POE DAM RADIAL GATE STRENGTHENING PROJECT: CHALLENGE ACCEPTED

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ABSTRACT

Poe Dam is a Pacific Gas & Electric Company (PG&E) dam located on the North Fork of the Feather River in Butte County, California. Constructed in the late 1950’s, the dam is about 70 feet high with a crest length of about 450 feet. The dam serves primarily as a diversion dam to feed a 6.3-mile-long tunnel to Poe Powerhouse located downstream on the Feather River. Poe Reservoir is approximately 1.7 miles long and has a storage capacity of approximately 1,203 acre-feet. Due to the high flood flows on the Feather River and limited storage capacity of the reservoir, the majority of the dam serves as the primary spillway with four 50-foot-wide by 41-foot-high radial gates.

As part of an ongoing dam safety program, PG&E commissioned a testing and analysis program to determine the structural adequacy of the aging radial gates. The results of this analysis indicated excess friction in the trunnions and overstressing of the gate arms.

Subsequently, URS Corporation (URS) performed an alternative study for remediation of the overstressed gate components. PG&E selected replacement of the gate end arms and trunnion assemblies as the preferred remediation alternative. Design for the remediation of the gate components was divided between HDR Engineering, Inc. (HDR) and URS. HDR was responsible for the trunnion replacement design, and URS responsible for the gate arm replacement design.

Execution of this option presented two major challenges:

- Selection and design of the gate isolation and dewatering system for replacement of the gate components, and
- Analysis and design of the new “replace in kind” trunnion assemblies

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INTRODUCTION

Poe Dam, owned by Pacific Gas & Electric Company (PG&E), is located on the North Fork of the Feather River in Butte County, California approximately 29 miles northeast of Oroville, California. Construction of the dam was completed in 1958. The dam is bounded by Highway 70 on the left abutment and the Union Pacific Railroad on the right abutment. Poe Reservoir is approximately 1.7 miles long and has a storage capacity of approximately 1,203 acre-feet.

Poe Reservoir supplies water to Poe Powerhouse for hydroelectric generation. Water is diverted from Poe Reservoir through a 6.3-mile-long tunnel to Poe Powerhouse located downstream on the Feather River.

The dam height is about 70 feet to the top of the spillway piers, with a crest length of about 450 feet. Due to the limited storage of the reservoir and high flood flows in the Feather River, most of the length of the dam serves as a gated spillway.

The primary spillway gates consist of four steel, radial gates, each 50-feet-wide by 41-feet-high (in the closed position) with a 50-foot-radius from the axis of rotation to the downstream face of the skin plate. The primary spillway gates are designated Gate 1 (closest to Highway 70, left side) through Gate 4 (closest to the railroad, right side).
Two smaller gates are located on either side of the primary spillway gates. A smaller radial gate, 22.5-foot-wide by 15-foot-high, is located on the left side and a 20-foot-wide by 7-foot-high bottom-hinged crest gate is located to the right. Figure 2 is an aerial view of the dam, and Figure 3 shows the upstream elevation.

Figure 2. Project Aerial.

Figure 3. Upstream Elevation View
In October 2007, Applied Technology Services performed strain gauge testing on the gates to measure radial arm deflections and to quantify trunnion friction at several locations. All four gates were instrumented to determine the in-situ deflections of the gate arms due to normal operating loads. Two of the gates were instrumented to measure trunnion friction. Test results showed a high coefficient of friction on Gates 1 and 2. Friction coefficients as high as 0.42 were measured, resulting in over-stressing of some members of the gate arms.

Consequently, PG&E requested an alternative study to evaluate and determine various retrofit options to strengthen the existing structures as appropriate. Four retrofit alternatives were considered:

(1) adding cover plates to strengthen the individual gate arm members;
(2) adding (gusset plates over the gate arm frame system to strengthen it;
(3) replacing the trunnion bushings to reduce the friction; and,
(4) replacing the gate arms with higher strength steel.

PG&E selected Options 3 (trunnion bushing replacement) & 4 (end arm replacement) for the gate remediation design. PG&E elected to replace the entire yoke-hub trunnion assembly because the condition of the contact surfaces between the bushing and trunnion hub are unknown and since a fit for service determination of the trunnion assembly would result in a delayed return to service date. Design for the remediation of the gate components was divided between HDR Engineering, Inc. (HDR) and URS Corporation (URS). HDR was responsible for the trunnion replacement design and URS responsible for the gate arm replacement design.

**DEWATERING SYSTEM DESIGN**

Replacement of the gate end arms and trunnions requires relieving the gates of hydrostatic pressure while maintaining normal operating pool. The original design included no provision to dewater the main spillway gates while maintaining the operational pool. The original design intent was to lower the reservoir and use a system of 10-foot-high flashboards to isolate one or more bays while bypassing base flow through the remaining open bays. However, sediment transport and downstream water quality issues associated with draining the reservoir were identified through the environmental permitting process for the project. These issues eliminated reservoir drawdown as a viable option for dewatering the spillway bays.

A design-build team consisting of Sybion Reid Construction (SRC), Schnabel Engineering (Schnabel), Aubian Engineering (Aubian) and Thompson Metal Fab (TMF) was retained to design, fabricate and install a temporary means to sequentially dewater the four primary spillway bays. An upstream bulkhead is required to allow dewatering of the bays. Tailwater conditions also required a downstream cofferdam to provide safe working conditions within a gate bay.
DESIGN CHALLENGES

Dewatering of a spillway bay at Poe Dam presented a number of design, construction and operational challenges, including:

- large size of the gate bay openings (50 feet wide and 51 feet high from the vertical wall below the ogee crest to the top of gate);
- close proximity of the gate skin plate to the bulkhead sealing surface (Figure 7);
- nearly 9-foot horizontal offset between the plane of the pier noses and the plane of the vertical wall below the ogee crest (Figure 7);
- wide range of potential reservoir elevations during bulkhead use;
- short allowable construction season, forcing the scheduling of the work as one gate per year;
- ease-of-maneuverability requirements for moving the bulkhead from gate to gate; and in and out of the reservoir for each of the four construction seasons; and
- requirement to re-establish the original hydraulic profile of the piers after removal of the bulkhead.

ALTERNATIVE SELECTION

To meet the design requirements, two approaches to an upstream floating bulkhead solution were evaluated during preparation of the dewatering system design:

- a horizontal bulkhead; and,
- a reverse needle-beam cofferdam.

These two approaches are discussed in the following sections.

Horizontal Bulkhead

The conventional approach for gate isolation is to provide a bearing surface at the pier noses, or vertical slots in the piers upstream of the gate, for installation of a gate isolation system such as stop logs, bulkheads or floating bulkheads that span horizontally across the spillway bay. The horizontal framing members of these gate isolation systems typically bear on the pier noses or the downstream vertical faces of the slot. Seals are placed along the sides and bottom of the gate isolation system so that reservoir water cannot flow into the intervening space between the gate isolation system and the gate once the space is dewatered.

Where the actual nose of the pier is straight and in-plane with the upstream face of the spillway crest, the horizontal bulkhead can be seated against the nose of the pier without modification. In the case of Poe Dam there is a 9-foot offset between the pier nose and the vertical face of the spillway. For the case of a non-planar sealing surface, use of a horizontal bulkhead requires structure modifications to create a planar sealing surface. Figure 4 illustrates examples of the pier modification options for support of horizontal
bulkheads. The photo on the left shows metal brackets installed on the pier walls, and the photo on the right illustrates a vertical notch cut into the pier wall, with strengthening anchors installed on the downstream side to prevent failure of the existing concrete. These types of bearing supports would extend from the vertical face of the spillway crest to above pool level creating a vertical U-shaped sealing plane.

![Images of metal brackets and vertical notches in a pier wall.](image)

**Figure 4. Horizontal Bulkhead Pier Modification Examples.**

At Poe Dam, either option would address the 9-foot offset of the ogee crest from the pier noses as the vertical brackets or notches could be located at the appropriate location along the pier faces. The brackets or notches would serve as the reaction and sealing surface for the horizontal members.

To meet the PG&E design requirement that the hydraulic profile of the gate bay be restored following removal of the bulkhead, either the steel brackets would have to be removed and the anchors cut or the notches in-filled after removal of the bulkhead. Either option presents scheduling challenges due to the short construction season, and limits options for future re-use of a horizontal bulkhead should it become necessary.

Also, construction of an individual slot or beam seat requires significant underwater work. The slot or beam seat needs to be surveyed and correctly located underwater to achieve a vertical uniform sealing plane without twist. Typically, divers are used to install a temporary cofferdam at each pier face so that the slot can be cut or the beam seat anchored in a dry environment or are used to assist with underwater cutting of the concrete or installation of anchors for the beam seat. Because there is significant underwater work, the cost to provide an acceptable slot or beam seat at each pier face can far exceed the cost to fabricate and install a horizontally spanning gate isolation system, particularly if there are a significant number of piers to be modified (Lux, 2010).
**Floating Reverse Needle Beam Cofferdam**

Due to the cost and extent of modifications required on the pier walls to allow use of a horizontal segmented bulkhead, coupled with meeting the PG&E design and operational requirements and a short construction season, a floating reverse needle beam cofferdam was selected as the preferred method for dewatering the gates at Poe Dam. This configuration can simply be thought of as the horizontal bulkhead rotated 90 degrees.

![Figure 5. Cutaway View of the Reverse Needle Beam Cofferdam Concept for Poe Dam. Needles are shown in white, with the support beam shown in light grey](image)

The needle beam cofferdam has traditionally been used where the gate opening is significantly wider than it is high. A needle beam cofferdam consists of a horizontal support girder that spans between piers above the water surface (the beam) and a series of beams placed vertically between the sill and horizontal support girder (the needles). Traditionally, the needles have consisted of timbers or steel sheet piles.

In the standard configuration, the bottom of the needles bears against the spillway crest in a slot, pockets or the vertical face of the spillway. The top of the needles bear against the support beam that spans the gate bay above the reservoir water surface. For a reverse needle beam cofferdam, the vertical needles pull against the support beam rather than bear against it (Boyd, 2005). A reverse needle beam cofferdam is typically used where the spillway vertical face is recessed back from the pier noses, such as at Poe Dam. While this arrangement complicates the needle connection to the support beam, it reduces the extent of pier modifications required for installation of the support beam.
The lateral water pressure load against the needles is transferred downward to the spillway and upward to the support beam. The support beam carries roughly 1/3 of the hydrostatic load while the bottom reaction carries the remaining 2/3. While this is an efficient load distribution, the long span of the support beam between piers means it will experience a large downstream acting load from the needles, especially on projects with large gate openings. In addition to the lateral hydrostatic loads, the support beam needs to support its own weight.

The support beam transmits two loads to the supporting piers. The first is a vertical load that, under normal operating conditions, is primarily the self-weight of the support beam as the needles are in a neutral buoyancy condition. The second load is a lateral load in the downstream direction when the gate bay is dewatered from the reservoir hydrostatic load transferred from the needles to the support beam.

Placing the support beam on top of the existing piers would provide vertical support, but no lateral support. To provide lateral support the pier noses will be cut above the water surface to form a shelf that provides both a vertical and lateral reaction for the support beam.

To restore the hydraulic profile of the uppermost portion of pier noses after removal of the cofferdam, fabricated steel shells matching the profile of the piers will be used to reconstruct the pier noses. The removable steel shells will restore the hydraulic profile of the bays, while allowing future re-installation of the needle beam cofferdam.

For the Poe Dam project, the reverse needle beam cofferdam offers a number of important advantages over the traditional horizontal segmented bulkhead:

- No guides, slots or notches are required on the inside face of the piers.
- No underwater modifications of the spillway bay are needed.
- The individual needles are easy to maneuver once ballasted and vertical for movement from one bay to the next.
- The independent needles and bottom seals are much more forgiving of variability in the alignment of the spillway ogee than horizontal caissons.
- Flap seals with adjustable mounts are used to seal the needles against the piers and can readily accommodate variations in the alignment and condition of the pier walls.
- The support beam can be readily lifted from bay to bay using a work barge with timber cribbing and moved from bay to bay by ropes or small skiffs.
- Once the bulkhead is removed from the bay, nothing remains. The hydraulic profiles of the pier walls are not modified and no removal of brackets or anchorages is required.
- Each needle can be easily disconnected from the support beam and floated to the offload area for retrieval, transport and storage.
The reverse needle beam cofferdam designed for use as the upstream cofferdam at Poe Dam consists of two major assemblies: support beam and seven floating needles.

**Support Beam:**

The support beam consists of a horizontal box girder that transfers the upper reaction of the needles to the piers. The beam consists of a built up box girder 67-inches-deep by 36-inches-high with a length of 65 feet. The support beam rests on sills cut in the nose of each concrete pier. Steel laminated elastomeric bearing pads mounted to the beam transfer the beam end reactions to the pier concrete. Bearing pads are also located on the bottom of the beam to transfer gravity loads to the piers. The support beam is transported on the reservoir using a barge for movement from one spillway bay to another or to launch and extract it from the reservoir.

The needles are bolted directly to the downstream flange of the support beam because of the limited clearance between the downstream flange of the support beam and the vertical face of the spillway crest.

**Floating Needles:**

The floating needles for this project use Aubian Engineering’s patented system consisting of HSS tubes sandwiched between plates. Each floating needle consists of two HSS 32 x 22 x 5/8” tubes spaced apart and welded to a downstream sealing plate. An intermediate plate spans between the upstream sides of the HSS tubes to create trim and ballast chambers. Three needle configurations will be used; two end needles (Nos. 1 and 7) each with a width of 84 inches, three intermediate needles (Nos. 2, 4 and 6) each with a width of 86 inches with no side seals, and two intermediate needles (Nos. 3 and 5) each with a width of 84 inches using side seals and a bypass filling pipe. The HSS tubes and intermediate chambers are sealed at each end to provide buoyancy. A set of valves are used to add or purge water from the trim and ballast chambers for each needle. When the intervening space between the gate and upstream bulkhead is dewatered, reservoir water pressure holds the vertical needles in position.

Each needle is transported to the project on a flatbed trailer, placed on the reservoir using a crane and floated to the gate being dewatered using a small skiff or ropes from the shore or dam. When the needle is completely empty it floats on the reservoir in a horizontal position. When the ballast chamber is filled, the needle rotates to a vertical position. The needle can be adjusted to the needed elevation to be connected to the support beam by adding water to the trim chamber to lower it or applying compressed air to displace water from the trim chamber to raise it.

Each floating needle is connected to the support beam using bolts through the HSS tubes. At the bottom, each needle bears against the upstream vertical face of the spillway crest. An elastomeric bearing pad runs along the bottom of each needle to make a seal between the needle bottom and the crest face. A flap seal is also used between each vertical needle to prevent water from passing through the joint between needles and the joint...
between the end needles and the piers. Plan and Section views of the needle beam cofferdam system are presented on Figures 6 and 7, as follows.

Figure 6. Plan View of the Reverse Needle Beam Upstream Cofferdam

Figure 7. Section View of the Proposed Cofferdams for Poe Dam
**Downstream Cofferdam**

The downstream bulkhead consists of a series of braced frames anchored to the concrete spillway surface downstream of the radial gates, as shown on Figure 7. Timber lagging spans between the braced frames and provides the support structure for an impermeable membrane which serves as the tailwater sealing surface.

**RADIAL GATE ARM REPLACEMENT DESIGN**

The radial gate arms at Poe Dam are typical among radial gate configurations. Analysis of the radial gate was performed using many of the guidelines published in the Army Corp of Engineers engineering manual EM 1110-2-2702 Design of Spillway Tainter Gates (EM 2702), using an upper bound friction factor of 0.30 for the replacement trunnion. A three-dimensional (3-D) linear elastic finite element model was developed by URS using the general-purpose finite element software SAP2000, implementing 3-D FRAME and SHELL elements. Figure No. 8 presents a photo of the finite element model.

![POE DAM RADIAL GATE: ARM RETROFIT](imageURL)

**Figure 8. Radial Gate Finite Element Model**

The strength ratios for all gate members were evaluated using the steel structure design code check provided in the post-processor for SAP2000. The effective length factor (K) for the arm members calculated in SAP were verified using manual calculations. If the Demand to Capacity ratio (D/C ratio) exceeded 1.0 per existing condition analysis, a modified case was implemented by replacing the steel members with higher yield strength. To represent the gate in operating condition, two vertical reaction points were placed at the end location of the lifting chains to support the gate in the model. The boundary conditions at the trunnion were represented by fixed connections in all directions and rotations except for the rotation parallel to the face of the gate. Asymmetrical gate hoisting was not considered.
Members of the existing gates were assumed to have standard steel shapes. The inspection report indicated that the radial gate material is ASTM A36 (yield strength, \( f_y = 36 \text{ ksi} \)) and all structural connections are made with ASTM A325 bolts, with threads excluded from the shear plane. Existing radial gate members not meeting the strength criteria were replaced with ASTM A992 material (yield strength, \( f_y = 50 \text{ ksi} \)). The strength of existing structural elements was evaluated based on the computed section stresses in various members. The criteria adopted for evaluating these results followed the AISC Manual of Steel Construction: Load and Resistance Factor Design.

**TRUNNION REPLACEMENT DESIGN**

The trunnion design at Poe Dam is unusual among radial gate configurations. The two most notable features are the use of a partial circumferential (cut-away rear) trunnion hub and a deep-beam, wing-like dead man anchorage supporting a trunnion yoke adapted for the partial circumferential hub. There is no standard naming convention for either of these trunnion features. The scope of work at Poe Dam for the trunnion refurbishment was for a “replacement in kind” retrofit using the existing trunnion design but fabricated with higher strength materials. Figure 9 is a photo of the trunnion and gate arm system at Poe Dam.

![Figure 9. Radial Gate Trunnion and Gate Arm Assembly](image)

HDR faced several trunnion replacement design challenges including:

- the uncommon trunnion assembly geometry;
- uncertainties in the actual condition of contact surfaces.

The trunnion design provides only a 140-degree bearing surface on the upstream side of the trunnion hub with the remaining 220-degrees consisting of flanges to contain the pin. The gates operate through 54 degree range (open – closed). Figure 10 presents isometric view of the hub and yoke assemblies. Figure 11 presents a photo of the partial-circumferential hub.
In a conventional trunnion, the hydrostatic forces travel from the gate arms to the trunnion hub and bushing, then to the pin. The pin is supported only at the ends by the trunnion yoke, which is in turn supported by a large trunnion beam or some other type of anchorage within the pier.

The overall design theory of the Poe Dam trunnion anchorage is that the primary hydrostatic forces are carried by the deep beam and dead man anchorage and all other forces and displacements are accounted for with the trunnion assembly.

With the Poe Dam trunnion the forces travel from the gate arms to the trunnion hub and bushing and into the pin as above; but the pin is supported both at the ends and across the middle at the back by the yoke casting. The casting bears on the deep beam that is anchored into the pier as a dead-man anchorage. The deep beam and anchorage are really only intended to carry the primary hydrostatic load. The dead load of the gate and trunnion, the lateral thrust forces, as well as trunnion friction moments are carried by the yoke. But due to the unbonded length of the anchorage, the entire trunnion yoke must also be able to displace as hydrostatic forces vary and the anchorage stretches and relaxes. In effect, the trunnion yoke casting is “floating” on the pier after the hydrostatic forces are taken out by the deep beam and anchorage.

**Trunnion Hub Analysis**

Replacement in kind first requires assurances that the current design is adequate. Complex boundary conditions for the trunnion required that a non-linear, finite-element analysis be used to evaluate the current design. A three-dimensional (3-D) finite element model was developed by HDR using solid elements in ADINA with eight nodes per element to model the hub. The analysis is nonlinear static due to the existence of contact surfaces.
The existing Poe Dam trunnion hub is a steel casting with an allowable yield stress ($f_y$) of 30 ksi. The materials and design for the replacement components assembly were selected based on guidelines published in EM 2702, using allowable stress design and an allowable stresses for forging and castings of 0.5 $\sigma_y$.

The replacement hub materials are:
- ASTM A105 ($\sigma_y = 36$ ksi) for the partial circumferential bearing plate and the circumferential ears; and,
- ASTM A709 F2 Grade 50 for the hub plate flange and webs.

Table 1 presents the principle stress magnitudes in different locations of the hub. Figure 12 depicts the Von-Mises stress contours in the hub.

Table 1. Poe Dam Trunnion Hub Maximum Shear Stresses ($\sigma_y$) Based on Treska Criterion

<table>
<thead>
<tr>
<th>Location</th>
<th>$\sigma_1$ Ksi</th>
<th>$\sigma_2$ Ksi</th>
<th>$\sigma_3$ Ksi</th>
<th>$\sigma_y$ Ksi</th>
<th>$\sigma_y/\sigma_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub flange at intersection w/ bearing plate</td>
<td>-7.0</td>
<td>-9.0</td>
<td>-23</td>
<td>50</td>
<td>0.46&lt;0.5</td>
</tr>
<tr>
<td>Bearing plate at intersection w/ hub flange</td>
<td>-7.0</td>
<td>-9.0</td>
<td>-23* (at intersection) -15 (within one inch distance)</td>
<td>36</td>
<td>0.42&lt;0.5</td>
</tr>
<tr>
<td>Bearing surface</td>
<td>2.0</td>
<td>-0.8</td>
<td>-7.2</td>
<td>36</td>
<td>0.256&lt;0.5</td>
</tr>
<tr>
<td>Ears</td>
<td>2.0</td>
<td>-0.8</td>
<td>-7.0</td>
<td>36</td>
<td>0.25&lt;0.5</td>
</tr>
</tbody>
</table>

*This amount of stress occurs exactly at the intersection with the hub plate and reduces dramatically within one inch distance from the intersection (green color on the contours on Figure 12).
Figure 12. Von-Mises Stress in Existing Poe Dam Trunnion Hub

**Hub Conclusion**

The existing hub geometry fabricated with the higher strength steel has adequate strength for the governing load case and the stress values in all hub subcomponents are below the $0.5\sigma_y$ allowable stress limit established in EM 2702. So replacement in kind is feasible for the hub with use of the higher strength materials.

**Trunnion Yoke Analysis**

A 3-D finite element model was also developed to model the yoke assembly using solid elements in ADINA with eight nodes per element, as shown below on Figure 13. The analysis is nonlinear static due to the existence of contact surfaces. The model consists of the yoke with three bearing interfaces that support the yoke through contact elements.
The model proved to be sensitive to the presence of friction at the contact surfaces. Consequently, only results where the boundary conditions were modeled as frictionless contact surfaces are reported. The contact elements transfer only compression forces and allow the yoke to detach from the bearing interfaces if any tensile stresses develop on the contact surfaces. The bearing faces are fixed in all directions. Bolts keep the yoke from moving in the Y and Z directions.

Figure 14 is a cross-section taken at the midpoint between the yoke ears that support the pin around the full 360° circumference. The existing yoke geometry includes voids in the base plate that facilitated the steel casting process. As shown on the Figure in yellow and red, peak stresses are evident in areas of reentrant corners and interior plate edges within the voids.

The analysis indicates that these stresses exceed the $0.5\sigma_y$ allowable by a significant margin. It is not known if these peak stress areas exhibit any physical signs of distress as the area is inaccessible. However, all eight radial gate trunnion castings were tested using the American Society of Mechanical Engineers (ASME) Section V – Non-destructive Examination, magnetic particle procedure. No indications of cracks or voids were found. During replacement these areas will be thoroughly examined.

This analysis indicated that the risers which connect the base plate to the partial circumferential surface undergo principle stress values that exceed the allowable stresses. In order to mitigate the stress intensity, the gap between the risers is filled as is shown (with blue hatch) on Figure 15, below. The two big slots in the base plates are also filled (red hatch). These two slots were provided in the plate to relieve the thermal stresses.
when the yoke was originally cast.

Figure 15. Filling the Areas of Excessive Stress in Yoke Assembly

Figure 16 indicates the stress distribution with the baseplate voids filled in. It can be seen that peak stresses are significantly reduced. The peak stress around the anchor hole in the yoke baseplate is of negligible concern. Field observation of the yoke baseplate holes confirms that model refinement to address these peak stresses is unwarranted.

Figure 16. Peak Stresses in Revised Yoke at Midpoint between Ears

The new yoke partial circumferential bearing plate, the section colored green on the Figure, will be fabricated from a single piece of forged material; the end plates (ears) will be welded and therefore the voids are not required as they were for the casting.
Similar analyses were completed along two other sections through the yoke assembly: adjacent to the ears, and at the ear itself.

Figure 17 is a cross-section taken adjacent to the yoke ears supporting the pin around the full 360° circumference using the existing yoke geometry. Peak stresses are again visible in similar locations as shown in Figure 14 above.

Figure 17. Peak Stresses in Existing Yoke Adjacent to Ears

Figure 18 is a cross-section taken adjacent to the yoke ears using the revised yoke design. Peak stresses are visible in similar locations as shown in above, but smaller in magnitude.

Figure 18. Peak Stresses Revised Yoke Adjacent to Ears
Figure 19 is a cross-section taken at the yoke ear using the existing yoke geometry. Peak stresses are visible in locations were maximum contact is expected between the pin and the yoke for the load case analyzed.

Figure 19. Peak Stresses in Existing Yoke at the Ear.

Figure 20 is the same cross-section taken at the yoke ear but using the new design. There are only minor differences in peak stresses.

Figure 20. Peak Stresses in Revised Yoke at the Ear.
Yoke Conclusion

The existing Poe Dam trunnion yoke is a steel casting possessing an allowable yield stress ($f_y$) of 30 ksi. The modeling assumed that higher strength steel would be used in the replacement yoke. The partial circumferential bearing plate was modeled as ASTM A709 F2 Grade 50 material with $\sigma_y = 50$ ksi. The replacement ears can potentially be made from ASTM A106 material with an allowable yield stress ($f_y$) of 36 ksi and welded on.

The modeling indicated that the existing yoke design, even with higher strength steel, has questionable adequacy with peak stress values exceeding the $0.5\sigma_y$ allowable stress limit by approximately 70%. The replacement design, with the open areas filled, reduces most peak stress to within the limits established in U. S. Army Corp of Engineers engineering manual Design of Spillway Tainter Gates EM 1110-2-2702.

Trunnion Assembly Conclusion

The project plans to replace all eight trunnions beginning in 2014, which will involve the following:

- new yoke and hub materials to replace existing cast steel;
- new composite bushing materials with a friction coefficient of 0.1 to replace the existing Lubrite partial circumferential bearing and hub rotational/thrust bushings;
- changing the pin materials; and,
- changing the bolts for the hub/gate arm splice connections.

About the only thing not changing is the horizontal stainless steel bearing plates between the yoke base plates and the existing Lubrite bearing bars that allow the yoke to float, otherwise all the other material properties will be changed. The overall system geometry is unchanged and the load path remains unchanged.

REFERENCES
