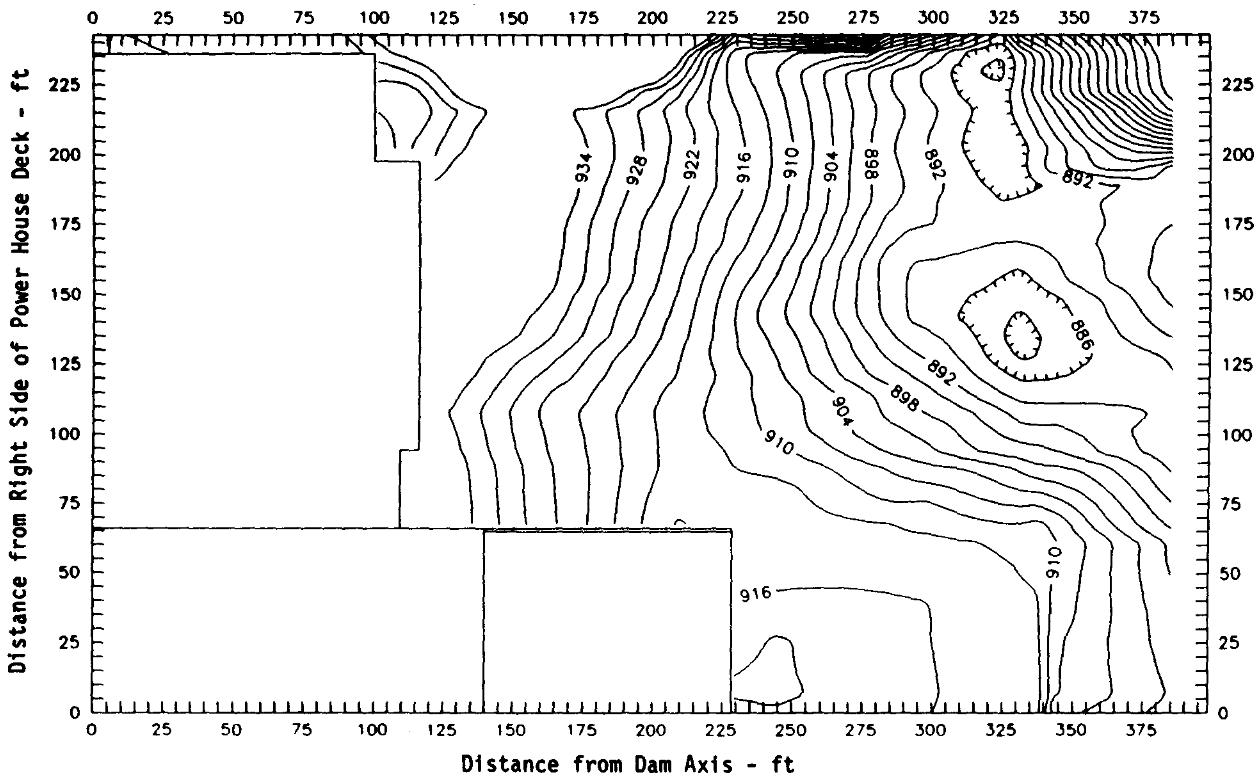


Figure 30. - Three-level flip bucket - bed contours after 50 percent of PMF.

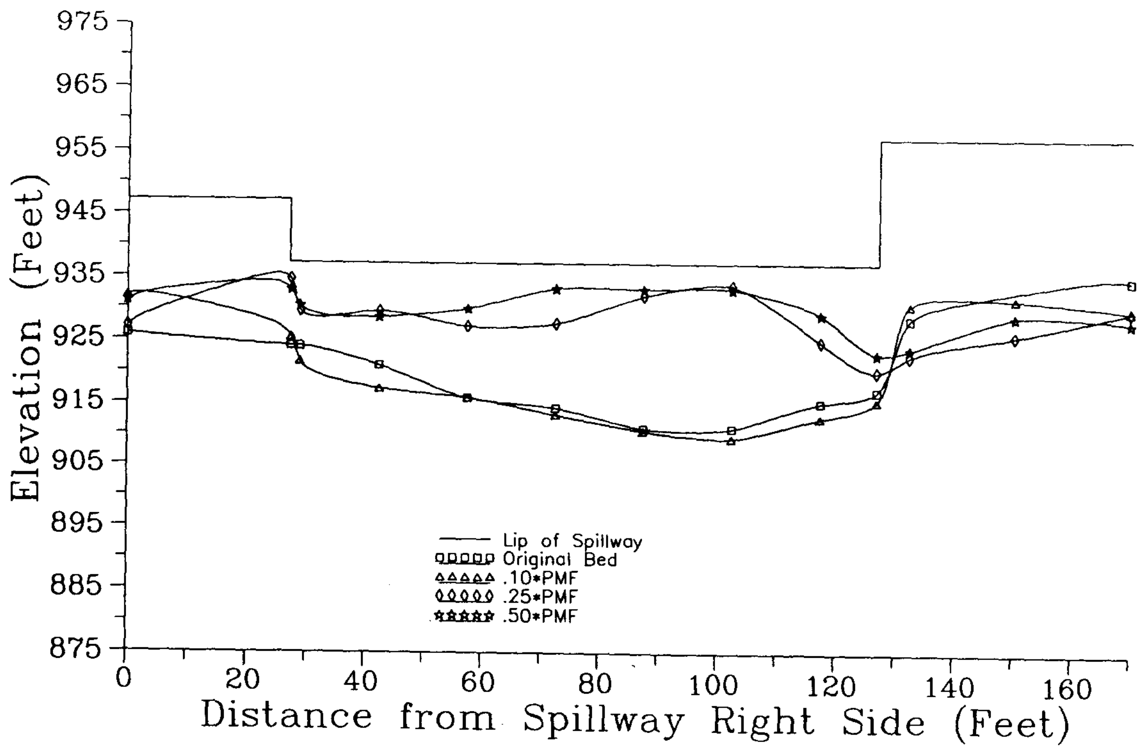


Figure 31. - Three-level flip bucket - bed profiles at toe of spillway.

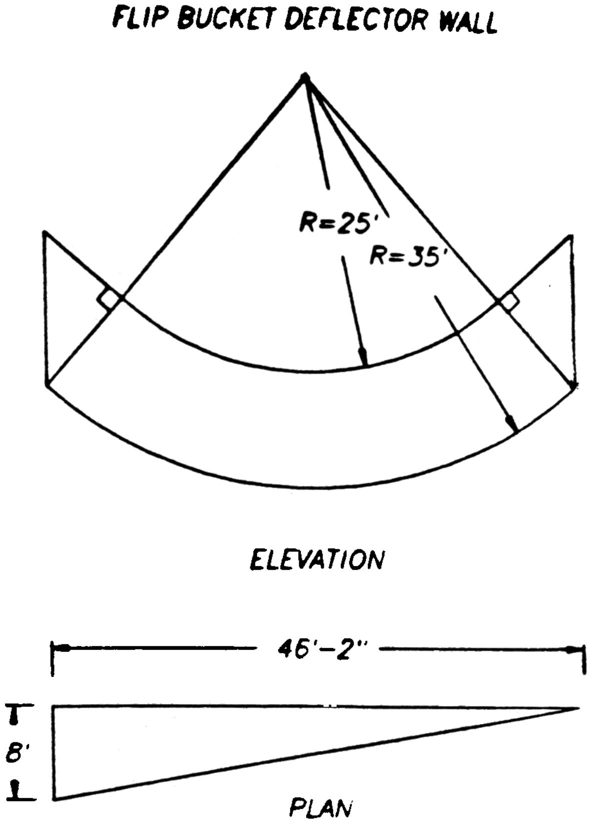


Figure 32A. - Deflector wall geometry.


Figure 32B. Three-level flip bucket spillway with deflector wall (25 percent of PMF).

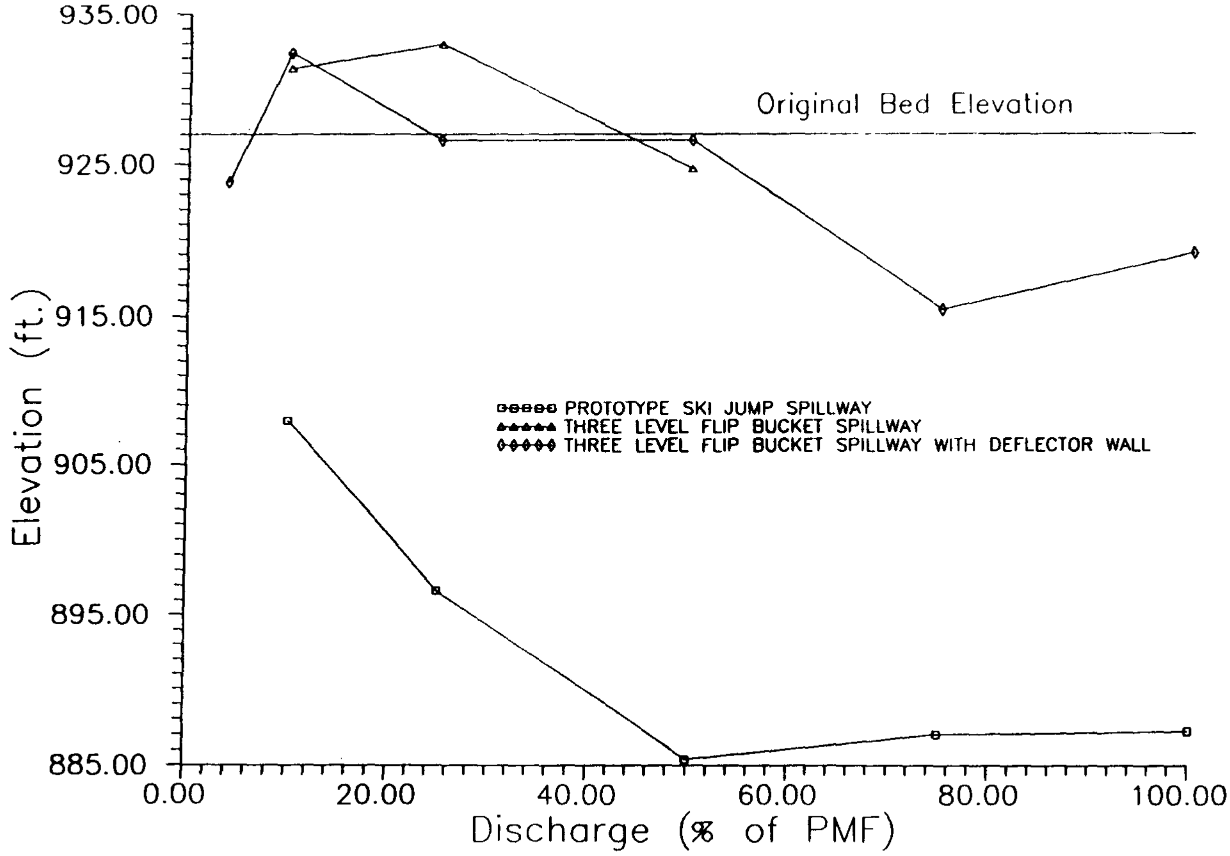


Figure 33. - Bed scour next to tailrace wall, 168 feet downstream of dam axis.

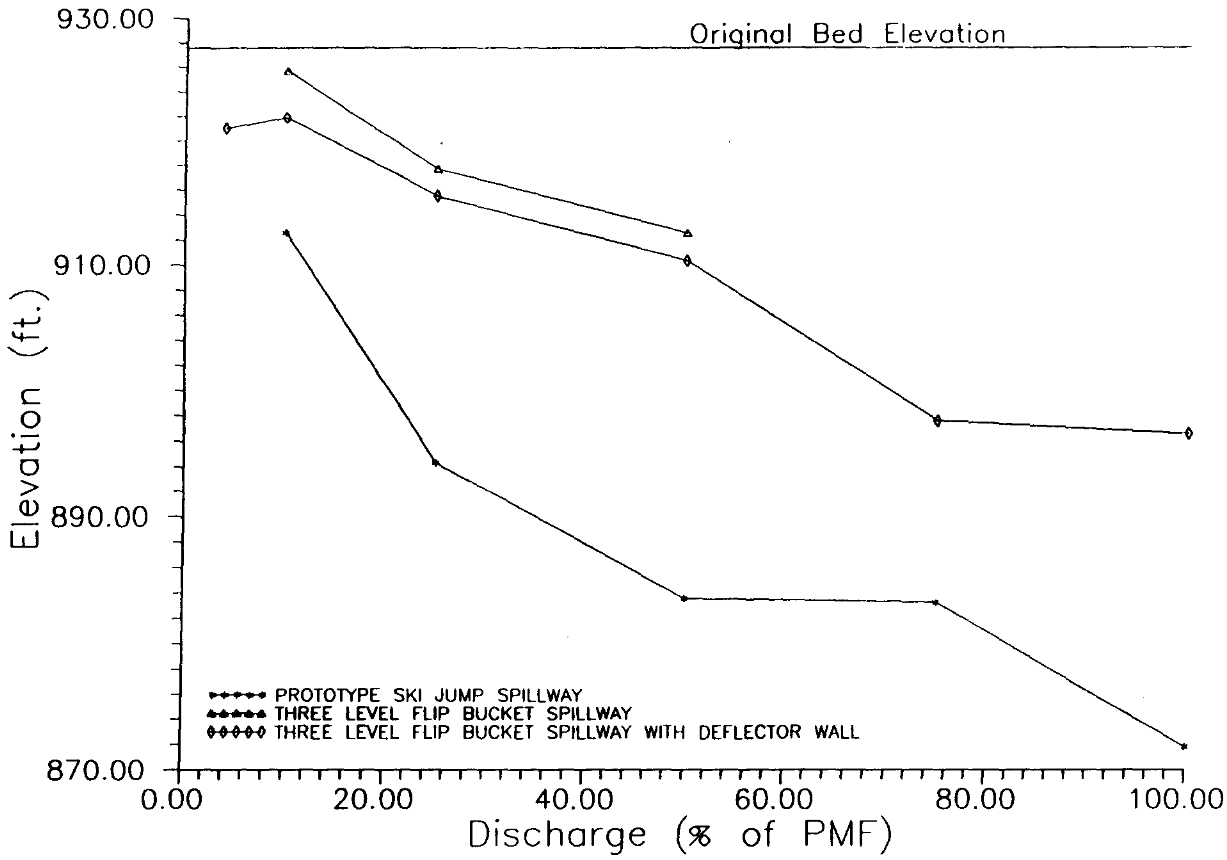


Figure 34. - Bed scour next to tailrace wall, 218 feet downstream of dam axis.

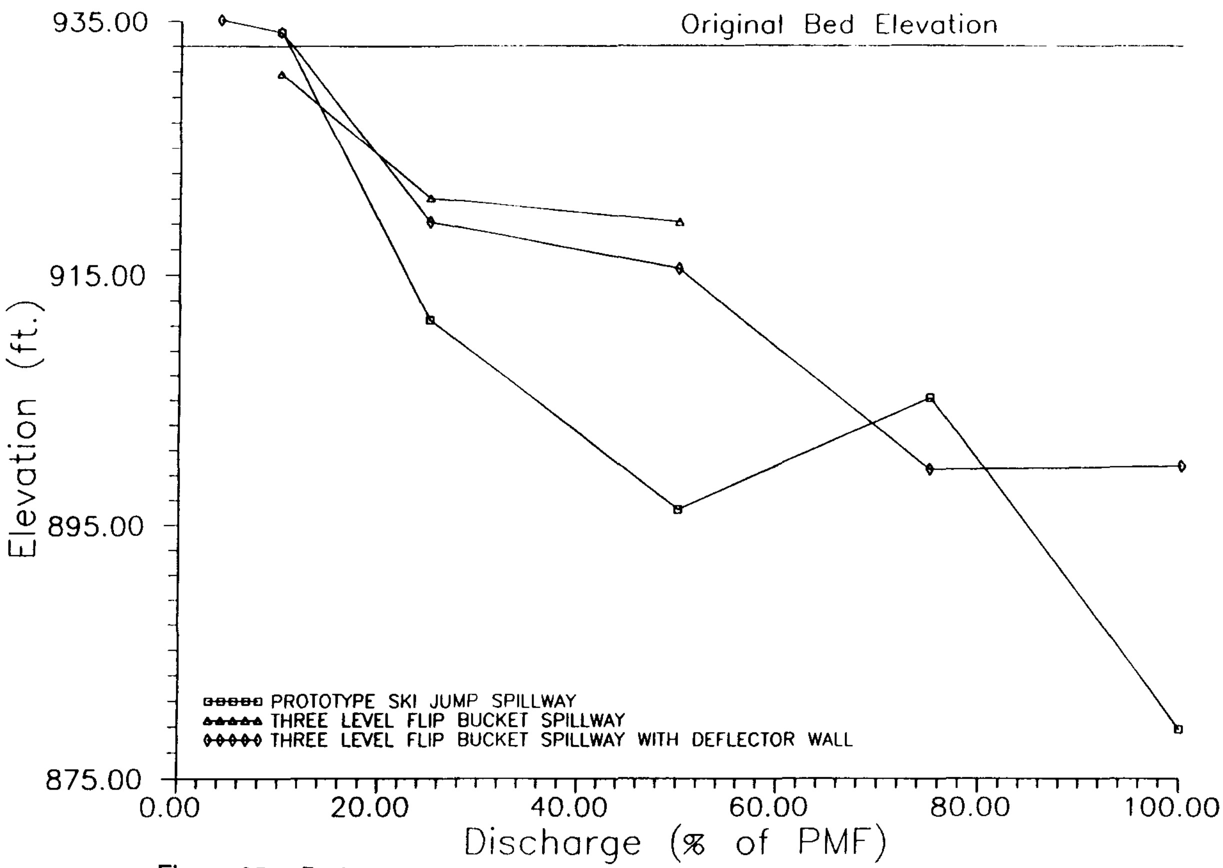


Figure 35. - Bed scour next to tailrace wall, 248 feet downstream of dam axis.

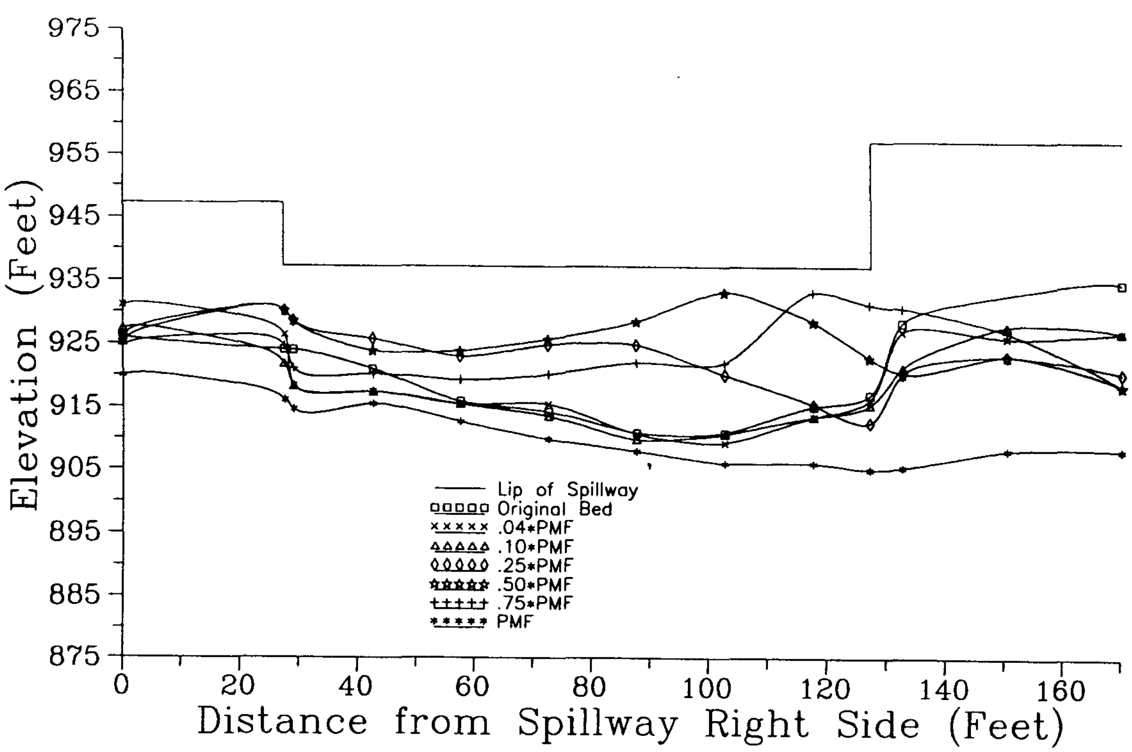


Figure 36. - Three-level flip bucket with deflector wall - bed profiles at toe of spillway.

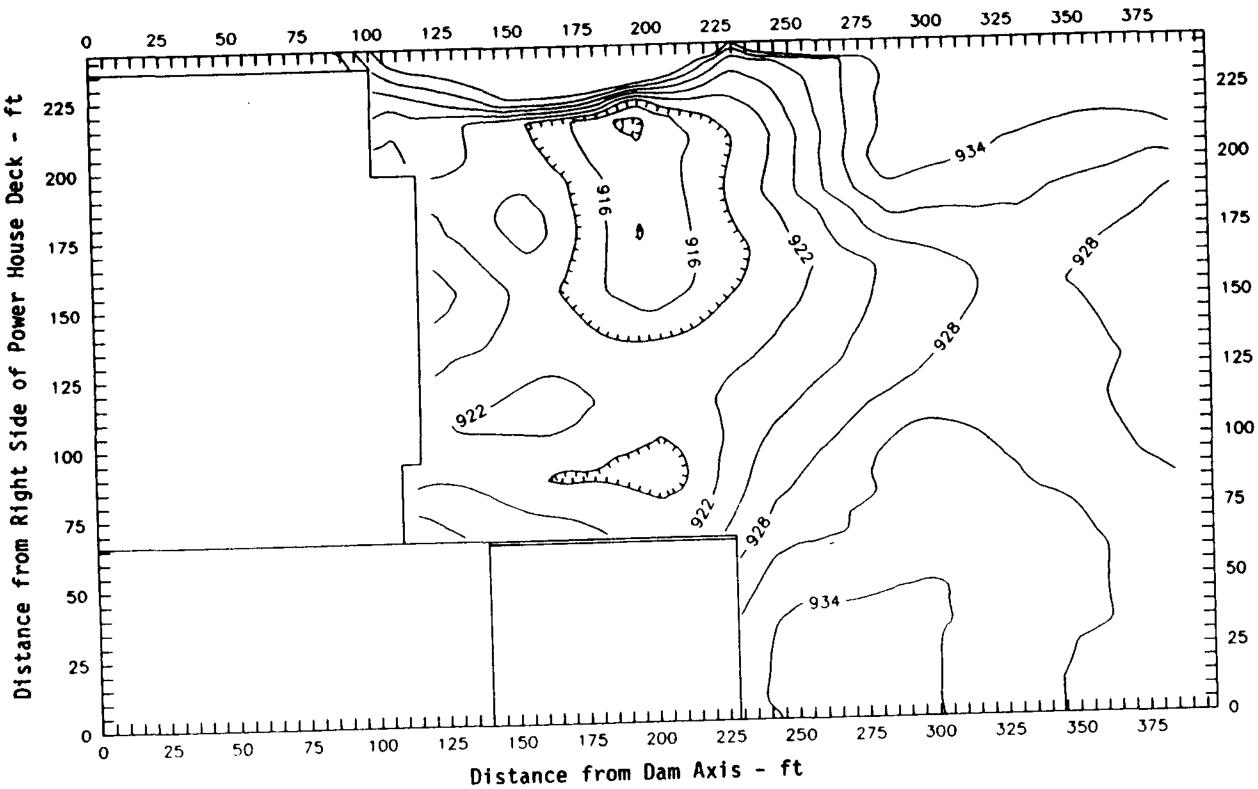


Figure 37. - Three-level flip bucket - bed with deflector wall - bed contours after 4 percent of PMF.

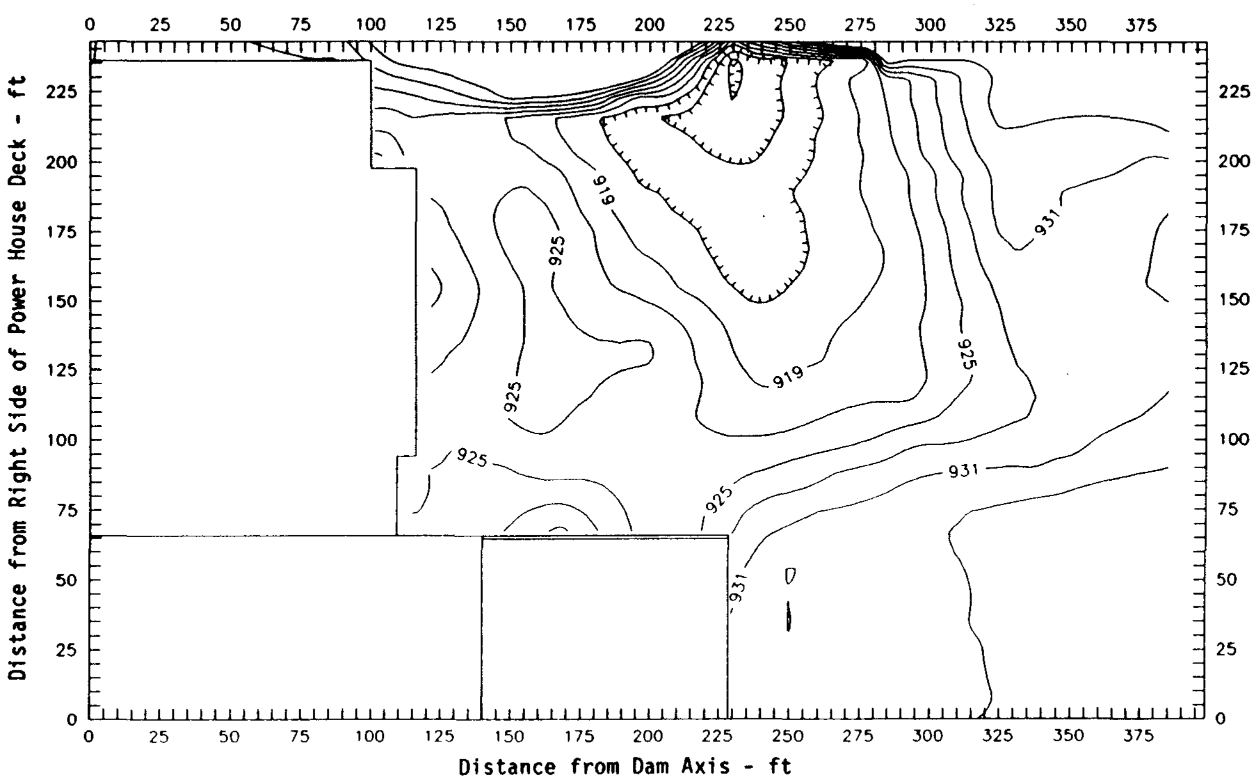


Figure 38. - Three-level flip bucket - bed with deflector wall - bed contours after 10 percent of PMF.

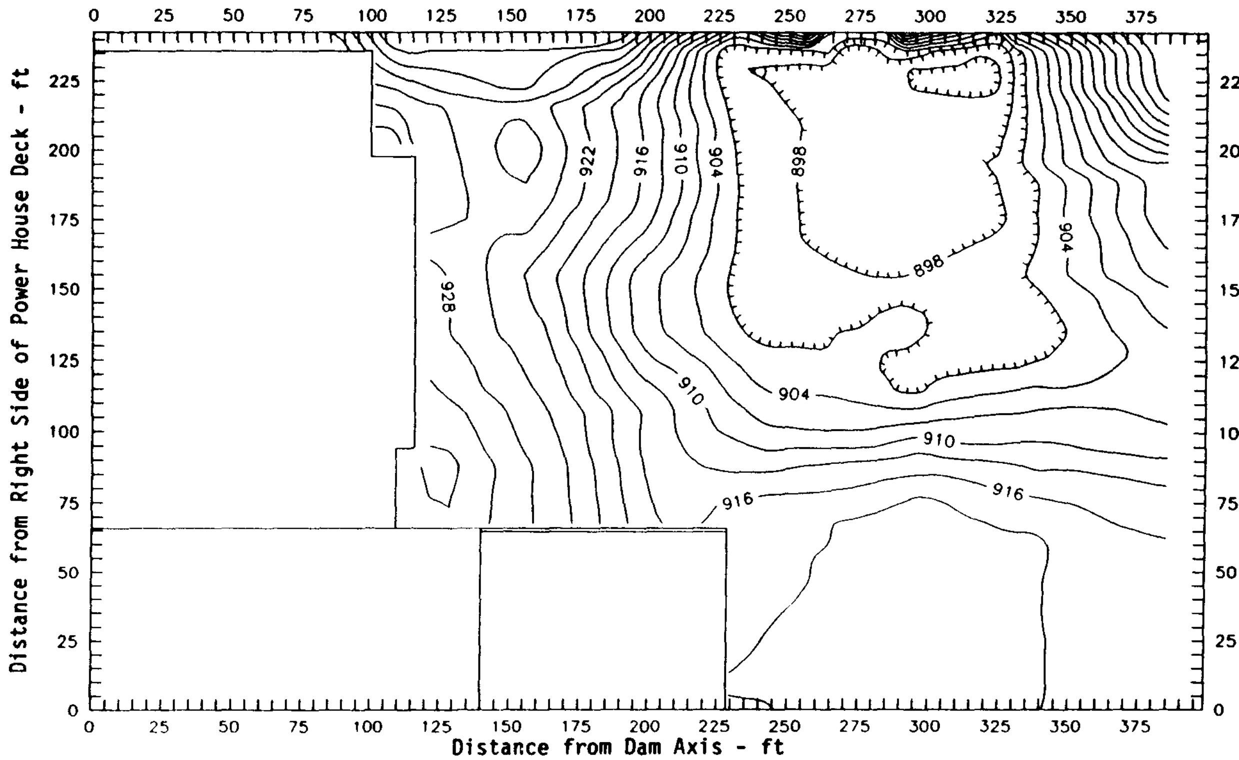


Figure 39. - Three-level flip bucket - bed with deflector wall - bed contours after 25 percent of PMF.

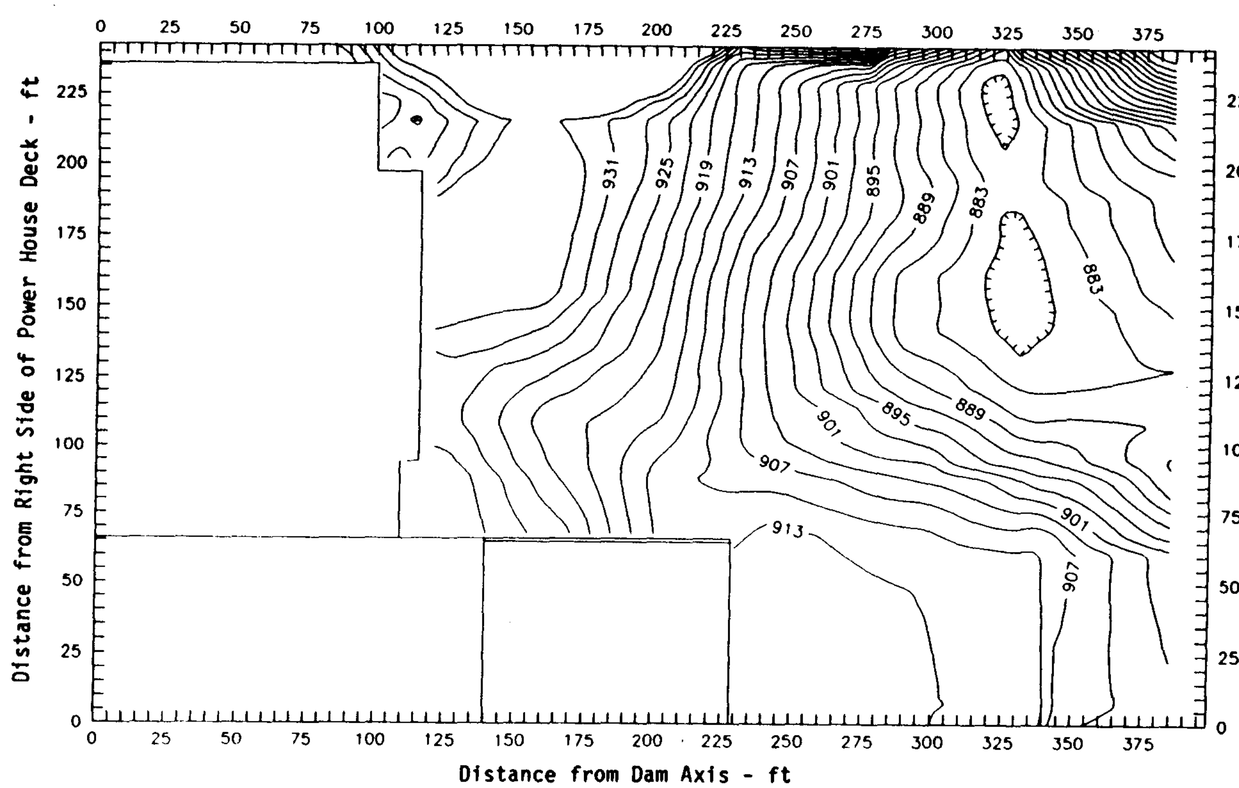


Figure 40. - Three-level flip bucket - bed with deflector wall - bed contours after 50 percent of PMF.

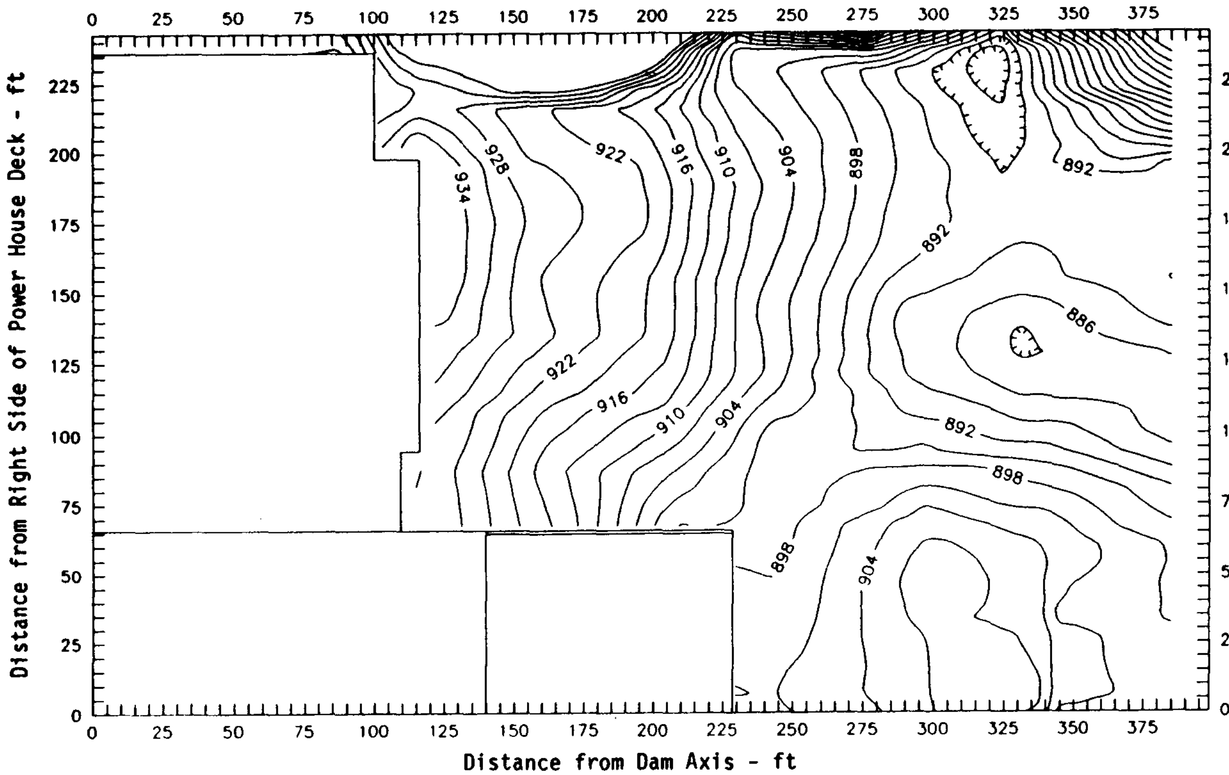


Figure 41. - Three-level flip bucket - bed with deflector wall - bed contours after 75 percent of PMF.

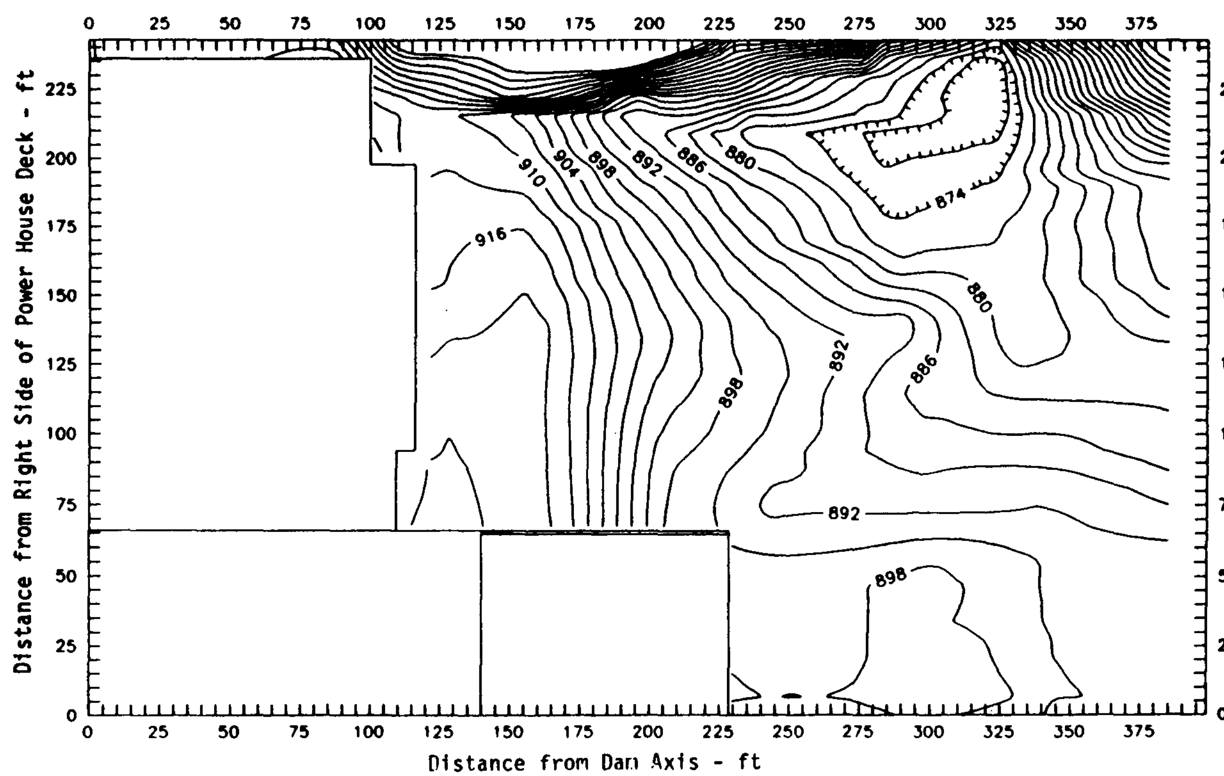


Figure 42. - Three-level flip bucket - bed with deflector wall - bed contours after 100 percent of PMF.

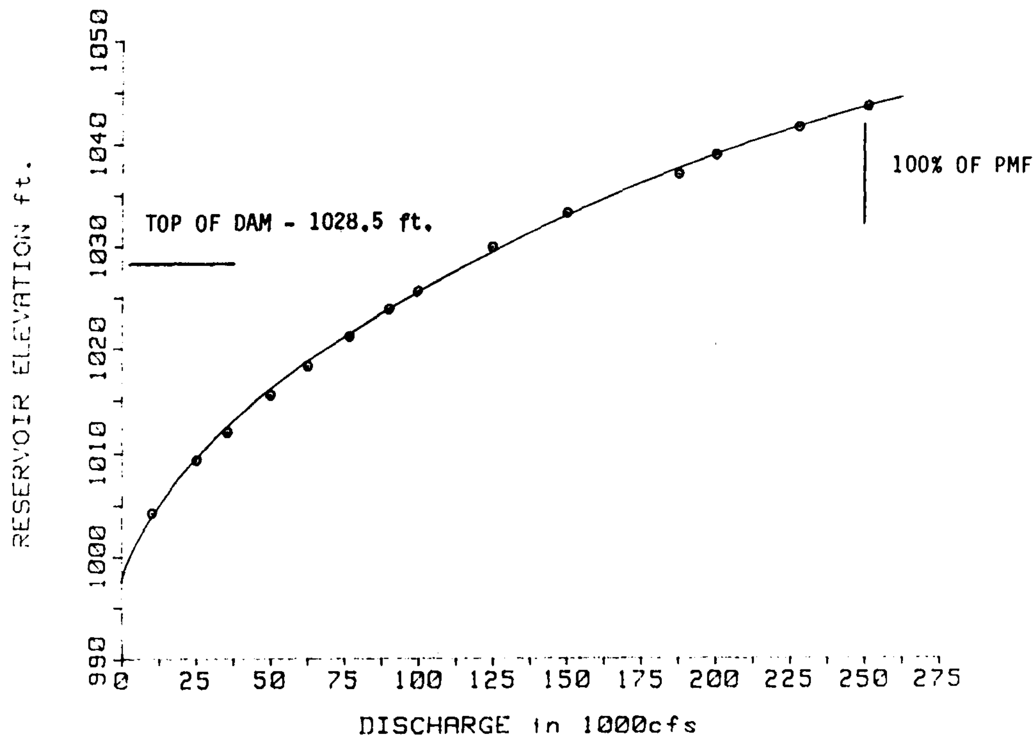


Figure 43. - Spillway/dam discharge rating curve.

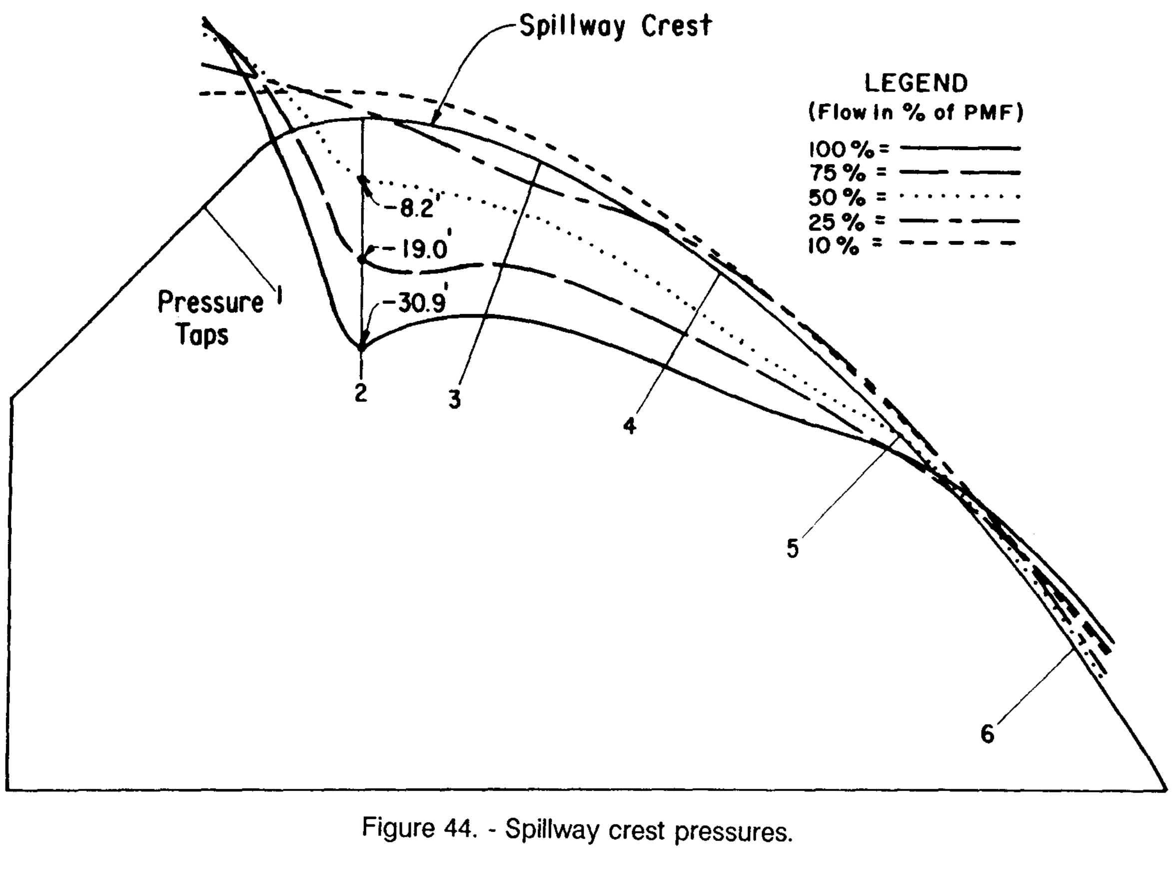
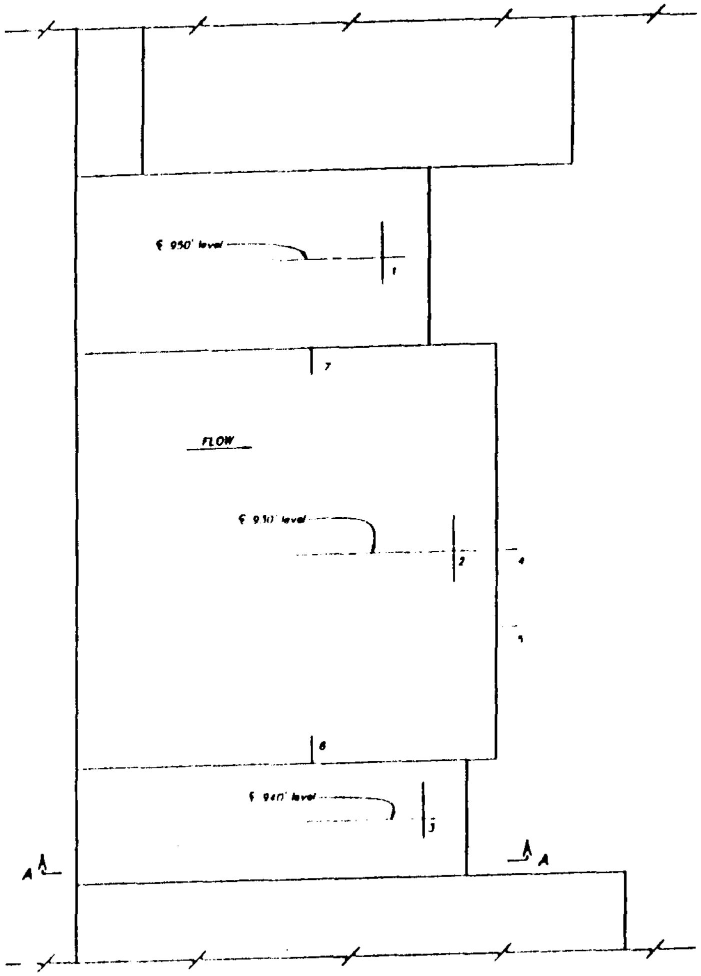
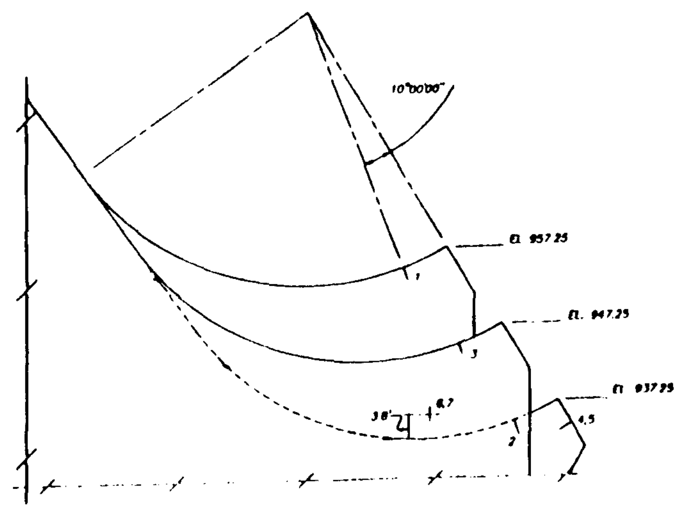


Figure 44. - Spillway crest pressures.



PLAN VIEW OF SPILLWAY



SECTION THROUGH SPILLWAY

Figure 45. - Flip bucket pressure tap locations.

APPENDIX

Research studies on slotted and slit-type flip buckets

APPENDIX

CONTENTS

TABLE

FIGURES

RESEARCH STUDIES ON SLOTTED AND SLIT-TYPE FLIP BUCKETS

Slotted and slit-type flip buckets are extensions of the standard solid flip bucket design. Slots or slits are designed into the bucket to expand the jet leaving the bucket, thus increasing the jet surface area and the stilling basin impingement area.

A hydraulic model design of a slotted ski-jump flip bucket for Cleveland Dam is shown on figure A-1 (Wilson, 1953). Wilson first studied the jet shape and measured downstream channel scour for smooth flip bucket geometries. The tests were repeated with the addition of splitter teeth to the bucket invert, herein referred to as a slotted flip bucket. Wilson observed the slotted bucket geometry distributed the jet over a larger area of the downstream river channel than the solid bucket. Measurements of channel scour supported his observations. Less scour occurred downstream of the spillway using the slotted bucket geometry. The apparent benefits of the slotted bucket design did not come without drawbacks. Wilson also conducted a limited study of the pressures on the sides of the slots. Low-pressure zones were found on the vertical edges of the slots which raised concerns about the slots acting as possible sources for cavitation. In general the low pressure zones as found in the Cleveland Dam study can probably be corrected by improved design of the slot shape. Little additional work on slotted flip bucket spillways has been done by Reclamation to date. The Chili Bar Dam model provided an excellent opportunity to conduct a further study to compare the channel scour resulting from equivalent operation of ski-jump, slotted bucket, and solid flip bucket designs.

Conclusions of Experimental Bucket Tests

For a free jet, depth of basin scour from the jet passing over the slotted and slit type buckets tested were similar to scour depths for a solid bucket. The slot and slit geometries tested did not force enough horizontal or vertical separation in the exiting jet to substantially alter the jet surface area or basin impact zone. This suggests the slots or slits should be designed large enough to pass the majority of the design flow between the bucket teeth, which in effect creates multiple jets.

Tailwater levels causing the jet to become suppressed, resulted in scour near the toe of the spillway structure. This resulted in greater bed scour immediately downstream of the structure than occurred for the solid bucket design.

Model tests of Three-Level Slotted Flip Bucket

The recommended three-level spillway bucket design was used to evaluate a slotted bucket geometry. Each of the three buckets were modified to a include slots (fig. A-2). As the bucket width on each level varied, the number of slots and their widths at each level also differed. The flip bucket geometry tested for the three level solid bucket was used for the slotted bucket teeth. The slots or grooves between the bucket teeth conformed to the original spillway surface. The slotted geometry was therefore constructed by adding a series of rectangular teeth to the original spillway surface. Slot and teeth widths were equal across a single bucket but varied between buckets due to the different widths of the three spillway segments on the prototype.

Tests were conducted on the slotted bucket geometry for flows of 10, 25 and 50 percent of the PMF. Like the solid bucket scour tests, the movable stilling basin material was contoured to the prototype topography before the 10-percent test. Scour was then allowed to progress for the three flows tested. The flow versus test-length relationships were also the same as for all previous tests. Table A.1 lists the unit discharge, the ratio of the slot depth to flow depth, slot width to tooth width, and entrance velocity to the bucket for the tests conducted. Estimates of the bucket flow parameters are also presented for the Cleveland Dam study.

Table A.1. - Comparison of slotted bucket tests

Cleveland Dam				Chili Bar Dam			
q (ft^3/s/ft)	D/H	V (ft/s)	S_w/T_w	q (ft^3/s/ft)	D/H	V (ft/s)	S_w/T_w
312	0.67	100	1.06	147	0.36	60	1.0
537	1.11	107	1.06	367	0.80	61	1.0
				735	1.43	67	1.0

q = spillway unit discharge
D/H = ratio of flow depth entering bucket radius to slot tooth height
V = velocity of flow entering bucket radius
S_w/T_w = slot width divided by tooth width

Basin scour during passage of 10 percent of the PMF occurred mainly downstream of the 952.6-foot elevation flip bucket (fig. A-3). The scour pattern and depths were vary similar to the results obtained for the solid bucket tests. The jet leaving the end of the spillway was saw-toothed in appearance, although the corrugated jet surface tended to blend together as the jet passed downstream (fig. A-4).

During the 25-percent PMF test, large material was observed moving upstream along the bottom immediately below the end of the 932.6-foot elevation bucket. At 25 percent of the PMF, the 932.6-foot elevation bucket sweeps out with the lower jet nappe fully suppressed by the tailwater. Rocks of up to 3.5-foot diameter were thrust against the bottom of the spillway teeth by the eddy driven beneath the exiting jet. The size and speed of material impinging on the downstream face of the spillway toe appeared much greater than was observed for any of the previous spillway designs tested.

Following the 25-percent PMF test, the maximum depth of scour downstream of the slotted flip bucket was less than measured for the prototype structure and approximately the same as that caused by the solid flip bucket (fig. A-5). Although, the maximum scour depth (located downstream of the 952.6-foot elevation bucket) was similar to the solid bucket scour, downstream of the lower elevation flip buckets the scour was greater than for the solid buckets. This suggests that under suppressed conditions the portion of the jet passing between the teeth again scours the basin floor as did the jet from the prototype spillway geometry.

The depth of maximum scour downstream of the 952.6-foot elevation bucket was less than found for the comparable solid bucket test after 50 percent of the PMF (fig. A-6). This scour was primarily caused by impingement of the free jet leaving the 952.6-foot elevation bucket. In contrast to the reduced scour measured, the influence of the slots at the free jet surface appeared small with the large flows.

Tests of Three-Level Slit-Type Flip Bucket

Slit-type flip buckets are characterized by slots with converging walls. The slit geometry forces greater vertical and longitudinal spread of the jet. The slit convergence is important to the performance of the bucket. In general, slits may converge along a single angle over the full bucket length or the slits may converge following a small angle and then converge sharply near the bucket lip. The later is typical of several free discharge flip bucket spillways constructed in China. The sharp convergence at the lip should be between 1:4 to 1:6 for Froude numbers between 4.5 to 10 (Jizhang et al., 1988). This style of slits is designed to pass flow predominately through the slits. Studies on Dong-jiang and Long-yang Xia Dams found the maximum scouring depths were reduced 40 to 60 percent when compared to similar tests with solid bucket flips.

A continuous slit convergence of 1:16 was chosen for study on the Chili Bar model to provide a comparison to the slot and solid bucket studies. The previously tested slot geometry was altered by adding triangular wedges to the existing slots (fig. A-7). Thus, the widths at the bucket lip of each of the previous slots were reduced by 5.4 feet.

Tests were conducted on the slit bucket geometry for flows of 10, 25, 50, and 75 percent of the PMF. Following the previous testing sequence, the movable stilling basin material was contoured to the prototype topography before the 10-percent test. Scour was then allowed to progress for the four flows tested. The flow versus test-length relationships were again held the same as for all previous tests of similar discharge.

During 10 percent of the PMF test, the free jet from the high bucket showed pronounced fins downstream of each slit (fig. A-8). The formation of vertical fins were nearly washed out on the lower buckets which were partially submerged by tailwater. At higher discharges the height or definition of the fins on the jet continued to diminish. This suggests the height and convergence of the slits must be large in relation to the flow depth to force significant vertical separation in the jet. To do so on the Chili Bar spillway was not considered practical due to the small radius of the flip buckets and the large flows being conveyed.

Scour depths and patterns measured after each test were similar to those incurred for the slotted and solid flip bucket geometries (figs. A-9 through A-12). Although the slit geometry produces stronger vertical spread of the jet, again as found for the slotted bucket, the bucket teeth were to small to create the needed increase in the jet surface area and impact zone.

Bibliography

Jizhang G., Qingchoa L., and Guifen, L., "A Study and Applications of Slit Type Flip Bucket," Proceedings, The International Symposium on Hydraulics for High Dams, pp. 315-322, 1988.

Wilson, L. V., *Hydraulic Studies of the Ski-Jump Spillway for Cleveland Dam,* Bureau of Reclamation Report No. HYD-369, Denver, Colorado, 1953.

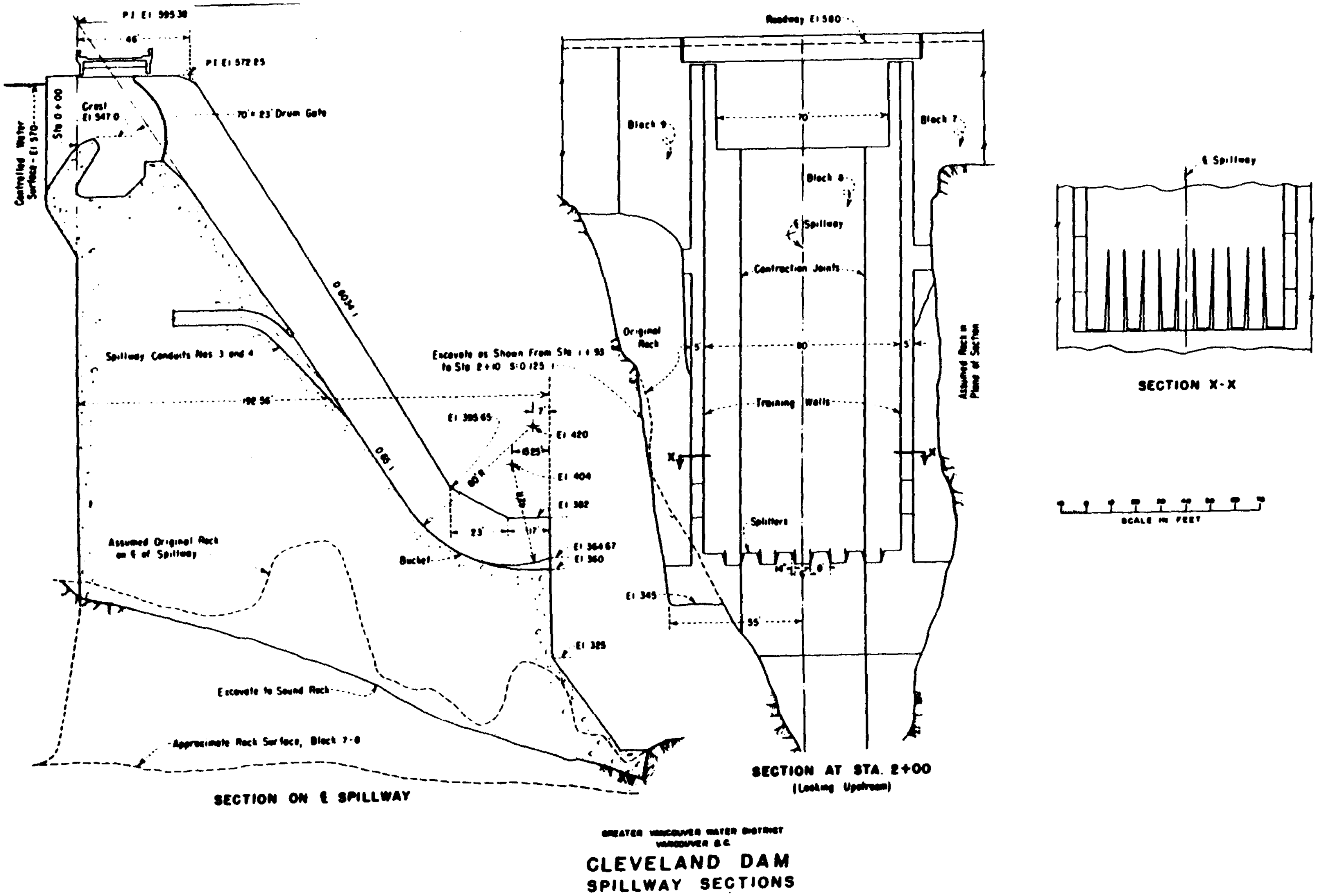


Figure A-1. - Slotted flip bucket design model tested for Cleveland Dam.

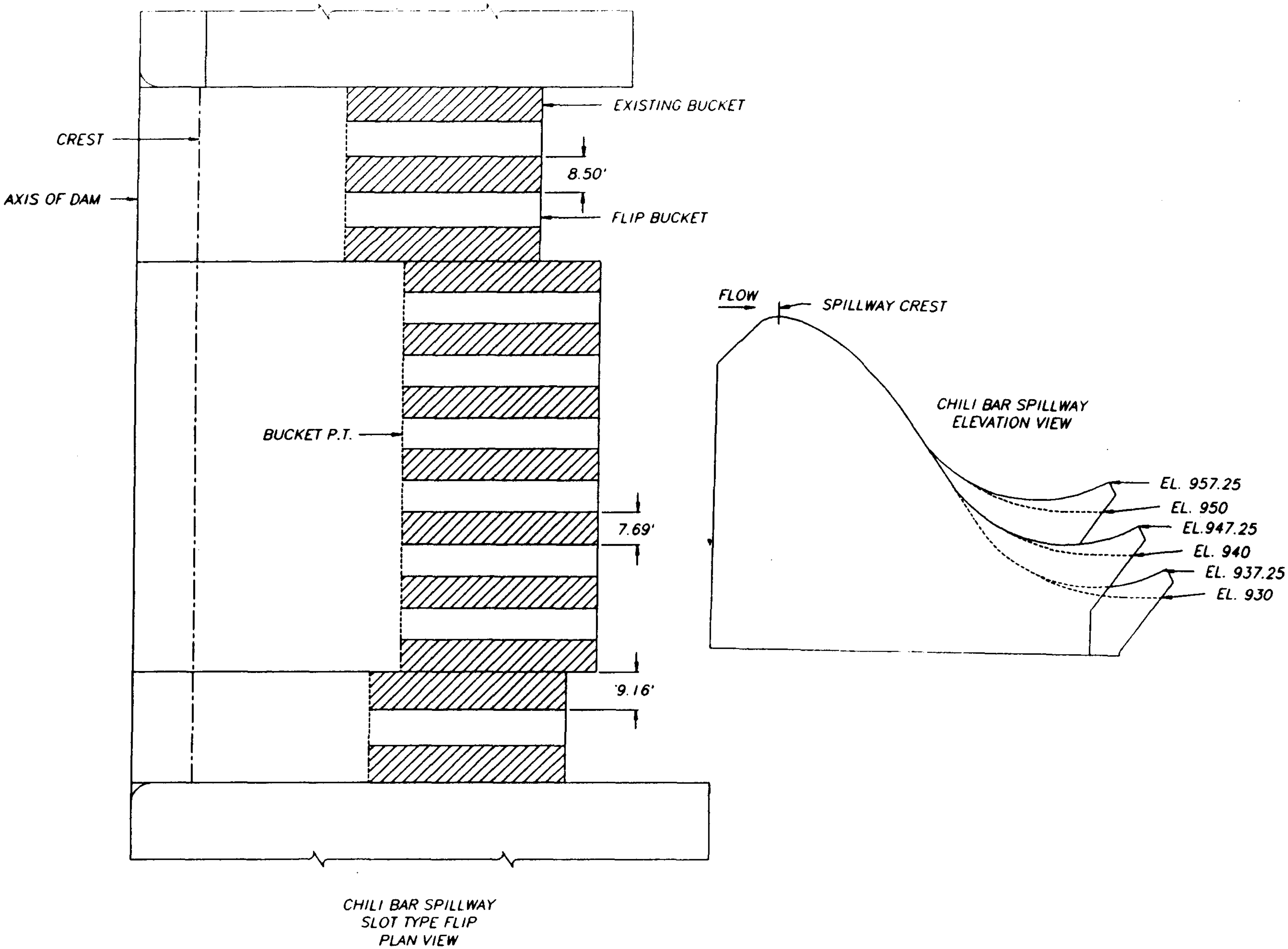


Figure A-2. - Slotted flip bucket design model tested for Chili Bar Dam spillway.

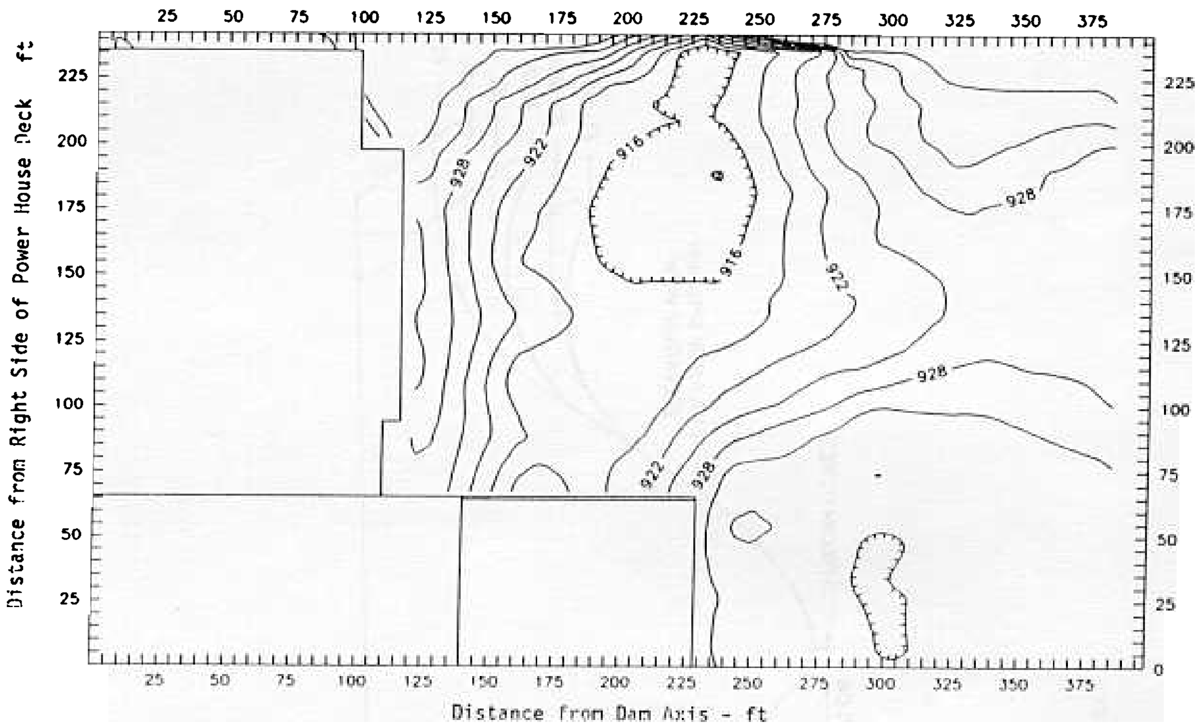


Figure A-3. - Slotted flip bucket spillway - bed contours after 10 percent of PMF.

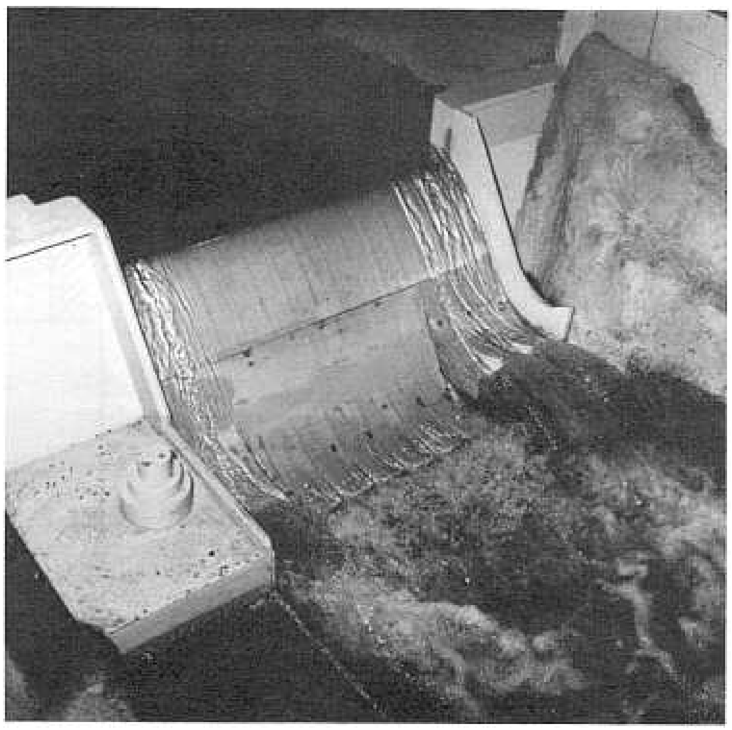


Figure A-4. - Three-level slotted flip bucket, 25,000 ft^3/s (10 percent of PMF).

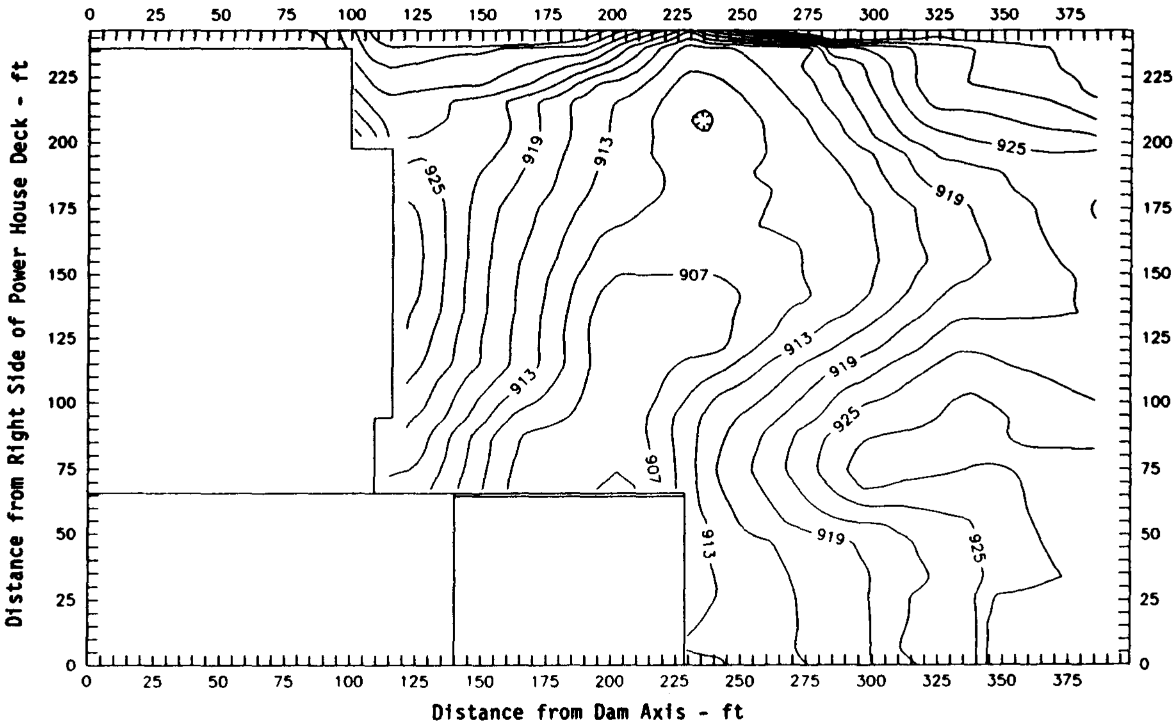


Figure A-5. - Slotted flip bucket spillway - bed contours after 25 percent of PMF.

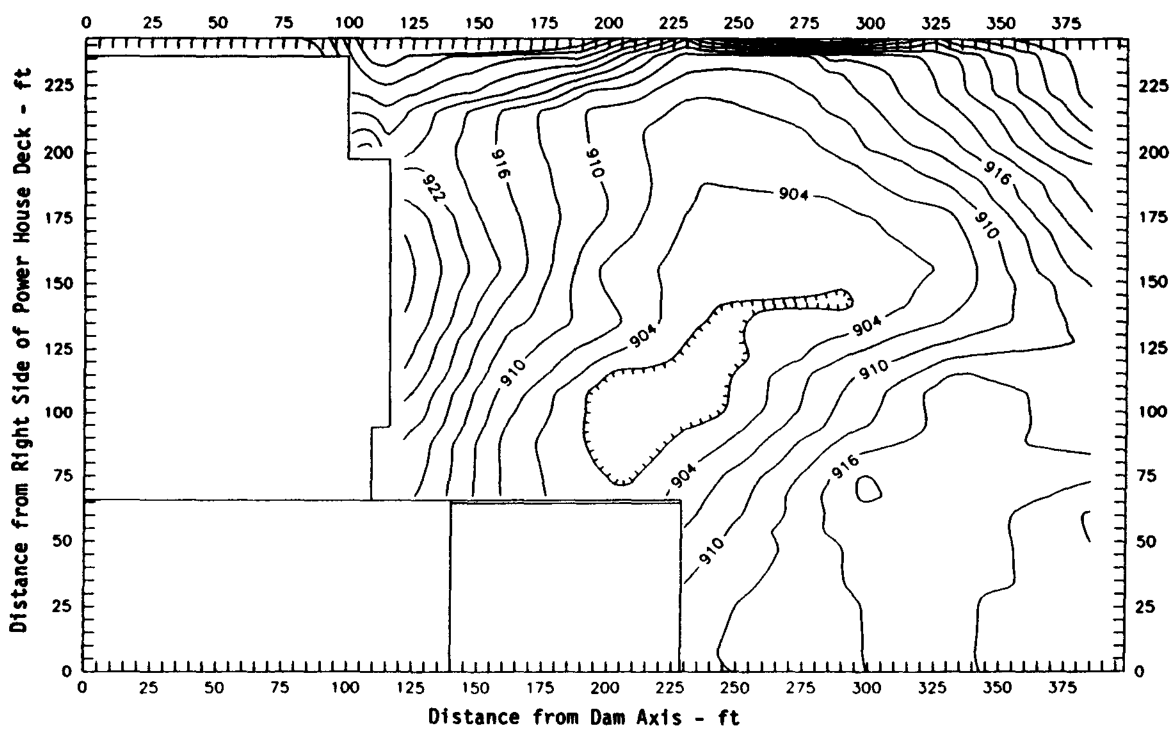


Figure A-6. - Slotted flip bucket spillway - bed contours after 50 percent of PMF.

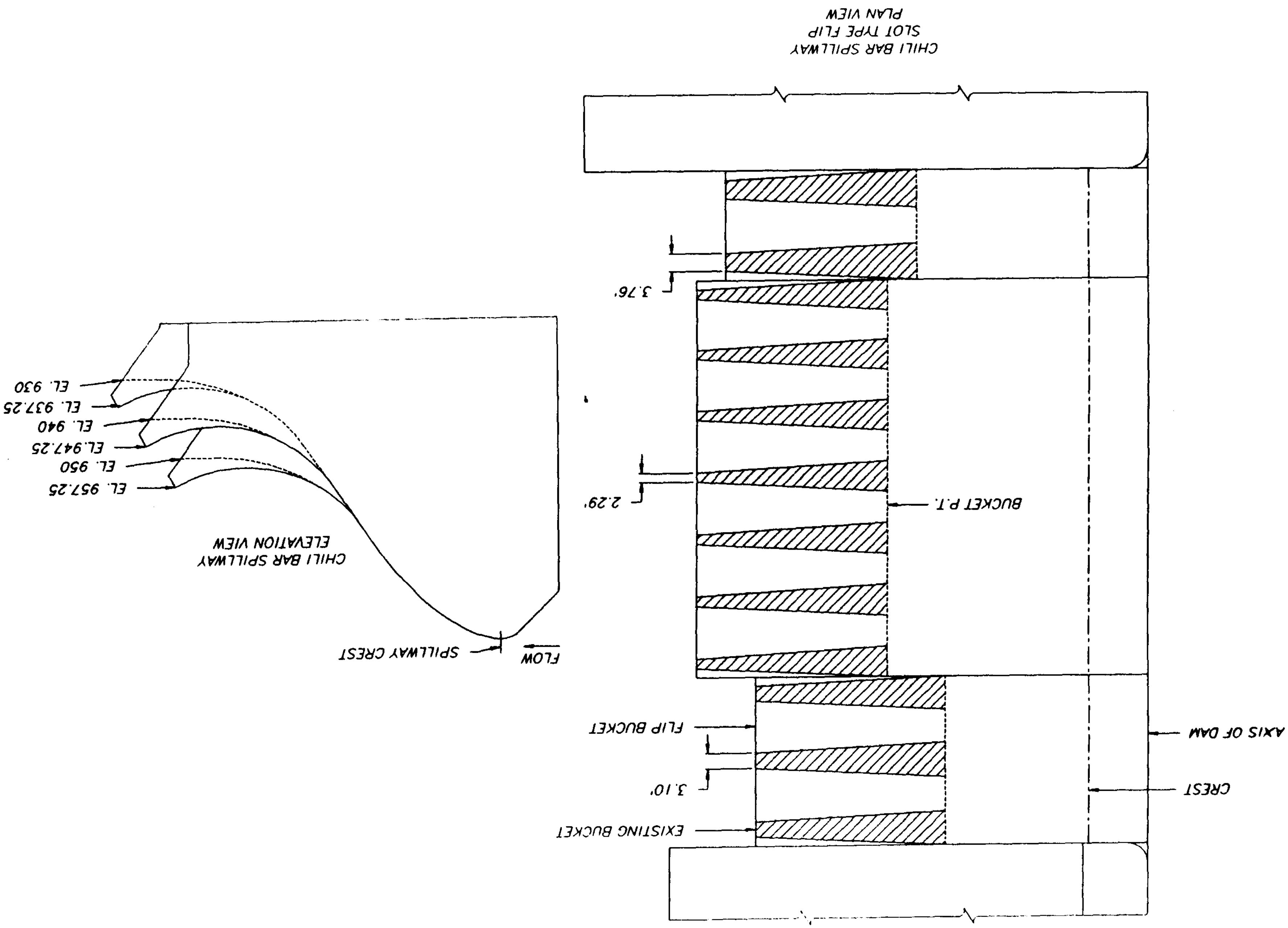


Figure A-7. - Slit-type flip bucket design model tested for Chili Bar Dam spillway.

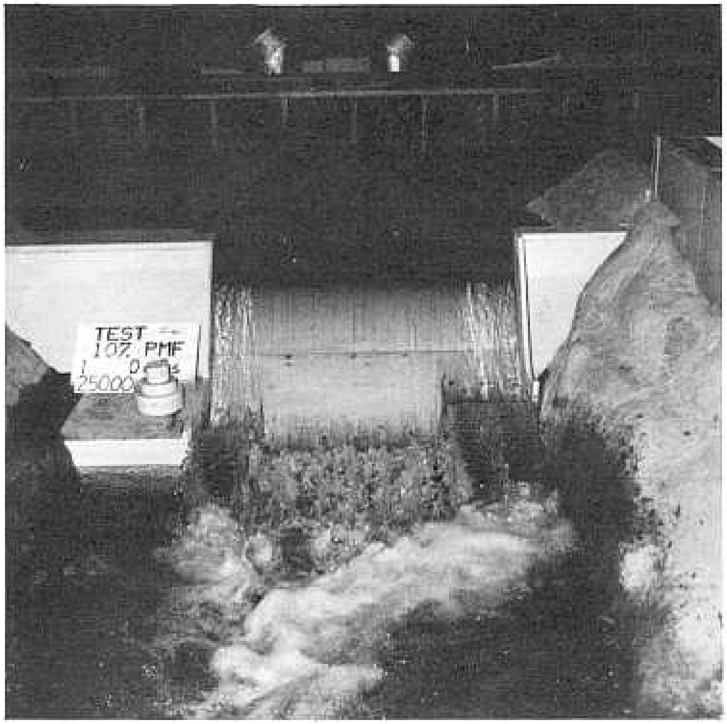


Figure A-8. - Three-level slit-type flip bucket, 25,000 ft^3/s (10 percent of PMF).

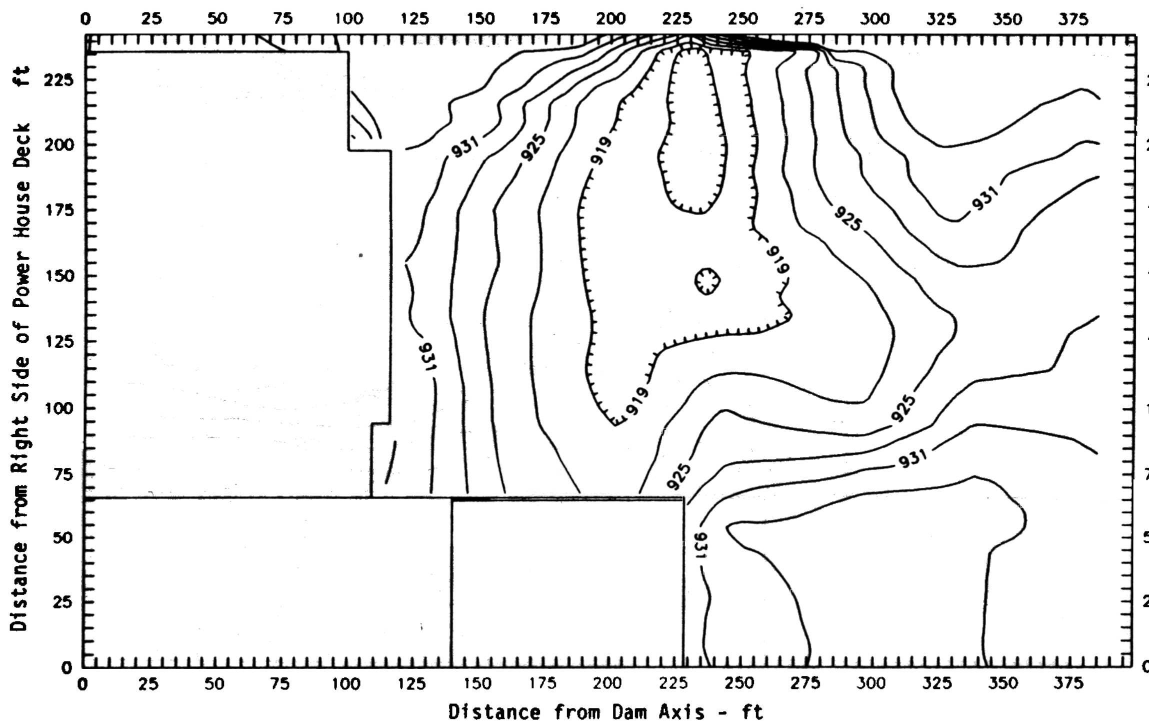


Figure A-9. - Slit-type flip bucket - bed contours after 10 percent of PMF.

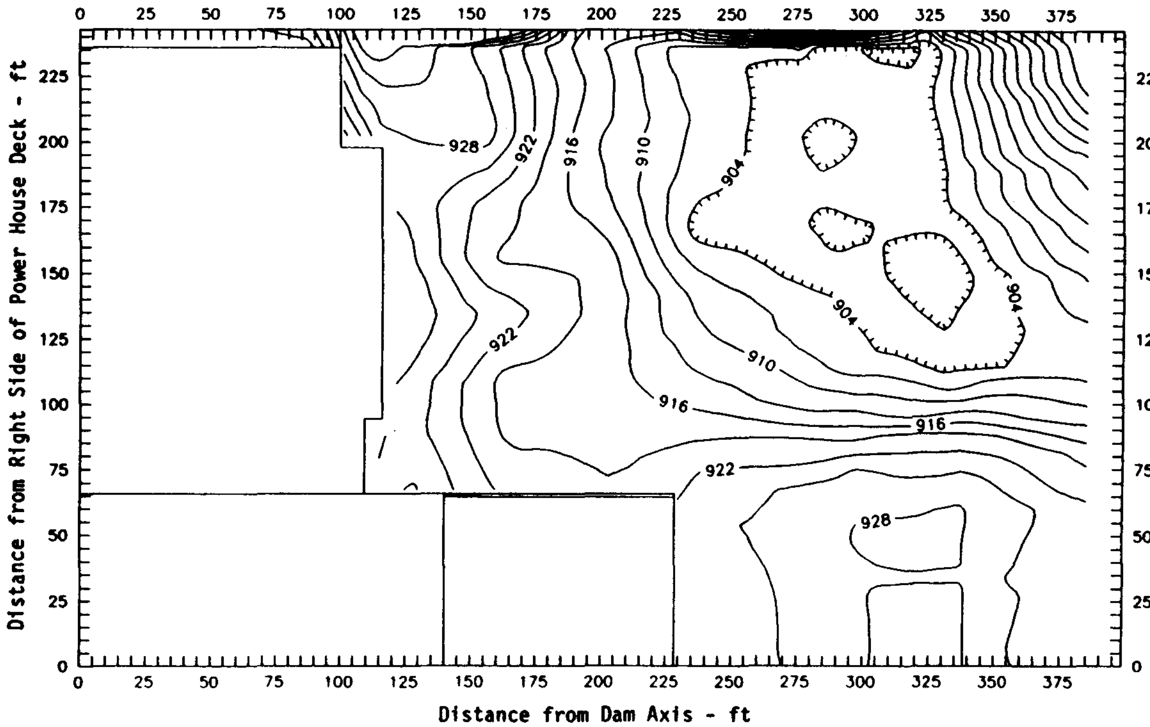


Figure A-10. - Slit-type flip bucket - bed contours after 25 percent of PMF.

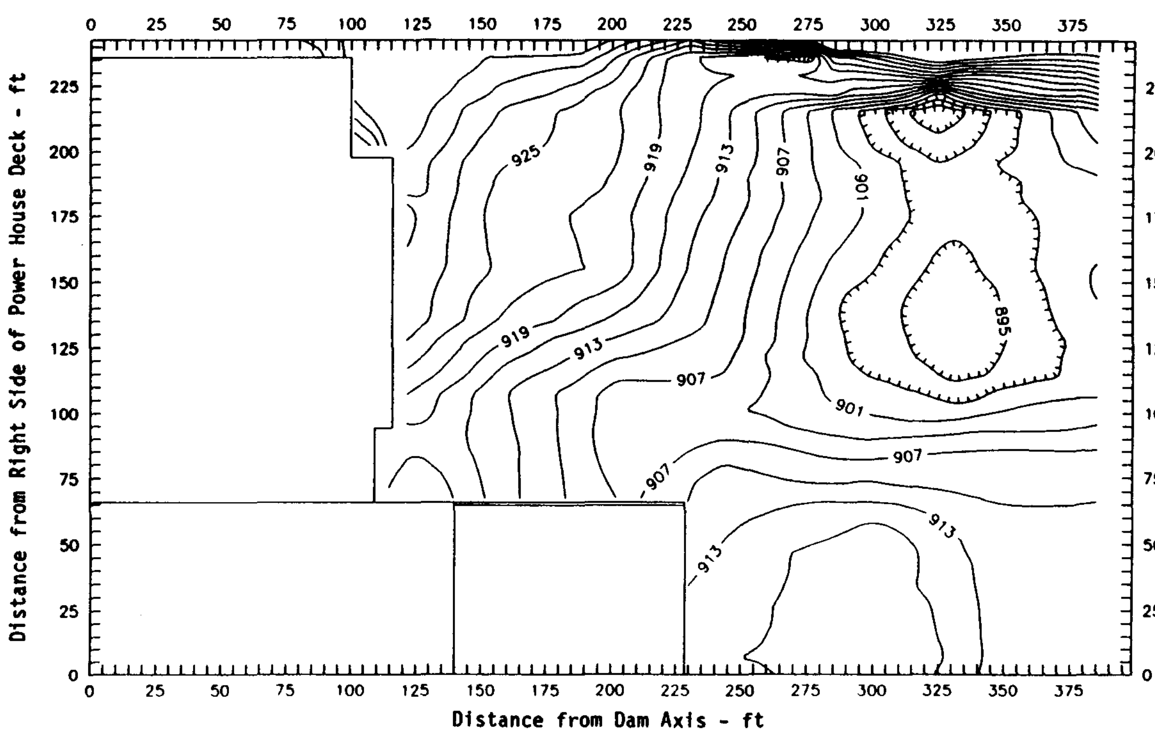


Figure A-11. - Slit-type flip bucket - bed contours after 50 percent of PMF.

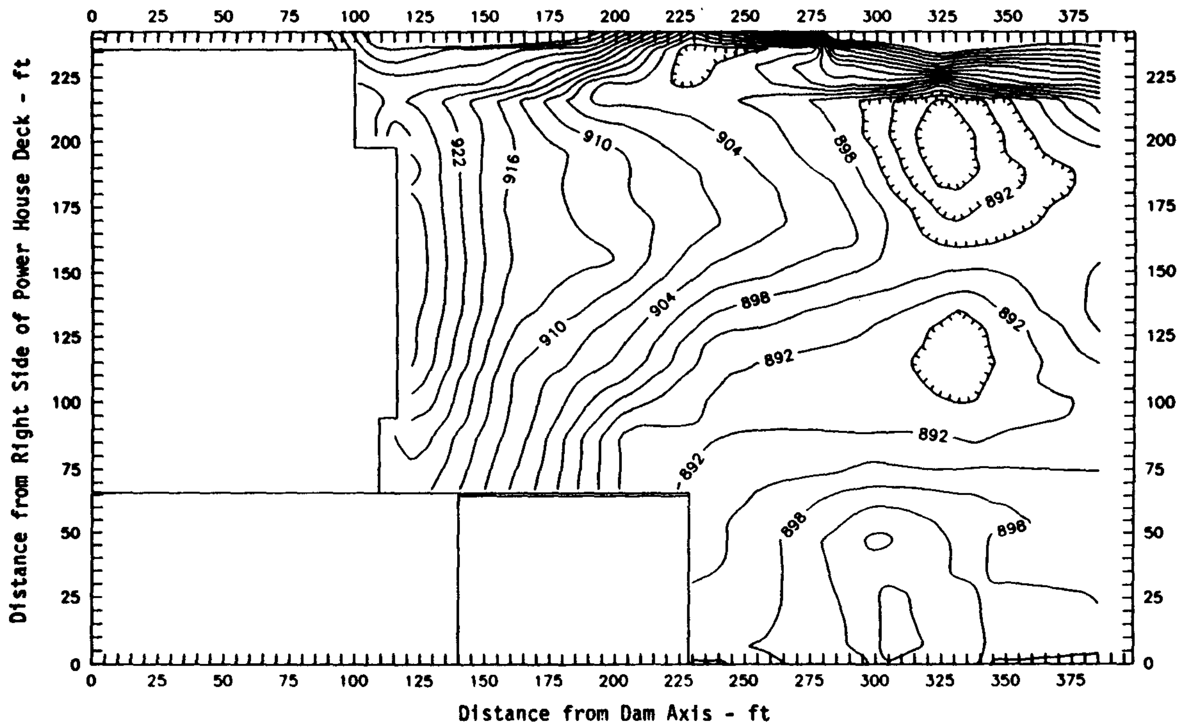


Figure A-12. - Slit-type flip bucket - bed contours after 75 percent of PMF.

★ U.S. GPO: 1990 773-182/20,001

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-7923A, PO Box 25007, Denver Federal Center, Denver CO 80225-0007.