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HYDRAULIC MODEL STUDY OF FOLSOM DAM SPILLWAY PERFORMANCE AND STILLING BASIN ABRASION

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The Bureau of Reclamation's Water Resources Research Laboratory conducted a 1:50-scale model study of the Folsom Dam service spillway and stilling basin. The purpose of the study was to evaluate flow conditions contributing to abrasion damage in the stilling basin and recommend operational and structural methods to minimize future damage. The scope of the study also included development of a new spillway discharge rating and establishment of new spillway and outlet works operational criteria. Model testing determined that nonuniform operation of the spillway crest gates caused recirculating currents in the stilling basin and exit channel. These currents transported loose rocks from the exit channel into the basin. The availability of loose rock in the exit channel, as well as the channel shape, contributed to this phenomenon. The study recommended that the spillway gates be operated uniformly and that the exit channel be reshaped and cleaned of loose rock.

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This hydraulic model study was conducted at the request of the Waterways and Concrete Dams Group of the Bureau of Reclamation's Technical Services Center (TSC). Bruce C. Muller and Ernest W. Hall of that group were instrumental in integrating the model study into the design process and providing critical feedback to the modeling effort. Michael J. Romansky, of the TSC's Geotechnical Engineering Group 2, along with Ernest W. Hall were the primary designers of the exit channel reshaping to achieve a stable condition based on naturally-occurring joints in the channel rock. Ernest W. Hall was also responsible for developing discharge rating curves from the laboratory data.

A number of laboratory staff assisted in the modeling effort. Kathleen H. Frizell was the primary architect of the model design. Neal L. Armstrong and Warren R. King were the principal craftsmen responsible for constructing the model. C. Dean Connor assisted in collection of velocity data, and Jerry R. Fitzwater assisted with many of the graphics used in this report.

Mission Statements

U.S. Department of the Interior

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Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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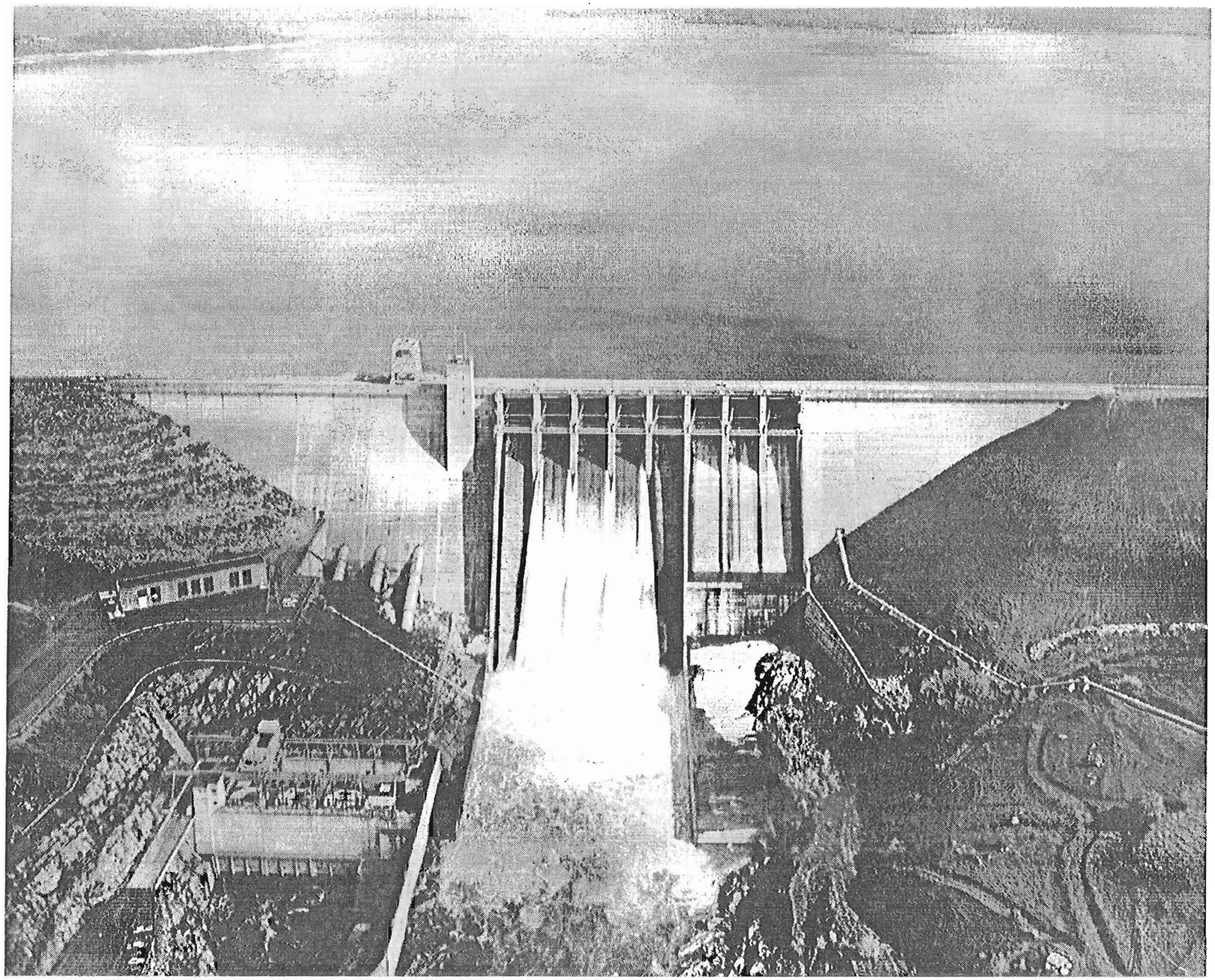


Folsom Dam and Reservoir on the American River near Sacramento, California

EXECUTIVE SUMMARY

Overview

A model study of Folsom Dam spillway performance and stilling basin abrasion was conducted at the Bureau of Reclamation's Water Resources Research Laboratory (WRRL) in Denver, Colorado. The initial purpose of the model study was to investigate the flow conditions which were causing native rock material to be drawn into the stilling basin and recommend operational and/or structural modifications which would help to alleviate these conditions. Subsequently, the scope of the study was expanded to include development of a new spillway-discharge rating curve, evaluation of proposed pier-nose modifications on said rating, and evaluation of general spillway and outlet works operational criteria.

The model study was conducted using a 1:50-scale physical model of pertinent features of Folsom Dam. The scale of the model was chosen to focus on the range of spillway discharges which had occurred during the life of the project (i.e., less than 130,000 ft^3/sec) and were thus related to the historical abrasion damage. Modeled features of the dam included the five 42-ft-wide radial crest gates atop the service spillway, the 242-ft wide service spillway and stilling basin, the eight 5-ft by 9-ft outlet conduits, and approximately 750-ft of topography downstream from the stilling basin, including the stilling basin exit channel and the power plant tailrace channel. Data collected from the model include discharge measurements using the WRRL's venturi flow-metering system, velocity measurements using a Sontek acoustic Doppler velocimeter (ADV), and qualitative flow visualization using indicators such as string or pea gravel placed into the flow.

A consultant review meeting concerning the Folsom Dam stilling basin abrasion issue was held on September 26, 1996. The consultants recommended that a number of structural modifications be evaluated in the model. Four such modifications were briefly evaluated. The tested modifications included adding flow-training walls in the stilling basin exit channel, uniformly raising the stilling basin end sill, raising the stilling basin end sill in the shape of a V-notch, and adding chute blocks at the upstream end of the stilling basin.

A Value Engineering Study of stilling basin abrasion and rehabilitation was performed during the period October 21-25, 1996. Based on life-cycle costs, the study recommended that the basin be rehabilitated in-kind and the rock exit channel be reshaped. Reshaping the stilling basin exit channel, which crested 25 ft higher than the basin end sill, would minimize the gravitational impetus for abrasive rock material to move back towards the stilling basin, remove the existing loose source material from the exit channel, stabilize the exit channel (i.e., minimize the potential for creation of new source material), and provide a "smooth" exit ramp for loose source material that might be created in the future to leave the exit channel and stilling basin area.

Model Observations

Testing in the physical model yielded a number of important observations.

- Nonuniform spillway gate operations created recirculating currents in the exit channel capable of drawing loose rock material into the stilling basin.

- The lower the total spillway discharge, the more sensitive stilling basin flow patterns were to even minor nonuniformities in gate settings.

- Uniform gate operations minimized recirculating currents, but did not completely eliminate the potential for rock material to migrate upstream into the basin.

- The large amount of loose rock material in the exit channel provided a constant source of abrasive material to the stilling basin.

- The 4:1 adverse slope of the stilling basin exit channel provided loose rock material with a gravitational impetus to move downslope towards the basin.

- Structural modifications to the stilling basin and exit channel were unable to overcome the capability of nonuniform spillway releases to move rock.

- A transition zone occurred between spillway gate-control and free-flow wherein the flow was unstable and discharges varied rapidly.

- For nonuniform flow conditions, center-dominated discharges created smaller recirculating currents than left- or right-dominated discharges.

Results and Recommendations

Based on observations from the model study and interdisciplinary consultations, the study yielded several results and recommendations.

- Uniform operation of the spillway gates is the single most effective method to minimize the migration of abrasive rock material into the stilling basin.

- A maximum gate opening variation of 0.5 ft is recommended during uniform spillway gate operations.

- Reshaping the exit channel to flatten the 4:1 adverse slope, remove loose rock material, and create a stable channel condition will further reduce the potential for rock material to migrate into the stilling basin.

- New spillway-discharge rating curves have been developed which take into account the addition of stop-log guides to the spillway-gate pier noses. The new ratings show a 2 percent decrease in spillway capacity (from 567,000 ft^3/sec to 555,000 ft^3/sec) at a reservoir elevation of 475.4 ft.

- Addition of a proposed vortex-reducing stop-log-guide cover would have little discernable impact on the new spillway-discharge rating curves.

- A relationship was developed between spillway discharge and gate opening to assure gate control.

- Although uniform operation is preferred, a single spillway gate or a single outlet conduit may be used with minimal rock-entraining potential, provided that the discharge is held to less than 3,000 ft^3/sec or 2,000 ft^3/sec, respectively.

- If nonuniform operation is necessary, such as during gate changes, it is preferable to temporarily center-dominate the flow rather than left- or right-dominate the flow. Thus, if all gates cannot be opened or closed simultaneously, it is better to open gates near the centerline of the basin first and then work towards the outer gates and reverse the process for gate closings.

- The maximum recommended difference in discharge between any two spillway gates during opening or closing is 3,000 ft^3/sec.

- The maximum recommended difference in discharge between any two outlet conduits on the same level is 2,000 ft^3/sec.

PURPOSE

This report documents a physical model study of the Folsom Dam service spillway and stilling basin. Specific objectives of the study included:

- Investigating the flow conditions which draw rock material upstream into the stilling basin and lead to abrasion damage.
- Evaluating and recommending operational and/or structural modifications to minimize future abrasion damage.
- Developing a new spillway discharge rating.
- Establishing new spillway and outlet works operational criteria for potential reoperation of Folsom Dam.

INTRODUCTION

Folsom Dam is located on the American River upstream and approximately 20 miles northeast of Sacramento, California. Constructed by the U.S. Army Corps of Engineers between 1948 and 1956, Folsom Dam is operated by the U.S. Bureau of Reclamation as part of the Central Valley Project. The dam is composed of a 340-ft-high, 1,400-ft-long concrete gravity section across the river channel, flanked by long earthfill wing dams extending from the ends of the concrete section to both abutments. The resulting reservoir has an active storage capacity of approximately 900,000 acre-ft. Together, the dam and reservoir form a multipurpose facility providing hydropower generation, flood control and water supply storage, and recreational opportunities.

Folsom Dam's concrete gravity section controls releases of water from Folsom Reservoir. The dominant feature of the concrete gravity section is an ogee-crest overflow spillway with a crest elevation of 418.0 ft. Flow over the spillway is controlled by eight 42-ft-wide radial gates (figure 1). Gates 1 through 5 (numbered from the right looking downstream) are 50 ft tall and control flow over the service spillway and into a 242-ft-wide stilling basin with an invert elevation of 115.0 ft (figure 2). Gates 6 through 8 are 53 ft tall and control flow over the emergency spillway and into a flip-bucket energy dissipater. The combined discharge capacity of the service and emergency spillways is 555,000 ft^3/sec at a reservoir elevation of 475.4 ft.

Eight 5-ft-wide by 9-ft-high outlet conduits pass through the concrete gravity section of the dam and emerge on the face of the service spillway. The outlets are configured in two tiers of four outlets each (figures 1 and 2). Flow through each outlet is controlled by a 5-ft by 9-ft slide gate located near the upstream end of the conduit. Discharge jets emanating from the outlets impact in the stilling basin before passing into the American River. The maximum discharge capacity of the outlets is 31,600 ft^3/sec at a reservoir elevation of 475.4 ft.

Folsom Powerplant is located at the foot of the dam along the right side of the concrete gravity section. Water is conveyed from the dam to the powerplant through three 15-ft-diameter penstocks. Discharge through the powerplant is typically 8,000 ft^3/sec or less. A concrete gravity training wall separates flows in the powerplant tailrace channel from flows exiting the stilling basin for a distance of 236 ft downstream from the basin end sill.

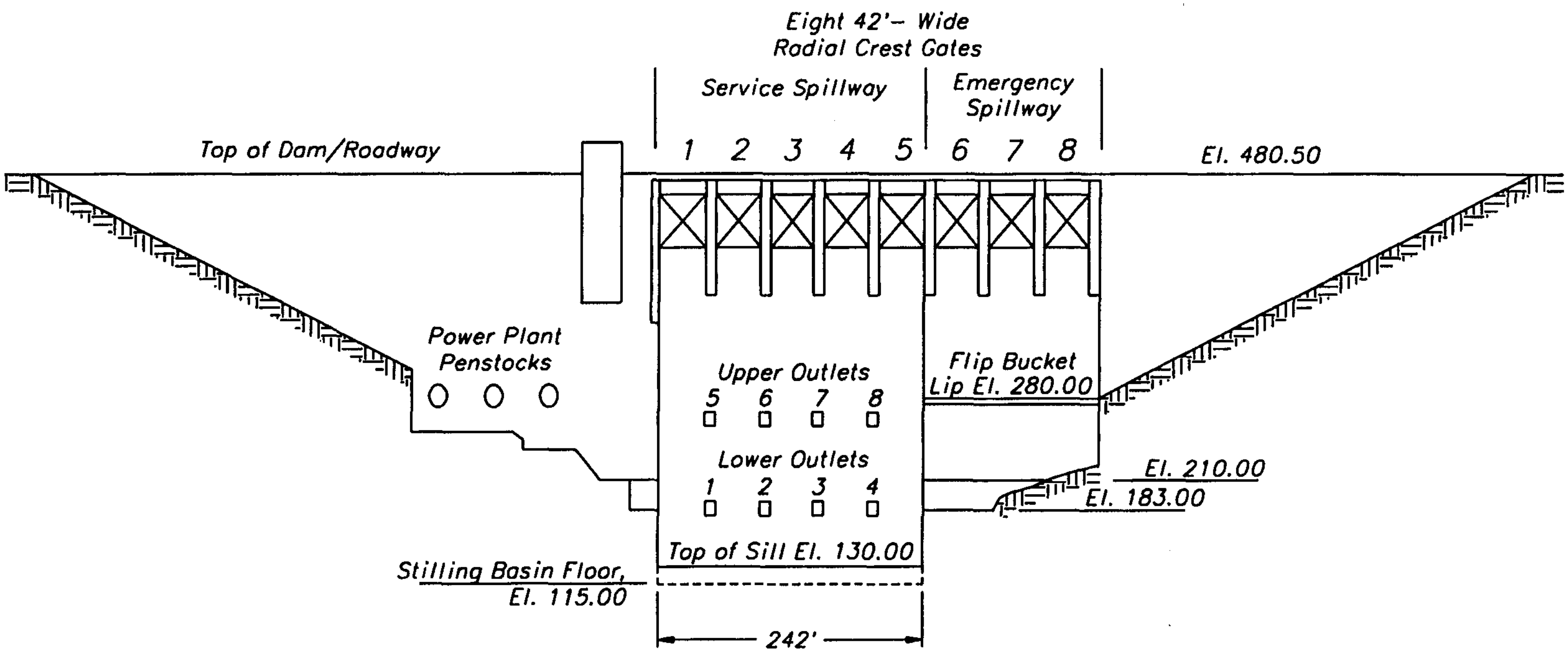


Figure 1.—Folsom Dam's concrete gravity section viewed from downstream.

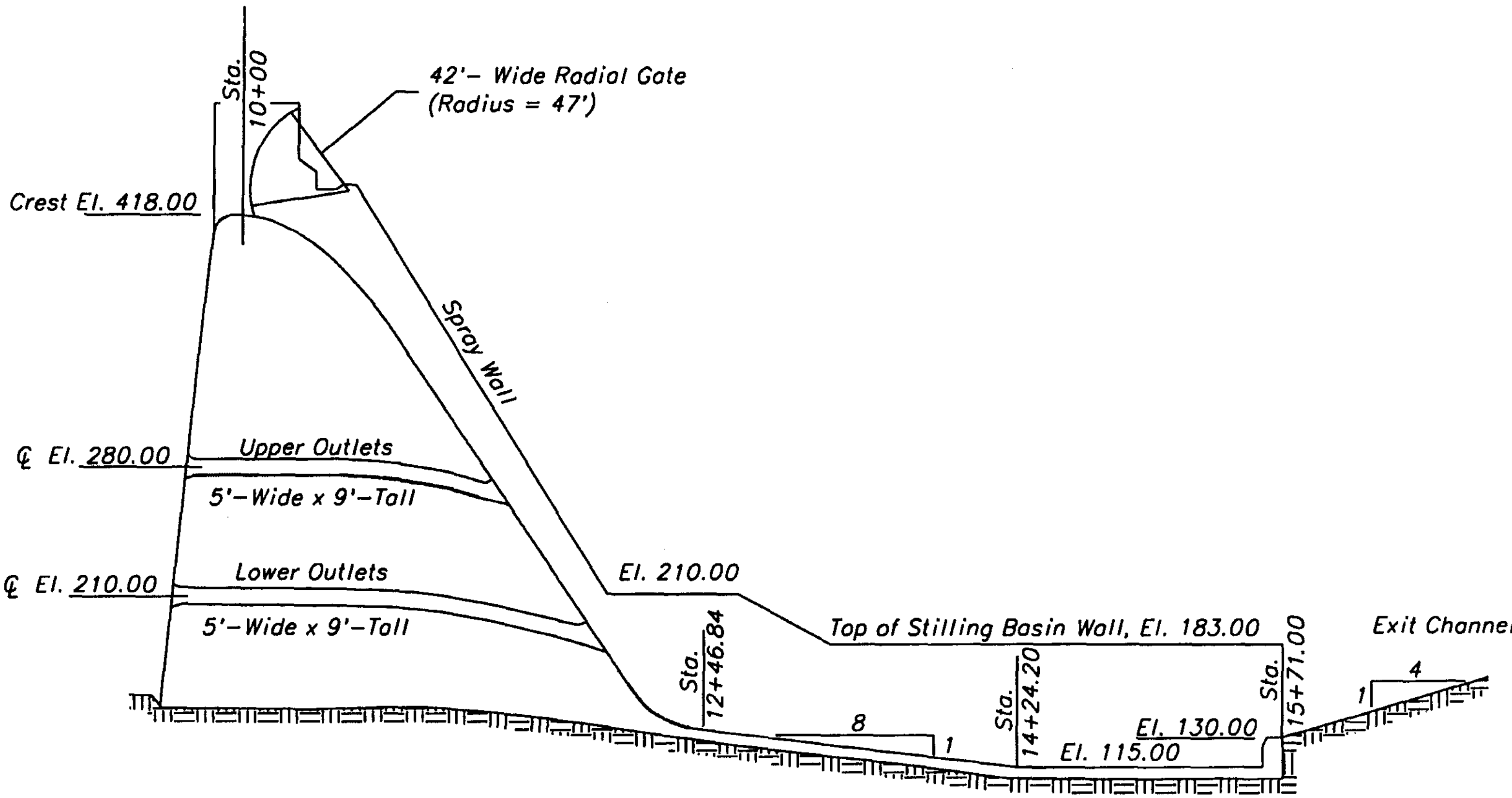


Figure 2.—Section view through Folsom Dam's service spillway and stilling basin.

Stilling Basin Abrasion

Throughout the 42-year operating life of Folsom Dam, the stilling basin at the toe of the service spillway has been periodically inspected for damage. In September of 1965, the stilling basin was dewatered and approximately 300 yd^3 of accumulated rock material was removed from the basin. The removed material ranged in size from gravel up to 2-ft-diameter boulders and was observed to be rounded and smooth. Abrasion damage to the concrete floor of the stilling basin was also noted at that time. Subsequent inspections found further accumulations of rock debris and abrasion damage in the basin.

The most recent removal of rock material from the basin occurred in January 1996, when the basin was dewatered following the July 17, 1995, failure of spillway gate 3. The volume of rock debris removed from the basin totaled approximately 220 yd^3. The debris ranged in size from gravel up to 3.5-ft-diameter boulders (figure 3). A survey of abrasion damage conducted at that time found that up to 2.5 ft of concrete had been eroded from some areas of the basin floor. This represented up to one-half the original floor thickness of 5 ft and constituted a significant maintenance issue requiring attention.

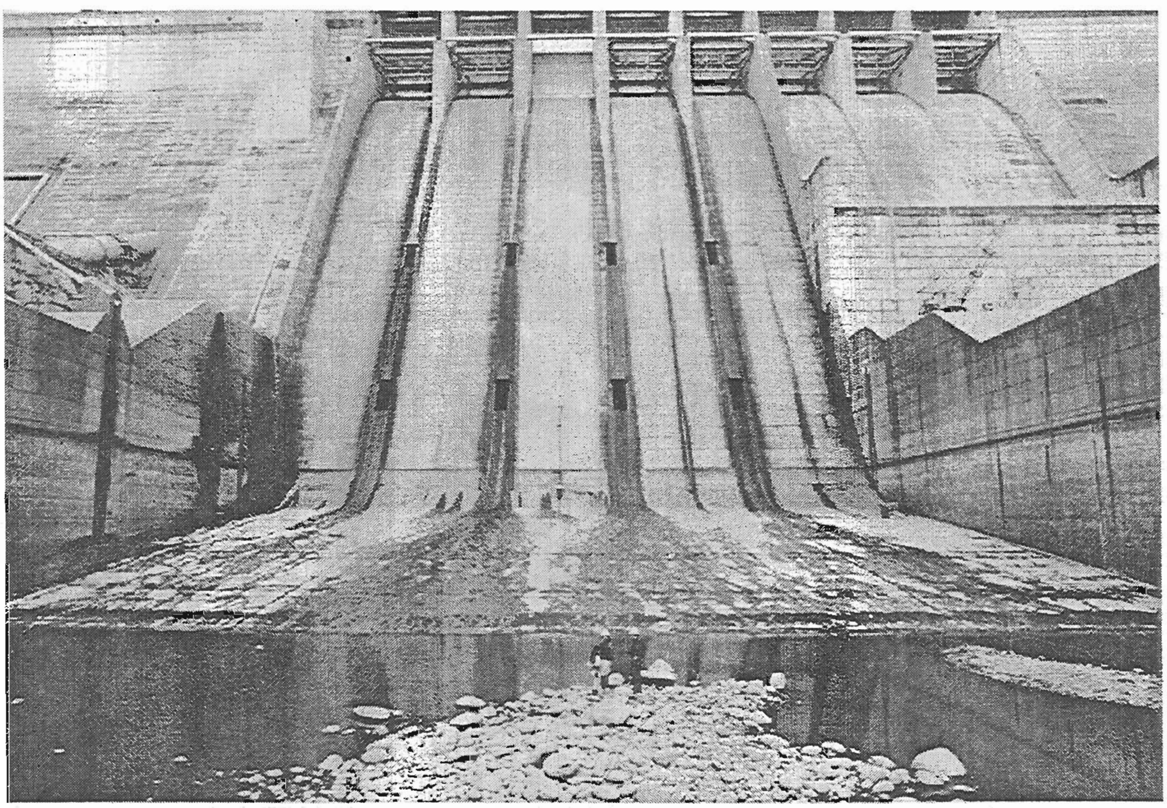


Figure 3.—Folsom Dam's 242-ft-wide service spillway and dewatered stilling basin with accumulated rock debris that caused abrasion damage (1996).

The exit channel downstream from the stilling basin is composed of jointed granite and contains numerous pieces of angular loose rock material remaining from dam construction activities. With no other readily available source of debris, it was concluded that rock material from the exit channel was being drawn upstream into the stilling basin by flow conditions resulting from spillway and outlet works operations. Once rock material entered the basin, the 15-ft-high basin end sill prevented the material from leaving. The trapped rocks were then ball-milled by the turbulent flows within the basin, reducing the angular stones to rounded shapes and causing abrasion damage to the basin floor.

Spillway and Stilling Basin Operations

Flow through Folsom Dam's stilling basin occurs whenever releases are made from the service spillway or the outlet works. Operation of the service spillway and/or outlet works becomes necessary when the required releases from Folsom Dam exceed the discharge capacity of the Folsom Powerplant. This has occurred a number of times during the operational history of the dam. The largest flow passed through the stilling basin was a peak discharge of 122,500 ft^3/sec, which occurred on February 19, 1986.

The failure of spillway gate 3 in 1995 resulted in a sudden release of 40,000 ft^3/sec through the stilling basin (Todd, 1997). To stop the release and repair the gate, a stop-log bulkhead was installed on the upstream side of the gate. Since there were no existing stop-log guides on the structure, a retrofit design was created by attaching 18-in by 22-in I-beams vertically to the upstream noses of the 4-ft-radius piers separating the spillway gates. After installation of the stop-log guides, field personnel observed vortices occurring near the piers on the upstream side of the spillway gates. This led to concern that the addition of the stop-log guides to the pier noses had altered flow conditions through the gates and caused the formation of the vortices. Subsequently, the vortex issue was studied using a numerical modeling approach (Higgs, 1997). That analysis concluded that vortices had always been present at the gates under certain flow conditions, but that the addition of the stop-log guides may have enhanced the formation of vortices.

To maximize the flood control benefits of Folsom Dam, a new operation plan has recently been devised and implemented. The goal of the plan is to reserve additional flood control storage in Folsom Reservoir during the annual flood season. To accomplish this goal, larger releases from the reservoir will be made at lower pool elevations. The result of this change in regulation is that the likelihood of spillway and outlet works releases in any given year is significantly increased. Also, the manner in which the spillway gates will be used to control discharges will change, with an emphasis on free-flow discharges until the downstream levee capacity of 115,000 ft^3/sec is reached, followed by a switch to gate control to maintain the discharge at 115,000 ft^3/sec while the reservoir continues to rise.

PHYSICAL MODEL

To study the flow conditions that contributed to the entrainment of rocks into the stilling basin and ultimately lead to abrasion damage, a 1:50-scale physical model was designed and constructed at the Bureau of Reclamation's Water Resources Research Laboratory in Denver, Colorado (figures 4 and 5). The model scale was chosen to focus on the range of spillway discharges which had occurred during the life of the project (i.e., less than 130,000 ft^3/sec) and were thus related to the historical abrasion damage. The limits of the model were selected to incorporate representations of a portion of Folsom Reservoir, the service spillway, spillway gates 1 through 5, the stilling basin, and approximately 750 ft of channel downstream from the stilling basin (figure 6). After the model was constructed, the scope of the study was expanded to include spillway operation issues related to the pier nose modifications and the new operation plan for the reservoir.

Similitude and Scaling

Froude similarity was chosen to scale the model parameters due to the dominance of gravitational forces in the open-channel flow processes being investigated. For a 1:50-scale model, scaling according to the Froude criteria produces the following relationships between model and prototype parameters:

$L_r = 1{:}50$	(Length ratio)
$V_r = L_r^{1/2} = 1{:}7.071$	(Velocity ratio)
$Q_r = L_r^{5/2} = 1{:}17{,}680$	(Discharge ratio)
$T_r = L_r^{1/2} = 1{:}7.071$	(Time ratio)

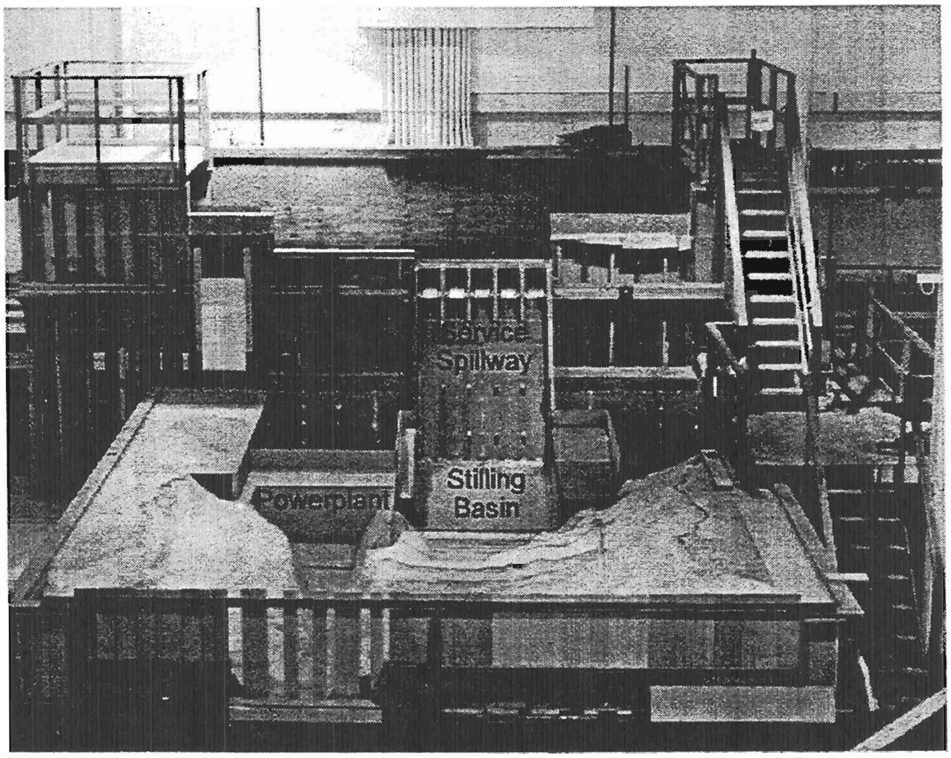


Figure 4.—1:50-scale model of Folsom Dam.

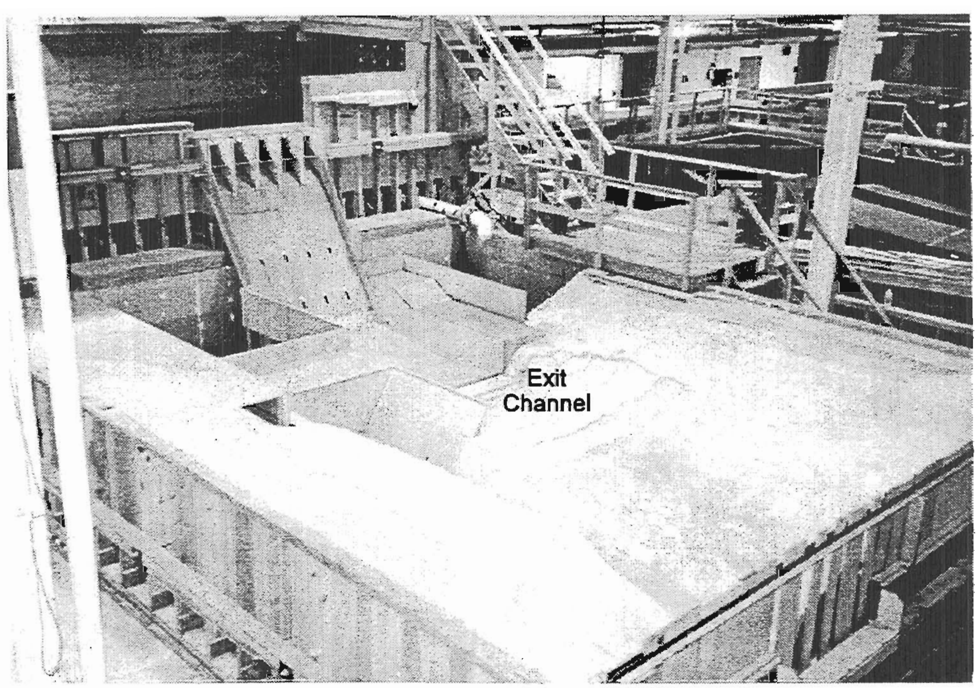


Figure 5.—1:50-scale model of Folsom Dam's service spillway, stilling basin, and exit channel.

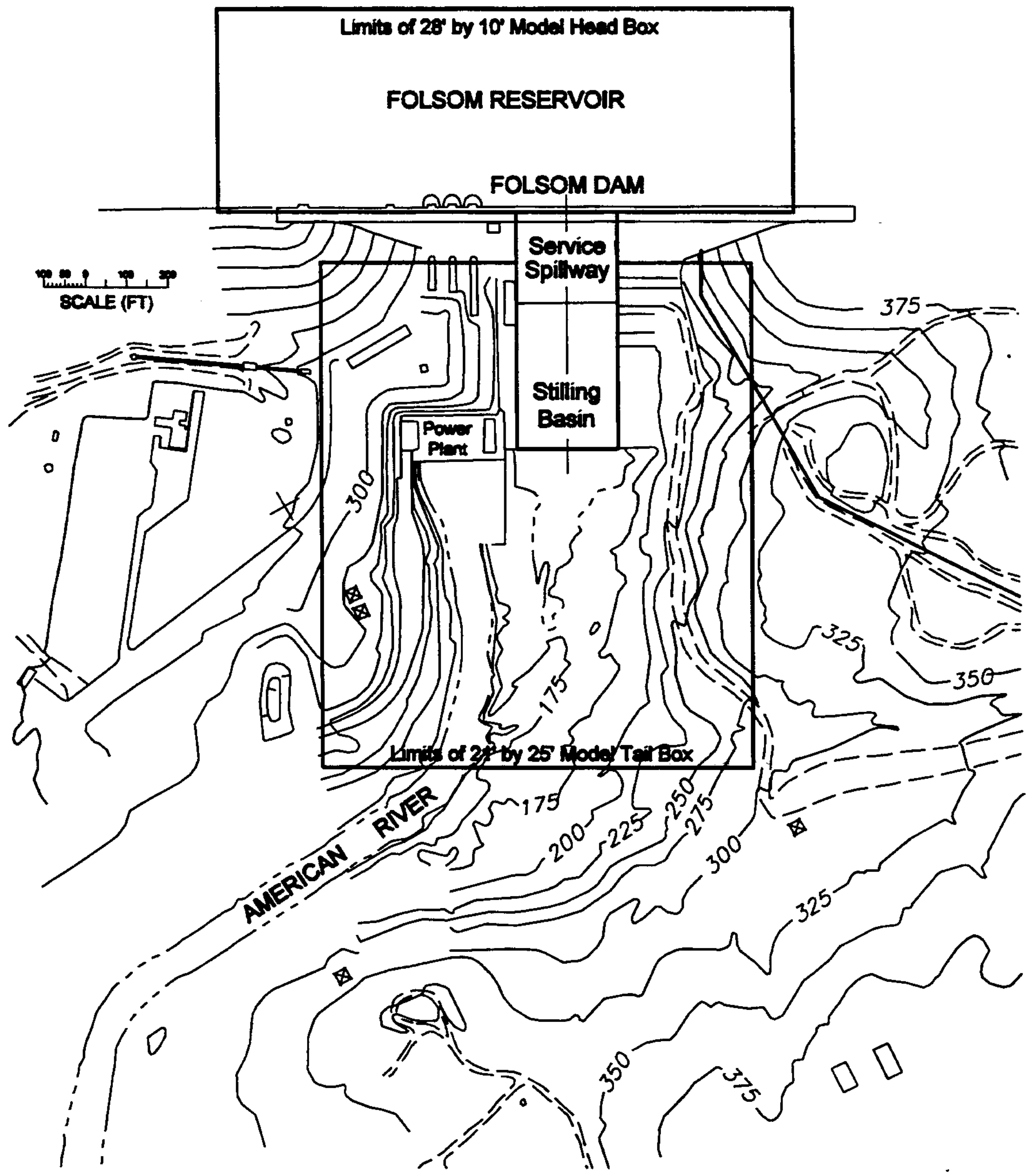


Figure 6.—Plan view of Folsom Dam and Reservoir with physical model limits superimposed.

Construction

The model was constructed using two watertight boxes (see figure 7). The 28-ft by 10-ft upper box served as a head box representing Folsom Reservoir. The 21-ft by 25-ft lower box served as a tail box and contained representations of the stilling basin and the exit channel topography. A steep, sloping channel connected the two boxes and simulated the service spillway. The topography of the area downstream from the stilling basin was created using concrete placed over a wire mesh and plywood contours. The shape of the contours was determined based on aerial topographic data, as well as data from a 1996 ground survey of the stilling basin and exit channel. Flow was supplied to the head box from a 12-in-diameter laboratory piping system. Discharges were measured using a bank of calibrated venturi meters. Flow depth in the tail box was controlled with a series of tailboards at the downstream end of the tail box.

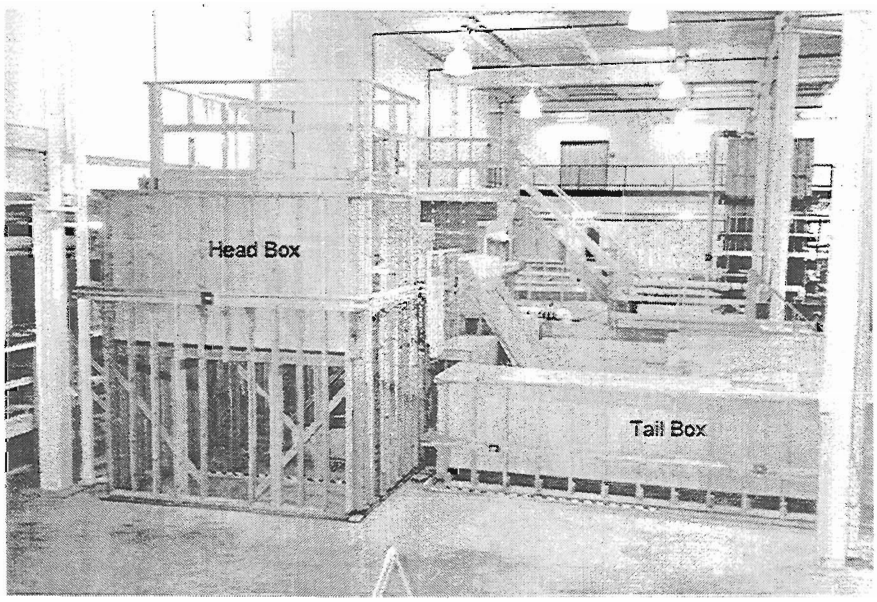


Figure 7.—Folsom Dam model head and tail boxes.

MODEL TESTING

Overview

Tests were conducted using the physical model to achieve several goals. The primary goal was to identify the flow conditions which were moving rock material from the exit channel into the stilling basin and to evaluate operational and structural methods of minimizing these conditions.

The second goal of the testing program was to develop a new spillway discharge rating. The addition of the stop-log guides to the spillway pier noses in 1995 not only raised concerns regarding the formation of vortices, but also called into question the validity of the spillway discharge rating which had been developed prior to the stop-log modification. The existence of the physical model which was constructed to investigate abrasion damage offered an opportunity to reassess the spillway discharge rating with the stop-log guides in place. In addition, the physical model also offered an opportunity to evaluate any discharge rating effects which might result from the addition of a proposed vortex-reducing stop-log-guide cover.

The final goal of the testing program was to develop spillway and outlet works gate operation criteria as part of the reoperation of Folsom Dam. This included identifying constraints on gate operations to minimize the potential for future abrasion damage following reoperation. It also included evaluating the transition between free-flow and gate-control for spillway gate operations in order to provide guidance for prototype operations.

Stilling Basin Abrasion

To investigate the mechanisms by which rock material was transported from the exit channel upstream into the stilling basin, model tests were conducted simulating prototype spillway discharges of 20,000; 50,000; 75,000; and 100,000 ft^3/sec. These discharges were chosen because they represented a range of historical discharges which the stilling basin had experienced. The laboratory data collected from these tests included a mix of qualitative and quantitative observations. The quantitative data consisted of velocity measurements made along the stilling basin end sill using a three-dimensional ADV manufactured by Sontek, Inc. The qualitative data consisted of observation of the stilling basin and exit channel flow patterns using flow visualization techniques such as strings attached to the top of the end sill and the bed of the exit channel and the movement of pea gravel distributed throughout the exit channel.

The ADV velocity measurements along the stilling basin end sill were an attempt to quantify the variation in velocity profiles both vertically in the water column and transversely across the end sill. At each point in the transect, velocity measurements were made for a period of 1 minute at a sampling rate of 25 Hz, yielding a total of 1,500 measurement values. Each set of 1,500 values was subsequently filtered to remove poor data, and the remaining values were averaged to determine the mean velocity at each location. While data were gathered in this manner for all of the discharge conditions tested, it quickly became apparent that as the spillway discharge increased, the amount of air entrainment and number of air bubbles occurring in the stilling basin flow also increased. This resulted in a decrease in the quality of the acoustic signal processed by the ADV and a subsequent loss in velocity measurement accuracy. Thus, while the velocity data set collected for the 20,000 ft^3/sec discharge was of excellent quality, each increase in discharge resulted in more air in the flow and less usable data to evaluate. For this reason, it was primarily the qualitative observations of flow patterns in the stilling basin and exit channel that were used to investigate rock movement into the stilling basin. The quantitative ADV data were used as a supplement to support these visual observations.

Contributing Flow Conditions

The testing program began with the hypothesis that the high-velocity jet of flow entering the stilling basin plunged to the basin floor and then separated from the floor, moving towards the surface as the flow passed out of the stilling basin and over the exit channel. In the separation zone beneath the rising jet a vertical roller would form which would then sweep rock material along the bed and upstream into the stilling basin. Such action had been observed in similar studies of other stilling basins (Hanna, 1996; Hanna and Cohen, 1997). Preliminary tests with uniform spillway gate settings over the range of discharges, however, failed to produce any indication of this type of action in the Folsom basin.

Testing of nonuniform spillway gate settings quickly revealed an alternative mechanism for the formation of rock-entraining recirculating currents in the Folsom stilling basin and exit channel. When the five 42-ft-wide service-spillway radial gates were not operated with identical gate openings, recirculating currents in the horizontal plane (i.e., rotating about a vertical axis) could easily be set up in the stilling basin and exit channel. This effect was demonstrated most dramatically at 20,000 ft^3/sec. With all spillway gates set equally to a 2.5-ft-prototype opening (measured vertically from the gate seat to the bottom lip of the gate) all flow crossing the end sill of the stilling basin moved in a downstream direction, with no recirculating currents evident. Pea gravel placed in the exit channel, ranging in size from 1/4-inch to 3/8-inch, was stable under this flow condition. When the opening of the right two gates (Gates 1 and 2) was increased slightly to 3-ft-prototype, the resulting imbalance of the spillway discharge created a counter-clockwise recirculating current in the stilling basin and exit channel. Flow exited the basin along the right wall while flow entered the basin along the left wall. This condition was clearly shown by the indicator strings attached to the end sill and bed of the exit channel (figure 8) and the movement of pea gravel upstream into the stilling basin over the left half of the end sill. Velocity measurements made along the end sill supported the visual observations, clearly indicating negative (upstream) velocities along the left half of the end sill (figure 9).

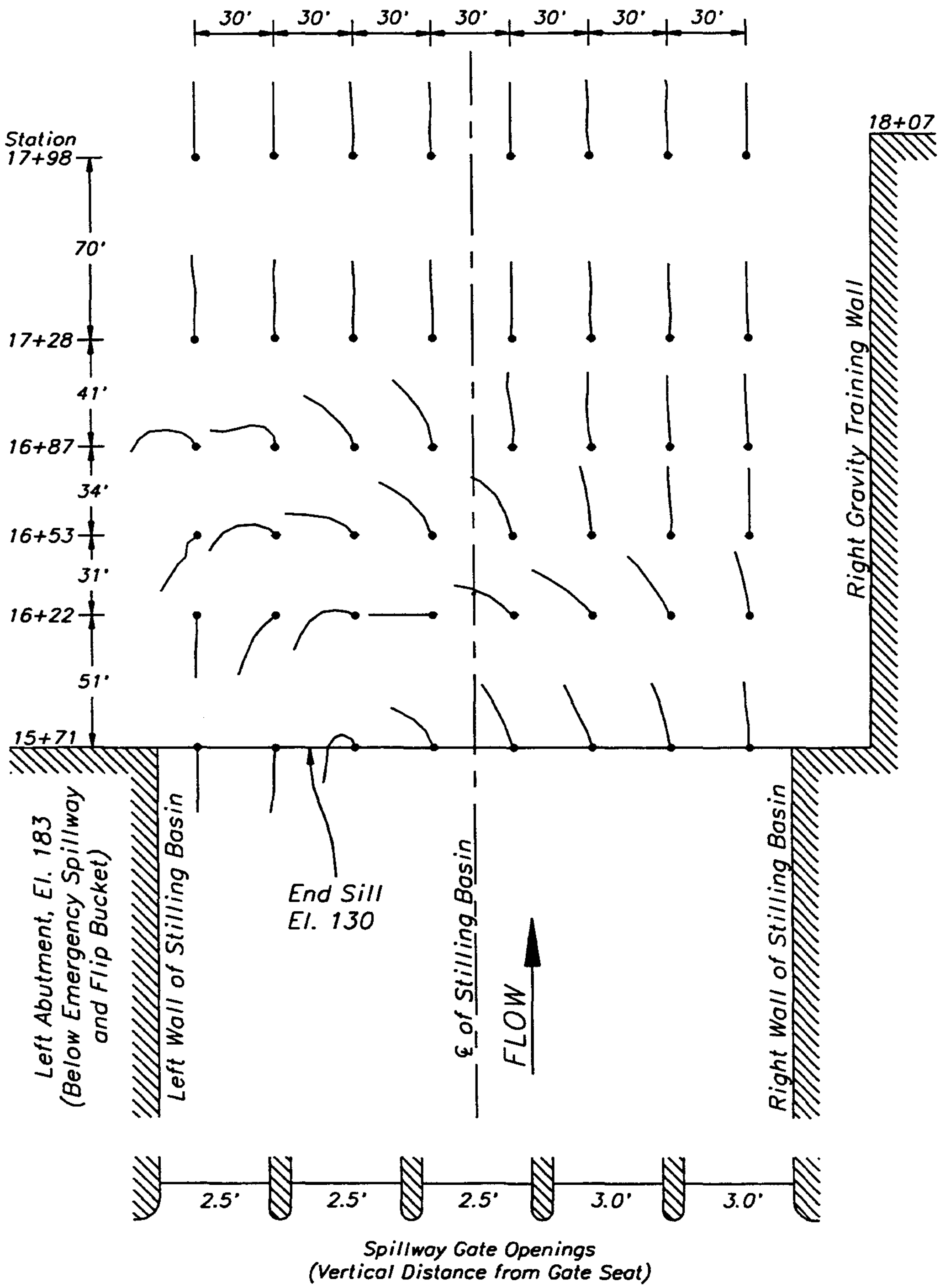


Figure 8.—Exit channel flow direction as indicated by bed-mounted strings for a nonuniform discharge of 20,000 ft^3/sec.

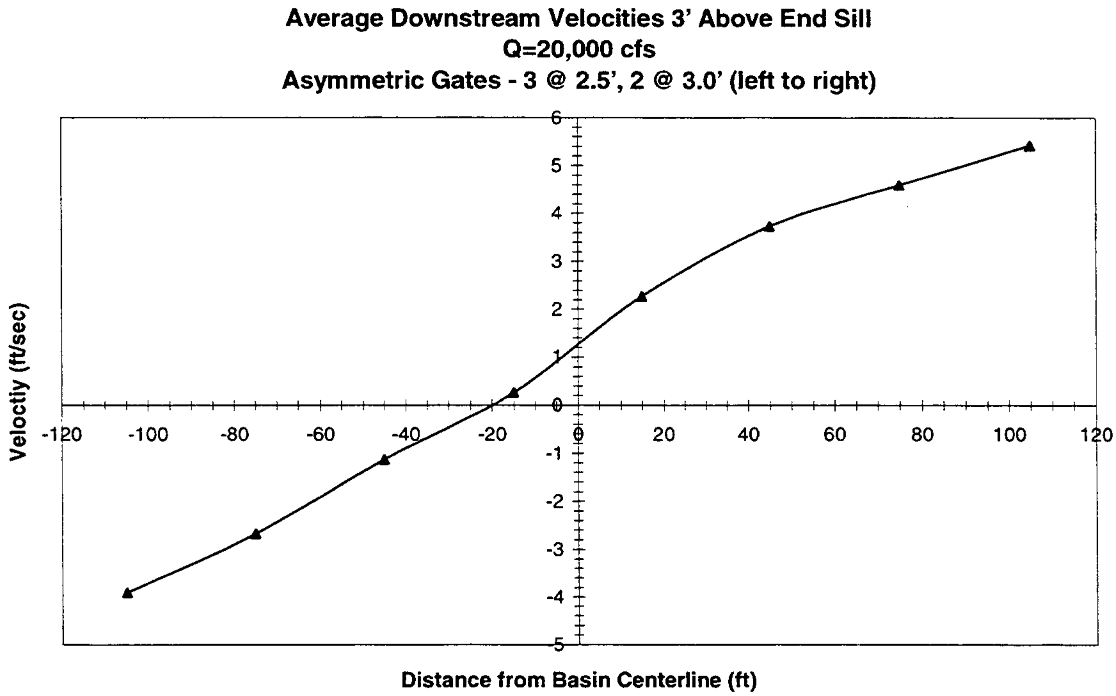


Figure 9.—Velocity profile along the stilling basin end sill for a nonuniform spillway discharge of 20,000 ft^3/sec.

Unbalanced spillway discharges due to nonuniform spillway gate operations created recirculating flow conditions similar to those observed for the 20,000 ft^3/sec condition for all of the discharges tested. The only significant variation of this trend with discharge was the amount of nonuniformity of gate position required to create recirculating flow conditions. As a general rule, the larger the total spillway discharge, the larger the variation in gate settings required to generate a well-defined recirculating current in the stilling basin and exit channel. Table 1 summarizes the spillway conditions which yielded well-defined recirculating currents.

Table 1. Nonuniform gate settings resulting in well-defined recirculating currents.

Total Spillway Discharge (ft^3/sec)	Prototype Vertical Gate Opening (ft)				
	Gate 1	Gate 2	Gate 3	Gate 4	Gate 5
20,000	3.0	3.0	2.5	2.5	2.5
50,000	10.0	10.0	6.0	6.0	6.0
100,000	19.0	19.0	10.0	10.0	10.0

The large recirculating currents could adopt either a clockwise or counterclockwise rotating pattern, depending upon whether the nonuniform spillway discharge was either left-dominated or right-dominated, respectively. The upstream-directed velocities associated with the recirculating currents were observed to occur in the exit channel at distances as far as 100 to 150 ft downstream from the stilling basin end sill.

Uniform Gate Operation

For all discharges tested, it was possible to draw loose rock material (pea gravel) from the exit channel and into the stilling basin by introducing nonuniformity into the spillway gate openings. Uniform operation of the spillway gates greatly improved the flow patterns in the stilling basin, virtually eliminating the strong recirculating currents so evident with nonuniform gate operation. Uniform operation did not, however, completely remove the potential for rock material to migrate from the exit channel into the stilling basin.

As uniform spillway discharges plunged into the stilling basin, the flow tended to spread laterally until encountering the basin side walls. This concentrating of the basin flow along the side-walls resulted in a nonuniform velocity profile across the stilling basin end sill, with higher velocity flow occurring near the side-walls, and lower velocity flow occurring near the basin centerline. Figure 10 depicts such a profile measured for a uniformly-gated spillway discharge of 100,000 ft³/sec.

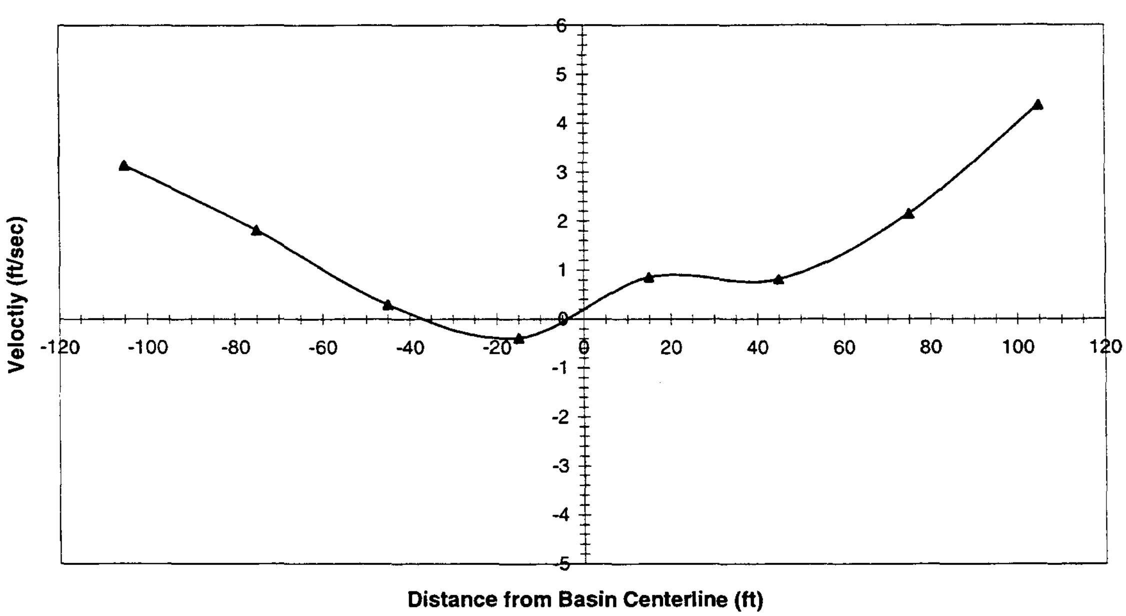


Figure 10.—Velocity profile along the stilling basin end sill for a uniform spillway discharge of 100,000 ft³/sec.

Weakness of the flow field near the center of the basin was observed with all uniform spillway discharges tested. Higher discharges, however, exhibited a much more pronounced variation in flow velocities from the side-walls of the stilling basin to the centerline. In these cases the average flow velocity measured near the centerline of the basin would sometimes be negative (i.e., moving upstream and into the basin) (figure 10). Under these conditions, the average negative velocities occurring near the centerline, combined with an occasional burst of negative velocity resulting from turbulence, were sometimes sufficient to move loose rock material from the near-field of the exit channel upstream and into the basin.

Structural Alternatives Considered

Observation of stilling basin and exit channel flow conditions over a range of discharges and gate operating conditions clearly demonstrated that the potential for exit channel rock material to migrate into the stilling basin could be greatly reduced by uniform gate operation. At low flows, in particular, flow conditions in the basin and exit channel were very sensitive to even minor inconsistencies in spillway gate openings.

An external consultant review board, convened on September 26, 1996, to consider the Folsom Dam abrasion problem and the model study findings to-date, agreed with the validity of these findings, but also recommended that additional consideration be given to structural alternatives which might eliminate the potential for abrasion damage regardless of spillway gate operating conditions. The consultants offered suggestions for a number of possible structural modifications which could be evaluated in the model to deal with the stilling basin abrasion problem. Of these alternatives, four stilling basin/exit channel enhancements were selected for evaluation in the model based on their perceived potential for success. These four modifications are depicted in figures 11(a-d).

The first modification (figure 11a) consisted of raising the end sill of the stilling basin 15 ft from a top elevation of 130 to a top elevation of 145. The premise of this action was that raising the end sill would force the flow exiting the stilling basin through a smaller cross-sectional area, resulting in higher overall velocities and increased headlosses. It was hoped that this constriction of the exit from the basin would force the basin flow to more uniformly distribute across the basin end sill, regardless of the spillway inflow conditions. Testing indicated that there was some truth to this hypothesis in that, while the raised end sill could not prevent recirculating currents from forming, it did necessitate a larger nonuniformity of gate operations before negative velocities over the end sill were observed. The undesirable aspect of this approach was that a strong vertical roller formed on the downstream side of the raised sill for all flow conditions, drawing loose rock material in the near-field of the exit channel upstream to the lee side of the sill. Fortunately, the raised sill acted as a rock trap, holding the upstream-moving rocks on the downstream side of the sill so that no rock material moved into the basin.

The second modification (figure 11b) consisted of raising the end sill in the shape of a V-notch, with a raise of 20 ft at either end of the sill varying linearly down to none at the center of the sill. As with the uniformly-raised end sill, the purpose of this modification was to generally restrict the exit flow area of the stilling basin while encouraging more flow to pass over the center of the end sill rather than along one or both ends. The result of this modification was even less satisfactory than for the uniformly-raised end sill. The V-notch end sill had a relatively minor effect on the observed flow distribution across the end sill when compared to the unmodified sill. For uniform flow conditions, flow passing over the raised portion of the V-notch created a vertical roller on the downstream side of the sill which tended to move loose material in the exit channel back towards the end sill and then laterally towards the center of the channel where the V-notch was lowest. For nonuniform flow conditions, recirculating currents occurred in the stilling basin and exit channel, and some loose material in the exit channel moved into the stilling basin over the lowest (center) portion of the V-notch end sill.

The third modification (figure 11c) consisted of adding 24 5-ft-high by 5-ft-wide chute blocks to the upstream end of the stilling basin at the toe of the spillway. These blocks were placed on 10 ft centers, yielding 5 ft of clear space between adjacent blocks. The goal of this modification was to break up the jet of flow entering the stilling basin in order to more uniformly distribute the flow across the width of the basin. In reality, the chute blocks had no visible impact on the stilling basin performance for either uniform or nonuniform spillway discharges. This was most probably due to the fact that the rising topography of the exit channel crested at elevation 155, maintaining a minimum of 40 ft of water above the stilling basin floor elevation of 115. This depth of water in the stilling basin was sufficient to dissipate the spillway jet without chute blocks.

The final modification (figure 11d) consisted of adding 2 flow-training walls to the exit channel beginning at the end sill of the stilling basin and extending 115 ft downstream along lines parallel to and offset from the basin centerline by 40 ft. The top elevation of these walls was 155, 25 ft above the top of the end sill. The purpose of the walls was to intercept recirculating currents induced by nonuniform gate operation and to redirect that flow in a downstream direction. In practice, however, the flow-training walls only intercepted a portion of the recirculating flows. The smallest test discharge (20,000 ft^3/sec) yielded a water-surface elevation of 169 at the basin end sill, 14 ft above the top of the flow-training walls. Thus, rotating currents in the exit channel poured over the top of the walls and created vertical rollers which drew material up against the lee side of the walls. Material beyond the reach of the vertical rollers was mobilized by the recirculating currents and pushed towards the stilling basin.

In the final analysis, all of the structural alternatives tested were found to be lacking. The raised end sill modification (modification #1) was the only option to completely exclude loose rock material from the stilling basin due to the fact that it created an effective 15-ft-high rock trap on its downstream side. It was rejected, however, due to concerns regarding the eventual buildup of rock material overtopping the raised sill and entering the basin, as well as structural concerns regarding the stability of a 15-ft-high vertical wall subjected to the strong and surging hydraulic forces of high stilling basin flows. The remaining options had little or no impact on the distribution and direction of flow velocities at the stilling basin end sill, either for uniform or nonuniform spillway operations, and thus were ineffective at keeping loose rock material out of the stilling basin. The exit channel flow-training walls (modification #4) did have some impact on the nature of the recirculating currents in the exit channel. For this option to become fully effective, however, the walls would have to extend up to the water surface to prevent spillover. The highest discharge tested (100,000 ft^3/sec) would require a top wall elevation of 186, 56 ft above the top of the basin end sill. This was considered impractical due to stability concerns for a 56-ft-high, unsupported wall subjected to varying hydraulic forces.

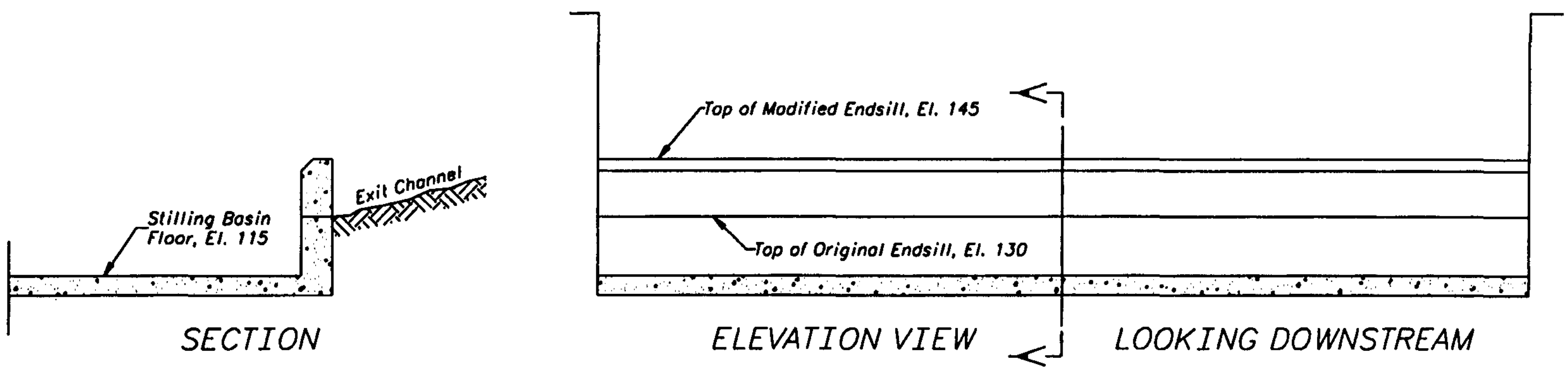


Figure 11a.—Structural modification #1, basin end sill raised 15-ft.

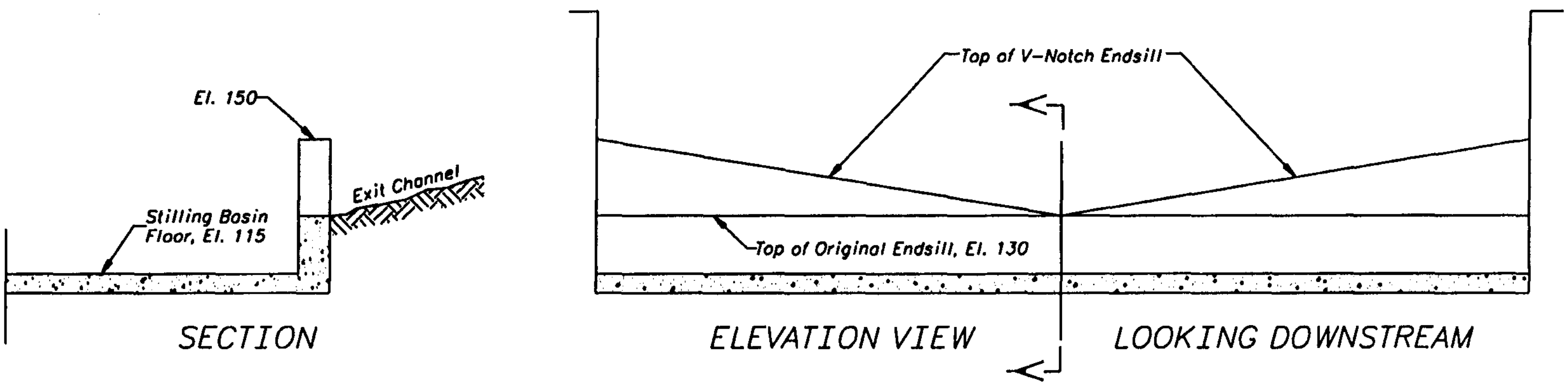


Figure 11b.—Structural modification #2, basin end sill raised 20-ft in a V-notch style.

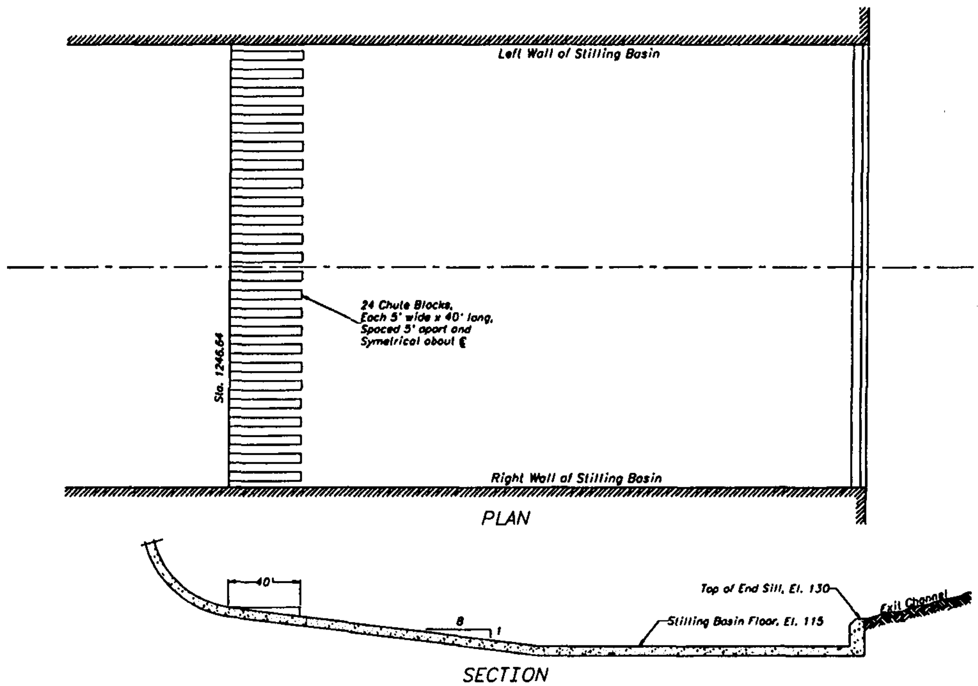
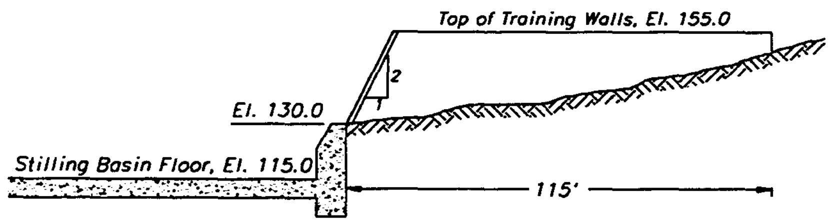
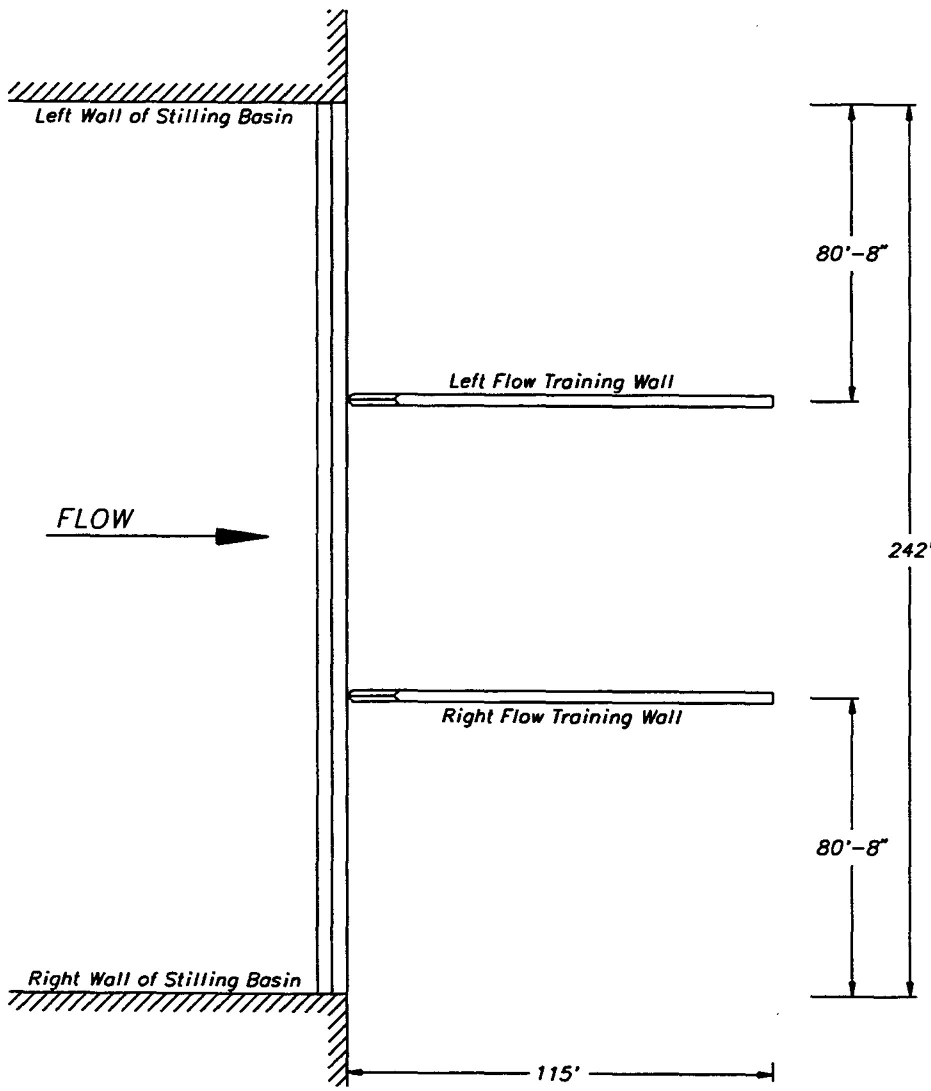


Figure 11c.—Structural modification #3, chute blocks added to stilling basin.



SECTION VIEW



PLAN VIEW

Figure 11d.—Structural modification #4, flow training walls added to exit channel.

Exit Channel Reshaping

Although model testing clearly indicated that spillway gate operations caused the movement of exit channel rock material upstream into the stilling basin, model and prototype observations also indicated that the condition of the exit channel played a significant role in the process. The bed of the exit channel was comprised of granite rock with numerous shears and joints. Loose rock material was abundantly available throughout the entire exit channel (figure 12), much of it left in place from the original excavation. The exit channel topography sloped upward at approximately a 4H:1V slope moving downstream away from the basin end sill (figure 13). Loose rock material resting on this slope had a gravitational impetus to move downhill (towards the stilling basin) which exacerbated the effects of any flow-induced recirculating currents. Therefore, lower recirculating velocities were needed to mobilize this loose material and move it into the stilling basin. A low area in the exit channel topography (figure 13) also tended to collect loose rock material during uniform flow conditions which then provided source material to enter the basin under recirculating flow conditions.

As part of the design process to alleviate abrasion damage and rehabilitate the stilling basin, a Value Engineering Study was conducted during the week of October 21-25, 1996. This study recommended that the concrete in the stilling basin be restored to its original condition, the spillway gates be automated to establish better gate position control (i.e., minimize the potential for nonuniform operation), and the exit channel of the stilling basin be excavated to establish a new channel shape. The latter recommendation was formulated to achieve three primary goals.

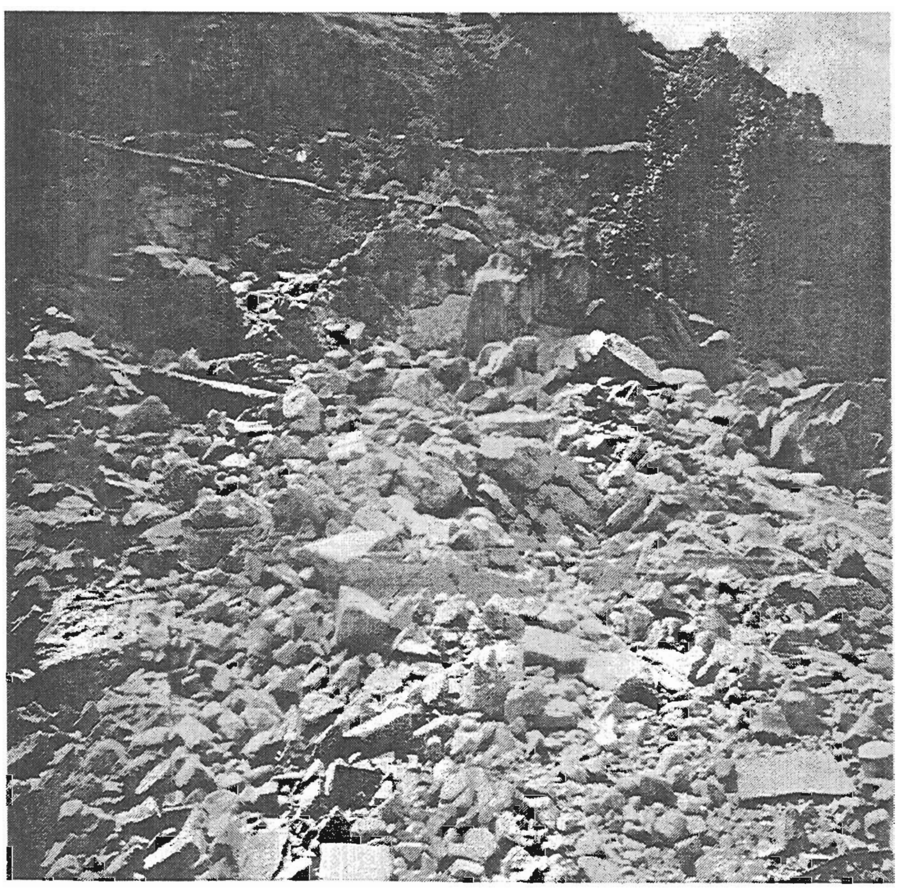


Figure 12.—Loose rock and faulted rock in the Folsom Dam exit channel.

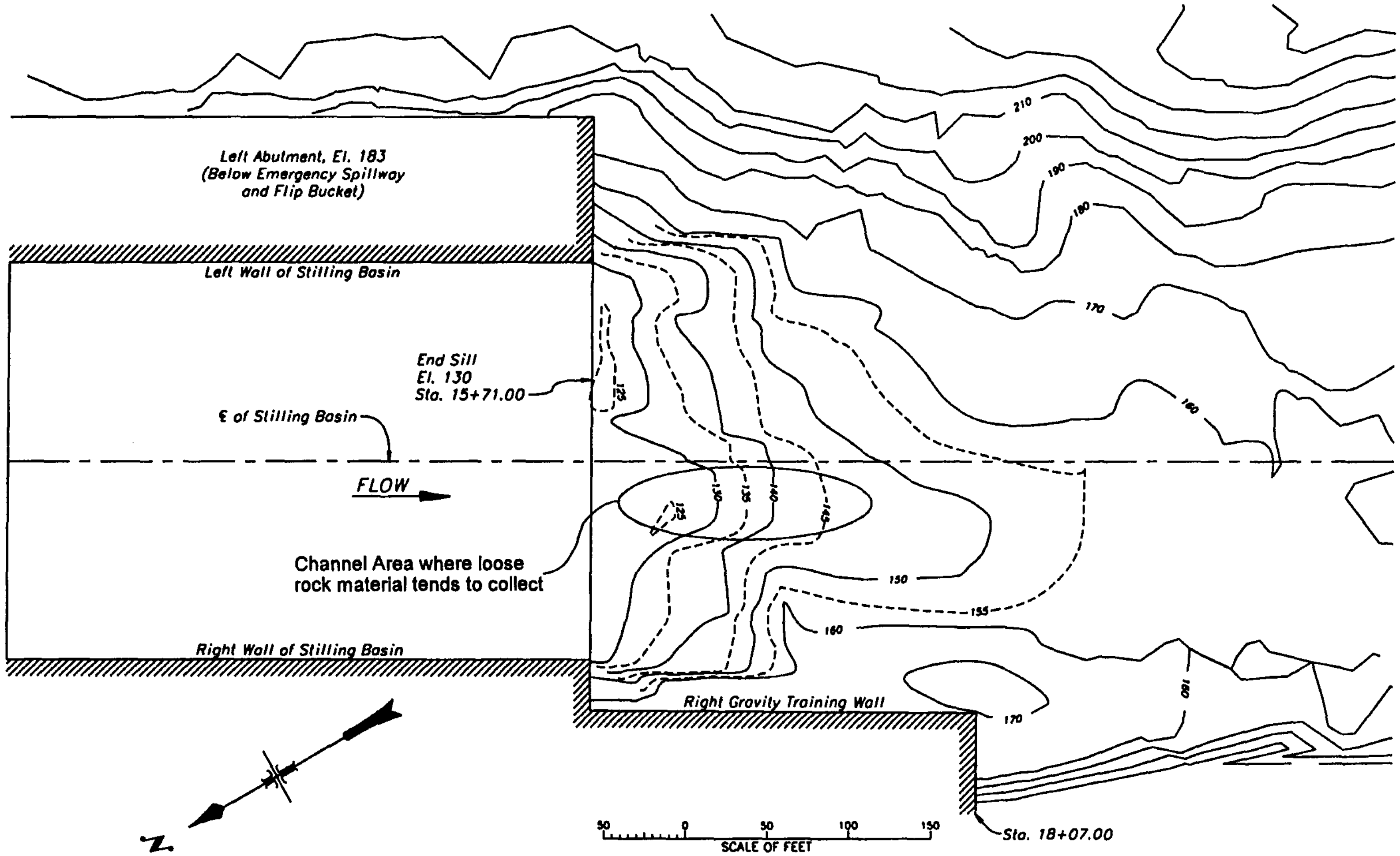


Figure 13.—Plan view of original stilling basin and exit channel topography.

The first goal of the exit channel reshaping was to eliminate the gravitational predisposition of loose material in the exit channel to move upstream into the basin by flattening out the 4H:1V uphill slope moving away from the basin. Instead, the exit channel would feature a flat area for the first 50 ft downstream of the basin end sill, followed by a more gradual 8H:1V slope up to the maximum invert elevation of 155. It was necessary to maintain the maximum invert elevation of 155 in the exit channel to avoid lowering the stilling basin tailwater elevation which might negatively impact the energy-dissipation performance. Reshaping the exit channel in this fashion would not only minimize the tendency for rock material to roll back towards the stilling basin, but would also create a smoother exit ramp by which loose material might more easily be transported downstream and away from the basin under sufficiently strong flow conditions.

The second goal of the exit channel reshaping was to remove as much of the existing loose rock material from the exit channel as possible. By removing the loose rock material, the availability of source material for abrasion damage could be greatly reduced or eliminated. By reshaping the channel in the manner described previously, not only could the loose rock material be removed, but the low area where loose material tended to collect could also be eliminated.

The final goal of the exit channel reshaping was to stabilize the bed material of the exit channel to prevent rock material from breaking free and providing new loose source material for abrasion damage. To achieve this goal, the shape of the reconfigured exit channel was chosen to follow naturally-occurring joint patterns in the exit channel rock whenever possible. The resulting exit channel topography is depicted in figure 14. To reach stable rock, the flat area immediately downstream from the basin end sill was specified with a top elevation of 125, 5 ft below the end sill crest elevation of 130. This resulted in the additional benefit of creating a 5-ft-deep rock trap on the downstream side of the end sill. Figure 15a depicts the location of six exit channel cross-sections which were used to define the modified exit channel topography, while figures 15b and 15c compare the original and modified section geometry for each of these sections.

Laboratory tests were conducted simulating a 20,000 ft^3/sec nonuniform spillway discharge and a 70,000 ft^3/sec uniform spillway discharge for both the original and modified exit channel configurations. Prior to each test, painted pea gravel was placed in four distinct color zones representing 50-ft-long segments of the exit channel downstream from the stilling basin end sill. Each test was run for a period of 3 hours 25 minutes, which simulated a 24-hour time period in the prototype. At the conclusion of each test, the cumulative movement and final location of the colored pea gravel was observed.

The most significant difference between the performance of the original and modified exit channels was in the amount of pea gravel migrating into the stilling basin. For the unmodified, nonuniform flow test, 31 percent of the pea gravel placed in the 50 ft of exit channel immediately downstream from the stilling basin was carried into the basin by the strong recirculating currents. For the unmodified, uniform flow test, 1.2 percent of material from the same area was carried into the basin by the weak and fluctuating velocities over the center of the end sill. When both tests were repeated with the modified exit channel no material was carried into the basin. This improvement in performance can be attributed to the general stability of rock material in the 50-ft flat portion of the modified exit channel, as well as the effective rock trap created by having the basin end sill 5 ft higher than the bed of the exit channel in this area.

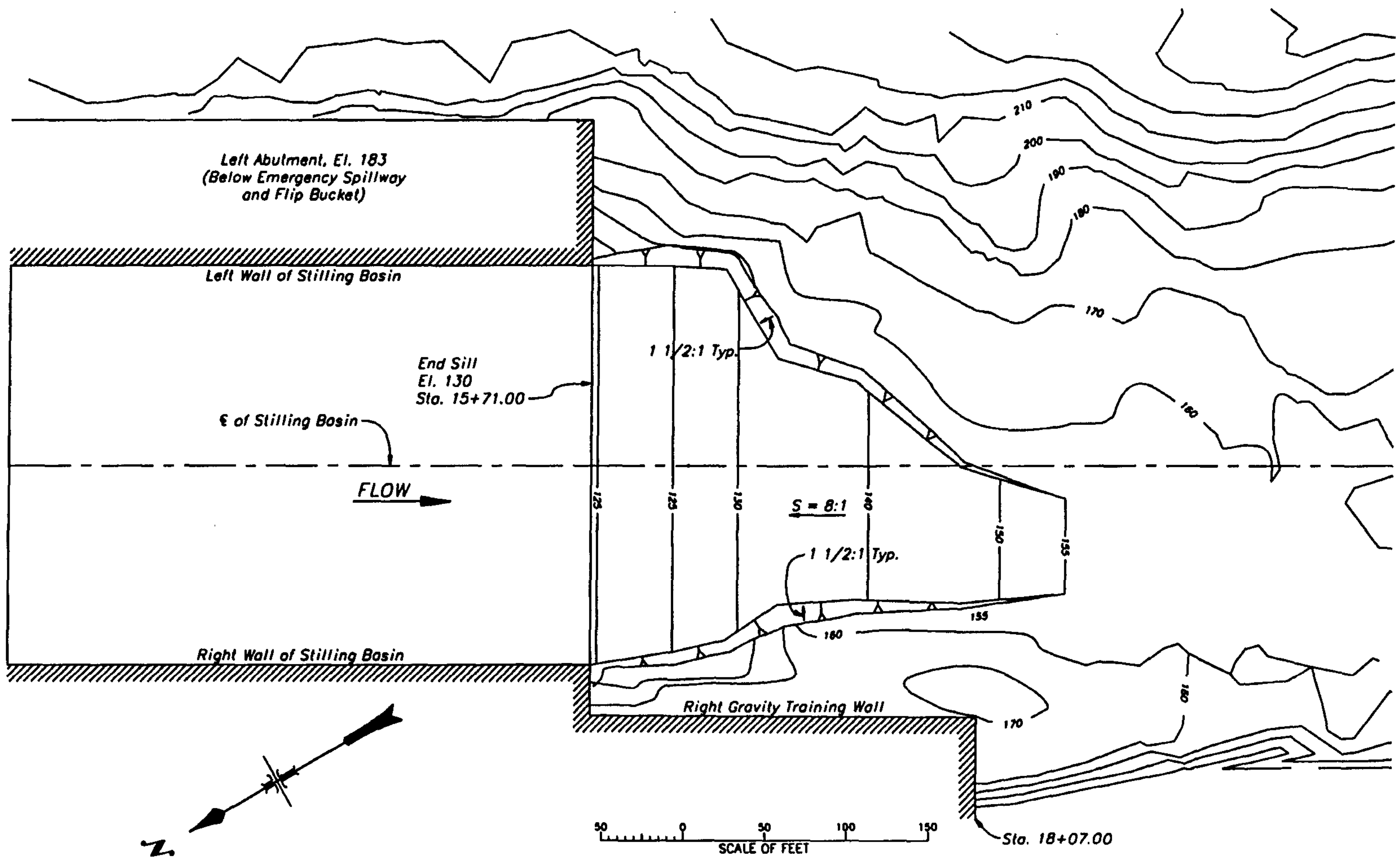


Figure 14.—Plan view of stilling basin and exit channel topography after excavation.

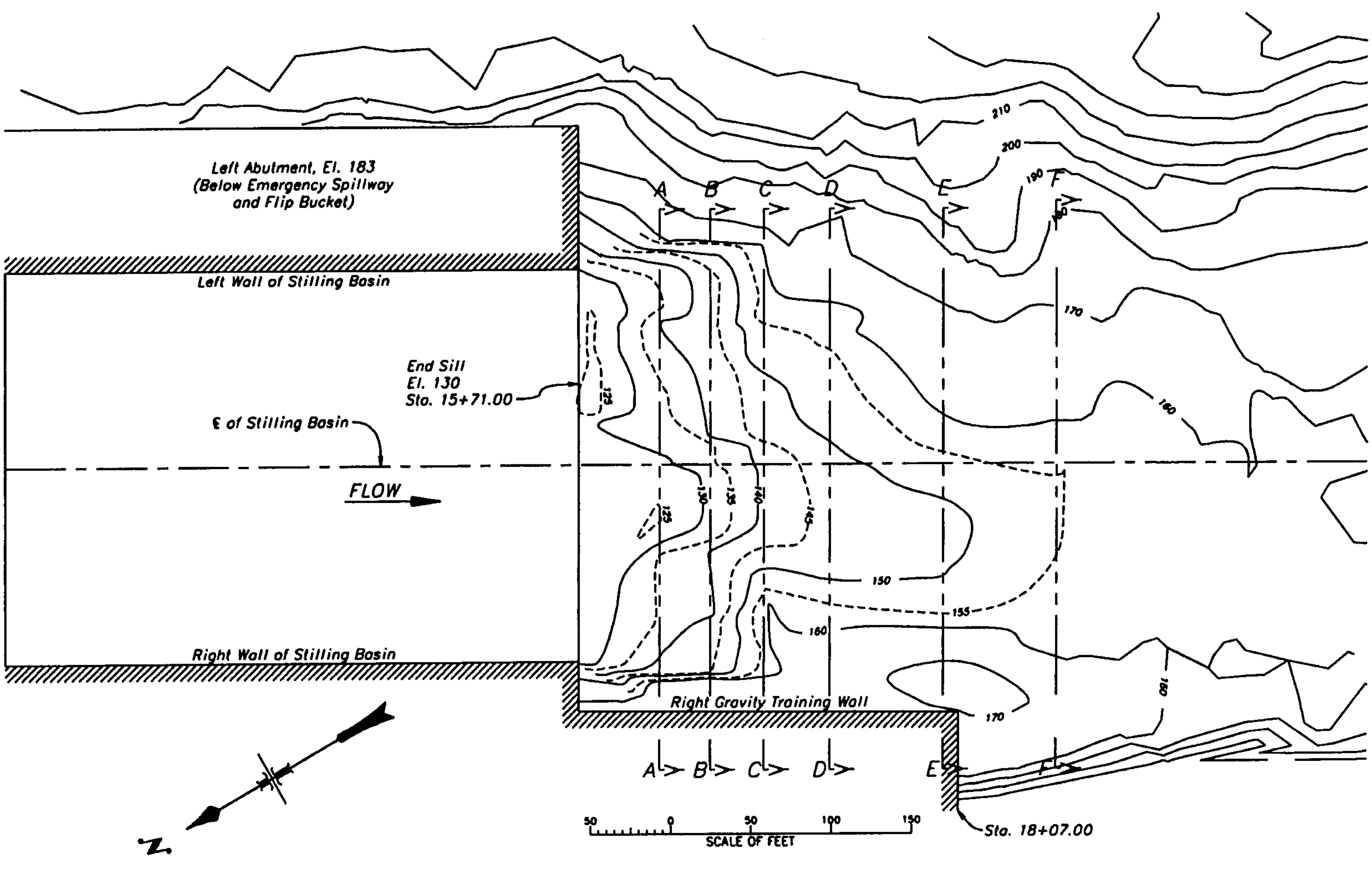


Figure 15a.—Plan view of stilling basin and exit channel depicting cross-section locations.

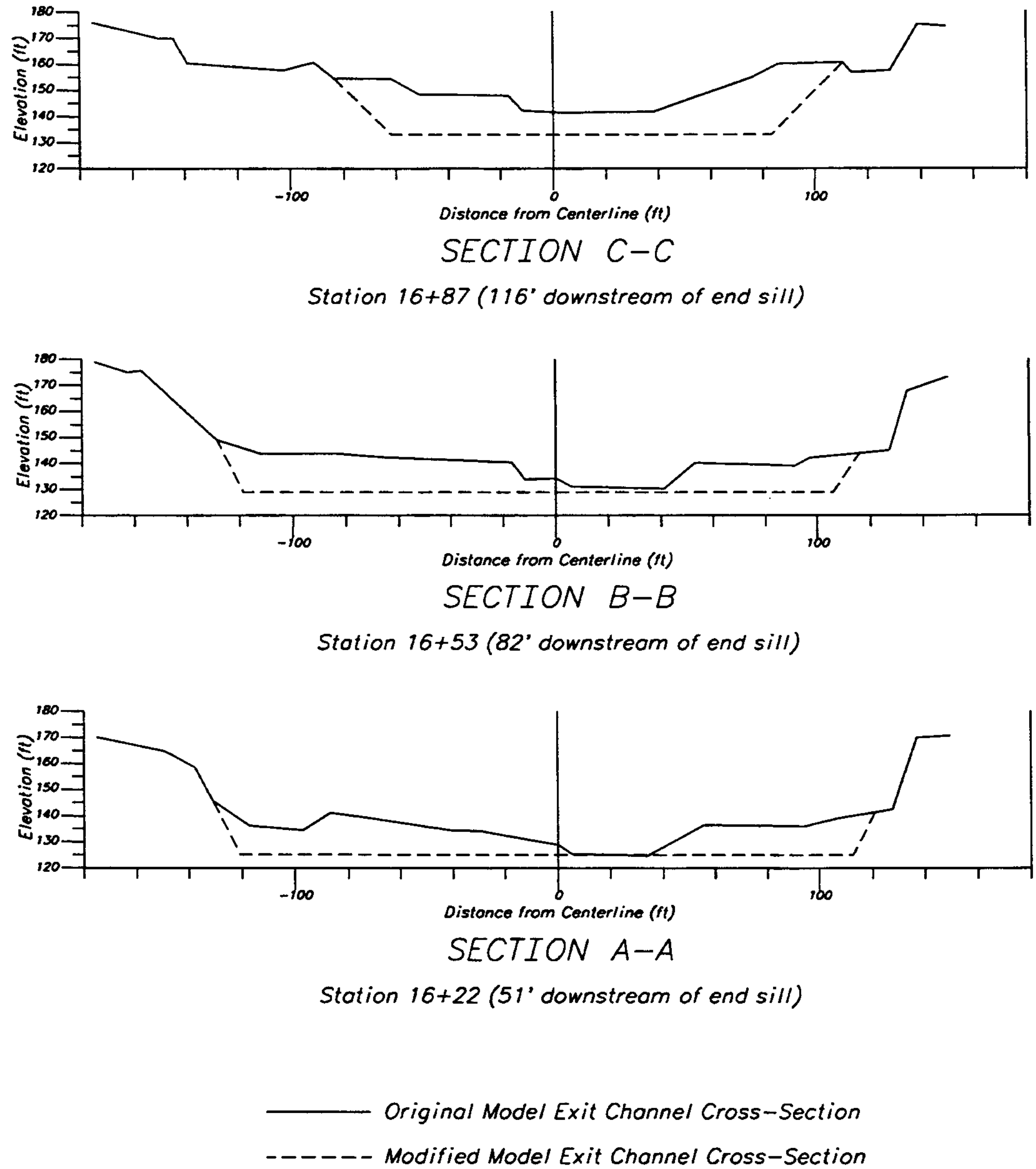


Figure 15b.—Exit channel cross-sections before and after excavation.

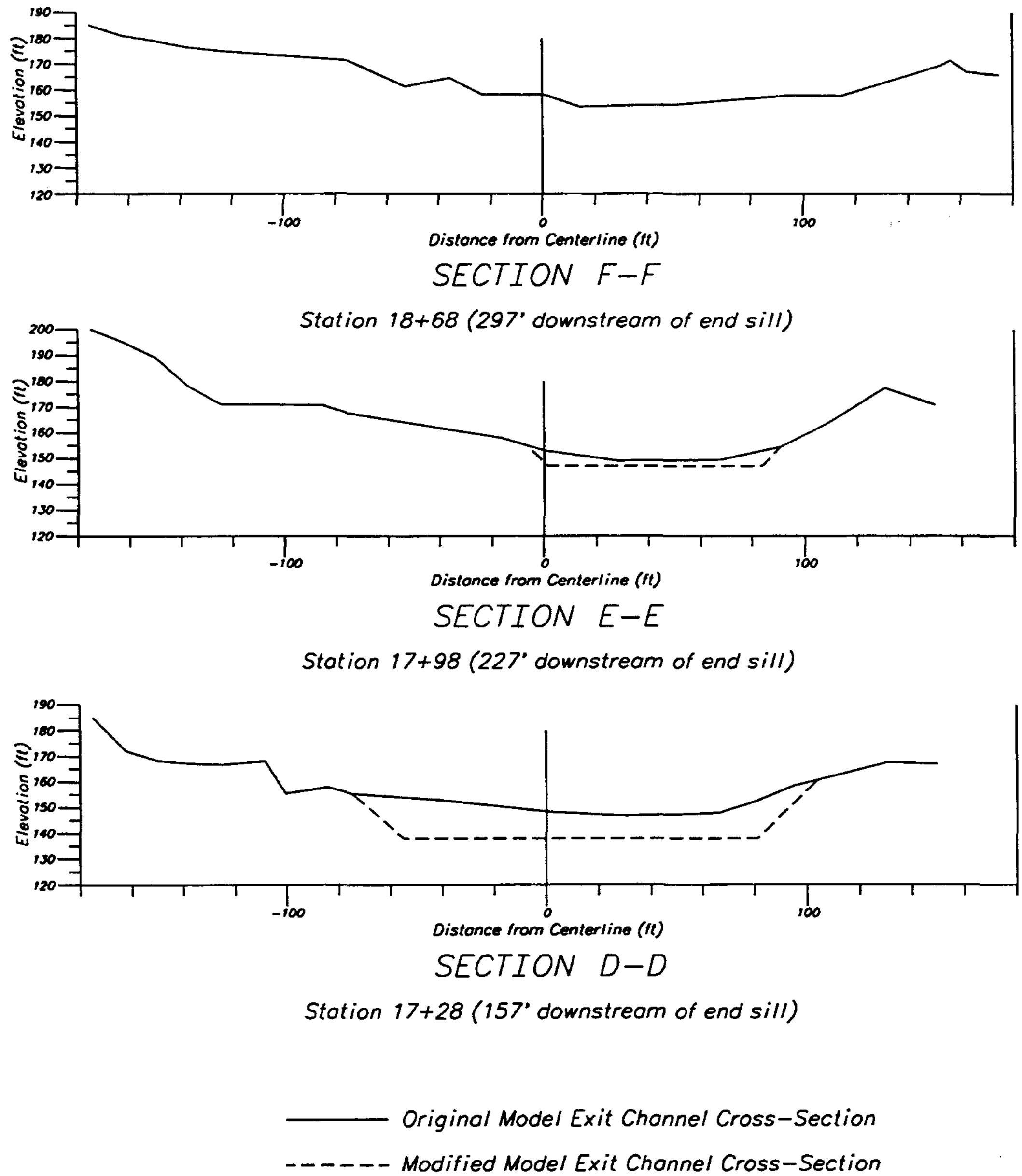


Figure 15c.—Exit channel cross-sections before and after excavation.

Spillway Rating

Spillway discharge tests were conducted to determine the reservoir pool-elevation/discharge relationship for Folsom Dam's five service-spillway radial gates. Three different pier nose conditions (figures 16a-c) were considered during the testing, consisting of the original (unmodified) pier noses, pier noses with stop-log guides added, and pier noses with proposed vortex-reducing stop-log-guide covers added. Each of these conditions was evaluated by passing a series of known discharges (determined from the laboratory venturi meters) over the model spillway with a variety of preset spillway gate settings, and then recording the resulting reservoir elevation for each discharge/gate setting combination.

For each test, all five spillway gates were operated uniformly. Spillway discharge conditions included both free-flow (ungated) and gated overflow. The gate settings represented in the model ranged from 5-ft gate openings to 35-ft gate openings, in 5-ft increments. All gate openings were measured based on the vertical distance from the gate seat (located downstream from the crest at elevation 417.17) to the bottom lip of the gate.

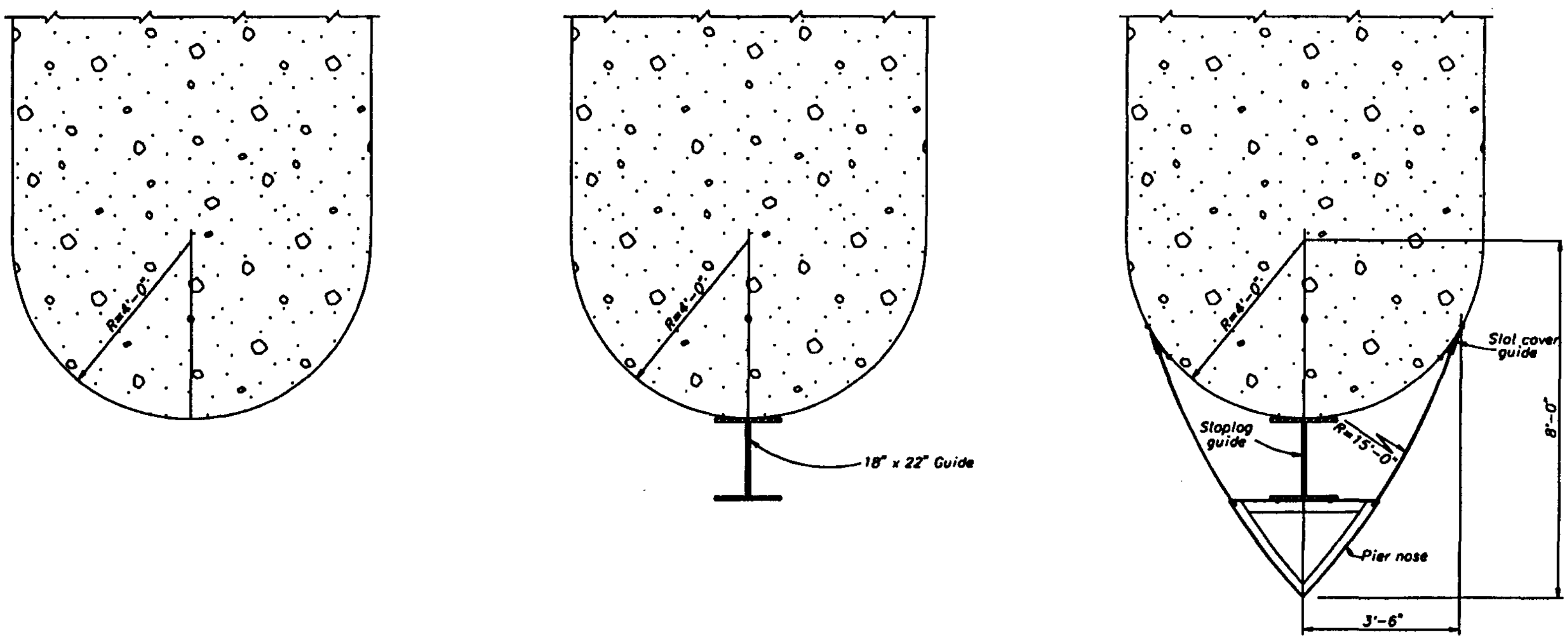
The discharge/pool elevation data collected during these tests are presented in figure 17. Only a limited amount of testing was devoted to the original pier nose condition (figure 16a), since that condition no longer existed in the prototype. Most of the data collected were for the pier-nose-with-stop-log-guide condition (figure 16b), since that was the condition of the prototype at the time of testing and for the foreseeable future. Final tests were conducted for the pier-nose-with-stop-log-guide-cover condition (figure 16c) in order to have base data for a rating should that design ever be adopted for the prototype.

Rating with Stop-log Guides

Using laboratory data from the pier-nose-with-stop-log-guide condition to calibrate the discharge coefficients, traditional hydraulic design techniques (U.S. Army Corps of Engineers, 1952) were used to develop rating curves for both free-flow and gated spillway discharges. These curves are included in figure 17 and compare very well with the model data. To facilitate prototype application of the new rating curves, the curves were modified to convert the vertical-gate-opening parameter to chain-hoist travel distance. The modified curves were then published, along with an extensive rating table, under separate cover (Hall and Einhellig, 1997). It is interesting to note that, although not included in the rating curve calibration, the data for both the original-pier-nose and the pier-nose-with-stop-log-guide-cover conditions compare well with the developed rating curves.

Transition Zone

A close examination of figure 17 reveals that the gated-discharge rating curves and the ungated-discharge rating curve do not touch, and that the model data in the intervening zone are inconsistent with either type of curve. This zone is the transition zone, where control of the discharge is changing between gated and free-flow. Prediction of the discharge in this zone is difficult, since the flow is unstable and control can shift rapidly between the two regimes. Measurements of discharge and pool elevation also vary widely in this zone, depending on whether the reservoir is rising or falling. For these reasons, no rating curve information was developed for flow in this zone.



a) Original Pier Nose

b) Pier Nose with Stoplog Guide

c) Pier Nose with Proposed Stoplog–Guide Cover

Figure 16(a-c).—Plan view of alternate pier nose configurations evaluated in the model.

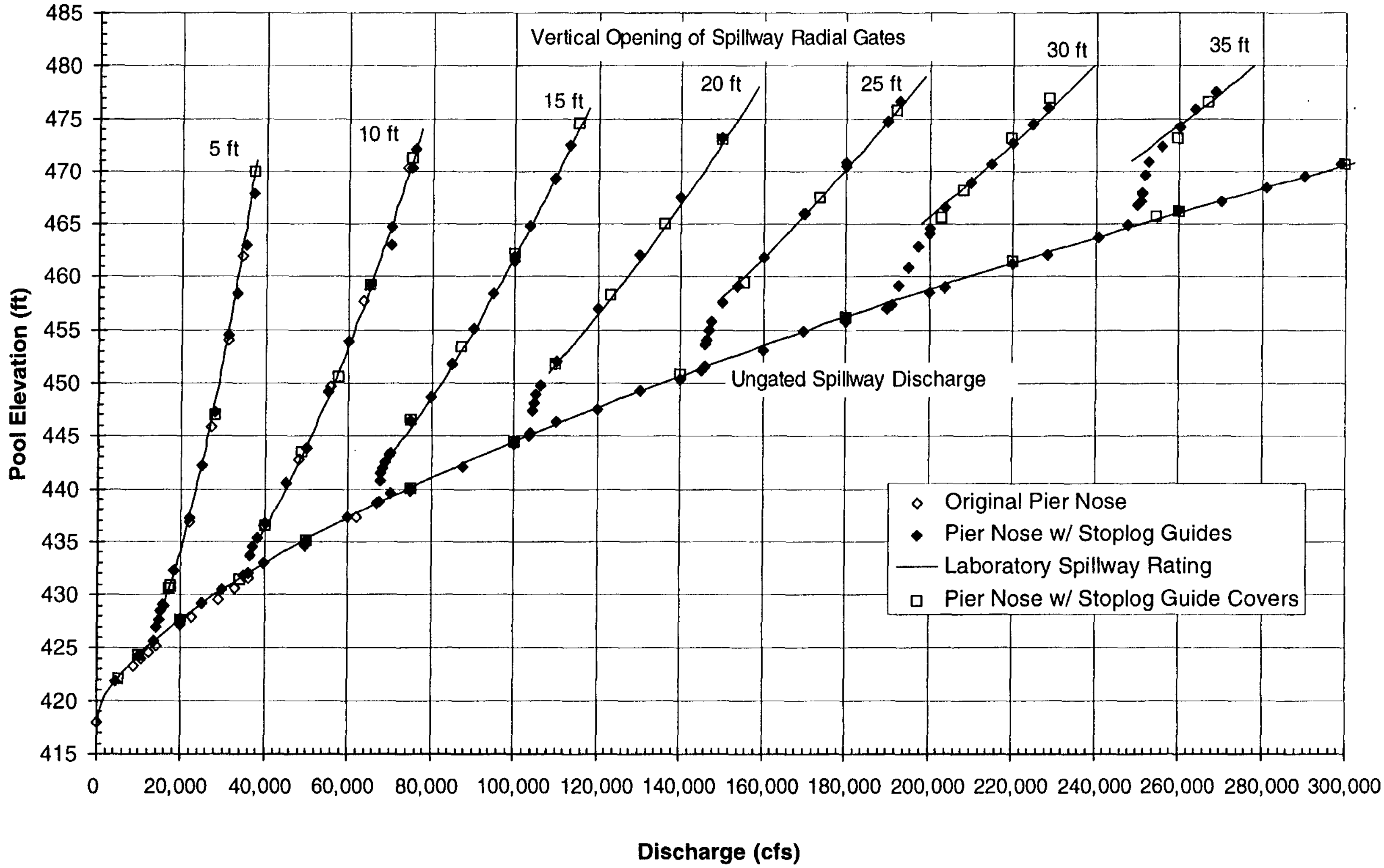


Figure 17.—Spillway discharge rating curves and data points for five spillway gates operated uniformly.

Reoperation Issues

Plans to modify the operation of Folsom Dam to include more frequent use of spillway and outlet works discharges raised a number of concerns and questions. Several of these concerns were evaluated using the physical model. In particular, the model was used to address issues related to establishing and maintaining gate control for spillway discharges when transitioning from a free-flow condition. The model was also used to help develop gate operational criteria for both the spillway and outlet works, particularly with respect to very low discharges where operating all gates uniformly at a very small opening may be impractical.

Transition From Free-flow to Gate Control

To conserve flood-control storage in the reservoir, the new operational plan for Folsom Dam called for allowing ungated spillway releases during rising pool conditions until the total release from the dam (power plant plus spillway and outlet works) reached the downstream levee capacity of 115,000 ft^3/sec. Once this discharge limit was reached, the spillway gates would be inserted into the water surface of the free overflow, and gate control would be established to hold the total releases at or below this limit. Prototype tests of this operating concept during 1997 were complicated by the fact that the existing spillway rating curves provided no guidance regarding the appropriate gate settings which would first touch the free water surface and then ultimately establish full gate control.

Responding to these concerns, measurements were made in the physical model to determine the gate position corresponding to the upper water surface of the free overflow for a variety of discharges. These data are plotted in figure 18.

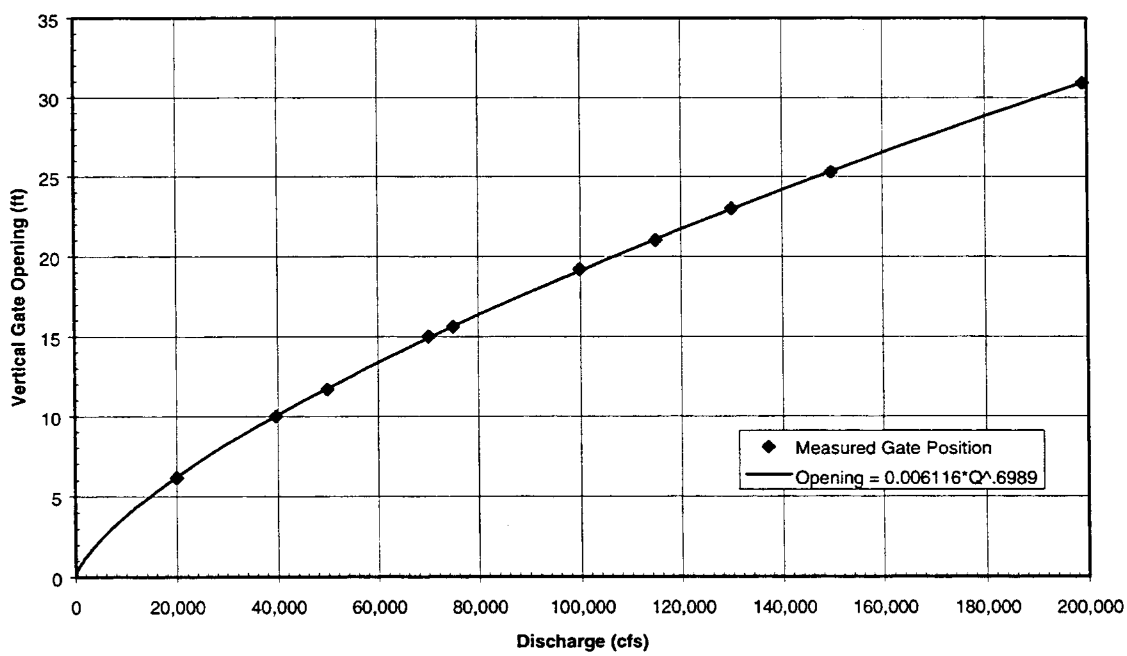


Figure 18.—Gate position corresponding to the point of contact between the bottom lip of the radial gates and the spillway free-flow water surface.

Based on the measured data plotted in figure 18, a relationship was developed to predict the vertical gate opening required for the bottom of the spillway gate to just make contact with the surface of a free overflow discharge. That relationship, which is also plotted in figure 18, can be expressed as:

$$VerticalGateOpening = 0.006116 \cdot SpillwayDischarge^{0.6989}$$

After the bottom gate lip touches the water surface, the gate must be inserted into the free-flow water column to establish gate control of the discharge. Evaluation of the rating curve data presented in figure 17 indicated that a relationship could be established between pool elevation and gate opening which would define the minimum acceptable pool elevation for which gate control could be established and maintained for a given gate opening. Data for developing this relationship were derived by graphically selecting the minimum point on each gate-rating data set (figure 17) before dropping into the transition zone between gate-control and free-flow conditions. These data points are plotted in figure 19.

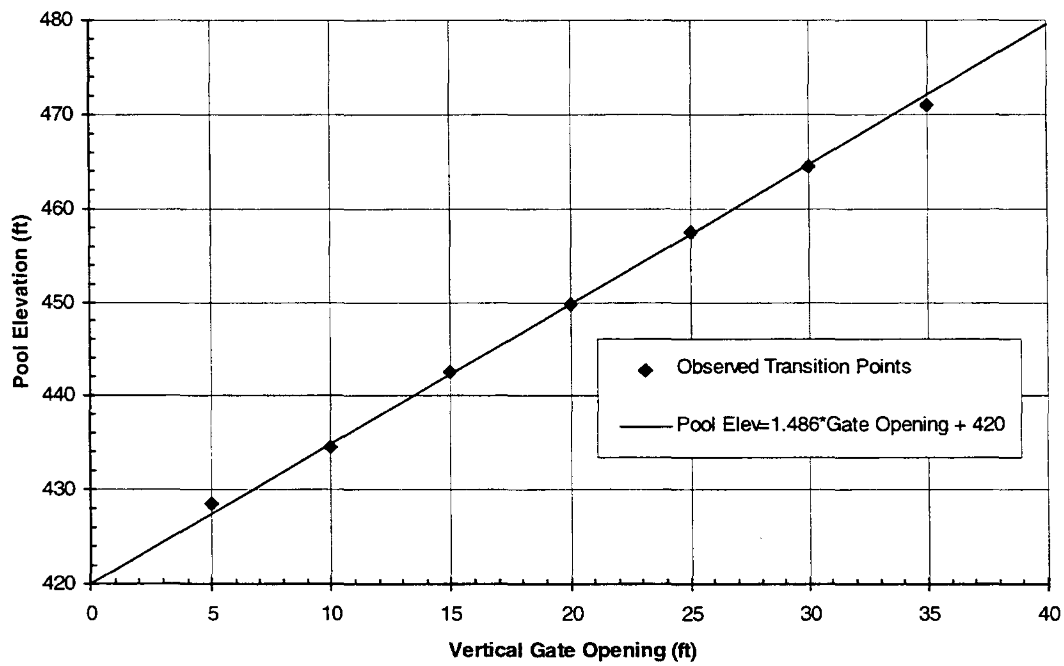


Figure 19.—Minimum pool elevation required to ensure full gate control for a given gate opening.

The relationship between minimum pool elevation and vertical gate opening to ensure gate controlled discharge can be described by the linear relationship:

$$MinPoolElev = 1.486 \cdot VerticalGateOpening + 420.00$$

This relationship can be rewritten to yield the maximum allowable vertical gate opening for a given pool elevation as follows:

$$MaxVertGateOpening = \frac{PoolElevation - 420.00}{1.486}$$

As with the spillway rating curves, the relationships between pool elevation and the vertical gate opening necessary to maintain gate control of the spillway discharge were modified to convert the vertical gate opening parameter to chain hoist travel distance (Hall and Einhellig, 1997).

Allowable Variation in Gate Settings

With the acknowledged benefits and desirability of operating the service spillway gates uniformly, questions arose regarding what the allowable deviations from this operating strategy were. In particular, for very small spillway releases, it was impractical from an operational standpoint to open all five spillway gates a few inches to distribute the flow evenly across all five bays. For such conditions, or when in the process of adjusting (opening or closing) spillway gates, clarification of the uniform operation philosophy was necessary.

Model testing of service spillway discharges was conducted to clarify the uniform gate operation strategy. These tests consisted of passing a small discharge through a single spillway gate and observing the resulting flow conditions in the stilling basin and exit channel. The discharge was then gradually increased until the flow conditions in the stilling basin and exit channel appeared unacceptable (i.e., the recirculating currents became consistent and strong, and loose pea gravel in the exit channel began to move). In this manner, single gate discharges ranging from 1,300 ft^3/sec up to 5,000 ft^3/sec were evaluated.

For all single gate discharges, some recirculation of flow from the exit channel into the stilling basin was evident. This was unavoidable due to the relatively narrow width of the flow jet issuing from a single, 42-ft-wide gate and into the 242-ft-wide basin. At a discharge of 4,000 ft^3/sec, however, the recirculating currents in the exit channel were judged to be too strong, and some of the pea gravel in the exit channel began to move. Recognizing that this observation was qualitative and subject to interpretation, a more conservative recommended discharge limit of 3,000 ft^3/sec for single gate operation was adopted.

Similar tests were conducted for operation of the outlet works conduits which discharge into the stilling basin. Flow conditions resulting from a single conduit discharging at rates ranging from 2,000 ft^3/sec to 3,000 ft^3/sec were evaluated. Based on observations of the resulting flow conditions, a single-conduit discharge of 2,500 ft^3/sec was determined to be the maximum allowable before recirculating flow conditions in the exit channel became unacceptable. This led to the adoption of a more conservative recommended single-conduit discharge limit of 2,000 ft^3/sec.

Following the single-gate and single-conduit tests, further tests were conducted using multiple, but not all, spillway gates or outlet conduits. As with the single-discharge tests, these tests evaluated the recirculating current effects of varying discharges passed nonuniformly over the spillway or through the outlet works. The results of these tests indicated that if spillway or outlet discharges were to be nonuniform, it was preferable to have the flow center-dominated (i.e., larger discharges along the centerline of the stilling basin) rather than left- or right-dominated and eccentric about the centerline. Eccentric or asymmetric discharges were observed to more easily form large recirculating currents in the stilling basin and exit channel than center-dominated discharges.

CONCLUSIONS

Stilling Basin Abrasion

Contributing Flow Conditions

Early in the model testing program, it became evident that spillway discharges that were not uniformly distributed across the entire 242-ft wide service spillway could cause large horizontal (i.e., rotating about a vertical axis) eddy currents and reverse flows in the stilling basin and exit channel. Depending on the magnitude and nonuniformity of the discharge, these currents had the capacity to move loose rocks from the exit channel into the stilling basin. The ease and consistency with which these currents are created in the physical model indicates that they are the most probable mechanism by which such movement occurs. The smaller the total spillway discharge, the greater the likelihood that recirculating currents will be established in the stilling basin and exit channel due to small differences in spillway gate openings. For this reason, a 0.5-ft maximum difference in spillway gate settings is recommended to minimize the formation of recirculating currents.

Uniform Gate Operation

Uniform operation of the spillway gates was identified as the most effective means to minimize the potential for recirculating currents to occur in the stilling basin and exit channel. Even if all spillway gates are operated uniformly, however, it is impossible to completely eliminate the potential for rock material in the exit channel to be drawn upstream into the stilling basin. Uniform operation of the spillway gates does not necessarily yield a uniform velocity distribution across the end sill of the stilling basin. As uniform flow from the spillway gates enters the stilling basin, it tends to spread laterally until it encounters the side-walls of the stilling basin. This results in a nonuniform flow distribution at the end sill, characterized by higher velocity flows across the left and right ends of the end sill, and lower velocity flow across the center of the end sill. This weakness in the downstream flow velocity at the center of the end sill, combined with occasional turbulent velocity fluctuations in the upstream direction, offers the potential for loose rock material in the exit channel, if available, to be moved upstream into the stilling basin under certain flow conditions.

Structural Alternatives

The stilling basin/exit channel structural modifications tested were found to provide little or no benefit in minimizing the recirculating currents that draw rock material upstream into the stilling basin. Raising the top elevation of the stilling basin end sill did prevent rock material from entering the stilling basin by creating an effective trap on the downstream side of the end sill. Without correcting the recirculating currents which are the root cause of material moving upstream towards the basin, however, the trap would eventually fill with rocks and overtop, allowing material to once again enter the basin.

Exit Channel Condition

The availability of loose rock source material in the exit channel, and the shape of the exit channel, contribute to the potential for material to migrate into the stilling basin. The 4:1 adverse slope of the exit channel immediately downstream from the basin end sill provides a gravitational impetus for loose to move back upstream towards the stilling basin, especially when recirculating currents are present. Reshaping the exit channel to reduce the adverse slope downstream from the end sill and remove the existing loose rock material will lower the potential for material to migrate upstream into the stilling basin.

Spillway Rating

New spillway-discharge rating curves were developed for both free-flow and gated-flow conditions. The rating curves were developed with stop-log guides present on the pier noses. The rating was also tested with proposed stop-log-guide covers on the pier noses. No significant difference in the discharge rating was noted between the two pier nose conditions.

A transition zone exists between gated and ungated spillway conditions. In this zone, the discharge is unstable and can vary rapidly as control shifts between the two conditions. For this reason, operation in this zone is not recommended.

Gate Sequencing

Uniform discharge through all spillway gates is the preferred method of operation. For very small spillway releases, however, it may be impractical to open all five gates a very small amount. Although recirculating currents were observed in the model for all spillway releases emanating from a single gate, the strength of these recirculating currents and their potential to induce damage varied with discharge. For releases up to 3,000 ft^3/sec a single spillway gate (preferably gate 3) may be used with little potential for the recirculating currents to be strong enough to pull loose material from the exit channel into the stilling basin.

When opening spillway gates, it is desirable to open all gates at the same time and rate. If this is not possible, the gates should be opened working from the center out. Thus, gate 3 should be opened first, followed by gate 4, then gate 2, then gate 5, and finally gate 1. During this process, the maximum difference in discharge between any two gates should be limited to no more than 3,000 ft^3/sec. Closing gates should follow the reverse sequence if all gates cannot be closed at the same time and rate.

Outlet works operations are similar to spillway operations in that it is preferable to have all four outlets at a given level (upper or lower) discharging the same amount of water. If necessary, however, a single outlet could be used to discharge up to 2,000 ft^3/sec with little adverse consequences. If all outlets at a given level cannot be opened or closed at the same time and rate, the maximum difference in discharge between any two outlets at a given level should be limited to no more than 2,000 ft^3/sec during the opening or closing procedure.

REFERENCES

Frizell, W.K., 1998, *Aeration Enhancements at the Folsom Dam Outlet Works: Reducing Cavitation Damage Potential*, Water Resources Research Laboratory Memorandum Report (PAP-786), Bureau of Reclamation, Denver, Colorado.

Hall, E., and R. Einhellig, 1997, *Recommended Flood Operations for Folsom Dam*, Technical Memorandum No. FD-8130-FD-TM-97-3, Bureau of Reclamation, Denver, Colorado.

Hanna, L.J., 1996, *Hydraulic Model Study of the Abrasion Damage to the River Outlet Stilling Basin at Ridgeway Dam*, Water Resources Research Laboratory Memorandum Report (PAP-721), Bureau of Reclamation, Denver, Colorado.

Hanna, L., and E. Cohen, 1997, Abrasion/Erosion in Stilling Basins, *Energy and Water: Sustainable Development*, in *Proceedings of Theme D, The 27th Congress of the International Association for Hydraulic Research*, August 10-15, 1997, San Francisco, California, pp. 60-65.

Higgs, J.A., 1997, *Folsom Dam Spillway Vortices Computational Fluid Dynamic Model Study*, Water Resources Research Laboratory Memorandum Report (PAP-757), Bureau of Reclamation, Denver, Colorado.

Isbester, T.J., 1971, *Hydraulic Model Studies of the Folsom Spillway-Outlet Junction*, REC-ERC-71-12, Bureau of Reclamation, Denver, Colorado.

Todd, R.V., 1997, Folsom Spillway Gate Failure and Lessons Learned, *Energy and Water: Sustainable Development*, in *Proceedings of Theme D, The 27th Congress of the International Association for Hydraulic Research*, August 10-15, 1997, San Francisco, California, pp. 66-71.

U.S. Army Corps of Engineers, 1952 (issued serially thereafter), *Hydraulic Design Criteria*, Waterways Experiment Station, Vicksburg, Mississippi.

U.S. Army Corps of Engineers, 1953, *Spillway for Folsom Dam, American River, California*, Technical Memorandum No. 2-369, Waterways Experiment Station, Vicksburg, Mississippi.

U.S. Army Corps of Engineers, 1965, *Spillway and Sluices, Red Rock Dam, Des Moines River, Iowa*, Technical Memorandum No. 2-673, Waterways Experiment Station, Vicksburg, Mississippi.

MISSION

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.