Scott Dam Spillway – Comparing Physical Model Study Results

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Abstract

Scott Dam, owned by Pacific Gas & Electric (PG&E) and located in northern California on the Eel River, impounds Pillsbury Lake and regulates flow to a tunnel diversion 11 miles downstream of the dam to the Potter Valley Powerhouse on the west side of the ridge separating the Eel River and Russian River drainages. The ogee-crest spillway is about 400 feet long and includes 26 slide gates and five radial gates to regulate flow. Training walls bounding the spillway chute along the right (north) and left (south) edges cause the spillway nappe to narrow as it descends down the chute until it converges at the bottom of the chute into a 185 ft wide stilling basin, which terminates with a simple low flip bucket. The training walls are between 12 and 20 ft high and include a 5.5 ft radius curved deflector along their top edges to redirect spillway flows toward the center of the chute.

Potential concerns regarding spillway capacity and structural stability of the spillway chute training walls under high flow and potential overtopping conditions motivated PG&E to conduct a physical model study of the structure to determine potential risks and evaluate modifications to address those risks. The complex flow field and unique spillway configuration presented a challenging modeling exercise to determine hydraulic performance and flow patterns through the spillway chute. This work evaluates the performance of the training walls and describes the balancing act between achieving the necessary discharge capacity of the spillway crest and preventing overtopping of the training walls. It also explains the benefits provided by the walls in terms of energy dissipation and discharge capacity; identifies some of the potential adverse concerns in their design; and discusses how the use of a physical model was able to mitigate the design deficiencies. Finally, the work compares the results of the current study with one conducted forty years earlier at a different scale and illustrates the consistency and repeatability of scaled physical modeling.
I. Introduction

The Scott Dam Spillway is located on the Eel River and impounds Lake Pillsbury, approximately 11 miles upstream of Cape Horn Dam and 30 miles northwest of Ukiah, California. The key hydraulic components of the structure include a concrete gravity dam; 6-ft diameter low level outlet controlled by a needle valve; and an ogee spillway controlled by 26 rectangular slide gates and 5 radial gates. As shown in Figure 1, Slide Gates 1 – 15 are located on north side of the spillway, Radial Gates 1 – 5 are located in the center of the spillway, and Slide Gates 16 – 26 are located on the south side of the spillway. Neglecting abutments and piers, the effective spillway length is 402 feet. The spillway crest elevation is 1821.2 ft\(^1\) and the parapet wall top elevation is 1845.9 ft. The slide gates are 10-ft tall and are situated within 20-ft high bays that allow the slide gates to reach a maximum opening of 17 feet. The majority of the slide gates are 9’-5” wide, with the exception of Gates 15 (6’-0”) and 26 (7’-4”). The five radial gates are each 32-ft wide and have a maximum opening of 10 feet.

Training walls bounding the spillway chute along the right (north) and left (south) edges cause the nappe width to narrow as it descends down the chute until it converges at the bottom of the chute into a 185 ft wide stilling basin, which terminates with a simple flip bucket (Figure 2). The training walls range from 12 to 20 ft high and include a 5.5 ft radius curved deflector along their top edges. Immediately downstream of the flip bucket and spillway terminus is a crib wall situated on the south bank and a concrete retaining wall on the north bank.

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\(^1\) All elevations reported in this paper reference the NAVD88 datum.
Figure 1: View looking upstream at Scott Dam spillway (low-level valve operating in foreground).

Figure 2: View looking downstream along north training wall, showing converging spillway chute, curved deflector along the top of the training wall and flip bucket at the toe of the chute.
The dam is designated by the Federal Energy Regulatory Commission (FERC) as a high-hazard dam, and at the design flow of 60,000 cubic feet per second (cfs) has a corresponding head of 11.5 feet. According to a Part 12D Inspection Report dated March 2013 (Hendron and Goodman 2010), the flood of record is 56,300 cfs while the Probable Maximum Flood (PMF) at the spillway has been calculated as 97,400 cfs (based on a PG&E study conducted in 1982). While a full update of the PMF event analysis was outside the scope of this study, NHC undertook a preliminary analysis using various components from two previous PMF studies conducted for Scott Dam along with the most recent HMR-59 to provide a preliminary PMF updated estimate of 120,000 cfs (NHC 2013).

A significant concern for this structure is discharge capacity of the spillway crest and training walls. Previous studies have identified overtopping hazards associated with flows larger than the flood of record. With the increase in the estimated PMF discharge, that hazard is likewise increased. A physical model study was commissioned to evaluate the capacity of the spillway crest and the training walls and to develop modifications to reduce or eliminate overtopping hazards.

II. Previous Studies

There have been a number of studies conducted at Scott Dam over the life of the project. Of particular note are two previous physical model studies. The first physical model tests were performed in 1936, apparently in support of modifications to the spillway apron and tailrace walls incorporated that same year. Photos of the tests are contained in PG&E's photo binders for the dam, but no reports regarding the tests have been found to date.

The second set of physical model tests was performed between 1973 and 1975 by PG&E Department of Engineering Research (Ghio 1975, PG&E 1973). This model was constructed and tested at an undistorted scale of 1:48 and was utilized to determine the maximum capacity of the spillway and investigate whether gate operations could be developed to prevent flows from overtopping the dam abutments or spillway training walls.

These tests found that with all radial and slide gates open, the spillway chute training walls were overtopped at flows above 50,000 cfs. It was also found that if some of the slide gates adjacent to
the north and south abutments were blocked, overtopping of the training walls could be prevented up to a flow of 109,000 cfs. Furthermore, it was determined that if all remaining slide gates were raised to an opening of 15 ft and radial gates were open to 13 ft, flows up to 109,000 cfs could be safely passed without overtopping the abutments. Modifications to the dam to incorporate these findings included adding 4-foot high parapet walls (resulting top elevation at El. 1845.9 ft – NAVD88 datum) to the dam abutments to prevent overtopping. California Division of Safety of Dams (DSOD) approved most of the proposed changes, which were subsequently incorporated, but did not allow permanent closure or blockage of the end gates. As a result, the potential for overtopping the spillway training walls continues to exist, leading to the current model study.

Figure 3: Image from model study report of the 1973 1:48 scale physical model showing a flow of 110,000 cfs (courtesy PG&E).
III. Study Methodology

A. Model Description

The Scott Dam Spillway physical hydraulic model was constructed at an undistorted scale of 1:40 in NHC’s Seattle laboratory. The model reproduced the full width of the Scott Dam to the top of the parapet wall (El. 1845.9 ft) and extended approximately 700 ft upstream and 800 ft downstream of the spillway crest (all dimensions are provided in prototype units unless indicated otherwise). The physical model included the concrete dam, the ogee-crest spillway, vertical slide gates, radial gates, spillway chute training walls, spillway stilling basin and flip bucket. All model components were fabricated in accordance with a 3-dimensional (3D) solid model provided to PG&E by WSI Applied Remote Sensing and Analysis. Recent bathymetric data were not available for the downstream channel so this area was initially installed using mobile-bed materials graded to simulate the historical bed survey data.

Figure 4: View of 1:40 scale model spillway looking north.
B. Model Measurements and Instrumentation

The following paragraphs summarize the key model controls and instrumentation that were used.

Model Discharge

Flow was supplied to the model using three centrifugal pumps regulated with butterfly valves connected to the model headbox diffusers. Inflow to the model was measured using ultrasonic flow meters installed on each of the three supply lines in accordance with manufacturer specifications.

Hydraulic Grade Line and Pressure Data

Hydraulic grade line and pressure data were recorded within the model forebay, spillway crest, spillway chute, stilling basin, and downstream river channel using 36 piezometric (static) pressure taps.
In addition to the piezometric pressures, dynamic pressure transducers were installed at key locations along the spillway chute training walls to evaluate the dynamic pressure fluctuations that may occur as a result of the turbulent flow impacting the walls.

The tailwater levels in the model were set in accordance with the prototype values corresponding to an updated rating curve supplied by PG&E\(^2\).

C. Test Program

Model testing was divided into the following three phases:

I. Existing Design Testing – Tests to document the hydraulic performance of the existing spillway, gate configuration, and training walls.


III. Final Design Testing – Detailed documentation tests on the final selected geometry and gate settings to ensure satisfactory performance over the full range of operating conditions.

IV. Results

A. Existing Design Testing

A total of five tests were conducted to evaluate the existing design of the Scott Dam Spillway. The existing spillway geometry was evaluated in terms of documenting the hydraulic capacity of the spillway crest and training walls, with the spillway gates operated in accordance with the existing gate operating orders: slide gates 1 – 4, 21, and 24 – 26 closed; slide gate 13 open 8 ft; slide gate 20 open 10 ft, all other slide gates open 15 ft; and radial gates open 10 ft.

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\(^2\)“Attachment 6-4 Calibration of Scott Dam tailwater curve,” PG&E document as provided by Mr. Rob White.
Figure 6: View looking upstream toward the spillway operating at 17,400 cfs on January 12, 1980.

Figure 7: View of 1:40 scale model looking upstream toward model spillway operating at 17,400 cfs. Note similarity in location of roller that forms along the south training wall and the flow patterns in the downstream river channel.

It was found that spillway capacity along the crest was sufficient with the existing gate configuration to pass the estimated PMF discharge of 120,000 cfs. However, direct overtopping
of the training walls occurred at flows exceeding 80,000 cfs due to the depth of flow passing over the tops of closed slide gates located at either end of the spillway (Gates 1 & 2 and 25 & 26).

Intermittent splash over the training walls, which occurs over a wider range of flows (above approximately 50,000 cfs), was also a significant concern as it could contribute to erosion on the back side of the training walls. This splash is generated where the flow rolling off the curved top of the training wall converges with the flow passing down the spillway chute. The severity of this splash is difficult to quantify due to scaling effects in the model; however, a qualitative comparison of minor, moderate, or severe was made where possible. It was noted that totally eliminating the splash, especially for higher discharges, is likely unachievable without significant changes to the spillway training walls. However, attempts were made during the design development testing phase of the study to eliminate moderate to severe splash. The splash and turbulence observed in the model likely underestimates the amount of turbulence and splash that will occur in the prototype, hence it is important to limit such conditions.

B. Final Design Testing

Design development testing evaluated modifications to the spillway gate operations and the spillway training walls. The primary objective of these modifications was to balance the capacity of the spillway crest with the capacity of the training walls to limit or prevent overtopping of the crest parapet walls or the chute training walls. Once a set of modifications was selected for final design, detailed documentation tests were conducted with flows of 30,000 cfs, 50,000 cfs, 80,000 cfs, 100,000 cfs, and 120,000 cfs.

Gate Operation Modifications

Various modifications to gate operations to improve spillway crest capacity and reduce overtopping of the training walls were tested. These modifications included combinations of completely blocked bays (up to the full height of the parapet wall), closed gates, and various open positions of the slide and radial gates. Data collected for these tests were limited to observations, select piezometric readings (forebay only), and photographic documentation. Numerous informal tests were used to gauge the sensitivity of gate operations to spillway capacity. Based on these tests, 10 separate gate operations were selected for more detailed examination.
Similar to the results of the 1973 model study, results indicated that direct overtopping of the training walls could be prevented only by completely blocking the bays next to the north and south abutments; simply closing the gates was not sufficient because flow passing over the top of the gates still resulted in the nappe exceeding the height of the training walls. Furthermore, at discharges approaching the estimated PMF discharge, additional gate closures adjacent to the blocked gates were required to prevent moderate to severe indirect overtopping (splashover) of the training walls.

As additional gates were closed, the capacity of the spillway crest was reduced, resulting in increases in the upstream reservoir pool elevation to the point where the parapet walls were overtopped. The key element of design development for gate operations was to balance the spillway crest capacity with that of the training walls. This was particularly difficult because splashover was present to some degree at all flows greater than 80,000 cfs. Options were explored to (1) raise the parapet wall to provide increased freeboard allowing more gates to be closed; and, (2) fully remove the raised slide gates and store them off site during winter months when flood concerns are typically much greater (maximum opening of the slide gates is currently restricted to 17 ft).

The final optimization examined the impacts of increasing the maximum opening of slide gates from the 15-ft to 17-ft (review of existing hoisting systems indicated that an additional 2 ft of gate opening could be achieved beyond the normal operating position). Gate positions for this tests are summarized as Bays 1 – 3, 19, and 24 – 26 completely blocked (no overtopping of the closed gates); Gates 4 – 7 and 21 – 23 closed (overtopping of closed gates permitted); Gate 13 left at its normal 8-ft opening; and Gates 8 – 12, 14 – 18, and 20 raised to a 17-ft opening. The parapet walls were also raised 6 inches (prototype). These modifications were selected for final design testing.

**Gate Optimization Final Design Testing**

Final testing of the gate positions optimized for the existing training walls resulted in no direct overtopping of the training walls. Splashover of the training walls was “minor” up to 50,000 cfs; moderate for lower portions of the north training wall up to 100,000 cfs; and moderate over both the north and south training walls at the estimated PMF discharge. During final design testing it was discovered that the prototype radial gates could be opened an additional three feet to an
overall height of 13 ft open. Using this additional capacity in the radial gates, the reservoir pool elevation at a discharge of 120,000 cfs dropped below the height of the existing parapet walls such that modifications to the parapet wall were not necessary.

**Training Wall Modifications**

As an alternative to modifying the spillway gate operations, a second series of tests were conducted to ascertain whether changes to the geometry of the spillway chute training walls could be developed to address significant direct and indirect (splashover) overtopping of the training walls and allow more slide gates to remain open. The primary modifications evaluated in the model included raising the height of the training walls by 10 feet, replacing the quarter-round deflector on top of the wall with a straight angled deflector, and varying the pitch of the angled deflector along the length of the training wall.

Raising the wall height was intended primarily to eliminate direct overtopping of the wall at the estimated PMF discharge. It was anticipated the additional height would also serve to reduce splashover. The changes to the deflector were made for two reasons. First, an angled deflector was thought to be easier, and thus cheaper, to construct than a quarter-round deflector. Second, much of the splashover was observed to emanate from the interface between the roller flow from the training wall and flow passing down the spillway chute. It was expected that changes to the deflector could change the trajectory of the deflected flow towards the centerline of the spillway, away from the spillway abutments.

Several informal tests were used to develop the proposed geometry of a modified wall. The preferred geometry was constructed with an additional 10 feet of height and a linear deflector angled 20 degrees from vertical. The angle of the deflector along the north (right) wall varied from 20 degrees at the upstream end to 30 degrees at the downstream end.

With the modified training walls installed, the optimal gate positions were re-evaluated by gradually opening previously closed gates and blocked bays until splashover increased beyond “minor.” The training wall modifications allowed most of the slide gates to be opened. The resulting gate positions included completely blocking off Bay 26, closing Gates 20 and 25, keeping Gate 13 at its 8-ft maximum height, and raising the remaining slide gates to a 17-ft opening. The radial gates also remained open and no extension to the parapet wall was required. The modified wall and associated gate openings were selected for final design testing.
Training Wall Optimization Final Design Testing

The modified training walls and the associated gate openings developed during design development testing resulted in a net decrease in the reservoir pool elevation of three feet compared to the Gate Optimization Final Design Test at 120,000 cfs. For all flows tested, splashover was “minor” and no direct overtopping of the walls occurred. The primary contributors to reducing splashover were the angled deflectors which were found to be effective at adjusting the trajectory of the rollers towards the centerline of the spillway chute. It was also noted the angled deflectors directed the trajectory of the roller higher up on the spillway chute such that it interfaced with spillway flow at a much shallower angle than the near perpendicular angle generated by the rollers of the existing quarter-round deflectors. The shallower angle resulted in deflected flow that was swept down the spillway chute rather than being re-directed up and away from the chute. A secondary contributor to the reduced splashover was the fact that the higher training walls resulted in a thinner roller jet deflected off the tops of the walls which in turn reduced the severity of the impact with spillway chute flow.

Figure 8: Front view of 1:40 scale model spillway during design development testing of modified training walls.
**Discussion of Testing Results**

The findings of the current model study agreed very closely with those of the 1973 model study. First, with all gates open the training walls are directly overtopped at a discharge of 50,000 cfs. Secondly, complete blockage of the outer gates (north and south) was necessary to prevent direct overtopping of the training walls. Finally, the recommended gate positions of this study compared to those developed in the previous study are summarized in Table 1. The similarity and consistency between two physical model studies completed at different modeling scales, by different entities, and at different times is remarkable.

Table 1: Comparison of Physical Model Study Recommendations between 1973 PG&E Model and 2014 NHC Model

<table>
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<tr>
<th></th>
<th>1973 PG&amp;E Model</th>
<th>2014 NHC Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocked Gates</td>
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<td>1 – 3, 19, 24 – 26</td>
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<tr>
<td>Number of Blocked Gates</td>
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<td>7</td>
</tr>
<tr>
<td>Closed Gates</td>
<td>4 – 8, 22 – 23</td>
<td>4 – 7, 21 – 23</td>
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<tr>
<td>Number of Closed Gates</td>
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<td>7</td>
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<tr>
<td>Partially Closed Gates</td>
<td>20 – 21 (9’-0”)</td>
<td>13 (8’-0”)</td>
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<td>Radial Gate Open Height</td>
<td>13’-3”</td>
<td>13’-0”</td>
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<tr>
<td>Open Slide Gate Height</td>
<td>15’-0”</td>
<td>17’-0”</td>
</tr>
<tr>
<td>Maximum Flow(^3)</td>
<td>110,000 cfs</td>
<td>120,000 cfs</td>
</tr>
</tbody>
</table>

The discharge capacity of the Scott Dam Spillway is significantly sensitive to gate positions. Enough gates need to be open to pass PMF discharge over the crest, but several gates also need to be closed to prevent direct and indirect overtopping of the training walls. To complicate matters, it was not possible with the existing training walls to satisfactorily reduce splashover (indirect overtopping) to minimal levels so a decision had to be made with regards to acceptable levels of splashover and the extent to which the height of the parapet walls could be increased. Furthermore, the converging spillway chute produced unique challenges with regards to spillway capacity and energy dissipation. While the converging training walls allowed for a much longer

\(^3\) Report indicated the spillway passed a flow of 137,000 cfs with 1 – 2 ft of overtopping of the parapet walls.
spillway crest, thereby increasing its capacity, the limiting factor then became the capacity of the training walls and the highly turbulent flow downstream of the spillway.

Using a physical model it was possible to optimize the training wall and deflector geometry to minimize direct and indirect overtopping thereby preserving the added spillway crest capacity. However, without the insight of the physical model, the interaction of the existing rollers with the spillway flow resulted in flow conditions that could jeopardize the safety of dam abutments.

The training walls and associated rollers accommodated an increased spillway capacity by lengthening the crest and then forcing the chute nappe to narrow down to the width of the downstream channel. Conversely however, particular attention is necessary to ensure the training walls are not overtopped by the increased flow over the spillway capacity. The flow patterns over the spillway chute focused energy dissipation at the center of the spillway chute by directing the north and south rollers towards the centerline of the spillway where the jets collided in a mass of turbulent, energetic flow. Flow through the center portion of the spillway, primarily downstream of the radial gates, pushed this turbulent flow over the flip bucket into the downstream river channel in a “rooster tail” pattern. A significant issue with the layout of the dam is that the north and south training walls are not symmetrical, therefore it is difficult to control how the two rollers align over the range of flows. Further evaluations of the stilling basin and flip bucket performance are warranted and planned in a future study.

V. Summary

A 1:40 scale physical hydraulic model of the Scott Dam Spillway physical model was constructed and tested to examine possible methods of safely passing the PMF discharge for the project. The model included the spillway, training walls, all slide gates and radial gates, 700 ft of the upstream reservoir, and 800 ft of the downstream channel. Existing design tests over a range of flows showed insufficient flow capacity for the training walls bounding the spillway chute.

Two potential final designs were developed and tested in the model. The first included modifications to gate operations by completely blocking off seven gates and closing seven additional gates while increasing the maximum opening of the remaining slide gates by 2 ft and the radial gates by 3 ft. This design eliminated direct overtopping of the training walls and reduced splashover intensity from “severe” to “moderate” (or less). Reinforcing the rock
protection along the north and south banks of the dam abutment is recommended to guard against erosion that could be generated as a result of the moderate splashover during extreme flow events.

The second final design was a modification that increased the height of the training walls by 10 feet and replaced the curved, quarter-round deflectors with angled deflectors. This modification allowed most of the gates to be opened and resulted in only minimal splashover, but would be costly to implement.

The training wall concept of the Scott Dam Spillway provides longer spillway crest capacity but also requires additional analysis to ensure the chute capacity is not exceeded by direct or indirect overtopping of the walls. In order to ensure optimal and safe operation of this concept, the spillway should be symmetrical and particular care given to the geometry and height of the walls and deflectors. A physical model is necessary to optimize the design and prevent the deficiencies identified in this study.

VI. References


Ghio, E.J. Scott Dam Model Study. April 1975.

Biographical Sketches

Dr. Darren Hinton is a registered professional engineer with 7 years of experience in the design and rehabilitation of hydraulic structures. He has a doctorate in civil engineering focused on bedload transport in gravel bed streams. His professional experience includes physical modeling of spillways, pump stations, and rivers; 1-dimension hydraulic modeling; stream revetment and river design; and the design of more than five miles of large diameter pipelines.
Brian Hughes is a registered professional engineer with over 25 years of experience. He has been a hydraulic engineer for NHC since 1988 and a Principal of the firm since 1994. He has acquired strong managerial and technical knowledge in the areas of hydraulic design, physical and numerical modeling, and river hydraulics. Physical and numerical modeling experience includes hydroelectric developments, fish passage projects, spillway design/rehabilitation, a variety of river processes, navigation and sediment transport investigations, and intake and pump station design studies. Mr. Hughes is currently the Director of NHC’s modeling operations and sits on the firm’s Board of Directors.

Ed Zapel is a civil engineer with more than 27 years of experience in hydraulic, hydrologic, and fisheries engineering developed in a variety of engineering assignments throughout the western United States. These include a wide variety of river engineering projects, including sedimentation and erosion analysis and management, debris flows, water intakes and diversions, fish passage barrier removal and channel restoration, habitat enhancement, fish passage design on low and high-head dams, and all aspects of fisheries engineering. Mr. Zapel's experience includes fourteen years in private consulting practice and thirteen years as a hydraulic engineer with the U.S. Army Corps of Engineers’ Seattle District.