The Hydraulic Design of an Arced Labyrinth Weir at Isabella Dam

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The Hydraulic Design of an Arced Labyrinth Weir at Isabella Dam

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ABSTRACT

The Sacramento District Corps of Engineers is designing modifications to the Isabella Dam located on the Kern River in the Tulare Lake Basin in the southern portion of the San Joaquin Basin, in Kern County, California. These modifications include raising the elevation of two high head dams (185 ft and 100 ft respectively) by 16 ft, modifying a service spillway to better suit the needs of flood capacity, and creating a new arced labyrinth weir emergency spillway in order to safely pass the probable maximum flood (PMF).

The rating curve for the arced labyrinth weir emergency spillway was based on information published in a PhD dissertation (Crookston, 2010) and a Master’s Thesis (Christensen, 2012) from Utah State University. The proposed prototype weir geometry was a 10-cycle arced labyrinth with a 16° sidewall angle. As the published hydraulic performance data were limited to arced labyrinth weirs with 6°, 12°, and 20° sidewall angles, a spreadsheet program was developed to predict the rating curve for the prototype 16° weir using a double quadratic spline interpolation of the 12° and 20° discharge coefficient data. The spreadsheet was used to tailor the design of the arced labyrinth weir to the specific project needs. The spreadsheet was also used to evaluate the hydraulic and economic implications of over six-thousand different arced labyrinth weir/apron designs.

The prototype design verification program used a composite spillways modelling approach, which included a 1:45 scale physical model study at the Utah Water Research Laboratory (Utah State University) and CFD modelling conducted by the USACE Portland District (Hydraulic Design Section). The goal of the composite modelling was to validate the theoretical rating curve for the arced labyrinth weir given a non-ideal approach condition with the potential for submergence effects decreasing the discharge over the weir. The selected arced labyrinth weir theoretical rating curve was compared to the physical model and the CFD model results of the labyrinth weir. The physical model and CFD model results confirmed that the rating curves developed using traditional methods (discharge coefficients, velocity head, etc.) are valid and that the designed configuration of the service spillway and labyrinth weir will safely pass the PMF within the target pool elevation.

Keywords: Labyrinth Weir, Cost Optimization, Rating Curve, Physical Model, CFD.
1. INTRODUCTION

Isabella Lake Reservoir is located on the Kern River in Kern County, California (See Figure 1). The project is approximately 42 miles northeast of the city of Bakersfield and one mile upstream of the town of Lake Isabella. Isabella Dam consists of two earthen embankment dams: a main dam blocking the Kern River and an auxiliary dam located in the hot springs valley (there are no historic evidences of an old riverbed in this valley). The two dams are separated by a natural topographic feature where the Kern County Fault is located.

Figure 1. Location of Lake Isabella

The main dam has a maximum height of 185 feet, a crest length of 1,695 feet, and a top width of 20 feet. The crest elevation is 2,637.26 feet, which provides 6.5 feet of freeboard above the original Spillway Design Flood elevation of 2,630.76 feet. The existing outlet works and spillway are located within the main dam and left abutment, respectively (See Figure 2).

The auxiliary dam has a maximum height of 100 feet, a crest length of 3,257 feet, and a top width of 20 feet. The crest elevation is 2,637.26 feet. There is 6.5 feet of freeboard above the Spillway Design Flood peak elevation of 2,630.76 feet. The Borel Canal conduit is located within the auxiliary dam embankment.

Figure 2. Existing Isabella Dam Project

Proposed spillway modifications include modifying the existing service spillway, constructing a new emergency arced labyrinth spillway, and creating a new spillway at Highway 155. In addition to the new and modified spillways, both the main dam and the auxiliary dam will be raised 16 feet as part of the overall project. The new
dam crest elevation will be 2653.26 (all elevations are referenced to North American Vertical Datum 1988 or NAVD88).

The general design procedure for the proposed arced labyrinth weir emergency spillway was based on information published in a PhD dissertation (Crookston (2010)) completed at Utah State University. Discharge coefficient data from Crookston (2010) and Christensen (2012) was used in developing the rating curve for the proposed labyrinth weir. In addition, a composite modelling approach was used that included CFD and physical modelling to develop the appropriate site specific approach conditions to the weir, verify the theoretical derived rating curve for the emergency labyrinth weir, and design the spillway chute to prevent submergence of the weir.

2. EMERGENCY SPILLWAY ALTERNATIVE SELECTION

An emergency spillway will be constructed at Isabella Dam between the main and auxiliary dams and next to the existing service spillway. The purpose of the new emergency spillway is to provide additional discharge capacity to pass the current estimated probable maximum flood (PMF). The new emergency spillway is designed as an arced labyrinth weir to reduce the footprint and minimize excavation requirements. The emergency spillway will discharge a short distance downstream of the existing service spillway into the Kern River.

During the Dam Safety Modification Report (DSMR) phase of the study, a large array of emergency spillway alternatives and dam raise alternatives were evaluated to increase Isabella Dam’s capacity to pass and attenuate the PMF. Among the spillway alternatives considered, the following were included: a gated spillway, an un-gated ogee spillway, a broad-crested weir spillway, a side-channel spillway, a fuse gate spillway, and a labyrinth spillway. The effects of each alternative on downstream discharge capacity, flood protection levels, maximum reservoir pool elevations, and existing spillway adequacy were investigated.

Various alternatives were evaluated either as a widening of the existing spillway or as a new emergency spillway separate from the existing spillway. The majority of the alternatives evaluated varied either the crest elevation of the spillway, the spillway approach elevation, or the maximum allowable reservoir pool elevation (determining the dam raise needed). Several of these spillway alternatives were ultimately eliminated due to excessive maintenance, response to earthquake loadings, low efficiency, and depths of excavation that could cause dam safety problems. Various configurations of a labyrinth or fuse gate spillway were studied in greater detail due to their efficiency of passing the PMF within a smaller footprint. A linear labyrinth weir was the preferred alternative proposed with the DSMR. At the start of the Planning, Engineering, and Design (PED) phase, an arced labyrinth weir layout was considered and ultimately selected since it provided even greater efficiency. The final refinements to the arced labyrinth weir included a cost comparison between several weirs, also ensuring that the weir abutments were tied into high ground and that the weir performance was optimized.

The crest and apron of the emergency spillway is at elevation 2637.26 and 2609.26, respectively. The emergency spillway is an arced labyrinth weir to increase the unit discharge and reduce the excavation. This configuration was chosen to prevent the excavation from encroaching into the weaker fault shear zone while still providing the hydraulic capacity to pass the updated PMF.

3. ARCED LABYRINTH WEIR DESIGN

3.1. Geometric Layout

The general design procedure and parameters for an arced labyrinth weir are described in Crookston (2010). The parameters are shown in Figure 3. There are several variables, making for a large number of potential design configurations compared to a linear labyrinth weir. An excel spreadsheet was setup with the support of a macro to generate the cost associated with over 6,000 different designs. Each design had a total discharge capacity of 402,000 cfs, which is sufficient to pass the PMF when combined with the service spillway. The weir height, P was set to 28 ft for all the designs. In addition, based on site specific constraints, the width or chord length of the arced
labyrinth weir, \( W_{\text{chord}} \) was set to \( W_{\text{chord}} \leq 800 \). Similarly, the central weir arc angle \( \Theta \) was constrained to \( \Theta \leq 120^\circ \).

A few key parameters were adjusted incrementally to generate the various designs and associated costs for the weir. Adjusted parameters included the sidewall angle, \( \alpha \), the cycle arc angle, \( \theta \), and the number of cycles, \( N \). The parameters were varied within the following ranges:

- Sidewall Angle: \( 6^\circ \leq \alpha \leq 20^\circ \)
- Cycle Arc Angle: \( 1^\circ \leq \theta \leq 30^\circ \)
- Number of Cycles: \( 4 \leq N \leq 30 \)

Figure 3. Arced Labyrinth Weir Geometric Layout (Crookston 2010).

The cost of the arced labyrinth weir was estimated assuming a unit cost for the labyrinth weir walls, abutment walls, and the concrete apron using unit costs of $1000/cubic yard, $500/cubic yard, and $300/cubic yard, respectively. The result of the estimated cost of each labyrinth design and weir length for each arced labyrinth weir evaluated is shown in Figure 4.

Figure 4. Estimated Cost of Labyrinth Weir vs. Side Angle and Weir Length.
The range of design parameters considered was limited to a range where existing experimental data were available. Based on the results of the spreadsheet analysis, the designs were narrowed down to three similar alternatives shown in Figure 5. The three weirs included a 20-cycle weir, a 12-cycle weir, and a 7-cycle weir. Additional information for each weir is shown in Table 1. The 12-cycle weir was ultimately selected by balancing needs for hydraulic efficiency and cost. The 12-cycle weir also closely represented weirs studied in the experimental data; hence, there was more confidence in its design. See the layout of the 12-cycle weir in Figure 6.

![Figure 5. Final Arced Labyrinth Designs](image)

<table>
<thead>
<tr>
<th>Labyrinth Weir Final Designs Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Angle of Side Legs</strong> $\alpha$</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>20-Cycle Weir</td>
</tr>
<tr>
<td>12-Cycle Weir</td>
</tr>
<tr>
<td>7-Cycle Weir</td>
</tr>
</tbody>
</table>

![Figure 6. 12-Cycle Weir Layout](image)
3.2. Rating Curve

The discharge for the arced emergency spillway was determined using the method described in Crookston (2010). Additional information for determining the discharge coefficient for arced labyrinth weirs was obtained from Christensen (2012). Equation 1 was used to calculate the discharge.

\[ Q = \frac{2}{3} C_d L_c \sqrt{2g} H_T^{3/2} \]  

Where:
- \( Q \) = Rate of Discharge (ft\(^3\)/sec)
- \( C_d \) = Discharge Coefficient \( f(H_T/P, \alpha, \theta, \text{Crest Shape}) \)
- \( L_c \) = Total Centerline Length of Weir (ft)
- \( g \) = Acceleration Constant of Gravity (ft/sec\(^2\))
- \( H_T \) = Total Upstream Head above Crest (ft)

Discharge coefficients used were taken from experimental results in Crookston (2010) and Christensen (2012). Experimental results were limited to a sidewall angle of 6\(^o\), 12\(^o\), and 20\(^o\). A spreadsheet program was developed to predict the rating curve for the prototype 16\(^o\) weir using a double quadratic spline interpolation of the available experimental discharge coefficient data. Figure 7 shows the discharge coefficient for sidewall angle of 16\(^o\) (with \( \theta = 10\(^o\) \)) derived from interpolation compared to the experimental results for sidewall angles of \( \alpha = 6\(^o\), 12\(^o\), and 20\(^o\) \), with varying cycle arc angles of \( \theta = 0\(^o\), 10\(^o\), 20\(^o\), and 30\(^o\) \). See Figure 11 for the resulting rating curve for the chosen design.

![Figure 7. \( C_d \) vs \( H_T/P \)](image)

4. MODEL VALIDATION

4.1. Physical Model

A physical model was created at the Utah Water Research Laboratory (UWRL) at Utah State University, located in Logan, Utah, to support design efforts of both the service and emergency spillways. The physical model was a 1:45 Froude scale model. The model included a portion of the reservoir, the ogee and labyrinth spillways, and discharge channels. Three separate configurations of the emergency spillway were evaluated with the physical model (See...
In each case the design and location of the labyrinth weir remained the same while the design of the downstream spillway chute changed. The initial (baseline) configuration resulted in submergence of the weir at the PMF discharge due to the orientation of the weir to the chute and the relative mild slope downstream of the weir. The submergence was most pronounced along the left side and middle of the weir looking downstream and, to a lesser extent, on the right side. This resulted in a reservoir pool above the target design reservoir pool elevation by about 2 ft. Figure 9 shows the submergence of the weir at the PMF discharge.

A subsequent design of the spillway chute (Mod-1 in Figure 8) eliminated the submergence issue by creating a steeper invert slope. The chute was further optimized with the use of the physical model by narrowing the chute to eliminate an area along the right side of the chute that was not actively conveying flow. The revised design resulted in a significant reduction in channel excavation and cost to the project. This revised design is Mod-2 shown in Figure 8, and the results of the physical model test at the PMF discharge are shown in Figure 10. Note in Figure 10 the lack of submergence on the weir.
Additional rating curve data for the labyrinth weir was developed from the physical model. This was done by blocking off the service spillway and only allowing flow over the labyrinth weir. The data points are compared to the theoretical rating curve in Figure 11. There is a good fit between the two data sets; the largest discrepancy is at the lower end of the curve, which is likely due to scale effects from low head on the labyrinth weir crest.

![Figure 10. Physical Model @ Q=506cfs (PMF Discharge) Final Emergency Spillway Configuration](image)

![Figure 11. Emergency Arced Labyrinth Spillway Rating Curve](image)

4.2. CFD Model

A series of three-dimensional (3D) computational fluid dynamics (CFD) models of the Isabella Reservoir and spillways was conducted to support the design calculations and physical model. CFD modeling was completed using Star-CCM+, a commercially available software package for 3D modeling applications. The numerical modeling effort focused mainly on the following:

- Verifying the spillway rating curves developed using design equations, which were validated with the physical model.
• Addressing concerns about physical model scale effects and truncation of the forebay in the physical model.
• Providing more hydraulic condition resolution than possible using either the physical model or the 2D numerical model (i.e. flow conditions over Engineer Point, flows down the spillway chutes, etc).

To assure appropriate representation of the labyrinth weir within the various CFD models, a sectional CFD model of a labyrinth spillway was first created to validate against existing physical model studies. The model grid was developed to ensure sufficient resolution in the CFD model; the primary goal was to provide adequate resolution near the weir to accurately resolve the free surface flowing over the weir, resulting in favorable comparisons to physical model measurements. For validation against existing physical model studies, Brian Crookston’s work (Crookston 2010) was used as a baseline for the comparison. The CFD model was developed to match the Utah Water Research Laboratory (UWRL) Flume and labyrinth weir geometry so that an appropriate comparison could be made. A comparison of the CFD model results is done through calculation of a discharge coefficient \( C_d \) from the model output, which is then compared to the physical model results. This comparison is shown in Figure 12. Results generally showed close agreement between the CFD modeling and the laboratory experiments, though there is lesser agreement at lower values of \( H_t/P \).

![Figure 12. Comparison of CFD Simulations to Physical Model Results (Crookston 2010)](image)

Discharge data for the design labyrinth weir was collected for the emergency spillway and compared to the design data. The comparison is shown in Table 2. The results show very close agreement between the emergency spillway design data and CFD model results.

### Table 2. Comparison of Flows for the Emergency Spillway Only

<table>
<thead>
<tr>
<th>Reservoir Elevation (feet, NAVD88)</th>
<th>Design Data (cfs)</th>
<th>CFD (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2637.26</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2641.76</td>
<td>115,514</td>
<td>117,054</td>
</tr>
<tr>
<td>2645.26</td>
<td>252,467</td>
<td>246,585</td>
</tr>
<tr>
<td>2649.26</td>
<td>402,000</td>
<td>399,845</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

The new emergency spillway weir for Isabella dam was designed as an arced labyrinth weir. The use of the design procedure and data from Crookston (2010) and Christensen (2012) proved successful in developing the design for a large arced labyrinth weir. The theoretical design based on published information was validated with both physical and CFD numerical modelling. The spillway chute, in particular, is an important feature because of the potential for submergence due to concentrated flows from the weir in the downstream chute. For an arced labyrinth weir, the chute must be properly oriented and the invert must be placed at a steep enough slope so that submergence of the weir does not occur for the critical design flows.

6. REFERENCES
