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MEMORANDUM

To: Program Manager, Technology Development (DSO Research)
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From: Patrick Maier , P.E.
Civil Engineer, Waterways and Concrete Dams Group 2 (86-68130)

Subject: Transmittal of the Dam Safety Technology Development Program Report No. DSO-2016-09, Precast Ogee Crest – Conceptual Design Study

Attached for your use is the Precast Ogee Crest – Conceptual Design Study Report that has been prepared by the Technical Service Center at the request of the Dam Safety Office.

Thank you for the opportunity to perform this work. If there are any comments or questions regarding this evaluation please feel free to contact Patrick Maier at pmaier@usbr.gov or at 303-445-2601 or Katie Bartojay at kbartojay@usbr.gov or at 303-445-2374.

Attachment

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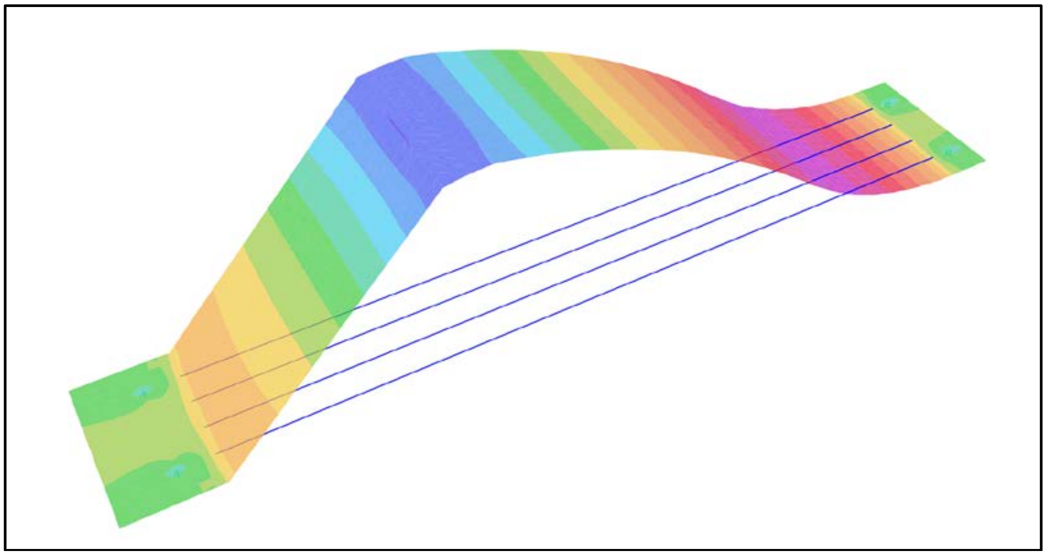
RECLAMATION
Managing Water in the West

Report DSO-2016-09

Precast Ogee Crest – Conceptual Design Study

Dam Safety Technology Development Program



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14. ABSTRACT
This research falls within the Dam Safety Program Technology Development Priority 1.4.4, Methods that investigate designs or construction techniques that would result in higher quality, in an effort to obtain a better final product. This document discusses and documents the recently completed conceptual designs for a precast concrete ogee crest. The conceptual designs included development of two general construction options for utilizing a precast concrete ogee crest as opposed to conventional cast-in-place methods of construction. Development of these designs included concrete outline drawings, reinforcement drawings, and an investigational finite element analysis. The finite element analysis was developed to understand what types of stresses a precast ogee crest would experience during fabrication, transportation and installation (including crane picks). Additionally, the team also investigated some constructability and transportation concerns regarding the precast ogee crest.

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

BUREAU OF RECLAMATION
Dam Safety Technology Development Program
Waterways and Concrete Dams Group 2, 86-68130

DSO-2016-09
Precast Ogee Crest Conceptual Design Study

, P.E. 10/25/16

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P.E. 10/25/16

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REVISIONS				
Description	Prepared	Checked	Technical approval	Peer review

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Introduction

This research falls within the Dam Safety Program Technology Development Priority 1.4.4, Methods that investigate designs or construction techniques that would result in higher quality, in an effort to obtain a better final product. This document discusses and documents the recently completed conceptual designs for a precast concrete ogee crest. The conceptual designs included development of two general construction options for utilizing a precast concrete ogee crest as opposed to conventional cast-in-place methods of construction. Development of these designs included concrete outline drawings, reinforcement drawings, and an investigational finite element analysis. The finite element analysis was developed to understand what types of stresses a precast ogee crest would experience during fabrication, transportation and installation (including crane picks). Additionally, the team also investigated some constructability and transportation concerns regarding the precast ogee crest.

Background

The ogee crest on an open channel water control structure is one of the most important elements of the structural / hydraulic design. The hydraulic design work to predict flow volume, characteristics and efficiency all relate back to the theoretical shape of the ogee crest. Constructing an ogee crest structure has proven to be difficult, costly and time consuming. The ogee crest of a control structure such as a spillway or canal headworks is a very critical element requiring tight tolerances. The shape of an ogee crest is based on extensive hydraulic designs and is shaped using one or several complex curves. Constructing an ogee crest requires difficult form and/or screed work and skilled concrete finishers, and typically in today's construction environment the selected contractor has never constructed one previously. Figures 1 and 2 show an ogee crest being constructed in the field at Minidoka Dam. Crest structures are not built as commonly as other structures (i.e. bridges, buildings) and therefore experience or common practice is usually lacking. Constructing an ogee crest is typically a learning experience regardless of contractor. Unfortunately this learning experience is costly, detrimental and most often results in irreversible defects. There are several consequences that could result from an improperly constructed ogee crest.

An improperly shaped ogee crest could result in different discharge capacities than designed, and potential adverse hydraulics such as separation of flow from the surface leading to unstable flow conditions. A reduced discharge capacity may cause flood routings to be inaccurate and may result in higher than expected reservoir water surface (RWS) elevations and could result in overtopping for more frequent flood events. A poorly constructed ogee crest could impact the hydrologic risks associated with; maximum passable flood (threshold flood event), dam overtopping, spillway chute wall overtopping (due to separation of flow and unstable flow conditions caused by poorly shaped crest), and/or cavitation damage of spillway chute slabs (downstream of crest caused by poor surface conditions such as spalling).

Figure 1 – Photograph showing construction workers placing reinforcement and formwork for an ogee crest at Minidoka Dam.

If an ogee crest is improperly constructed in the field, simply removing and rebuilding the crest is not usually an option. Extensive and costly grinding of the surface or patching of problem areas is a common way these deficiencies are repaired. Grinding eliminates the protective top surface of the concrete leaving the aggregate and potentially the reinforcement exposed. Additionally, cutting out and patching of the concrete merely produces more joints that will only cause serviceability issues in the future. These issues can also cause maintenance problems in the future, especially when there is an inadequate bond at the repair interface or if thin repairs are performed on the surface.

Another common problem associated with complex concrete surfaces is "over-finishing" of the concrete surface. As an unformed surface, the ogee crest will require vibration followed by screeding, and then troweling of a mix that is stiff to accommodate vertical curves on the exposed surface. Due to the strict tolerances regarding the shape and smoothness of an ogee crest, the surface of the concrete is commonly overworked in an attempt to satisfy these tolerances. This overworking of the surface can have severe detrimental effects such as scaling or spalling in the future. In applications where air entrained concrete is used this overworking can quickly eliminate the air entrainment on the upper surface leaving the concrete surface more vulnerable to freeze-thaw damage. An overworked concrete surface will ultimately have a higher water to cement ratio (w/c) caused by working in excess bleed water, lower strength, decreased air content and decreased durability. An overworked concrete surface will likely spall from freeze-thaw damage in the future. Once the concrete surface begins to spall, there is little that can be done to repair or reverse continued deterioration. Patching the concrete will only cause further roughness of the surface and the patching will ultimately come off in the future.

The formwork required to construct an ogee crest is complex, and not an off-the-shelf item. This complex formwork requires significant time and energy to produce. Custom shaped floats and other finishing accessories are typically formulated in the field. These field fabricated forms are usually a learn-as-you-go situation resulting in poorly shaped crests which do not match design specifications. Figures 2 and 3 show examples of these field fabricated tools used at Minidoka Dam and Scofield Dam, respectively. As can be seen in Figure 2, two flat bars were used at each end of the crest as a guide for the roller screed (which is inadequately sized). The work surface is cumbersome, and there is also significant congestion of the work area. It is not uncommon to specify mass concrete for an ogee crest, however, due to workability concerns, a contractor may request structural concrete be used for the top one or two feet (vibrated together during concrete placing activities so no internal joint is formed). This technique was done at Minidoka. The ogee crest at Scofield Dam shown in Figure 3 was improperly constructed and was later ground down with concrete saws in an attempt to repair surface deficiencies.

Figure 2 – Photograph showing field fabricated tools and methods used while forming an ogee crest at Minidoka Dam.

Figure 3 – Photograph showing an ogee crest placement at Scofield Dam.

Precast Concrete

The precast concrete industry has successfully been used to fabricate large scale concrete products such as highway bridge beams, wall panels, underground vaults, etc. that are then transported to the jobsite and installed. Precast concrete offers distinctive advantages that may eliminate the problems faced with constructing an ogee crest. The greatest advantage that precast offers is the ability to precisely form the ogee crest, thus eliminating the guess work of complicated field fabricated forms and screeding tools. Self-consolidating concrete (SCC) could be used, or vibrators to consolidate the concrete against the formwork eliminating the need to hand finish the surface with floats and trowels. Formwork could be designed and fabricated using a computer numerical control (CNC) machine if needed, and strict tolerances could be achieved. This formwork could also easily be re-used multiple times.

Figure 4 illustrates one example of what an upside down placement of a precast ogee crest may look like. A precast ogee crest would only need to be an outer shell, being as thin as practically possible, and designed to fit over a traditional mass concrete core. The precast concept greatly increase the chances of meeting exact design tolerances as well as eliminates the threat of losing air entrainment at the concrete surface. Precast also offers the unique ability to control the concrete quality and curing regimen while ultimately giving the ability to achieve the best possible finished product with regards to strength, proper air entrainment, crack resistance, etc. There is little forgiveness in the field when placing concrete and the first chance is usually the only chance. Each precast ogee crest could be inspected and verified before shipment, placement and acceptance. A unique benefit that precast concrete offers is the ability to reject a product not meeting specification requirements before it is installed.

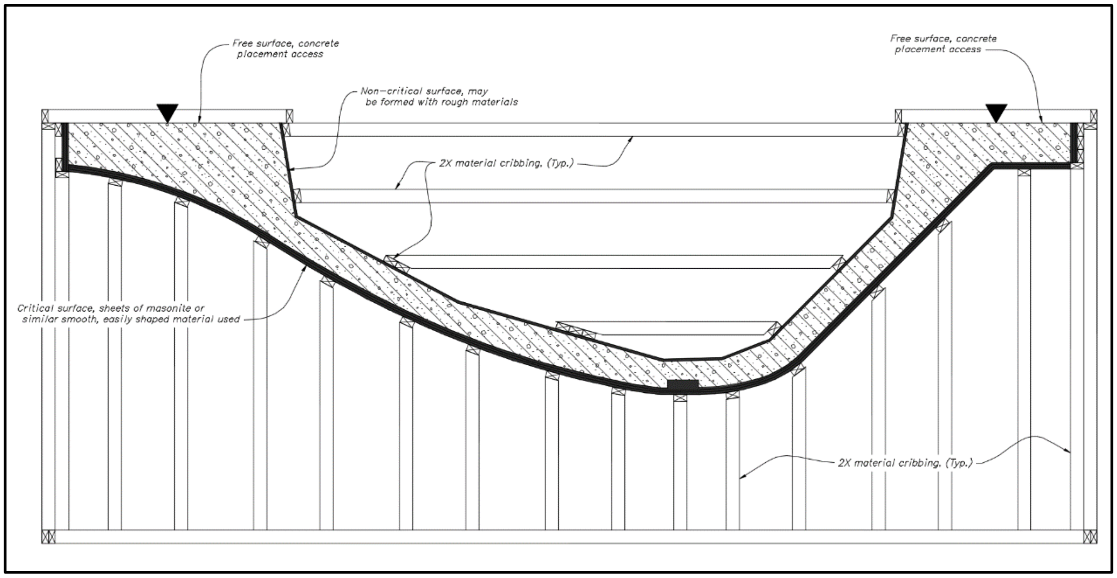


Figure 4 – Typical illustration depicting an upside down placement of a precast ogee crest and the critical vs. non-critical surfaces.

This research further builds upon the potential for utilizing the precast industry to build an ogee crest. Conceptual design drawings were completed, and several conceptual structural analysis models analyzed with the intent of determining if this is a plausible alternative to constructing an ogee crest in the field using cast-in-place concrete. These design drawings include possible solutions regarding how to handle joint details, waterstop incorporation, how to adequately anchor the crest to a spillway foundation (or mass concrete core), and possible size limitations (with regards to shipping and placing). Whether or not precast concrete is a viable alternative to cast-in-place concrete cannot be answered by this document alone. This document only discusses the conceptual designs that have been conducted to date, and recommends further consideration for future projects that may involve an ogee crest construction or rehabilitation.

Design and Analysis

General Considerations / Concrete Outline Drawings

A very large range of spillways and ogee crest sizes exist within Reclamation's inventory. The team decided to use the ogee crest size from Minidoka Dam service spillway for the conceptual design drawings and analysis. The height of the crest was approximately 10 feet, and the length approximately 37 feet. The ogee crest shown in Figure 2 at Minidoka Dam may be considered a large size crest, with regards to transportation constraints. The team felt that the maximum benefit of utilizing precast concrete is in the area of the crest where compound curves exist. Upstream and downstream of the ogee crest (within the spillway inlet, chute, etc.), conventional methods of concrete construction are well established and efficient.

There are multiple constraints that exist with regards to using a precast product. The maximum size and weight that can be reasonably transported is the biggest constraint that limits the practicality of a precast product. A spillway crest construction may involve replacement of an existing crest (Scofield Dam, Figure 3), or as part of a new spillway project (Minidoka Dam, Figures 1 and 2). The largest dimension on a spillway crest may be the overall height of the crest, or the width of the spillway. The width of a spillway can be reasonably split up into sections, however, this now requires joints between each individual section. Longitudinal joints that run parallel to the flow surface are much more acceptable than joints perpendicular to the flow surface due to potential for stagnation pressures. Ultimately, where the start and stop point is for the precast product will depend upon project specific conditions and will vary greatly.

The thickness of the precast ogee crest shell depends on several factors. The primary factor relates to strength while transporting and handling the crest from the precast plant to the field. The strength of the crest will also depend on reinforcing steel, however, the thickness may also limit the amount of steel that can be accommodated. As thickness increases, so does the overall weight of the crest. The weight of the precast crest will limit whether or not the crest can be reasonably transported, regardless of whether or not a crane can handle the weight. The team decided to analyze three different thicknesses for the crest; 12-inch, 9-inch and 6-inch. For small size ogee crests, there may be potential to develop the entire crest thickness from precast concrete. The majority of crest sizes would likely fall in the range of medium to small. Transportation of medium to large precast crests would likely be a problem, since the maximum weight may exceed the capacity of the truck. The weights of the precast crests varied depending on thickness; 12-inch = 8,425 lb per foot width, 9-inch = 7,467 lb per foot width, 6-inch = 6,516 lb per foot width, based on a section having a height of 10-feet and a length of 37-feet.

Assuming the precast portion of the crest is only the outer shell, the void space below would need to be backfilled or preplaced with concrete. The size of this void space would depend on overall crest size and also whether or not the crest is for a new spillway or rehabilitation project. The team discussed various techniques that could be utilized to fill the void space, and developed two general alternatives. The first alternative (Option A) is shown in Figure 5. This alternative involves backfilling the void space with a high slump mass concrete, or an SCC via access ports provided in the precast crest. Access ports would need to be located on the upstream side of the crest to allow for a concrete placement. The exact location and number of access ports will depend on project size and other considerations. Concerns have been expressed regarding temperature of the backfill concrete due to the size of the placements on larger crests. This is a legitimate concern, and would need to be analyzed more thoroughly on a case by case basis since the temperature would be related to the type of concrete, cementitious types, aggregate size, placement dimensions, etc. As shown in Figure 5, the backfill concrete could be placed in multiple lifts if needed to help control temperature rise. However, this causes other concerns related to treatment of each lift line and whether or not bond between joints would be required, since access to treat each lift line would be difficult. However, bond may not be as important since the precast concrete shell restrains the mass block below.

A second alternative was developed based on concerns for the backfill concrete temperature, and also addresses potential rehabilitation projects more accurately. This option assumes preplacement of the mass concrete backfill for new construction projects, and also represents a rehabilitation project where a significant amount of original crest would remain in place. Figure 6 illustrates the second alterative, Option B. It would be difficult if not impossible to size these mass blocks perfectly, or gauge demolition work such that no void space existed. Therefore, grout nipples would be incorporated in the precast ogee crest to fill any remaining void space with cementitious grout. As shown in Figure 5 and 6, both alternatives involve some amount of cementitious grout.

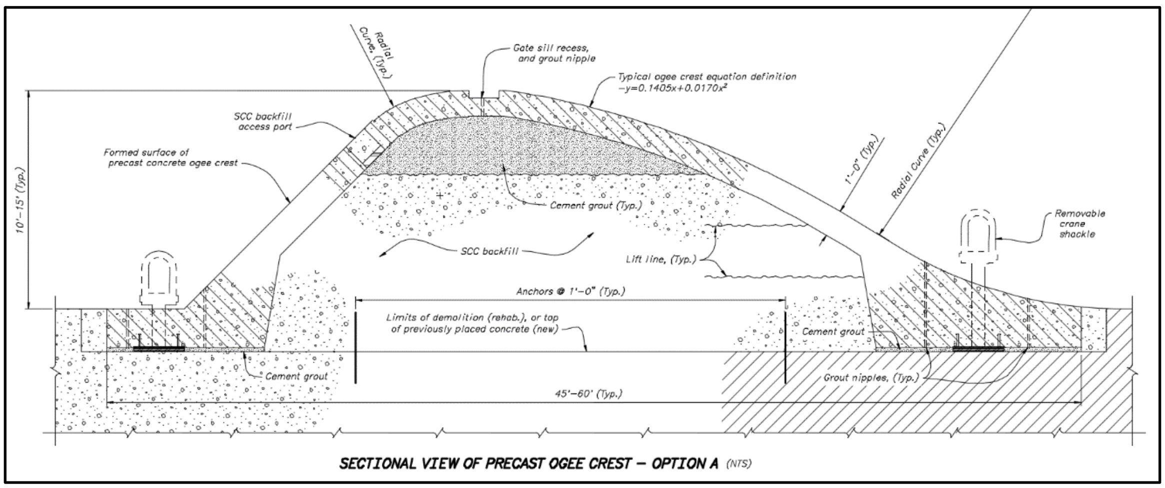


Figure 5 – Showing Precast Concrete Ogee Crest, Option A, SCC Backfill and Cement Grout

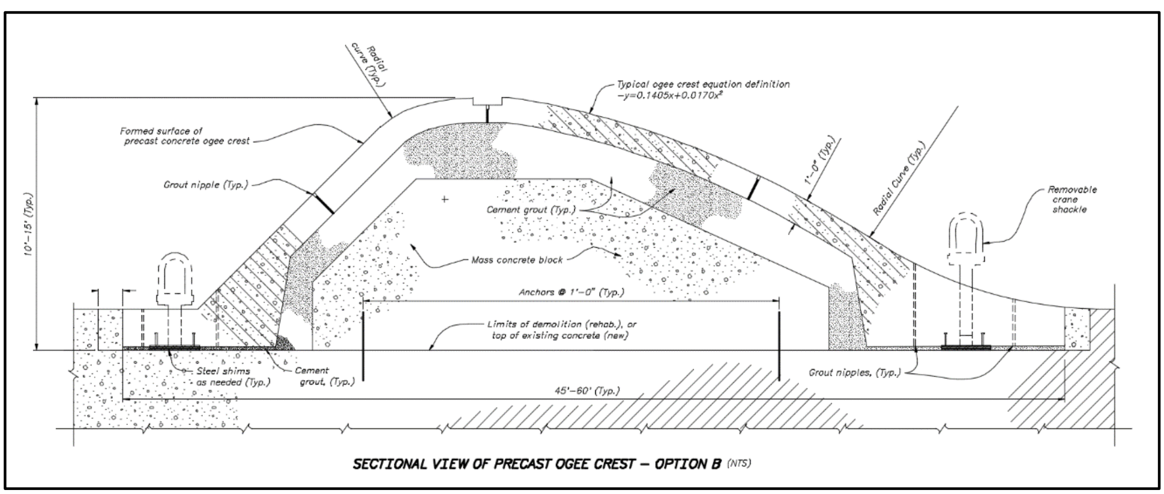


Figure 6 – Showing Precast Concrete Ogee Crest, Option B, Concrete Blocks and Cement Grout

The joints between the precast crest and foundation, backfill area and mass concrete blocks are assumed to all be treated as construction joints (CJ) (see Appendix A). The joint call outs may also be unique to each project, and could change significantly. The joints between the existing or new spillway walls would be treated as expansion joints (EJ), and would likely require sponge rubber joint filler, and possibly waterstop. The longitudinal joints between each precast section, running parallel to the flow surface, would be treated as contraction joints (Cr.J) and may require waterstops. Since the reinforcement between each precast ogee crest, and between the precast ogee crest and spillway walls would not be continuous across the joint, it may be possible to avoid the use of waterstops. However, the team decided to develop designs assuming waterstops would be required at the Cr.J's and EJ's. Depending on the spillway structure width and the width of each precast crest section, there may be several Cr.J's. Figure 7 illustrates the joint details for a typical Cr.J and EJ. Both new construction and a rehabilitation project are shown in the figure. To ensure full encapsulation around the waterstop at each joint, grout nipples would need to be incorporated along one edge, or both depending on the scenario.

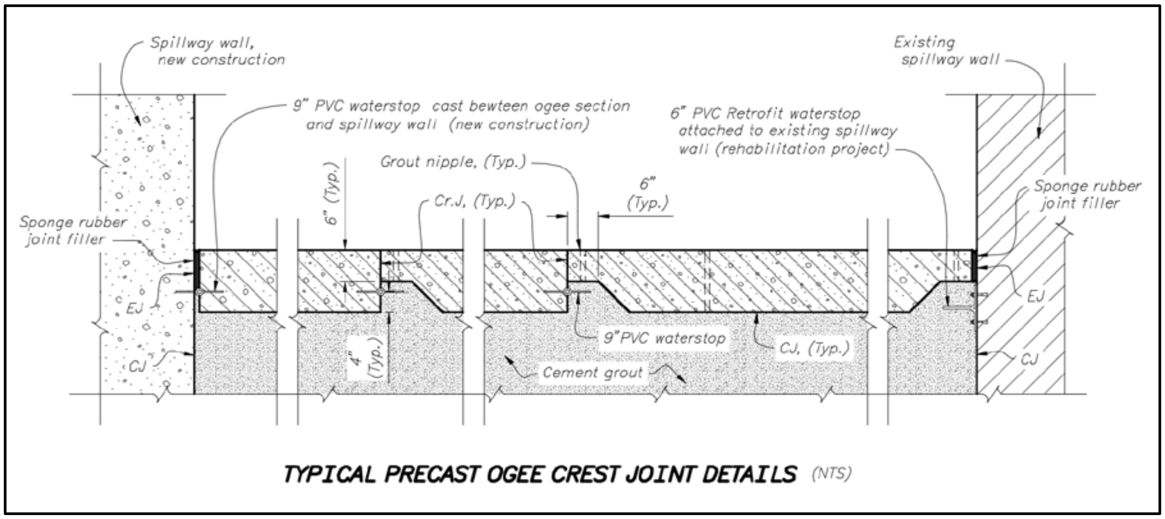


Figure 7 – Showing typical joint details between each crest section, and spillway walls. New construction is shown on the left, and rehabilitation on the right.

Anchorage between the precast crest and the spillway foundation could be achieved through the use of dowel bars and/or cement grouted anchors depending on application. If the project is new construction, placement of dowel bars between the foundation and backfill concrete or mass concrete blocks would be required. For a rehabilitation project, drilling and grouting of anchor bars would be required. Additional anchorage would also be required from the precast ogee crest to the backfill area. Dowel bars would be incorporated into the crest in the backfill areas to help bond the two surfaces together and make the overall crest act as one unit. As shown in Figure 1, reinforcement for an ogee crest is primarily along the bottom and top of the crest. The middle portion of a crest is typically mass concrete and contains little or no reinforcement. The reinforcement that does exist on a conventionally constructed crest is typically for temperature and shrinkage. However, a precast ogee crest will experience stresses during transportation and placing/handling that a cast-in-place crest does not experience. To determine the reinforcement necessary, finite element models were developed and analyzed.

To move the precast crest from the precast plant to the construction site would require lifting type hardware to be embedded in the precast crest. For smaller type crests, the precast industry has many options for type of hardware. However, for the crest size chosen to be analyzed (large), the weight of the crest limits typical lifting hardware. The weight of this large size crest required an embedded steel plate and threaded structural tube to allow for insertion of a lifting eye. However, as previously mentioned, each project would be specific and may not require such elaborate lifting hardware and details. Regardless of size, there would need to be lifting hardware attached to each side of the precast crest to allow for rotation after being fabricated in the precast plant. The lifting hardware shown in Figures 5 and 6 are reversible, and the lifting eye can be threaded into the top or bottom of the crest. Once the crest is placed in the field, the lifting eyes could be removed and used again for another crest. The embedded structural tube would need to be recessed at least 2-inches to allow for dry-packing concrete to fill the void space. If different hardware is used, having the ability to remove the hardware and drypack is essential to eliminate any obstructions protruding into the flow surface.

Whether it is a rehabilitation project or new construction, tolerances for the precast crest and spillway structure will need to be accounted for. The foundation surface could be intentionally placed at a lower elevation, or the demolition could extend a small amount further to allow for these tolerances. Steel plates located along the bottom four corners will allow the crest to be placed and leveled in the field. Steel shims could be placed between the embedded steel plate and foundation surface as needed. Grout nipples would also be located around the embedded steel plates to allow grouting of these areas prior to backfilling the main void space. Alternatively, once the crest has been verified and steel shims have been set, the crest could be lifted off the surface while non-shrink grout is placed liberally around the shim areas. The crest could then be lowered onto the shims and non-shrink grout (before the grout has initially set). Ultimately, the contractor means and methods may vary.

The completed conceptual concrete outline drawings for Option A and B are included in Appendix A, Figures 1A, 2A, and 1B, 2B, respectively.

Structural Analysis / Reinforcement Design

The finite element program, SAP 2000[1] was used to evaluate the stresses on the precast ogee crest during fabrication, lifting and transportation. As previously mentioned, a crest shape similar to the Minidoka Dam ogee crest was used as an example. There were two different support condition scenarios analyzed for the precast ogee crest, 4-supports and 2-supports. After the crest has been fabricated in the precast plant, the crest will need to be lifted and turned over. Although there may be multiple ways to achieve this, the team decided to analyze what was believed to be the most likely scenario, which involved suspending the crest from two supports at one end. Once the crest is right side up, the remaining support conditions, transportation, lifting, and final placement all involve the use of 4-supports. Figures 8 and 9 illustrate the two general finite element model conditions. The 2-support model required additional restraints in the horizontal direction to stabilize the model.

For each support condition, three separate models were developed for the three different crest shell thicknesses, 12-inch, 9-inch and 6-inch. The only difference between each model was the thickness of the shell element. The bars running parallel to the crest were required due to the high stresses that develop in the crest, regardless of the support condition. These tie bars were sized as No. 11 bars in the model, and primarily act only in tension. It is not difficult to visualize the stresses that would develop immediately if these bars were not present. Without these bars, the crest shape would want to "flatten" out due to gravity alone with either support condition. These bars may not be necessary for smaller sized precast crests. If the tie bars are needed for a spillway rehabilitation project, some consideration (slots or recesses in underlying concrete) may be needed for setting the precast crest in place.

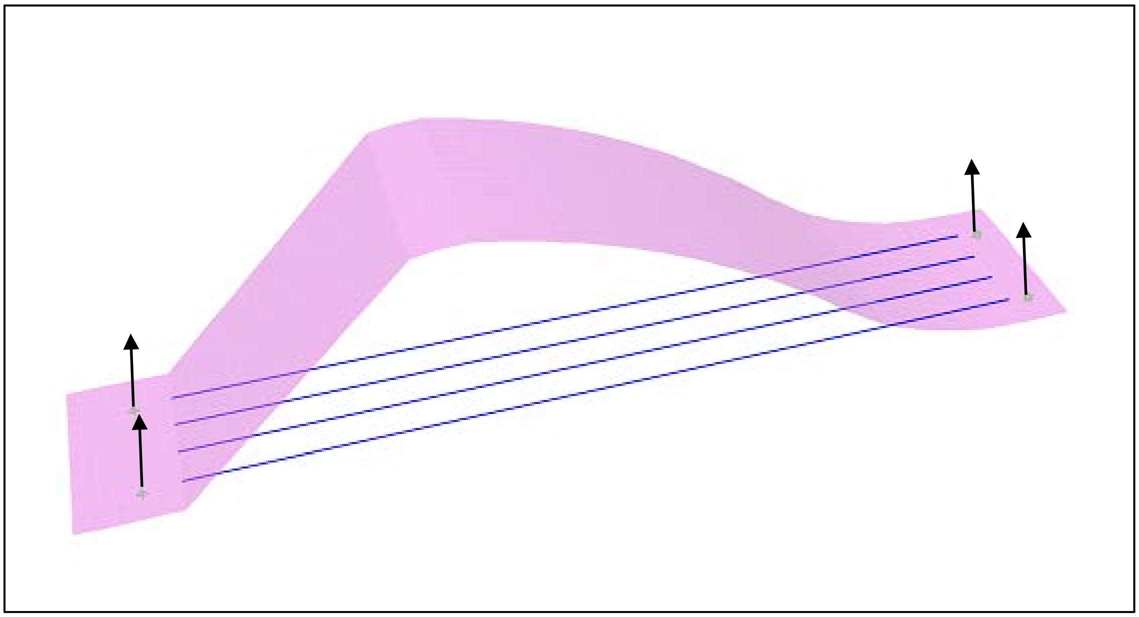


Figure 8 – Showing the finite element model used to represent 4-support conditions. Arrows were added to highlight the support reactions.

The loading scenarios analyzed only included dead loads. Although the crest would experience seismic and hydraulic loading in the long-term, these forces would be acting on the completed structure after backfilling, and should act as one solid rigid unit from the crest to the foundation. However, this does not imply that these scenarios would not need to be considered, rather, they should be considered after construction is complete for the spillway structure/rehabilitation project in whole. The dead loads for the analysis included the weight of the crest shell and weight of the No. 11 bars. Load factors were not applied to the model. This was a non-conservative approach, and application of load factors should be examined if chosen for an actual project. The team also discussed the possibility for impact type loading that could occur during transportation or handling.

Although these forces may exist in reality, there are many ways that precast products can be protected by use of cribbing to help buffer these types of forces.

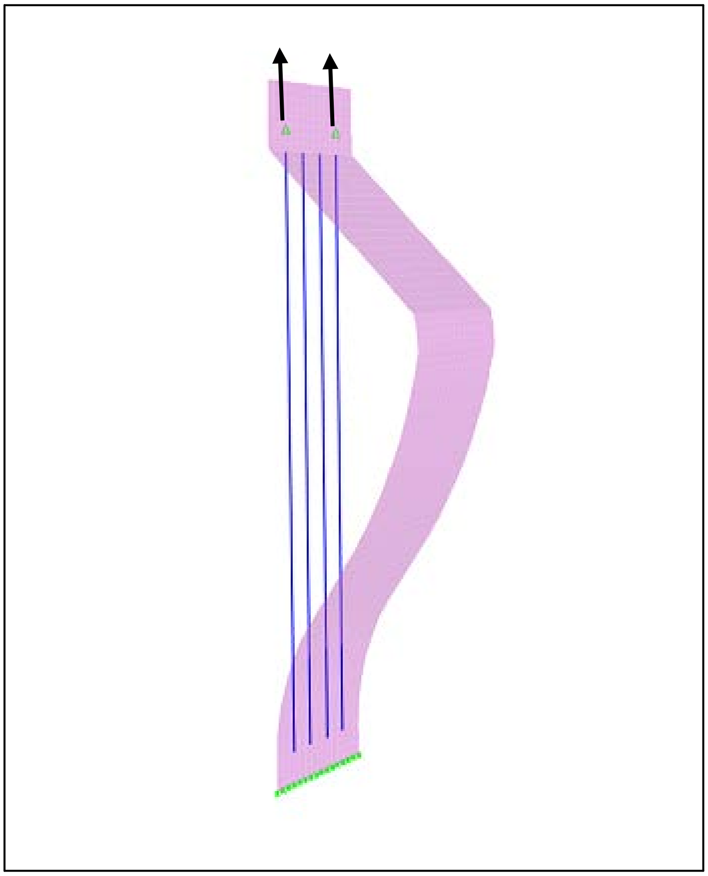


Figure 9 – Showing the finite element model used to represent 2-support conditions (while lifting). Arrows were added to highlight the support reactions.

An analysis was performed for each crest thickness, and for each support condition (6-total). After the analysis was complete, stress plots were developed and used to develop maximum force tables. These stress plots are included in Appendix B. Stress plots were developed for tension and compression axial forces, bending, and out of plane shear forces. Force plots were also generated for the No. 11 tension tie bars that span the void space beneath the ogee crest. Figures 10 through 15 illustrate examples of force plots from a 12-inch thick model assuming 4-supports and 2-supports. Tables 1, 2 and 3 include the maximum and minimum internal force results for all scenarios analyzed. Bending and axial forces occur in both vertical and horizontal directions, however, only one direction is shown in the following figures. The units shown on all of the force plots are Kips and feet. The typical sign convention used for SAP 2000 is as follows: Compression = negative, Tension = positive.

The internal axial tension and compression forces were shown to be minimal with the exception of localized areas near the supports and apex of the crest (see Figure 10). The high force concentrations at the No. 11 bar attachment locations (within the crest shell) are not accurately depicted. In reality, these forces would be developed along the embedment length of the bar, and would not be concentrated at the end points only. The longitudinal bending moments, which were the most significant when compared with horizontal, were greatest near the apex of the crest, and along the lower portion of the compound vertical curve. After analyzing the internal forces that the precast ogee crest would experience, the team moved on to general reinforcement design. Reinforcement was sized based upon axial tension/compression and combined bending moments. Although out-of-plane shear forces exist around the support locations, design for shear was not performed since this was only a conceptual analysis. A quick check showed that the shear forces were not unreasonably high, and shear reinforcement could be accommodated around the supports if needed.

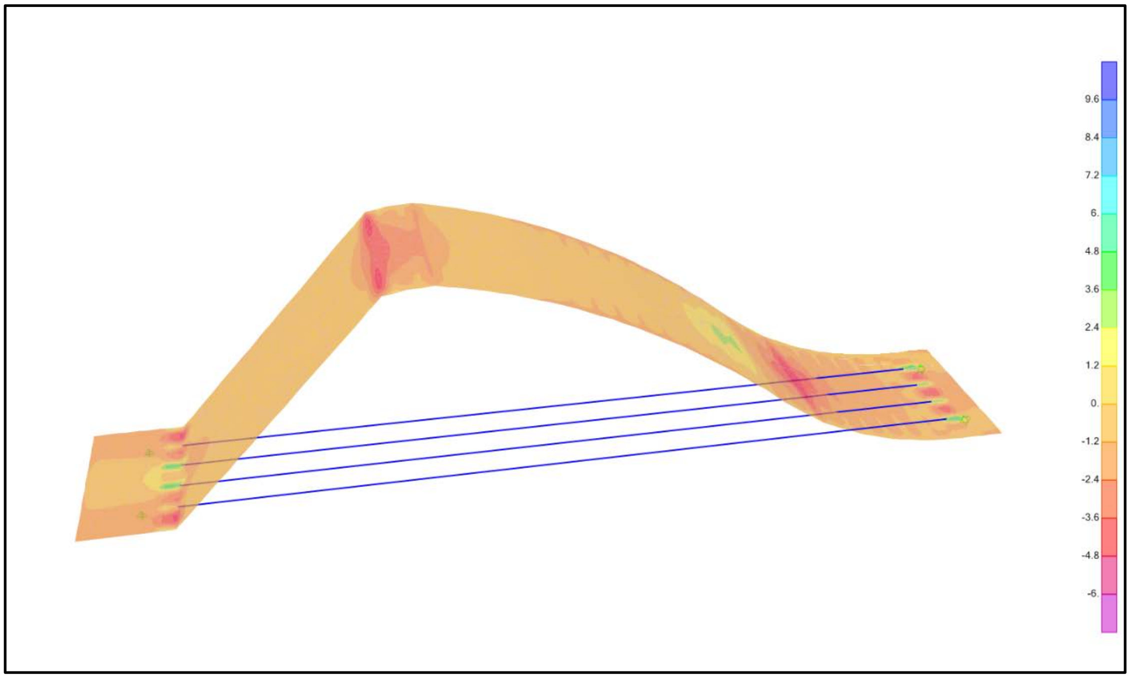


Figure 10 – Showing axial force plot (tension / compression) for 12-inch thick precast ogee crest with 4-supports (Kip).

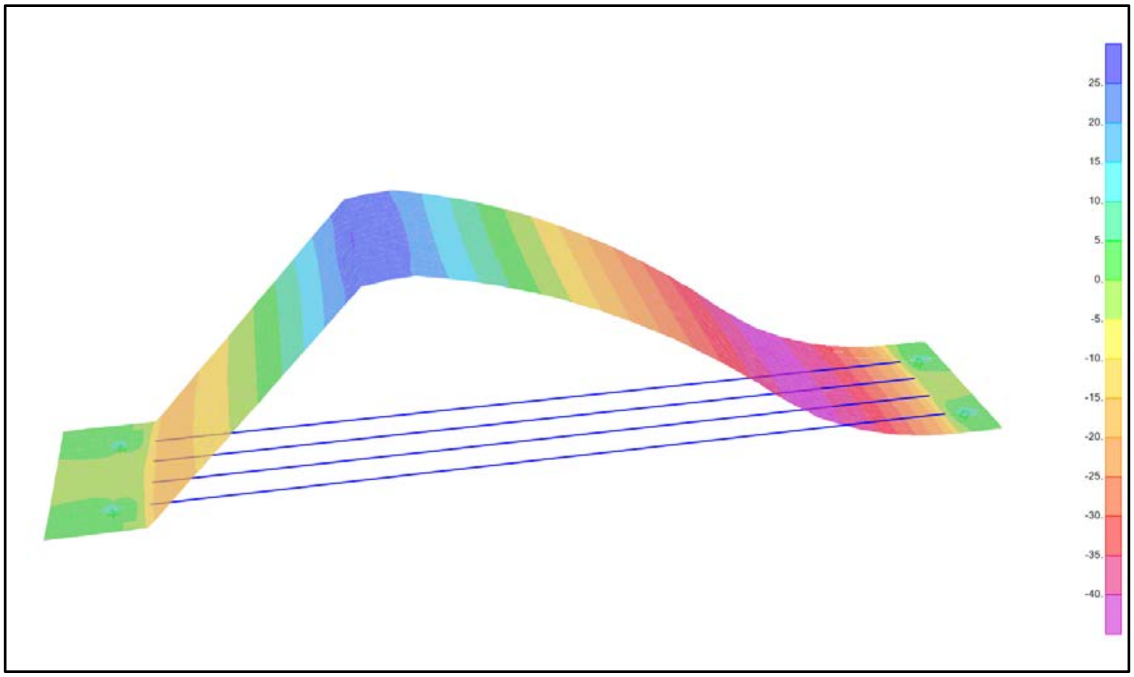


Figure 11 – Showing a longitudinal bending moment force plot for 12-inch thick precast ogee crest with 4-supports (Kip-ft).

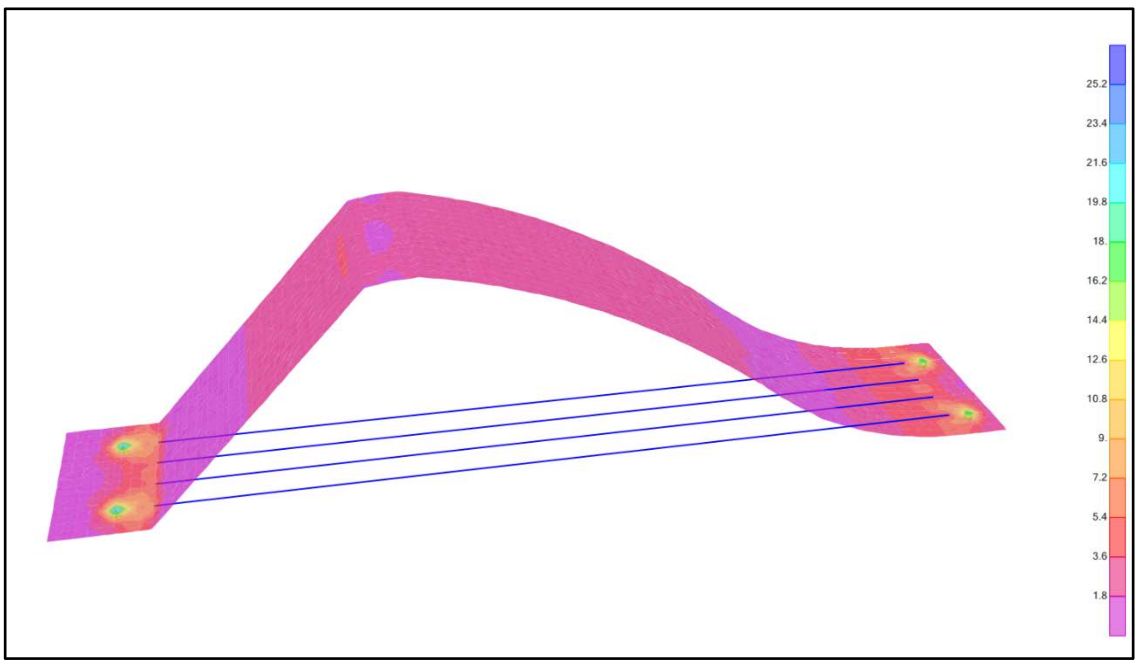


Figure 12 – Showing an out-of-place shear force plot for a 12-inch thick precast ogee crest with 4-supports (Kip).

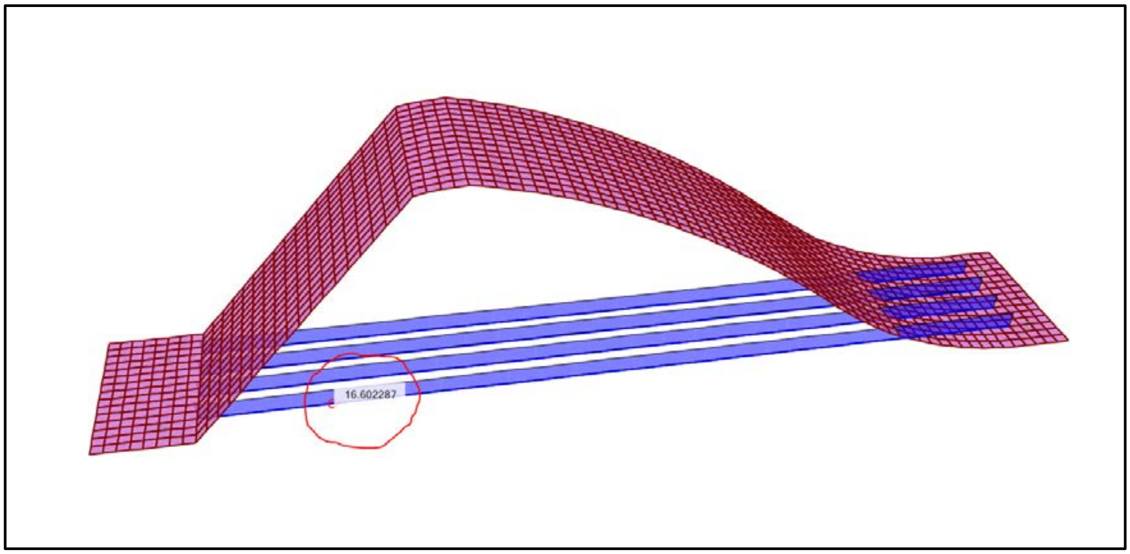


Figure 13 – Showing the force results in the No. 11 tension tie bars. The circled area highlights the constant tension force experienced throughout each bar (16.6 kip).

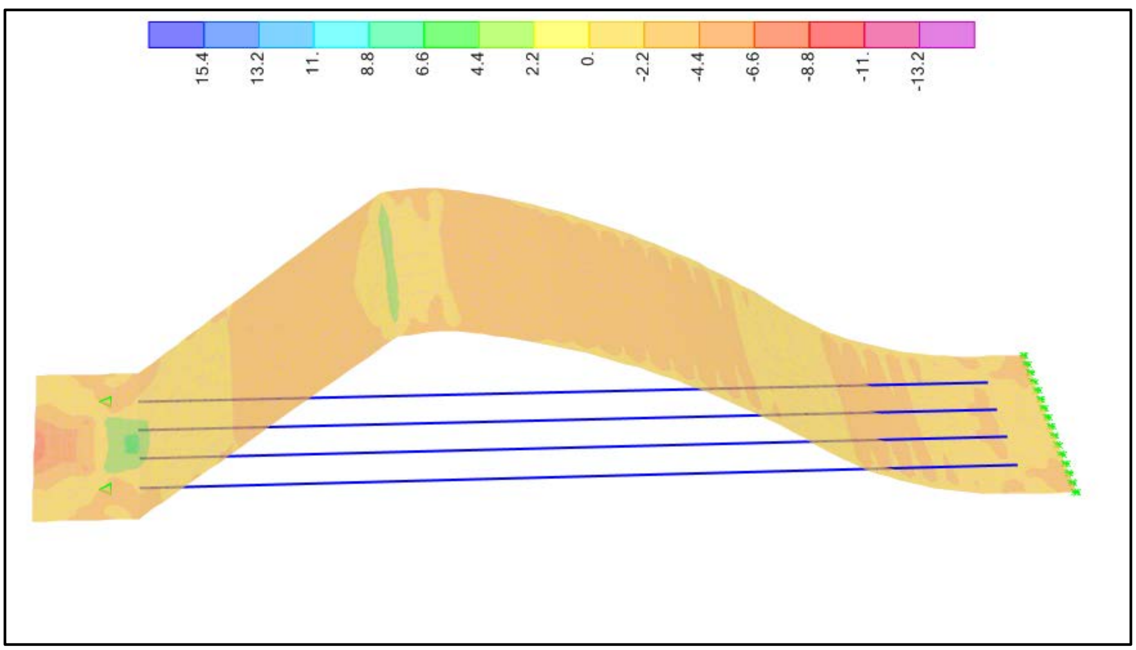


Figure 14 – Showing axial force plot (tension / compression) for 12-inch thick precast ogee crest with 2-supports (Kip). NOTE: Figure has been rotated 90 degrees to fit.

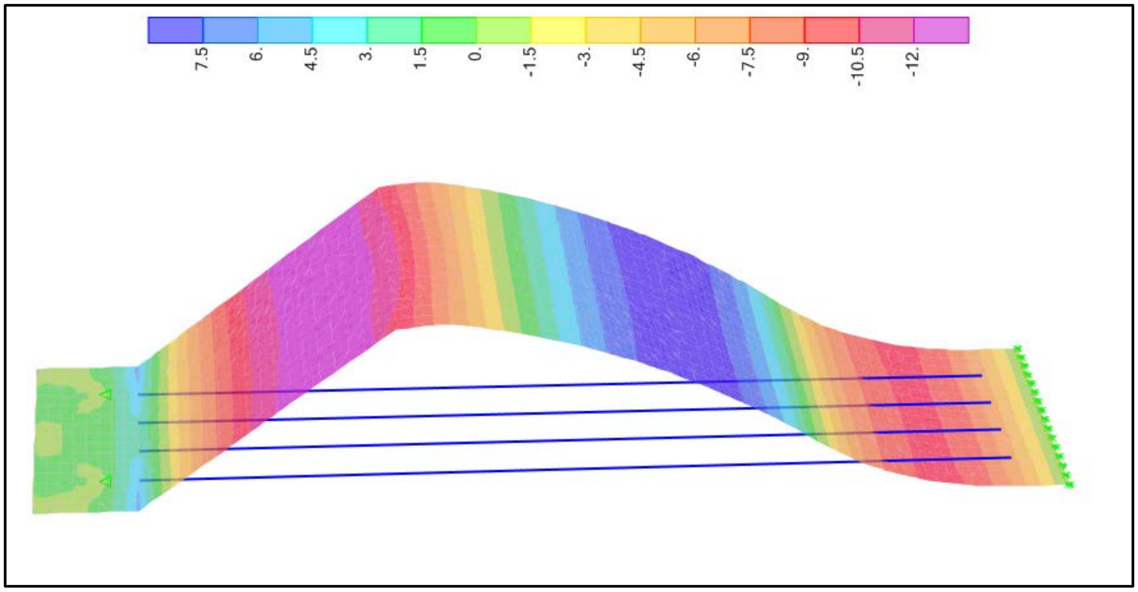


Figure 15 – Showing longitudinal bending moment plot for 12-inch thick precast ogee crest with 2-supports (Kip-ft). NOTE: Figure has been rotated 90 degrees to fit.

Table 1 – 12-Inch Precast Ogee Crest – Internal Force Results

4-Supports	**M11 (kip-ft)**	**M22 (kip-ft)**	**F11 (kip)**	**F22 (kip)**	**Vmax (kip)**
Max	8	25	5	15	20
Min	-9	-42	-5	-17	
2-Supports	**M11 (kip-ft)**	**M22 (kip-ft)**	**F11 (kip)**	**F22 (kip)**	**Vmax (kip)**
Max	1.5	8	4.5	44	6
Min	-2.5	-13	-6	-26	

Table 2 – 9-Inch Thick Precast Ogee Crest – Internal Force Results

4-Supports	**M11 (kip-ft)**	**M22 (kip-ft)**	**F11 (kip)**	**F22 (kip)**	**Vmax (kip)**
Max	7	20	4	20	17
Min	-7	-30	-6	-16	
2-Supports	**M11 (kip-ft)**	**M22 (kip-ft)**	**F11 (kip)**	**F22 (kip)**	**Vmax (kip)**
Max	1	7	4	33	4
Min	-1.5	-9	-4	-22	

Table 3 – 6-Inch Thick Precast Ogee Crest – Internal Force Results

4-Supports	**M11 (kip-ft)**	**M22 (kip-ft)**	**F11 (kip)**	**F22 (kip)**	**Vmax (kip)**
Max	4	14	4	18	12
Min	-4.5	-22	-6	-1.5	
2-Supports	**M11 (kip-ft)**	**M22 (kip-ft)**	**F11 (kip)**	**F22 (kip)**	**Vmax (kip)**
Max	1	5	2	22	3
Min	-1	-5	-2	-15	

To determine the reinforcement necessary, the analysis program PCA Column was used [2]. For simplicity, a 12-inch wide section or slice was analyzed (i.e. designed on a per foot basis). If this were an actual analysis for a site specific project, section cuts would be used to determine precise demands on the crest and reinforcement designed accordingly. The clear cover requirements were set at 2-inches, even though precast products can typically achieve tighter tolerances. However, 2-inches is typical clearance for hydraulic structures and minimum clearance by Reclamation standards. Even though the axial tension/compression forces and bending moments did not occur in the exact same locations, for conservative purposes the maximum tension force and compression force was combined with the maximum bending moment (positive and negative). Since the bending moments reverse several times along the crest, two rows of reinforcement were assumed in each direction (i.e. top and bottom, each way) for the 12-inch and 9-inch thick crests, and a single row of reinforcement, each direction for the 6-inch crest. The PCA Column results, shown as P-M diagrams, are included in Appendix C. A typical P-M diagram for a 12-inch thick, 9-inch thick, and 6-inch thick precast ogee crest are shown in Figures 16, 17 and 18, respectively.

The results indicated that the 12-inch thick ogee crest would require No. 6 bars spaced at 6-inch centers, each way and each face. The 9-inch thick ogee crest would require slightly more steel, No. 6 bars and No. 8 bars alternately spaced at 6-inch centers. The analysis indicated that the 6-inch thick ogee crest would not be feasible, since the amount of reinforcement required could not be accommodated. Unfortunately, the decrease in crest thickness did not linearly correlate with a decrease in stress experienced by the crest. Two rows of reinforcement would be difficult to accommodate in the 6-inch crest, and only single rows were analyzed. This of course applies to a larger size crest which was used as the example, and may or may not be the case depending on project specific requirements. The No. 11 tension tie bars that span the void space are well within acceptable limits. The ultimate capacity of a No. 11 bar would be approximately 94,000 lb, per bar. Even after applying strength reduction factors, the bars are adequate. These bars could likely be reduced depending on project specific requirements and size of the crest.

Another consideration that should be discussed is the potential for higher stresses while rotating the ogee crest after constructing (from upside down to right side up). The team only analyzed what was believed to be the worst case scenario while rotating (i.e. 2-supports, crest at 90-degrees). While the crane operators are maneuvering the crest from the formwork, there is potential to induce higher stresses at some other angle between the horizontal and 90-degree. The actual shape of the ogee crest and support locations for each project could also impact this worst case angle. There are countless possibilities, and the team could only analyze what was believed to be the worst case scenario for a larger size crest shape.

The conceptual reinforcement drawings for Option A and B are included in Appendix A, Figures 3A and 3B, respectively.

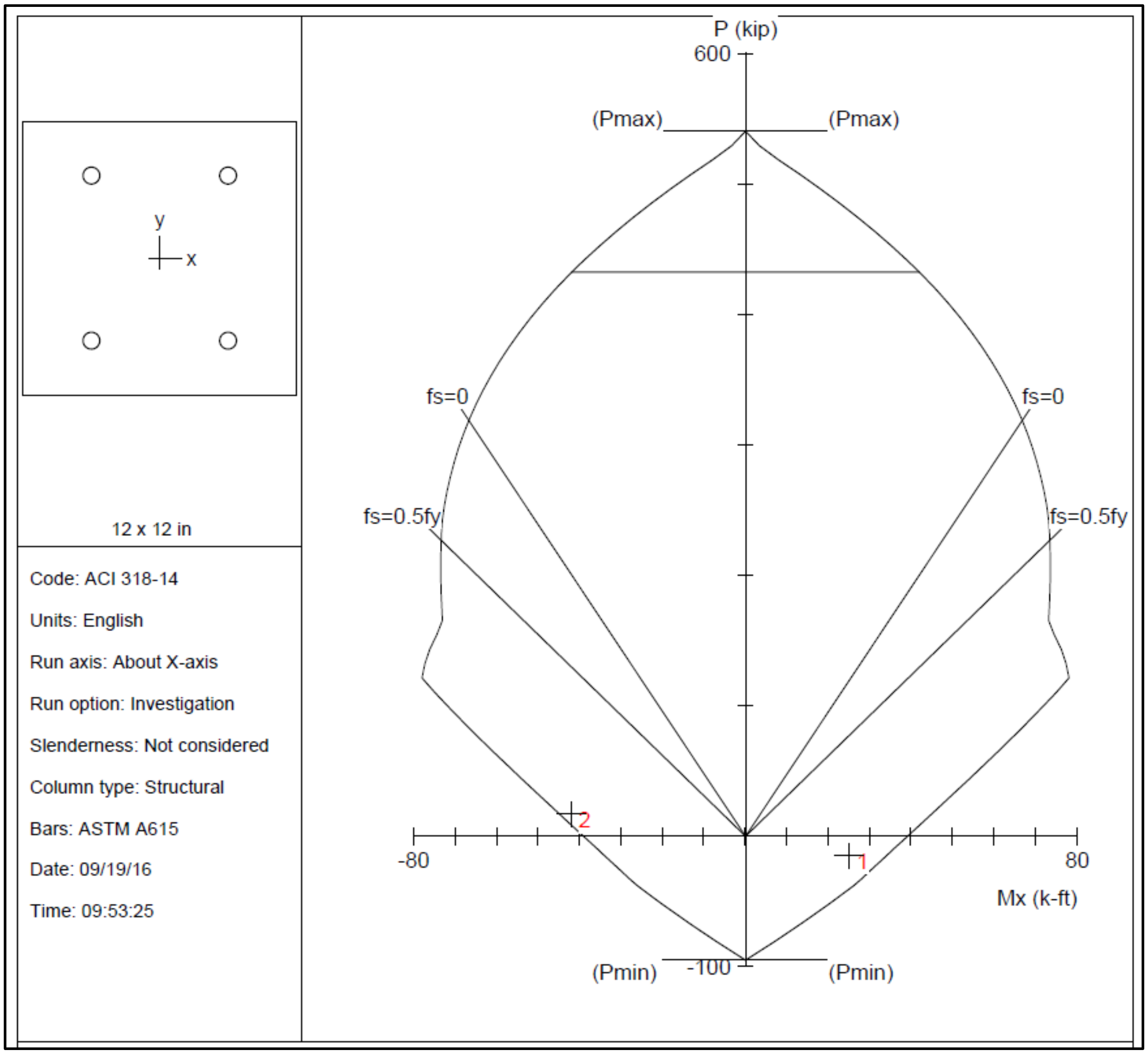


Figure 16 – Showing a P-M (Axial – Bending) Diagram for a 12-inch thick precast ogee crest with No. 6 bars spaced at 6-inches, each face. Maximum loading scenarios have also been applied.

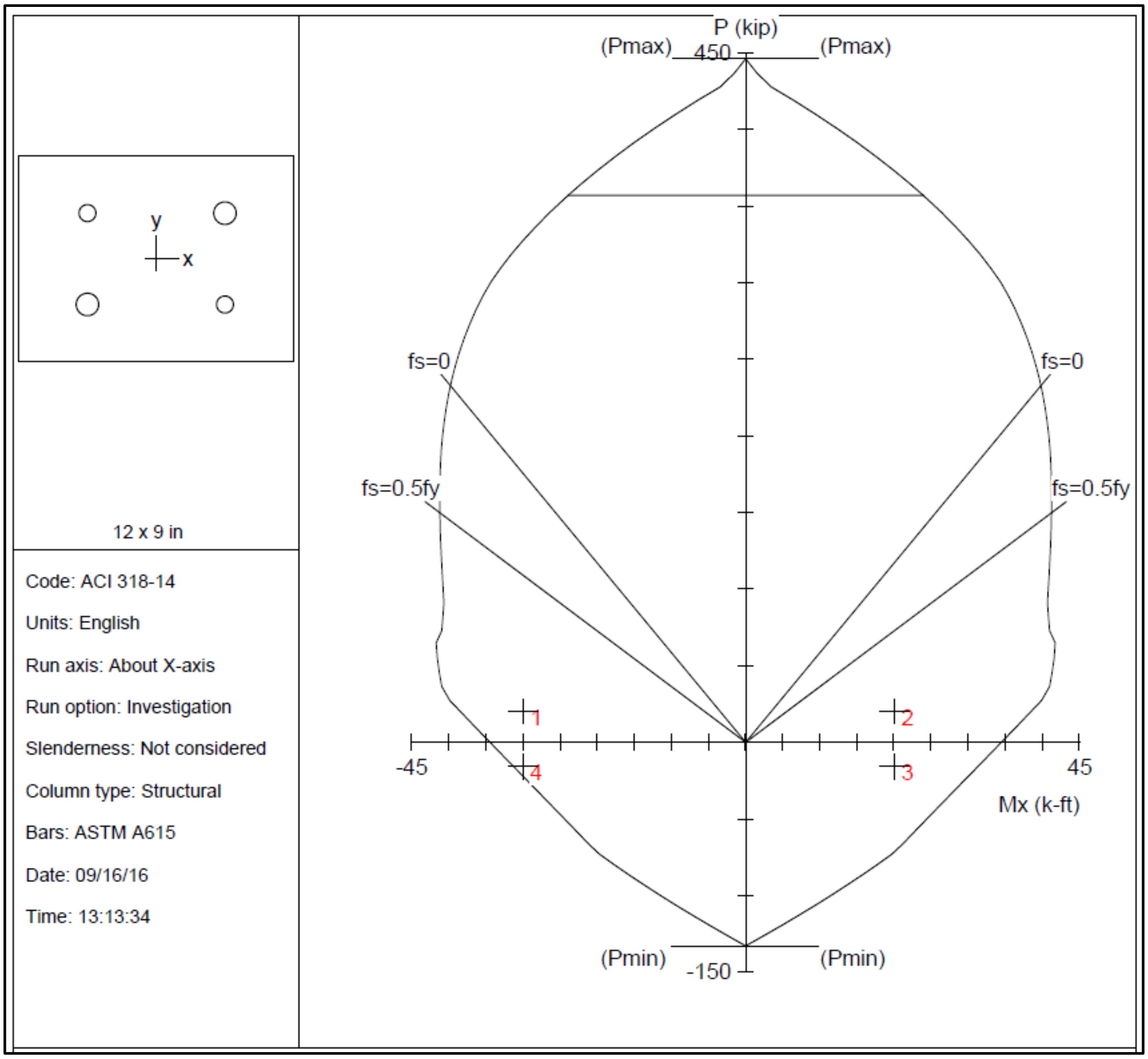


Figure 17 – Showing a P-M (Axial – Bending) Diagram for a 9-inch thick precast ogee crest with No. 6 bars and No. 8 bars alternately spaced at 12-inches, each face. Maximum loading scenarios have also been applied.

Conclusions and Recommendations

The difficulties associated with constructing an ogee crest in the field with cast-in-place concrete are well known at Reclamation. The formwork and finishing techniques employed by the contractor are commonly figured out by trial and error in the field, since it is likely they have never constructed a concrete surface with compound curves. Unfortunately, the shape, finish and durability of the ogee crest surface is negatively impacted as a result. In today's fast paced world, contractors are always looking for ways to save money and time, which does not always benefit the client. More often than not, completing a job on time and within (or under) budget is the primary goal, regardless of product quality. Although significant time may be focused on developing specifications that attempt to hold the contractor to a high standard of quality, completed work will rarely be rejected to the point of removal and replacement. The use of precast concrete may not eliminate this issue entirely, however, it is much easier to maintain strict tolerances in a controlled environment, and reject a product before it is installed.

On a conceptual level, the design team believes that precast concrete offers a potential solution to the difficult construction issues associated with ogee crests. However, there are many other issues and constraints that are project specific that are not within the scope of this document. The analysis results indicated that transporting a precast ogee crest would very likely be feasible from a strength and durability standpoint. However, the analysis performed was very generic, and each specific project would have unique shapes and cutoff points (between precast and cast-in-place). These cutoffs would drastically change the overall shape of the precast crest being considered, and the types of stresses the crest may experience when being transported.

Due to the complicated formwork and congestion of the work area, the precast method of constructing an ogee crest may be a preferred option that a contractor would also embrace. It is difficult to say whether or not this method decreases or increases overall costs. The size of the precast crest would limit whether or not precast operations could be done at the precast plant, or if an onsite precast casting area would be required in the field near the project. Transportation to and from the precast plant may be problematic and costly if the crest size is large and should be considered early on in a project. Where the project is located may also significantly affect whether transportation is feasible. Many of Reclamations facilities are located in remote areas, and a precast manufacturer is not likely to be located nearby. Although the team believes that precast methods would produce the best possible finished product, precast concrete may not be the most feasible alternative.

Ultimately, the team feels that if a project is in the conceptual stages of development, this method should be considered if the project includes replacement or construction of an ogee crest for a spillway or canal structure. Precast companies have solved complex construction challenges for making and installing precast components and may have an innovative way to meet the needs of a specific project. This would provide a cost comparison between a cast-in-place method and the precast method. The equipment required to construct with precast for medium to small crest sizes would not be highly specialized, since the contractor would likely have a suitable crane onsite for other reasons. If the crest is larger, the crane size may be an issue, especially if the crest is to be located at the top of a dam.

Another consideration that is proposed for future research is to develop a small scale prototype of a precast ogee crest in the laboratory. This could shed more light on the quality of the finish that can be achieved and the complexity or performance of the joints. Development of a small scale model could also help design teams identify other unknown issues.

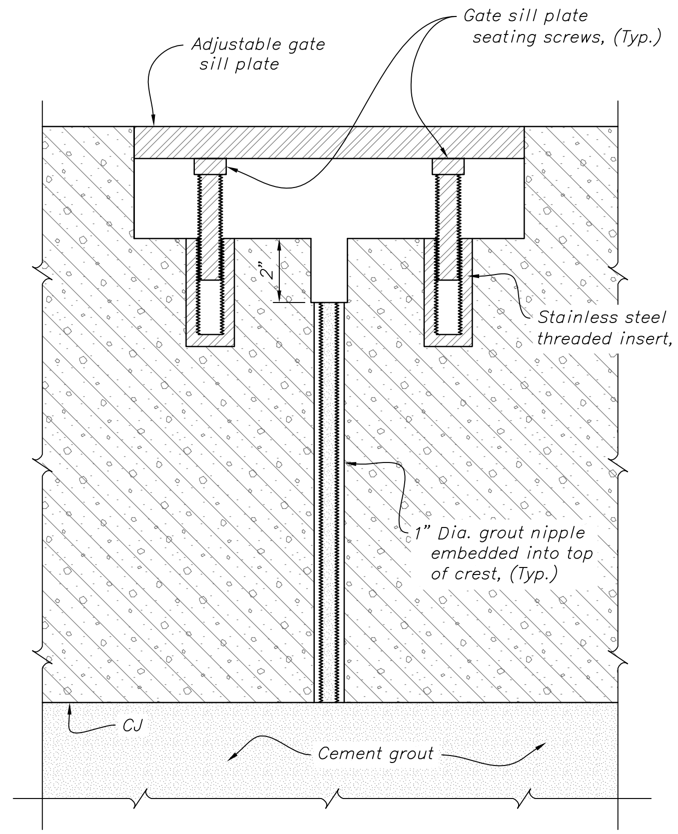
References

[1] SAP2000, Integrated Software for Structural Analysis and Design, Computers and Structures, Inc., Berkeley, California, USA.

[2] PCA Column, Portland Cement Association, Structure Point LLC, Concrete Software Solutions

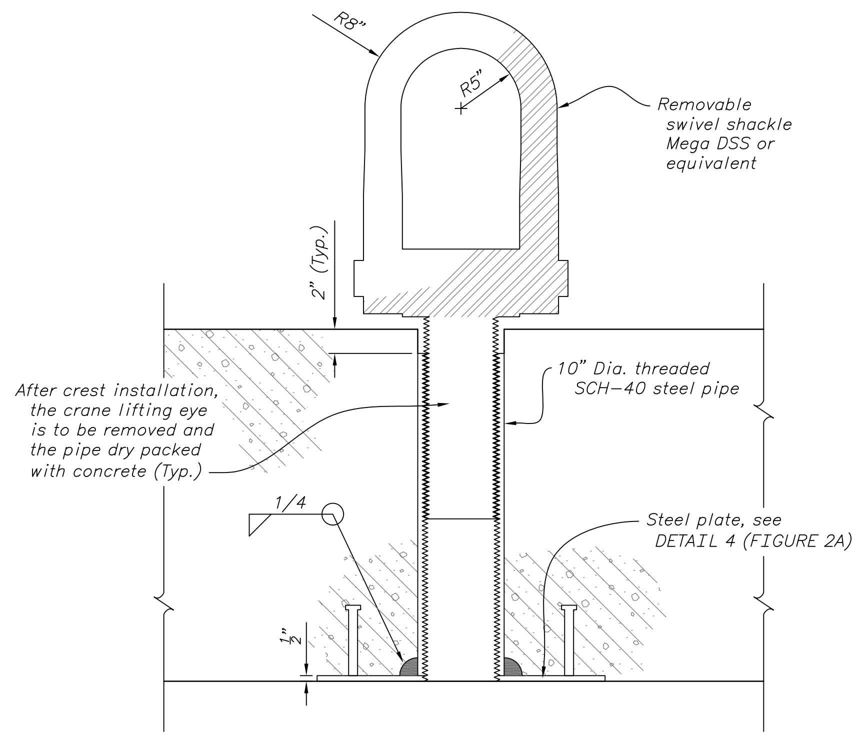
Appendix A

Conceptual Design Drawings



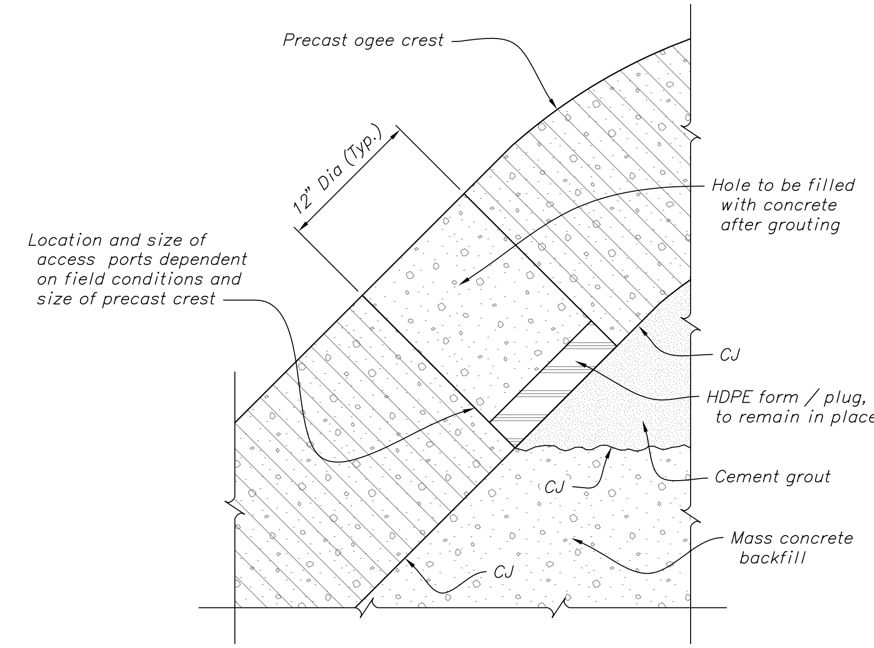
DETAIL 1 (NTS)

TYPICAL GROUT NIPPLE / GATE SILL PLATE DETAIL.



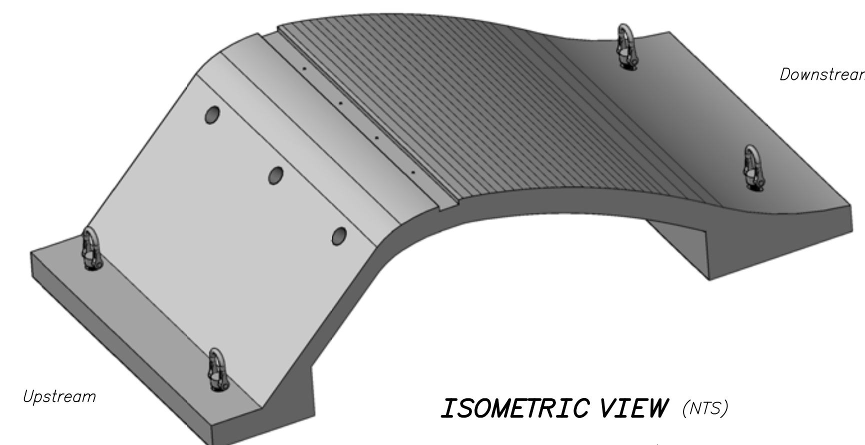
DETAIL 2 (NTS)

TYPICAL VIEW OF REMOVABLE CRANE SHACKLE AND CRANE SHACKLE EMBEDDED PLATE.

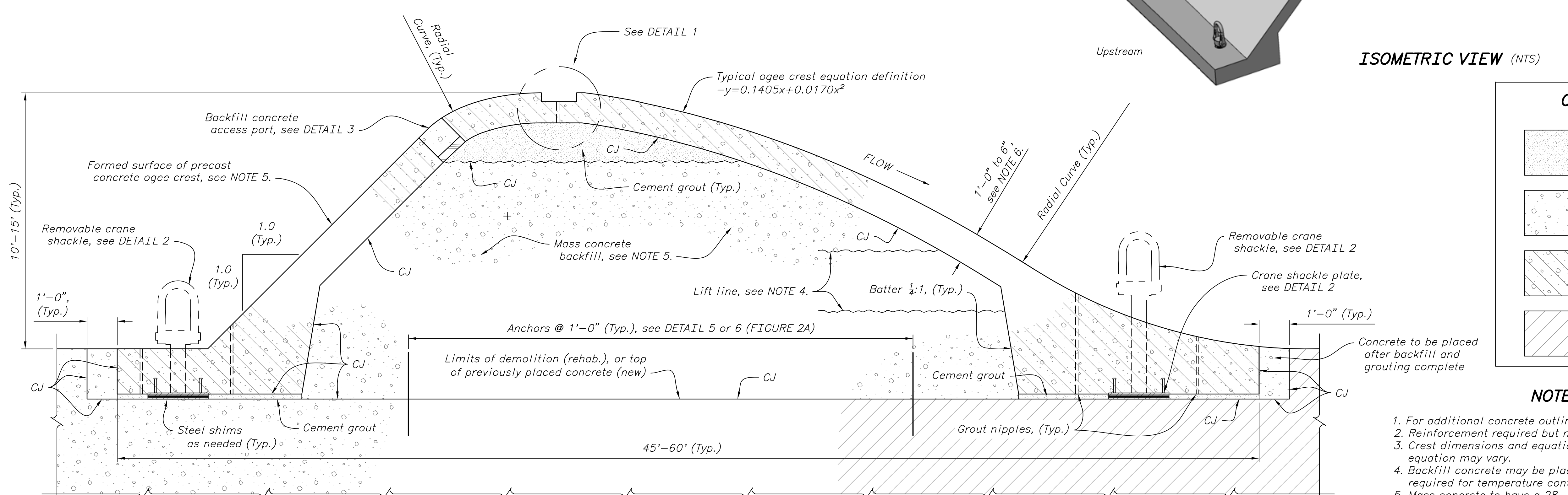


DETAIL 3 (NTS)

TYPICAL SCC CONCRETE ACCESS PORT



ISOMETRIC VIEW (NTS)



SECTIONAL VIEW OF PRECAST OGEE CREST (NTS)

(ADDITIONAL ANCHORAGE REQUIRED BUT NOT SHOWN, SEE FIGURE 3A)

CONCRETE LEGEND

- Cement Grout
- Concrete
- Precast Concrete
- Existing Concrete

NOTES

1. For additional concrete outline notes, see 40-D-7012.
2. Reinforcement required but not shown.
3. Crest dimensions and equation shown are examples, actual equation may vary.
4. Backfill concrete may be placed in multiple lifts if required for temperature control.
5. Mass concrete to have a 28-day compressive strength of 3,000 psi (minimum). Precast concrete to have a 28-day compressive strength of 4,500 psi, (minimum).
6. Thickness of precast crest will vary depending on size and project requirements. Typical thickness; Large crest = 1'-0" to 9", Medium and small crests: 9" to 6".

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PRECAST OGEE CREST CONCEPT

OPTION A: SCC BACKFILL

DESIGNED MAIER / TOOTHMAN
DRAWN MAIER
CHECKED
TECH. APPR.
APPROVED
DENVER, CO

CONCRETE OUTLINE

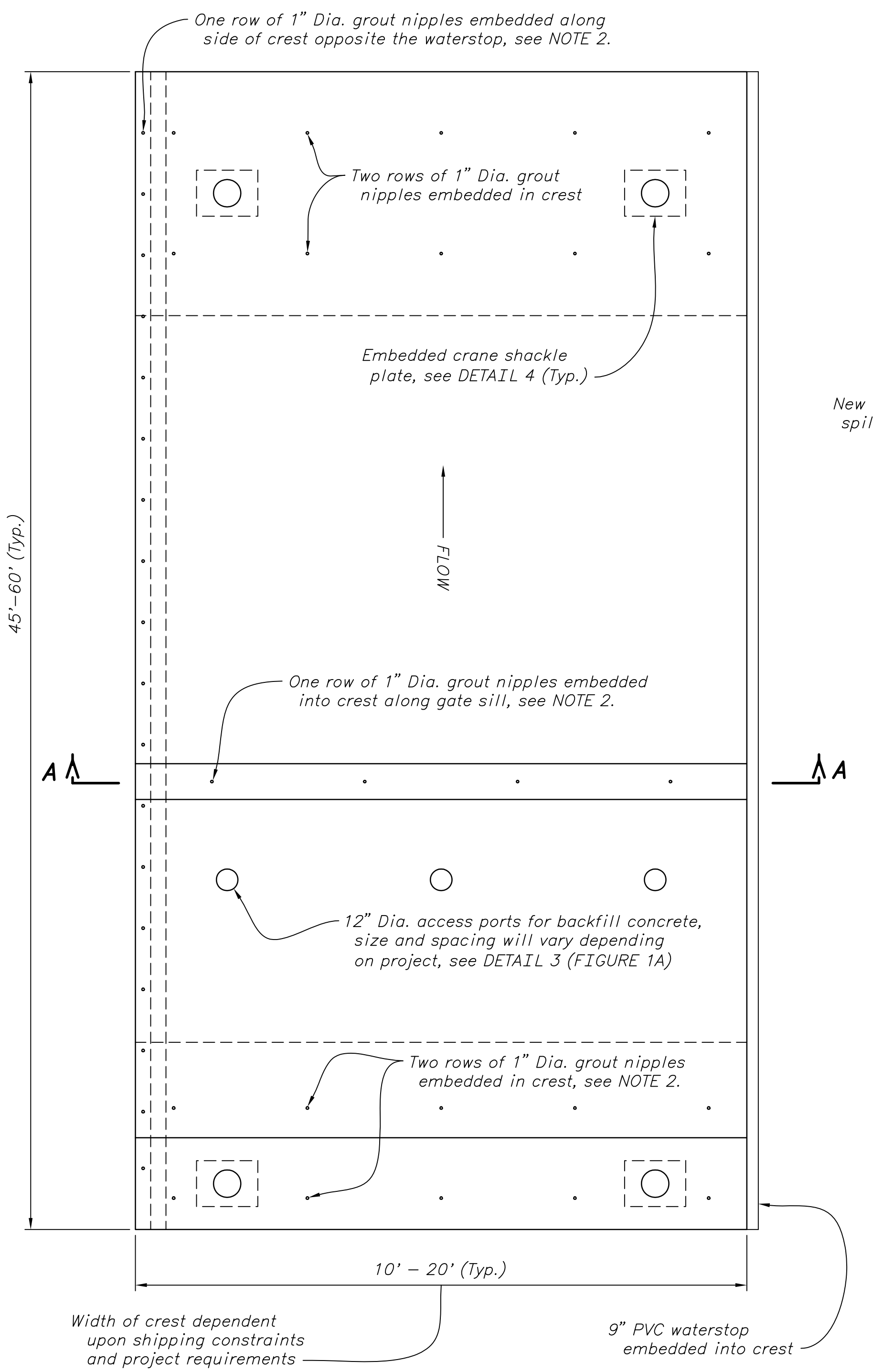
SECTIONAL VIEW, ISOMETRIC VIEW AND DETAILS

FIGURE 1A

SHEET 1 OF 3

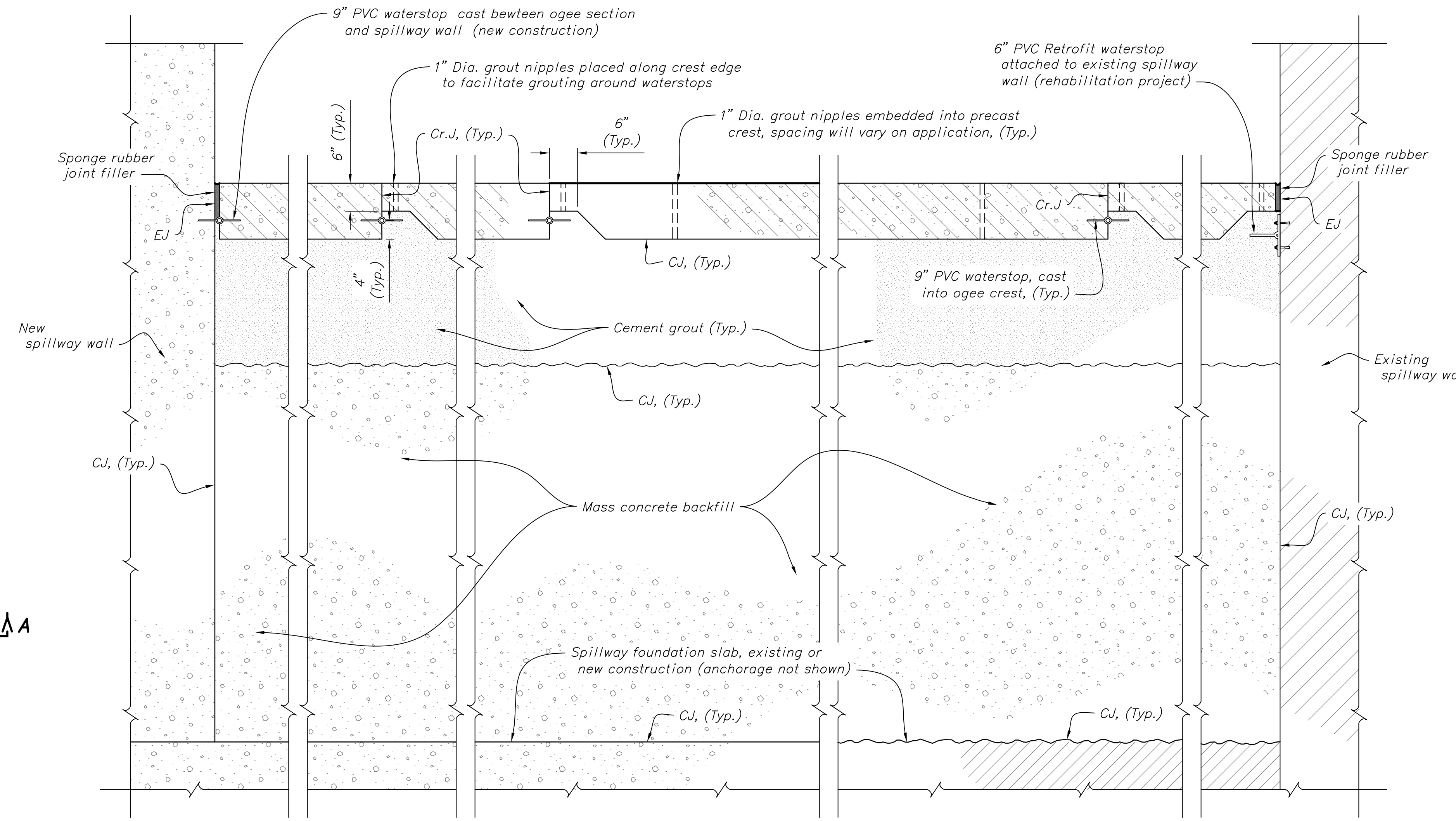
DATE AND TIME PLOTTED Not Plotted
PLOTTED BY Not Plotted

CAD SYSTEM AUTOCAD
CAD FILENAME UNKNOWN



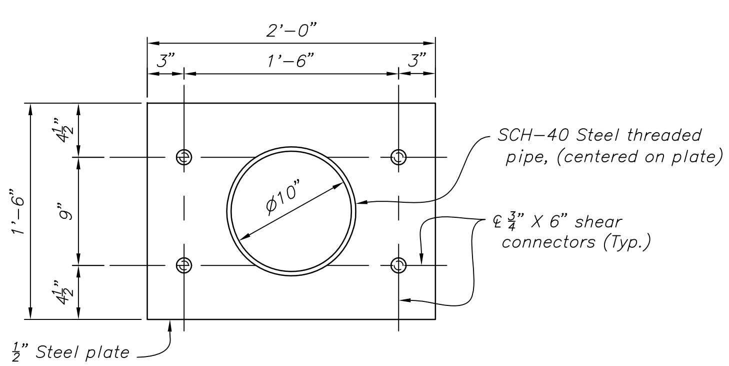
PLAN (NTS)

TYPICAL PLAN VIEW OF PRECAST OGEE CREST



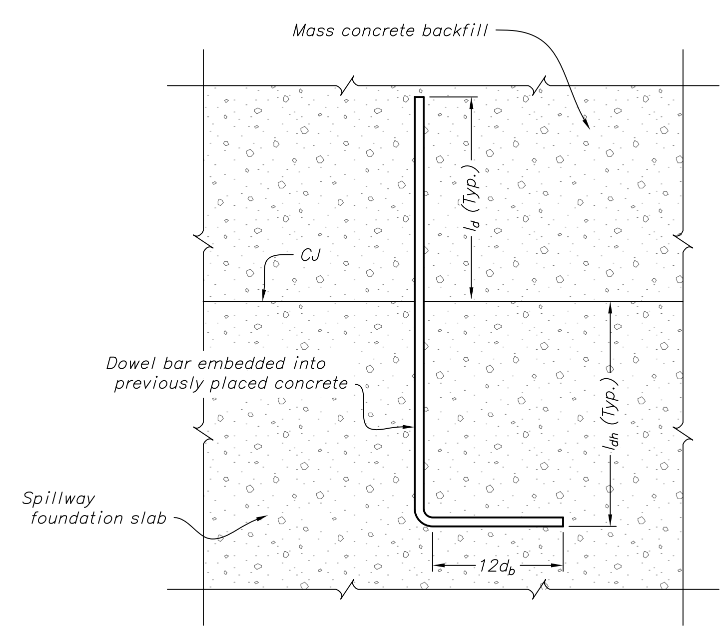
SECTION A–A (NTS)

SECTION VIEW THROUGH SPILLWAY CREST LOOKING DOWNSTREAM
(SHOWING NEW CONSTRUCTION ON LEFT, AND REHABILITATION PROJECT ON RIGHT)



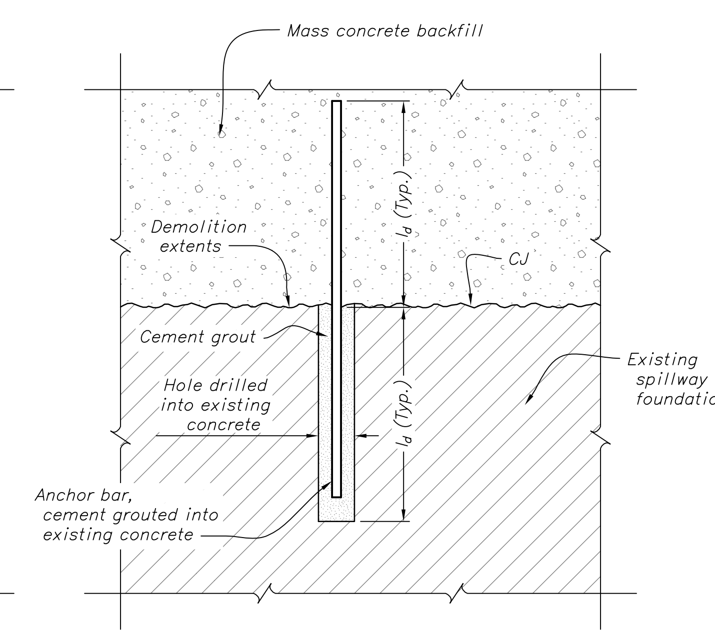
DETAIL 4 (NTS)

LIFTING SHACKLE EMBEDDED PLATE DETAIL



DETAIL 5 (NTS)

ANCHORAGE DETAIL
NEW CONSTRUCTION



DETAIL 6 (NTS)

ANCHORAGE DETAIL
REHABILITATION PROJECT

NOTES

1. For additional NOTES, see FIGURE 1A.
2. Grout nipple placement will depend on project specific requirements and may vary from what is shown.

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PRECAST OGEE CREST CONCEPT

OPTION A: SCC BACKFILL

MAIER / TOOTHMAN
DESIGNED
MAIER
DRAWN
CHECKED
TECH. APPR.
APPROVED
ADMIN APPROVAL –
DENVER, CO

CONCRETE OUTLINE

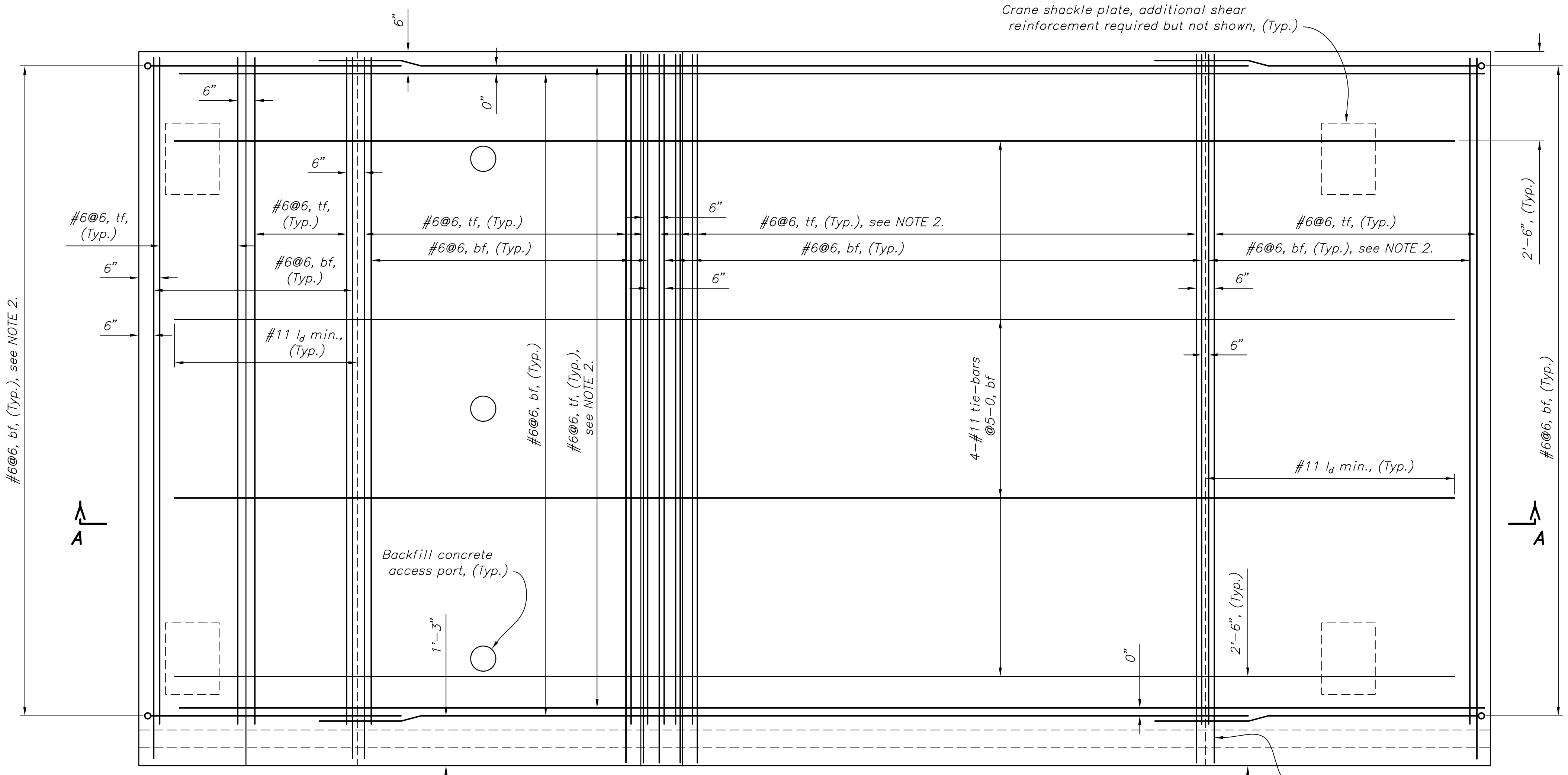
SECTIONS, ISOMETRIC VIEW AND DETAILS

FIGURE 2A

SHEET 2 OF 3

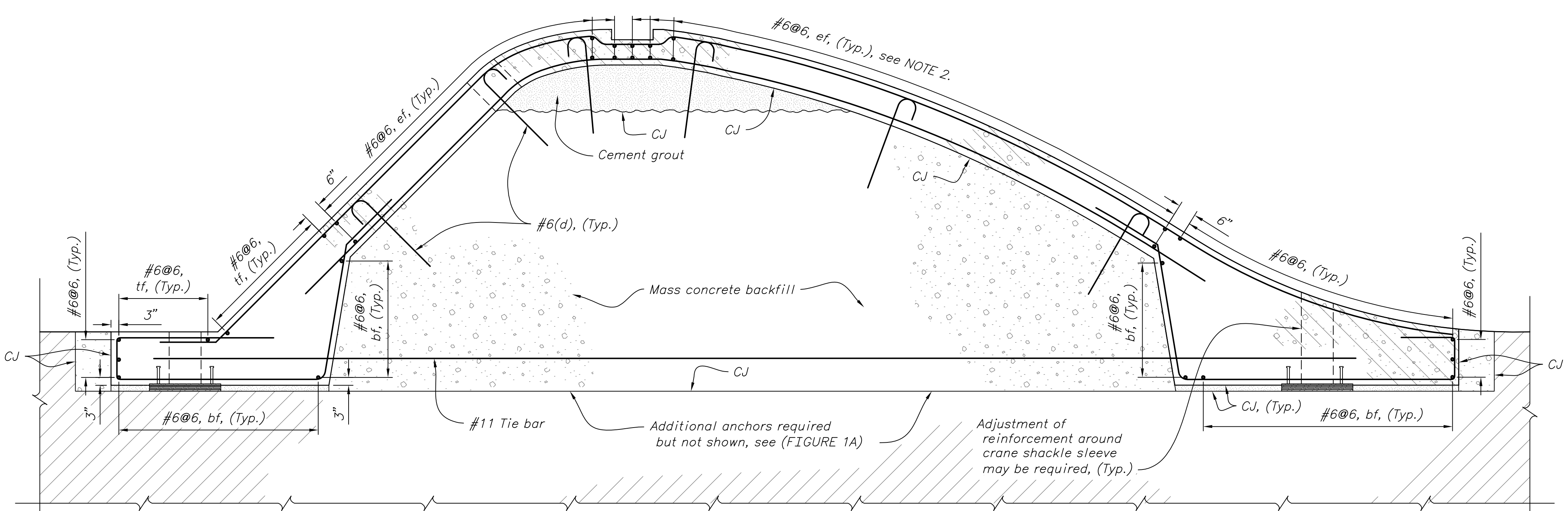
DATE AND TIME PLOTTED
Not Plotted
PLOTTED BY
Not Plotted

CAD SYSTEM
AUTOCAD
CAD FILENAME
UNKNOWN



REINFORCEMENT PLAN

(GROUT NIPPLES AND PVC WATERSTOP NOT SHOWN)



SECTION A–A

SECTION VIEW SHOWING TYPICAL PRECAST OGEE CREST REINFORCEMENT.

NOTES

1. For additional NOTES and minimum requirements for detailing reinforcement, see (40–D–6023).
2. Reinforcement layout shown is general, and will change depending on project requirements. The general requirement for a large, 12–inch thick crest (as shown) is #6 @ 6", ew, ef.

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CAD FILENAME UNKNOWN

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PRECAST OGEE CREST CONCEPT

OPTION A: SCC BACKFILL

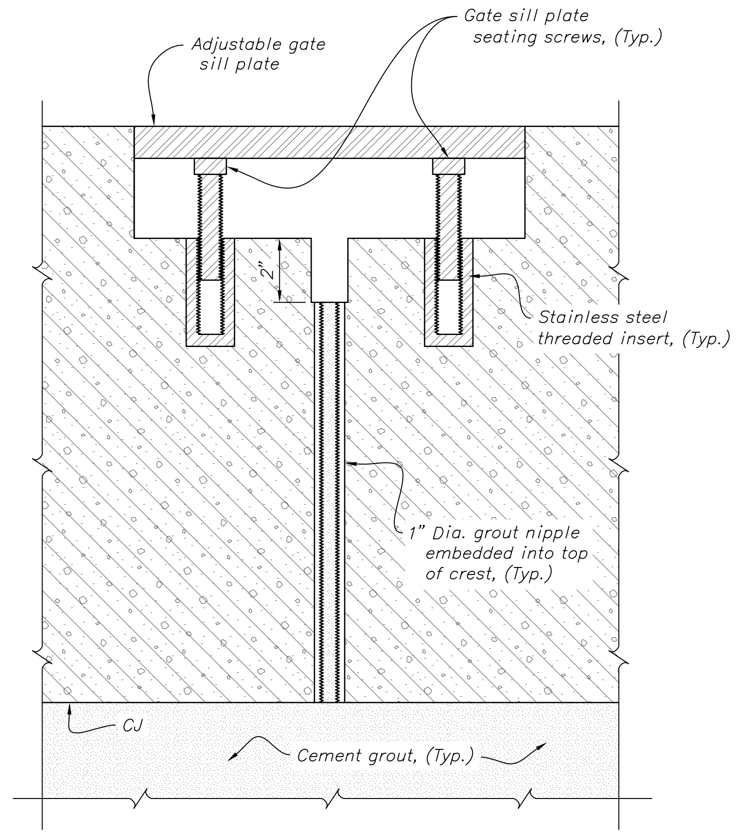
DESIGNED	MAIER / TOOTHMAN
DRAWN	MAIER
CHECKED	
TECH. APPR.	
APPROVED	
DENVER, CO	

REINFORCEMENT

PLAN AND SECTION

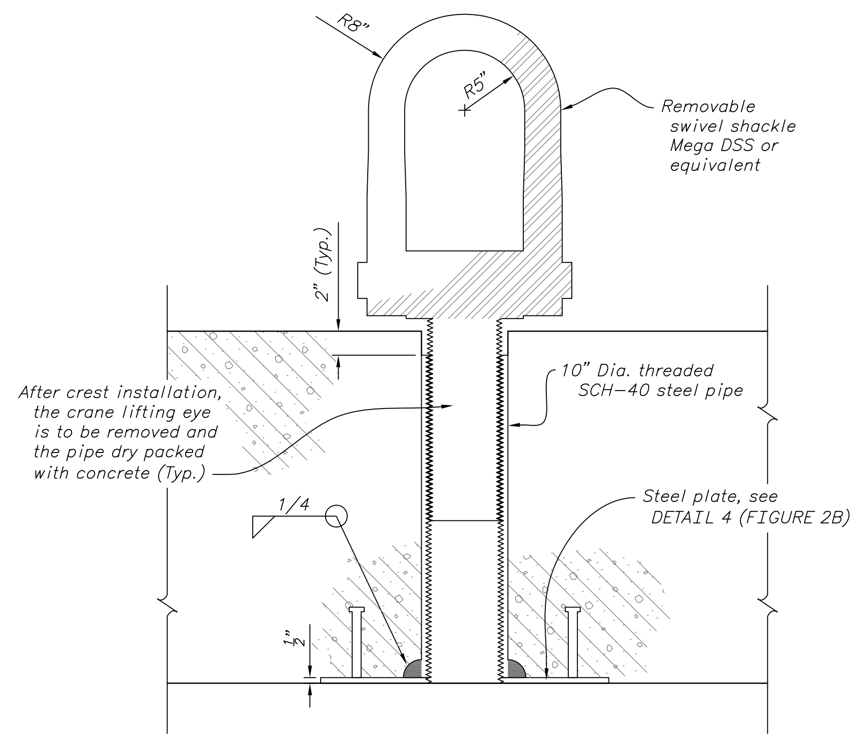
FIGURE 3A

SHEET 3 OF 3



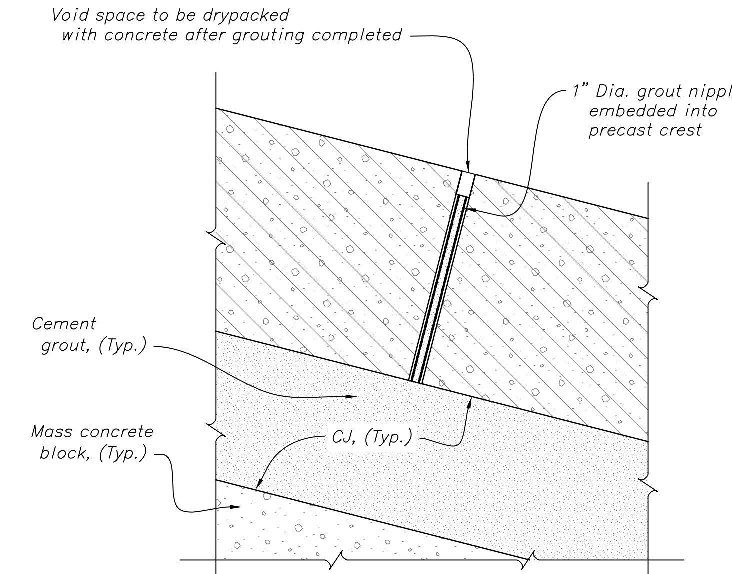
DETAIL 1 (NTS)

TYPICAL GROUT NIPPLE / GATE SILL PLATE DETAIL



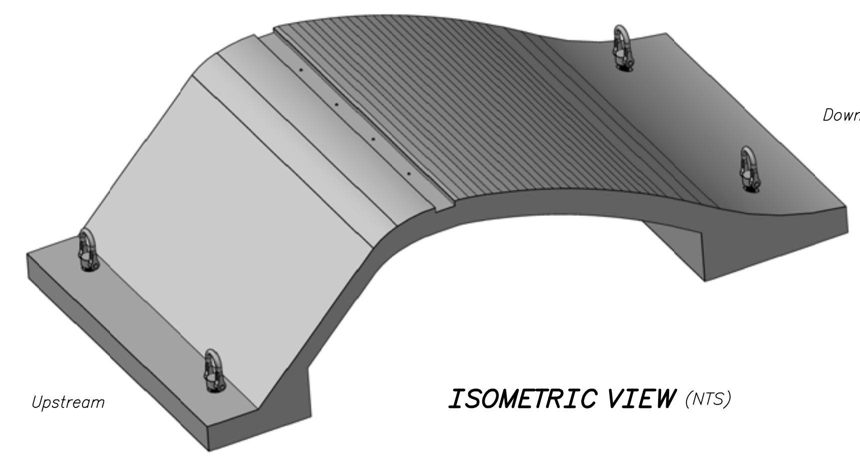
DETAIL 2 (NTS)

TYPICAL VIEW OF REMOVABLE CRANE SHACKLE AND CRANE SHACKLE EMBEDDED PLATE.

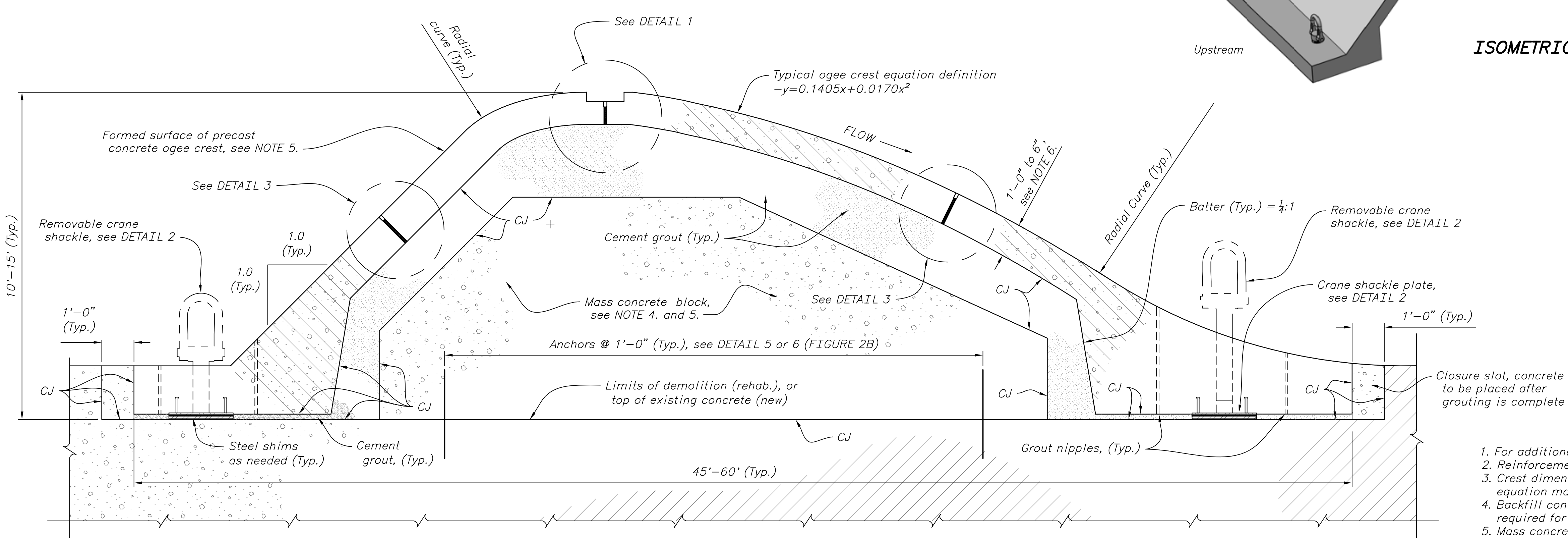


DETAIL 3 (NTS)

TYPICAL EMBEDDED GROUT NIPPLE DETAIL



ISOMETRIC VIEW (NTS)



SECTIONAL VIEW OF PRECAST OGEE CREST (NTS)

(ADDITIONAL ANCHORAGE REQUIRED BUT NOT SHOWN. SEE FIGURE 3A)

CONCRETE LEGEND

- Cement Grout
- Concrete
- Precast Concrete
- Existing Concrete

NOTES

1. For additional concrete outline notes, see 40-D-7012.
2. Reinforcement required but not shown.
3. Crest dimensions and equation shown are examples, actual equation may vary.
4. Backfill concrete may be placed in multiple lifts if required for temperature control.
5. Mass concrete to have a 28-day compressive strength of 3,000 psi (minimum). Precast concrete to have a 28-day compressive strength of 4,500 psi, (minimum).
6. Thickness of precast crest will vary depending on size and project requirements. Typical thickness; Large crest = 1'-0" to 9", Medium and small crests: 9" to 6".

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PRECAST OGEE CREST CONCEPT
OPTION B: MASS CONCRETE BLOCK

MAIER / TOOTHMAN
DESIGNED
MAIER
DRAWN
CHECKED
TECH. APPR.
APPROVED
ADMIN APPROVAL -
DENVER, CO

CONCRETE OUTLINE

SECTIONAL VIEW, ISOMETRIC VIEW, AND DETAILS

FIGURE 1B

SHEET 1 OF 3

DATE AND TIME PLOTTED Not Plotted
PLOTTED BY Not Plotted

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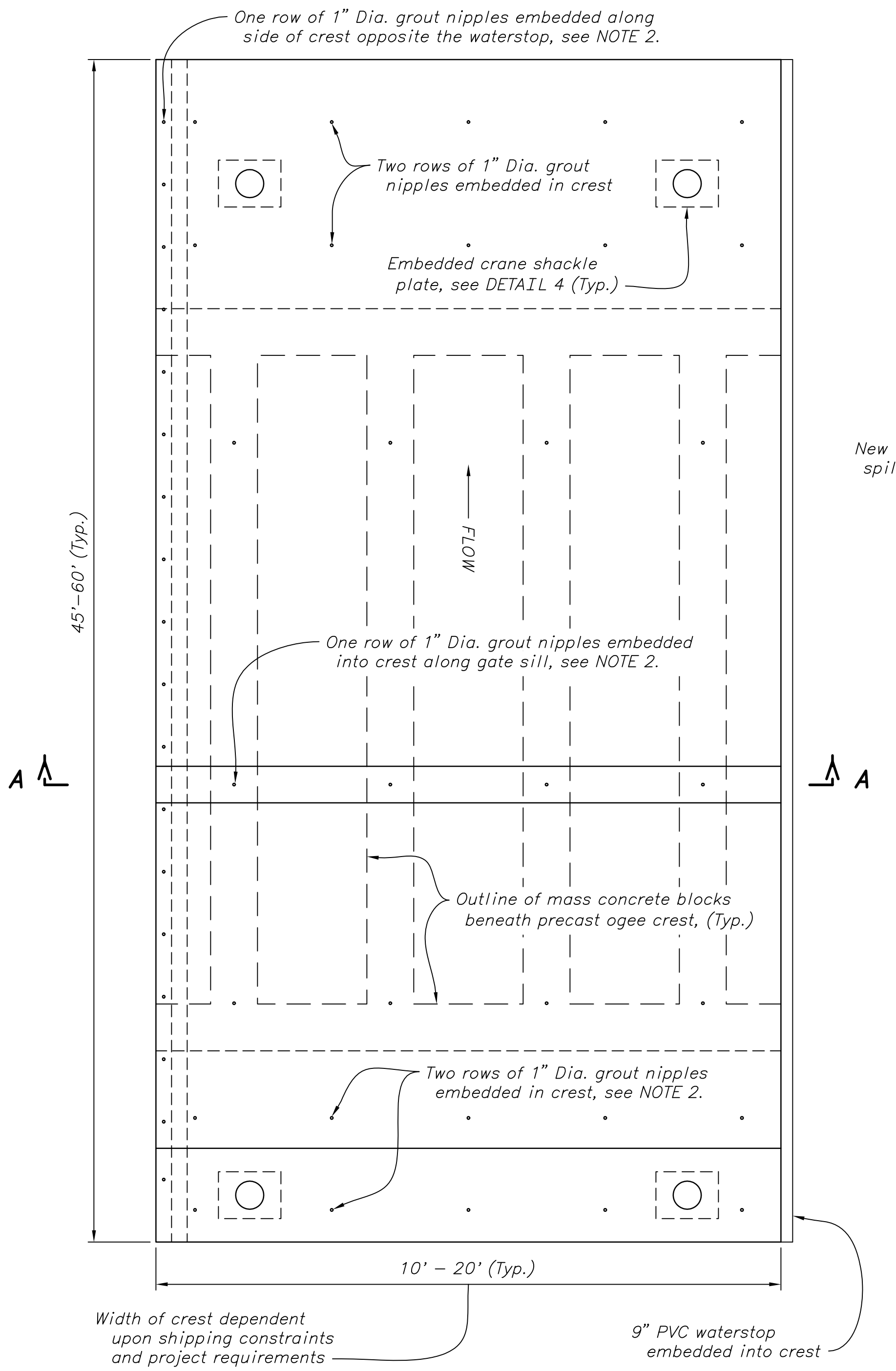
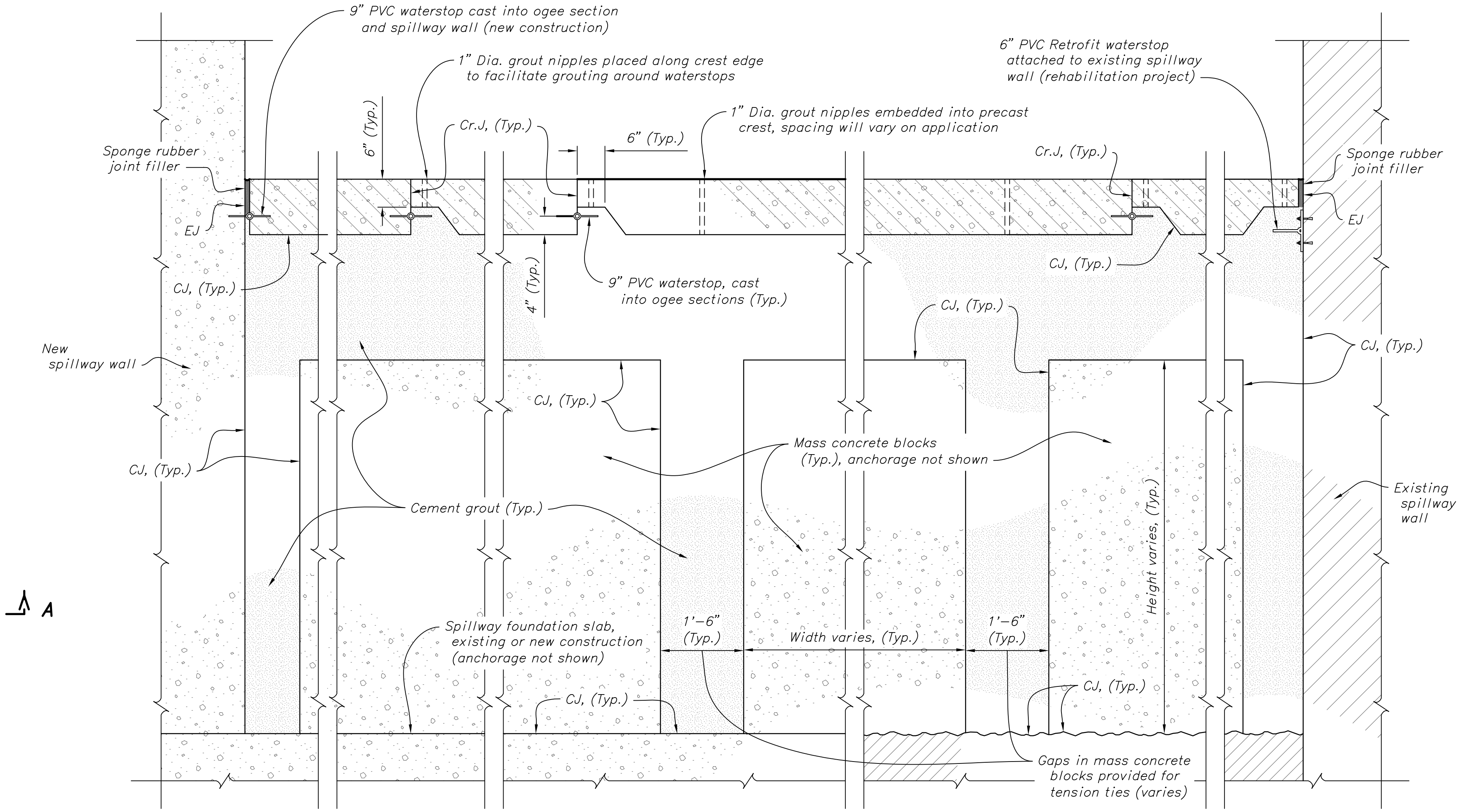


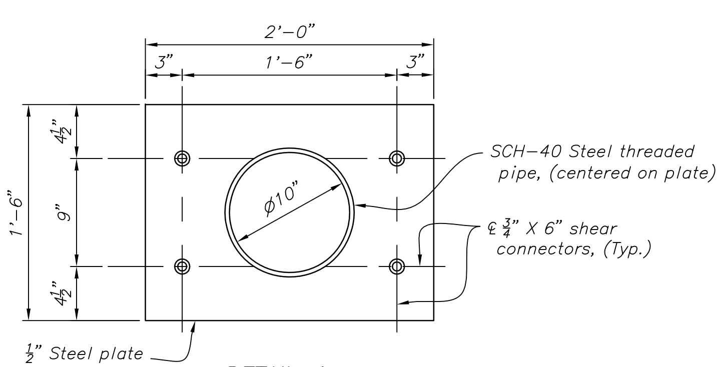
PLAN (NTS)

TYPICAL PLAN VIEW OF PRECAST OGEE CREST



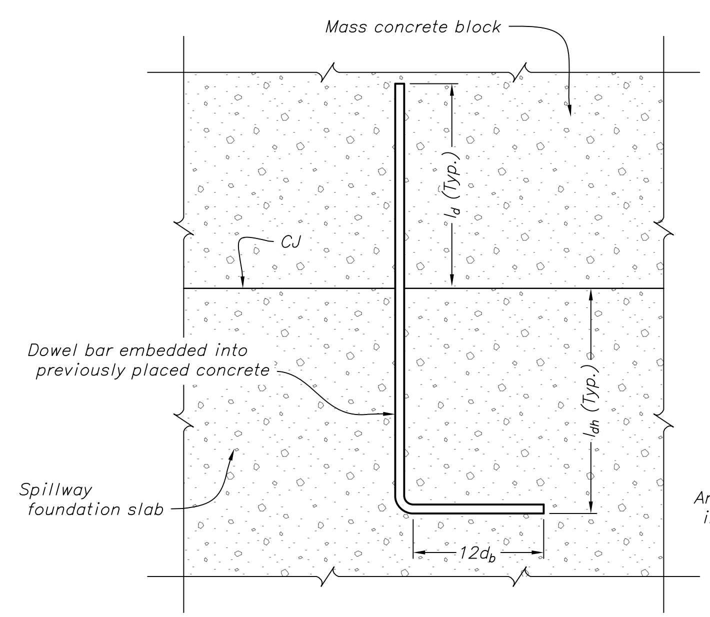
SECTION A–A (NTS)

SECTION VIEW THROUGH SPILLWAY CREST LOOKING DOWNSTREAM
(SHOWING NEW CONSTRUCTION ON LEFT, AND REHABILITATION PROJECT ON RIGHT)



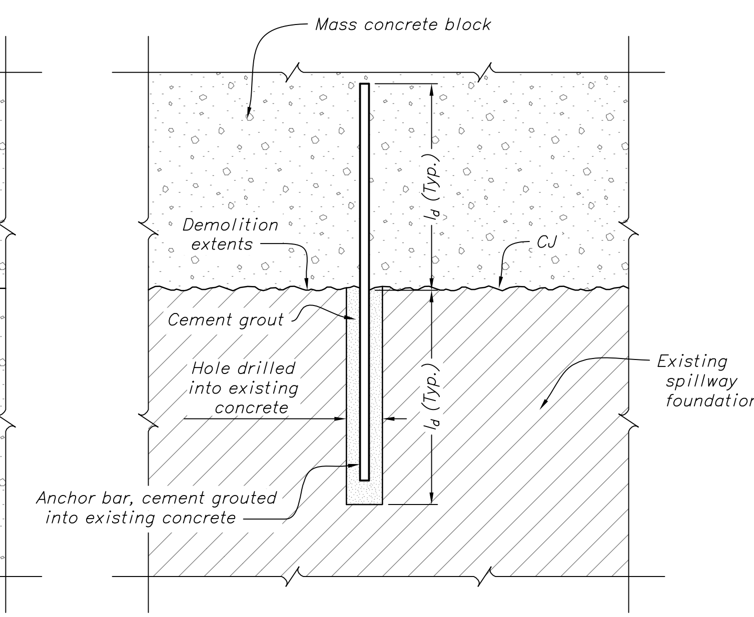
DETAIL 4 (NTS)

LIFTING SHACKLE EMBEDDED PLATE DETAIL



DETAIL 5 (NTS)

ANCHORAGE DETAIL
NEW CONSTRUCTION



DETAIL 6 (NTS)

ANCHORAGE DETAIL
REHABILITATION CONSTRUCTION

NOTES

1. For additional NOTES, see FIGURE 1B.
2. Grout nipple placement will depend on project specific requirements and may vary from what is shown.

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PRECAST OGEE CREST CONCEPT

OPTION B: MASS CONCRETE BLOCK

MAIER / TOOTHMAN
DESIGNED
MAIER
DRAWN
CHECKED
TECH. APPR.
APPROVED
ADMIN APPROVAL –
DENVER, CO

CONCRETE OUTLINE

PLAN, SECTIONS AND DETAILS

FIGURE 2B

SHEET 2 OF 3

DATE AND TIME PLOTTED Not Plotted
PLOTTED BY Not Plotted

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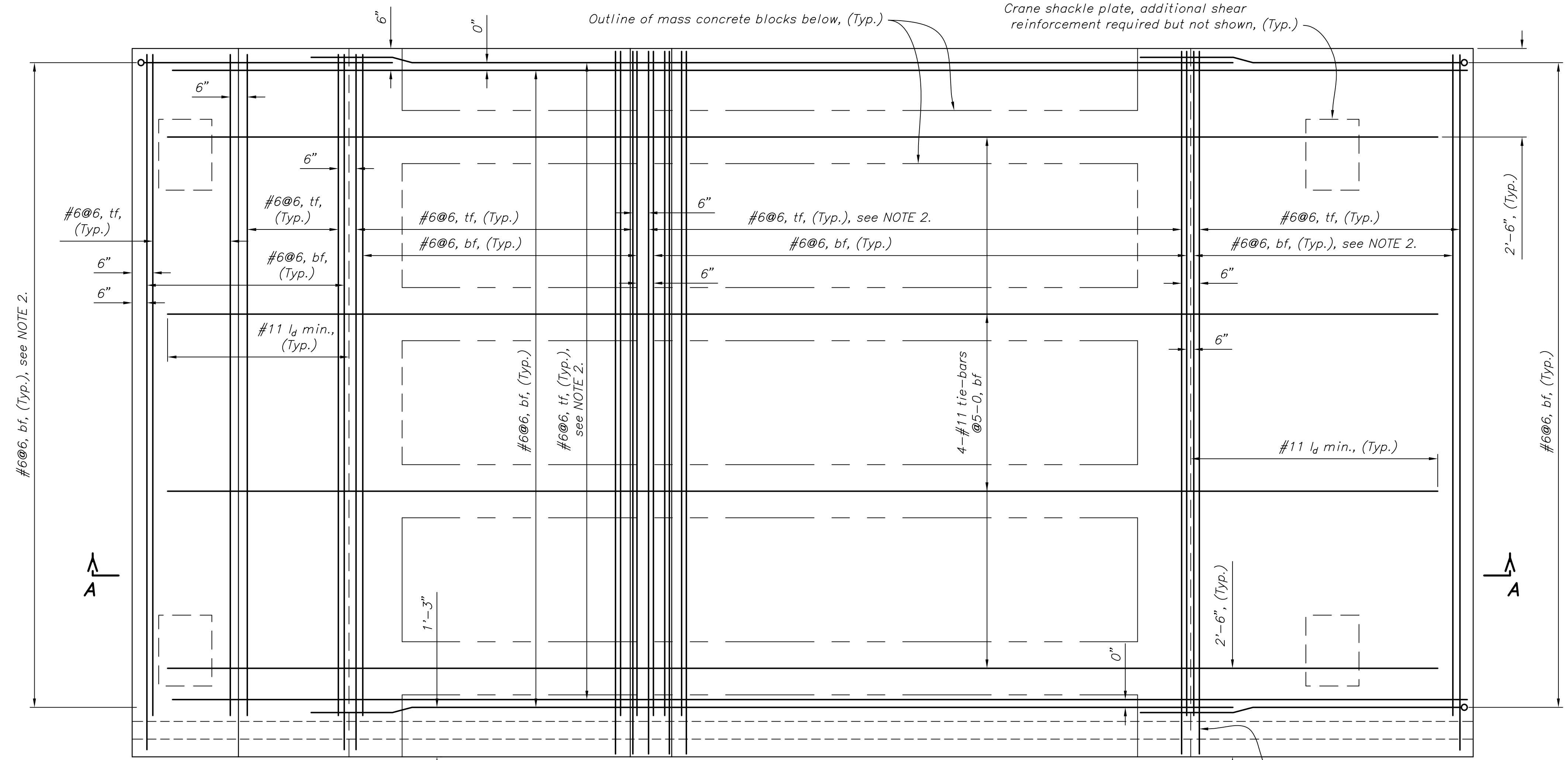
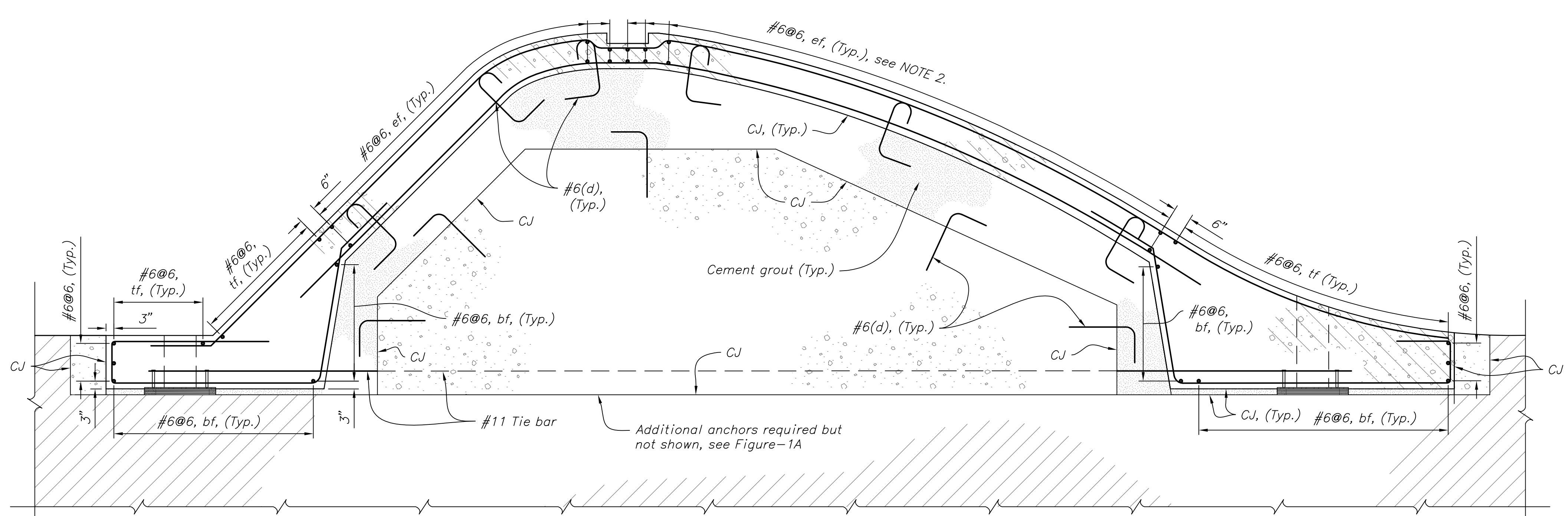


REINFORCEMENT PLAN

(GROUT NIPPLES AND PVC WATERSTOP NOT SHOWN)



SECTION A–A

SECTION VIEW SHOWING TYPICAL PRECAST OGEE CREST REINFORCEMENT AND ANCHORAGE BETWEEN PRECAST OGEE CREST AND MASS CONCRETE BLOCK

NOTES

1. For additional NOTES and minimum requirements for detailing reinforcement, see (40–D–6023).
2. Reinforcement layout shown is general, and will change depending on project requirements. The general requirement is #6 bars spaced at 6", each way, each face.

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PRECAST OGEE CREST CONCEPT

OPTION B: MASS CONCRETE BLOCK

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MAIER
DRAWN
CHECKED
TECH. APPR.
APPROVED
ADMIN APPROVAL –
DENVER, CO

REINFORCEMENT PLAN AND SECTION

FIGURE 3B

SHEET 3 OF 3

DATE AND TIME PLOTTED Not Plotted
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CAD SYSTEM AUTOCAD
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Appendix B

Internal Force Plots

12-Inch Thick Precast Ogee Crest (4-Supports)

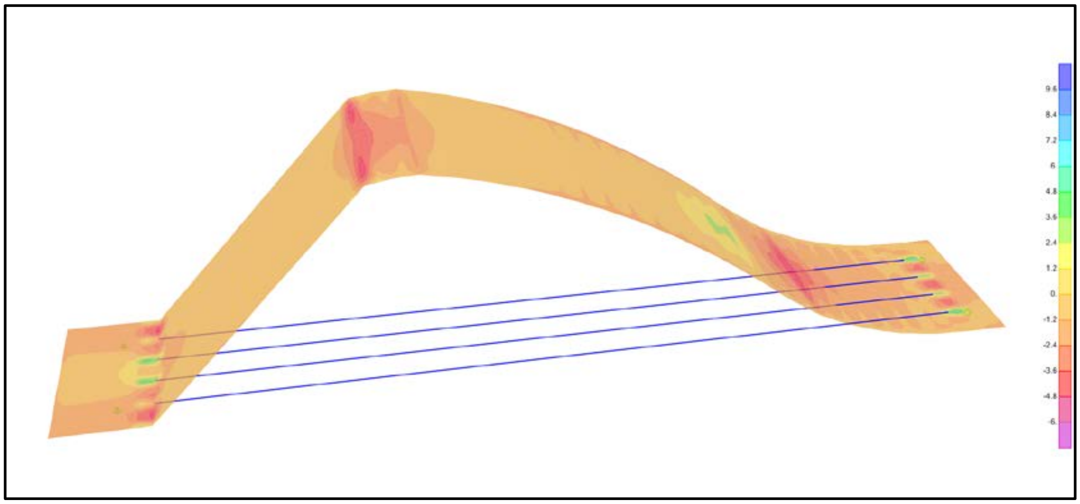


Figure 1 – Showing F11, horizontal axial tension / compression (kip).

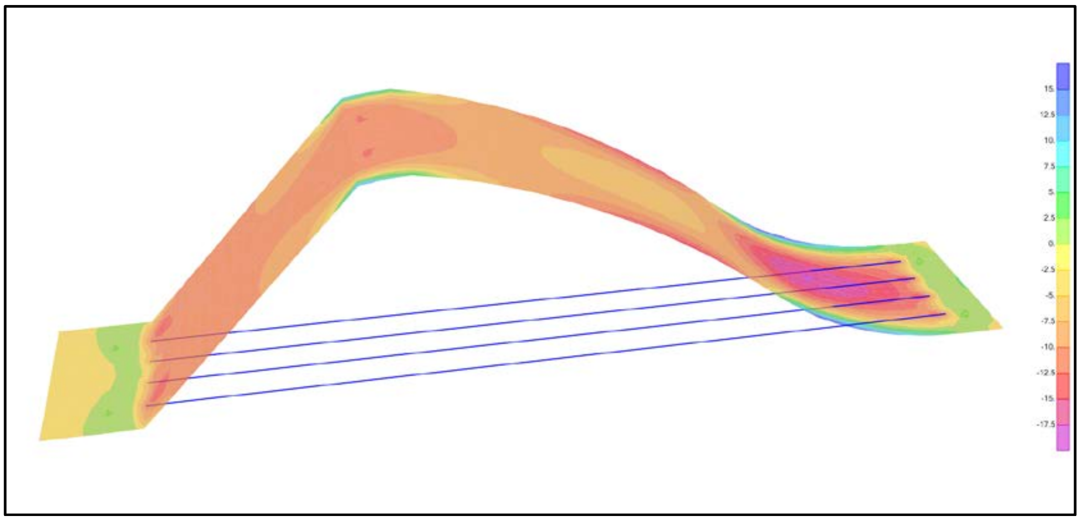


Figure 2 – Showing F22, vertical axial tension / compression (kip).

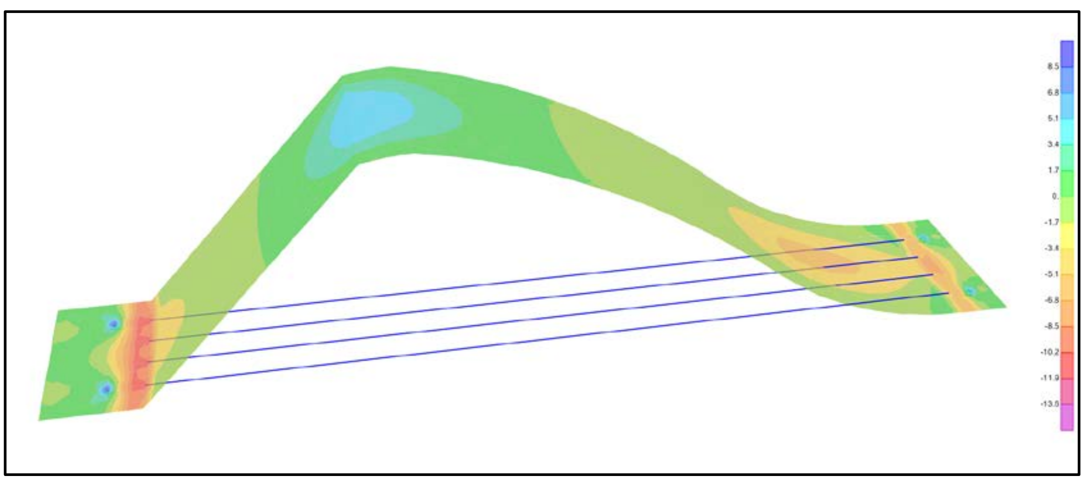


Figure 3 – Showing M11, horizontal bending moment (kip-ft).

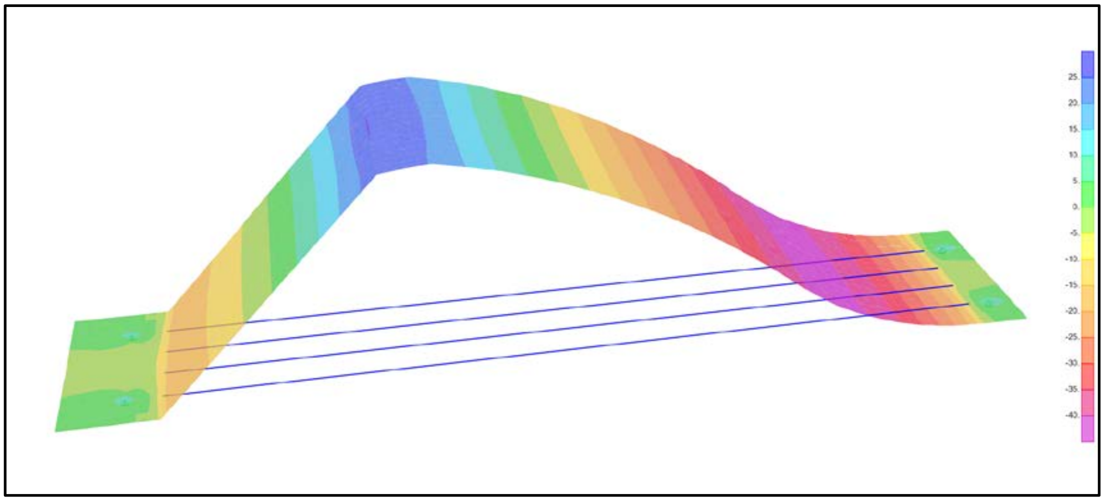


Figure 4 – Showing M22, vertical bending moment (kip-ft).

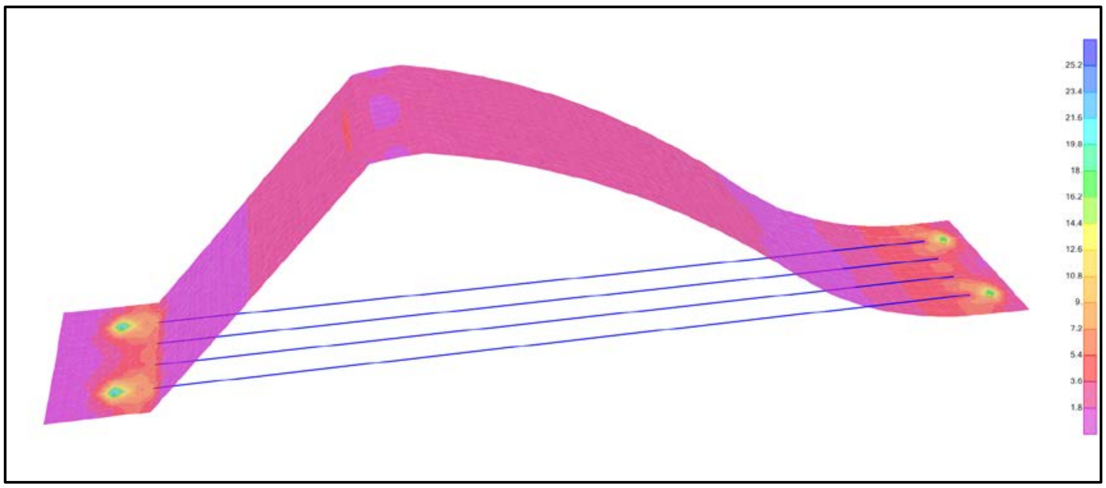


Figure 5 – Showing Vmax, out-of-plane shear (kip).

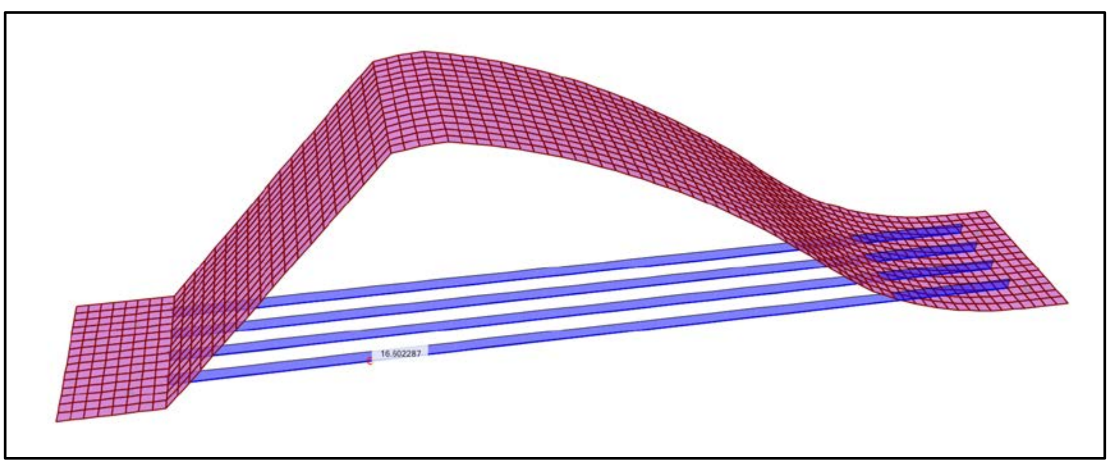


Figure 6 – Showing the axial tension / compression on the No. 11 tension tie bars (kip).

12-Inch Precast Ogee Crest (2-Supports)

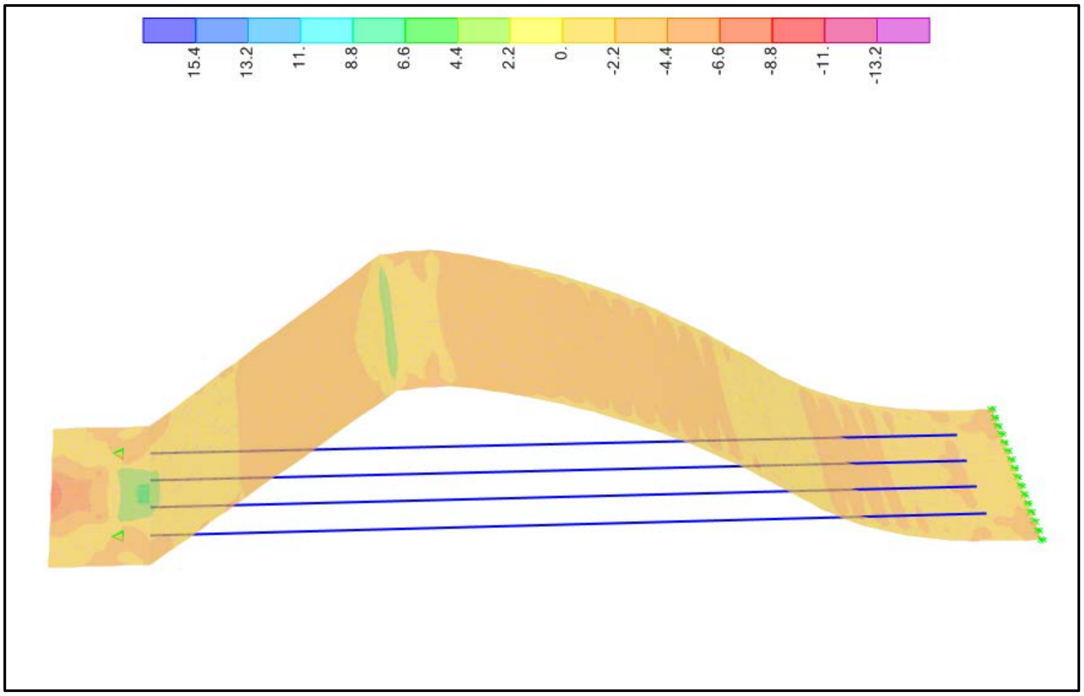


Figure 7 – Showing F11, horizontal axial tension / compression (kip). Rotated view.

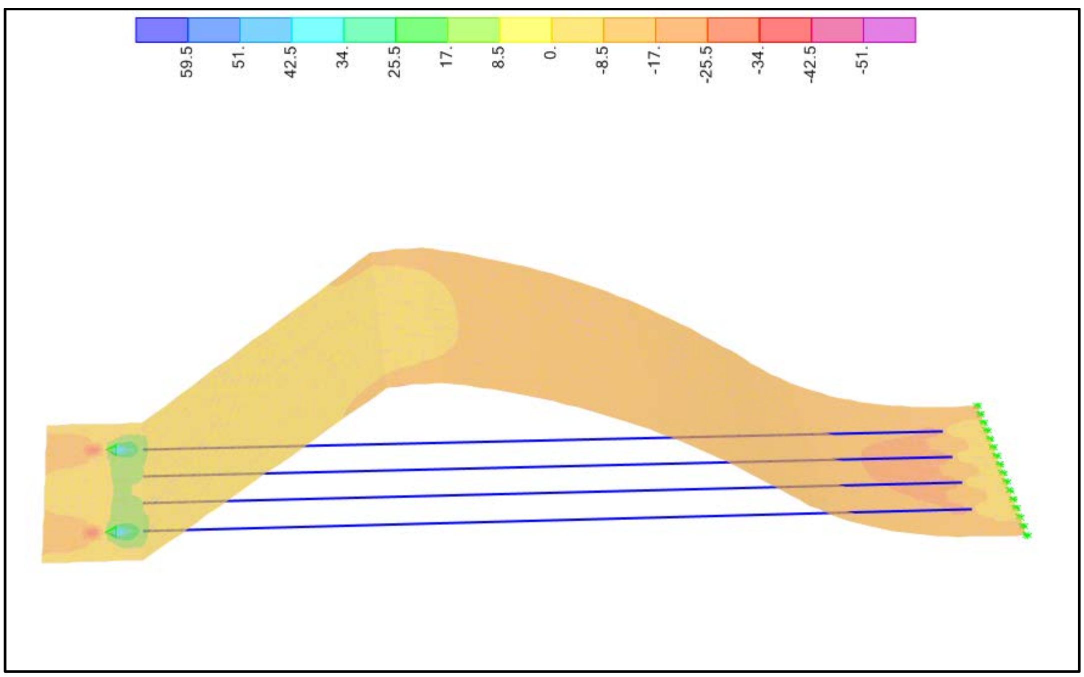


Figure 8 – Showing F22, vertical axial tension / compression (kip). Rotated view.

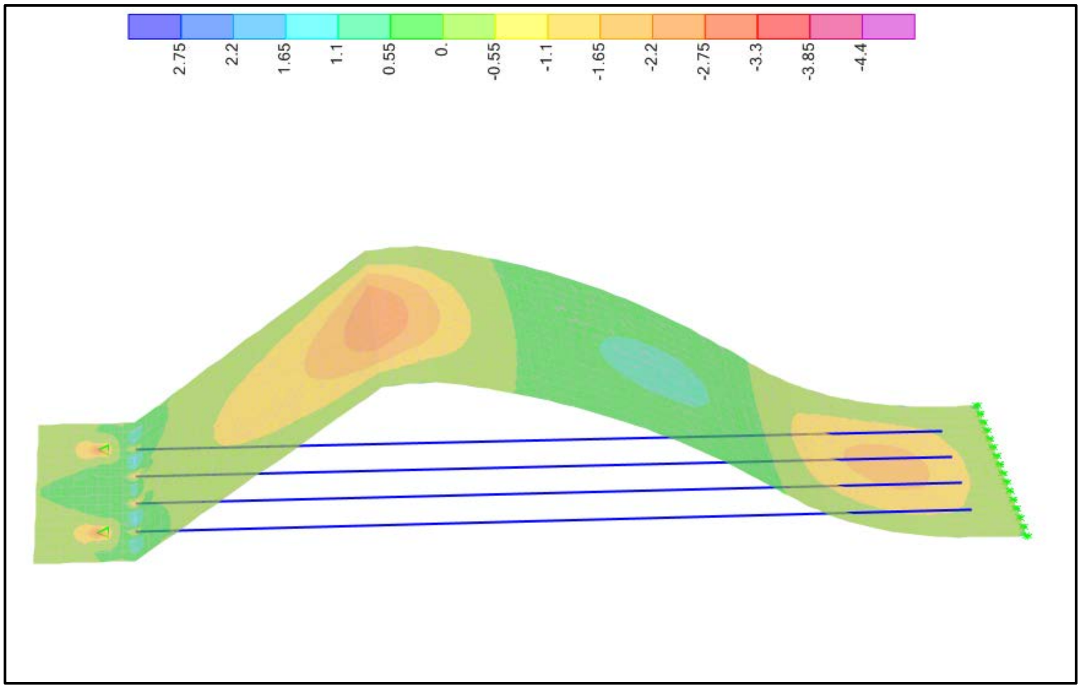


Figure 9 – Showing M11, horizontal bending moment (kip-ft). Rotated view.

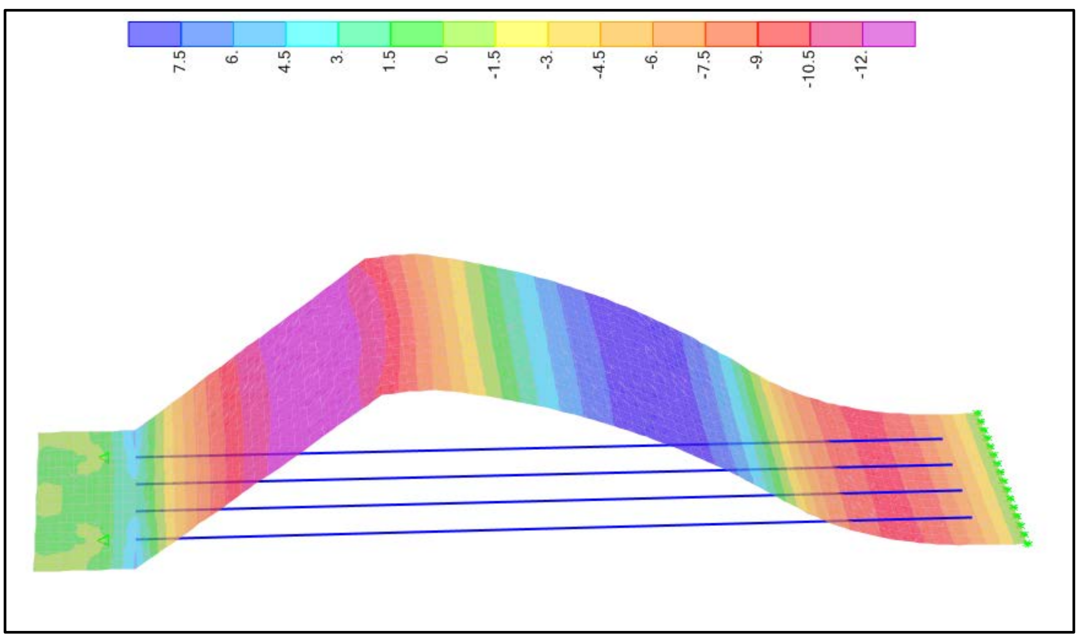


Figure 10 – Showing M22, vertical bending moment (kip-ft). Rotated view.

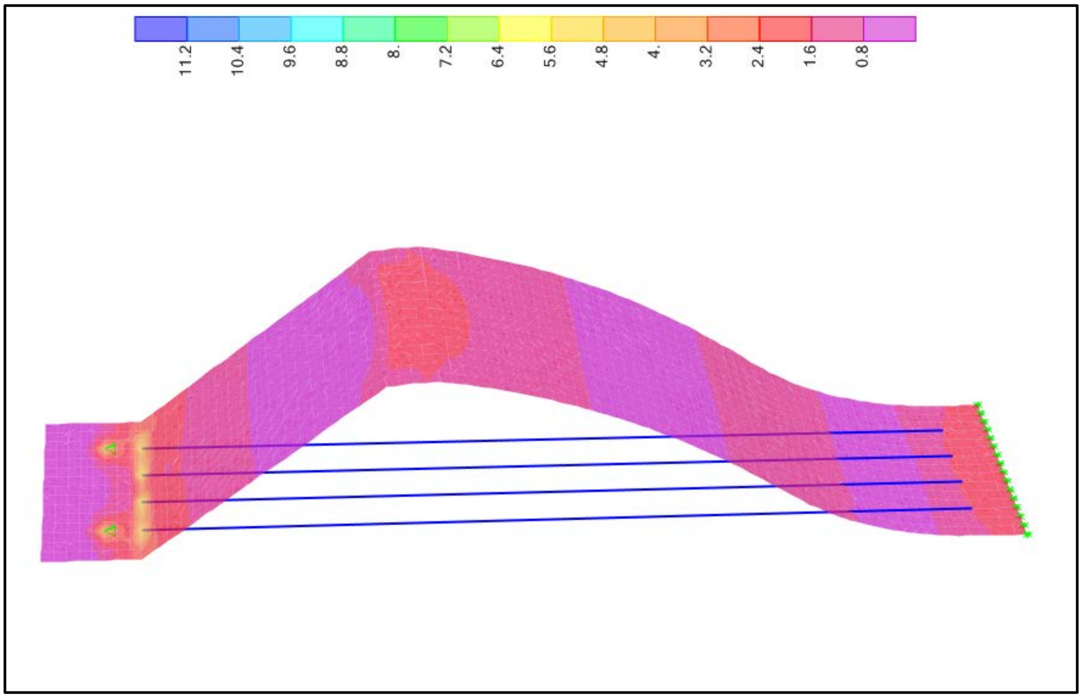


Figure 11 – Showing Vmax, out-of-plane shear (kip) Rotated view.

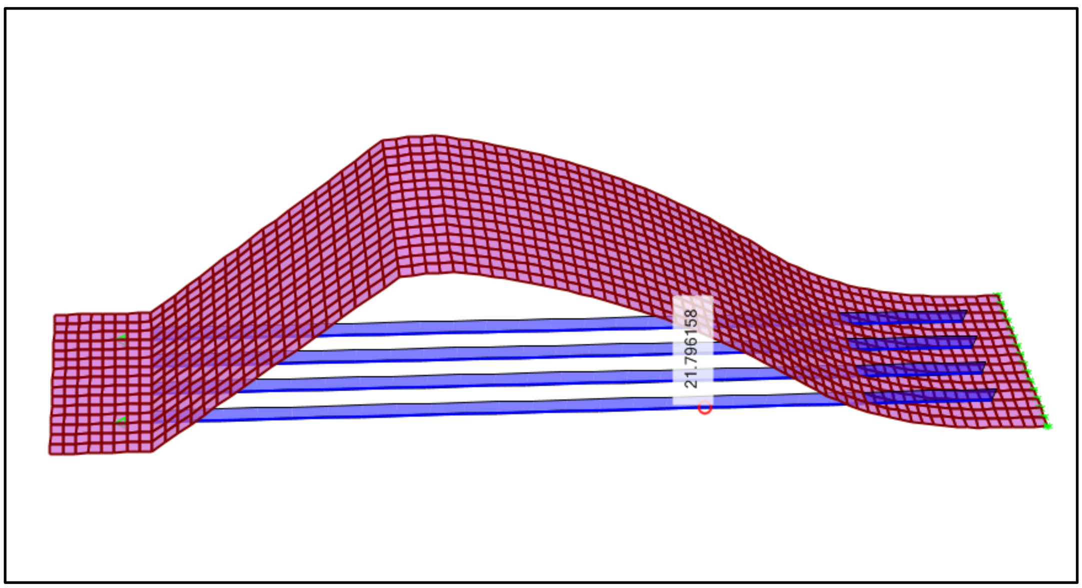


Figure 12 – Showing the axial tension / compression on the No. 11 tension tie bars (kip).

9-Inch Thick Precast Ogee Crest (4-Supports)

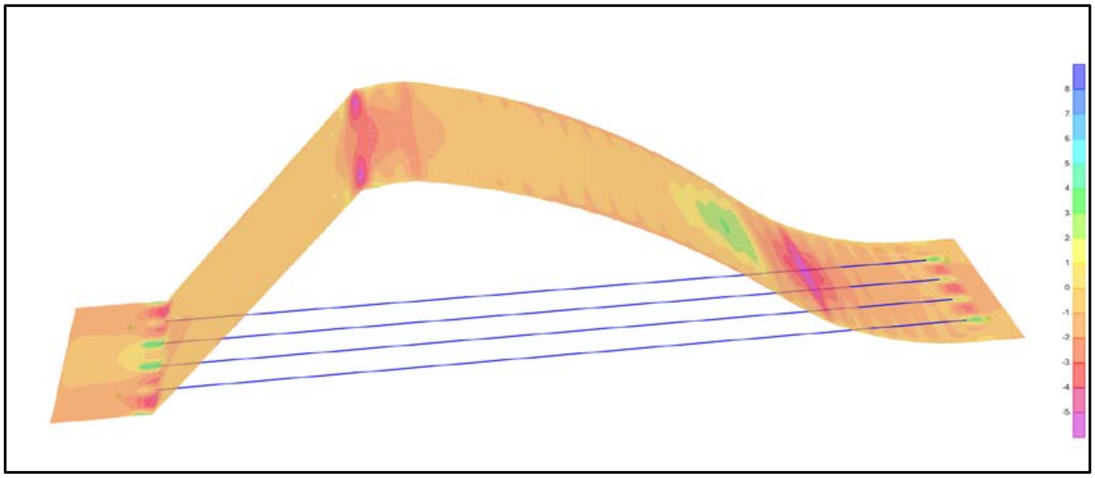


Figure 13 – Showing F11, horizontal axial tension / compression (kip).

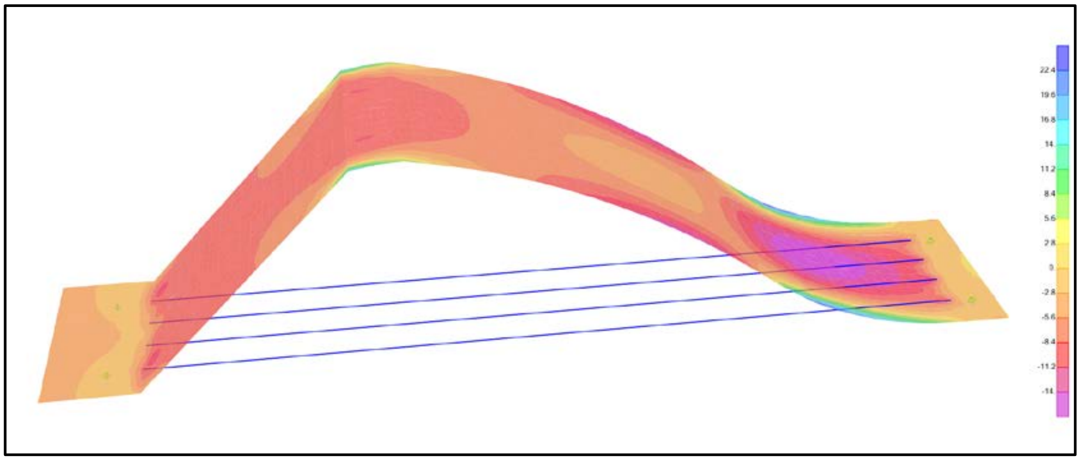


Figure 14 – Showing F22, vertical axial tension / compression (kip).

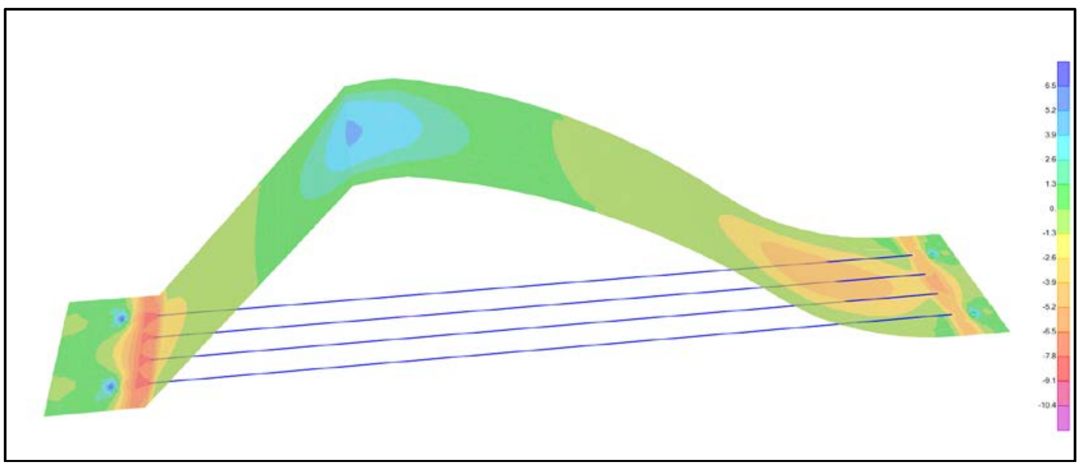


Figure 15 – Showing M11, horizontal bending moment (kip-ft).

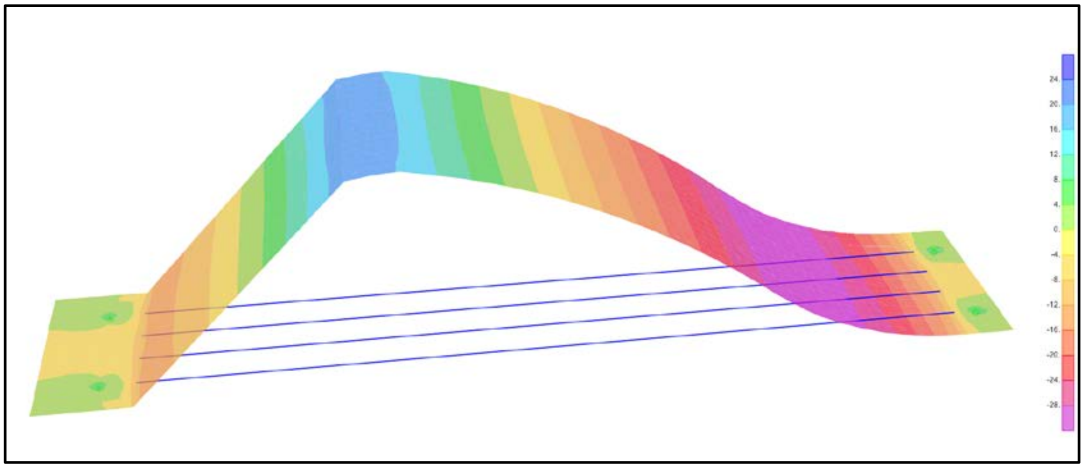


Figure 16 – Showing M22, vertical bending moment (kip-ft)

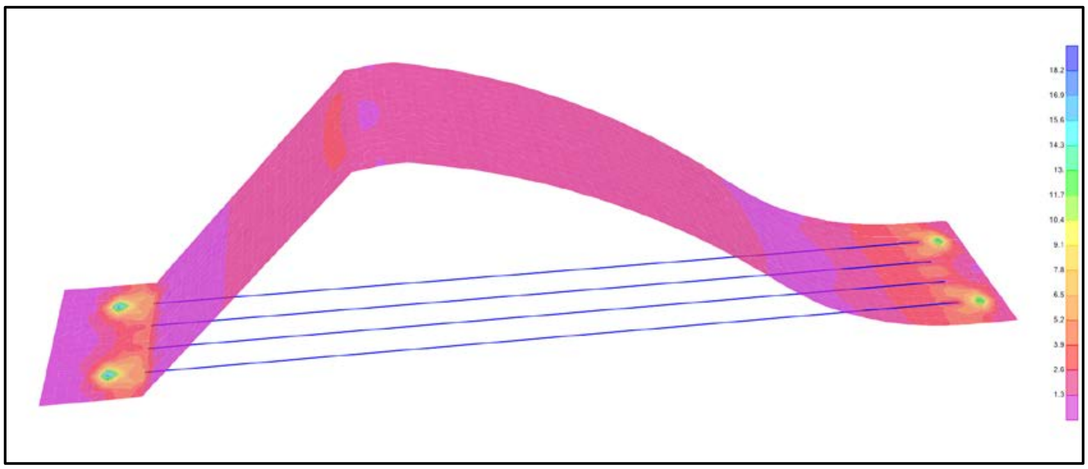


Figure 17 – Showing Vmax, out-of-plane shear (kip).

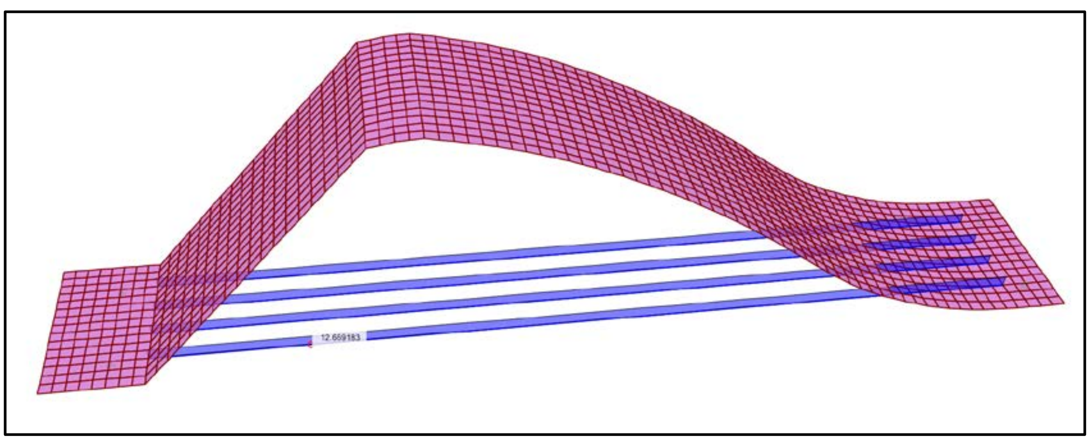


Figure 18 – Showing the axial tension / compression on the No. 11 tension tie bars (kip).

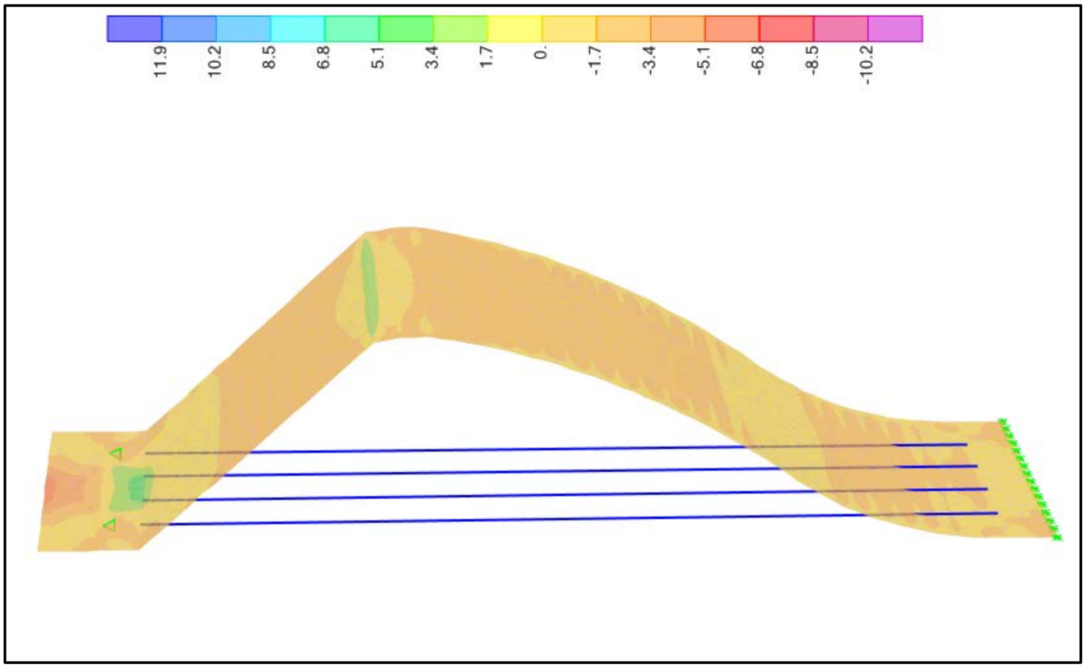


Figure 18 – Showing F11, horizontal axial tension / compression (kip).

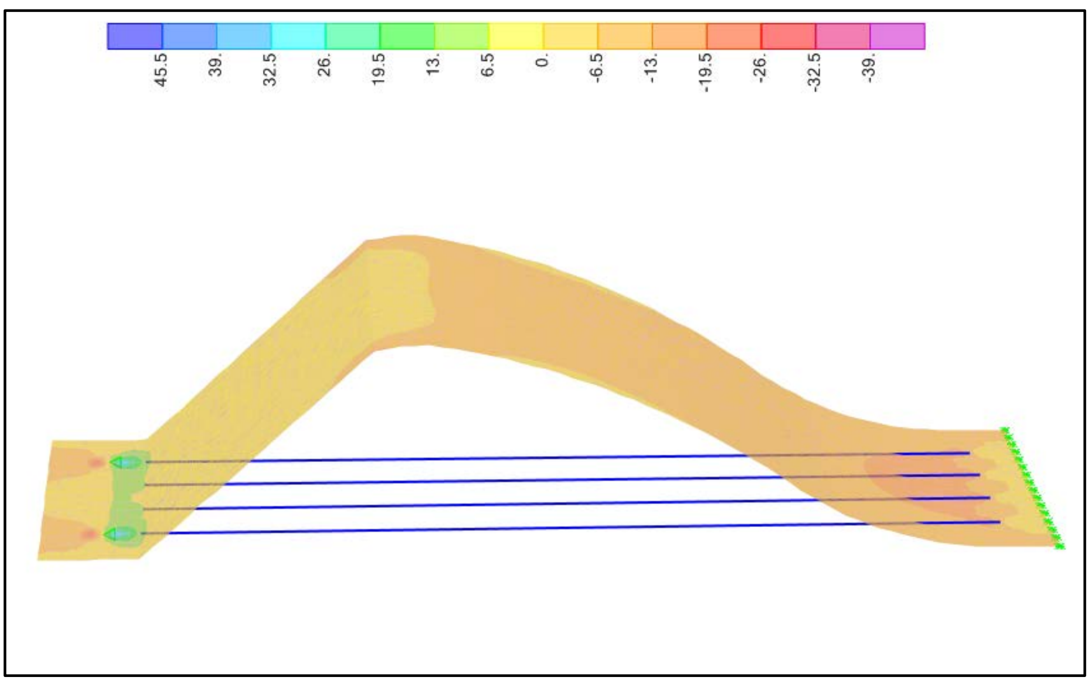


Figure 19 – Showing F22, vertical axial tension / compression (kip).

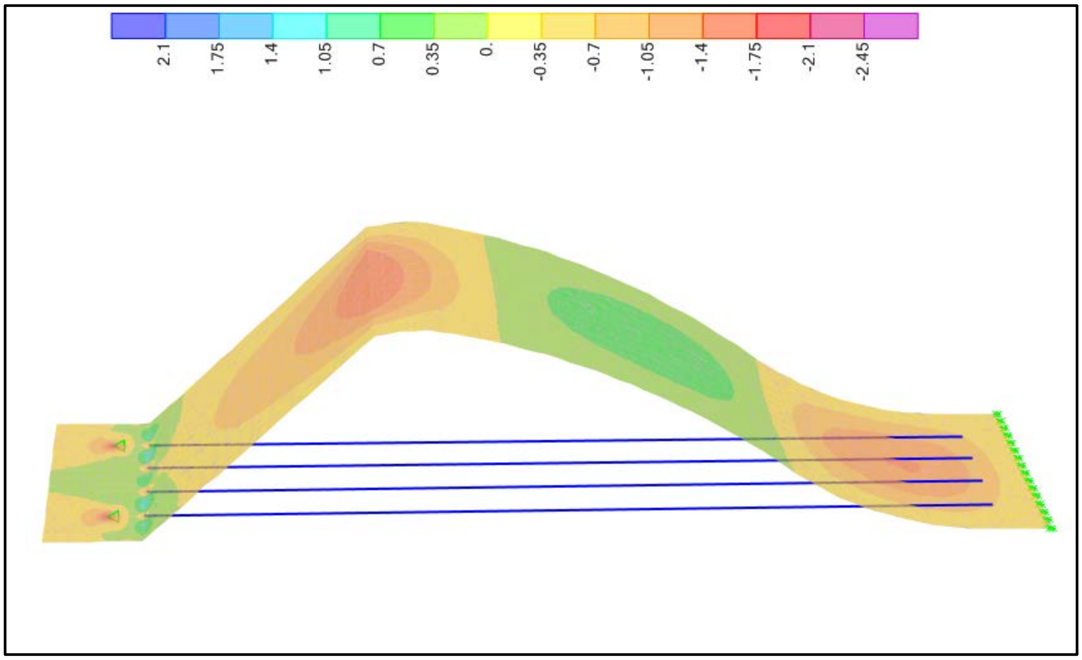


Figure 20 – Showing M11, horizontal bending moment (kip-ft).

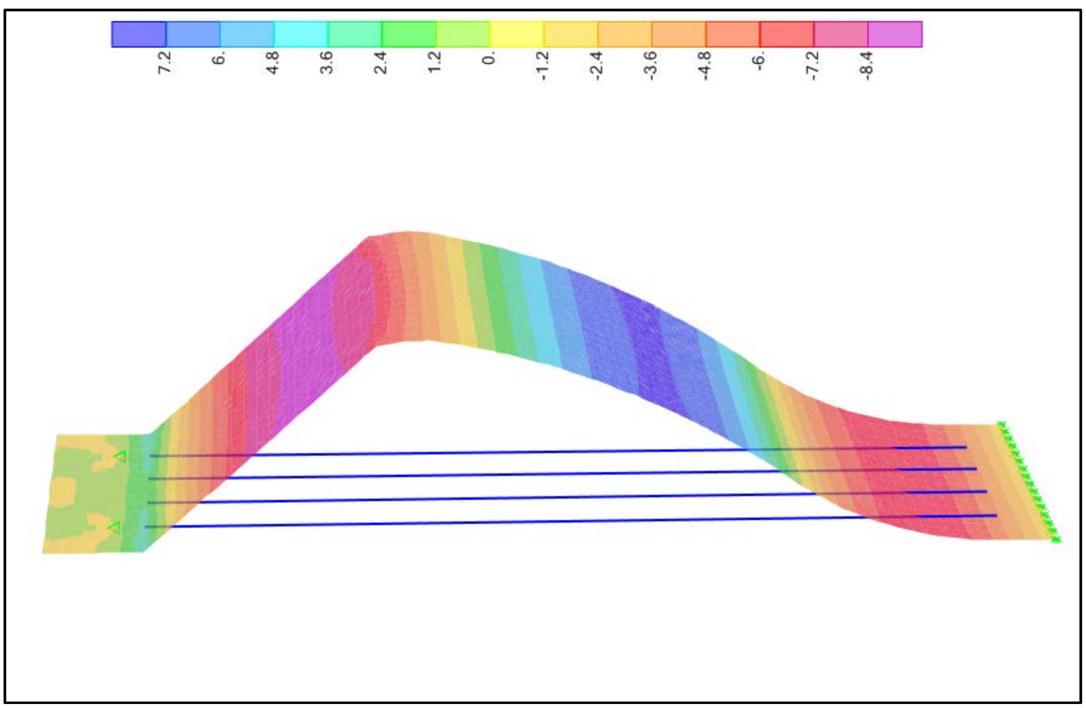


Figure 21 – Showing M22, vertical bending moment (kip-ft)

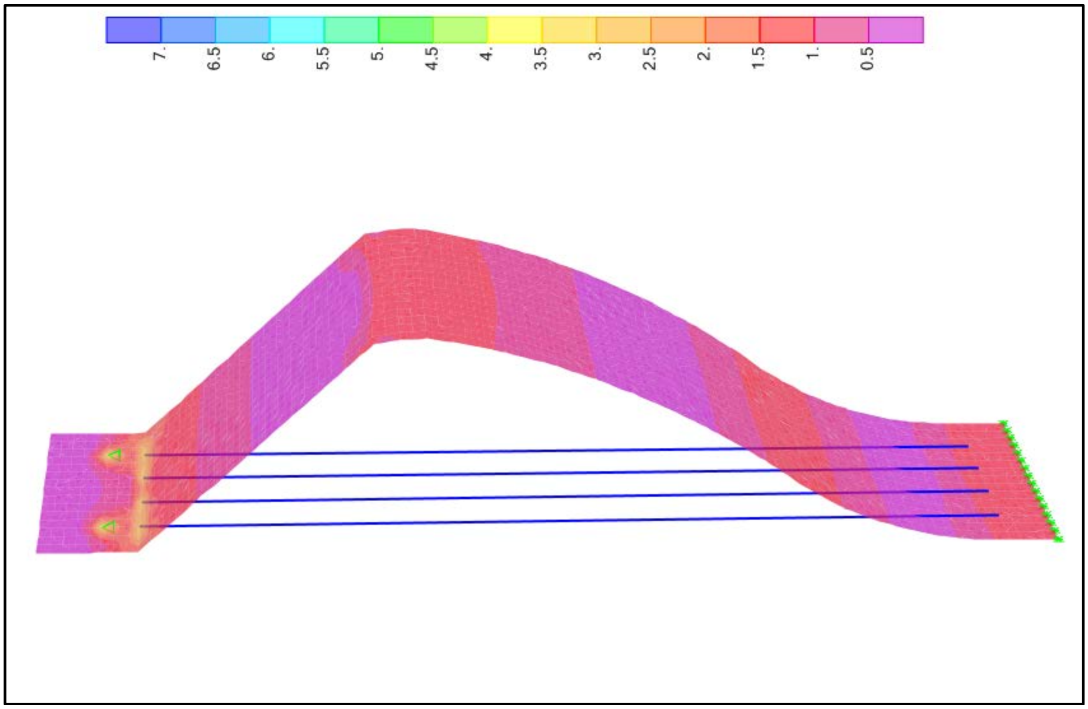


Figure 22 – Showing Vmax, out-of-plane shear (kip).

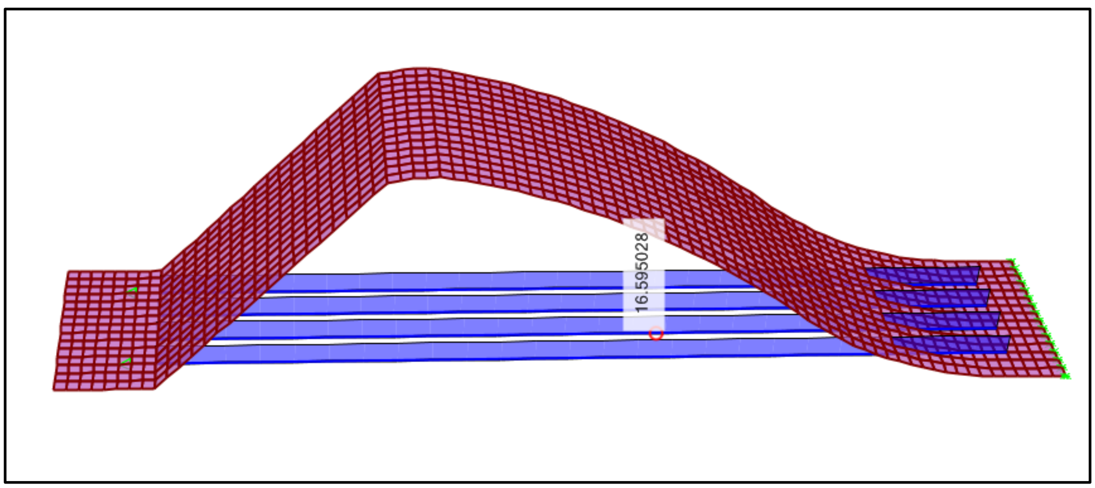


Figure 23 - Showing the axial tension / compression on the No. 11 tension tie bars (kip).

6-Inch Precast Ogee Crest (4-Supports)

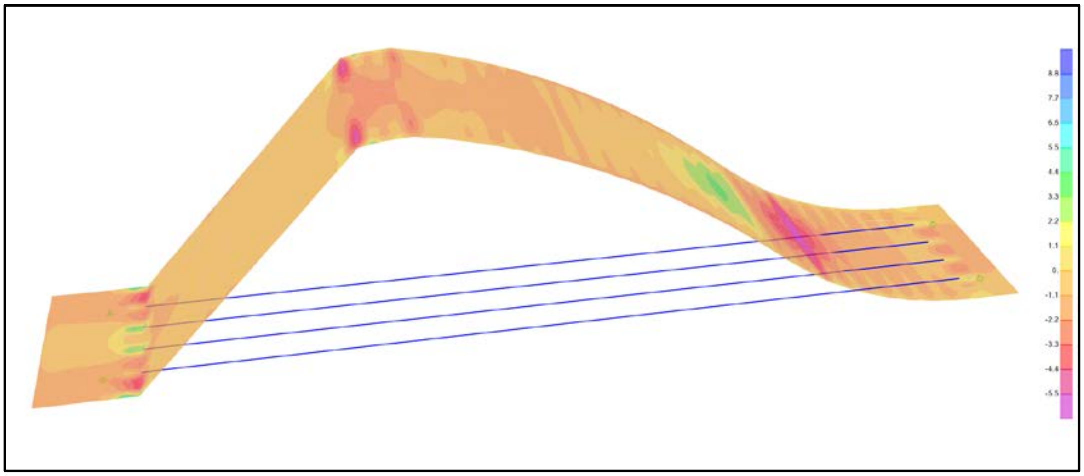


Figure 24 – Showing F11, horizontal axial tension / compression (kip).

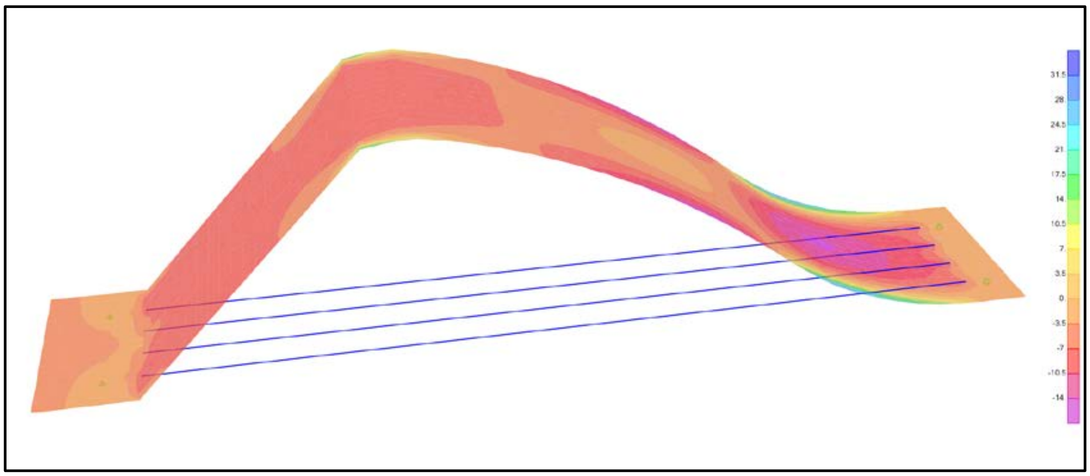


Figure 25 – Showing F22, vertical axial tension / compression (kip).

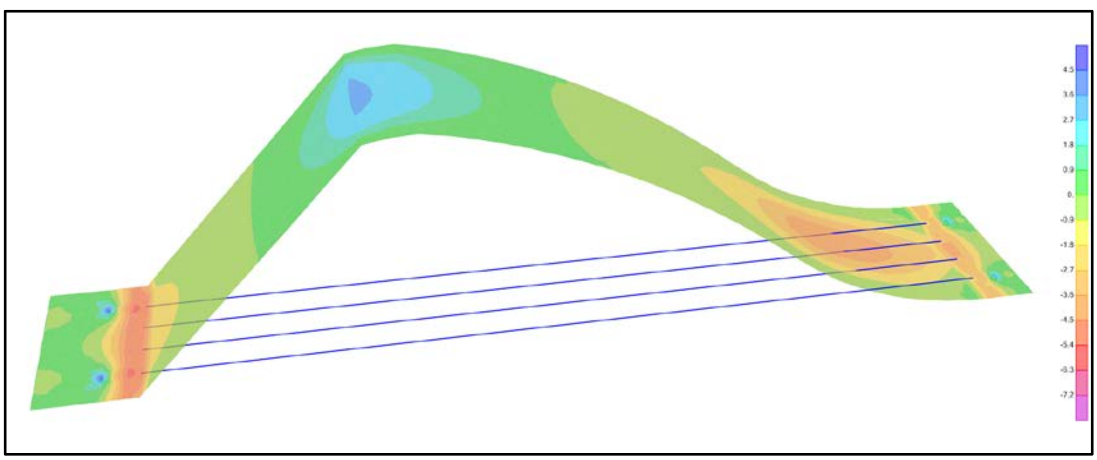


Figure 26 – Showing M11, horizontal bending moment (kip-ft).

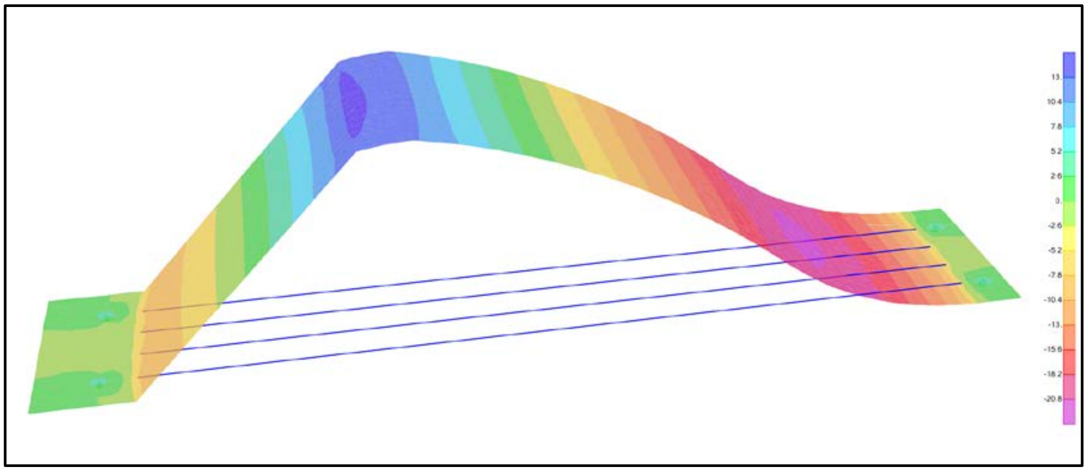


Figure 27 – Showing M22, vertical bending moment (kip-ft).

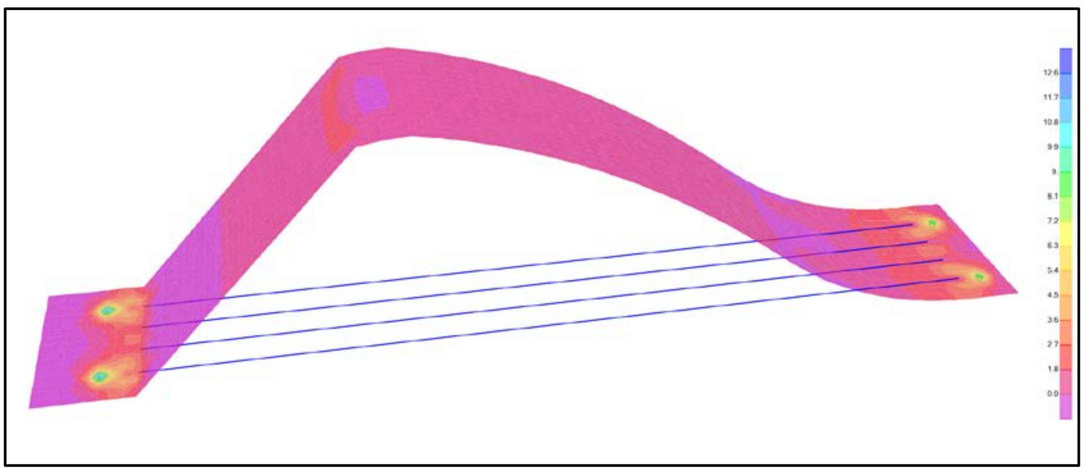


Figure 28 – Showing Vmax, out-of-plane shear (kip).

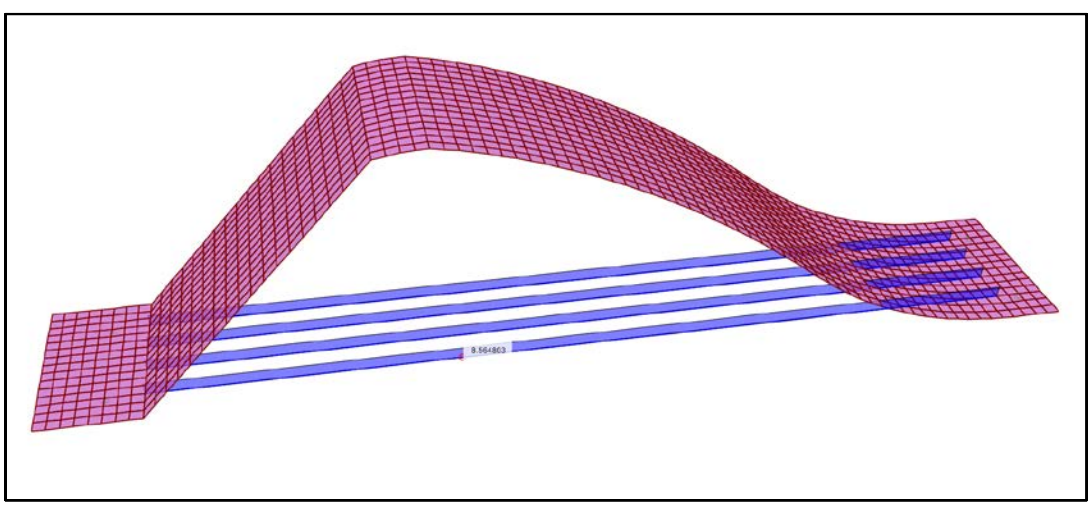


Figure 29 – Showing the axial tension / compression on the No. 11 tension tie bars (kip).

6-Inch Thick Ogee Crest (2-Supports)

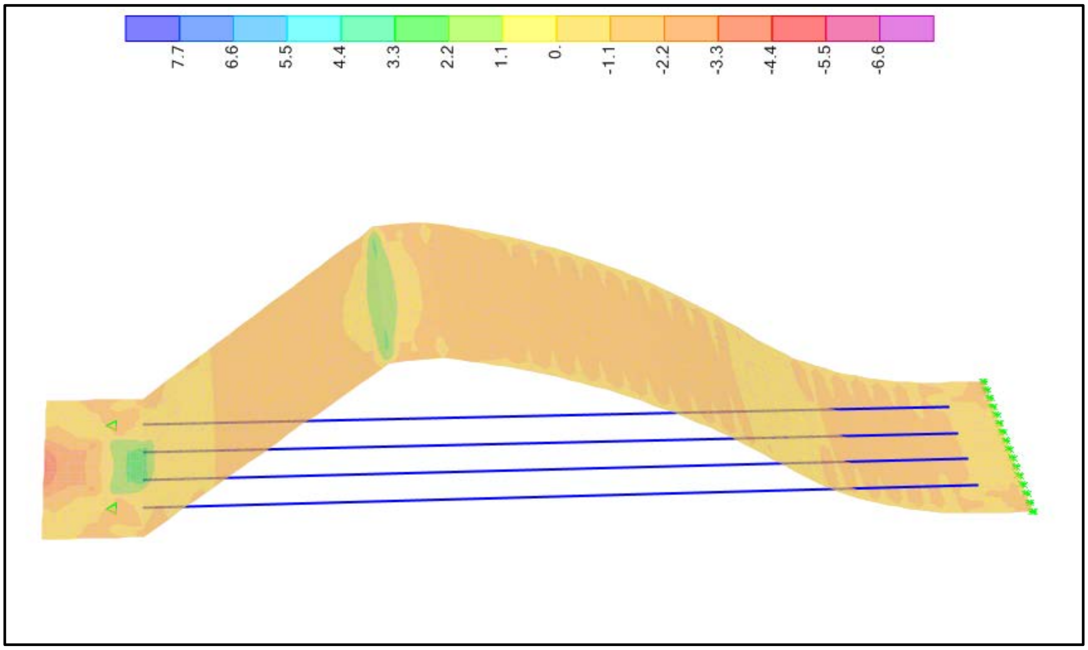


Figure 30 – Showing F11, horizontal axial tension / compression (kip).

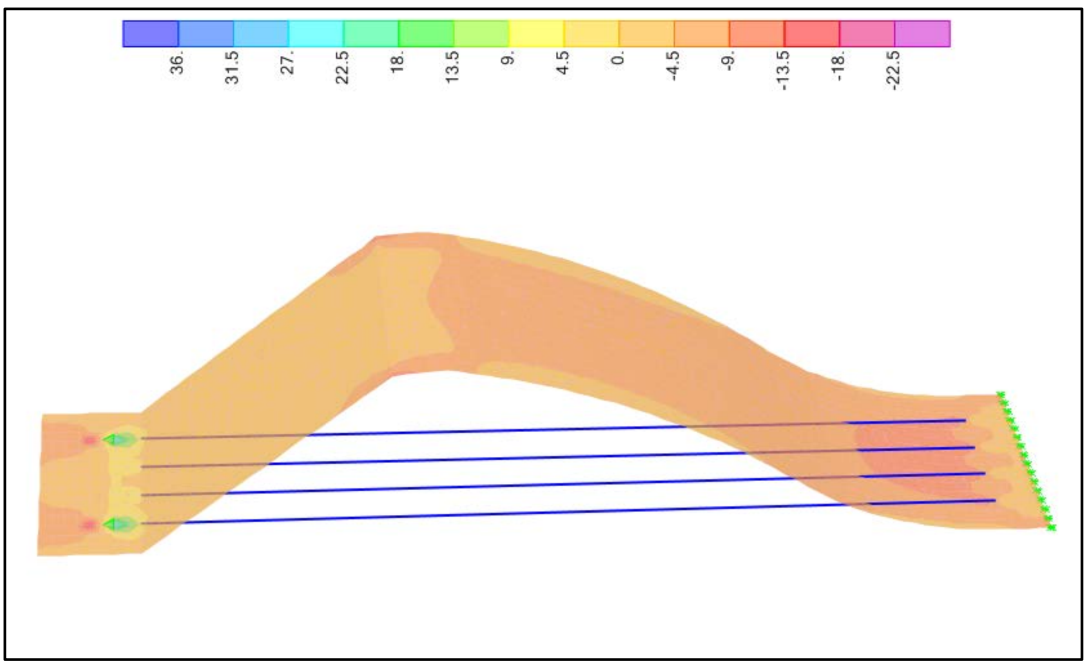


Figure 31 – Showing F22, vertical axial tension / compression (kip).

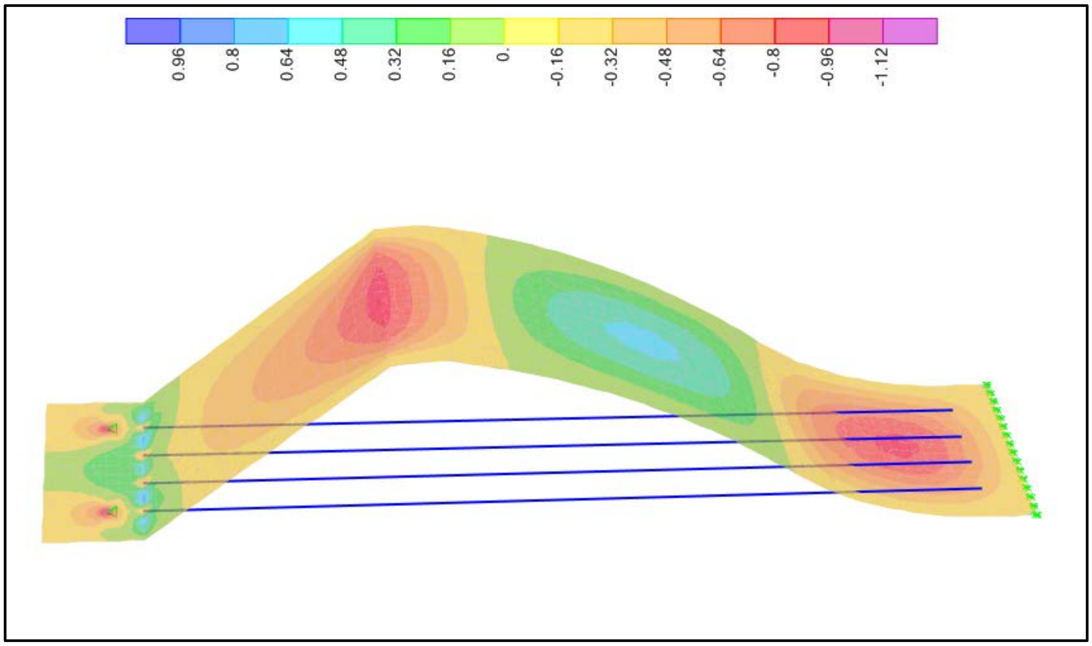


Figure 32 – Showing M11, horizontal bending moment (kip-ft).

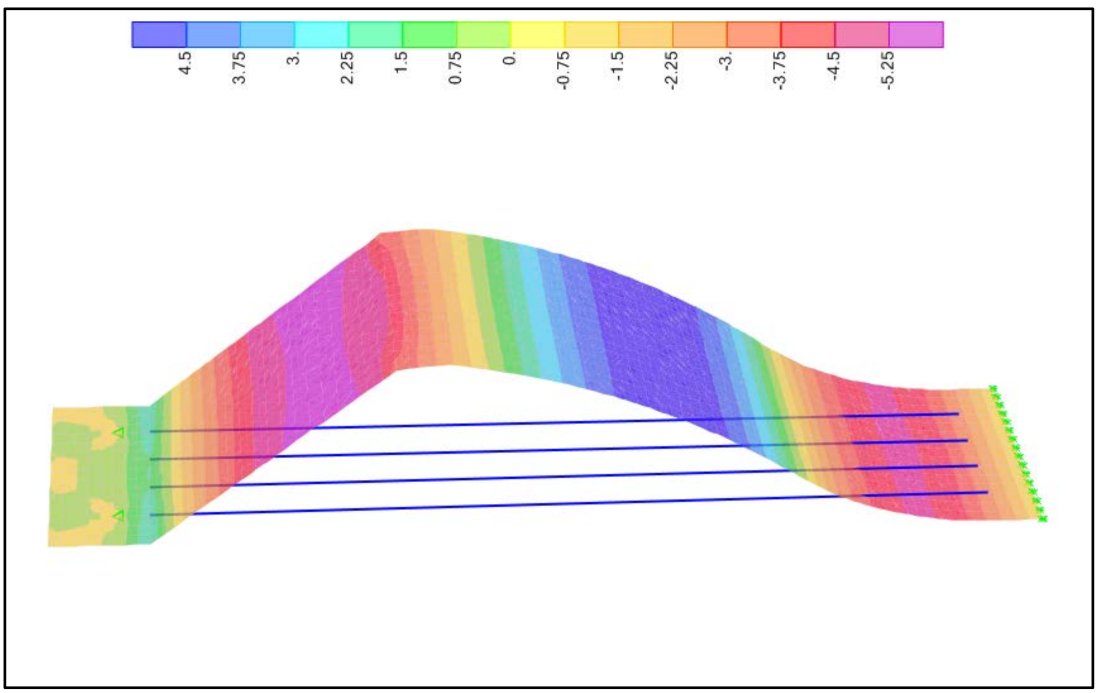


Figure 33 – Showing M22, vertical bending moment (kip-ft).

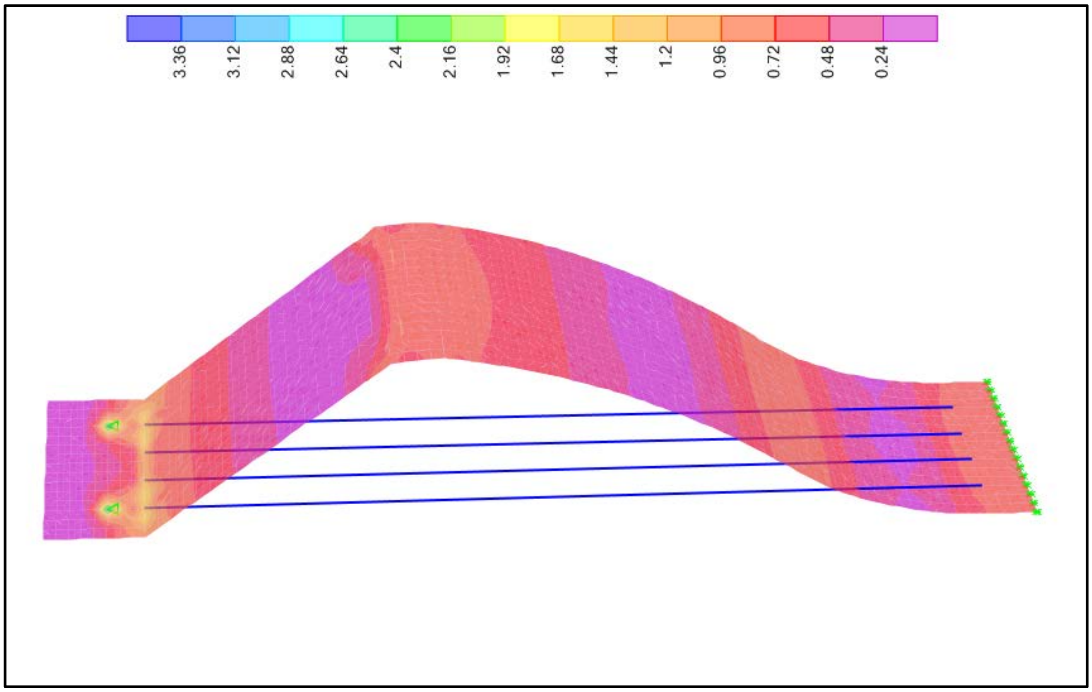


Figure 34 – Showing Vmax, out-of-plane shear (kip).

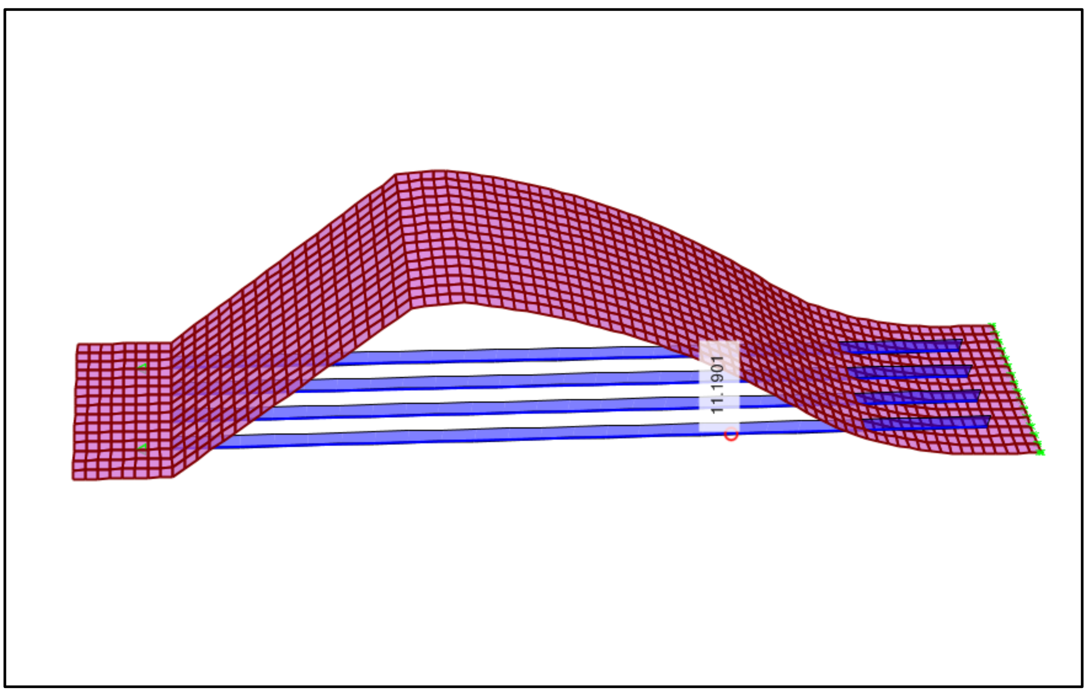


Figure 35 – Showing the axial tension / compression on the No. 11 tension tie bars (kip).

Appendix C

P-M Diagrams

12-Inch Thick Precast Ogee Crest (4-supports)

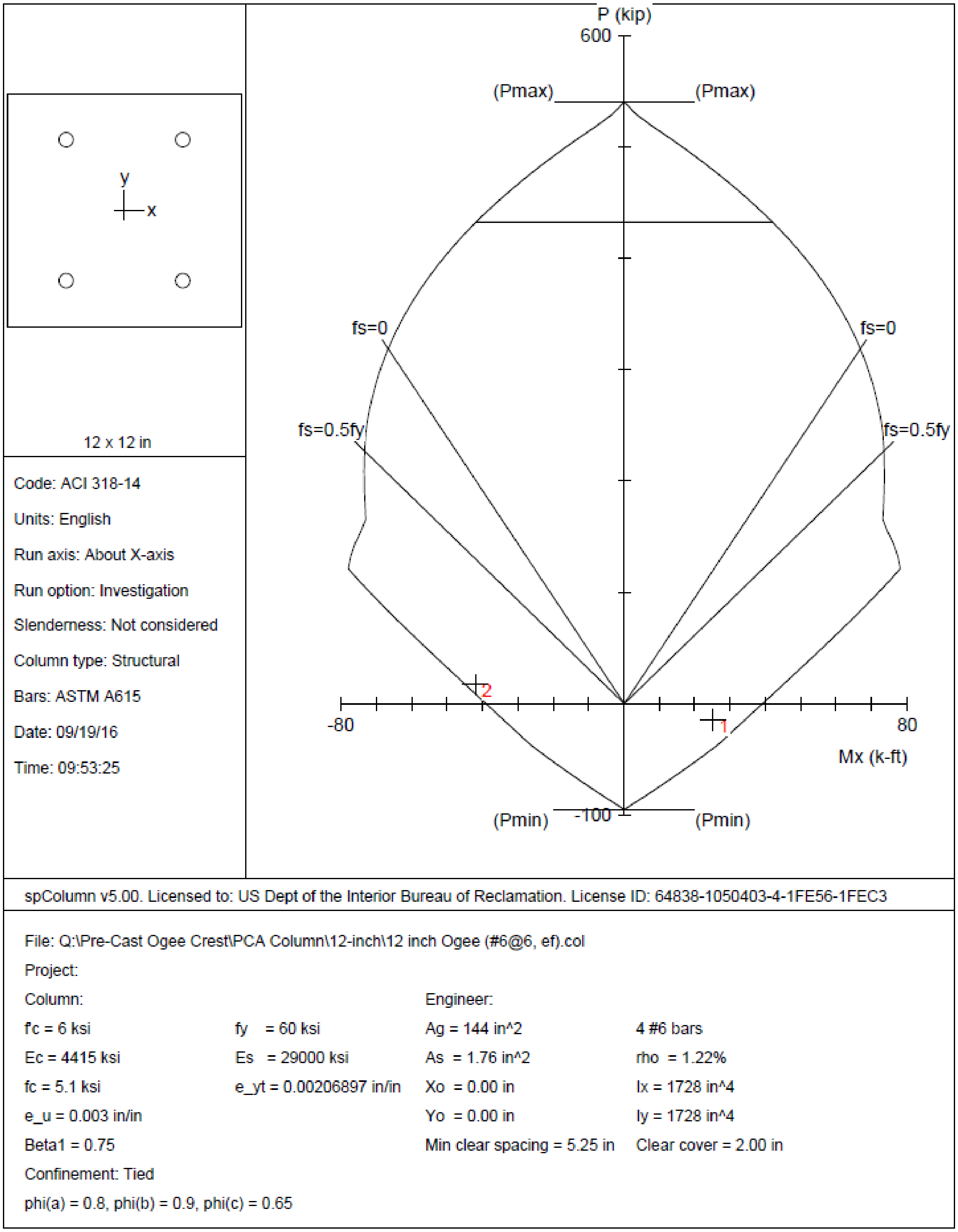
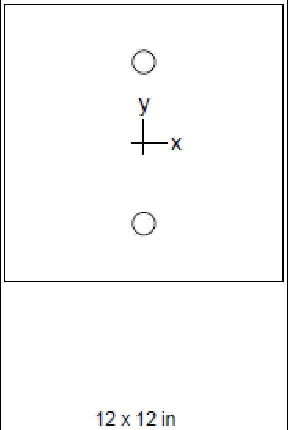


Figure 1 – Showing P-M Diagram for No. 6 bars spaced at 6-inch, each face.



Code: ACI 318-14

Units: English

Run axis: About X-axis

Run option: Investigation

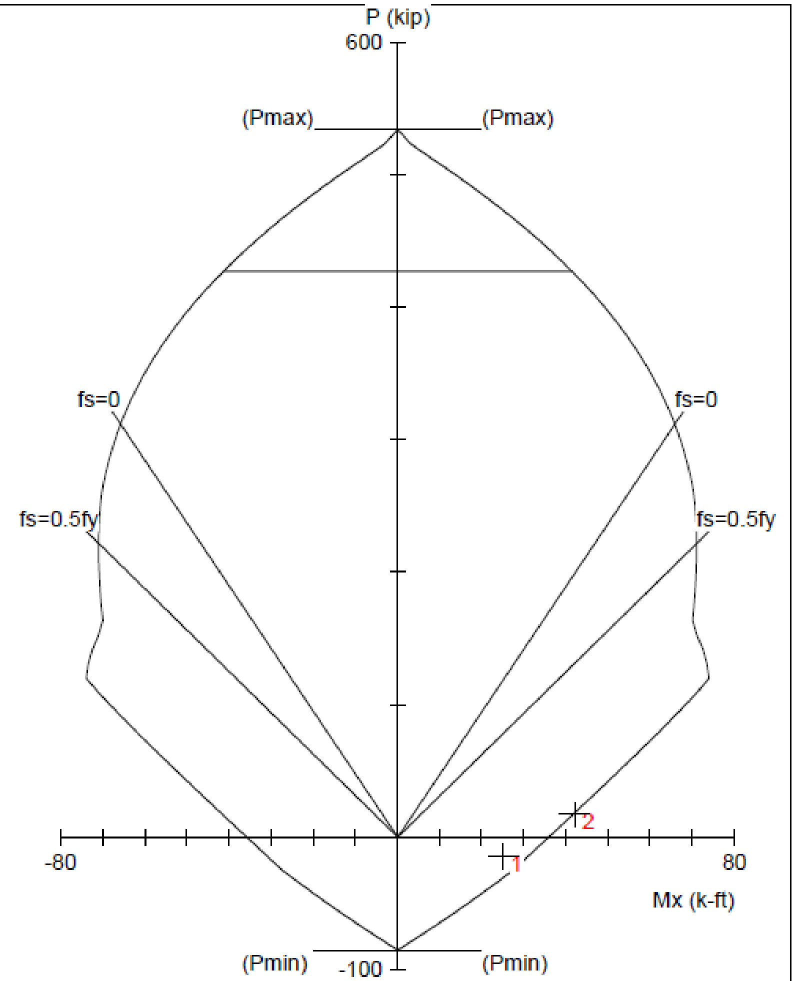
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 09/08/16

Time: 15:54:52



spColumn v5.00. Licensed to: US Dept of the Interior Bureau of Reclamation. License ID: 64838-1050403-4-1FE56-1FEC3

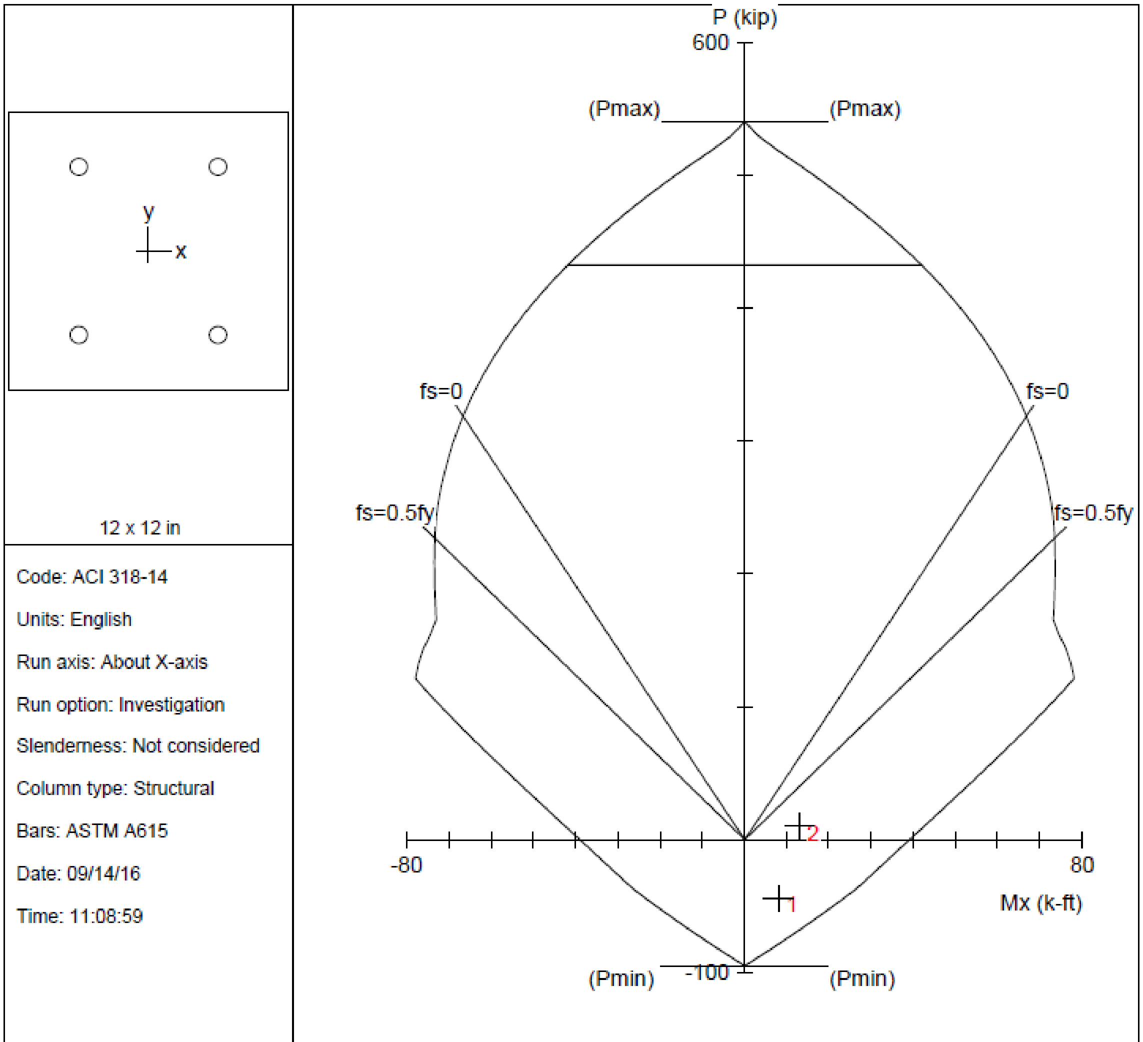
File: Q:\Pre-Cast Ogee Crest\PCA Column\12-inch\12 inch Ogee (#8@1-0, ef).col

Project:

Column:		Engineer:	
f'c = 6 ksi	fy = 60 ksi	Ag = 144 in^2	2 #8 bars
Ec = 4415 ksi	Es = 29000 ksi	As = 1.58 in^2	rho = 1.10%
fc = 5.1 ksi	e_yt = 0.00206897 in/in	Xo = 0.00 in	Ix = 1728 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 1728 in^4
Beta1 = 0.75		Min clear spacing = 6.00 in	Clear cover = 2.00 in
Confinement: Tied			
phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65			

Figure 2 – Showing P-M Diagram for No. 8 bars spaced at 1-foot, each face.

12-Inch Thick Precast Ogee Crest (2-Supports)



spColumn v5.00. Licensed to: US Dept of the Interior Bureau of Reclamation. License ID: 64838-1050403-4-1FE56-1FEC3

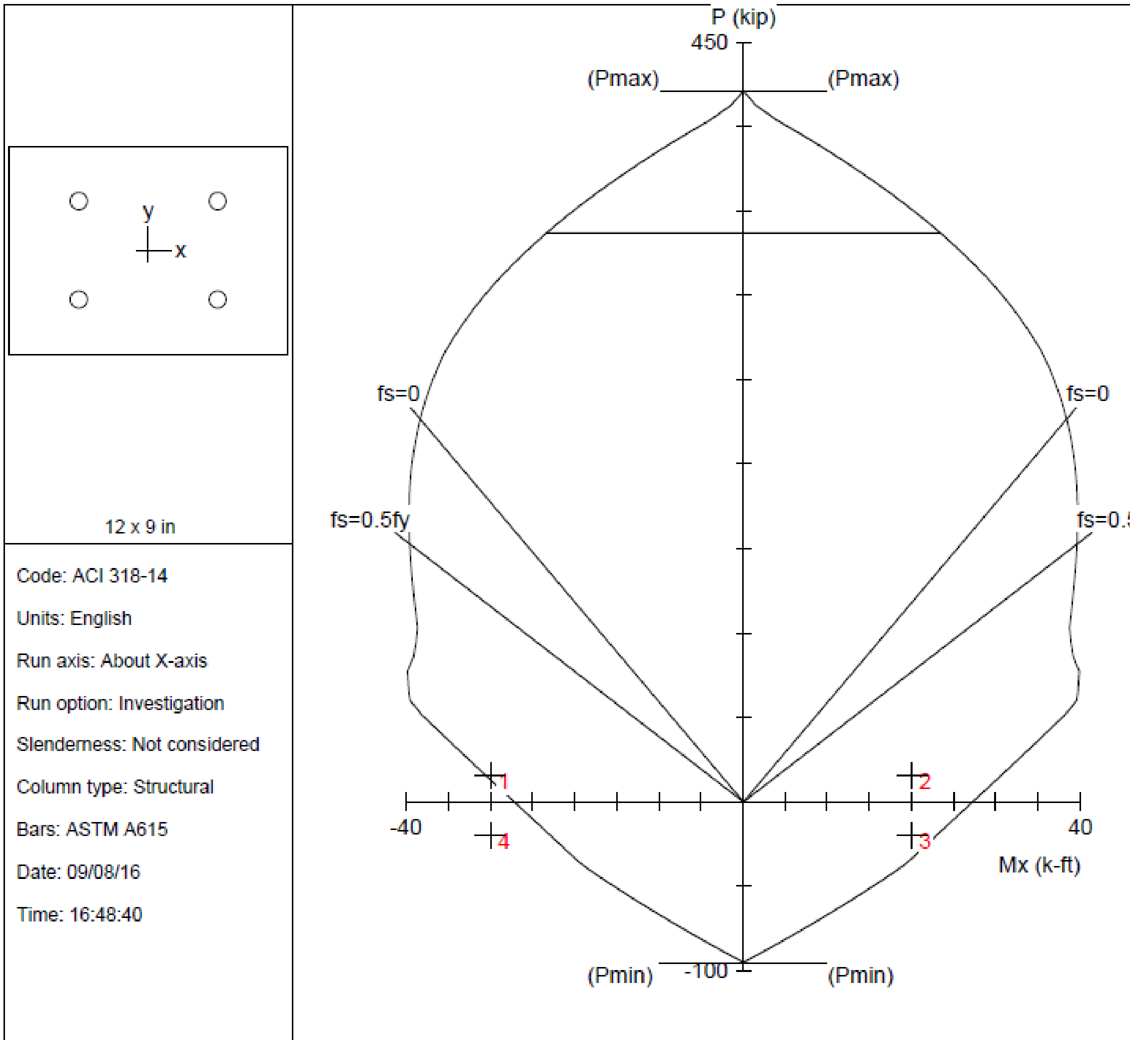
File: Q:\Pre-Cast Ogee Crest\PCA Column\12-inch\12 inch Ogee (#6@6, ef) (2-supports).col

Project:

Column:		Engineer:	
f'c = 6 ksi	fy = 60 ksi	Ag = 144 in^2	4 #6 bars
Ec = 4415 ksi	Es = 29000 ksi	As = 1.76 in^2	rho = 1.22%
fc = 5.1 ksi	e_yt = 0.00206897 in/in	Xo = 0.00 in	Ix = 1728 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 1728 in^4
Beta1 = 0.75		Min clear spacing = 5.25 in	Clear cover = 2.00 in
Confinement: Tied			
phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65			

Figure 3 – Showing a P-M Diagram for No. 6 bars spaced at 6-inch, each face.

9-Inch Thick Precast Ogee Crest (4-Supports)



spColumn v5.00. Licensed to: US Dept of the Interior Bureau of Reclamation. License ID: 64838-1050403-4-1FE56-1FEC3

File: q:\pre-cast ogee crest\pca column\9-inch\9 inch ogee (#6@6, ef).col

Project:

Column:

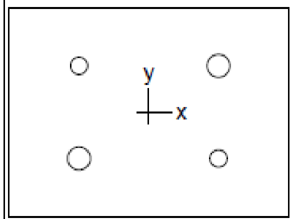
Engineer:

f'c = 6 ksi	fy = 60 ksi	Ag = 108 in^2	4 #6 bars
Ec = 4415 ksi	Es = 29000 ksi	As = 1.76 in^2	rho = 1.63%
fc = 5.1 ksi	e_yt = 0.00206897 in/in	Xo = 0.00 in	Ix = 729 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 1296 in^4
Beta1 = 0.75		Min clear spacing = 3.50 in	Clear cover = 2.00 in

Confinement: Tied

phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65

Figure 4 – Showing P-M Diagram for No. 6 bars spaced at 6-inch, each face.



12 x 9 in

Code: ACI 318-14

Units: English

Run axis: About X-axis

Run option: Investigation

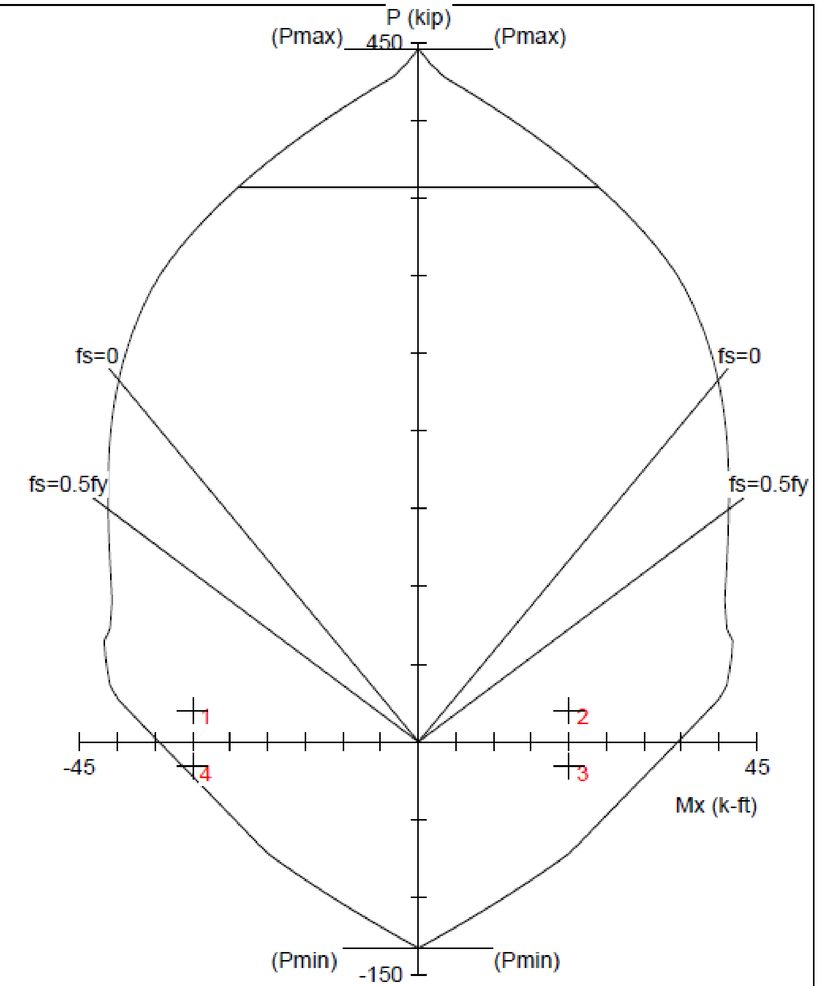
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 09/16/16

Time: 13:13:34



spColumn v5.00. Licensed to: US Dept of the Interior Bureau of Reclamation. License ID: 64838-1050403-4-1FE56-1FEC3

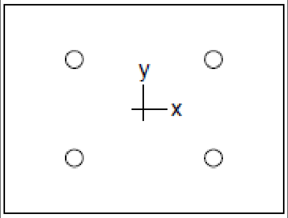
File: Q:\Pre-Cast Ogee Crest\PCA Column\9-inch\9 inch Ogee (#8@1-0 and #6@1-0, ef).col

Project:

Column:		Engineer:	
f'c = 6 ksi	fy = 60 ksi	Ag = 108 in^2	4 bars
Ec = 4415 ksi	Es = 29000 ksi	As = 2.46 in^2	rho = 2.28%
fc = 5.1 ksi	e_yt = 0.00206897 in/in	Xo = 0.00 in	Ix = 729 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 1296 in^4
Beta1 = 0.75		Min clear spacing = 3.12 in	Clear cover = 2.00 in
Confinement: Tied			
phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65			

Figure 5 – Showing P-M Diagram for No. 8 bars and No. 6 bars alternating, spaced at 1-foot, each face.

9-Inch Thick Precast Ogee Crest (2-Supports)



12 x 9 in

Code: ACI 318-14

Units: English

Run axis: About X-axis

Run option: Investigation

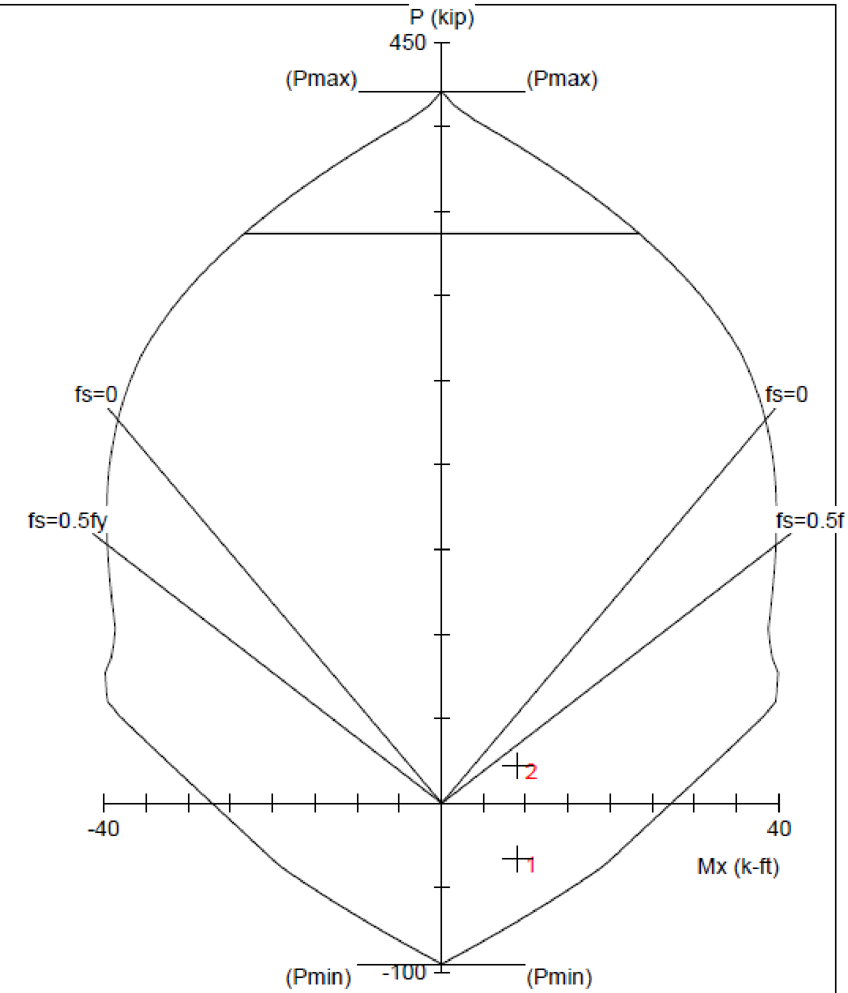
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 09/14/16

Time: 13:38:41



spColumn v5.00. Licensed to: US Dept of the Interior Bureau of Reclamation. License ID: 64838-1050403-4-1FE56-1FEC3

File: Q:\Pre-Cast Ogee Crest\PCA Column\9-inch\9 inch Ogee (#6@6, ef) (2-Supports).col

Project:

Column:

Engineer:

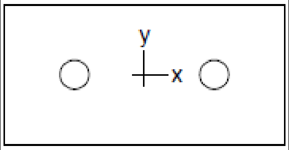
f'c = 6 ksi	fy = 60 ksi	Ag = 108 in^2	4 #6 bars
Ec = 4415 ksi	Es = 29000 ksi	As = 1.76 in^2	rho = 1.63%
fc = 5.1 ksi	e_yt = 0.00206897 in/in	Xo = 0.00 in	Ix = 729 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 1296 in^4
Beta1 = 0.75		Min clear spacing = 3.50 in	Clear cover = 2.00 in

Confinement: Tied

phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65

Figure 6 – Showing P-M Diagram for No. 6 bars spaced at 6-inch, each face.

6-Inch Precast Ogee Crest (4-Supports)



12 x 6 in

Code: ACI 318-14

Units: English

Run axis: About X-axis

Run option: Investigation

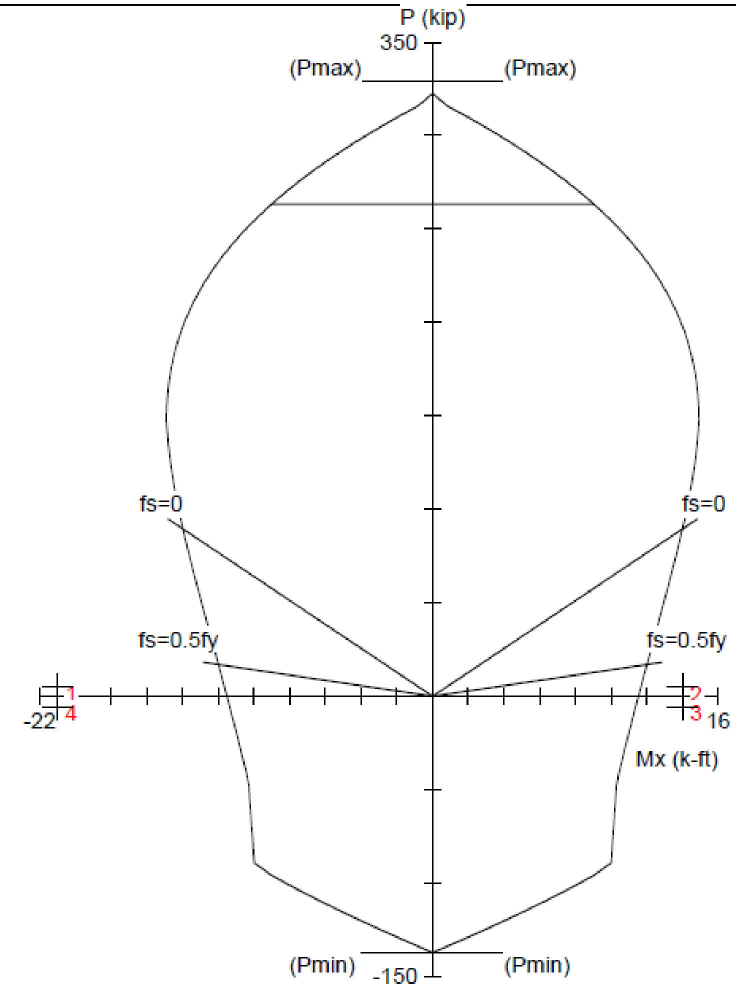
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 09/16/16

Time: 13:51:16



spColumn v5.00. Licensed to: US Dept of the Interior Bureau of Reclamation. License ID: 64838-1050403-4-1FE56-1FEC3

File: Q:\Pre-Cast Ogee Crest\PCA Column\6-inch\6 inch Ogee (#10@6).col

Project:

Column: Engineer:

f'c = 6 ksi	fy = 60 ksi	Ag = 72 in^2	2 #10 bars
Ec = 4415 ksi	Es = 29000 ksi	As = 2.54 in^2	rho = 3.53%
fc = 5.1 ksi	e_yt = 0.00206897 in/in	Xo = 0.00 in	Ix = 216 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 864 in^4
Beta1 = 0.75		Min clear spacing = 4.73 in	Clear cover = 2.36 in

Confinement: Tied

phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65

Figure 7 – Showing P-M Diagram for No. 10 bars spaced at 6-inch.