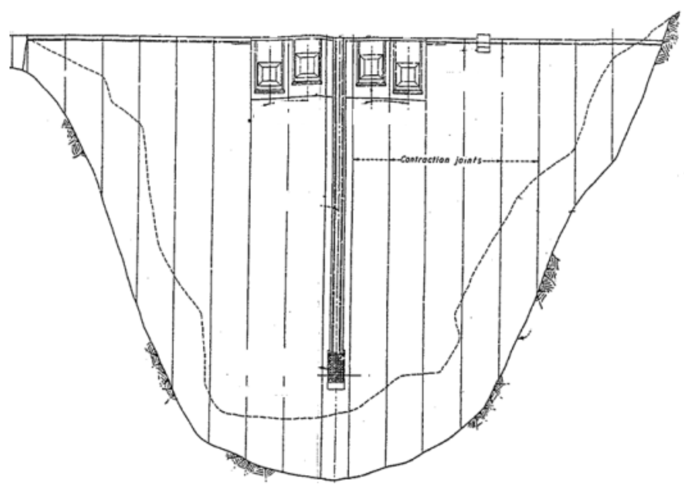
RECLAMATION
Managing Water in the West

Technical Memorandum No. EM36-86-68110 (IN PROGRESS)

IN PROGRESS
Design of Double-Curvature Arch Dams
Planning, Appraisal, Feasibility Level
(Final Report scheduled for FY 2013)



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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.

Technical Memorandum No. EM36-86-68110-2012-01

DRAFT
Double Curvature Arch Dams – Planning, Appraisal, and Feasibility Level
(Final Report Scheduled for FY 2013)

Technical Service Center

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Peer Review

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REVISIONS					
Date	Description	Prepared	Checked	Technical Approval	Peer Review

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Symbols

H	- Structural height [ft].
T_C	- Dam thickness at crest [ft].
T_B	- Dam thickness at base [ft].
$T_{0.45H}$	- Dam thickness of crown cantilever at 0.45H above base [ft]
USP	- Upstream projection is a distance measured from the axis of the dam [ft]
DSP	- Downstream projection measured from the axis [ft]
USP_C	- USP at the crest
USP_B	- USP at the base
DSP_C	- DSP at the crest
DSP_B	- DSP at the base
L_1	- Straight line distance at crest elevation between abutments excavated to sound rock [ft].
L_2	- Straight line distance at 0.15H above base between abutments excavated to sound rock [ft].
V	- Estimated volume of dam concrete [cu yd].
R_{axis}	- Horizontal distance at the crest from the axis to the line of centers.
R_{3C}	- Same as R_{axis} except measured to the outer line of centers.

1 General

1.1 Objectives and Scope

The objective of this Memorandum funded under the Manual and Standard Development Program is to propose revisions to Engineering Monograph No. 36, Guide for Preliminary Design of Arch Dams, based on the most recent technical developments related to layouts of arch dams. The Monograph No. 36 was first published by the Bureau of Reclamation (Reclamation) in 1966 and reprinted in 1975 and 1977. No revisions have been made to the Monograph since its first publication.

The Technical Monograph No. 36 has been widely used through Reclamation and by the industry. The original Monograph contains valuable information useful in the preliminary design of arch dams. In the original Engineering Monograph No. 36, a procedure to simplify a very complex process of laying out a double curvature arch dam was developed. The goal was to make it easy for field engineers to estimate the cost of an arch dam during the planning process.

Special thanks are given to Howard Boggs (retired structural engineer from Reclamation and the author of EM No.36) who inspired the work presented in this report.

1.2 Summary of FY2012 and FY2011 Phases

The summary of accomplishments in FY2012 is as follows:

- *Added a database of world-wide roller-compacted concrete double-curvature arch dams (Appendix C).*
- *Expanded the Excel spreadsheet that determines basic geometrical relation in the arch dam layout to include plots and computations for the crown cantilever, line-of-centers, plan view of the arches, and profile view of the dam looking upstream developed along the axis of the dam (Appendix E).*
- *Worked with Mr. Howard Boggs to capture the thought process used to adjust the arch dam layout using program ADSAS to minimize tensions in the dam and optimize the dam geometry. Howard Boggs is the foremost authority on the design of arch dams and his help and knowledge will greatly add to the usefulness of this document.*
- *Wrote a Visual Basic program in an Excel spreadsheet, ADSASREAD, to extract useful data from the voluminous ADSAS output for easy reference and plotting of the results (Appendix G).*
- *Developed a Visual Basic program in program SURFER 11 to read the data from ADSASREAD and create plots of stress, eccentricity, moment, and thrust values, contours, and vectors (Appendix H)*
- *Included guidelines to compute the internal temperatures of an arch dam (Appendix I).*

- *Developed layouts and designs of single-centered uniform-thickness doubly-curved thin-arch dam for a wide U shaped canyon (Morrow Point Dam) showing the progression from layout through design (Appendix J1).*
- *Developed layouts and designs of single-centered uniform-thickness doubly-curved arch dam for a very-wide V shaped canyon (Upper San Joaquin Dam) showing the progression from layout through design (Appendix J2).*
- *Developed layouts and designs of single-centered uniform-thickness doubly-curved arch dam for a medium-wide V shaped canyon (Upper San Joaquin Dam with thrust blocks) showing the progression from layout through design (Appendix J3).*

The summary of the FY2011 phase is as follows:

- *Definition of arch dam types and historical developments of double-curvature arch dams (Section 2).*
- *An appraisal level procedure for initial layout of arch dams (Section 4).*
- *Comparison between EM No.36 formulas and the data from a double-curvature arch dam database (Section 5).*
- *Collection of references related to the layout of arch dams (References).*
- *Glossary of terms related to arch dams (Glossary).*
- *Database of double-curvature arch dams, including both Reclamation and non-Reclamation dams. (Appendix C).*
- *Excel spreadsheets developed to determine basic geometrical relation in the arch dam layout (Appendix A).*
- *Definition of the scope for the future research (Section 1.3).*

1.3 Scope for the future phase

The following steps are planned for future research for this project:

- *Develop further the procedure for the layout of arch dams for Feasibility and Final Design levels to include more canyon shapes and 3-centered layouts. This will be useful in the layout of Reclamation's proposed 650-foot-high Upper San Joaquin.*
- *Expand the database of existing double-curvature arch dams and roller compacted concrete arch dams.*
- *Based on the database information, if necessary, adjust the formulas for crown cantilever from Engineering Monograph No. 36.*
- *Finalize the pre-processor program TRUEGRIDARCH to create an input file, based on ADSAS layout input, for program TRUEGRID to create a finite element model in LS-DYNA for static and seismic structural analysis of a dam.*

2 Arch Dams - General

Reclamation has made significant engineering contributions to the advancement and evolution of arch dam analysis, design, and construction since the formation of Reclamation in 1902. There are several documents published by the Reclamation that are extensively used by the industry in layout and design of the arch dams. The most significant publications include:

- Guide for Preliminary Design of Arch Dams, EM No. 36, Third Ed. 1977
- Design Manual for Concrete Arch Dams, 1977.

There are about 30 arch dams in Reclamation's inventory (Table C-2) including five double curvature arch dams (Table 1).

Table 1 – Double-curvature arch dams designed by Reclamation

Project name	Year build	Location	Design Engineer	Inventory
East Canyon Dam	1966	Utah	Howard Boggs	Reclamation
Swift Dam	1967	Montana	Howard Boggs	PacifiCorp
Morrow Point Dam	1968	Colorado	Howard Boggs	Reclamation
Wild Horse Dam	1969	Nevada	Howard Boggs	BIA
Mountain Park Dam	1975	Oklahoma		Reclamation
Crystal Dam	1976	Colorado	Darian Ingram	Reclamation
Nambe Falls Dam	1976	New Mexico	Howard Boggs	Reclamation

The first double-curvature arch dam constructed by the Reclamation was East Canyon Dam in 1966 and the largest is Morrow Point Dam with its structural height of 465 feet. Morrow Point Dam was designed before East Canyon Dam, but East Canyon Dam was constructed before Morrow Point Dam.

2.1 General Concept of Arch Dams

Arch dams are intended to carry static and dynamic loads into the abutments and foundation as efficiently and effectively as possible. To efficiently carry the loads, arch dams are shaped as thin as possible to optimize the strength of the concrete. Arch dams with high static stressesthat exceed the criteria should be reshaped to redistribute the loads to arch and cantilever members that are understressed. Arch dams with low static stresses may not be utilizing the full potential and strength of the concrete and in essence, wasting concrete. To effectively carry the loads, arch dams are shaped to carry the loads in a relatively smooth and uniform manner i.e. the upstream and downstream arch faces are smooth circles, cantilevers are smooth upstream and downstream lines without reentrant corners, and the keyway profile is smooth, also without reentrant corners. Thus, the loads are efficiently transferred through the arch dam into the foundation. There is no reinforcement in an arch dam, so tensile stresses are to be minimized by shaping to reduce the potential for cracking in the concrete.

The shape of arch dams has changed at Reclamation over the years (Figure D-1). Crown cantilevers have evolved from shapes that look more like thin gravity dams with straight segments for the upstream and downstream faces to curved upstream and downstream faces in an effort to minimize cantilever tensile stresses. The horizontal arch shapes have evolved also. Some of the early arch dams used vertical lines of centers with constant radii from abutment to abutment and the same radius centers for the upstream and downstream faces producing uniform thickness arches. Fillets were used along the abutments to spread out the load and reduce the bearing stresses into the rock. The lines of centers changed: 1) from a vertical line to sloping lines producing variable radius centers that varied the amount of curvature by elevation, 2) to separate lines for the extrados and intrados that also vary the thickness of the arches at the abutments. Reclamation has typically used circular arcs to define the arches of the dam. Other countries have also used ellipses, hyperbolic parabolas, logarithmic spirals, and catenary curves.

2.1.1 Single-Curvature or Double-Curvature Arch Dam

The shape of the crown cantilever defines whether an arch dam is a single-curvature or double-curvature arch dam.

A single curvature arch dam has curvature in arches, but not in the crown cantilever. Warm Springs Dam is an example of a single curvature arch dam (see Figure 1 showing L-O-C for Warm Springs Dam). The crown cantilever does not have any curvature, being composed of a vertical upstream face and 2 line segments for the downstream face. The only curvature the dam has is in the arches.

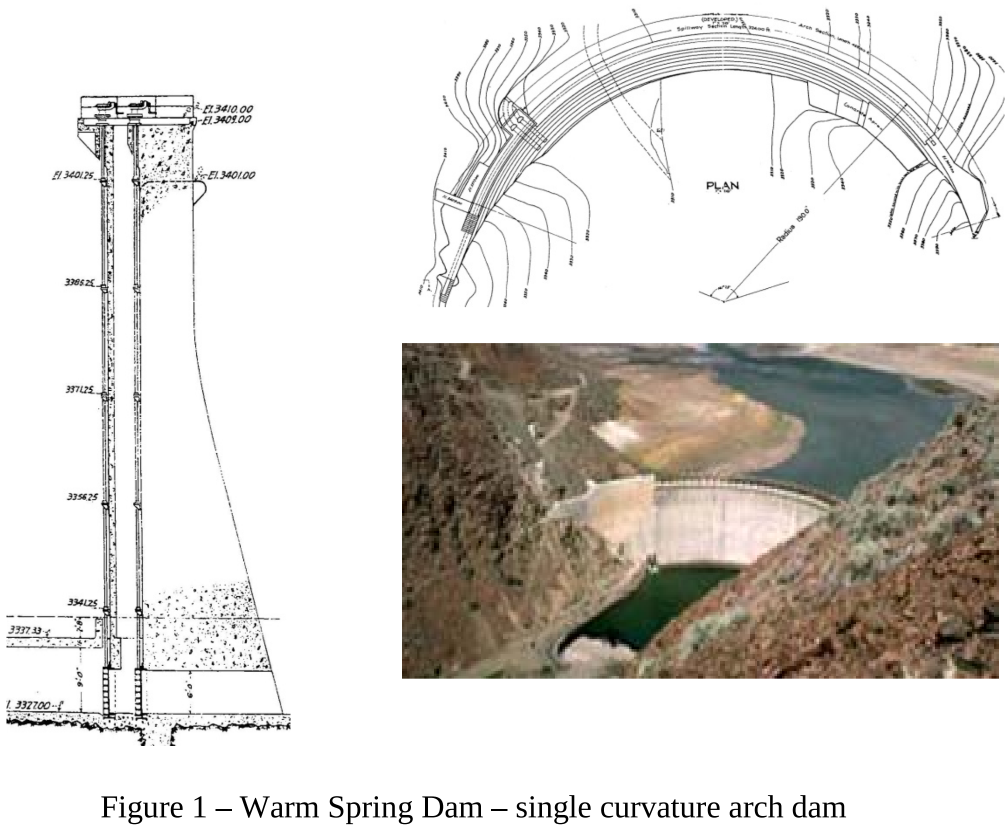

Figure 1 – Warm Spring Dam – single curvature arch dam

A double curvature arch dam has curvature in the arches and in the crown cantilever. Morrow Point Dam is an example of a double curvature arch dam (see

Figure 2 showing L-O-C for Morrow Point). The upstream and downstream faces of the crown cantilever are defined with a series of circular arcs. The upstream face typically undercuts the middle of the dam minimizing cantilever tensions at the heel of the dam. The downstream face typically overhangs the middle of the dam minimizing cantilever tensions near the top of the dam on the downstream face.

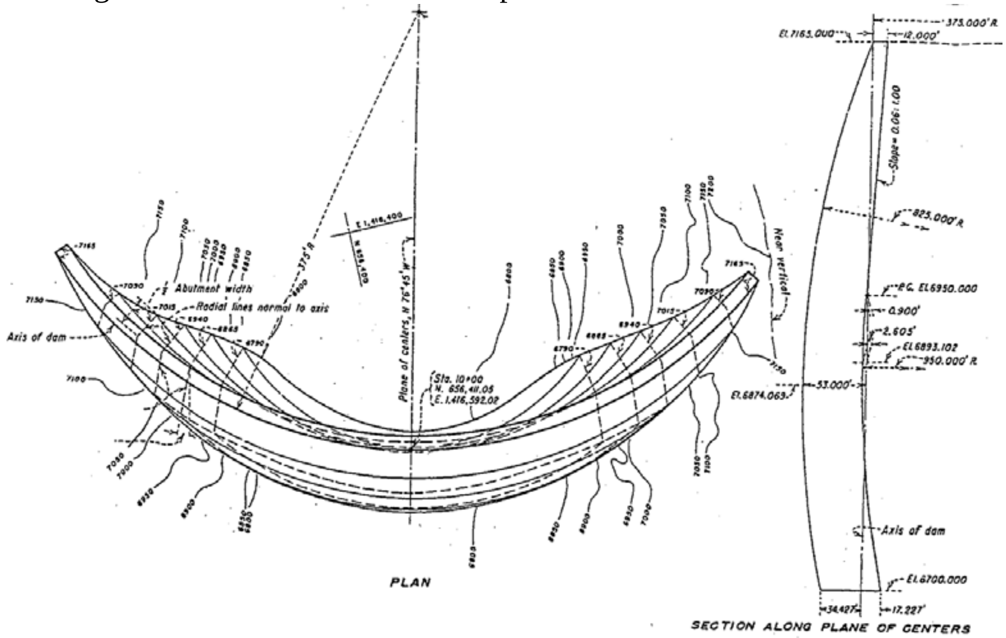

Figure 2 – Morrow Point Dam – double-curvature arch dam

2.1.2 Dam Thickness

Arch and gravity dams vary in thickness from the crest to the base. Over the years, arch dams have been called thin arch dams, medium-thick arch dams, and thick arch dams. This determination is based on the ratio of base width of the dam to the structural height of the dam as shown in the following table. Table 2 groups the inventory of Reclamation dams by their base to height ratio. An arch dam relies on arching action for support. Sometimes a gravity dam is curved in plan view, but this does not make it an arch dam because the dam does not need arching action for stability. The appropriate designation for this type of dam is a curved gravity dam signifying it is stable by gravity action.

Table 2 – Type of dams base on Reclamation inventory (Table C-3).

Type of Dam	Base to Height Ratio
Thin arch	< 0.2
Medium-thick arch	0.2 to 0.4
Thick arch	0.4 to 0.65
Curved gravity	> 0.65

2.1.3 Lines of Centers

The lines of centers define the horizontal shape of the arches in an arch dam. The shape of the arches starts at the crown cantilever and curves horizontally downstream toward the abutments. The line of centers create the geometry of the circular arcs at each elevation of the dam for the upstream and downstream faces by defining the center point of a circle and the radius of the circle. Depending on the shape and number of lines of centers, the arches can be 1) uniform thickness from abutment to abutment, 2) variable thickness from abutment to abutment, 3) different on the left side of the dam compared to the right side of the dam, or 4) different in the center of the dam compared to the outer part of the dam.

2.1.3.1 Single-, Two-, or Three- Centered Arch Dams

The number of lines-of-centers determines whether the arches are the same on the left and right side of the dam, are different on the left and right sides of the dam, or different on the inner and outer parts of the dam.

A single centered arch dam has a single line-of-centers that results in the same circular arcs from the left to the right abutment.

A 2-centered arch dam has two lines-of-centers that result in different circular arcs for the left side and right sides of the dam.

A 3-centered arch dam has two lines-of-centers that result in different circular arcs near the crown cantilever (inner) and near the abutments (outer). The radii for the inner arcs are shorter than the outer arcs.

2.1.3.2 Uniform- or Variable Thickness Arch Dams

The number of lines that define the line-of-centers determines whether the arches are uniform thickness or variable thickness arches.

The arches have uniform thickness if there is one line defining the extrados and intrados line-of-centers. This means that the radius center for the upstream and downstream faces is the same. The radii lengths are different at each elevation, but since the radius center is the same, the thickness of the arch is uniform.

The arches vary in thickness if there are two lines defining the extrados and intrados line-of-centers. This means that the radius centers for the upstream and downstream faces are in different positions in space forcing the circular arcs of the arches to diverge.

2.2 Historical Developments

The Ithaca Dam, build in 1903 in New York State, appears to be the first double-curvature shape arch dam (Figure 3). The 90-ft high dam was built in a narrow rock gorge by Professor G.S. Williams [Trans. Am. Soc. C.E., Vol. 53, p 183].

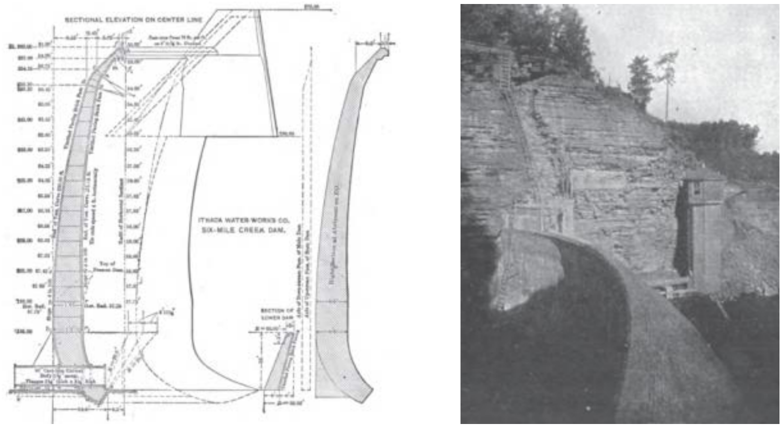

Figure 3 – Ithaca Dam, New York State, USA [Wegmann 1918]

Fabio Niccolai constructed Osiglietta Dam 1939 as a double-curved dome-structure similar to the one Williams had designed for Ithaca Dam. At that time the new concept of double-curvature dams became popular in Italy and other European countries.

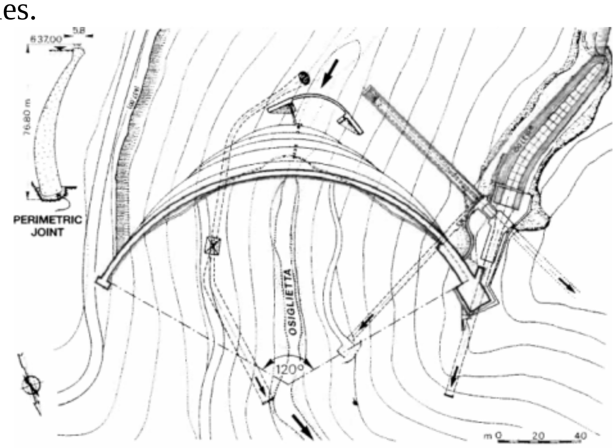

Figure 4 – Osiglietta Dam, Italy [Schitter 1994]

Subsequent to Mr. Oscar Rice, Chief, Dams Branch, visit to Europe about 1960, Merlin Copen and George Rouse of the Dams Branch and George Wallace of the Concrete Laboratory toured Portugal, France and Italy dams, especially concrete dams for the purpose of updating Reclamation designs. From their observations, the first double curvature dam, Morrow Point, became a reality.

3 Arch Dam Layout EM No.36

3.1 Introduction

In 1966, Engineering Monograph (EM) No. 36 was written explaining the initial steps to laying out a double-curvature arch dam. The monograph presents formulas and charts to rapidly determine the initial dimensions and concrete volume for a double curvature arch dam. The volume estimates are based on statistical data of geometrical properties of twelve arch dam layouts as requested by the District Offices. The monograph was primarily intended as an aid for planners in the field to estimate the volume of concrete and subsequently to estimate appraisal level costs for an arch dam.

The primary data used in the guide to compute the concrete volume included:

- The structural height of dam (H) knowing the crest elevation and approximate base elevation of the dam, estimated below the streambed and into sound rock,
- The cross-canyon distance to the original ground surface between the abutments at the crest of the dam (L_1),
- The cross-canyon distance to the original ground surface between abutments at the lowest theoretical arch elevation at 0.15H (L_2). This is based on an elevation at which arching action starts to dominate theshearing resistance. The shape of canyon (U or V shape) was incorporated in the formulas by using this canyon width at 15 percent of the structural height above the base, canyon width, and height of the dam as input parameters.

The document was also be used as a preliminary guide for the initial layout of an arch dam given H, L1, and L2 above. The following can be determined.

- The thickness of the dam, upstream projection of the upstream face, and downstream projection of the downstream face can be determined at the crest, at 45 percent of the dam height, and at the base of the dam along the crown cantilever. Circular arcs can be computed through the 3 points along the upstream and downstream faces.
- The distance between the crest of the dam and the line-of-centers at the crest of the dam (R_{axis}) is determined based on L_1.
- Given the shape of the crown cantilever and the position of the line-of-centers, arches at various elevations can be determined.

An initial stress analysis, ignoring thermal loads, can be performed given the above geometry along with:

- the sustained modulus of elasticity of concrete and rock and,
- the reservoir elevation.

3.2 Empirical formulas for Crown Cantilever Thickness

The shape of the crown cantilever is defined by three thicknesses, upstream projections (USP) and downstream projections (DSP) at the crest, at the base, and at 0.45H elevation by the following empirical formulas:

Crest thickness $$T_c = 0.01[H + 1.2L_1]$$

$USP = 0.0$
$DSP = T_c$

Thickness at *0.45H*

$T_{0.45H} = 0.95\ T_B$

At *0.45H* projection

$max.\ USP = 0.95T_B$
$min.\ DSP = 0.0$

Base thickness

$$T_B = \sqrt[3]{0.0012 H L_1 L_2 \left(\frac{H}{400}\right)^{\left(\frac{H}{400}\right)}}$$

Base projection

$USP = 0.67T_B$
$DSP = 0.33T_B$

Crest projection

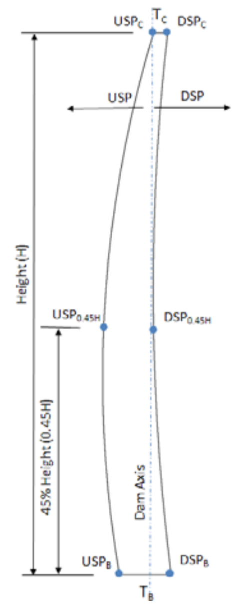

Figure 5 –Points defining the Crown Cantilever

The formulas are applicable within the limits for crest thickness T_c from 3-ft to 84-ft and base thickness T_B from 5-ft to 654-ft. Minimum thickness of 3 feet at the crest is limited by other than stress factors. (Howard questions this paragraph)

3.3 Empirical formulas for Concrete Volume estimations

The formula for computing the volume of concrete in cubic yards [cu yd] is:

$$V = 0.000002\, H^2 L_2 \left[\frac{(H + 0.8L_1)^2}{L_1 - L_2}\right] + 0.0004\, H\, L_1 [H + 1.1L_1]$$

Accuracy of the formula for volumes was estimated to be about 10 percent designed volumes for 75 percent of the investigated double curvature dams. However, the formula was adjusted to assure conservative quantities are estimated initially.

4 Procedures for Laying Out an Arch Dam

The following procedures describe the process to determine the concrete volume of an arch dam for planning purposes and the initial layout and stress analyses for an appraisal level design.

4.1 Determine a Planning Level Concrete Volume

The following are the procedures to determine the concrete volume for use in planning and conceptual level estimates for an arch dam.

1. The tools needed to determine the planning level concrete volume for an arch dam include a topography map, a pencil, a red pencil, and an engineering scale. Geometric calculations can be done with a hand calculator, AUTOCADD, MATHCAD, or a spreadsheet.

2. The layout of the dam starts with knowing the crest elevation of the dam. The crest elevation of the dam is usually determined from hydrology studies and hydraulic flood routing and spillway size studies. The crest of the dam is usually at the normal maximum reservoir water surface plus freeboard.

3. Determine the base elevation of the dam. This location is to sound rock and, if that distance is unknown, can be assumed to be about 25 feet below lowest contour in the river bed.

4. Compute the height of the dam (H), crest elevation to the estimated base.

5. Obtain a print of the topography of the proposed dam site at a scale of 1”:100’ with 5 or 10-foot contour intervals.

6. On the topography map, trace the ground contours at the crest elevation in red pencil along the left and right abutments in the desired location for the dam.

7. Determine the dimensions of the canyon. Measure the cross-canyon distance (L_1) between the right and left abutment red lines at the crest of the dam. Measure the cross-canyon distance (L_2) between the right and left abutment red lines at 0.15 H. The H, L_1, and L_2 dimensions indicate the shape of the canyon (V wide-V, U, or wide U) and are used in the previous equations.

8. Compute the initial volume of the dam.

4.2 Determine an Appraisal Level Arch Dam Layout

An appraisal level layout for the arch dam can proceed from the data computed in the previous section. In this example, the arch dam will be a dam with double curvature single-centered, uniform-thickness arches.

1. Tools needed for a layout. The tools needed for an arch dam layout include a topography map, an engineering scale, a pencil, a red pencil, a protractor, a beam compass, a straight edge, a French curve, an erasure, and graph paper. Geometric calculations can be done with a hand calculator, AUTOCADD, MATHCAD, or a spreadsheet.

2. Determine R_{axis}= 0.6 L1 and round the value of R_{axis} up to the nearest 10 to 50 feet. This is the initial layout, so no need for decimal accuracy.

3. If the topography map is of the ground surface, change the contours to represent the position of sound rock. If the depth to sound rock is not known, 25 feet beneath the ground surface can be assumed (15 feet of common excavation and 10 feet of rock excavation). Trace the contour of the top elevation for sound rock with the red pencil so it is easily identified through the tracing paper in the next step.

4. Position the dam in the canyon. Draw a circular arc with radius R_{axis} on a piece of tracing paper at the same scale as the topography map. This arc is the axis of the dam and is the upstream side of the crest. Move the axis around the propose dam location to position the top of the dam in the canyon. The angle of incidence of the axis into the left and right abutments should be approximately equal to produce a geometrically symmetric dam in the canyon.

5. Position the crown cantilever and the reference plane in the canyon. On the axis, locate a point about midway between the abutments and in the riverbed. This is the location of the crown cantilever. The radius of the axis at this point is the orientation of the reference plane and the line of centers. The reference plane is a vertical plane through the crown cantilever and generally parallel to the stream bank.

6. Determine the shape of the crown cantilever. From the equations provided, compute T_C, T_B, $T_{0.45H}$, USP_C, $USP_{0.45H}$, USP_B, DSP_C, $DSP_{0.45H}$, and DSP_B. These equations define 3 points along the upstream face and the downstream face. Round the crest thickness of the dam up to the nearest foot.

7. Determine the geometry of the upstream and downstream face along the crown cantilever. A circle can be drawn through the 3 points computed for the upstream face in Step 6. Likewise, a circle can be drawn through the 3 points computed for the downstream face. The circles can be determine graphically on the graph paper, computed on AUTOCAD, or computed using the equations in Appendix A or in the Excel spreadsheet in Appendix E. The position of the upstream and downstream circular arcs are positioned in space by the horizontal distance from the axis to the radius center (XR), the elevation of the radius center (YR), and the radius. For ease of future computations, R and YR should be rounded to the nearest whole number and XR recomputed to maintain the thickness of the crest. This will slightly change the location of the upstream and downstream face at the 0.45H and base elevations.

8. Draw the upstream and downstream face along the crown cantilever. On a sheet of 11inch by 17 inch graph paper, draw a vertical line near the left side of the paper representing the axis of the dam at the crown cantilever. Draw horizontal lines at the crest and base of the dam. Draw circular arcs for the upstream and downstream faces using the respective XR, YR, and R values just computed.

9. Select 6 to 8 arch elevations on the crown cantilever to define the 3D dam. Select the lowest arch elevation starting at about 15% H. Then between 15% H and the crest, try to select 6 to 8 arches evenly spaced vertically and rounded to nearest contour elevation. Even spacing arches permit best evaluation of the ADSAS results.

10. On the topography map, draw the upstream and downstream projections of the crown cantilever and downstream arc at the crest on the reference plane. Using the same radius center as the axis, draw the circular arc for the downstream side of the crest using the radius ($R_{axis} – T_c$). On the reference plane draw points at each arch elevation on the upstream and downstream faces.

11. Draw the upstream groin of the dam. On the topography map with a French curve, draw smooth curves on the left and right sides of the dam from the heel of the dam to the intersection of the axis at the crest and abutment. This curve will be upstream from the axis and slowly transition from the heel to merges with (tangent to) the axis at or near the crest abutments.

12. Draw the upstream and downstream curves for the 6 to 8 arches selected above from abutment to abutment for a constant thickness arch dam.

a. Draw the upstream face arch starting with the first arch below the crest. Use an initial guess for the line of centers as a 0.2:1 sloping line. Select the radius center on the line of centers at this elevation. Draw an arc from the left to right abutment using this center and a radius to the upstream face at this elevation. Take the arc to a point on the abutment that intersects the elevation contour and the French curve line.

b. Draw the downstream face arch at this same elevation. At the same radius center as the upstream face at this elevation, draw an arc from the left to right abutment with a radius to the downstream face at this elevation. Take the arch to a point on the abutment that matches the upstream angle to the abutment. The angle to the abutment will have to be increased if the downstream face does not extend to the rock contour to position the downstream face in rock and not in midair (see Figure _). The upstream face is naturally deeper into the abutment than the downstream face.

c. Repeat this procedure for the each arch elevation.

13. Draw the canyon profile. Using a sheet of graph paper, draw the profile of the shape of the canyon along the axis looking upstream using the angles just determined to the abutments for each arch elevation. Make the dam to foundation contact as smooth as possible. If necessary, adjust the angles to the abutments at the arch elevation to achieve a smooth canyon profile. Smooth profile means not only no reentrant corners, but almost flat from crest to the lowest arch with not “wiggles”. The shape below the lowest arch should approximate a parabola.

5 Comparison of EM No36 empirical formulas

The following section show the correlation between the empirical formulas used in Engineering Monograph No. 36 and existing dams from arch dams around the world.

A database of 30 existing double-curved arch dams was created as a part of this study. Table C-1 contains information for selected US and international dams from Italy, Austria, Swiss, Portugal, and Japan. Figure 6a shows the dam thickness at the crest T_c for the dams listed in Table C-1. Figure 6b shows the dam thickness at the crest derived from EM No.36 empirical formula $T_c = 0.01(H+1.2L1)$ for the height H and the width L1 of the same dams from Table C-1. Results from the database of the existing dams, shown on Figure 8a, validate the empirical formula for T_c from EM No.36 shown on Figure 8b.

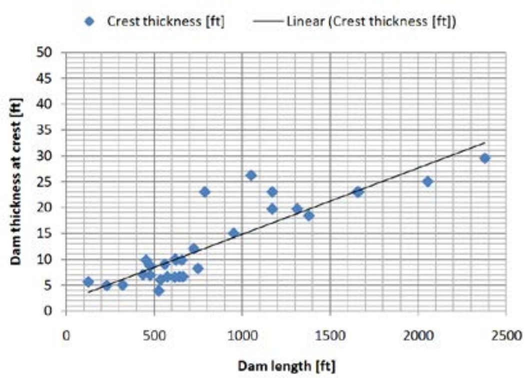

Figure 6a – Actual dam thickness at crest T_c for existing dams listed in Table C-1.

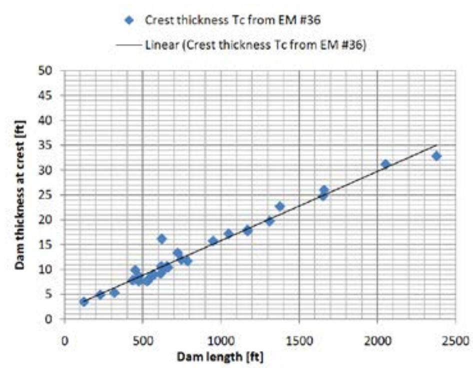

Figure 6b – Dam thickness at crest derived from EM No.36 formula $T_c = 0.01(H+1.2L1)$ for dams listed in Table C-1.

6 Criteria

Reclamation philosophy of concrete dam design is founded on rational and consistent criteria which provide for safe, economical, functional, durable, and easily maintained structures. This section explains the criteria used in the design of an arch dam. The criteria should be developed before the design process begins. It is not desirable to modify the criteria during the design process because it is too easy to relax the requirements instead of making diligent changes in the arch dam shape to meet the criteria. The following criterion is documented in Reclamation publications, Technical Records of Design and Construction, and discussions with Howard Boggs.

6.1 Factors of Safety and Risk Criteria

Reclamation's criteria are intended to produce safe, yet economical designs. Design data must be determined as accurately as possible. Data must be derived from field and laboratory tests plus measurements taken from in-service dams. Safety factors are due to uncertainty in the service loads, the variability of materials, construction practices, and correctness of analyses. Safety factors are selected based on experience and judgment.

For the dam, established factors of safety are 3.0 for usual loads, 2.01 for unusual loads, and 1.0 for extreme loads.

For the foundation, established factors of safety are 4.0 for usual loads, 2.7 for unusual loads, and 1.3 for extreme loads. Also from the Geotechnical Guidelines, _______.

Risk criteria are ___________.

6.2 Concrete and Foundation Properties

Concrete properties change with age, so specified properties need to accommodate early load and construction requirements as well as long-term serviceability requirements. Typically concrete strengths are specified at an age at 1 year.

6.2.1 Modulus of elasticity

The deformation that occurs immediately with application of load depends of the instantaneous elastic modulus and is initially assumed for designs as 5,000,000 lb/in^2.

The increase in deformation that occurs over a period of time with constant load as a result of creep is accounted for by a sustained modulus of elasticity and is initially assumed for designs as 3,000,000 lb/in^2 (60 to 70 percent of the instantaneous modulus).

The dynamic modulus of concrete should be determined from laboratory testing of cast concrete cylinders. Experience has shown that the dynamic modulus can vary from 80 percent to 120 percent of the instantaneous modulus of concrete.

6.2.2 Compressive strength

The design compressible strength of the concrete is typically assumed for designs as 4,000 lb/in^2 but can range from 3000 to 5000 lb/in^2.

The maximum allowable compressive stresses in the dam for all usual static normal operating conditions should be equal to the specified compressive strength divided by a factor of safety of 3.0, but should not exceed 1500 lb/in^2. The maximum allowable compressible stress for Morrow Point Dam was 900 lb/in^2. This comes from trying to be slightly more conservative than a factor of safety of 3 applied to a design concrete strength of 3,000 lb/in^2 at 28 days (4000 lb/in^2 at 1 year). (Howard questions this last sentence)

The maximum allowable compressive stresses in the dam for all unusual static normal operating conditions should be equal to the specified compressive strength divided by a factor of safety of 2.0, but should not exceed 2,250 lb/in^2.

6.2.3 Tensile strength

Whenever practicable, tensile stresses should be avoided by redesign of the dam; however, this is almost impossible to achieve for all loading conditions. For this reason, limited amounts of tensile stress may be permitted in localized areas for the usual load combinations.

The maximum allowable tension stresses in the dam for all static normal operating and construction conditions should be 150 lb/in^2. This comes from assuming a concrete tensile strength of 5 percent of the design compressive strength (3000 lb/in^2 x 0.05 = 150 lb/in^2). The maximum allowable tensile stress for Morrow Point Dam was 100 lb/in^2. (Howard questions this last sentence.)

The maximum allowable tensile stresses in the dam for all unusual loading conditions should be 225 lb/in^2.

6.2.4 Thermal properties of concrete

The effects of temperature changes in an arch dam are often a major part of the design considerations for an arch dam and can induce larger stresses than from the reservoir load. Thermal stresses in the dam depend on restraint, stress-free temperature (temperature of the concrete at the time of contraction joint grouting), ambient air temperatures, reservoir temperatures, solar radiation, thickness of the dam, coefficient of thermal expansion, thermal conductivity, specific heat, and mass density. The diffusivity of the concrete is a measure of how fast temperatures go in and out of the concrete mass. Typical values for the thermal properties of the concrete for preliminary designs are 0.000005 in/in/˚F for coefficient of thermal expansion and 0.045 ft^2/hour for diffusivity.

6.3 Loads

6.3.1 Gravity (Dead Load)

(To Be Added)

6.3.2 Reservoir and tailwater

Reservoir and tailwater loads applied to the dam are obtained from reservoir operation studies and tailwater curves. These studies are based on operating and hydrologic data, reservoir capacity, storage allocations, streamflow records, flood hydrographs, and planned reservoir usage. Arch dam designers need to know the maximum reservoir level, normal operating reservoir level (Top of Joint Use), minimum drawdown level, and predicted seasonal reservoir levels. The mean annual temperatures, the depth of the reservoir, and the amount of predicted releases through the outlets verses reservoir capacity will help determine the seasonal reservoir temperatures.

The minimum tailwater level associated with each reservoir level should be used.

6.3.3 Temperatures

Appendix I describes the process to compute the internal temperatures of an arch dam. For thin arch dams, ($T_B/H < 0.2$, temperatures are most likely the primary load.

6.3.4 Earthquake

(To Be Added)

6.3.5 Load Combinations

The following load combinations provide appropriate levels for design. Combinations of transitory loads, each having only a remote probability of occurring, are not considered as appropriate load combinations. The appropriate factors of safety are applied to these various load combinations. These load combinations are used to design the dam and make sure the foundation is stable.

Usual Load

1. Minimum usual concrete temperatures, most probable reservoir, and associated dead load (gravity), tailwater, ice and silt.
2. Maximum usual concrete temperatures, most probable reservoir, and associated dead load, tailwater, ice and silt.
3. Normal design reservoir and usual concrete temperatures at the time, and associated dead load, tailwater, ice and silt.

4. Minimum design reservoir and usual concrete temperatures at the time, and associated dead load, tailwater, ice and silt.

Unusual Load

1. Maximum design reservoir and mean concrete temperatures at the time, and associated dead load, tailwater, ice and silt.

Extreme

1. Arch dams should be designed for five to seven 3-component ground motions having return periods of 10,000 and 50,000 year return periods with associated normal design reservoir, mean concrete temperatures at the time, dead, tailwater, ice and silt. Resulting risk analysis based on results from the structural analysis should be one order of magnitude below Reclamation risk-based guidelines.

Other

1. Construction sequence.
2. Dead load

7 Rules of Thumb

This section provides rules of thumb developed over the years by various arch dam designers. It is only enough experience that these rules of thumb are developed. The following rules of thumb are provided:

- The geometry defining the upstream face, the downstream face, the lines of centers, the dam to foundation contact, the heel line, and the toe line should be smooth without any kinks or corners.
  - Lines transitioning into curves should be tangent.
  - Circles transitioning into circles should be tangent at the point of compound curvature. This is accomplished by having the radii of the 2 circles parallel at the point of compound curvature.
  - Lines should not transition to adjacent lines of different slope. The only exception to this rule is in the top 5 feet of the arch as explained below. A circle or fillet should be used to transition a line into another line of differing slope.
  - It is paramount that the dam to foundation contact be smooth either by excavating the irregularities or filling in the depressions.
- A grout temperature (stress-free temperature) of 40˚ F is a reasonable assumption for design. Grout temperatures at East Canyon were 34˚ F.
- Load goes to the stiffer part of the dam. So, in the design process, this fact can be used to shift load from the cantilevers to the arches or vice versa.
  - Arches with smaller radii are stiffer than arches with longer radii.
  - Shorter arches are stiffer than longer arches.
  - Thicker cantilevers are stiffer than narrower cantilevers.

- Try to carry most of the load in an arch dam with the arches. At Morrow Point Dam, it was determined that the arches carry about 76 percent of the total gravity and reservoir load.
- Try to get the load off the foundation and into the body of the arch dam. This is done by reducing the radii of the upper arches, thus making them stiffer, letting them take load off the cantilevers. Most of the load should be carried in the middle third of the dam.
- The central angle, angle from the left to right abutment in plan view, should be between 105˚ and 120˚, (EM 19 says 90˚ to 110˚) 105˚ being optimum causing the inflection point closer to the foundation.
- The angle of incidence of a tangent to the intrados with the contours for competent rock should not be less than 30˚.
- An estimate for stresses in the dam due to gravity load is about 1 psi per foot of dam height. This comes from the stress caused by one cubic foot of concrete (150 lbs. / 144 in^2 = 1.04 lb/in^2). So stresses at the base of a 200 foot high concrete dam from self-weight should be about 200 lb/in^2.
- The controlling design load for the dam is typically reservoir and low temperatures. This induces the farthest downstream deflection of the dam with both loads deflecting the dam downstream. Having less total impact, high temperature and reservoir are competing loads with reservoir pushing the dam downstream while high temperatures push the dam upstream.
- A 1˚ F change in temperature causes about 10 lb/in^2 change in arch stress at the abutment.
- When adjusting the shape of an arch dam, take concrete away from the tensile areas and put in the compression areas.
-
- Arch thrusts should be oriented at least 30˚ into the foundation. This is determined in ADSAS by the XY resultant at the abutment.

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Glossary

The terms defined in this glossary use industry-accepted definitions whenever possible. The source of the definition is indicated in parentheses. These definitions are consistent with other technical references and are also listed in the Federal Guidelines for Dam Safety, Federal Emergency Management Agency, Glossary of Terms.

Abutment – An abutment is that part of the valley wall against which the dam is constructed and the part of a dam that contacts the riverbank. An artificial abutment is sometimes constructed, as a concrete gravity section, to take the thrust of an arch dam where there is no suitable natural abutment. Typical orientation and terminology in the dams industry is to position oneself at the base of the dam looking downstream and thus orient the heel of the dam, the toe of the dam, the left abutment, and right abutment.

ADSAS (Arch Dam Stress Analysis System) **–** A computer program for stress analysis in arch dams based on the trial load method. ADSAS was initially developed by the engineers at the Bureau of Reclamation in the mid-1970' and converted for microcomputers by USCES in the mid-1990'.

Aggregate – Aggregate is crushed rock or gravel screened to sizes for use in road surfaces, concrete, or bituminous mixes. It is a mass or cluster of rock particles, often having a characteristic shape.

Arch dam – An arch dam is a concrete or masonry dam that is curved in plan view so as to transmit the major part of the water load to the abutments.

Arches or arching action – Arches of an arch dam are horizontal sections through the dam from abutment to abutment. Arching action cause horizontal stresses in the dam and transmit load into the abutments. Straight gravity dams do not have arching action, but resist the reservoir by shearing resistance along the foundation.

Axis of dam – The axis of the dam is a vertical cylindrical reference plane along the upstream side of the dam crest.

Axis radius – The axis radius (R_{axis}) is the horizontal distance along the reference plane from the axis of the dam at the crest to the line of centers and defines the axis of the dam.

Base – Bottom surface of the dam resting on the foundation.

Base width or thickness – Base width is the radial thickness of a dam measured horizontally between upstream and downstream faces and normal to the axis of the dam, but excluding projections for outlets or other appurtenant structures. The maximum base thickness is typically at the crown cantilever of an arch dam.

Cantilevers or cantilever action – The cantilevers of a concrete dam are vertical sections through the dam perpendicular to the axis of the dam. For a gravity dam this is in the upstream to downstream direction. For an arch dam or curved gravity dam, this is radial to the curvature in plan view. Cantilever action cause vertical stresses in the dam and transmit forces down into the foundation.

Central Angle – Angle at extrados center formed by lines extended to left and right arch abutments for use in stress analysis by ADSAS.

Cofferdam - A cofferdam is a temporary structure or dam upstream or downstream or both enclosing all or part of the construction area so that construction can proceed in the dry. A diversion cofferdam diverts a river into a pipe, channel or tunnel around the site.

Cold joint – A cold joint is an unplanned joint resulting when a concrete surface hardens before the next batch of concrete is placed against it.

Construction joint - Construction joints are purposely placed in concrete to facilitate construction; to reduce initial shrinkage stresses and cracks; to allow time for the installation of embedded metalwork; or to allow for the subsequent placing of other concrete. Bond is required at construction joints regardless of whether or not reinforcement is continuous across the joint. A construction joint allows a reasonable size concrete placement or a point to terminate a placement. It is also the interface between two successive concrete placements where bond, and not permanent separation, is intended. To achieve bond, the hardened surface must be sand or water blasted to remove the laitance.

Contraction joint - Contraction joints are radial vertical joints placed in concrete to provide for volumetric shrinkage of a monolithic unit or movement between monolithic units. Contraction joints have no bond between the concrete surfaces forming the joint. Reinforcement is never continuous across a contraction joint, except if dowels are provided. Contraction joints transfer compression and no tension. Shear is transmitted along the joints when in compression or with the inclusion of shear keys. Contraction joints provide a mechanism by which heat of hydration is dissipated resulting in separation between adjacent blocks ultimately filled with grout thus restoring the arches to continuous shapes.

Control joint - Control joints are joints placed in concrete to provide for control of initial shrinkage stresses and cracks of monolithic units. Control joints are similar to contraction joints except that reinforcement is continuous across the joint. Control joints are unbonded joints to provide weak areas for cracking. Control joints transfer compression in the concrete and reinforcement and only tension in the reinforcement. Shear is transmitted along the joints when in compression or with the inclusion of shear keys.

Crest – The crest is the top surface of the main body of the dam (excluding parapet walls) or the high point of a spillway. A roadway may be constructed across the crest to permit vehicular traffic or facilitate operation, maintenance, and examination of the dam. Allow 5 feet vertically along the crest abutment to abutment for freeboard.

Crest width - The crest width is the thickness of a dam at the crest.

Crown or crown cantilever - The crown or crown cantilever is a vertical upstream to downstream section through an arch dam at the maximum height. This is generally also along the reference plane.

Curved gravity dam **–** A curved gravity dam is a concrete gravity dam that is curved in plan view. The distinction between a curved gravity dam and an arch dam is that a curved gravity dam is stable statically mainly by gravity action. Minimal arching action occurs due to the curvature in plan view for static stability. The downstream face is generally steeper that with a straight gravity dam.

Depth of Excavation – Depth from the ground surface to sound rock as determined from available geological sources.

Double-curvature arch dam - A double curvature arch dam is an arch dam that is curved in plan (horizontally) and in elevation (vertically), with undercutting of the heel and has a downstream overhang near the crest.

Downstream projection (*DSP*) **–** The downstream distance measured from the axis of the dam to the downstream face.

Extrados – The extrados defines upstream face of the horizontal arches.

Foundation – Total mass of sound rock supporting the dam. In ADSAS terminology “abutments” are the rock supporting the arches and “foundation” supporting the cantilevers.

Grout - Grout is a fluid mixture of cement and water or sand, cement, and water used to seal joints and cracks in a rock foundation. It is a fluid material that is injected into soil, rock, concrete, or other construction material to seal openings and to lower the permeability and/or provide additional structural strength. There are four major types of grouting materials: chemical, cement, clay, and bitumen. Water cement grout is used to fill the contraction joints, once the mass concrete temperature is lowered to a pre-specified value.

Heel of dam - The heel of the dam is the intersection of the upstream face of a concrete dam with the foundation.

Intrados – The intrados defines the horizontal arches of the downstream face.

Line of centers – The lines of centers define the geometry of the centers of radii of the upstream and downstream faces horizontal arcs of an arch dam along the reference plane. The top of the lines of centers is R_{axis} downstream from the axis of the dam.

Mass concrete - Mass concrete, with a maximum sized aggregate of 6 inches, is any large volume of concrete cast-in-place, generally as a monolithic structure. Dimensions of the structure are of such magnitude that measures must be taken to cope with the generation of heat and the resulting volume changes and cracking.

Medium-thick arch dam – A medium-thick arch dam is an arch dam with a base thickness to structural height ratio between 0.2 and 0.4 (previously defined as between 0.3 and 0.5).

Multiple-arch dam – A multiple arch dam is a special type of buttress dam where the upstream face is a series of reinforced concrete arches.

Point of compound curvature (PCC) – The point of compound curvature is the common point between two circular arcs in the same plane with parallel radii.

Point of intersection (PI) – The point of intersection is the intersection point of two curves or two lines.

Reference plane – The reference plane is an imaginary upstream to downstream vertical section through the crown cantilever of a concrete dam and line of centers. The orientation of the dam can be defined by positioning the top of the line of centers by State Plane coordinates and the bearing of the reference plane from this point. The geometry of the upstream face, downstream face, and lines of centers are along the reference plane.

Roller-compacted concrete dam (RCC) - A roller-compacted concrete dam is a concrete gravity or arch dam constructed by the use of a dry mix concrete transported by conventional construction equipment and compacted by rolling, usually with vibratory rollers.

Sand – Sand are mineral grains whose particle size vary from a No. 4 sieve to a No. 200 sieve also considered a loose soil composed of particles between 1/16 mm and 2 mm in diameter.

Shear keys – Shear keys are intentionally formed undulations along contraction joints, lift surfaces, or any potential slide plane to provide shear resistance.

Single-curvature arch dam – A single-curvature dam is curved in plan only and not in section view. The upstream and downstream faces are straight lines.

Site Shape - Arch dams are typically in relatively narrow canyons with V, wide-V, U, wide-U shapes. The canyon width to dam height is normally less than 7 to 1.

Structural height – Structural height is the distance between the lowest point in the excavated foundation (excluding narrow fault zones) and the top of dam. The structural height of a concrete dam is the vertical distance between the top of the dam and lowest point of the excavated foundation area, excluding narrow fault zones.

Tailwater - The tailwater is the water in the natural stream immediately downstream from a dam. The elevation of water varies with discharge from the reservoir.

Thick-arch dam – A thick arch dam is an arch dam with a base thickness to structural height ratio of 0.4 to 0.65 (previously defined as 0.5 or greater).

Thickness of dam– Horizontal distance between upstream and downstream projection of dam on a line normal to axis of the dam.

Thin-arch dam – A thin arch dam is an arch dam with a base thickness to structural height ratio of 0.2 or less (previously defined as 0.3 or less).

Thrust block – A thrust block in the context of dams is a massive block of concrete built as a supplemental or artificial abutment to withstand the thrust from an arch dam.

Toe of the dam – The toe of the dam is the point of intersection between the downstream face at the base of the dam and the ground.

Trial Load Analysis Method –The method divides the arch dam structure in to 1-ft wide arches and 1-ft wide cantilever elements and distributes the load between the arches and cantilevers in a trial process until the deflections of the common points are in agreement.

Uplift – Uplift is the water pressure in the pores of a material (interstitial pressure). Usually uplift is thought of at the base of a dam, but it actually is along any plane in a dam.

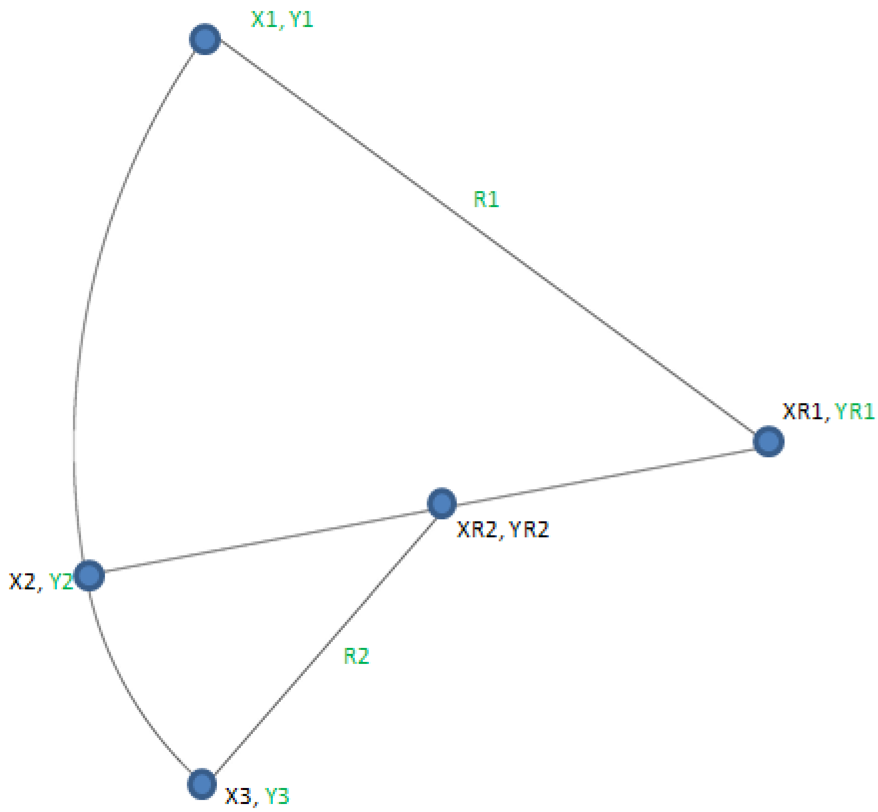
Appendix A – Computation of Dam Geometry

The figures in Appendix A are geometric aids in laying out arch dams. The upstream face and downstream face along the crown cantilever and the line-of-centers along the reference plane are made up of segments of straight lines and curves. This may include segments transitioning from straight lines to curves, curves to curves, and curves to straight lines. To make sure the faces of the dam and the lines-of-centers are smooth, the transitions into curves must be tangent to the circle.

Figure A-1 is the geometry for a circle transitioning into another circle. The radius of circle 1 must be along the radius of circle 2 to have a tangent transition at point X2, Y2. In the layout of the upstream or downstream face, the position of point X1, Y1, the radii R1 and R2, and the elevations YR1, Y2, and Y3 are known. The equations compute the remaining unknown variables X2, XR2, YR2, XR1, and X3. Variables Y1, Y2, Y3, R1, R2, XR1, and YR2 are used in program ADSAS.

Similarly, other Figures A-2 through A-9, are included in the Excel spreadsheet in Appendix E to solve these geometric computations typically used in the layout of the upstream face, downstream face, and lines-of-centers for arch dams.

Compute Geometry of 2 Circular Arcs



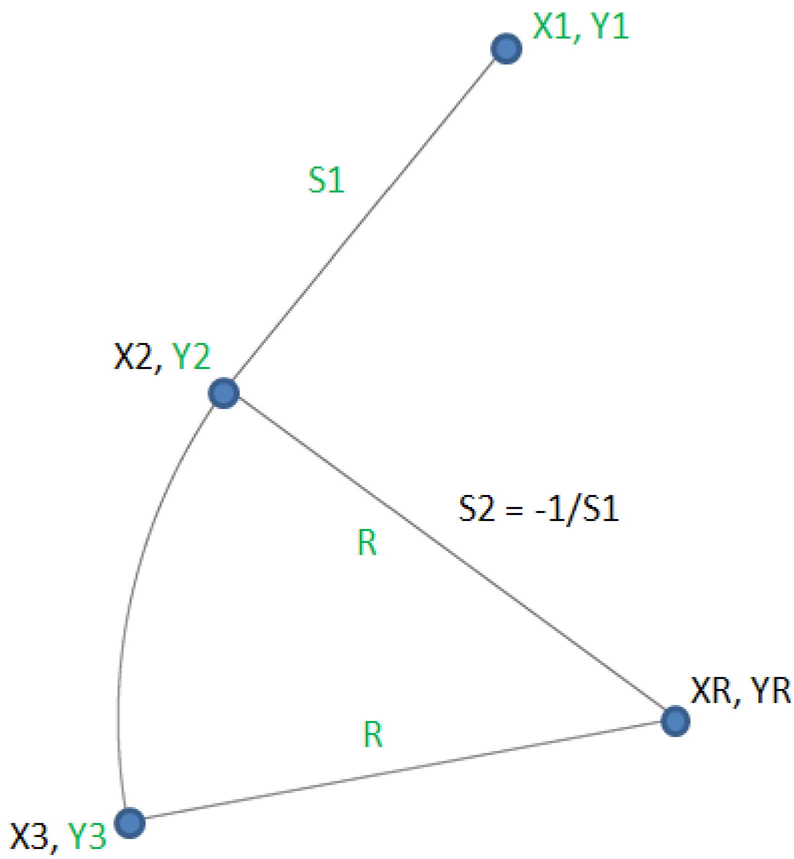
Given: X1, Y1, R1, R2, YR1, Y2, and Y3

Compute: XR2, YR2, X2, and X3

$$XR1 = X1 + \mathrm{sqrt}(R1^2 - (Y1 - YR1)^2)$$
$$X2 = XR1 - \mathrm{sqrt}(R1^2 - (Y2 - YR1)^2)$$
$$XR2 = X2 + (X2 - XR1) * R2/R1$$
$$YR2 = Y2 - (Y2 - YR1) * R2 / R1$$
$$X3 = XR2 - \mathrm{sqrt}(R2^2 - (YR2 - Y3)^2)$$

Fig A-1 Compute Geometry of two Circular Arcs

Compute Geometry of Line Transitioning Tangent to a Circular Arc



Given: X1, Y1, S1, R, Y2, and Y3

Compute: X2, S2, XR, YR, and X3

$X2 = X1 - (Y1 - Y2)*S1$

$S2 = -1 / S1$

$r = \mathrm{sqrt}(S2^2 + 1^2)$

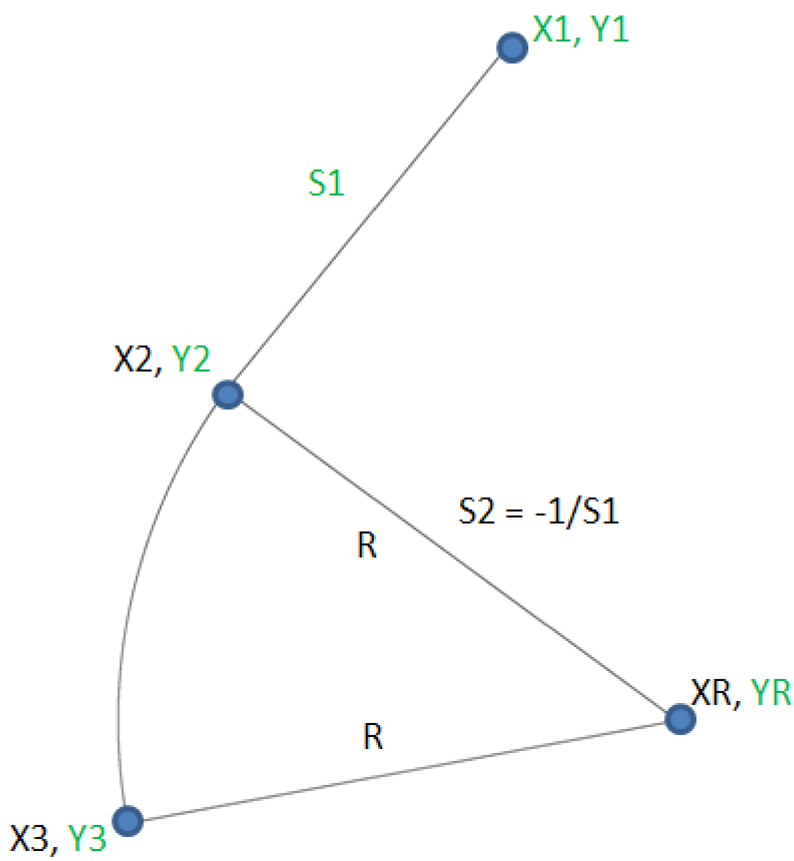
$YR = Y2 - R * 1 / r$

$XR = X2 + R * S2 / r$

$X3 = XR - \mathrm{sqrt}(R^2 - (YR - Y3)^2)$

Fig A-2 Compute Geometry of Line Transitioning Tangent to a Circular Arc

Compute Geometry of Line Transitioning
Tangent to a Circular Arc

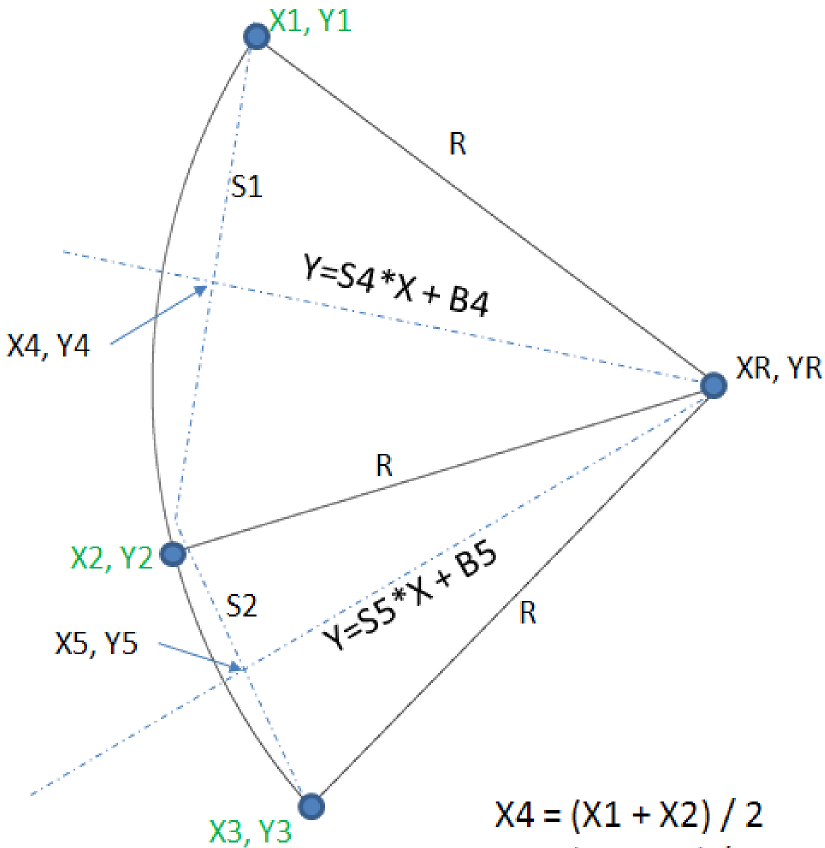


Given: X1, Y1, S1, YR, Y2, and Y3
Compute: X2, S2, XR, R, and X3

$X2 = X1 - (Y1 - Y2)*S1$
$S2 = -1 / S1$
$XR = X2 + (Y2 - YR) * S2$
$R = \mathrm{sqrt}((X2-XR)^2 + (Y2 - YR)^2)$
$X3 = XR - \mathrm{sqrt}(R^2 - (YR - Y3)^2)$

Fig A-3 Compute Geometry of Line Transitioning Tangent to a Circular Arc

Compute Geometry of a Circular Arc from 3 Points



Given: X1, Y1, X2, Y2, X3, Y3
Compute: YR, XR, and R

Legend:
S1, S2, S4, and S5 = Slope
R = Radius
B4, B5 = Y Intercept

$X4 = (X1 + X2) / 2$
$Y4 = (Y1 + Y2) / 2$
$S1 = (X1-X2)/(Y1-Y2)$
$S4 = -1 / S1$
$B4 = Y4 - S4 * X4$
Likewise: X5, Y5, S2, S5, B5
$YR = S4 * XR + B4 = S5 * XR + B5$
THUS:
$XR = (B5 - B4) / (S4 - S5)$
$YR = S4 * X6 + b4$
$R = sqrt((X1-X6)^2 + (Y1-Y6)^2)$

Fig A-4 Compute Geometry of a Circular Arc from 3 Points

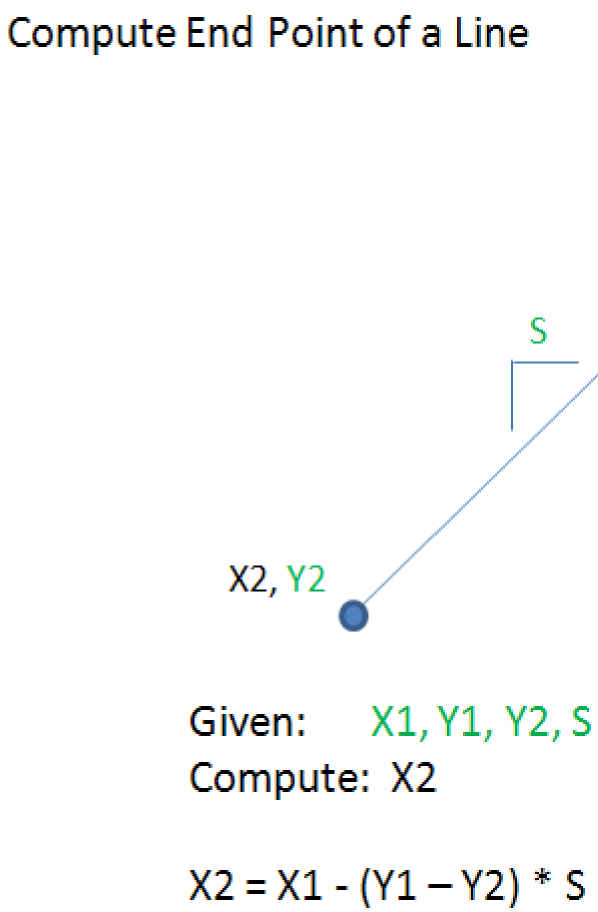
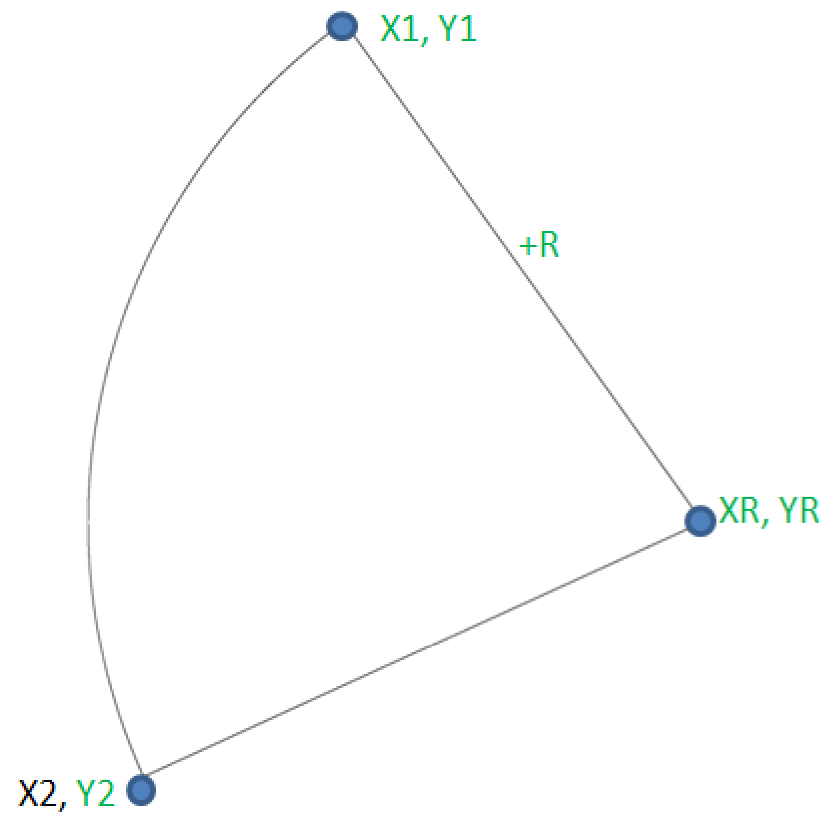


Fig A-5 Compute End Point of a Line

Compute End Point of a Circular Arc



Given: X1, Y1, R, YR, and Y2

Compute: XR, X2

If $R > 0$:

$XR = X1 + \mathrm{sqrt}(R^2 - (Y1 - YR)^2)$

$X2 = XR - \mathrm{sqrt}(R^2 - (YR - Y2)^2)$

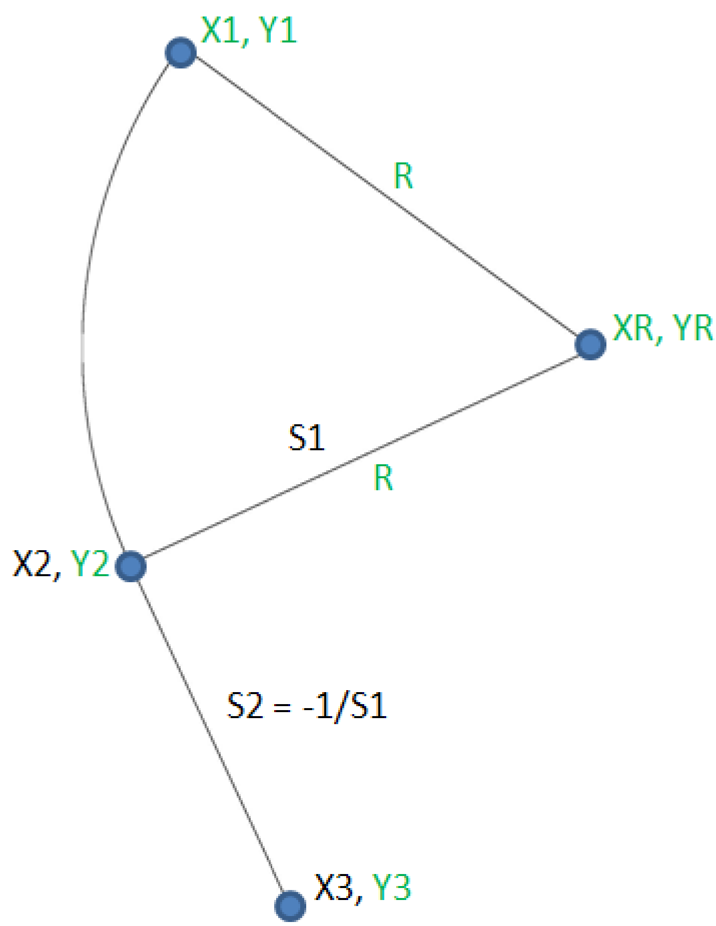
If $R < 0$:

$XR = X1 - \mathrm{sqrt}(R^2 - (Y1 - YR)^2)$

$X2 = XR + \mathrm{sqrt}(R^2 - (YR - Y2)^2)$

Fig A-6 Compute End Point of a Circular Arc

Compute Geometry of Line Transitioning
Tangent to a Circular Arc



Given: X1, Y1, XR, YR, R, Y2, and Y3
Compute: X2, S1, S2, and X3

$X2 = XR - \mathrm{sqrt}(R^2 - (YR - Y2)^2)$
$S1 = (X2-XR)/(Y2-YR)$
$S2 = - 1 / S1$
$X3 = X2 + (Y2 - Y3)*S2$

Fig A-7 Compute Geometry of Line Transitioning Tangent to a Circular Arc

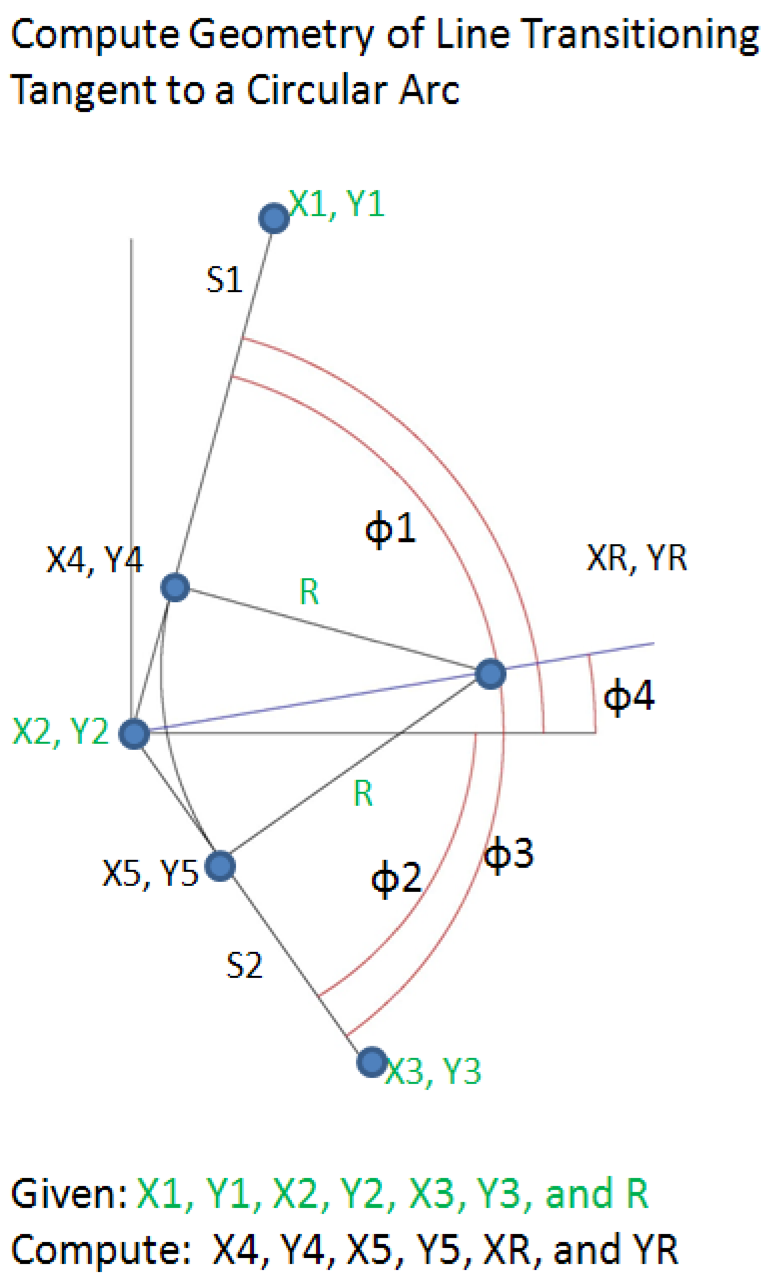
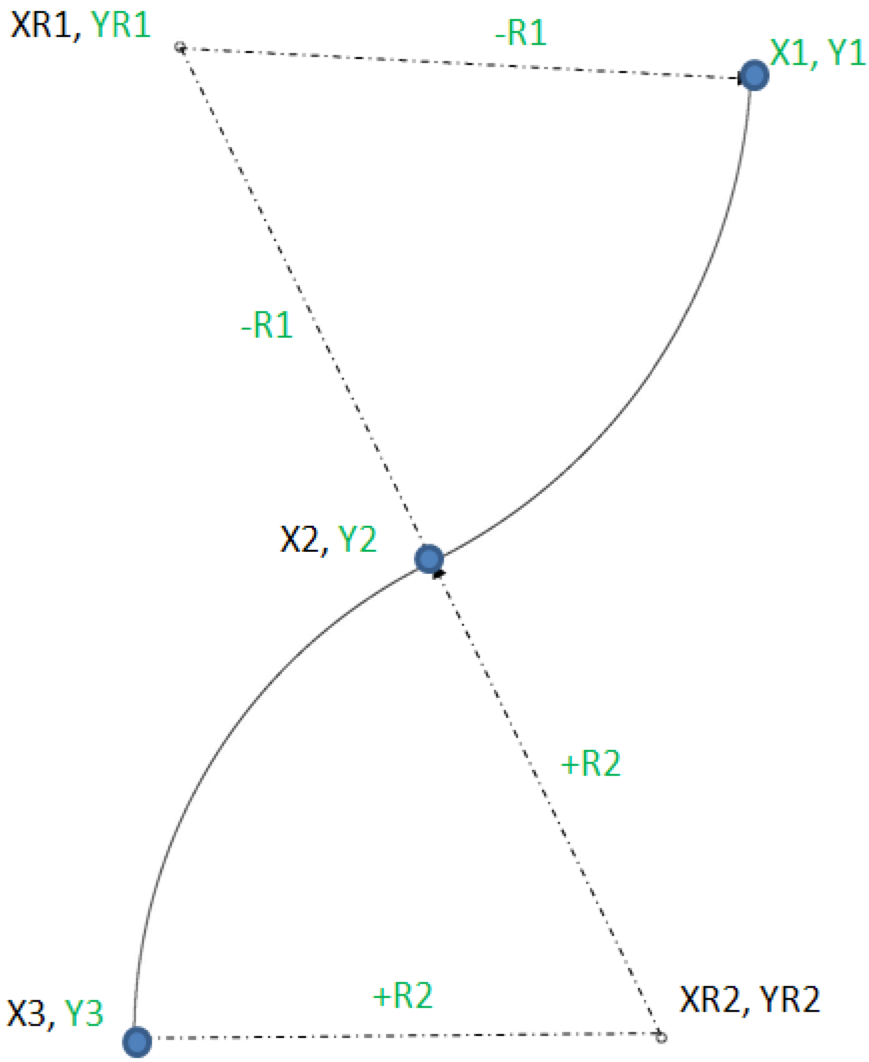


Fig A-8 Compute Geometry of Line Transitioning Tangent to a Circular Arc

Compute Geometry of 2 Circular Arcs



Given: X1, Y1, R1, R2, YR1, Y2, and Y3

Compute: XR2, YR2, X2, and X3

$XR1 = X1 - \mathrm{sqrt}(R1^2 - (Y1 - YR1)^2)$

$X2 = XR1 + \mathrm{sqrt}(R1^2 - (Y2 - YR1)^2)$

$XR2 = X2 + (X2 - XR1) * R2/R1$

$YR2 = Y2 - (Y2 - YR1) * R2 / R1$

$X3 = XR2 - \mathrm{sqrt}(R2^2 - (YR2 - Y3)^2)$

Fig A-9 Compute Geometry of 2 Circular Arcs

Appendix B – Drawings Showing Arch Dam Dimensions and Dam Types

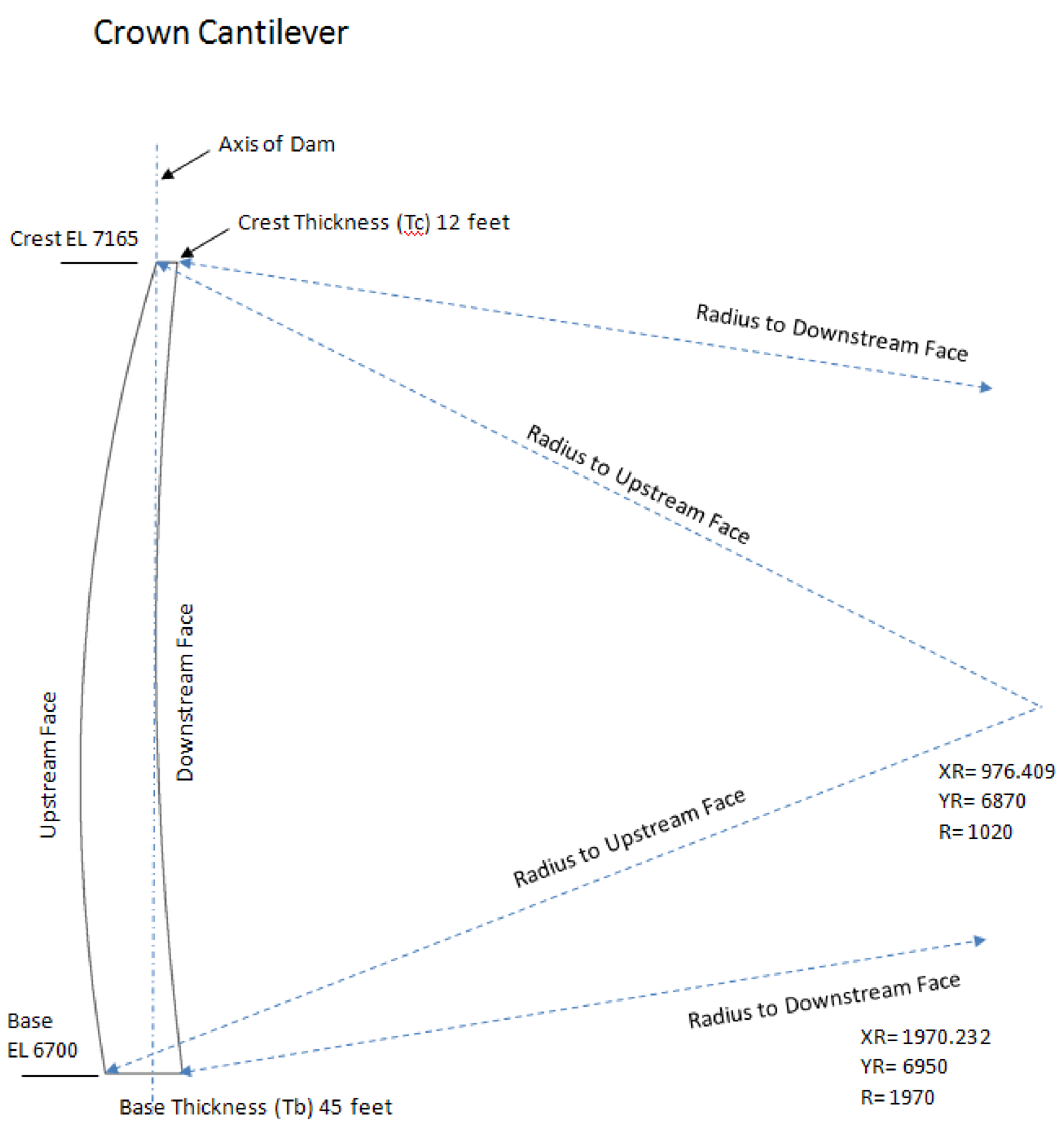


Fig B-1 Crown Cantilever

Line of Centers
Single Line of Centers, Constant Thickness Arch

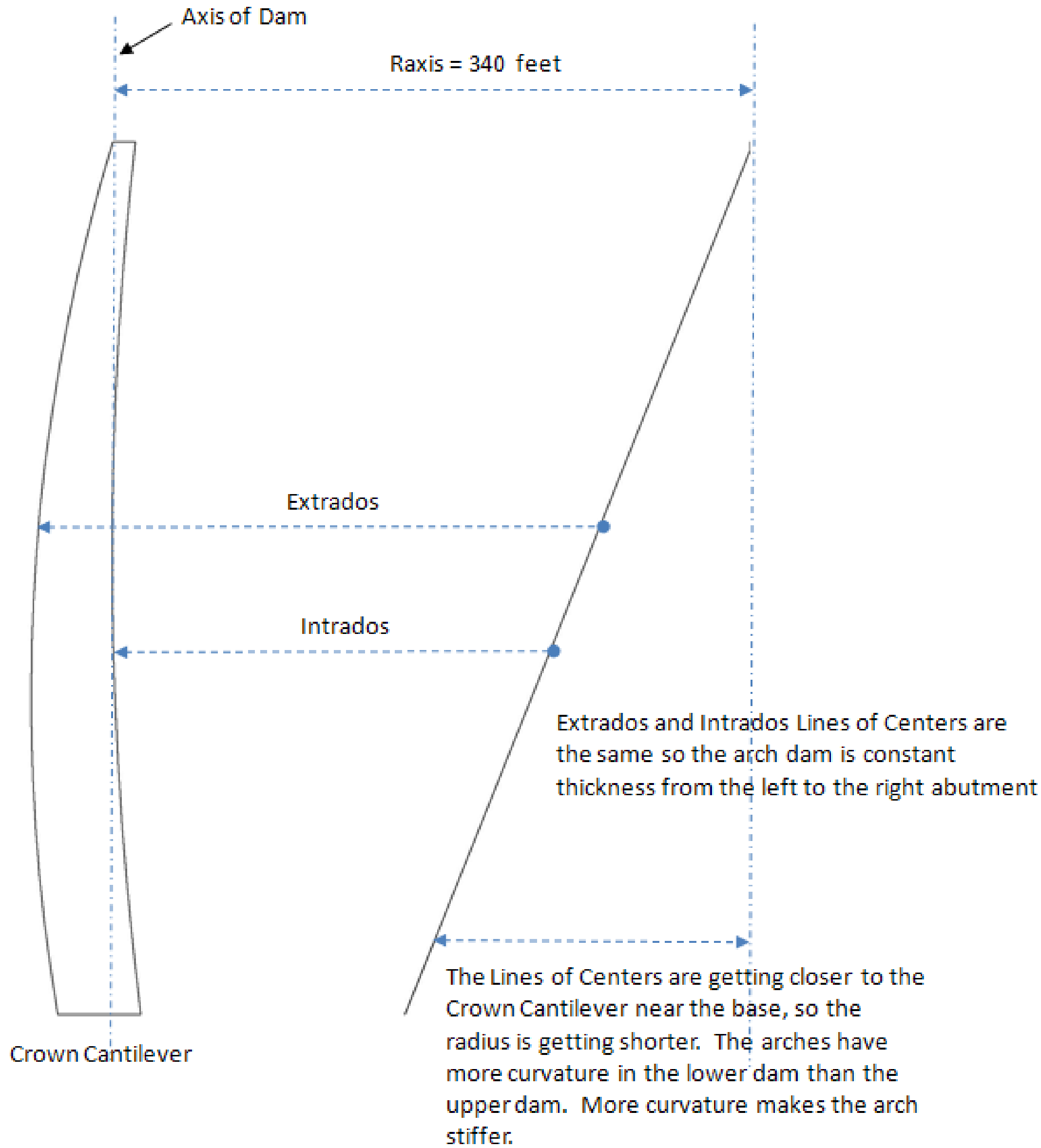


Fig B-2 Line of Centers Single Line of Centers, Constant Thickness Arch

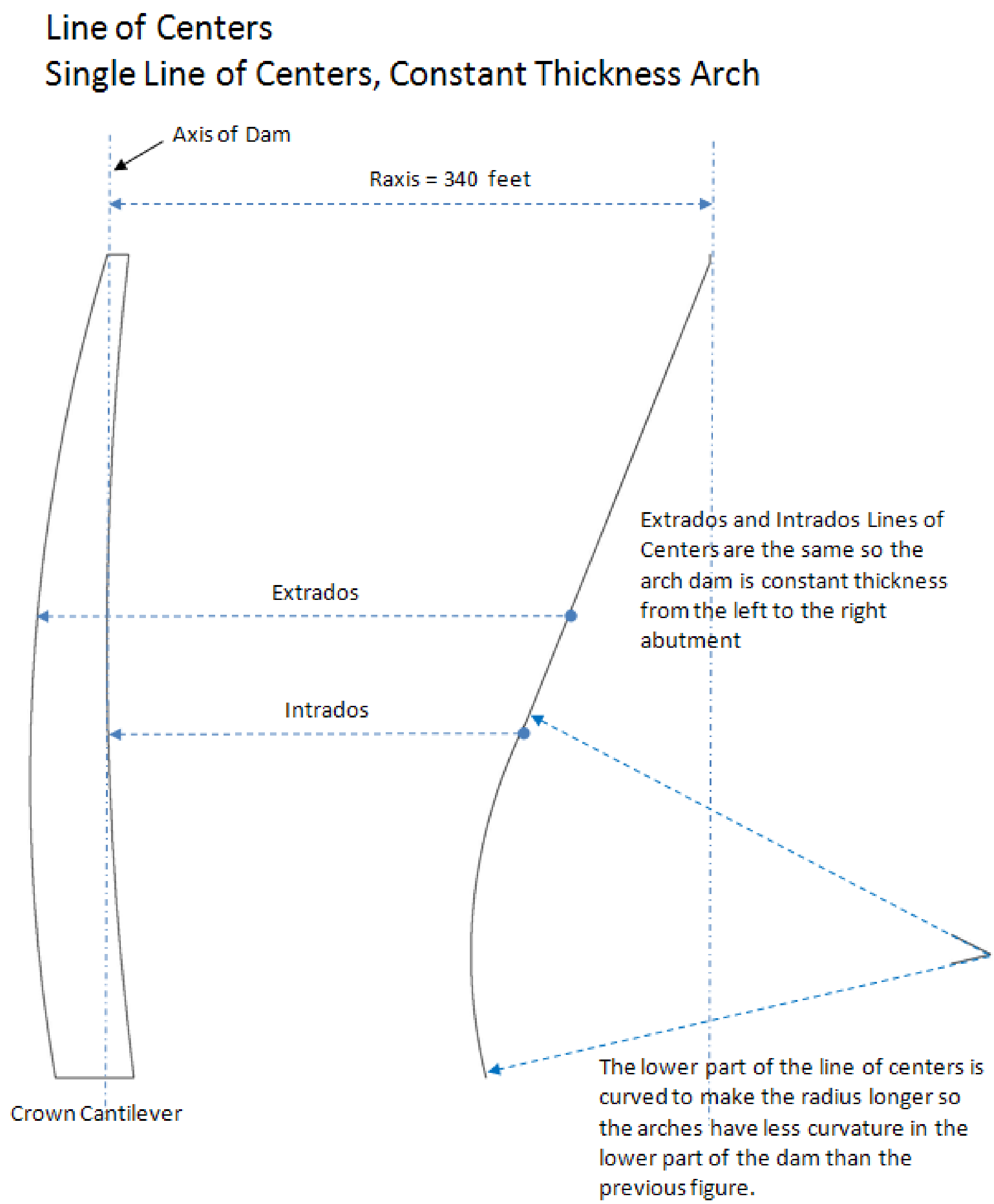


Fig B-3 Line of Centers Single Line of Centers, Constant Thickness Arch

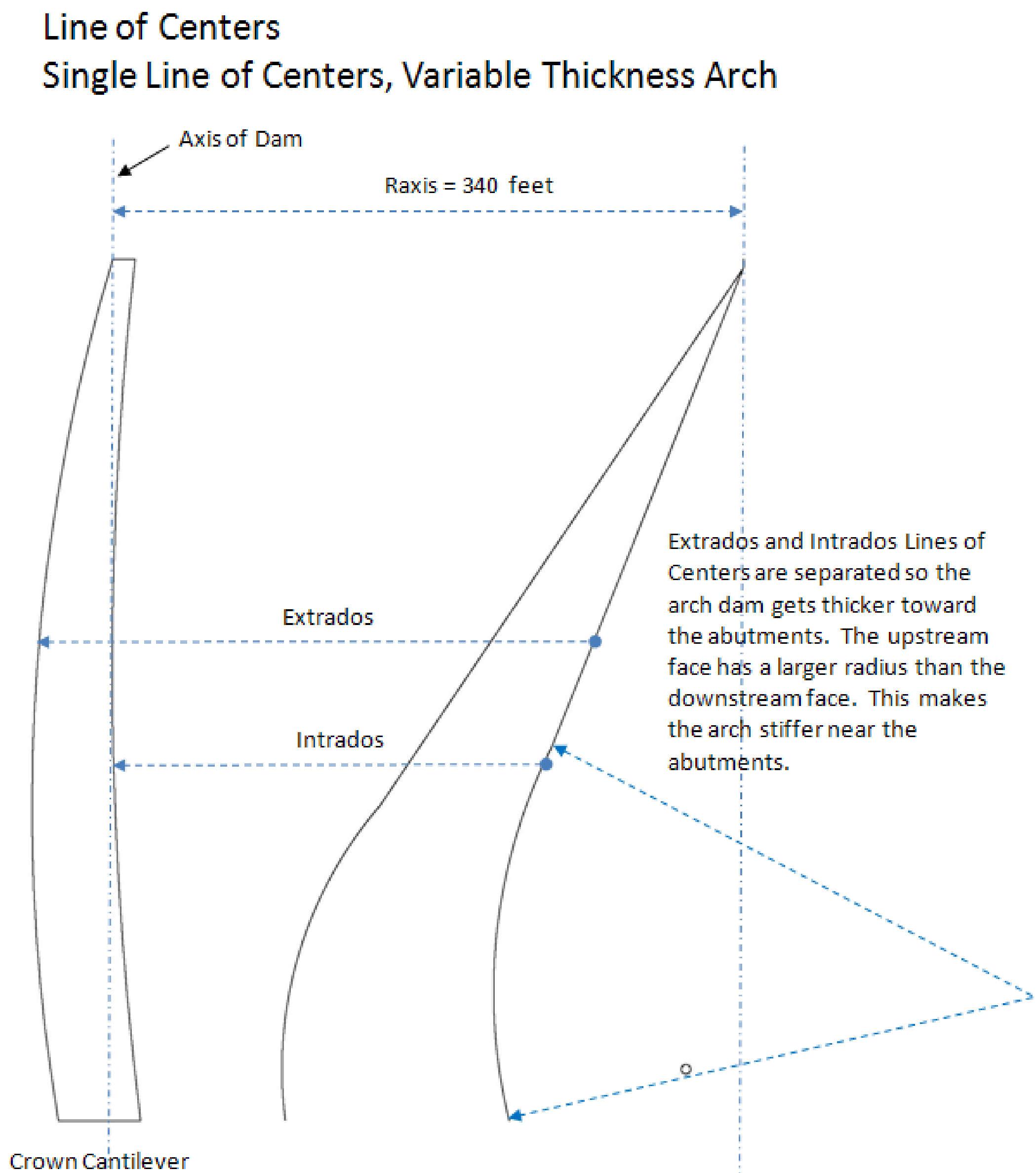


Fig B-4 Line of Centers Single Line of Centers, Variable Thickness Arch

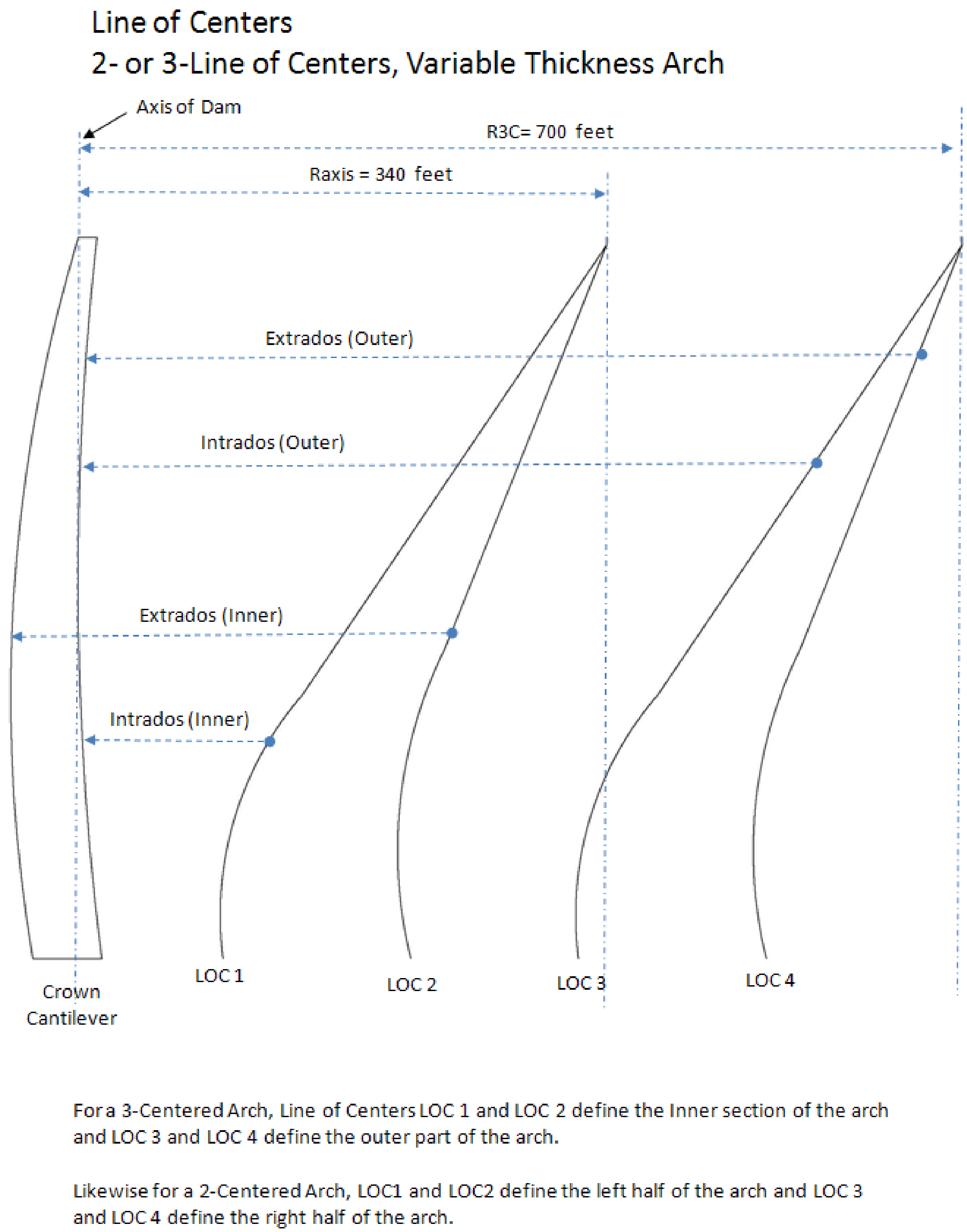


Fig B-5 Line of Centers 2- or 3-Line of Centers, Variable Thickness Arch

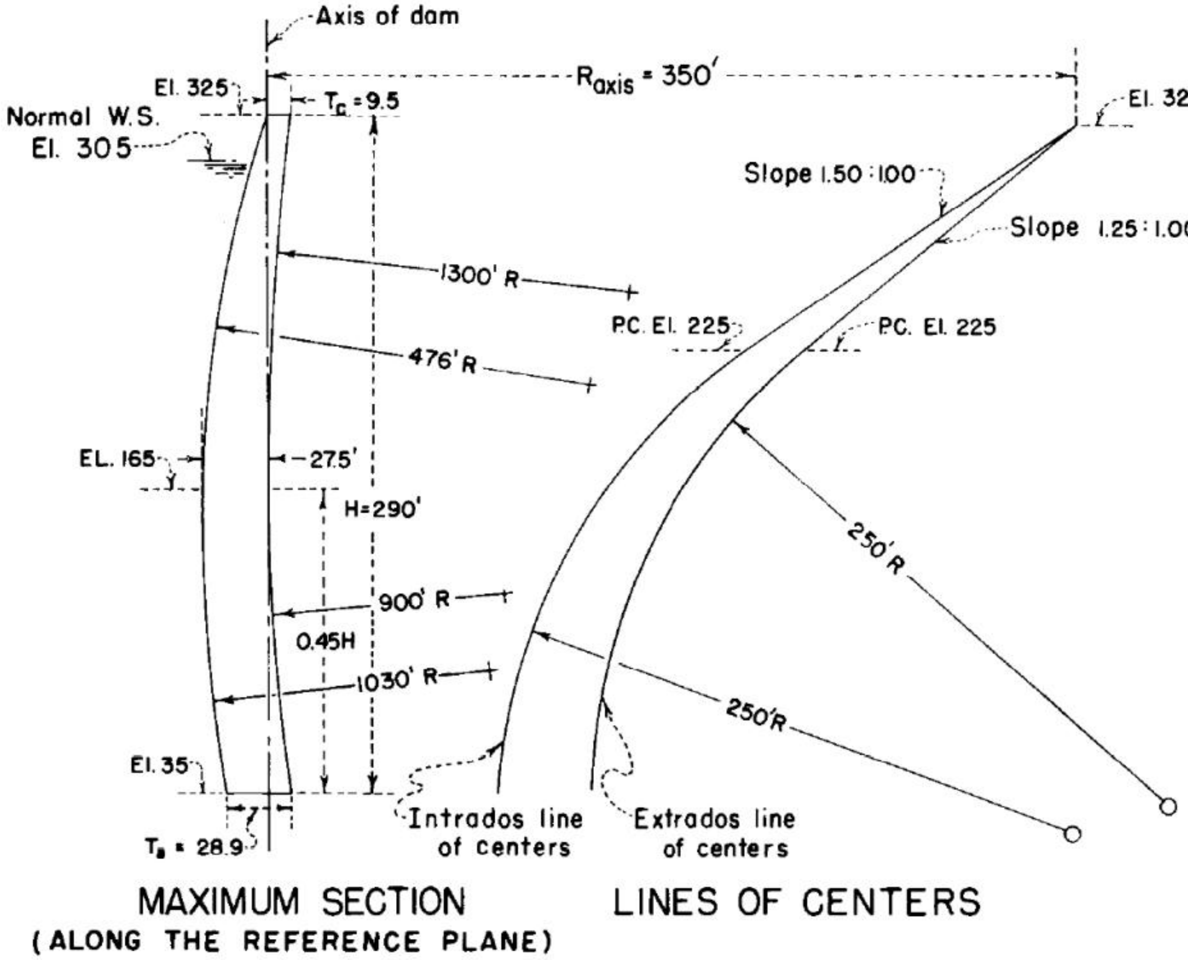


Fig B-6 Layout drawing along the reference plane

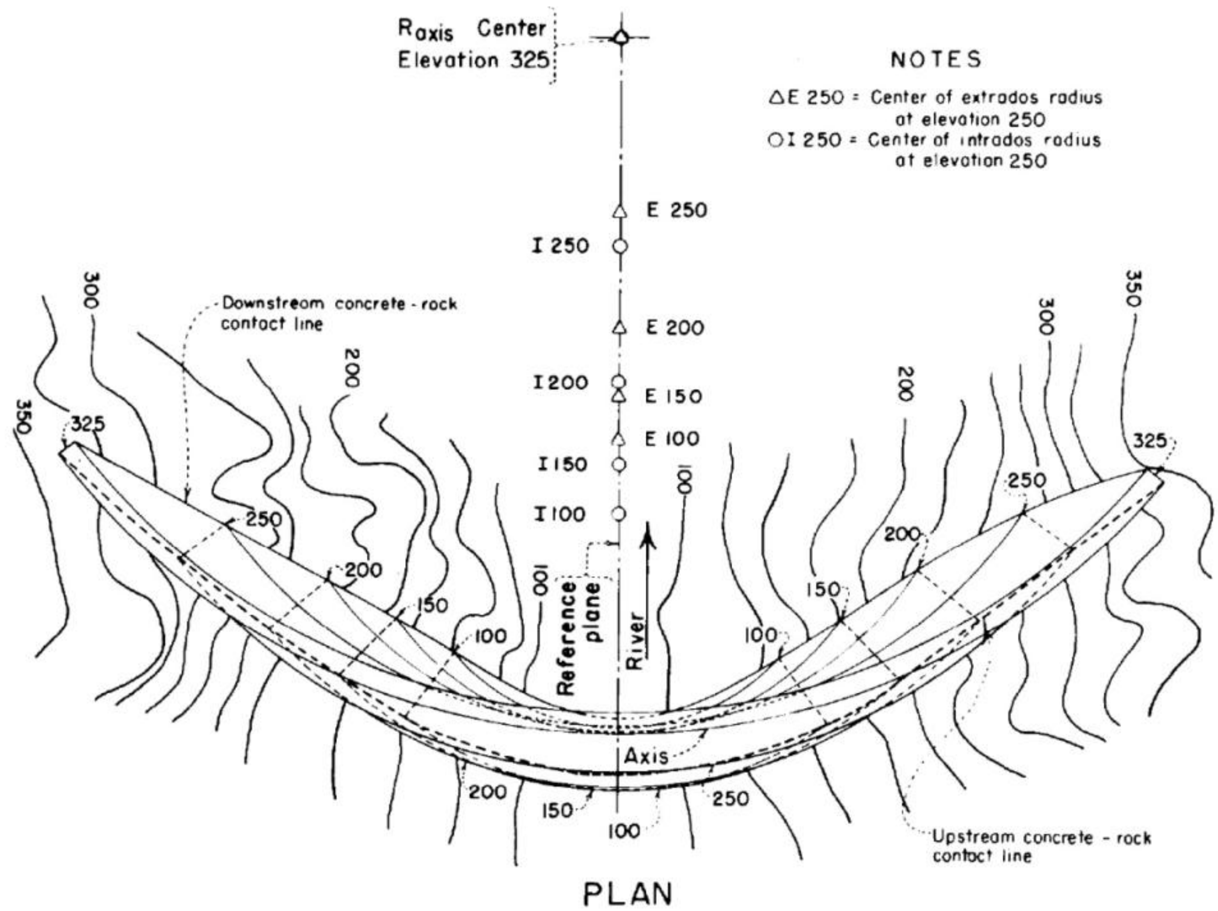


Fig B-7 Design drawing of a single centered arch in a nearly symmetrical canyon

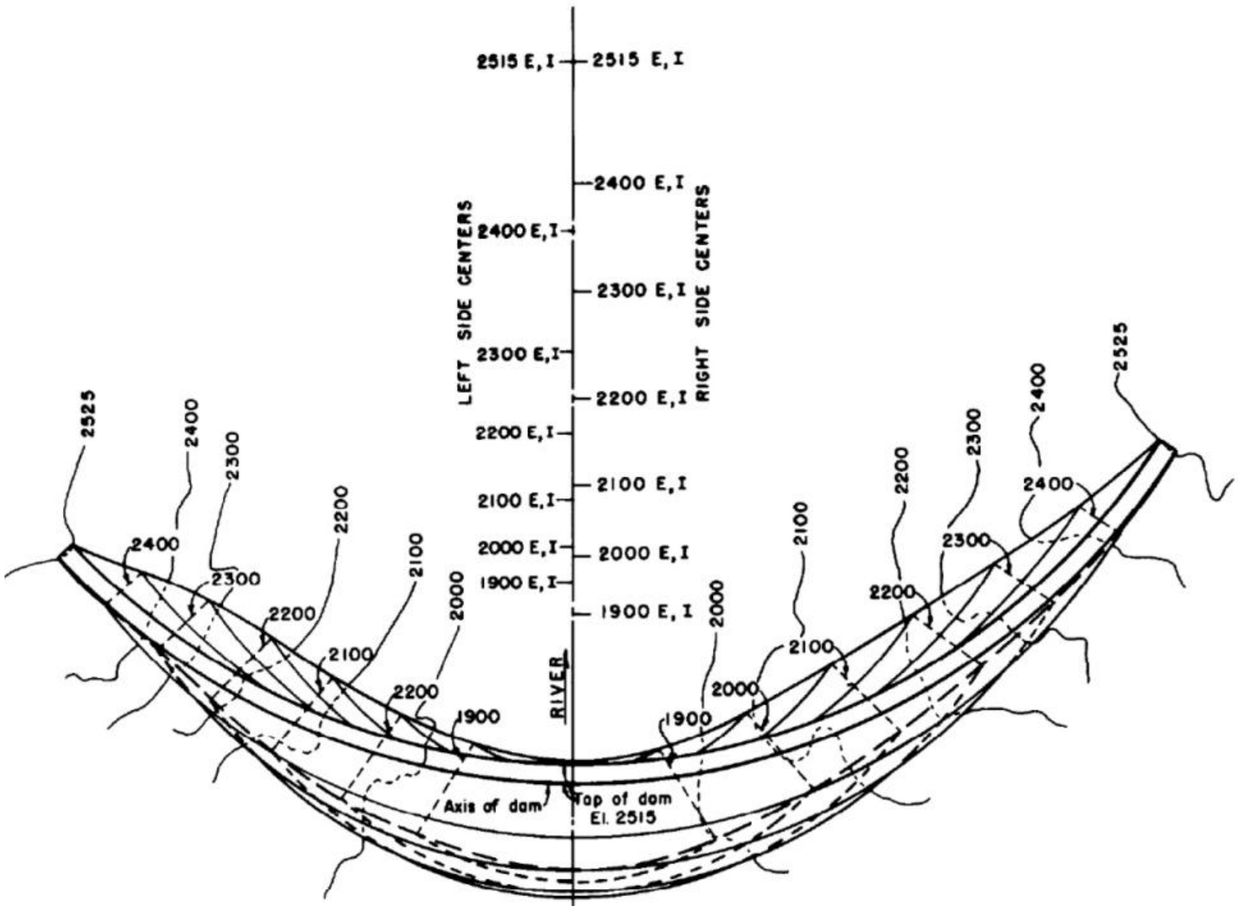


Fig B-8 Layout drawing of a two planes of centers arch dam with uniform thickness arches

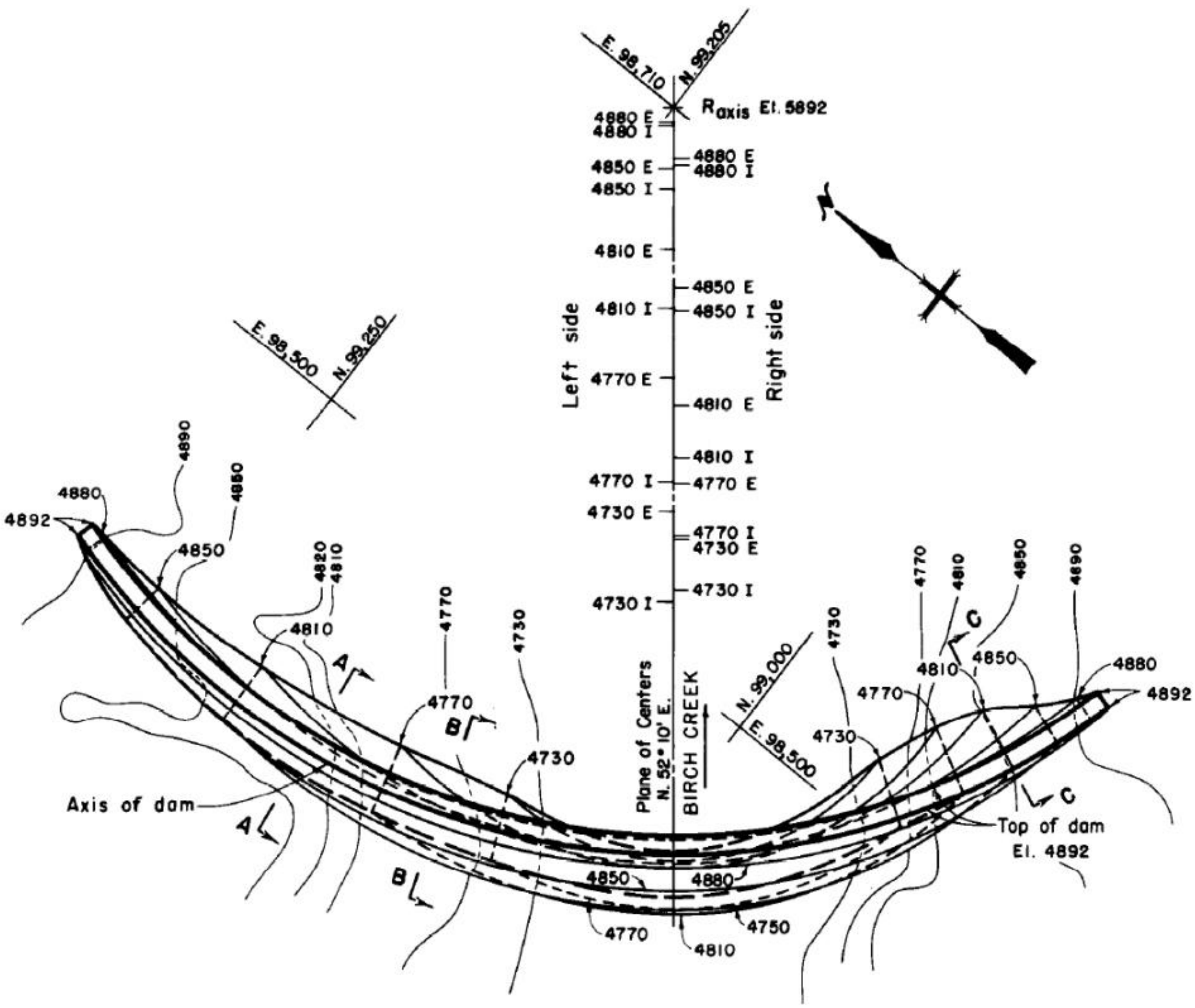


Fig B-9 Layout drawing of a two planes of centers arch dam with variable-thickness arches in a nonsymmetrical canyon

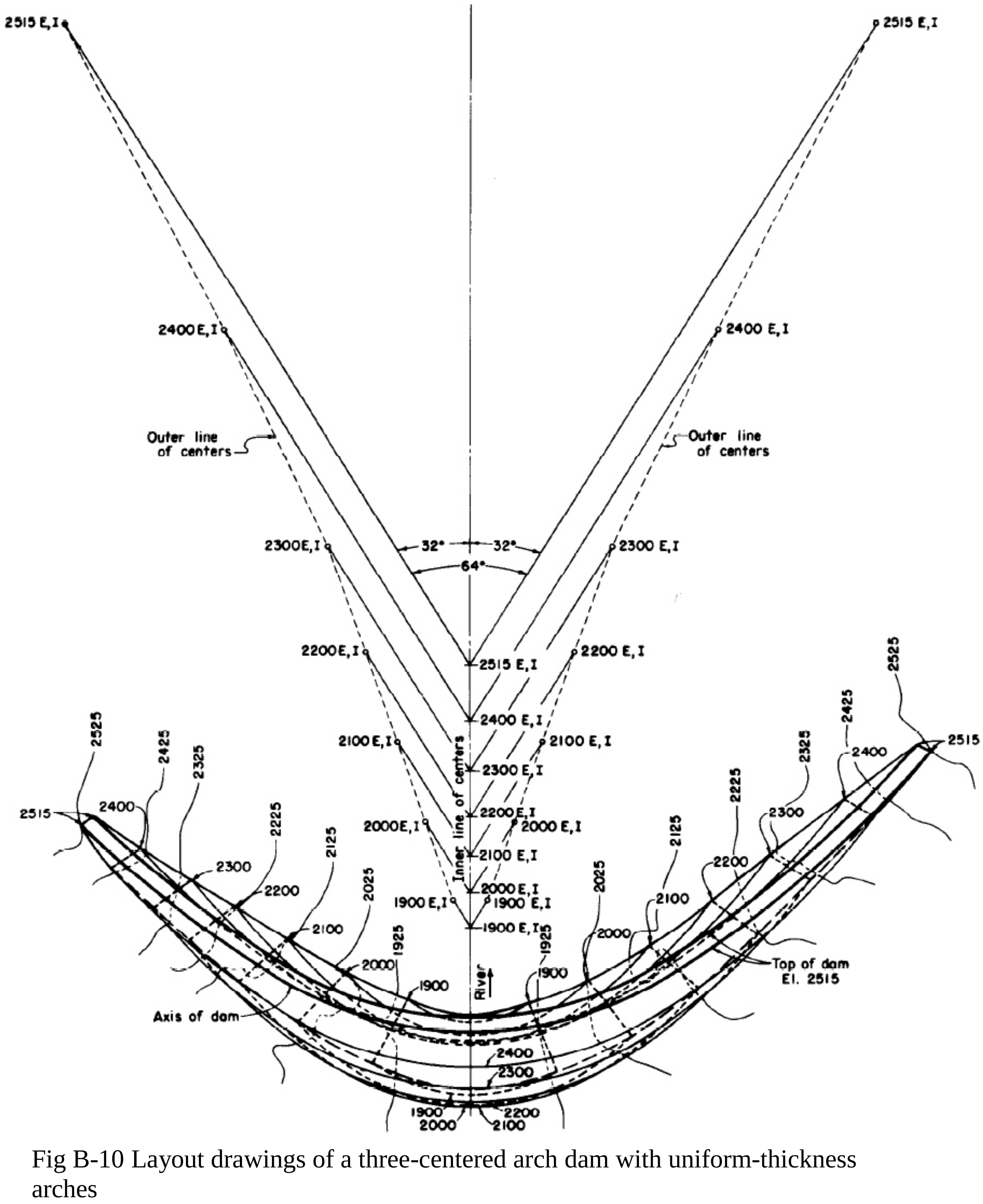


Fig B-10 Layout drawings of a three-centered arch dam with uniform-thickness arches

Appendix C – Double-Curvature Arch Dams Database

Table C-1 US and international double-curvature Arch Dams (initial database)

Project Name	Year of construction	Dam Height [ft]	Dam width L1 [ft]	Crest thickness [ft]	Base thickness [ft]	Concrete Volume [cu yd]	Ration L1/H	Ratio H/TB	Ratio L1/Tc	Crest thickness Tc from EM #36
East Canyon Dam	1966	260	436	7	20	35,716	1.68	0.08	62.3	7.8
Swift Dam	1967	205	560	9	22	54,000	2.73	0.11	62.2	8.8
Morrow Point Dam	1968	468	724	12	52	365,180	1.55	0.11	60.3	13.4
Mountain Park Dam	1975	133	535	6	17	18,160	4.02	0.13	89.2	7.8
Crystal Dam	1976	323	620	10	29	154,400	1.92	0.09	62.0	10.7
Nambe Falls Dam	1976	150	320	5	15	238,672	2.13	0.10	64.0	5.3
Tekezee Dam	2009	616.8	1377.6	18.4	91.8	1,351,000	2.23	0.15	74.9	22.7
Canicada Dam	1954	249	643	6.6	29	116,000	2.58	0.12	97.4	10.2
Salamonde Dam	1953	246	663	6.6	21	123,000	2.70	0.09	100.5	10.4
Cabril Dam	1953	433	951	15	62	477,000	2.20	0.14	63.4	15.7
Bouca Dam	1955	207	574	6.6	23	92,000	2.77	0.11	87.0	9.0
Maina di Sauris Dam	1947	446	453	9.8	52	131,000	1.02	0.12	46.2	9.9
Ambiesta Dam	1959	194	476	6.9	26	38,000	2.45	0.13	69.0	7.7
Valle di Cadore Dam	1950	200	125	5.6	10	6,000	0.63	0.05	22.3	3.5
Pontesei Dam	1956	295	476	8.7	26	85,000	1.61	0.09	54.7	8.7
Vodo Dam	1960	138	525	3.9	14	13,000	3.80	0.10	134.6	7.7
Vaiont Dam	1960	870	623	9.8	72	462,000	0.72	0.08	63.6	16.2
Val Gallina	1951	302	748	8.2	49	130,000	2.48	0.16	91.2	12.0
Zerveila Dam	1957	494	1653	23	115	818,300	3.35	0.23	71.9	24.8
Malpasset Dam	1954	216	230	4.9	23	62,690	1.06	0.11	46.9	4.9
Limberg Dam	1951	394	1170	19.7	121.4	580,000	2.97	0.31	59.4	18.0
Drossen - Limberg	1955	367	1170	23	82	461,000	3.19	0.22	50.9	17.7
Ottenstein Dam	1956	226	787	23	79	161,000	3.48	0.35	34.2	11.7
Kops Dam	1966	400	1312	19.7	98.4	630,000	3.28	0.25	66.6	19.7
Schlegeis Dam	1971	430	2378	29.5	111.5	1,248,000	5.53	0.26	80.6	32.8
Klaus Dam	1975	180	616	6.5	30.8	50,700	3.42	0.17	94.8	9.2
Kolnbrein Dam	1979	656	2053	25	134.5	2,054,000	3.13	0.21	82.1	31.2
Zillergrundl Dam	1986	610	1660	23	137.7	1,781,000	2.72	0.23	72.2	26.0
Kawaji Dam	1981	460	1050	26.2	76.4	910,000	2.28	0.17	40.1	17.2
Asahi Dam	1978	282	656	9.8	62.3	192,000	2.33	0.22	66.9	10.7

Table C2 – Worldwide Database of Roller Compacted Concrete (RCC) Dams

Table C-3 List of concrete dams in Reclamation's inventory

Name	Type	Height	Thickness	T/H
East Park Dam	Concrete Curved-Gravity	139	86	0.62
Owyhee Dam	Concrete Curved-Gravity	417	265	0.64
Clear Creek Dam	Concrete Curved-Gravity	84	54	0.64
Arrowrock Dam	Concrete Curved-Gravity	350	233	0.67
Hoover Dam	Concrete Curved-Gravity	726.4	660	0.91
Shasta Dam	Concrete Curved-Gravity	602	883	1.47
Upper Stillwater Dam	Concrete Gravity	285	70	0.25
Red Bluff Diversion Dam	Concrete Gravity	52	20	0.38
Elwha (NPS)	Concrete Gravity	108	50	0.46
American Falls Dam	Concrete Gravity	103.5	59	0.57
Brantley Dam - Concrete	Concrete Gravity	140	82.5	0.59
Easton Diversion Dam	Concrete Gravity	66	45	0.68
Putah Diversion Dam	Concrete Gravity	29	20	0.69
Keswick Dam	Concrete Gravity	157	110.6	0.70
Black Canyon Dam	Concrete Gravity	183	132	0.72
Jackson Lake Dam	Concrete Gravity	68	50	0.74
Elephant Butte Dam	Concrete Gravity	301	228	0.76
Boise River Diversion Dam	Concrete Gravity	68	52	0.76
Kortes Dam	Concrete Gravity	244	193	0.79
Folsom Dam	Concrete Gravity	340	270	0.79
Friant Dam	Concrete Gravity	319	267	0.84
Grand Coulee Dam	Concrete Gravity	550	500	0.91
Yellowtail Afterbay Dam	Concrete Gravity	72	106	1.47
Nimbus Dam	Concrete Gravity	87	135	1.55
Anchor Dam	Concrete Medium-Arch	208	54.2	0.26
Deadwood Dam	Concrete Medium-Arch	165	62	0.38
Flaming Gorge Dam	Concrete Medium-Arch	502	131	0.26
Warm Springs Dam	Concrete Medium-Arch	106	28	0.26
Yellowtail Dam	Concrete Medium-Arch	525	147	0.28
Seminoe Dam	Concrete Medium-Arch	295	85	0.29
Parker Dam	Concrete Medium-Arch	320	96.5	0.30
Buffalo Bill Dam	Concrete Medium-Arch	350	108	0.31
Monticello Dam	Concrete Medium-Arch	304	100	0.33
Glen Canyon Dam	Concrete Medium-Arch	710	300	0.42
Link River Dam	Concrete Spillway	22	-1	-0.05
Carson River Dam	Concrete Spillway	23	-1	-0.04
Three Mile Falls Diversion Dam	Concrete Spillway	28	-1	-0.04
Derby Diversion Dam	Concrete Spillway	31	-1	-0.03
Roza Diversion Dam	Concrete Spillway	67	-1	-0.01
Lake Tahoe Dam	Concrete Spillway	18	19	1.06
Granite Reef Dam	Concrete Spillway	29	42	1.45
Pathfinder Dam	Concrete Thick-Arch	214	96.5	0.45
Theodore Roosevelt Dam	Concrete Thick-Arch	357	184	0.52
Altus Dam	Concrete Thick-Arch	110	64	0.58
Hungry Horse Dam	Concrete Thick-Arch	564	330	0.59
Gibson Dam	Concrete Thick-Arch	199	117	0.59
East Canyon Dam	Concrete Thin-Arch	260	20	0.08
C. C. Cragin	Concrete Thin-Arch	170	14	0.08
Mormon Flat Dam	Concrete Thin-Arch	224	20	0.09
Crystal Dam	Concrete Thin-Arch	323	29	0.09
Glines Canyon (NPS)	Concrete Thin-Arch	210	20	0.10
Nambe Falls - Concrete Dam	Concrete Thin-Arch	150	15	0.10
Morrow Point Dam	Concrete Thin-Arch	468	52	0.11
Mountain Park Dam	Concrete Thin-Arch	133	17	0.13
Sun River Diversion Dam	Concrete Thin-Arch	132	20	0.15
Stewart Mountain Dam	Concrete Thin-Arch	207	33	0.16
Horse Mesa Dam	Concrete Thin-Arch	305	57	0.19
Gerber Dam	Concrete Thin-Arch	84.5	17.85	0.21

Note:

1. Suggest making T/H ratios < 0.2 for thin arch dams, 0.2 to 0.40 for medium-thick arch dams, 0.45 to 0.65 for thick arch dams, and > 0.65 for gravity or curved-gravity

Appendix D – Reclamation Concrete Dams Shapes

Figure D1 shows various plan views of dams in the Reclamation inventory. Figure D2 shows section views through the same dams. All the dams are drawn to the same scale for comparisons.

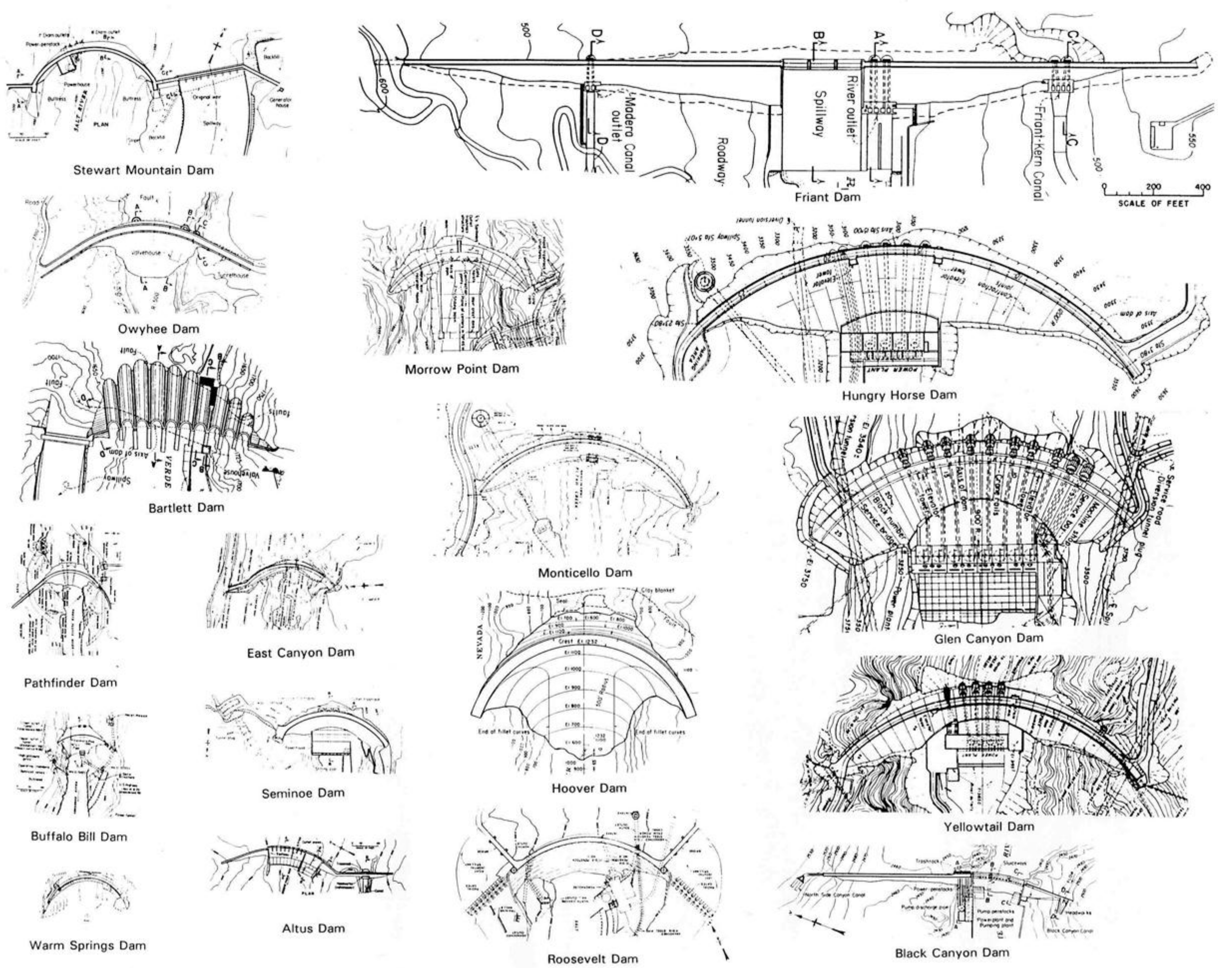


Fig D-1 Plan View of selected Reclamation Dams drawn to the same scale

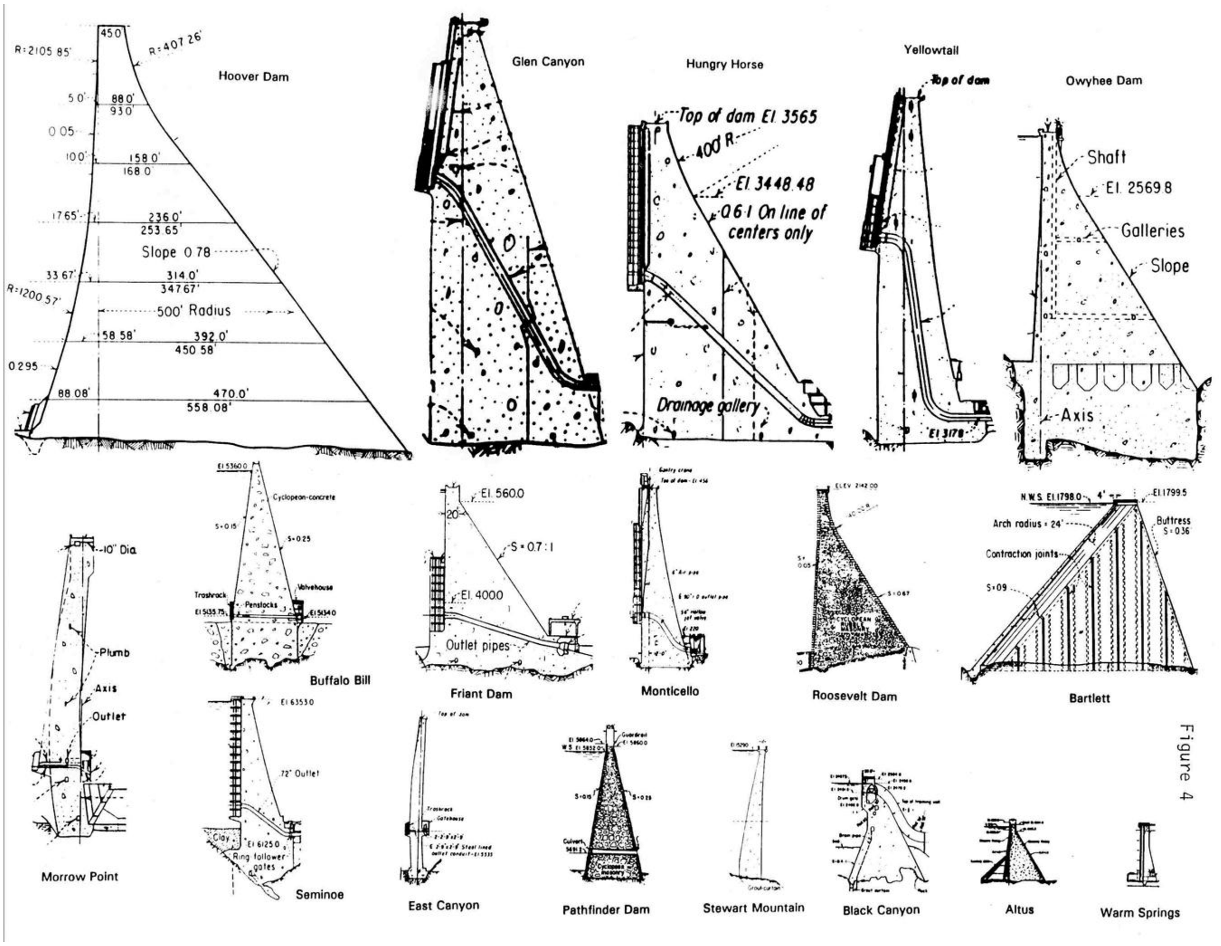


Fig D-2 Vertical section through the crown cantilever of many Reclamation dams drawn to the same scale

Appendix E – Arch Dam Layout - Excel Program

Program ARCH DAM LAYOUT was written in Microsoft Excel to help in the layout process for thin arch dams. The program uses the established process in EM No. 36. The user must first do some preliminary work on the site topography to position the dam, establish the orientation of the reference plane, measure distances across the canyon for L1 and L2, draw in the arches at various elevations, and measure the left and right angles off the axis center to the downstream side of the dam to the abutments. The user then inputs into the light green cells values (example values) for the depth of excavation to sound rock (25 feet), crest elevation (1005 feet), base elevation (340 feet), L1 (1782 feet), and L2 (500 feet). The program calculates (light purple cells) and rounds (yellow cells) values for the crest thickness, base thickness, R_{axis}, three points for the upstream projection of the upstream face, and three points for the downstream projection of the downstream face. The user can used the rounded values or select their own values (orange cells).

Upper San Joaquin

USJ-TBSL0.9C, Thrust Blocks, Raxis=1100, TEL=1005, BEL=340, Height=650, Crest=29, LOC SL 0.9C

Thursday, August 30, 2012

By Jerzy Salamon and Larry Nuss

General Dimensions

	Calculation	Rounded		
To rock	25			Excavation to sound rock
EL Crest	1005			Top of dam
EL Base	340			Base of dam to known sound rock
	365			Base of Alluvium
H	665			Height of dam
L1	1782			Distance across the canyon at H to sound rock (510 + 50)
0.15 H	99.75	100		15% Height of the dam
Elev at 0,15H	440			Elevation to 0.15 H
L2	500			Distance across the canyon at 0.15 H to sound rock (190 + 50)
Tc	28.034	29		Crest thickness
TB	118.2947893	118		Base thickness
T45	112.1	112		Thickness at 45% height of dam = 95% of TB
EL 0.45 H	639.25	640		Elevation at 0.45 H of dam
Raxis	1069.2	1070	1100	Distance from the axis to the top of the Line of Centers

(green)	=Input
(yellow)	= Rounded
(purple)	= Computed Result
(orange)	= Use

Upstream Face (Projections from Axis)

	USP		Elevation										
USP Crest	0		1005	x1, y1									
USP 0.45H	-112.1	-112	640	x2, y2									
USP Base	-79.06	-79	340	x3, y3									
	Center of curve through 3 points (see Figure A1)												
	x4	y4	s1	s4	b4	x5	y5	s2	s5	b5	XR	YR	Radius
	-56	822.5	3.258928571	-0.30684932	805.3164384	-95.5	490	-9.09090909	0.11	500.505	731.2269142	580.9399606	823.4545932
										Rounded:	701.266711	580	820
New USP Given Rounded Radius and Radius Elevation													
	USP		Elevation										
USP Crest			1005										
USP 0.45H		-116.535221	640										
USP Base		-82.8251203	340										

Downstream Face (Projections from Axis)

	DSP		Elevation										
DSP Crest	29		1005	x1, y1									
DSP 0.45	0	0	640	x2, y2									
DSP Base	38.94	39	340	x3, y3									
	Center of curve through 3 points												
	x4	y4	s1	s4	b4	x5	y5	s2	s5	b5	XR	YR (Elev)	Radius
	14.5	822.5	12.5862069	-0.07945205	823.6520548	19.5	490	-7.69230769	0.13	487.465	1605.07881	696.1252453	1595.591279
										Rounded:	1599.660689	700	1600
New USP Given Rounded Radius and Radius Elevation													
	USP		Elevation										
DSP Crest		29	1005										
DSP 0.45H		0.786084796	640										
DSP Base		40.68666742	340										

Figure E1 – First sheet of the ARCH DAM LAYOUT Excel spreadsheet

Next the user inputs elevations between the crest and base elevations into the line of centers worksheet (see Figure E2). , Then the user copies and pastes (values only) the radius length (feet), the distance of the radius center to the axis (XR), and the elevation of the radius center (YR). Points will be calculated at each elevation and plotted along the reference plane (see Figure E3). In Figure E2, the upstream face of the dam is defined by one circle with a radius of 820 feet and centered at 723.9993 feet from the axis at elevation 620. Notice the radius and elevation are rounded, but XR must be computed to permit a zero upstream projection at the crest. The extrados and intrados lines have a circle below elevation 600 and a line segment sloping at 0.9 from elevation 600 to 1000, and a vertical line between elevations 1000 to 1005. Elevations must be established at changed in geometry, such as points of tangency or points of compound curvature.

Upstream Face (Segments)							**Downstream Face (Segments)**							
Elevation	Dist U/S from Axis	Slope	Radius	XR	YR	DAMTEMP U/S Slope	Elevation	Dist D/S from Axis	Slope	Radius	XR	YR	DAMTEMP D/S Slope	Dam Thickness
1005	0	0	820	723.9993	620		1005	29	0	1600	1613.1007	780	-0.14	29.0
1000	-2.6368	0	820	723.9993	620	0.53	1000	28.2979	0	1600	1613.1007	780	-0.14	30.9
950	-26.6671	0	820	723.9993	620	0.48	950	22.1576	0	1600	1613.1007	780	-0.12	48.8
900	-46.7146	0	820	723.9993	620	0.40	900	17.6070	0	1600	1613.1007	780	-0.09	64.3
850	-63.0839	0	820	723.9993	620	0.33	850	14.6327	0	1600	1613.1007	780	-0.06	77.7
800	-76.0007	0	820	723.9993	620	0.26	800	13.2257	0	1600	1613.1007	780	-0.03	89.2
750	-85.6302	0	820	723.9993	620	0.19	750	13.3820	0	1600	1613.1007	780	0.00	99.0
700	-92.0889	0	820	723.9993	620	0.13	700	15.1019	0	1600	1613.1007	780	0.03	107.2
650	-95.4517	0	820	723.9993	620	0.07	650	18.3907	0	1600	1613.1007	780	0.07	113.8
625	-95.9854	0	820	723.9993	620	0.02	625	20.6262	0	1600	1613.1007	780	0.09	116.6
600	-95.7568	0	820	723.9993	620	-0.01	600	23.2579	0	1600	1613.1007	780	0.11	119.0
575	-94.7650	0	820	723.9993	620	-0.04	575	26.2878	0	1600	1613.1007	780	0.12	121.1
550	-93.0074	0	820	723.9993	620	-0.07	550	29.7182	0	1600	1613.1007	780	0.14	122.7
525	-90.4791	0	820	723.9993	620	-0.10	525	33.5517	0	1600	1613.1007	780	0.15	124.0
500	-87.1727	0	820	723.9993	620	-0.13	500	37.7912	0	1600	1613.1007	780	0.17	125.0
475	-83.0788	0	820	723.9993	620	-0.16	475	42.4400	0	1600	1613.1007	780	0.19	125.5
450	-78.1852	0	820	723.9993	620	-0.20	450	47.5018	0	1600	1613.1007	780	0.20	125.7
425	-72.4773	0	820	723.9993	620	-0.23	425	52.9805	0	1600	1613.1007	780	0.22	125.5
400	-65.9374	0	820	723.9993	620	-0.26	400	58.8806	0	1600	1613.1007	780	0.24	124.8
375	-58.5446	0	820	723.9993	620	-0.30	375	65.2070	0	1600	1613.1007	780	0.25	123.8
340	-46.7146	0	820	723.9993	620	-0.34	340	74.7899	0	1600	1613.1007	780	0.27	121.5

Intrados Line of Centers (Segments)							**Extrados Line of Centers (Segments)**						
Elevation	Dist D/S from Axis	Dist U/S from Raxis	Slope	Radius	XR	YR	Elevation	Dist D/S from Axis	Dist U/S from Raxis	Slope	Radius	XR	YR
1005	1100	0.0000	0	0			1005	1100	0.0000	0	0		
1000	1100.0000	0.0000	0.9	0			1000	1100.0000	0.0000	0.9	0		
950	1055.0000	45.0000	0.9	0			950	1055.0000	45.0000	0.9	0		
900	1010.0000	90.0000	0.9	0			900	1010.0000	90.0000	0.9	0		
850	965.0000	135.0000	0.9	0			850	965.0000	135.0000	0.9	0		
800	920.0000	180.0000	0.9	0			800	920.0000	180.0000	0.9	0		
750	875.0000	225.0000	0.9	0			750	875.0000	225.0000	0.9	0		
700	830.0000	270.0000	0.9	0			700	830.0000	270.0000	0.9	0		
650	785.0000	315.0000	0.9	0			650	785.0000	315.0000	0.9	0		
625	762.5000	337.5000	0.9	0			625	762.5000	337.5000	0.9	0		
600	740.0000	360.0000		500	1111.647073	265.5176342	600	740.0000	360.0000	0.9	0		
575	718.9377	381.0623		500	1111.647073	265.5176342	575	717.5000	382.5000		500	1111.647073	265.5176342
550	700.4661	399.5339		500	1111.647073	265.5176342	550	700.4661	399.5339		500	1111.647073	265.5176342
525	684.2492	415.7508		500	1111.647073	265.5176342	525	684.2492	415.7508		500	1111.647073	265.5176342
500	670.0386	429.9614		500	1111.647073	265.5176342	500	670.0386	429.9614		500	1111.647073	265.5176342
475	657.6458	442.3542		500	1111.647073	265.5176342	475	657.6458	442.3542		500	1111.647073	265.5176342
450	646.9254	453.0746		500	1111.647073	265.5176342	450	646.9254	453.0746		500	1111.647073	265.5176342
425	637.7638	462.2362		500	1111.647073	265.5176342	425	637.7638	462.2362		500	1111.647073	265.5176342
400	630.0721	469.9279		500	1111.647073	265.5176342	400	630.0721	469.9279		500	1111.647073	265.5176342
375	623.7807	476.2193		500	1111.647073	265.5176342	375	623.7807	476.2193		500	1111.647073	265.5176342
340	617.2258	482.7742		500	1111.647073	265.5176342	340	617.2258	482.7742		500	1111.647073	265.5176342

Figure E2 – Worksheet cells for the upstream, downstream, extrados, and intrados lines

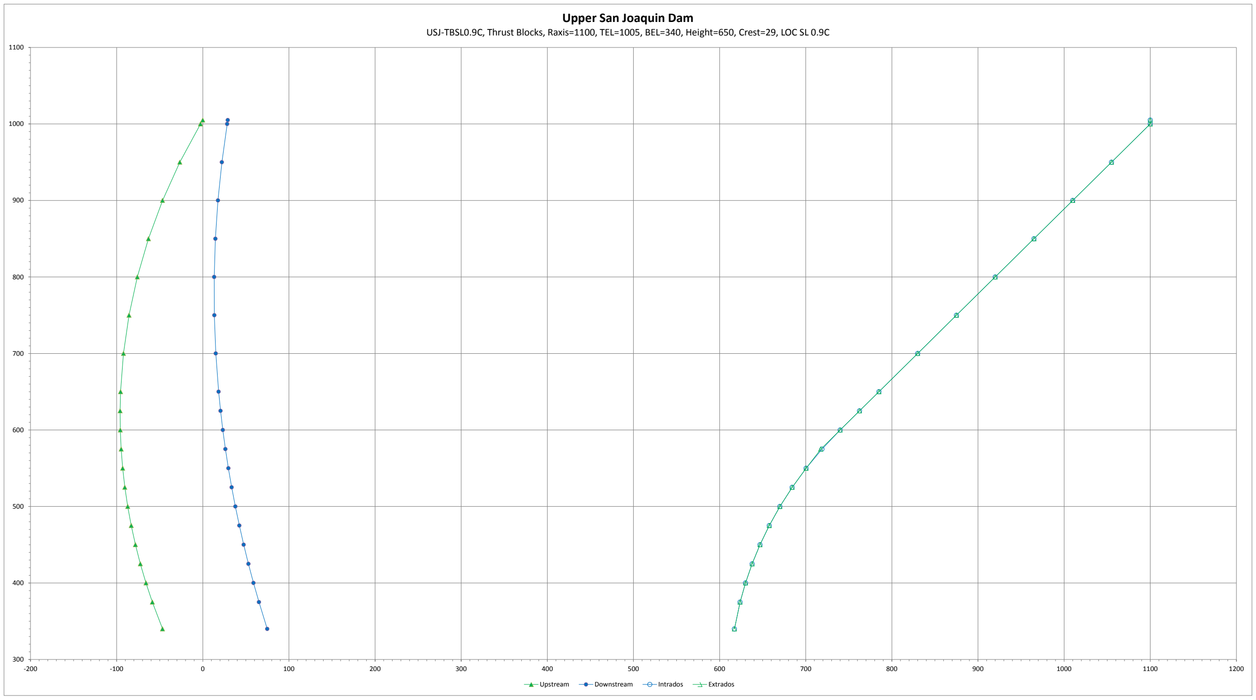


Figure E3 – Plot of the upstream and downstream faces and the extrados and intrados lines of centers.

The user then inputs left and right angles (looking upstream) about the axis center from the crown cantilever to the abutment alluvium in contact with the downstream face of the dam (see Figure E4). This establishes the geometric shape of the canyon visible canyon.

The depth of excavation to sound rock is computed perpendicular to the slope of the canyon and added to the alluvium profile to establish the sound rock profile.. Arc lengths are calculated and the profile is plotted (see Figure E5).

The user then inputs elevations and angles to establish a smooth canyon for design. The elevations may be the same as before or different depending if the excavation needs to be deeper than the standard 25 feet. The smooth canyon shape is plotted in Figure E5 along with the original canyon shape for comparison. The user can iterate and try different angles to establish the desired smooth canyon shape.

Upper San Joaquin

USJ-TBSL0.9C, Thrust Blocks, Raxis=1100, TEL=1005, BEL=340, Height=650, Crest=29, LOC SL 0.9C

Thursday, August 30, 2012

By Jerzy Salamon and Larry Nuss

Given			Conversions:	
Raxis	1100	ft	Deg 2 Rad	0.017453293
Excavation	25	ft	Rad 2 Deg	57.29577951

Old Raxis	1100
New Raxis	1100

Angle and Arc Length from Raxis Point

Elevations to Alluvium	Angle at Raxis to D/S Alluvium	Axis Arc Length to Alluvium	Average Angle Into Abutment at Each Elevation	Elevation to Sound Rock	Add Excavation to Sound Rock	Elevation to Smooth Canyon	Angle at Raxis to Smooth Canyon	Arc Length to Smooth Canyon	Plots Lines from Raxis on Plan View					Used One Time to Adjust New Angles to Ground in Raxis Changes	
Left Angle	(deg)	(ft)					(deg)	(ft)			1175				
1005	-60.000	-1152	-38.00	985.3	-1167.3	1005	-62	-1190		Left		Right		-60.000	-60.000
900	-53.000	-1018	-37.33	880.1	-1032.7	900	-55	-1056	S1005	0	-1037.46342	0	1037.463422	-53.000	-53.000
800	-46.000	-883	-33.48	779.1	-896.9	800	-48	-922		0	551.6290863	0	551.6290863	-46.000	-46.000
700	-37.000	-710	-28.80	678.1	-722.4	700	-40	-768	S900	0	-962.503652	0	962.503652	-37.000	-37.000
600	-27.000	-518	-27.51	577.8	-529.9	600	-30	-576		0	673.9523127	0	673.9523127	-27.000	-27.000
500	-17.000	-326	-28.80	478.1	-338.4	500	-20	-384	S800	0	-873.19517	0	873.1951699	-17.000	-17.000
400	-8.000	-154	-21.96	376.8	-162.9	400	-10	-192		0	786.2284625	0	786.2284625	-8.000	-8.000
365	0.000	0	0.00	340	0.0	340	0	0	S700	0	-755.275441	0	755.2754414	0.000	0.000
400	8.000	154	21.96	376.8	162.9	400	10	192		0	900.1022207	0	900.1022207	8.000	8.000
500	17.000	326	28.80	478.1	338.4	500	20	384	S600	0	-587.5	0	587.5	17.000	17.000
600	27.000	518	27.51	577.8	529.9	600	30	576		0	1017.579849	0	1017.579849	27.000	27.000
700	37.000	710	28.80	678.1	722.4	700	40	768	S550	0	-401.873668	0	401.8736684	37.000	37.000
800	46.000	883	33.48	779.1	896.9	800	48	922		0	1104.138829	0	1104.138829	46.000	46.000
900	53.000	1018	37.33	880.1	1032.7	900	55	1056	S510	0	-204.036609	0	204.0366088	53.000	53.000
1005	60.000	1152	38.00	985.3	1167.3	1005	62	1190		0	1157.14911	0	1157.14911	60.000	60.000
Right Angle															

Figure E4 – Angles to establish the shape of the canyon and the smoothed canyon shape

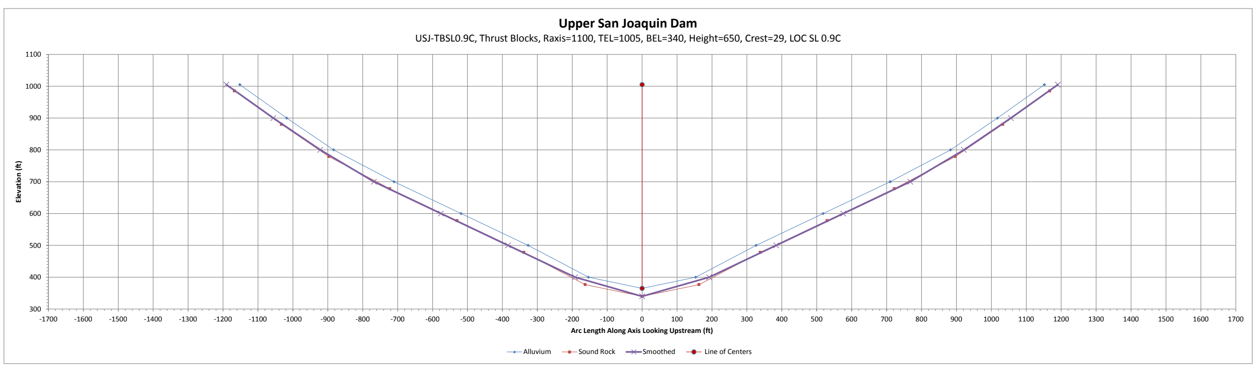


Figure E5 – Drawing showing the canyon shape of the alluvium, estimated location to sound rock, and the designer's desired profile for a smooth canyon.

Angles and Arc Lengths from Extrados and Intrados Lines of Centers

Elevation	Location of Extrados LOC (Y6)	Location of Intrados LOC (Y4)	Location Between Y6 and Y4 (Y5)	Upstream Face Projection (Y1)	Downstream Face Projection (Y3)	Mid-Thickness Projection(Y2)	D64	D43	D75	D52	Angle at Raxis (A7)	A9	Angle Between A4 and A6 (A5)	Point at Center of Abutment Thickness (X9)	Point at Center of Abutment Thickness (Y9)	Angle at Extrados for ADSAS (A6)	Angle at Intrados on Dam (A10)	Angle at Intrados (A4)	Radius from Raxis to U/S	Radius from Raxis to D/S	Radius from LOC to U/S	Radius from LOC to D/S
1005	0.0000	0.0000	0.0000	0.0000	29.0000	14.5	0.0000	1071.0000	0.0000	1085.5000	-62.0	0	-62	-958.439612	509.6113814	-62.0	0	-62	1100.00	1071.00	1100.00	1071.00
900	90.0000	90.0000	90.0000	-46.7146	17.6070	-14.553804	0.0000	992.3930	90.0000	1024.5538	-55.0	-4.1264	-59.1263911	-879.375921	615.7456487	-59.1	0	-59.1263911	1146.71	1082.39	1056.71	992.39
800	180.0000	180.0000	180.0000	-76.0007	13.2257	-31.3874972	0.0000	906.7743	180.0000	951.3875	-48.0	-8.0826	-56.0826271	-789.50238	710.8711355	-56.1	0	-56.0826271	1176.00	1086.77	996.00	906.77
700	270.0000	270.0000	270.0000	-92.0889	15.1019	-38.4934892	0.0000	814.8981	270.0000	868.4935	-40.0	-11.5271	-51.5271258	-679.945975	810.3280589	-51.5	0	-51.5271258	1192.09	1084.90	922.09	814.90
600	360.0000	360.0000	360.0000	-95.7568	23.2579	-36.2494101	0.0000	716.7421	360.0000	776.2494	-30.0	-13.4080	-43.4080299	-533.430314	923.9284059	-43.4	0	-43.4080299	1195.76	1076.74	835.76	716.74
500	429.9614	429.9614	429.9614	-87.1727	37.7912	-24.6907422	0.0000	632.2474	429.9614	694.7294	-20.0	-12.2204	-32.2204124	-370.414214	1017.70469	-32.2	0	-32.2204124	1187.17	1062.21	757.21	632.25
400	469.9279	469.9279	469.9279	-65.9374	58.8806	-3.52838366	0.0000	571.1914	469.9279	633.6004	-10.0	-7.3997	-17.3997431	-189.469668	1074.535885	-17.4	0	-17.3997431	1165.94	1041.12	696.01	571.19
340	482.7742	482.7742	482.7742	-46.7146	74.7899	14.03764204	0.0000	542.4359	482.7742	603.1882	0.0	0	0	0	1085.962358	0.0	0	0	1146.71	1025.21	663.94	542.44
400	469.9279	469.9279	469.9279	-65.9374	58.8806	-3.52838366	0.0000	571.1914	469.9279	633.6004	10.0	7.3997	17.39974315	189.4696682	1074.535885	17.4	0	17.39974315	1165.94	1041.12	696.01	571.19
500	429.9614	429.9614	429.9614	-87.1727	37.7912	-24.6907422	0.0000	632.2474	429.9614	694.7294	20.0	12.2204	32.22041244	370.4142143	1017.70469	32.2	0	32.22041244	1187.17	1062.21	757.21	632.25
600	360.0000	360.0000	360.0000	-95.7568	23.2579	-36.2494101	0.0000	716.7421	360.0000	776.2494	30.0	13.4080	43.40802991	533.4303138	923.9284059	43.4	0	43.40802991	1195.76	1076.74	835.76	716.74
700	270.0000	270.0000	270.0000	-92.0889	15.1019	-38.4934892	0.0000	814.8981	270.0000	868.4935	40.0	11.5271	51.52712585	679.9459754	810.3280589	51.5	0	51.52712585	1192.09	1084.90	922.09	814.90
800	180.0000	180.0000	180.0000	-76.0007	13.2257	-31.3874972	0.0000	906.7743	180.0000	951.3875	48.0	8.0826	56.08262714	789.5023796	710.8711355	56.1	0	56.08262714	1176.00	1086.77	996.00	906.77
900	90.0000	90.0000	90.0000	-46.7146	17.6070	-14.553804	0.0000	992.3930	90.0000	1024.5538	55.0	4.1264	59.12639108	879.3759209	615.7456487	59.1	0	59.12639108	1146.71	1082.39	1056.71	992.39
1005	0.0000	0.0000	0.0000	0.0000	29.0000	14.5	0.0000	1071.0000	0.0000	1085.5000	62.0	0	62	958.439612	509.6113814	62.0	0	62	1100.00	1071.00	1100.00	1071.00

Figure E6 – Computed angles from the Extrados Line of Centers for Input into ADSAS

A plan view is drawn of the various arches (see Figure E7). Dotted lines from the axis center to the abutments show the location of the smooth profile. Solid lines show the angles from the extrados and intrados lines of centers to the abutment.

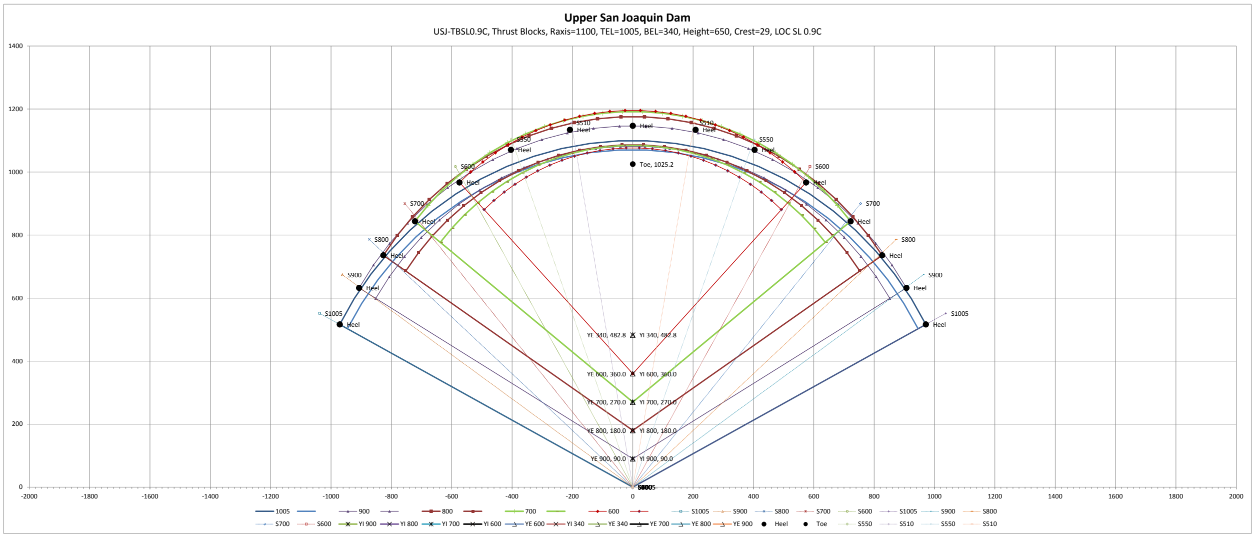


Figure E7 – Plan drawing of the arches to the smooth canyon

To establish the horizontal extent of the arches, ADSAS uses the angles about the extrados center from the reference plane to the abutment. In program ARCH DAM LAYOUT, the radii about the axis center to the smooth canyon shape are fixed and the angles ADSAS needs are computed (see Figure E6 light purple column). This angles are input directly intp the ADSAS input file in the 7 1 cards.

The geometry for an arch dam must have smooth transitions to not introduce stress concentrations. This requires the lines of centers to have smooth transitions: sloping lines tangent to circles, circles tangent to circles, etc. Line and circle geometry is input into ADSAS by defining points of tangency, radius lengths, centers of circles, and slopes of lines. This geometry can be computed in AUTOCAD, by hand, or in program ARCH DAM LAYOUT (see Figure E7.

Calculation Toolboxes

A Line with Slope S Transitioning into a Circle with Radius R

Given X1, Y1, S, Y2, Y3, and R — see Figure A2

Calculate XR, YR, X2, and X3

X1	Y1	S1	S2	X2	Y2	XR	YR	R	X3	Y3	r
1005	1100	0.9	-1.11111111	740.0	600	1111.6471	265.5176	500	617.2258	340	1.494847116

A Line with Slope S Transitioning into a Circle with Center on YR

Given X1, Y1, S, Y2, Y3, and YR — see Figure A3

Calculate XR, R, X2, and X3

X1	Y1	S1	S2	X2	Y2	XR	YR	R	X3	Y3
340	7165	0.4	-2.5	234.0	6900	698.23825	6714.3047	500.000	198.4430	6700

A Circle with Radius R1 Transitioning into a Circle with Radius R2

Given: X1, Y1, Y2, R1, YR1, Y3, and R2 — see Figure A4

Compute: X2, XR1, X3, XR2, and YR2

X1	Y1	X2	Y2	R1	XR1	YR1	X3	Y3	R2	XR2	YR2
38	1005	-1.1074	680	1370	1368.892558	680	87.01021602	340	700	698.8925576	680

A Sloping Line

Given: X1, Y1, S, and Y2 — see Figure A5

Compute: X2

X1	Y1	S	X2	Y2
340	7165	0.7	14.5	6700

Compute the Center of a Circle through 3 Points

Given: X1, Y1, X2, Y2, X3, Y3 — see Figure A4

Compute: XR, YR, R

X1	Y1	X2	Y2	X3	Y3							
38	1005	50	575	87	340							
x4	y4	s1	s4	b4	x5	y5	s2	s5	b5	XR	YR	Radius
44	790	-35.8333333	0.027906977	788.772093	68.5	457.5	-6.35135135	0.157446809	446.7148936	2640.55615	862.4620321	2597.567051
									Rounded:	2633.953582	860	2600

Slightly Rotate the Radius Around the Top Point

Given: X1, Y1, R, XR, YR, Delta Angle — Compute New XR — r2d 57.29577951 — d2r 0.017453293

X1	Y1	R	XR	YR	Old Angle	Delta Angle	New Angle	New XR	New YR	Radius
29	1005	1600	1599.6607	700	-10.9892607	3	-7.98926072	1613.47062	782.620021	1600
							Rounded:	1613.100691	780	1600

Compute the End of a Circle

Given: X1, Y1, Y2, R, and YR — see Figure A6

Compute: XR and X2

X1	Y1	X2	Y2	XR	YR	Radius
0	7165	-29.3243	6700	976.4092	6870	1020.0

A Circle with Radius R Transitioning into a Tangent Line

Given: X1, Y1, XR, YR, R, Y2, and YR — see Figure A7

Compute: X2 and X3

X1	Y1	X2	Y2	XR	YR	Radius	S1	S2	X3	Y3
0	7165	-43.5908	6900	976.4092	6900	1020.0	Infinity	0	-43.5908	6700

A Circular Fillet of Radius R Between 2 Lines

Given: X1, Y1, X2, Y2, X3 Y3 and R — see Figure A8

Compute: XR and YR — r2d 57.2958 — d2r 0.0175

X1	Y1	X2	Y2	X3	Y3	R			
500.0	500.0	0.0	0.0	500.0	-500.0	200.0			
T1	T2	T3	T4	D	XR	YR			
45.0000	-45.0000	90.0000	0.0000	282.8427	282.8427	0.0000			
s1	s2	s3	s4	r3	r4	X4	Y4	X5	Y5
1.0000	-1.0000	-1.0000	1.0000	1.4142	1.4142	141.4214	141.4214	141.4214	-141.4214

Chord Length Given Arc Length

Compute Chord Length Given Arc Length and Radius

Arc Length	Radius	Angle	Chord
2200	1000	126.0507	1782.4147

Compute Arc Length Given Chord Length and Radius

Chord	Radius	Angle	
1782.41472	1000	126.0507149	2200

ADSAS Input Help

	USP at Base	DSP at Base	B2	B1	Raxis			
3 1	46.7146	74.7899	482.7742	482.7742	1100	1000	3	1
	U/S Face	Slope	XR	YR	Radius			
5 1 1 1	1005.0000		701.2667	580.0	820.0			
	D/S Face	Slope						
5 1 2 1	1005.0000		1599.6607	700.0	1600			
	Base EL	Crest EL	Reservoir	Tailwater	Grout EL			
6 1	340	1005						

Figure E7 – Calculation Toolbox of Pre-established Geometries to Help in the Layout Process

Appendix F – ADSAS Input File and Program

F

Appendix G – Program to Extract Useful ASDAS Output

ADSAS produces considerable output, typically over 100 pages. A Visual Basic script in a Microsoft Excel spreadsheet is developed to read an ADSAS output file and write the data in columns based on station and elevation. In this form, the information is read into other programs for plotting. Data collected are arch moment, arch thrust, arch shear, upstream arch stress, downstream arch stress, upstream cantilever stress, and downstream cantilever stress. Eccentricities in the arch direction are computed by dividing the arch moment by the arch thrust.

Station	Elevation	Moment	Thrust	Shear	Ecc	U/S Arch	D/S Arch	U/S Cantilever	D/S Cantilever
2190.31	1005	454547	1260450	-178677	0.36	324.4	279.3	0	0
2057.35	1005	-765575	2120380	-61124	-0.36	469.8	545.7	0	0
1927.18	1005	-1463420	2734934	2488	-0.54	582.4	727.4	0	0
1776.10	1005	-1783482	3073453	9021	-0.58	647.6	824.3	0	0
1583.74	1005	-1247330	3157624	-16215	-0.40	694.3	817.9	0	0
1387.39	1005	346590	3168557	-19646	0.11	775.9	741.6	0	0
1193.14	1005	2261115	3133866	-13651	0.72	862.5	638.4	0	0
1000.00	1005	3170388	3108683	-268	1.02	901.5	587.3	0	0
806.86	1005	2260494	3131595	-13759	0.72	861.9	637.9	0	0
612.61	1005	348390	3170225	-19584	0.11	776.4	741.9	0	0
416.26	1005	-1247522	3157289	-16090	-0.40	694.3	817.9	0	0
223.90	1005	-1782988	3073318	9106	-0.58	647.6	824.3	0	0
72.82	1005	-1463704	2734815	2545	-0.54	582.4	727.4	0	0
-57.35	1005	-766052	2120322	-61071	-0.36	469.8	545.7	0	0
-190.31	1005	453231	1260442	-178643	0.36	324.3	279.4	0	0
2057.35	900	3037300	3532189	-37283	0.86	411.9	350.8	183	-19
1927.18	900	-12877570	4311438	-140043	-2.99	335.8	595.2	192	-23
1776.10	900	-15669670	5459820	-114051	-2.87	431.7	747.3	193	-15
1583.74	900	-14123370	6786748	-78266	-2.08	590.5	875.0	187	3
1387.39	900	1150601	7445564	-112660	0.15	815.4	792.3	182	18
1193.14	900	22202410	7538663	-89551	2.95	1037.5	590.3	178	28
1000.00	900	31911220	7492348	122	4.26	1130.3	487.5	175	33
806.86	900	22189360	7540024	-89573	2.94	1037.5	590.6	178	28
612.61	900	1156383	7444476	-112772	0.16	815.4	792.1	182	18
416.26	900	-14129260	6786959	-78260	-2.08	590.5	875.0	187	3
223.90	900	-15668510	5459836	-114123	-2.87	431.7	747.3	193	-15
72.82	900	-12875090	4311481	-140073	-2.99	335.8	595.2	192	-23
-57.35	900	3041760	3532200	-37293	0.86	412.0	350.7	183	-19
1927.18	800	-18387540	5154670	-348111	-3.57	305.0	497.4	223	88
1776.10	800	-37269480	6272845	-379906	-5.94	293.2	683.3	278	38
1583.74	800	-38856060	8045361	-388453	-4.83	422.8	829.5	273	62
1387.39	800	-4299629	9647346	-386180	-0.45	728.3	773.3	276	75

Figure G1 – Data extracted from an ADSAS output file by program ADSASREAD

Appendix H – Numerical, Contour, and Vector Plots of ADSAS Data

Commercially available program SURFER 11 is used to read the data from ADSASREAD (see Appendix G) and create plots of the numerical output, contour plots, and vector plots.

The first step in using SURFER 11 is to create a Blanking file (.bln) of the perimeter along the axis of the dam of the profile of the dam. This data can be cut, pasted, and slightly modified from the ADSASREAD file.

```
16,0
2190.31,1005
2057.35, 900
1927.18, 800
1776.10, 700
1583.74, 600
1387.39, 500
1193.14, 400
1000.00, 340
806.86,  400
612.61,  500
416.26,  600
223.90,  700
72.82,   800
-57.35,  900
-190.31,1005
2190.31,1005
```

Figure H1 – SURFER 11 Blanking File (.bln)

```
Sub Main

'Declare the variable that will reference the application
    Dim SurferApp As Object
    Set SurferApp = CreateObject("Surfer.Application")
    SurferApp.Visible = True

'Declares Plot as an object
    Dim Plot As Object
    Set Plot = SurferApp.Documents.Add

    Set ExcelCol = 6        '6 = Eccentricity, 7 = Upstream, 8 = Downstream
    Set UserPath = "c:\Users\lnuss\Nuss Eng\Boggs\USJ TB SL0.9 C B340 S\"
    Set Plotfile = "Temporary.jpg"
' -------------------------------------------------
'  ARCH STRESSES

'Creates a post map and assigns the map frame to the variable "MapFrame"
'  3=Moment, 4 = Thrust, 5=Shear, 6=Ecc, 7=U/S Arch, 8=D/S Arch, 9=U/S Cant, 10=D/S Cant
    Set MapFrame = Plot.Shapes.AddPostMap( _
    UserPath + "ADSASread_5.xlsm", LabCol:=ExcelCol)

'Declares PostMap as an Object and assigns the post map to variable "PostMap"
    Dim PostMap As Object
    Set PostMap = MapFrame.Overlays(1)

'Sets the label properites
  'Sets the label format properties. For all options, see LabelFormat object.
    PostMap.LabelFormat.NumDigits = 0
    PostMap.LabelFormat.Type = srfLabFixed                     'srfLabFixed, srfLabExpon,
srfLabGeneral

  'Sets the label font properties. For all optiosn, see FontFormat object.
    PostMap.LabelFont.Face = "Arial"
    PostMap.LabelFont.Size = 6
    PostMap.LabelFont.ForeColorRGBA.Color = srfColorBlue
    PostMap.LabelFont.Bold = True

'Sets the angle for the label text
    PostMap.LabelAngle = 0           ' Use 0 for Arch, 90 for Cantilever

'Sets the label position relative to the symbol (Center, Left, Right, Above, Below, User)
    PostMap.LabelPos = srfPostPosUser       'or use:   srfPostPosAbove, Below, Left, Right, User
'   PostMap.LabelPos = srfPostPosUser
    PostMap.LabelXOffset =  0.1          ' Use X Offset = 0.2 for Arch, -0.05 for Cant
    PostMap.LabelYOffset = -0.02        ' Use YOffset = 0.05 for Arch,  0.2 for Cant

If ExcelCol > 6 Then
'-----------------------------------------------------------------------------
' CANTILEVER STRESSES
'Creates a post map and assigns the map frame to the variable "MapFrame"
'  3=Moment, 4 = Thrust, 5=Shear, 6=Ecc, 7=U/S Arch, 8=D/S Arch, 9=U/S Cant, 10=D/S Cant
    Set MapFrame = Plot.Shapes.AddPostMap( _
    UserPath + "ADSASread_5.xlsm", LabCol:=ExcelCol+2)

'Declares PostMap as an Object and assigns the post map to variable "PostMap"
'   Dim PostMap As Object
    Set PostMap = MapFrame.Overlays(1)

'Sets the label properites
  'Sets the label format properties. For all options, see LabelFormat object.
    PostMap.LabelFormat.NumDigits = 0
    PostMap.LabelFormat.Type = srfLabFixed                     'srfLabFixed, srfLabExpon,
srfLabGeneral

  'Sets the label font properties. For all optiosn, see FontFormat object.
    PostMap.LabelFont.Face = "Arial"
    PostMap.LabelFont.Size = 6
    PostMap.LabelFont.ForeColorRGBA.Color = srfColorRed
    PostMap.LabelFont.Bold = True
```

```
'Sets the angle for the label text
    PostMap.LabelAngle = 80         ' Use 0 for Arch, 90 for Cantilever

'Sets the label position relative to the symbol (Center, Left, Right, Above, Below, User)
    PostMap.LabelPos = srfPostPosUser        'or use:   srfPostPosAbove, Below, Left, Right, User
'   PostMap.LabelPos = srfPostPosUser
    PostMap.LabelXOffset =  -0.02       ' Use 0.2 for Arch, -0.05 for Cant
    PostMap.LabelYOffset =   0.1        ' Use 0.05 for Arch,  0.2 for Cant

End If
' ----------------------------------------------------------------------
'BASEMAP

    Set MapFrame = Plot.Shapes.AddBaseMap( _
    UserPath + "USJBlankCant.bln")
    Dim BaseMap As Object
    Set BaseMap = MapFrame.Overlays(1)

' ------------------------------------------------
Plot.Export(Filename:= _
        UserPath + Plotfile)

Wait 1
'   Plot.Close(SaveChanges:=1)

End Sub
```

Figure H2 – Visual Basic script for SURFER 11 to plot numeric data

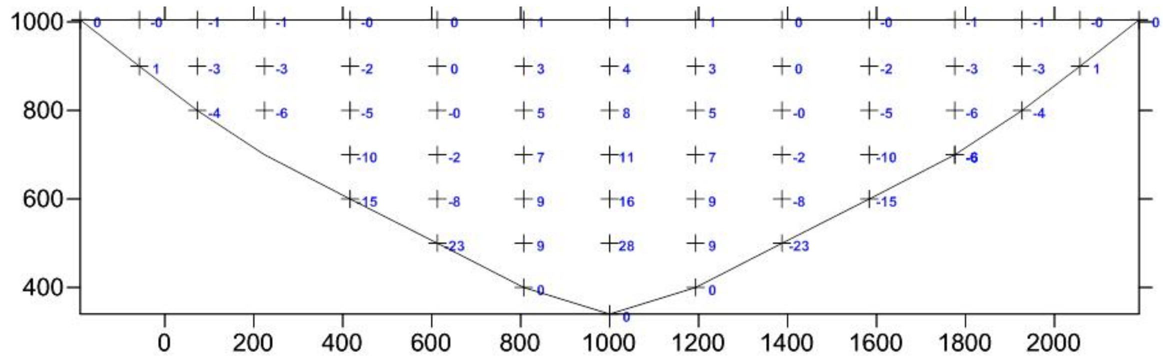


Figure H3 – Plot of Arch Eccentricity using SURFER 11

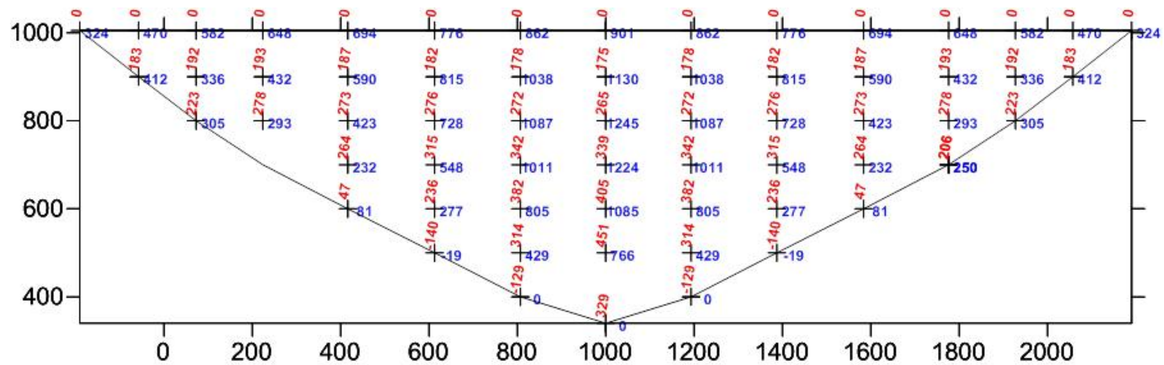


Figure H4 – Plot of Upstream Arch and Cantilever Stresses using SURFER 11

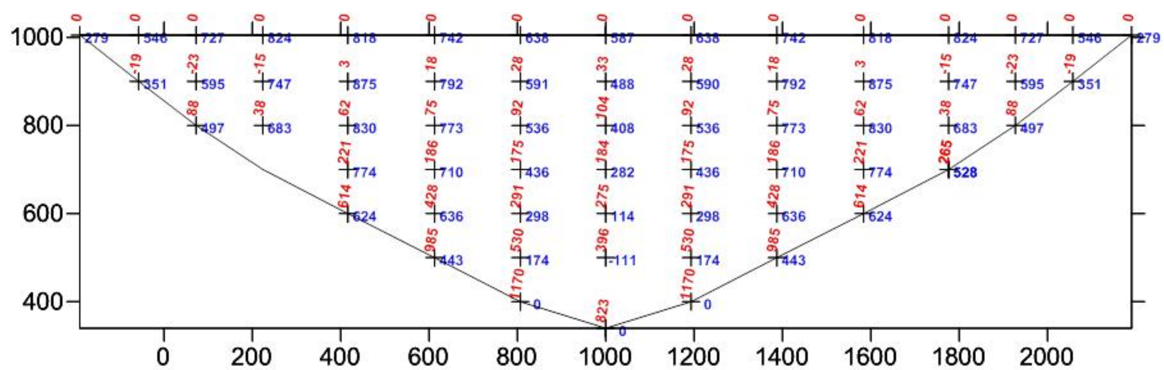


Figure H5 – Plot of Downstream Arch and Cantilever Stresses using SURFER 11

Appendix I – Compute Internal Temperatures in an Arch Dam

Program DAMTEMP calculates the range of mean concrete temperatures in mass concrete as explained in Engineering Monograph #34 (revised reprint 1981). The program requires 1) at various dam elevations: the dam thickness, reservoir temperatures, terrain factors, and the slope of the upstream and downstream face, 2) monthly average maximum and minimum temperatures, the lowest temperature on record, the highest temperature on record, and the angle off North of 3 locations on the dam (P1, P2, and P3).

Temperature Data, Latitude, Elevation, and Length of Record

Monthly maximum and minimum ambient air average temperatures, lowest temperature on record, and highest record on record can be obtained at website:

http://www.wrcc.dri.edu/climsum.html

The ambient air temperature record should be in relatively close proximity to the dam site, be at approximately the same elevation, and be a long time duration (20 years or more are preferable). DAMTEMP will adjust the temperature record to match the site. An increase of 250 feet in elevation decreases the temperature 1°F, and an increase in 1.4° in latitude decreases the temperature 1°F.

Maximum and minimum reservoir temperature at various depths can be obtained from Engineering Monograph #34 in figures 12, 13, and 14. The reservoir data selected from these figures should be from sites that have similar mean annual air temperatures and mean annual reservoir discharge rates.

Diffusivity

Diffusivity is a measure of the rate concrete undergoes temperature change and is computed from conductivity, specific heat, and density:

$$h^2 = \frac{K}{C\gamma}$$

where: h^2 = diffusivity (ft^2/hour)
K = conductivity (BTU/ft/hr/°F)
C = specific heat (BTU/lb)
γ = density (lb/ft^3)

Values for diffusivity for concrete at numerous Reclamations dams and for various coarse aggregates are listed in table I in Engineering Monograph #34. An average value and a reasonable value to use for diffusivity is 0.045 ft^2/hr.

Solar Radiation

The effect of solar radiation on the surfaces of the dam is a function of the latitude of the site, the orientation of the surface relative to North, the terrain factor, and the slope of the surface off vertical. DAMTEMP computes the effect of solar radiation at 3 vertical sections across the dam at locations defined by the user.

Surface orientation - The orientation of the upstream and downstream face relative to North at Points 1, 2, and 3 are input in degrees between 0° and 180° (variables P1US, P1DS, P2US, P2DS, P3US, and P3DS; 0° ≤ values ≤ 180°).

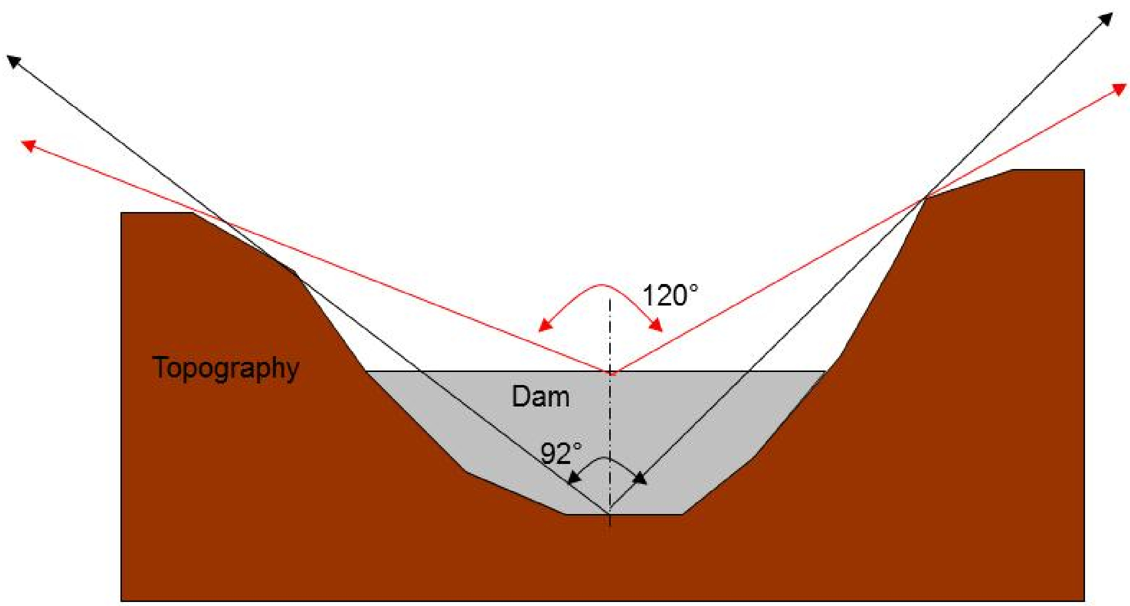
Slope of face – The slope of the upstream and downstream face relative to vertical (0 = vertical) are input in fraction of horizontal to 1.0 vertical (variables S1US, S1DS, S2US, S2DS, S3US, S3DS) at each elevation.

Terrain factor - The terrain factor is the fraction of the angle the sun shines on the dam given the topography of the site to the angle of flat ground (180°).

Terrain factors for this example:

for top of dam = 120°/180° = 0.66

for the base of the dam = 92°/180° = 0.51



Elevation View Along East-West Plane Through Dam

Input File Directions:

Card	Variable	Format	Description
0	Heading	a80	80 character title

Input data at various elevations:

Card	Variable	Format	Description
1	Elevation	*	Elevation
	Thick	*	Dam thickness at this elevation
	Water Low	*	Low water temperature at this elevation
	Water high	*	High water temperature at this elevation
	TFact	*	Terrain factor at this elevation
	S1US	*	Slope of upstream face at point 1
	S1DS	*	Slope of downstream face at point 1
	S2US	*	Slope of upstream face at point 2
	S2DS	*	Slope of downstream face at point 2
	S3US	*	Slope of upstream face at point 3
	S3DS	*	Slope of downstream face at point 3
1+	0,0,0,0,0,0,0,0,0,0,0		Enter as many card 1's as desired. Terminate this section with 11 zeros

Input about location of dam and where temperature data was measured

Card	Variable	Format	Description
2	DElev	*	Elevation at damsite
	DLat	*	Latitude of the dam site (degrees)
	TElev	*	Elevation of temperate data record
	TLat	*	Latitude of temperature data record (degrees)
3	Town	a10	Name of weather station
4	State	a10	State of weather station

Input 12 cards of mean minimum and maximum temperature pairs for each month

Card	Variable	Format	Description
5	MonthMin	*	Mean monthly minimum for January
	MonthMax	*	Mean monthly maximum for January

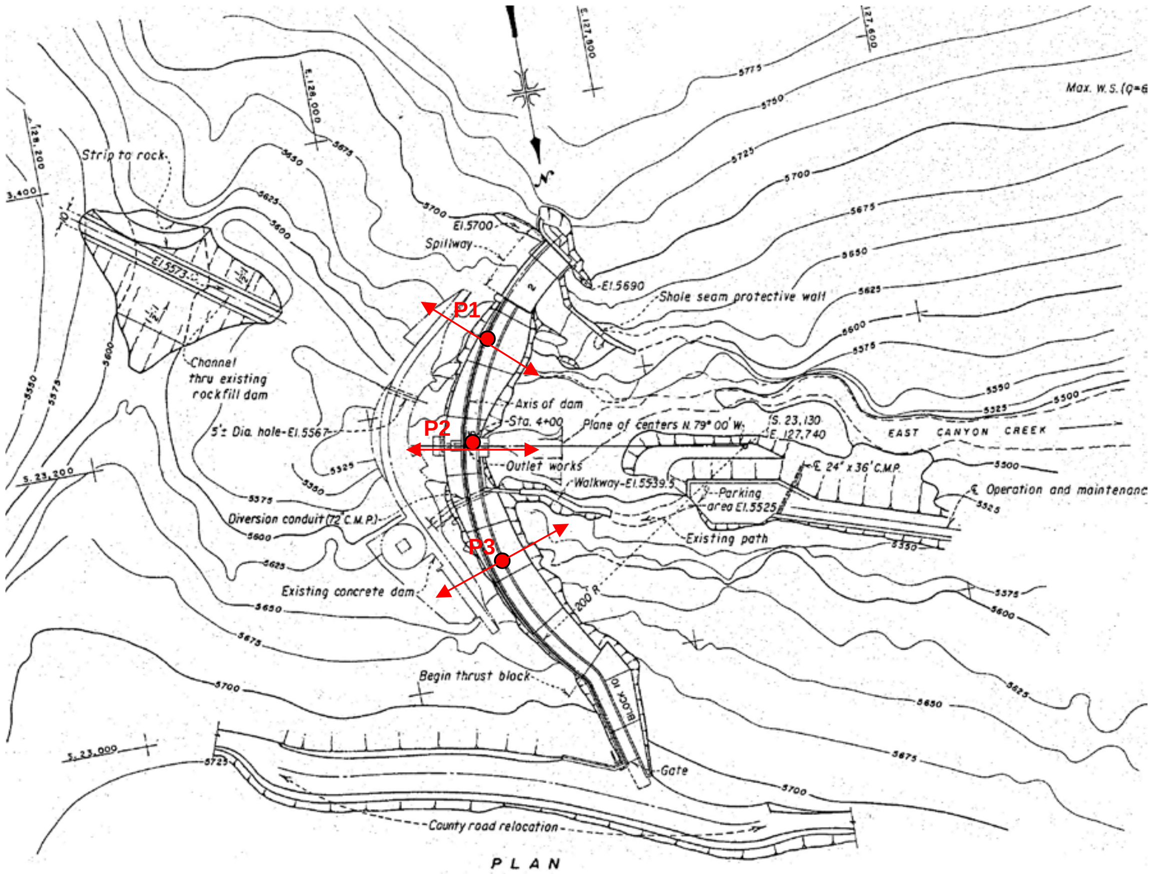
Input extreme temperatures and thermal property of the concrete

Card	Variable	Format	Description
6	TLowest	*	Lowest temperature on record
	THighest	*	Highest temperature on record
	Diff	*	Diffusivity

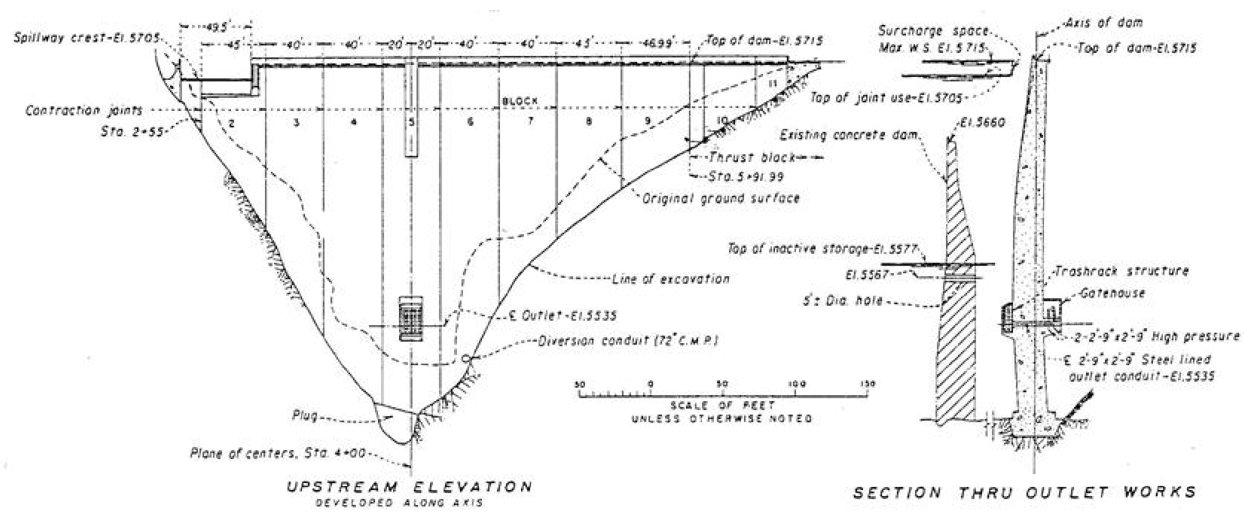
Input angle (0 to 180) between North and vector normal to the face at 3 locations selected by the user. Locations are typical at the quarter points of the dam:

Card	Variable	Format	Description
7	P1US	*	Upstream face of point 1
	P1DS	*	Downstream face of point 1
	P2US	*	Upstream face of point 1
	P2DS	*	Downstream face of point 1
	P3US	*	Upstream face of point 1
	P3DS	*	Downstream face of point 1
8	TGrout	*	Grout temperature

East Canyon Dam Example



Location and Orientation of P1US, P1DS, P2US, P2DS, P3US, and P3DS



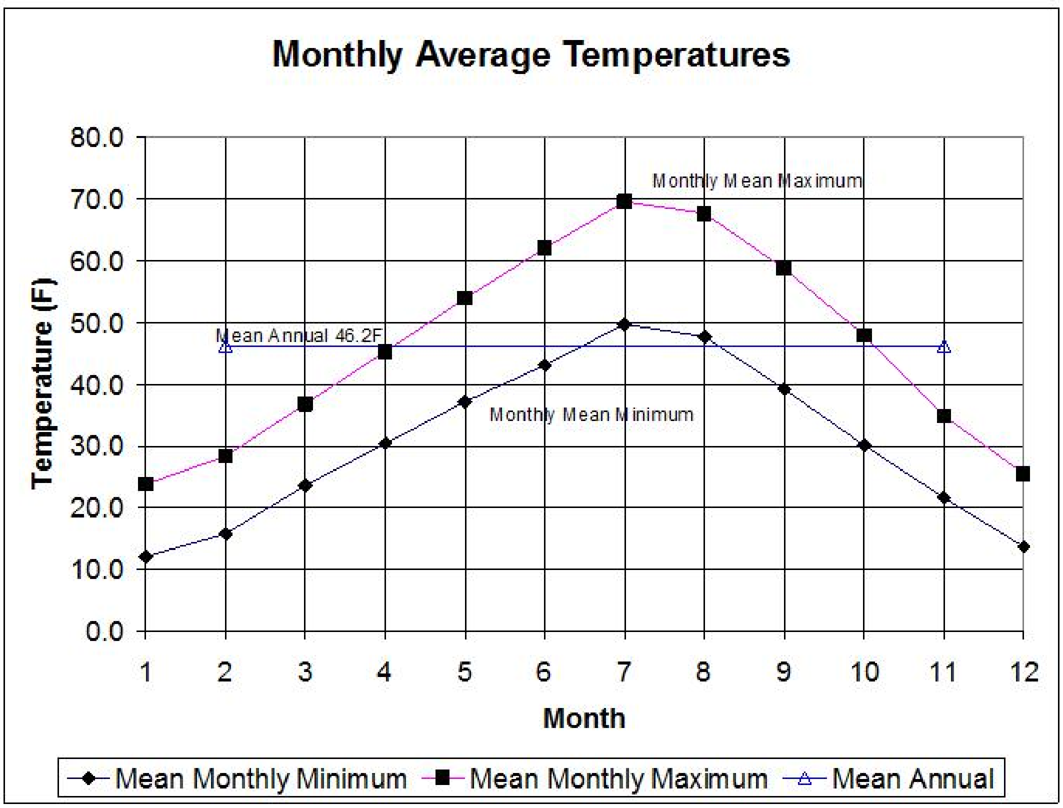
Plan, Profile, and Section of Dam

East Canyon Dam

Ambient Air Temperatures (Fahrenheit)
Monthly Maximum and Minimum Temperatures
Morgan, Utah - Record from 1948 to 2004
www.wrcc.dri.edu

Month	Mean Low (F)	Mean High (F)	Average (F)
Jan	12.1	35.5	23.8
Feb	15.8	40.9	28.4
Mar	23.6	50.0	36.8
Apr	30.4	60.2	45.3
May	37.2	70.6	53.9
Jun	43.1	81.0	62.1
Jul	49.7	89.5	69.6
Aug	47.7	87.6	67.7
Sep	39.2	78.2	58.7
Oct	30.1	65.8	48.0
Nov	21.6	48.2	34.9
Dec	13.7	37.3	25.5
Average	30.4	62.1	46.2

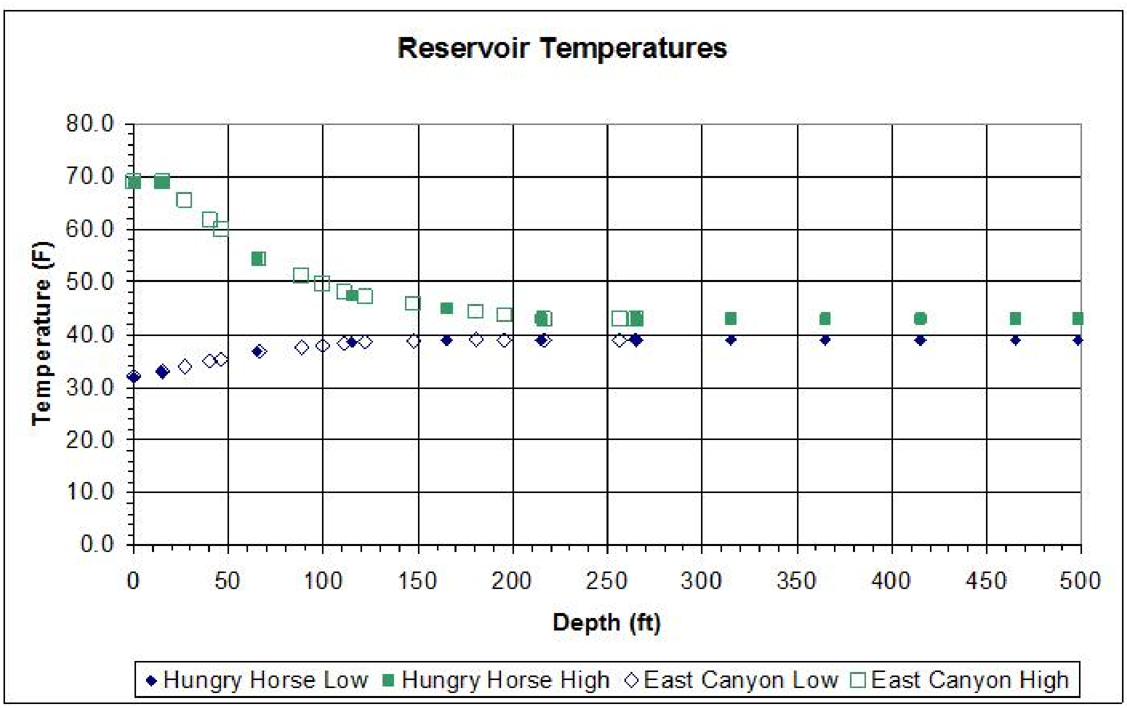
Historic Maximum 105.0 July 14, 2002
Historic Minimum -33.0 January 23, 1990



Mean Monthly Temperatures From Website

EAST CANYON DAM
RESERVOIR TEMPERATURES INTERPOLATED FROM HUNGRY HORSE DAM

Hungry Horse Reservoir Temperatures					East Canyon Reservoir Temperatures			
Elev	Depth	Low	High		Elev	Depth	Low	High
3067	498	39.0	43.0					
3100	465	39.0	43.0					
3150	415	39.0	43.0					
3200	365	39.0	43.0					
3250	315	39.0	43.0					
3300	265	39.0	43.0					
					5450.0	265.0	39.0	43.0
					5458.5	256.5	39.0	43.0
					5498.6	216.4	39.0	43.0
3350	215	39.0	43.0					
					5519.3	195.7	39.0	43.8
					5534.3	180.7	39.0	44.4
3400	165	39.0	45.0					
					5567.4	147.6	38.8	45.9
					5592.9	122.1	38.6	47.1
3450	115	38.5	47.5					
					5604.0	111.0	38.4	48.1
					5615.5	99.5	38.0	49.7
					5626.7	88.3	37.6	51.2
					5649.0	66.0	36.8	54.4
3500	65	36.8	54.5					
					5669.0	46.0	35.4	60.0
					5675.0	40.0	34.9	61.8
					5688.0	27.0	33.9	65.5
					5700.0	15.0	33.0	69.0
3550	15	33.0	69.0			15	33.0	69.0
3565	0	32.0	69.0		5715.0	0.0	32.0	69.0

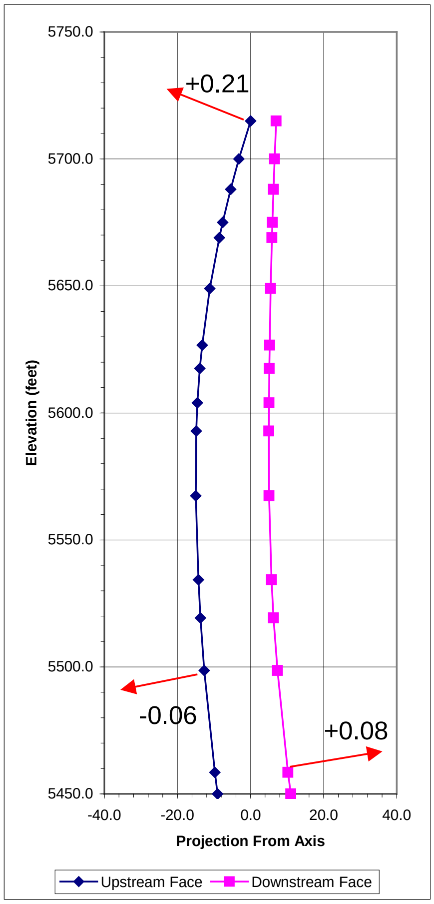


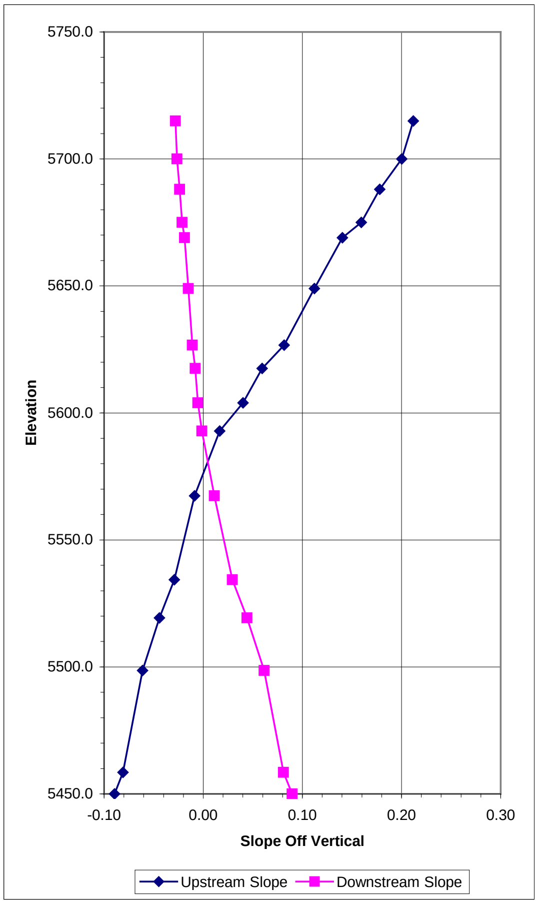
Reservoir Temperatures Interpolated from Hungry Horse Dam in EM #34,

East Canyon Dam
Crown Cantilever and Axis Centers (feet)

Elevation (feet)	Thickness (feet)	Upstream Projection (feet)	Downstream Projection (feet)	Intrados Radius (feet)	Extrados Radius (feet)	Slope (H/V) Upstream	Slope (H/V) Downstream
5450.0	20.010	-8.994	11.016	45.545	69.550	-0.09	0.09
5458.5	20.009	-9.755	10.254	46.525	70.382	-0.08	0.08
5498.6	20.006	-12.648	7.358	55.000	77.790	-0.06	0.06
5519.3	20.005	-13.693	6.312	62.020	83.974	-0.04	0.04
5534.3	20.003	-14.259	5.744	68.343	89.536	-0.03	0.03
5567.4	20.001	-14.944	5.057	86.464	105.363	-0.01	0.01
5592.9	19.883	-14.865	5.018	105.128	121.396	0.02	0.00
5604.0	19.594	-14.532	5.063	114.850	129.610	0.04	-0.01
5617.5	19.009	-13.856	5.154	128.288	140.776	0.06	-0.01
5626.7	18.463	-13.224	5.239	138.370	149.030	0.08	-0.01
5649.0	16.639	-11.117	5.522	162.687	167.476	0.11	-0.01
5669.0	14.395	-8.526	5.868	178.753	179.496	0.14	-0.02
5675.0	13.608	-7.618	5.990	182.350	182.500	0.16	-0.02
5688.0	11.722	-5.443	6.279	189.000	189.000	0.18	-0.02
5700.0	9.759	-3.179	6.580	195.000	195.000	0.20	-0.03
5715.0	7.000	0.000	7.000	200.000	200.000	0.21	-0.03

Height (feet)	Crest Length (feet)	Crest Left (feet)	Crest Right (feet)	Raxis (feet)	R3C (feet)	ACC (degrees)
265	363.736	171.75	191.986	200	N/A	55



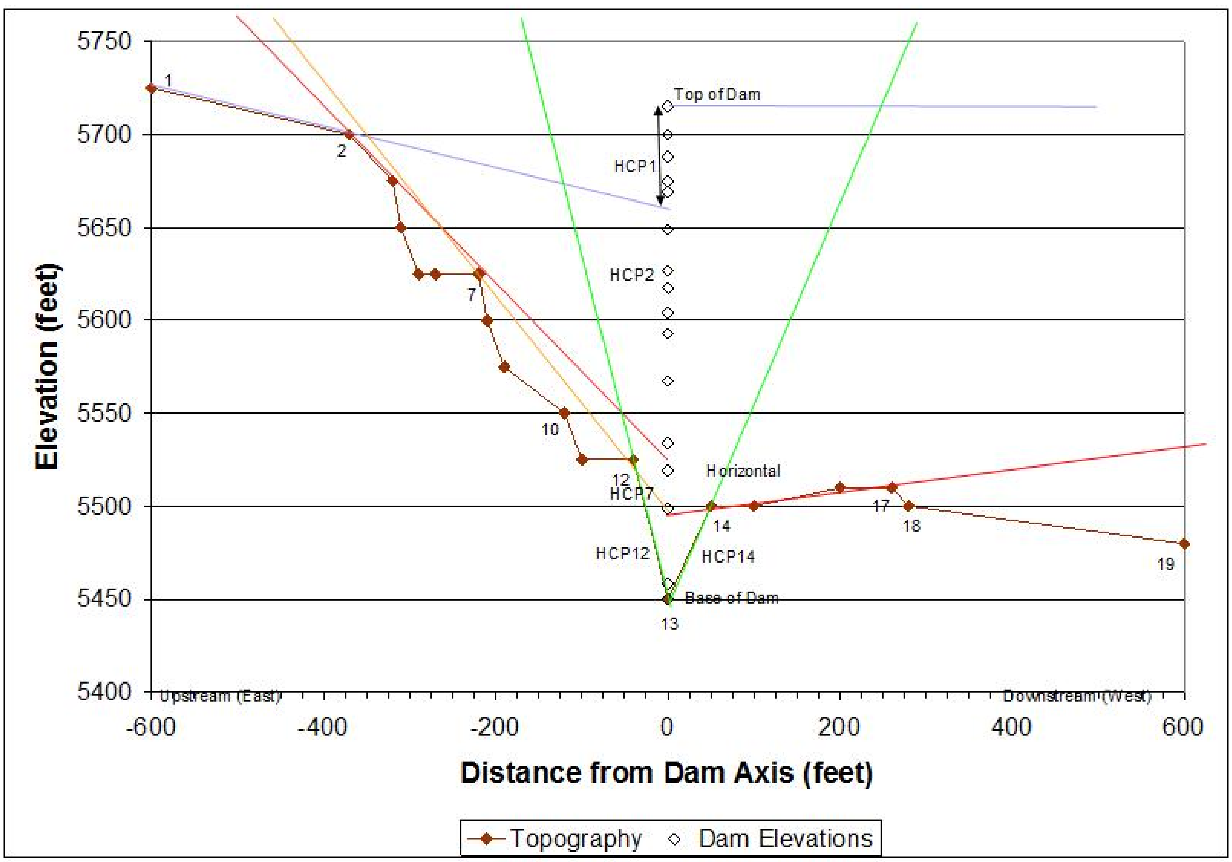


Slope of the Upstream and Downstream Face. Positive is up.

East Canyon Dam

West to East Topography and Terrain Factor

Horizontal Point Number	Topography		Crown Cantilever		Upstream		Downstream		Terrain Factor	
	Distance From Line of Centers	Elevation	Distance From Line of Centers	Elevation	Horizon Control Point	Angle To Terrain	Horizon Control Point	Angle To Terrain		
East - U/S	-600	5725	0	5715	1	89.05	Horizontal	90.00	0.99	1
2	-370	5700	0	5700	1	87.61	Horizontal	90.00	0.99	2
3	-320	5675	0	5688	1	86.47	Horizontal	90.00	0.98	3
4	-310	5650	0	5675	1	85.24	Horizontal	90.00	0.97	4
5	-290	5625	0	5669	1	84.67	Horizontal	90.00	0.97	5
6	-270	5625	0	5649	2	82.15	Horizontal	90.00	0.96	6
7	-220	5625	0	5626.7	2	78.79	Horizontal	90.00	0.94	7
8	-210	5600	0	5617.5	2	77.43	Horizontal	90.00	0.93	8
9	-190	5575	0	5604	2	75.45	Horizontal	90.00	0.92	9
10	-120	5550	0	5592.9	2	73.86	Horizontal	90.00	0.91	10
11	-100	5525	0	5567.4	2	70.28	Horizontal	90.00	0.89	11
12	-40	5525	0	5534.3	2	65.88	Horizontal	90.00	0.87	12
13	0	5450	0	5519.3	7	64.34	Horizontal	90.00	0.86	13
14	50	5500	0	5498.6	7	60.12	14	88.40	0.83	14
15	100	5500	0	5458.5	12	31.03	14	50.31	0.45	15
16	200	5510	0	5450	12	28.07	14	45.00	0.41	16
17	260	5510								
18	280	5500								
West-D/S	600	5480								



Terrain Factor Calculations – East to West Profile (Determine the location on the topography where the sun will shine on a given point on the dam and determine the angle.

```
        PROGRAM DAMTEMP - RANGE OF MEAN CONCRETE TEMPERATURES
             "CONTROL OF CRACKING IN MASS CONCRETE STRUCTURES"
             U.S. BUREAU OF RECLAMATION
             ENGINEERING MONOGRAPH NO. 34
             REVISED REPRINT 1981.


         INPUT DATA FILE:

East Canyon Dam, Damtemp                                                          CARD  1
5450.0 20.00 39.0 43.0 0.41 -0.09  0.09 -0.09  0.09 -0.09  0.09                   CARD  2
5458.5 20.00 39.0 43.0 0.45 -0.08  0.08 -0.08  0.08 -0.08  0.08                   CARD  3
5498.6 20.00 39.0 43.0 0.83 -0.06  0.06 -0.06  0.06 -0.06  0.06                   CARD  4
5528.3 20.00 39.0 43.8 0.86 -0.04  0.04 -0.04  0.04 -0.04  0.04                   CARD  5
5545.3 20.00 39.0 44.4 0.87 -0.03  0.03 -0.03  0.03 -0.03  0.03                   CARD  6
5567.4 20.00 38.8 45.9 0.89 -0.01  0.01 -0.01  0.01 -0.01  0.01                   CARD  7
5592.9 19.88 38.6 47.1 0.91  0.02 -0.00  0.02 -0.00  0.02 -0.00                   CARD  8
5604.0 19.59 38.4 48.1 0.92  0.04 -0.01  0.04 -0.01  0.04 -0.01                   CARD  9
5617.5 19.00 38.0 49.7 0.93  0.06 -0.01  0.06 -0.01  0.06 -0.01                   CARD 10
5626.7 18.46 37.6 51.2 0.94  0.08 -0.01  0.08 -0.01  0.08 -0.01                   CARD 11
5640.0 17.46 36.8 54.4 0.96  0.11 -0.01  0.11 -0.01  0.11 -0.01                   CARD 12
5654.8 16.05 35.4 60.0 0.97  0.14 -0.02  0.14 -0.02  0.14 -0.02                   CARD 13
5675.0 13.60 34.9 61.8 0.97  0.16 -0.02  0.16 -0.02  0.16 -0.02                   CARD 14
5688.0 11.72 33.9 65.5 0.98  0.18 -0.02  0.18 -0.02  0.18 -0.02                   CARD 15
5700.0  9.75 33.0 69.0 0.99  0.20 -0.03  0.20 -0.03  0.20 -0.03                   CARD 16
5715.0  7.00 32.0 69.0 0.99  0.21 -0.03  0.21 -0.03  0.21 -0.03                   CARD 17
0 0 0 0 0 0 0 0 0 0 0 0 0 0                                                       CARD 18
5450 40.9206 5070 41.05                                                           CARD 19
Morgan                                                                            CARD 20
Utah                                                                              CARD 21
12.1 35.5                                                                         CARD 22
15.8 40.9                                                                         CARD 23
23.6 50.0                                                                         CARD 24
30.4 60.2                                                                         CARD 25
37.2 70.6                                                                         CARD 26
43.1 81.0                                                                         CARD 27
49.7 89.5                                                                         CARD 28
47.7 87.6                                                                         CARD 29
39.2 78.2                                                                         CARD 30
30.1 65.8                                                                         CARD 31
21.6 48.2                                                                         CARD 32
13.7 37.3                                                                         CARD 33
-33.0  105.0  0.045                                                               CARD 34
107.0  73.0  79.0 101.0  50.0 129.0                                               CARD 35
36.0                                                                              CARD 36

    AMBIENT AIR TEMPERATURES IN DEGREES FAHRENHEIT
                Morgan    , Utah
                EL.5070.00   LAT. 41.05N
------------------------------------------------------------
        MONTH     MIN       MEAN      MAX
         JAN       12.10     23.80     35.50
         FEB       15.80     28.35     40.90
         MAR       23.60     36.80     50.00
         APR       30.40     45.30     60.20
         MAY       37.20     53.90     70.60
         JUN       43.10     62.05     81.00
         JUL       49.70     69.60     89.50
         AUG       47.70     67.65     87.60
         SEP       39.20     58.70     78.20
         OCT       30.10     47.95     65.80
         NOV       21.60     34.90     48.20
         DEC       13.70     25.50     37.30
------------------------------------------------------------
```

BASE AMBIENT AIR TEMPERATURES IN DEGREES FAHRENHEIT

	SOURCE	CORRECTED
MEAN ANNUAL	46.21	44.60
HIGH MEAN MONTHLY	69.60	67.99
LOW MEAN MONTHLY	23.80	22.19
HIGHEST MEAN MONTHLY MAXIMUM	89.50	87.89
LOWEST MEAN MONTHLY MINIMUM	12.10	10.49
LOWEST MINIMUM	-33.00	-34.61
HIGHEST MAXIMUM	105.00	103.39
LOWEST DIFFERENCE BETWEEN MEAN MONTHLY MAXIMUM AND MEAN MONTHLY MINIMUM	23.40	23.40

ELEVATION AND LATITUDE CORRECTION BETWEEN SITE AND SOURCE

SITE EL.5450.00 ; CORRECT	-1.52	= 1 DEG / 250 FT
SITE LAT. 40.92N; CORRECT	-.09	= 1 DEG / 1.4 LAT
TOTAL	-1.61	

AMPLITUDIES OF AIR TEMPERATURES

PERIOD	MEAN CONDITIONS ABOVE MEAN	MEAN CONDITIONS BELOW MEAN	USUAL CONDITIONS ABOVE MEAN	USUAL CONDITIONS BELOW MEAN
YEARLY	23.392	22.408	23.392	22.408
365.HR	.000	.000	15.950	22.550
DAILY	11.700	11.700	11.700	11.700

CONCRETE AND THICKNESS COEFFICIENTS

ELEV	THICK	YEARLY RANGE L1	YEARLY RANGE CURVE	365-HR RANGE L1	365-HR RANGE CURVE	DAILY RANGE L1	DAILY RANGE CURVE
5450.00	20.00	1.01	.8418	7.27	.1100	19.25	.0416
5458.50	20.00	1.01	.8418	7.27	.1100	19.25	.0416
5498.60	20.00	1.01	.8418	7.27	.1100	19.25	.0416
5528.30	20.00	1.01	.8418	7.27	.1100	19.25	.0416
5545.30	20.00	1.01	.8418	7.27	.1100	19.25	.0416
5567.40	20.00	1.01	.8418	7.27	.1100	19.25	.0416
5592.90	19.88	1.00	.8444	7.23	.1106	19.13	.0418
5604.00	19.59	.99	.8504	7.12	.1123	18.85	.0424
5617.50	19.00	.96	.8626	6.91	.1158	18.28	.0438
5626.70	18.46	.93	.8734	6.71	.1192	17.76	.0450
5640.00	17.46	.88	.8925	6.35	.1260	16.80	.0476
5654.80	16.05	.81	.9173	5.84	.1370	15.44	.0518
5675.00	13.60	.68	.9535	4.95	.1617	13.09	.0611
5688.00	11.72	.59	.9744	4.26	.1877	11.28	.0709
5700.00	9.75	.49	.9888	3.55	.2256	9.38	.0853
5715.00	7.00	.35	.9946	2.55	.3142	6.74	.1188

DIFFUSIVITY = .045 FT/HR
L1 YEARLY = .0504 X THICKNESS
L1 168-HR = .3637 X THICKNESS
L1 DAILY = .9623 X THICKNESS

Temperature exposed to air or water on both faces without solar radiation

Uniform Temperatures (T_u) without solar radiation

RANGE OF CONCRETE TEMPERATURES

ELEV	EXPOSED TO AIR ON BOTH SURFACES: MEAN CONDITIONS: AMPLITUDE ABOVE MEAN	AMPLITUDE BELOW MEAN	TEMPERATURE MAX	TEMPERATURE MIN	USUAL CONDITIONS: AMPLITUDE ABOVE MEAN	AMPLITUDE BELOW MEAN	TEMPERATURE MAX	TEMPERATURE MIN	WATER TEMPERATURE: MAX	MIN	AVE	AMP	AMP	MEAN CONC. TEMP. EXPOSED TO WATER ON BOTH FACES: MAX	MIN	AIR ON D.S. FACE WATER ON U.S. FACE: MEAN CONDITIONS MAX	MEAN CONDITIONS MIN	USUAL CONDITIONS MAX	USUAL CONDITIONS MIN
5450.	20.2	19.3	64.8	25.2	21.9	21.8	66.5	22.8	43.0	39.0	41.0	2.0	1.7	42.7	39.3	53.7	32.3	54.6	31.0
5459.	20.2	19.3	64.8	25.2	21.9	21.8	66.5	22.8	43.0	39.0	41.0	2.0	1.7	42.7	39.3	53.7	32.3	54.6	31.0
5499.	20.2	19.3	64.8	25.2	21.9	21.8	66.5	22.8	43.0	39.0	41.0	2.0	1.7	42.7	39.3	53.7	32.3	54.6	31.0
5528.	20.2	19.3	64.8	25.2	21.9	21.8	66.5	22.8	43.8	39.0	41.4	2.4	2.0	43.4	39.4	54.1	32.3	55.0	31.1
5545.	20.2	19.3	64.8	25.2	21.9	21.8	66.5	22.8	44.4	39.0	41.7	2.7	2.3	44.0	39.4	54.4	32.3	55.3	31.1
5567.	20.2	19.3	64.8	25.2	21.9	21.8	66.5	22.8	45.9	38.8	42.3	3.6	3.0	45.3	39.4	55.1	32.3	55.9	31.1
5593.	20.2	19.4	64.8	25.2	22.0	21.9	66.6	22.7	47.1	38.6	42.8	4.3	3.6	46.4	39.3	55.6	32.2	56.5	31.0
5604.	20.4	19.6	65.0	25.0	22.2	22.1	66.8	22.5	48.1	38.4	43.3	4.8	4.1	47.4	39.1	56.2	32.1	57.1	30.8
5618.	20.7	19.8	65.3	24.8	22.5	22.5	67.1	22.1	49.7	38.0	43.8	5.9	5.0	48.9	38.8	57.1	31.8	58.0	30.5
5627.	21.0	20.1	65.6	24.5	22.9	22.8	67.5	21.8	51.2	37.6	44.4	6.8	5.9	50.3	38.5	57.9	31.5	58.9	30.1
5640.	21.4	20.6	66.0	24.0	23.4	23.4	68.0	21.2	54.4	36.8	45.6	8.8	7.9	53.5	37.7	59.7	30.9	60.7	29.5
5655.	22.1	21.2	66.7	23.4	24.2	24.3	68.8	20.3	60.0	35.4	47.7	12.3	11.3	59.0	36.4	62.8	29.9	63.9	28.4
5675.	23.0	22.1	67.6	22.5	25.6	25.7	70.2	18.9	61.8	34.9	48.3	13.5	12.8	61.2	35.5	64.4	29.0	65.7	27.2
5688.	23.6	22.7	68.2	21.9	26.6	26.9	71.2	17.7	65.5	33.9	49.7	15.8	15.4	65.1	34.3	66.7	28.1	68.2	26.0
5700.	24.1	23.2	68.7	21.4	27.7	28.2	72.3	16.4	69.0	33.0	51.0	18.0	17.8	68.8	33.2	68.8	27.3	70.6	24.8
5715.	24.7	23.7	69.3	20.9	29.7	30.8	74.3	13.8	69.0	32.0	50.5	18.5	18.4	68.9	32.1	69.1	26.5	71.6	23.0

SOLAR RADIATION VALUES

ELEV	TERRAIN FACT.	POINT 1 UPSTREAM NORM ANGLE = 107.: SLOPE	TEMP RISE 100%	TEMP RISE ACT.	POINT 1 DOWNSTREAM NORM ANGLE = 73.: SLOPE	TEMP RISE 100%	TEMP RISE ACT.	POINT 2 UPSTREAM NORM ANGLE = 79.: SLOPE	TEMP RISE 100%	TEMP RISE ACT.	POINT 2 DOWNSTREAM NORM ANGLE = 101.: SLOPE	TEMP RISE 100%	TEMP RISE ACT.	POINT 3 UPSTREAM NORM ANGLE = 50.: SLOPE	TEMP RISE 100%	TEMP RISE ACT.	POINT 3 DOWNSTREAM NORM ANGLE = 129.: SLOPE	TEMP RISE 100%	TEMP RISE ACT.
5450.0	.41	-.09	5.93	2.43	.09	4.77	1.95	-.09	4.48	1.83	.09	6.65	2.73	-.09	2.59	1.06	.09	7.80	3.20
5458.5	.45	-.08	5.99	2.69	.08	4.73	2.13	-.08	4.51	2.03	.08	6.60	2.97	-.08	2.61	1.18	.08	7.74	3.48
5498.6	.83	-.06	6.10	5.06	.06	4.65	3.86	-.06	4.59	3.81	.06	6.50	5.39	-.06	2.67	2.21	.06	7.61	6.31
5528.3	.86	-.04	6.22	5.35	.04	4.57	3.93	-.04	4.67	4.02	.04	6.39	5.50	-.04	2.72	2.34	.04	7.47	6.43
5545.3	.87	-.03	6.27	5.46	.03	4.53	3.94	-.03	4.71	4.10	.03	6.34	5.52	-.03	2.75	2.39	.03	7.41	6.45
5567.4	.89	-.01	6.39	5.69	.01	4.45	3.96	-.01	4.79	4.26	.01	6.24	5.56	-.01	2.80	2.49	.01	7.28	6.48
5592.9	.91	.02	6.55	5.96	.00	4.41	4.01	.02	4.91	4.47	.00	6.19	5.64	.02	2.88	2.62	.00	7.21	6.56
5604.0	.92	.04	6.66	6.13	-.01	4.37	4.02	.04	5.00	4.60	-.01	6.14	5.65	.04	2.94	2.70	-.01	7.15	6.57
5617.5	.93	.06	6.77	6.29	-.01	4.37	4.07	.06	5.08	4.72	-.01	6.14	5.71	.06	3.00	2.79	-.01	7.15	6.65
5626.7	.94	.08	6.88	6.46	-.01	4.37	4.11	.08	5.16	4.85	-.01	6.14	5.77	.08	3.05	2.87	-.01	7.15	6.72
5640.0	.96	.11	7.04	6.76	-.01	4.37	4.20	.11	5.29	5.08	-.01	6.14	5.89	.11	3.14	3.01	-.01	7.15	6.86
5654.8	.97	.14	7.20	6.99	-.02	4.34	4.21	.14	5.42	5.25	-.02	6.08	5.90	.14	3.23	3.13	-.02	7.08	6.87
5675.0	.97	.16	7.31	7.09	-.02	4.34	4.21	.16	5.50	5.34	-.02	6.08	5.90	.16	3.28	3.19	-.02	7.08	6.87
5688.0	.98	.18	7.42	7.27	-.02	4.34	4.25	.18	5.59	5.48	-.02	6.08	5.96	.18	3.34	3.28	-.02	7.08	6.94
5700.0	.99	.20	7.53	7.46	-.03	4.30	4.26	.20	5.67	5.62	-.03	6.03	5.97	.20	3.40	3.37	-.03	7.02	6.95
5715.0	.99	.21	7.58	7.50	-.03	4.30	4.26	.21	5.71	5.65	-.03	6.03	5.97	.21	3.43	3.39	-.03	7.02	6.95

MEAN CONCRETE TEMPERATURES INCLUDING SOLAR EFFECTS

ELEV	THICK	EFFECT OF SOLAR RADIATION (CALC. FROM SOLAR RAD. VALUES): U.S.	D.S.	AVE	1/2 DS	MEAN CONCRETE TEMPERATURES: EXPOSED TO AIR ON BOTH' FACES: MEAN CONDITIONS MAX	MEAN CONDITIONS MIN	USUAL CONDITIONS MAX	USUAL CONDITIONS MIN	AIR ON D.S. FACE WATER ON U.S. FACE: MEAN CONDITIONS MAX	MEAN CONDITIONS MIN	USUAL CONDITIONS MAX	USUAL CONDITIONS MIN
5450.00	20.00	1.78	2.63	2.20	1.31	66.97	27.45	68.73	24.97	55.04	33.59	55.92	32.35
5458.50	20.00	1.97	2.86	2.41	1.43	67.19	27.66	68.94	25.18	55.16	33.71	56.04	32.47
5498.60	20.00	3.70	5.19	4.44	2.59	69.22	29.69	70.97	27.21	56.32	34.87	57.20	33.63
5528.30	20.00	3.90	5.29	4.59	2.64	69.37	29.84	71.12	27.36	56.74	34.96	57.62	33.72
5545.30	20.00	3.98	5.30	4.64	2.65	69.42	29.89	71.17	27.41	57.02	34.99	57.90	33.75
5567.40	20.00	4.15	5.33	4.74	2.67	69.51	29.99	71.27	27.50	57.72	34.97	58.60	33.73
5592.90	19.88	4.35	5.40	4.88	2.70	69.71	30.06	71.48	27.57	58.34	34.93	59.22	33.68
5604.00	19.59	4.48	5.42	4.95	2.71	69.93	29.99	71.72	27.46	58.89	34.79	59.78	33.53
5617.50	19.00	4.60	5.47	5.04	2.74	70.32	29.79	72.17	27.18	59.83	34.52	60.75	33.21
5626.70	18.46	4.73	5.53	5.13	2.77	70.68	29.63	72.58	26.94	60.71	34.25	61.66	32.90
5640.00	17.46	4.95	5.65	5.30	2.83	71.33	29.34	73.34	26.50	62.57	33.72	63.57	32.30
5654.80	16.05	5.12	5.66	5.39	2.83	72.05	28.83	74.24	25.74	65.65	32.76	66.74	31.21
5675.00	13.60	5.21	5.66	5.43	2.83	73.05	27.95	75.63	24.30	67.22	31.85	68.51	30.03
5688.00	11.72	5.34	5.72	5.53	2.86	73.75	27.46	76.74	23.23	69.51	30.98	71.01	28.86
5700.00	9.75	5.48	5.72	5.60	2.86	74.33	27.04	77.92	21.95	71.62	30.18	73.42	27.64
5715.00	7.00	5.52	5.72	5.62	2.86	74.87	26.54	79.88	19.45	71.94	29.37	74.44	25.83

Temperature exposed to air on both faces with solar radiation

Uniform Temperatures (T_u) with solar radiation

11

ADSAS TEMPERATURE INPUT FOR (03) AND (02) LOADING - GROUT TEMP = 36.0 F

ELEV	UNIFORM TEMPERATURE LOADING (02) AIR DS FACE/WATER US FACE				LINEAR TEMPERATURE LOADING (03) AIR DS FACE/WATER US FACE				UNIFORM TEMPERATURE LOADING (02) EXPOSED TO AIR ON BOTH FACES				LINEAR TEMP LOADING EXPOSED TO AIR BOTH FACES
	MEAN COND		USUAL COND		MEAN COND		USUAL COND		MEAN COND		USUAL COND		
	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM	MINIMUM	
5450.00	19.04	-2.41	19.92	-3.65	22.09	-14.07	23.84	-16.55	30.97	-8.55	32.73	-11.03	.85
5458.50	19.16	-2.29	20.04	-3.53	22.09	-14.07	23.84	-16.55	31.19	-8.34	32.94	-10.82	.89
5498.60	20.32	-1.13	21.20	-2.37	22.09	-14.07	23.84	-16.55	33.22	-6.31	34.97	-8.79	1.49
5528.30	20.74	-1.04	21.62	-2.28	21.35	-14.13	23.11	-16.61	33.37	-6.16	35.12	-8.64	1.38
5545.30	21.02	-1.01	21.90	-2.25	20.80	-14.18	22.55	-16.66	33.42	-6.11	35.17	-8.59	1.32
5567.40	21.72	-1.03	22.60	-2.27	19.44	-14.12	21.19	-16.60	33.51	-6.01	35.27	-8.50	1.18
5592.90	22.34	-1.07	23.22	-2.32	18.40	-14.08	20.16	-16.57	33.71	-5.94	35.48	-8.43	1.05
5604.00	22.89	-1.21	23.78	-2.47	17.61	-14.08	19.40	-16.62	33.93	-6.01	35.72	-8.54	.94
5617.50	23.83	-1.48	24.75	-2.79	16.39	-14.05	18.24	-16.66	34.32	-6.21	36.17	-8.82	.87
5626.70	24.71	-1.75	25.66	-3.10	15.21	-13.96	17.11	-16.65	34.68	-6.37	36.58	-9.06	.80
5640.00	26.57	-2.28	27.57	-3.70	12.58	-13.71	14.59	-16.55	35.33	-6.66	37.34	-9.50	.70
5654.80	29.65	-3.24	30.74	-4.79	7.68	-12.98	9.86	-16.07	36.05	-7.17	38.24	-10.26	.54
5675.00	31.22	-4.15	32.51	-5.97	6.44	-13.01	9.02	-16.66	37.05	-8.05	39.63	-11.70	.45
5688.00	33.51	-5.02	35.01	-7.14	3.12	-12.37	6.12	-16.61	37.75	-8.54	40.74	-12.77	.38
5700.00	35.62	-5.82	37.42	-8.36	-.07	-11.76	3.52	-16.85	38.33	-8.96	41.92	-14.05	.24
5715.00	35.94	-6.63	38.44	-10.17	.35	-11.18	5.36	-18.27	38.87	-9.46	43.88	-16.55	.21

ADSAS TEMP INPUT FOR A TYPICAL MONTH - GROUT TEMP = 36.00 F , AIR DS FACE / WATER US FACE

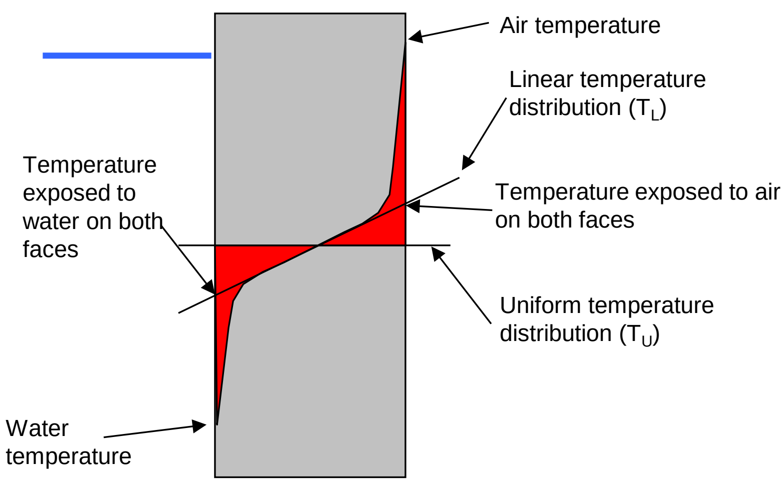
ELEV	JAN AVE=22.19 F		FEB AVE=26.74 F		MAR AVE=35.19 F		APR AVE=43.69 F		MAY AVE=52.29 F		JUN AVE=60.44 F	
	UNIFORM	LINEAR	UNIFORM	LINEAR	UNIFORM	LINEAR	UNIFORM	LINEAR	UNIFORM	LINEAR	UNIFORM	LINEAR
5450.00	-5.07	-17.48	-3.13	-12.26	1.43	-4.48	6.01	3.35	10.64	11.29	15.05	18.77
5458.50	-5.07	-17.48	-3.13	-12.26	1.43	-4.48	6.01	3.35	10.64	11.29	15.05	18.77
5498.60	-5.07	-17.48	-3.13	-12.26	1.43	-4.48	6.01	3.35	10.64	11.29	15.05	18.77
5528.30	-5.01	-17.61	-3.13	-12.26	1.49	-4.61	6.14	3.09	10.84	10.89	15.32	18.24
5545.30	-4.96	-17.71	-3.13	-12.26	1.54	-4.71	6.24	2.89	10.99	10.59	15.52	17.84
5567.40	-4.91	-17.80	-3.23	-12.06	1.59	-4.80	6.43	2.52	11.32	9.94	15.99	16.90
5592.90	-4.90	-17.83	-3.33	-11.86	1.60	-4.83	6.56	2.25	11.57	9.44	16.35	16.17
5604.00	-4.90	-17.83	-3.43	-11.66	1.60	-4.83	6.66	2.05	11.77	9.04	16.65	15.57
5617.50	-4.93	-17.76	-3.63	-11.26	1.57	-4.76	6.79	1.79	12.07	8.44	17.12	14.64
5626.70	-4.97	-17.68	-3.83	-10.86	1.53	-4.68	6.91	1.55	12.34	7.89	17.55	13.77
5640.00	-5.04	-17.55	-4.23	-10.06	1.46	-4.55	7.18	1.02	12.94	6.69	18.49	11.90
5654.80	-5.16	-17.31	-4.93	-8.66	1.34	-4.31	7.64	.09	13.99	4.59	20.12	8.64
5675.00	-5.21	-17.20	-5.18	-8.16	1.29	-4.20	7.78	-.18	14.32	3.94	20.64	7.60
5688.00	-5.32	-16.98	-5.68	-7.16	1.18	-3.98	8.06	-.75	14.99	2.59	21.70	5.47
5700.00	-5.41	-16.81	-6.13	-6.26	1.09	-3.81	8.34	-1.31	15.64	1.29	22.72	3.44
5715.00	-5.82	-15.98	-6.63	-5.26	.68	-2.98	8.01	-.65	15.39	1.79	22.55	3.77

ADSAS TEMP INPUT FOR A TYPICAL MONTH - GROUT TEMP = 36.00 F , AIR DS FACE / WATER US FACE

ELEV	JUL AVE=67.99 F		AUG AVE=66.04 F		SEP AVE=57.09 F		OCT AVE=46.34 F		NOV AVE=33.29 F		DEC AVE=23.89 F	
	UNIFORM	LINEAR	UNIFORM	LINEAR	UNIFORM	LINEAR	UNIFORM	LINEAR	UNIFORM	LINEAR	UNIFORM	LINEAR
5450.00	19.16	25.65	18.52	23.04	13.71	14.75	8.00	4.67	1.14	-7.71	-3.89	-16.45
5458.50	19.16	25.65	18.52	23.04	13.71	14.75	8.00	4.67	1.14	-7.71	-3.89	-16.45
5498.60	19.16	25.65	18.52	23.04	13.71	14.75	8.00	4.67	1.14	-7.71	-3.89	-16.45
5528.30	19.49	24.99	18.92	22.24	14.04	14.09	8.27	4.14	1.34	-8.11	-3.76	-16.71
5545.30	19.74	24.49	19.22	21.64	14.29	13.59	8.47	3.74	1.49	-8.41	-3.66	-16.91
5567.40	20.35	23.27	19.97	20.14	14.90	12.37	8.94	2.80	1.82	-9.06	-3.47	-17.28
5592.90	20.84	22.30	20.57	18.94	15.39	11.40	9.30	2.07	2.07	-9.56	-3.34	-17.55
5604.00	21.24	21.50	21.07	17.94	15.79	10.60	9.60	1.47	2.27	-9.96	-3.24	-17.75
5617.50	21.87	20.24	21.87	16.34	16.42	9.34	10.07	.54	2.57	-10.56	-3.11	-18.01
5626.70	22.46	19.05	22.62	14.84	17.01	8.15	10.50	-.33	2.84	-11.11	-2.99	-18.25
5640.00	23.73	16.52	24.22	11.64	18.28	5.62	11.44	-2.20	3.44	-12.31	-2.72	-18.78
5654.80	25.94	12.09	27.02	6.04	20.49	1.19	13.07	-5.46	4.49	-14.41	-2.26	-19.71
5675.00	26.65	10.67	27.92	4.24	21.20	-.23	13.59	-6.50	4.82	-15.06	-2.12	-19.98
5688.00	28.11	7.75	29.77	.54	22.66	-3.15	14.65	-8.63	5.49	-16.41	-1.84	-20.55
5700.00	29.49	4.99	31.52	-2.96	24.04	-5.91	15.67	-10.66	6.14	-17.71	-1.56	-21.11
5715.00	29.41	5.15	31.52	-2.96	23.96	-5.75	15.50	-10.33	5.89	-17.21	-1.89	-20.45

WATER TEMPERATURES ASSUMING AUGUST HOTTEST AND FEBRUARY COLDEST MONTHS

ELEV	AUG	SEP	OCT	NOV	DEC							
5450.00	39.67	39.00	39.67	40.33	41.00	41.67	42.33	43.00	42.33	41.67	41.00	40.33
5458.50	39.67	39.00	39.67	40.33	41.00	41.67	42.33	43.00	42.33	41.67	41.00	40.33
5498.60	39.67	39.00	39.67	40.33	41.00	41.67	42.33	43.00	42.33	41.67	41.00	40.33
5528.30	39.80	39.00	39.80	40.60	41.40	42.20	43.00	43.80	43.00	42.20	41.40	40.60
5545.30	39.90	39.00	39.90	40.80	41.70	42.60	43.50	44.40	43.50	42.60	41.70	40.80
5567.40	39.98	38.80	39.98	41.17	42.35	43.53	44.72	45.90	44.72	43.53	42.35	41.17
5592.90	40.02	38.60	40.02	41.43	42.85	44.27	45.68	47.10	45.68	44.27	42.85	41.43
5604.00	40.02	38.40	40.02	41.63	43.25	44.87	46.48	48.10	46.48	44.87	43.25	41.63
5617.50	39.95	38.00	39.95	41.90	43.85	45.80	47.75	49.70	47.75	45.80	43.85	41.90
5626.70	39.87	37.60	39.87	42.13	44.40	46.67	48.93	51.20	48.93	46.67	44.40	42.13
5640.00	39.73	36.80	39.73	42.67	45.60	48.53	51.47	54.40	51.47	48.53	45.60	42.67
5654.80	39.50	35.40	39.50	43.60	47.70	51.80	55.90	60.00	55.90	51.80	47.70	43.60
5675.00	39.38	34.90	39.38	43.87	48.35	52.83	57.32	61.80	57.32	52.83	48.35	43.87
5688.00	39.17	33.90	39.17	44.43	49.70	54.97	60.23	65.50	60.23	54.97	49.70	44.43
5700.00	39.00	33.00	39.00	45.00	51.00	57.00	63.00	69.00	63.00	57.00	51.00	45.00
5715.00	38.17	32.00	38.17	44.33	50.50	56.67	62.83	69.00	62.83	56.67	50.50	44.33



For SAPCORD or ADSAS:

$T_{Upstream} = T_U - T_L/2$

$T_{Downstream} = T_U + T_L/2$

T_L is positive if the internal temperature increases from upstream to downstream.

$T_L = T_{AirOnBoth} - T_{WaterOnBoth}$

Concrete is a very good insulator. As such, daily air and water temperature variations affect only the surface of the concrete to a shallow depth. There is a steep thermal gradient at the surface. Interior temperatures are affected by weekly and monthly variations. The procedure in Engineering Monograph #34 computes the interior temperatures that influence the response of the dam (T_U and T_L). T_U and T_L temperatures should be used in finite element structural analysis for temperature at nodes.

Appendix J – Example Single-Centered Arch Dam Layouts

This Appendix guides the reader through the design process for an arch dam. In Section 3, the initial layout process from Engineering Monograph #36 was described. The resulting arch shape was developed based on 12 previous layouts at Reclamation. Three empirically developed parameters are used, namely the height of the dam (H), the cross-stream dimension of the canyon at the crest (L1), and the cross-stream dimension of the canyon at 0.15 height of the dam (L2). It would not be used to build an arch dam, but could be used by field personnel to estimate the volume of an arch dam for planning purposes.

Morrow Point dam site was used to describe the initial layout process in Section 3. This section continues from this initial layout through the design process and ultimately terminates with the final Morrow Point design.

The last part of this section designs single-centered arch dams for differing canyon shapes and shows how the designs might vary. Again, these canyon shapes are related to H, L1/H, and L2/L1. As can be seen if Figure _, the L2/L1 range from a minimum of 0.15 (V-shaped canyon) to a maximum of 1.0 (rectangular U-shaped canyon). Realistically, L1/H varies from a minimum of about 0.5 to a maximum of around 6.0. It will be shown that the maximum L1/H for a single centered arch dam is about 4.0. Arch dams with larger ratios of L1/H probably need to be 3-centered. Appendix K provides an example of a 3-centered layout for a very wide V shaped canyon.

Appendix J1 – Wide U Shaped Canyon (Morrow Point)

Morrow Point is used as an example of a thin arch dam in a wide U-shaped canyon (see Figure J1-1).

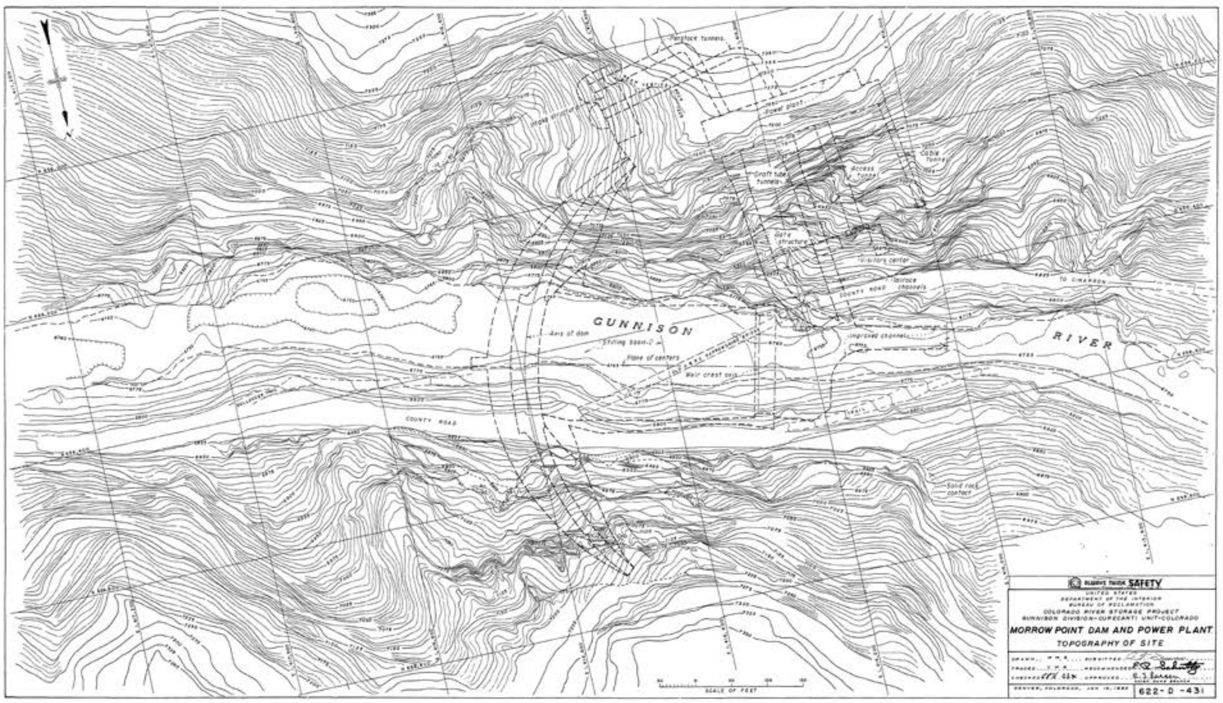
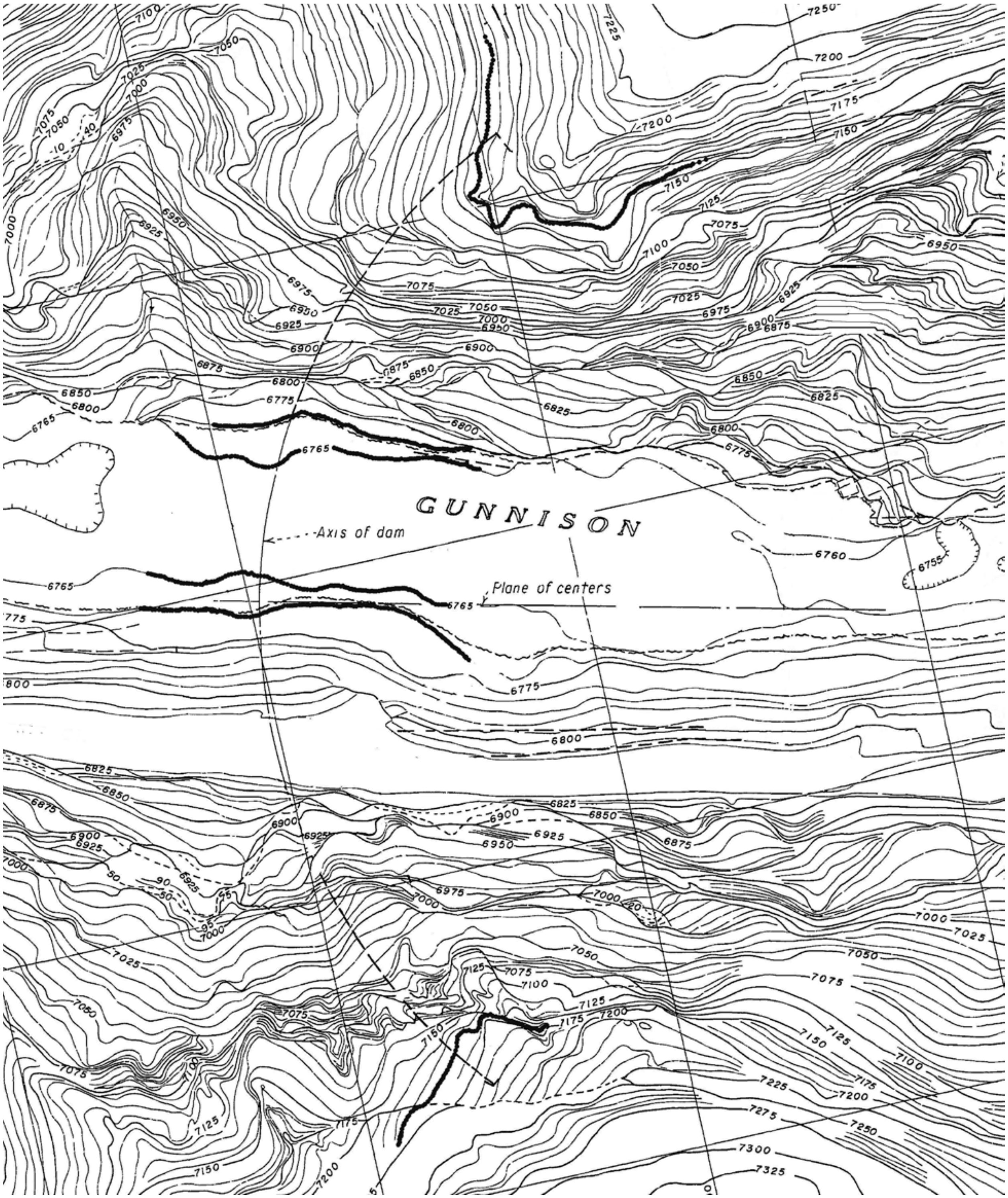


Figure J1-1 – Topography and position of Morrow Point Dam


GUNNISON
Axis of dam
Plane of centers

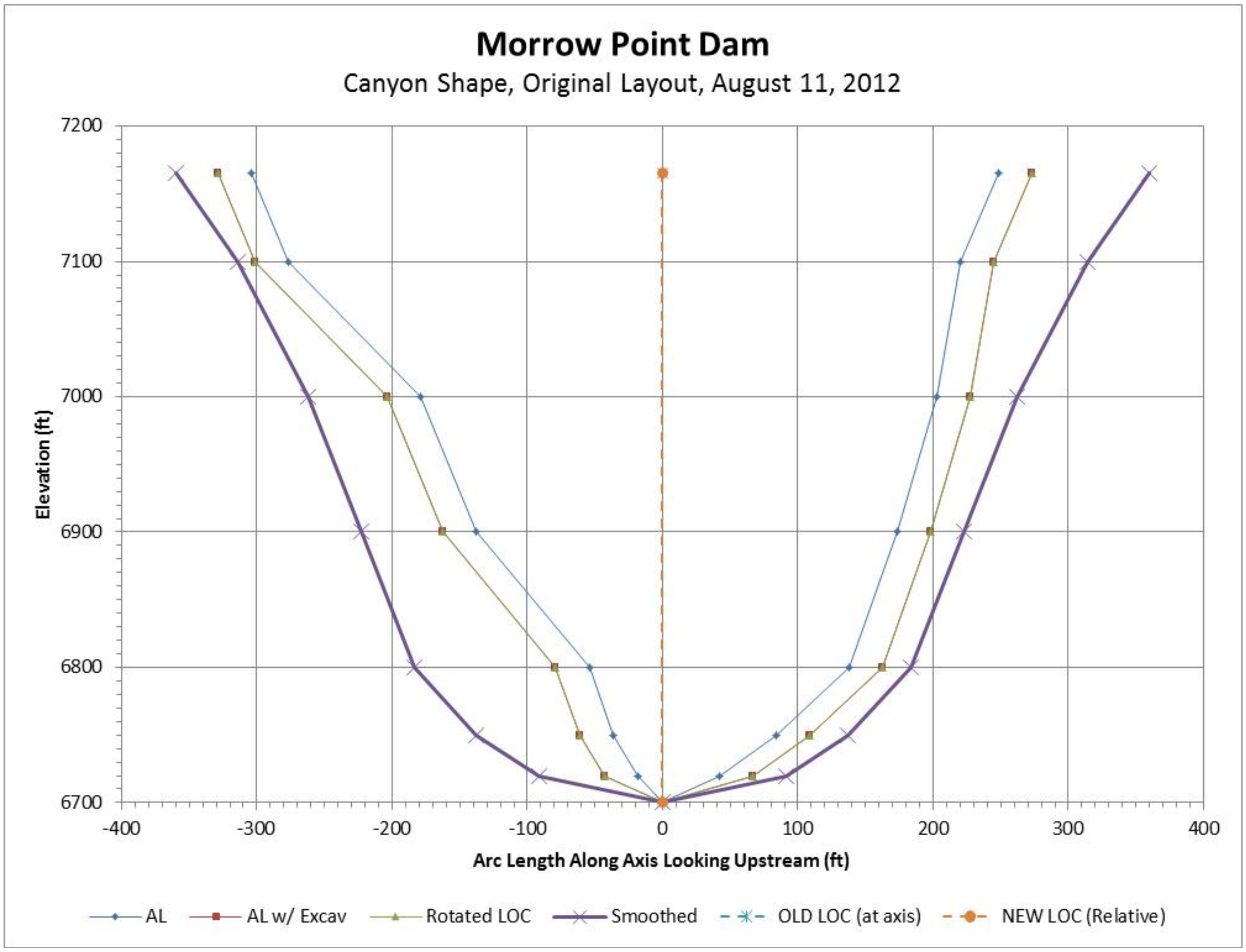


Figure J1-3 – Final smoothed canyon compared to the original topography and 25-feet of assumed excavation

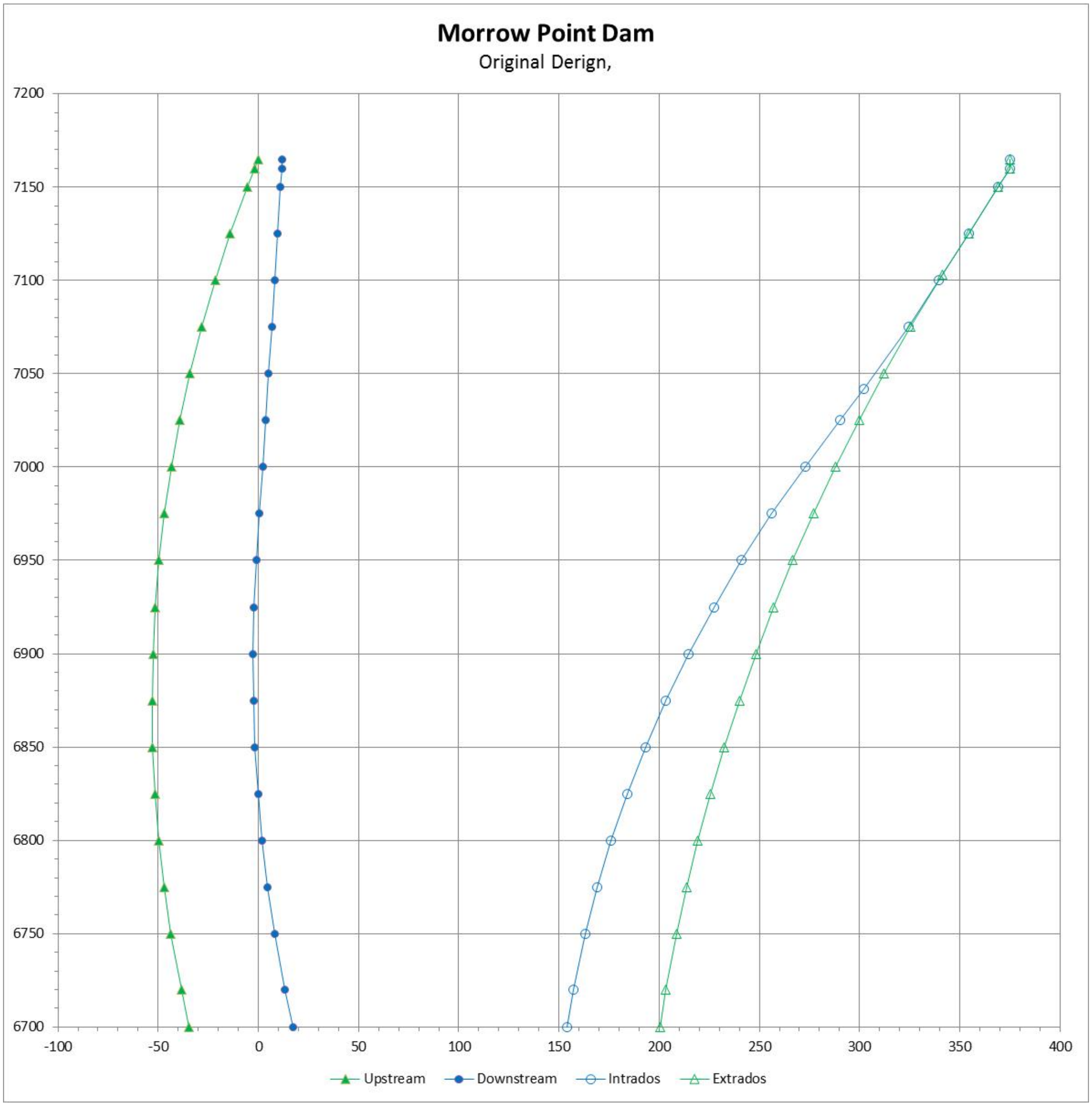


Figure J1-4 – Final designed crown cantilever and line-of-centers

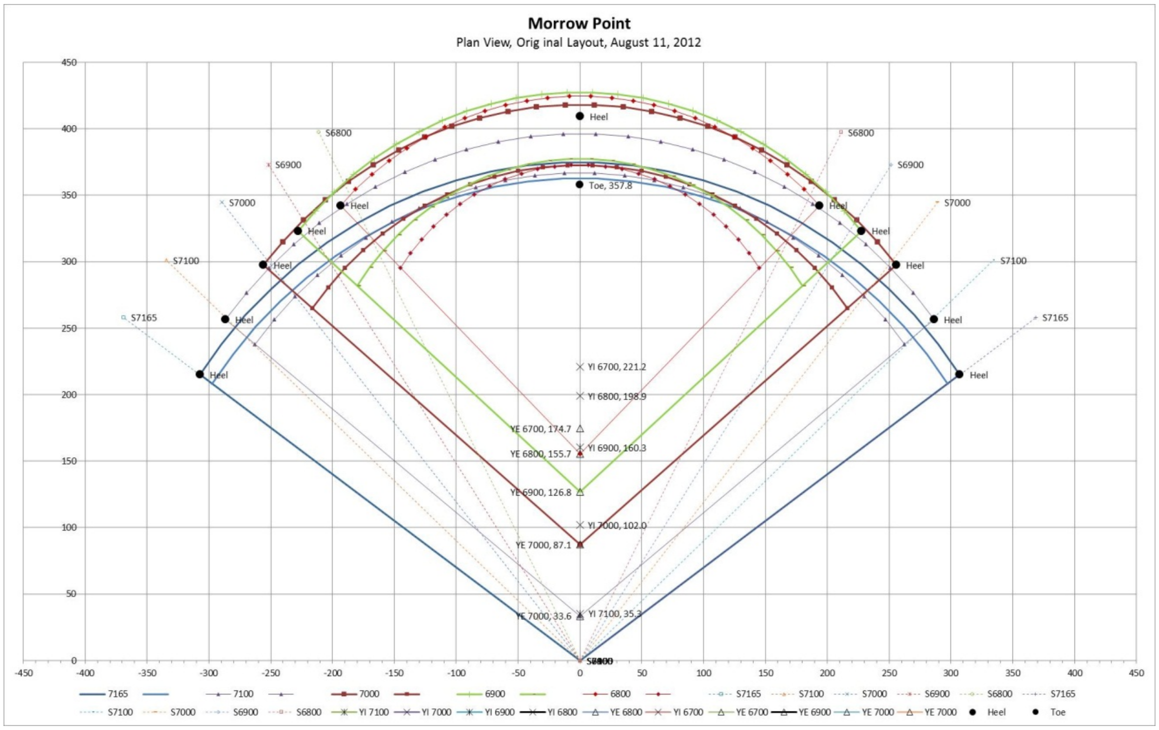


Figure J1-5 – Plan view of the arches

```
MASTERIO  111011111                       MORPT60
1   0     M.P.DAM ORIGINAL 2               16         0                        9701
2   0     111111101                                                            9701
3   0     300000000000      3.000  .200  5.60 150.00  2.500  .200  .00    .00 9701
4   0      6700.000 7165.000 7160.000 6700.000 7165.000 7165.000 6700.000     9701
5  1
5  2
5  3                                      MORROW POINT DAM AUG 10, 2012
5  4      M STRESS ANALYSIS SYSTEM OVERLAY TAPE
1   1     11    1      1      1                                                9701
3   1       34.42700  17.22700  221.1513  174.6713  375.0000     .0000  3  19701
5   1 1 1   7165.00000      .00000   772.00000  6874.06870   825.00000         9701
5   1 2 1   6950.00000      .00000   947.39460  6893.10230   950.00000         9701
5   1 2 2   7165.00000      .06000      .00000      .00000      .00000         9701
5   1 3 1   7000.00000      .00000   846.46210  6598.57650   700.00000         9701
5   1 3 2   7041.62220      .70000      .00000      .00000      .00000         9701
5   1 3 3   7100.00000      .00000  -421.58820  7548.22880  -883.41740         9701
5   1 3 4   7160.00000      .58880      .00000      .00000      .00000         9701
5   1 3 5   7165.00000      .00000      .00000      .00000      .00000         9701
5   1 4 1   7103.00800      .00000  1289.33770  6544.88930  1100.00000         9701
5   1 4 2   7160.00000      .58880      .00000      .00000      .00000         9701
5   1 4 3   7165.00000      .00000      .00000      .00000      .00000         9701
6   1           .00000   12.00000     .00000     .00000     .00000     .000009701
7   110000 6700.00000 00.000 00.000                +0.0  +0.0
7   150000 6720.00000 29.000 29.000
7   100000 6800.00000 46.000 46.000
7   100000 6900.00000 49.200 49.200
7   100000 7000.00000 50.600 50.600
7   100000 7100.00000 52.100 52.100
7   100000 7165.00000 55.000 55.000
1   2           1   1 11111    01                                              9701
1   4     00 00     100000000000          10  0               10100110000009701
1   3     000000000000000 00100001 00001 00110010101000 00                     9701
10005     1     1   11  1     0 000 0   000       2          11111  01
1  10      1            1
*ENDFILE
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Figure J1-6 – ADSAS Input file

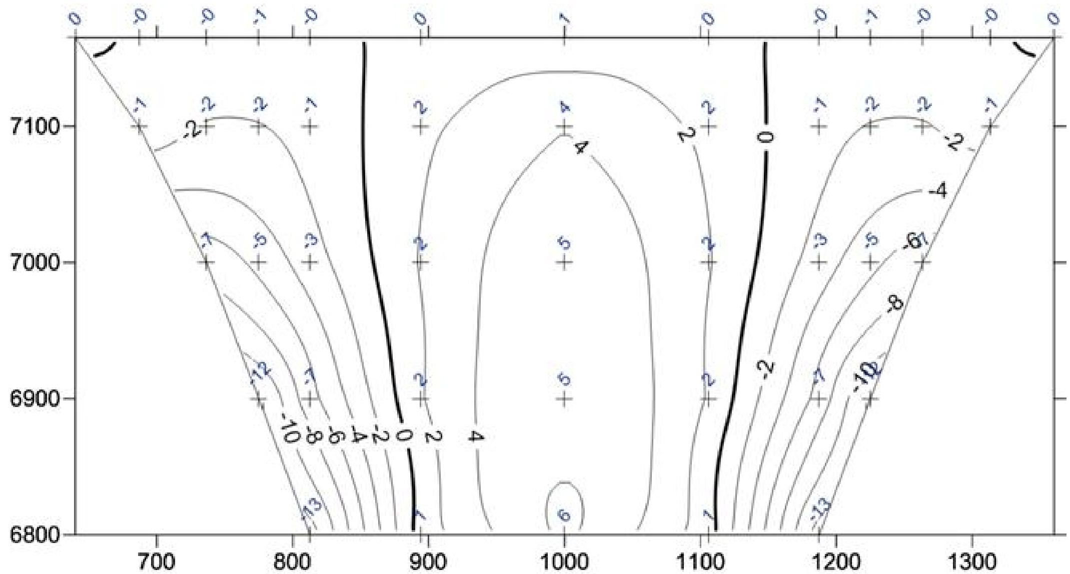


Figure J1-7 – Arch Eccentricities

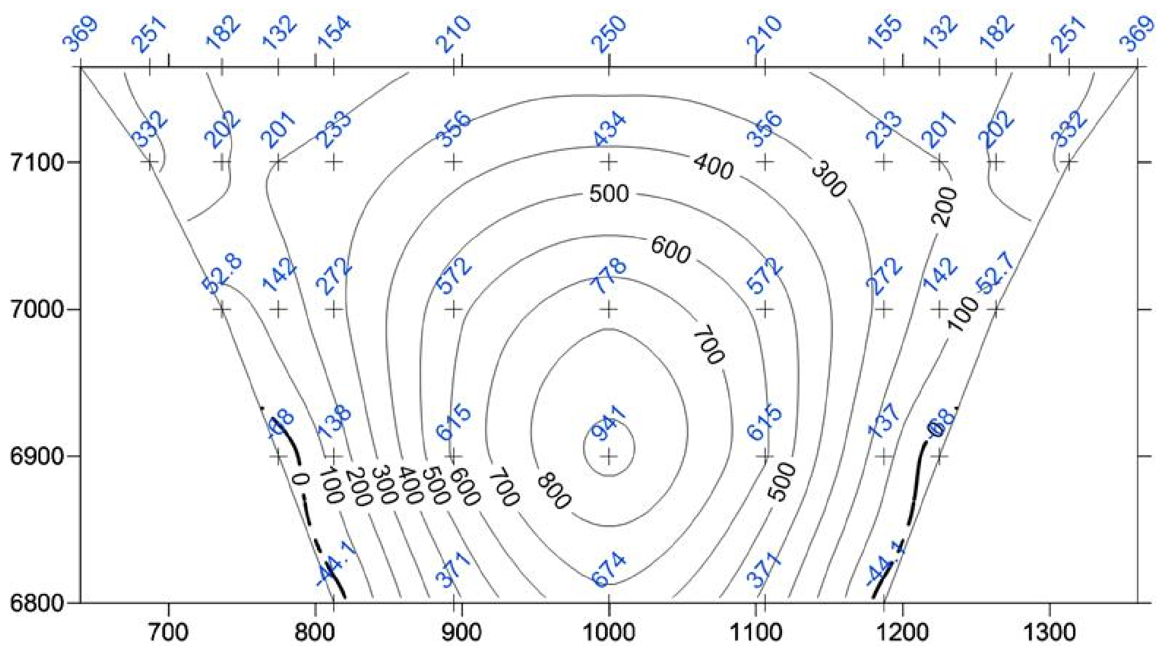


Figure J1-8 – Upstream arch stress contours and stress values

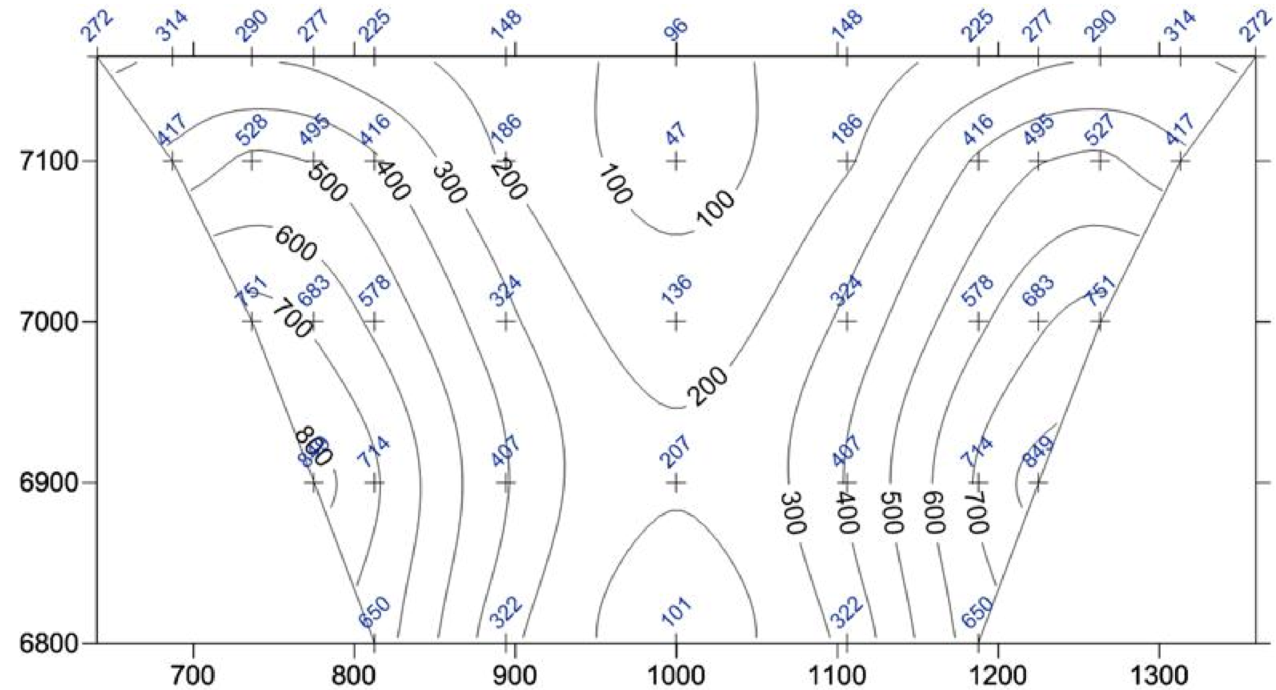


Figure J1-9 – Downstream arch stress contours and stress values

Appendix J2 – Very Wide V Shaped Canyon (Upper San Joaquin)

Upper San Joaquin is in a very wide V-shaped canyon. The ratio of canyon width to dam height (L1/H = 2570/650) is about 4 and the ratio of canyon width at 15 percent of the height to the canyon width at the crest (L2/L1 = 430/2570) is about 0.17.

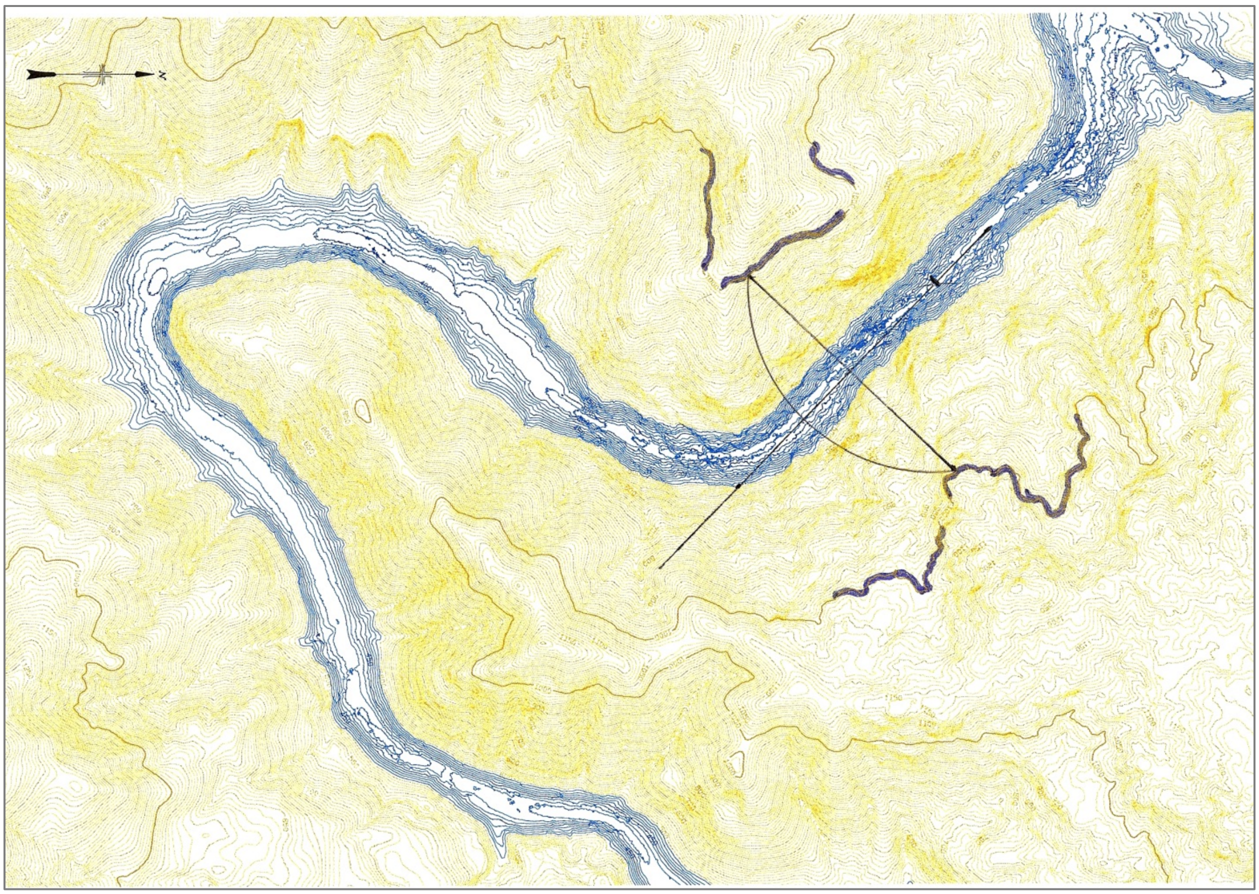


Figure J2-1 – Upper San Joaquin topography at a 400:1 scale with axis positioned

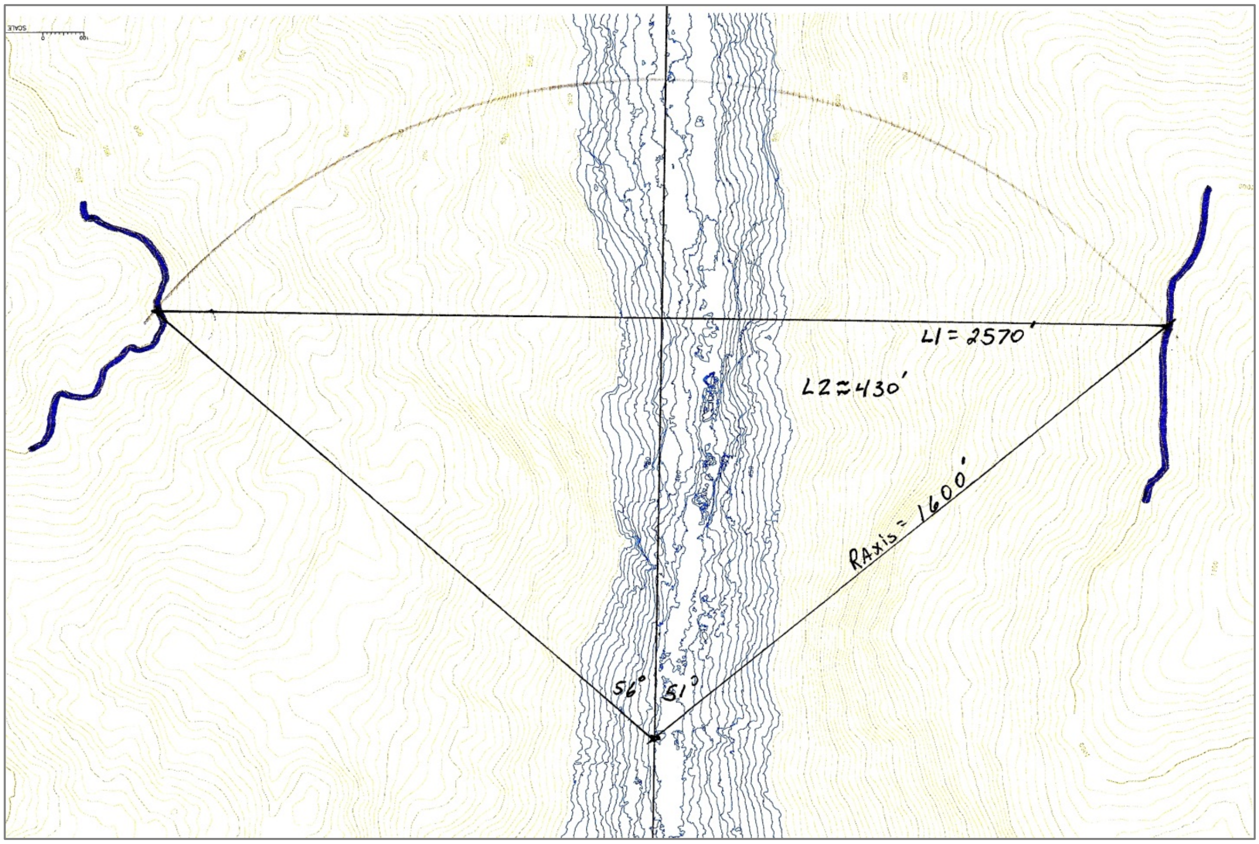


Figure J2-2 – Upper San Joaquin topography at 100 scale with an axis positioned. (R_{axis} = 1600 feet, L1 = 2570 feet, L2 = 430 feet, and central angles of 56˚ left and 51˚ right.

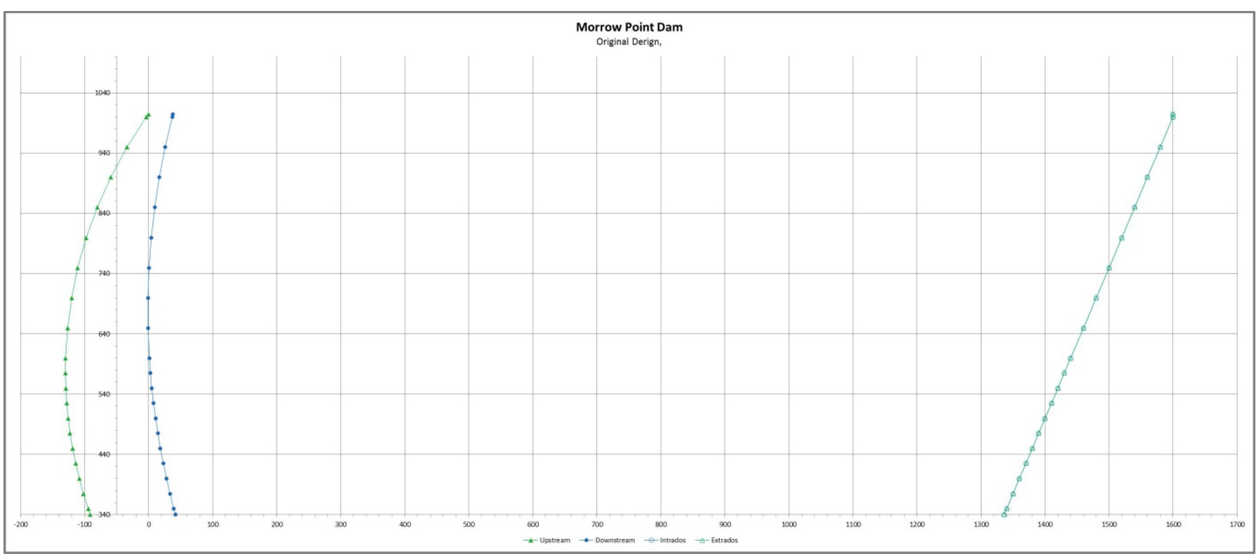


Figure J2-3 – Crown cantilever and line-of-centers. Line-of-centers has a constant slope of 0.8:1.

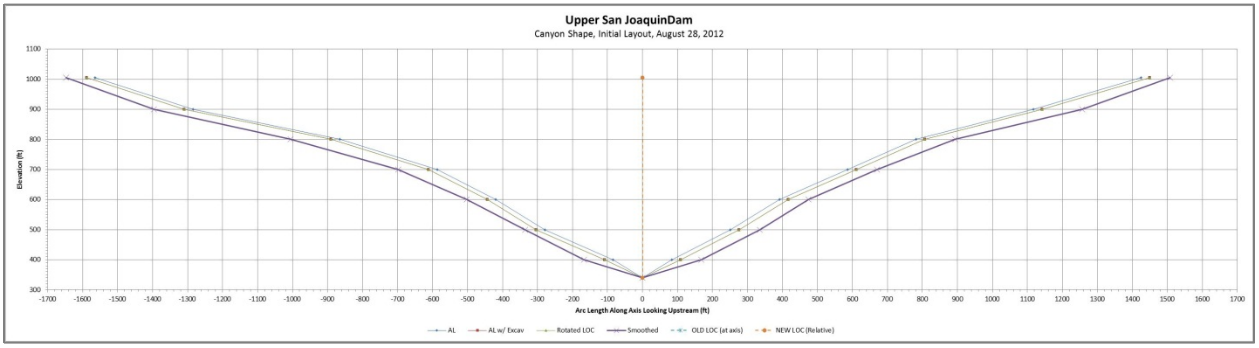


Figure J2-4 – Profile of the dam looking upstream with original ground surface, estimated excavation to sound rock, and approximate smooth canyon profile.

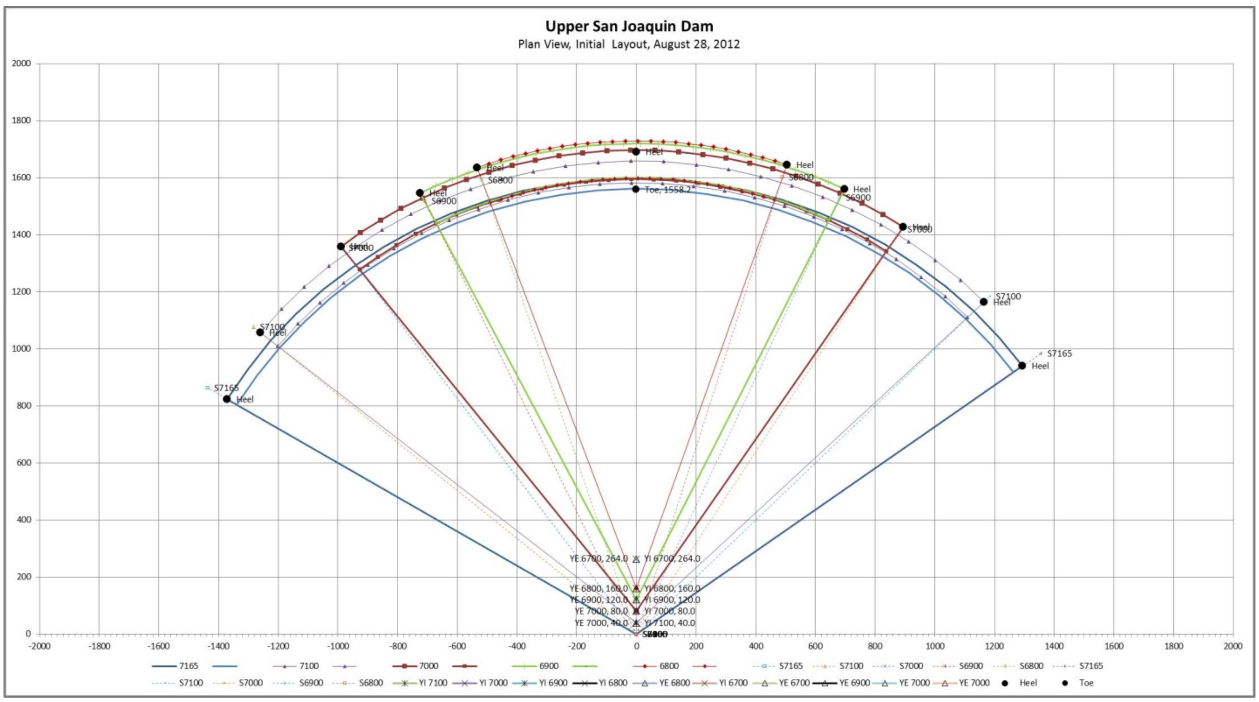


Figure J2-5 – Plan view of arches

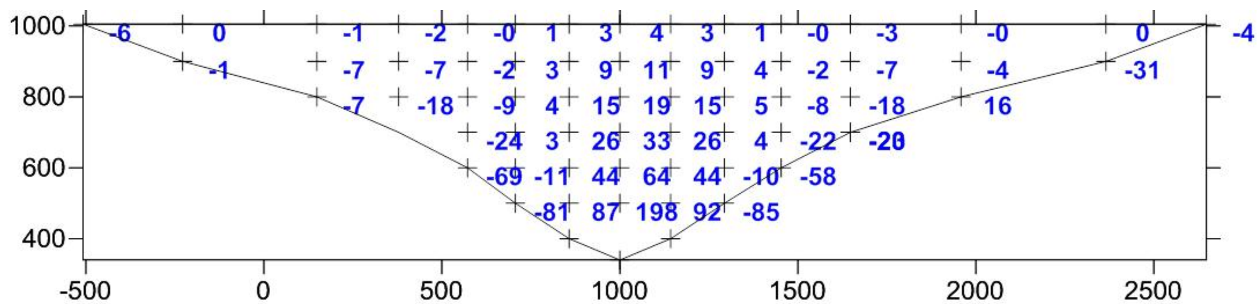


Figure J2-6 – Eccentricity in the arch direction (moment / thrust)

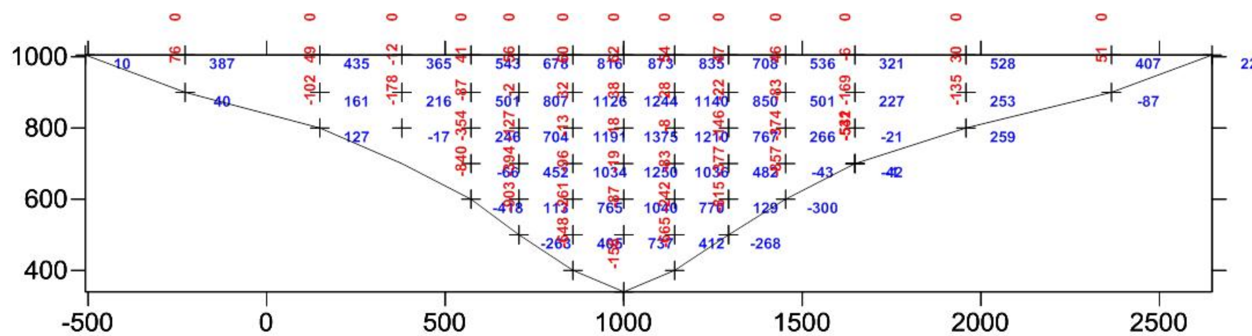


Figure J2-7 – Upstream arch and cantilever stresses

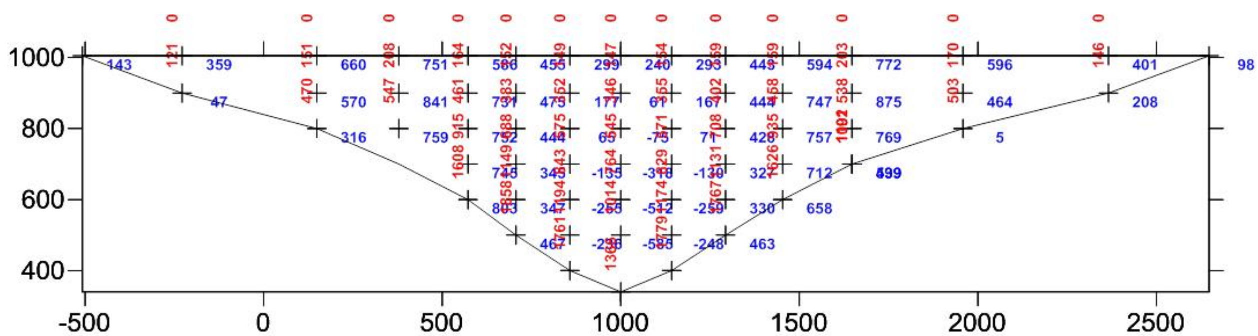
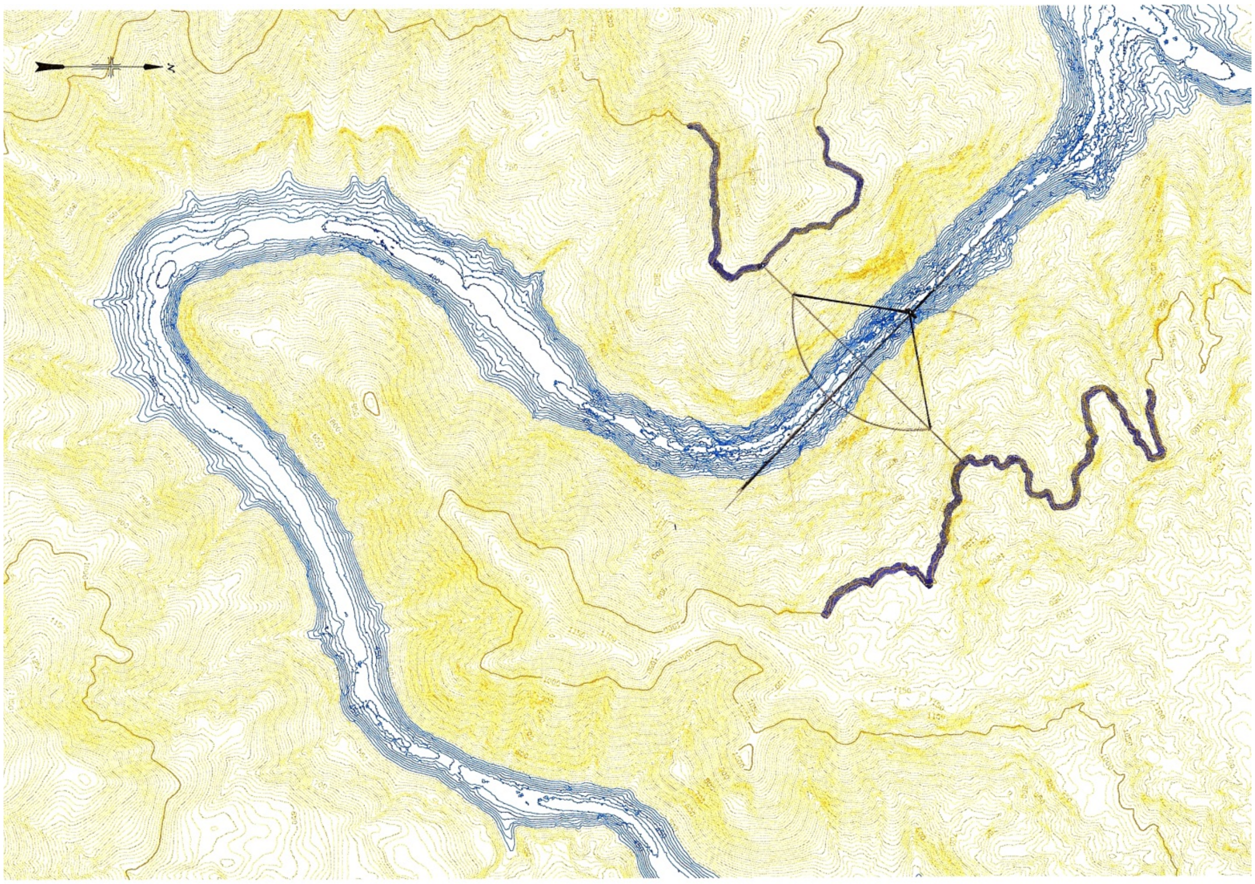


Figure J2-8 – Downstream arch and cantilever stresses



Appendix J3 – Medium Wide V Shaped Canyon (Upper San Joaquin with Thrust Block)

Appendix J4 – Narrow V Shaped Canyon (East Canyon)

J4

Appendix K – Example Three-Centered Layouts

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