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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 head dams (56.4 m or 185 ft and 30.5 m or 100 ft) by 4.88 m (16 ft); modifying a service spillway to better suit the needs of flood capacity, and creating a new labyrinth weir emergency spillway. To aid in the design of both spillways, a series of three-dimensional (3D) computational fluid dynamics (CFD) models of the Isabella Reservoir and outlet works were developed.

CFD model results were also used to evaluate hydraulic conditions in and down the spillway chute. Velocity, water surface elevation, and stream power were computed so that appropriate measures could be taken to protect the chutes from damaging erosion.

Keywords: CFD, Labyrinth Weir, Rating Curve, Physical Model, Stream Power

1. INTRODUCTION

Isabella Lake Reservoir is located on the Kern River in Kern County, California and lies within the Sacramento District’s (CESPK) area of responsibility. The project is approximately 67.6 km (42 miles) northeast of the city of Bakersfield and one mile upstream of the town of Lake Isabella. Isabella Lake Reservoir is formed by two earthen embankment dams: a main dam located where the Kern River once was and an auxiliary dam located in the hot springs valley (there is no historic evidence of an old riverbed in this valley). The two dams are separated by a natural topographic feature called Engineer Point, which runs perpendicular to the dams where the Kern County Fault is located. Figure 1 shows the layout of the two dams; the main dam with an ungated overflow spillway is on the left and the auxiliary dam is on the right.
Figure 1. Isabella Main Dam and Auxillary Dam

Spillway adequacy studies were performed, revising the Probable Maximum Flood with the current peak inflow PMF of 16,452 m$^3$/s (581 Kcfs). These studies concluded that the Isabella Dam, as constructed, could not safely pass the revised PMF. The new PMF is 67 percent larger (by volume) than the original spillway design flood. Routing of the PMF through Isabella Lake while assuming any reasonable starting storage level produces overtopping of the dam. Only about 50 percent of the PMF can be routed through the project before the dam is overtopped, assuming the reservoir is at gross pool at the beginning of the flood. It is estimated that overtopping of the dam currently has about a probability of 1 in 4,100 annual chance exceedance. In order to pass the revised PMF, modifications to the project have been proposed.

The proposed design will increase the height of the existing dams by 4.88 m (16 ft). The existing service spillway crest elevation will remain unchanged at 795.3 m (2609.26 ft). The revised capacity of the service spillway will not pass the flood flows; therefore, additional capacity will be provided with a new emergency spillway. In order to optimize use of existing space while minimizing the required construction and excavation, the new emergency spillway is being designed as an arced labyrinth weir design, allowing for increased spillway crest length in a smaller footprint than a traditional spillway design. See Figure 2.

The design has been developed by Sacramento District Corps of Engineers (CESPK). Portland District Corps of Engineers (CENWP) supported CESPK by performing Computational Fluid Dynamics (CFD) Modeling of the proposed configuration. The CFD effort was done in conjunction with a 1:45 scale physical model performed by Utah State University, Utah Water Research Laboratory.

Figure 2. Proposed Spillway Configuration for Isabella Dam
2. NUMERICAL MODELS

CENWP selected Star-CCM+, a commercially available software package, as the computational code for the CFD portion of the analysis. Star-CCM+ has the ability to model rigid lid flows (defined water surface, single fluid analysis) and free surface flows (CFD calculated interaction between air and water, two fluid analysis), plus the ability to “map” a solution from one model to another to provide initial conditions and/or boundary conditions for the subsequent models.

A series of models were built:

- A CFD sectional model of a labyrinth spillway evaluated in a physical model (Crookston, 2012). It was developed to identify appropriate modeling techniques (minimum cell size, cell growth away from the labyrinth, relaxation coefficient, etc) for the labyrinth weir. The sectional model was validated against the physical model studies.
- A large coarse grid model (CFD₁) was developed to evaluate the flow direction from the reservoir into the spillway approach channels for two scenarios: service spillway operation only and service and emergency spillway operations in tandem. CFD₁ was a rigid lid model that included portions of the North Fork and the South Fork Kern River and both the Main Dam and Auxiliary Dam. CFD₁ was used to generate boundary conditions for CFD₃, a transient free-surface model of the service and emergency spillways.
- CFD₃ is a free surface CFD model of the forebay just upstream of the emergency spillway, service spillway, and channels. CFD₃ was used to describe the approach conditions such as approach flow distribution and flow bulking along the weir crest, as well as define the spillway rating curve, and evaluate effective crest length of the spillways. CFD₁ was also used to describe the hydraulic conditions in the spillway chutes.
- A CFD_pm model of the physical model was also produced. This model was used to evaluate concerns associated with physical model footprint and potential scale effects.

2.1. Model Geometry, Grid, and Boundary Conditions

As the first step in CFD model development, a solid model of the Isabella Reservoir bathymetry and structures was created. The bathymetry was generated from topographic maps developed prior to dam construction, a limited number of soundings, and photogrammetric data representing the existing reservoir bathymetry. The assortment of survey data was combined using ArcGIS, a subset of data points representing bathymetry data was triangulated into multiple surfaces (required due to file size constraints) in Microstation V8. Those bathymetry surfaces were combined into a single surface and imported into StarCCM+, where a simulated water surface and upstream boundary surfaces were added to create a 3D volume representing the computational domain of CFD.

The existing reservoir bathymetry was then altered to represent design conditions using files provided by CESPK. The alterations to the existing bathymetry included the following:

- Raising of the main and auxiliary dams;
- Addition of a spur dike to the main dam;
- Modifications to the right wall of the service spillway, the spillway crest, and the left wall;
- Excavation of the emergency spillway area and channel; and
- Addition of the labyrinth weir and abutment walls

The point (*.txt) files provided by CESPK were turned into surfaces in Microstation V8, which were then turned into 3D volumes in StarCCM+. These 3D volumes along with the service spillway and emergency spillway 3D solids were then subtracted from or added to the original bathymetry volume in StarCCM+.

An arc surface was included in the model approximately 304.8 m (1000 ft) upstream of the labyrinth weir apexes to allow mapping of CFD₁ solution data to the upstream boundary of CFD₃. Horizontal planes were also included at Engineer Point to allow flexibility in applying and monitoring flow conditions over Engineer Point.
The grids for the CFD1 model runs were created in Star-CCM+ version 8.02. The development of the model grid parameters to be used for CFD1 model runs was an iterative process that involved testing and adjusting grid development strategies. The same general cell resolution settings were used to develop the grids for all of the models:

- Base grid: 10 m cells, one 1m thick prism layer
- Refinement within ~200 m of spillways: 3 m cells, one 0.5 m thick prism layer
- Refinement within ~100 m of spillways: 1 m cells, two prism layers (0.5 m total thickness – notionally 1/3 and 2/3 thickness)
- Service Spillway water surface refinement ~100 m upstream and downstream of ogee: 0.5 m cells
- Emergency Weir refinement: 0.1 m min, 1 m target size, two prism layers (0.2 m total thickness)

Figure 3 shows the resolution of the CFD1 grid near the service and emergency spillways. The yellow arc surface is the surface from which CFD1 run data is mapped to the CFD3 upstream boundary.

Figure 3. Grid Resolution CFD1

The single CFD3 upstream boundary was set as a velocity inlet with the velocity magnitudes and directions mapped from the results of corresponding CFD1 runs. Upstream boundary air/water interface elevations for all runs were set at the rigid lid of corresponding CFD1 runs. At the upstream boundary, only air can move in above the air/water interface and only water can move in below the air/water interface. The interface was only prescribed on the boundary, and the free surface allowed the air water interface to adjust as needed away from the boundary.

The downstream boundary conditions for both the Service and Emergency Spillways was a "stagnation inlet" in Star CCM+ terminology, which is an outlet where flow moves out of the model. The flow split (between air and water) is defined by a field function; only water is allowed to leave the model below the specified tailwater elevation, and only air is allowed to leave the model above the specified tailwater elevation. The physical model results were used to estimate the tailwater elevation at the downstream boundary. A second field function is used to apply hydrostatic pressure boundary based on the fluid type/depth (air or water) on the downstream boundary surface.

The boundary at the top of the model domain was set as a pressure boundary allowing air to enter and exit freely. Interface boundaries that do not influence the computation were included in the model just downstream of the service spillway crest and at the crest of each labyrinth weir cycle as locations to monitor discharge. All other region boundaries were set as default wall boundaries, including the bathymetry, concrete structures, and inactive flow outlets.
In addition to mapping CFD1 velocity results to the CFD3 upstream boundary, initial velocities and water surface elevations throughout the CFD1 model domain were also mapped. For all runs, initial pressures were hydrostatic based on a constant 101,325 Pascal (1.0 atm, 14.7 psi). Other initial conditions were left at StarCCM+ default values.

The same model geometry was applied for all of the models: CFD1, CFD3, and the physical model. Figure 4 shows the geometry truncated by the footprint of the physical model.

2.2. Model Results

The CFD model results are shown in Figure 5. Figure 5 shows an early version of the labyrinth weir in which both the physical and numerical model showed that the labyrinth was submerged on the right side of the image. The design was modified and tested in both the physical and numerical model.
Physical and CFD model results were compared at similar locations. Details on data collection in the physical model are defined in Utah Water Research Report Number 2999, 2014. Comparisons were made between the results from the CFDPM model at physical model scale, CFDPM model at prototype scale, and the Physical Model; see Figure 6 for a sample comparison. Scale effects for the PMF were not evident when the physical model results of the CFDPM model at physical model scale and prototype scale are compared. The physical model discharge was 14,640 m$^3$/s (517 Kcfs) versus the 15263 m$^3$/s (539 Kcfs) discharge for the CFDPM model scale, approximately a 4% difference. The comparison of the various rating curves is depicted in Figure 7.

![Figure 5. Physical Model Measurements Compared to CFD of Physical Model at Model Scale. Plan View of Velocity Vectors](image)

![Figure 6. Isabella Spillway Rating Curves](image)
3. DESIGN DATA

The modeling effort (physical and numerical) has confirmed that the rating curve developed using traditional methods (discharge coefficients, velocity head, etc.) are accurate and that the current configuration of the service spillway and labyrinth weir (mod 10) will pass the PMF at a forebay elevation of less than 807.5 m (2649.26 ft).

The CFD model results were probed to provide additional information to the designers. In particular velocities, pressures and stream power were extracted from the model results. Several profiles and cross sections were placed in the model. All of the model nodes with cells that the sections touched were exported to a text file. Figure 8 shows all of the profiles/cross sections taken from the CFD models.

![Figure 7: Location of Profiles and Cross Sections](image)

Stream power can be used to evaluate the potential for erosion to occur. Stream Power is one variable that is combined by specific rock properties. Stream Power is computed from the dimensional equation:

$$SP = \gamma \times q \times S_f$$

where $SP$ = Stream Power (kW/m$^2$), $\gamma$ = unit weight of water (kN/m$^3$) and equal to 9.807 kN/m$^3$, $S_f$ = energy slope, (m/m), and $q$ = unit discharge, (m$^3$/s/m).

Stream power was computed for profiles where an energy slope was available. Stream power was also computed for the three labyrinth arcs shown in Figure 8 where stream power was computed for the center arc with the energy slope being defined between the outer arcs.

Figures 9 and 10 show the water surface elevation down the service spillway and emergency spillway for different CFD model runs. The legend is total $Q$ for the project, not $Q$ through the specific spillway.
Figures 11 and 12 show stream power for the same conditions plotted in Figures 9 and 10. The PMF water surface is included in the figures. The stream power plots are all shown with a scale of 0 to 2000. There is a spike in stream power at the spillway crest (significant change in energy slope). The magnitude of stream power at the spillway crest is large, but the crest is also concrete. In the service spillway, the stream power values spike at the downstream end of the chute where the slope of the chute is extremely steep. In the emergency spillway, the stream power...
values tend to be higher at the lower end of the chute right downstream of the change in the invert slope. The spikes in stream power occur well downstream of the dam’s crest.

Figure 10. Stream Power – Service Spillway

Figure 11. Stream Power of Emergency Spillway
4. CONCLUSIONS

The design process for the emergency spillway was streamlined using a composite modeling approach employing both physical and CFD modeling of the labyrinth weir. Utah State University, Utah Water Research Laboratory constructed a 1:45 scale physical model of a portion of the main dam forebay, emergency spillway, and service spillway. CENWP hydraulic engineers developed CFD models of the Isabella Dam forebay, auxiliary dam, and service and emergency spillways to provide an efficient test bed for design alternatives for the spillways, support rating curve development, and to validate information obtained in the physical model.

5. REFERENCES