Analysis and Design of Large-Scale Civil Works Structures Using LS-DYNA®

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Abstract

The Folsom Joint Federal Project (JFP) Auxiliary Spillway is a high profile addition to the Folsom Dam, located approximately thirty miles upstream of Sacramento, California. Total concrete placements on the project will exceed 140,000 cubic yards at a projected cost of nearly $1 billion. The main component of the JFP is a large concrete control structure with steel bulkhead gates, submerged tainter gates, and post-tensioned anchorage. As a critical piece of the flood control system in a densely populated, active seismic region, the JFP demanded a rigorous analysis of a scale never before used by the U.S. Army Corps of Engineers to design a civil works structure. The Sacramento District of the Corps developed a three-dimensional LS-DYNA model of the control structure, foundation, and reservoir in order to capture the fluid-structure and soil-structure interaction during a seismic event, something not possible with standard dam analysis procedures. The model incorporated anomalies within the foundation; their effects were significant and could not have been established and properly accounted for without the LS-DYNA model. The analysis examined seven suites of ground motions and two pool elevations that envelope the expected demand on the structure. Results from the model were used for both evaluation and design purposes.

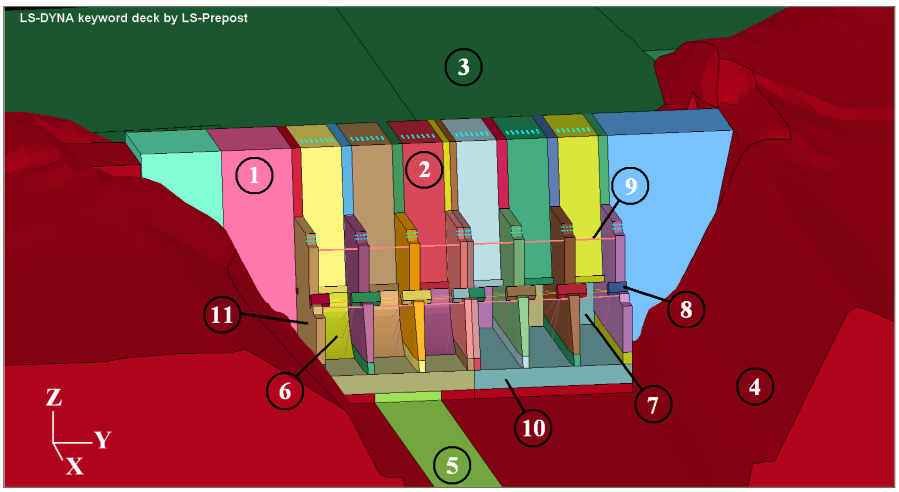
This paper presents suggestions on the modeling of large scale civil works structures such as the JFP. Included is an overview of lessons learned regarding contact definitions and troubleshooting, the application and scaling of seismic input, and methods for accurately modeling the behavior and load paths. Extensive verification of the LS-DYNA results was conducted using another widely used finite element analysis program; the procedures and results are discussed. Additionally, the paper advises on items to be considered during model development, with a focus on generating output suitable for design.

Project Introduction

The city of Sacramento, located in the central valley of California, is protected by a network of levees on the Sacramento and American Rivers. Approximately 29 miles upstream on the American River sits the Folsom Dam, impounding nearly 1,000,000 acre-feet of water and providing a mechanism to control the flow of the river and limit flooding. The Joint Federal Project (JFP) is an addition to the dam: an auxiliary spillway intended to provide greater flexibility of water releases and increase the flood protection level of the Sacramento metropolitan area. The main component of the JFP is a concrete control structure that houses six bulkhead gates and six submerged tainter gates.

The Folsom JFP Mesh

An important benefit of using LS-DYNA to model structures like the Folsom JFP is that it has a wide selection of elements and materials that allow it to capture the fluid-structure and soil-structure interaction between the concrete control structure, foundation, and reservoir. A number of structural features were included in the model: concrete monoliths, steel bulkhead and radial tainter gates, gate lifting equipment, and steel struts that affect the behavior of the reinforced concrete piers (see Figure 1). The concrete monoliths include massive unreinforced non-flow-through (NFT) sections that tie into the abutments and flow-through (FT) sections with slender piers that support the various gates and equipment. The overall dimensions of the model were chosen based on guidance from the U.S. Bureau of Reclamation's (USBR) state-of-the practice manual (1), and are 900 feet upstream/downstream, 606.29 feet vertically, and 1212.58 feet cross-canyon.



1. Non-flow-through Monolith
2. Flow-through Monolith
3. Reservoir
4. Foundation
5. Shear Zone
6. Tainter Gate
7. Bulkhead Gate
8. Trunnion Girder
9. Pier Strut
10. Invert Slab
11. Pier

Figure 1 - Folsom JFP Layout

The concrete control structure, reservoir, and foundation made up the majority of the mesh and were composed of solid elements, mostly using linear isotropic materials (*MAT_ELASTIC). Material properties within the control structure varied based on the target concrete strengths: four different materials were used, each with a different elastic modulus and Poisson's ratio. The reservoir was an incompressible fluid defined using *MAT_NULL and the physical properties of water. The foundation was mostly uniform, which simplified the application and scaling of ground motions, but it included a large shear zone – a section of weak foundation material – that was discovered during excavation. This section was directly beneath one of the flow-through monoliths and was discovered to affect the behavior of the control structure significantly, in both seismic (by amplifying the ground motions) and static cases (changing the distribution of load through the piers). *MAT_RIGID was used for the solid elements of the trunnion girder, which transmits load from the tainter gate to the anchorage and was examined in more detail in separate models.

Shell and beam elements (using *MAT_RIGID and *MAT_ELASTIC, resp.) and nodal masses made up the remainder of the model. Each conduit in the control structure has a bulkhead gate and a tainter gate. The bulkhead gate was composed entirely of shell elements and was located in either a raised or a lowered position, depending on the operational scenario being examined. The tainter gate skin plate was modeled with shell elements; its load is carried to the trunnion girder through steel strut arms that were modeled with beam elements. Beam elements were also used to model the pier struts; these are steel beams that span each conduit to provide rigidity to the pier system and force the piers to deflect synchronously during an earthquake. Finally, nodal masses represented the gate lifting equipment; these structures are designed with separate models and calculations, so their purpose in the model was to impart gravity and inertial loads to the piers. The completed mesh is shown in Figure 2.

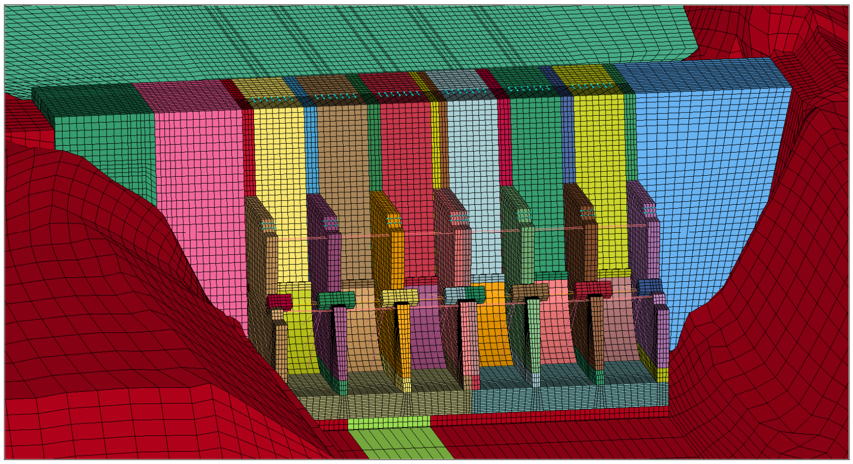


Figure 2 - Folsom JFP Mesh

Contacts, Constraints, and Boundaries

Tied contacts (*TIED_SURFACE_TO_SURFACE) within the piers of each concrete FT monolith were defined at three elevations: the base of each pier (where it connects to the invert slab), at the top of the conduit, and a plane between these two. The contacts in each pier should be defined separately, and at the least must be split at any monolith joint to ensure the proper load path is being modeled. Between adjacent monoliths, sliding (*AUTOMATIC_SURFACE_TO_SURFACE) contacts allowed force transfer orthogonal to the plane of the monolith joint; these contacts were conservatively defined with no friction. Preliminary tests during the troubleshooting phase indicated that the CONTRACTION_JOINT option might accurately represent the resistance provided by trapezoidal shear keys, inhibiting one direction of relative displacement between monoliths, though this has not been validated completely.

The contact surfaces between the control structure and the foundation were defined as sliding contacts with friction coefficients provided by geotechnical engineers. The reservoir-to-foundation contact was also defined as a sliding contact, but with no friction. This is contrary to information presented in the USBR state-of-the-practice manual, published in 2006, which suggests that the contact should be tied. Private communications with the USBR in 2010 indicated that a sliding contact should be used. This did solve some problems, but resulted in inaccurate pressures in some regions of the model, presumably due to the segments not aligning well enough. Care should be taken to ensure that the reservoir and foundation meshes align very well near any structure being analyzed or designed based on the model. Note that all contacts discussed above were segment-based, not part-based; LS-DYNA configured the normal vectors internally and these were user-verified.

As mentioned previously, the tainter gate skin plate was modeled as a rigid material and connected to steel beam element strut arms. These struts were constrained to the trunnion girders using *CONSTRAINED_EXTRA_NODE_SET. In the early stages of the model, the trunnion girders were tied to the piers, transmitting the entire load from the tainter gate at that interface. As the anchorage for the girder developed, it became a post-tensioned system with the dead ends of the anchorage in the invert slab. To model this load path, the trunnion girders were constrained to points that approximated the dead ends. This ignores the post-tensioning effects on the pier; an investigation to include the tendons in the model is currently underway.

Boundaries in the model varied for seismic or static conditions. Before running seismic cases, the model was run through the ramp and quiet time with single point constraints (SPCs) at nodes on the base and the four sides (*BOUNDARY_SPC). The SPCs restrained translation in the degree of freedom orthogonal to the face; at edges and corners, two and three degrees of freedom were restrained, respectively. After the model finished running, the output from the SPCFORC file was added back into the model using *LOAD_NODE_POINT; these nodal forces replaced the SPCs and were ramped with the same curve as the static loads. Non-reflective boundaries were included on the five planar faces of the model, preventing artificial amplification of the seismic waves.

Several other contact issues are encountered easily and were troubleshot during the development of the Folsom JFP model. First, contacts should not be continuous across monolith joints, with one exception: when something with a defined area, such as the base of the invert slab, can move over a larger area, such as the foundation. In this event, the larger surface should be defined as the master side of the contact and the smaller side should be the slave. This condition was included in the JFP model at the monolith-to-foundation contacts and the contacts between the reservoir and the upstream pier faces at the joint between FT monoliths. In the original JFP model, one of the tied contacts within the piers was implemented with a single contact definition; this caused errors when LS-DYNA internally applied the nodal constraints. Essentially, nodes on one side of the monolith joint were constrained to nodes on the other; this expressed itself as a disruption in the load path. On a rigid foundation, similar piers on identical monoliths should carry the same load, which they did not until the contact was split.

Initially, the bulk of the reservoir was defined as a single part with one sliding contact between the reservoir and the pier faces. One of the effects of the shear zone within the foundation is that the two FT monoliths displaced relative to each other. When they did, the fluid elements against the pier deformed to make up the difference; in doing so, the elements lost contact with the pier and a free surface was created, which resulted in the affected fluid elements having zero pressure. A partial solution to this problem was to split the reservoir part in two along the plane of the monolith joint; the majority of the interface was tied, but the portion closest to the control structure was connected using a sliding contact and constraints in the global Y and Z directions. This allowed the reservoir parts to slide relative to one another and stay with both piers. The master side of the contact was defined as the segments on the piers and extended across the monolith joint; this allowed the slave segments (on the fluid elements) to cross the joint during the earthquake and still maintain pressure.

Ideally, all water-to-structure contacts within the conduits would be frictionless sliding contacts; however, an iterative process was required, with different combinations of sliding and tied contacts, until accurate pressures were obtained throughout the conduit. The upstream portion of the conduit required tied contacts while the remainder was sliding. Additionally, no contact was defined between the gates and the reservoir; instead, the coincident nodes were merged. One impact of this is that any contact surface adjacent to the merged reservoir/gate should include Optional Card A with a SOFT value of 0. This changes the calculation for the interface stiffness from a constraint formulation based on the nodal mass to a penalty formulation based on the bulk modulus. When using a SOFT value of 1, there were unrealistic spikes in the X- and Y-forces in the piers at the downstream end of the tainter gates.

Static Loads and Seismic Input

Most of the static loads in the model were accounted for simply by applying gravity using the *LOAD_BODY_Z card with a scale factor of 32.2 (units in the model were pounds and feet). The at-rest pressure of soil backfill on the exterior piers was accounted for with *LOAD_NODE_POINT; loads were calculated outside LS-DYNA and were applied to individual nodes. All static loads were ramped from 0 to 2 seconds to prevent divergence; four seconds of quiet time was included to allow the model to come to equilibrium before the application of the ground motions. An additional quiet time of approximately four seconds at the end allowed the structure return to a static condition.

The ground motions used in the finite element analyses were developed by URS using spectrally matched seed earthquakes and the Next-Generation Attenuation curves (2). The free field time histories were developed for the top of rock in the vicinity of the control structure (elevation 405). When using explicit integration, LS-DYNA currently requires ground motions to be input at depth; therefore, the free-field motions had to be scaled and verified to ensure that the amplitude and frequency content was not altered.

To scale the ground motions for this analysis, the free field motions were input as force time histories at elevation 50 in a separate foundation block model (Figure 3). The force time histories were applied using *LOAD_SEGMENT_SET_NONUNIFORM with scale factors calculated based on the elastic modulus and seismic wave velocities. The block model had a flat surface cut off at elevation 405 to eliminate the topographic effects above the foundation-to-dam contact; non-reflecting boundaries were placed on all faces except the top. Each direction of each ground motion was applied to the model individually. The resulting response spectrum at the top was compared to the smooth design spectrum; this showed if the ground motion needed to be scaled. From this point in the process, there were two options to scale the force time histories: uniform scaling and spectrum matching.

Uniform scaling applies a single scaling factor to the entire time history to match the target spectrum over a particular period or frequency range (typically the fundamental period), but this can cause significant disparities in the response spectrum at other periods. Spectrum matching requires the output and target acceleration time histories to be compared in the frequency domain; the conversion was accomplished using fast Fourier transforms (FFT). A correction factor is calculated for each frequency, equal to the ratio between target and computed magnitudes. This factor is then applied to the original input motion in the frequency domain and converted back to the time domain with an inverse FFT. This process is repeated until a reasonable match (less than 10% difference) is produced at every frequency, with the range of frequencies close to the fundamental frequency producing better matches (less than 5%

difference). Spectrum matching was used to scale the ground motions for this analysis. Note that the number of iterations needed to obtain an acceptable match will vary depending on the complexity of the foundation.

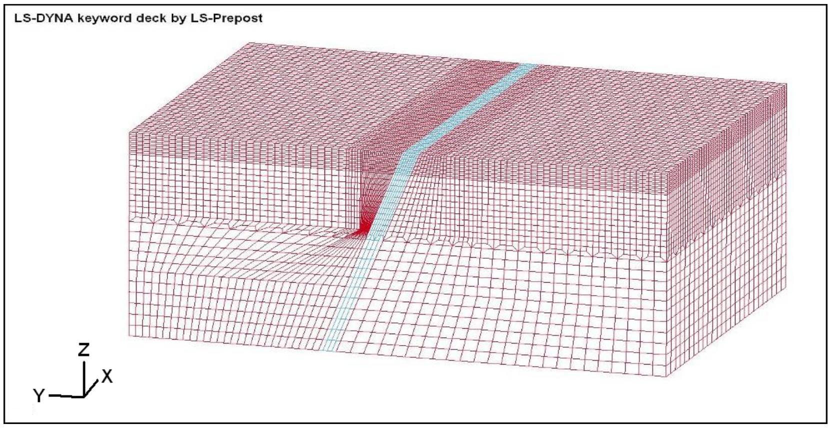


Figure 3 - Foundation Block Model

It is important for the foundation block model to use the same damping as the foundation in the full model. This ensures that the ground motions obtained from the scaling procedure propagate in the same manner in the full model. Frequency independent damping was used in the foundation, reservoir, and control structure with *DAMPING_FREQUENCY_RANGE; damping ratios ranged from 3% to 5% of critical.

Parallel Analysis and Verification

The parallel analysis of the Folsom JFP was conducted using SAP2000® (3) in order to verify the results obtained in LS-DYNA. The comparison was limited to a single FT monolith, 89'-9" wide x 144'-9" long x 142'-6" tall, with boundary conditions applied as single point constraints in all three translational degrees of freedom along the base of the structure. All calculation options, as described below, were kept as similar as possible given the expected variations between the two programs.

The full LS-DYNA model of the dam uses the explicit integration method; however, because SAP2000 does not have this capability, the parallel analysis was run using the implicit method. The modal analysis was carried out using Eigenvectors and solved for the first 50 modes; mass and stiffness proportional damping (Rayleigh) was used with equal coefficients based on the first and second periods of the monolith. The material properties (e.g., density and elastic modulus) were identical, but there were minor geometry differences due to the date at which each of the models was first developed; these should not have a significant effect on the results. All loads in the LS-DYNA model were applied using *LOAD_BODY; gravity was applied this way in SAP2000 but the acceleration time history excited only the supports at the base.

Static verification of the model examined the distribution of vertical forces within the piers and the vertical displacements at the crest of the dam; this provides a comparison of the mass and stiffness calculations of the two programs. Figure 4 shows good correlation between the two models. Note that the results from SAP2000 are shown in blue and LS-DYNA results are red; this convention holds true for all verification plots.

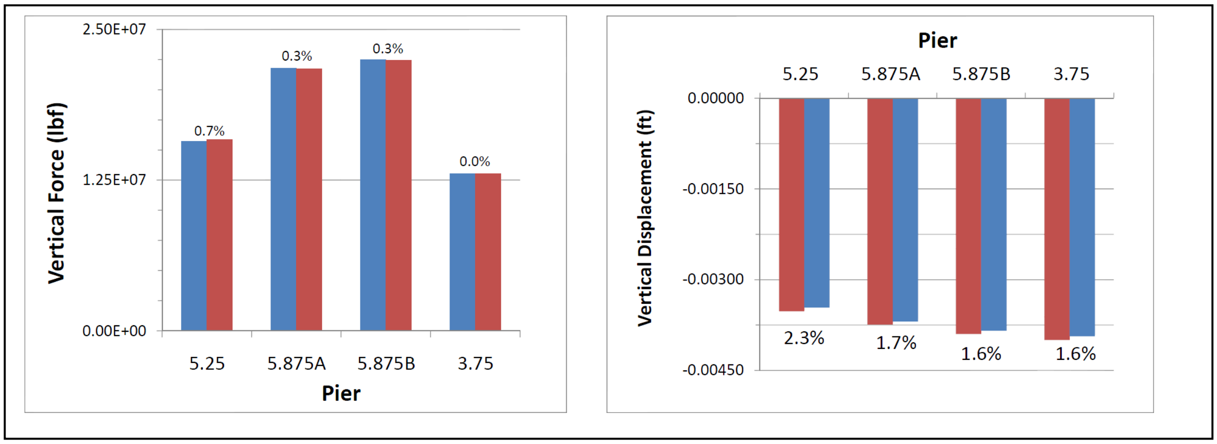


Figure 4 - Vertical Force and Displacement Verifications

Figure 5 shows similar results for periods and mass participation ratios for each mode. Both programs computed a fundamental period of the monolith of approximately 0.23 seconds. Velocity and displacement histories were recorded at the top of each of the piers. Figure 6 shows results for the Y-direction that are similar in terms of amplitude and frequency content; results for the vertical direction showed more disagreement, likely due to the different manners in which the loads were applied. Still, the authors believe the LS-DYNA model to be sufficiently validated by the SAP2000 model.

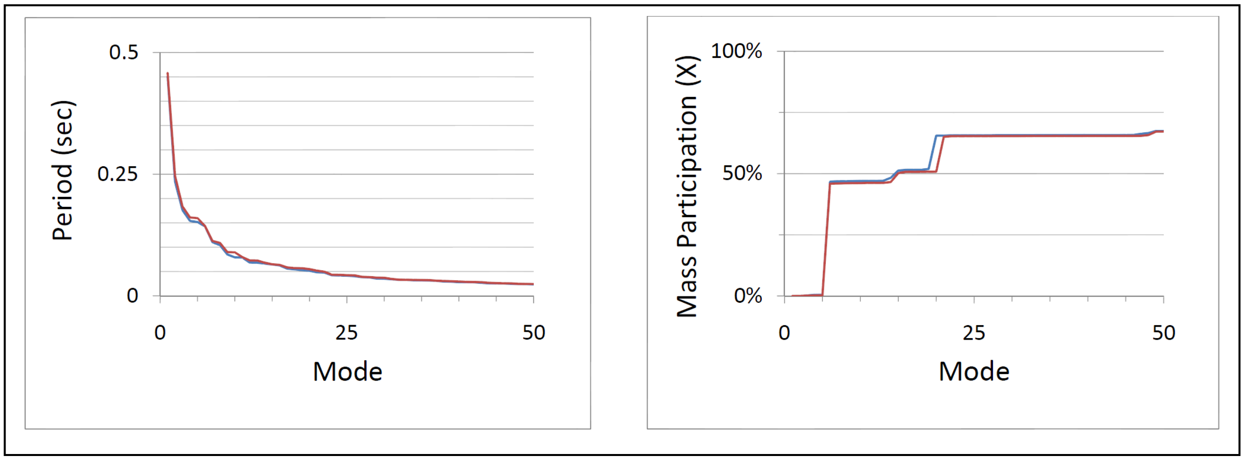


Figure 5 - Modal Analysis Comparisons

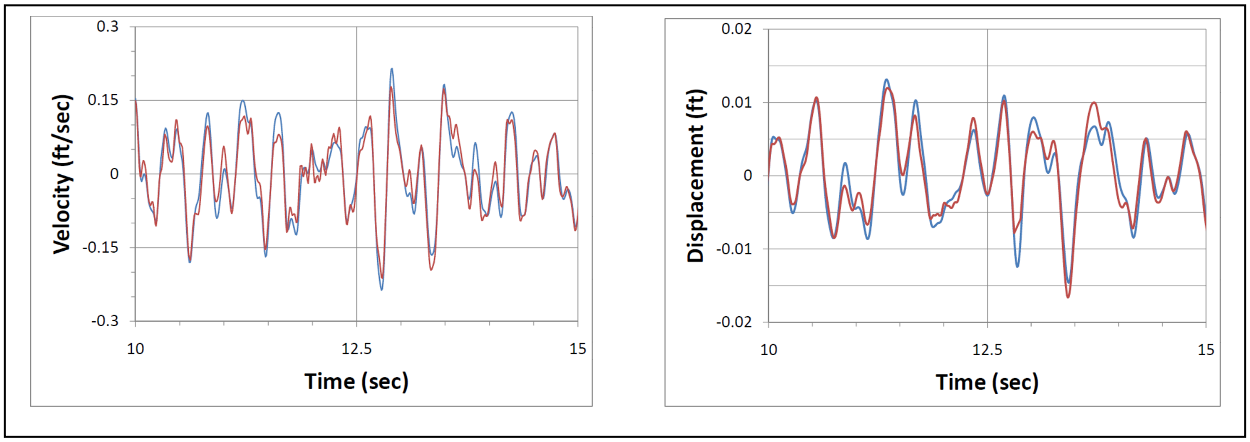


Figure 6 – Time History Comparisons

Verification of static loads within the full LS-DYNA model was done using a series of hand calculations. The total hydrostatic force on a contact within the control structure is easily extracted from the RCFORC file and can be compared to a value calculated based on the depth of water and area of the surface. The accuracy of this task is improved by splitting contacts up by conduit and pier instead of by monolith. This allows the user to determine if a problem is caused by an error in a single location or if it is more globally based. Figure 7 shows the pressure contours on a section of the reservoir behind one of the flow-through monoliths.

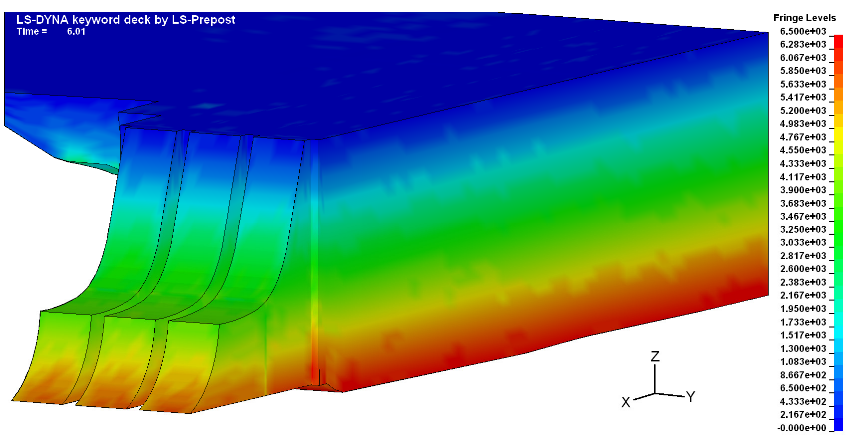


Figure 7 - Static Reservoir Pressure Contours

Dynamic loads in the full model were compared to the generalized Westergaard approximation discussed in USACE Engineering Manuals. This was done by plotting pressure time histories for the fluid elements against the upstream pier faces, bulkhead gates, and tainter gates; each pressure was multiplied by its tributary area on the structural feature. The summation of forces in each location revealed some interesting trends: the dynamic force component against the tainter gates was higher in the outer conduits than it was in the interior conduits, and all were at least three times greater than the Westergaard approximation. Forces were higher than expected against the bulkhead gates and pier faces as well.

Considerations during Model Development

When developing a model from which output will be used for design, it is important for the analyst responsible for the modeling to interface with those relying on the output (and vice versa). It is crucial for designers to be aware of the limitations of the data obtainable from LS-DYNA and how it can be formatted and saved using LS-Prepost. Conversely, it is important for the modeler to know what elements will need output for design. Ideally, both parties would be intimately familiar with both sides of the equation, but this is rarely the case in practice. The suggestions made in this section are the results of experiences from modeling and designing the spillway piers and pier struts of the Folsom JFP and should be taken as a starting point for those planning to design from LS-DYNA output.

Nodal forces from contact interfaces are recorded to the NCFORC file as the analysis runs; flags designating which data should be written to the file must be set before starting the analysis. The output for both the master and slave segments can be written to the file, but these forces should be identical. The size of the NCFORC file can be halved by only writing one side, but the side chosen should be consistent across all similar contacts; this will help prevent sign errors when determining the direction of a force during design. Planar contacts should be provided at several locations within each object of interest, using tied contacts with the constraint formulation (i.e., without the OFFSET option); this will allow the user to determine how demand changes throughout the structure and vary the capacity accordingly.

The amount of data provided by such an approach lends itself well to spreadsheet-based calculations. It is relatively simple to set up a command file to extract the nodal forces using LS-Prepost in batch mode. Each set of output – for example, the nodal forces on one contact in one direction – can be saved as its own comma-delimited file. Given the nature of spreadsheet software, strong consideration should be given to mesh uniformity in the areas of design output; each variation in mesh density or orientation will require unique treatment in design, thereby reducing the utility of each spreadsheet and increasing overall development time.

Finally, there are a few suggestions on the efficient use of time during troubleshooting and production runs. When attempting to fix problems in the static condition, stripping the model down to as few components and building it back up helped to isolate where problems originated. Also, time can be saved by examining results before the run is completed; LS-Prepost allows the output (d3plots, RCFORC files, etc.) to be opened while processing, so if the force on a contact halfway through the ramp is not approximately 50% of the target value, there is probably an error in the model. Once the troubleshooting has progressed to the dynamic cases, consider reducing the amount of quiet time before the earthquake begins and truncating the ground motion shortly after the most severe accelerations. This will save time when trying to establish that the final condition is similar to the initial condition.

During production runs, keep in mind that there is not a linear relationship between the number of LS-DYNA licenses running a model and the speed at which it runs. Depending on the specific computer setup, significant amounts of time can be saved by running more models at once with fewer licenses each: for example, on an eight-processor machine, one model may finish in 10 hours, but two models could be completed in 13 hours. The Folsom JFP involves 56 seismic cases; the total savings in processing time will be nearly three weeks.

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3. Computers & Structures Inc. “CSI Analysis Reference Manual for SAP2000®, ETABS®, and SAFE™.” June 2008.