IIT Hyderabad

Internship Report

Seismic analysis of double curvature arch dam

Author:
M Ganesh Kumar

Supervisor:
Dr. Surendra Nadh Somala

July 17, 2018

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Abstract

The construction of double-curvature arch dams is an attractive solution from an economic viewpoint due to the reduced volume of concrete necessary for their construction as compared to conventional gravity dams. In this report we did seismic analysis of a double curvature arch dam by changing the radius of curvature of the dam in plan view and radius of curvature of the abutment side curves. Circular equations are used of the geometry of the dam. The dimensions of the idukki dam in kerala are used for all the models not considering the curvature. The maximum stresses at three points on the crown cantilever are considered for analysis. A branched fault system is considered for earthquake data.

1 Introduction

A gravity dam is a dam constructed from concrete or stone masonry and designed to hold back water by primarily utilizing the weight of the material alone to resist the horizontal pressure of water pushing against it.

Concrete dams include mass concrete dams made of conventional concrete or roller-compacted concrete(RCC), masonry dams and hollow gravity dams.

Gravity dams can be classified by plan (shape) as straight and having axis curved to add stability through arch action.

Concrete arch dams are economical compared to other types of concrete dams as an arch dam is built of less concrete compared to other types of concrete dams of the same reservoir capacity. Arch dams are classified with respect to the shape of the arches and the highest cross-section which is commonly located in the riverbed. Single-curvature arch dams are only curved in plan (horizontally), while double-curvature arch dams are curved in plan (horizontally) and in elevation (vertically) [Figure 1].

We first started working on modeling of a straight dam in abaqus. The dimensions of Nagarjuna Sagar dam located in telangana, India. Then went on to study arch dams with single curvature and double curvature. We took dimensions of Idukki dam located in kerala, India.

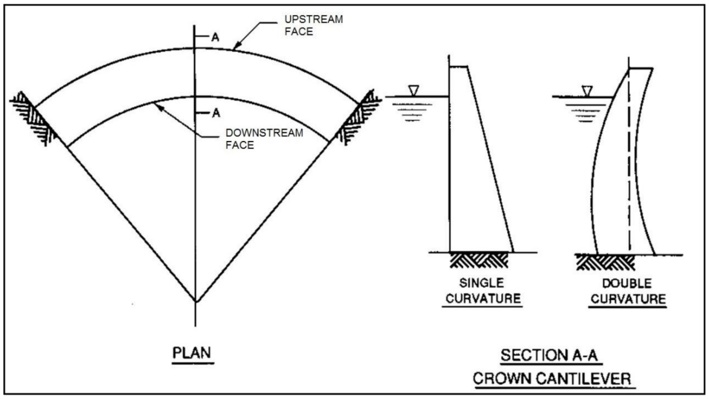


Figure 1: Single and double-curvature arch dam

2 Arch Dams

2.1 Classification based on dam thickness

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. 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.

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

Table 1: Type of dams based on USBR

2.2 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.

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.

2.2.1 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.

We mainly focused on single centered arch dam for modeling the arch dams.

2.2.2 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.

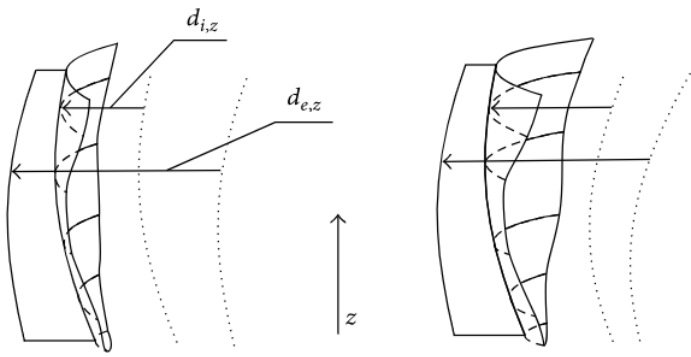


Figure 2: Definition of lines of centers (focuses in the case of parabolas) for both intrados and extrados faces. The shape variation in the intrados is depicted for illustration purposes

3 Considerations

In double curvature dams the radius of the curve of the circular arch in plan view and that of the abutments arches are changed. Both the arches are single centered and the thickness of the dam changes from the bottom to the top. Let R1 be the radius of the plan view arch and R2 be the radius of the abutment side arches.

We considered the dimensions of the idukki dam which is a double curvature dam. Height: 168.91 meters Length of the dam on its top: 365.85 meters Bottom width: 19.81 meters Top width: 7.62 meters

The geometry of the dam we are considering is a simplified geometry as the detailed topographic information is not considered for the study.

There are arch dams located in valleys of different shapes: narrow-V, wide-V, narrow-U, or wide-U.

For our arch dam models we considered wide-U valley as the geographical condition.

According to United States Bureau of Reclamation the arches should have a small central angle between 80 to 100°

The contraction joints are not considered in the models

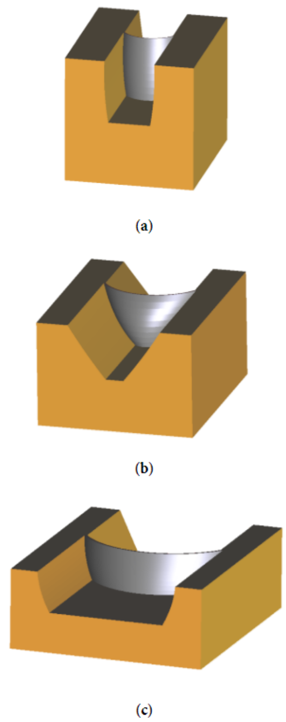


Figure 3: three dam models with different site shapes: (a) narrow-U, (b) narrow-V, and (c) wide-U valleys.

4 Earthquake data

We considered a earthquake rupture for branched fault system

Where the TPV14 is the situation where the earthquake wave propagates in straight path and In TPV15 the maximum wave propagation is into the branch fault.

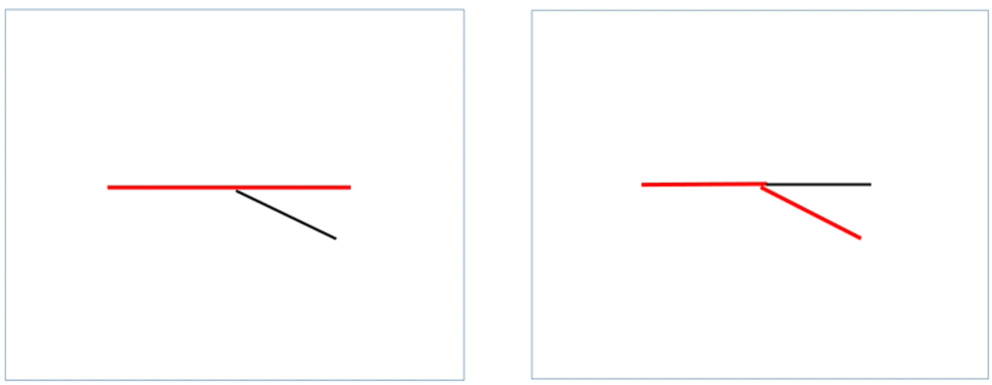
The station 1 is situated at 20 kilometers from the center of the fault in x-direction and station 2 is at 20 kilometers from center at angle of 30°

Magnitude of generated dynamic earthquake rupture : (Mw) **7**

The angle between the branch fault is 30°

We only considered the horizontal acceleration data (i.e in X-direction)

The following figures are the accelerograms of stations 1 and 2 for tpv14 and tpv15.



(a) Right-lateral strike slip rupture (b) Left-lateral strike slip rupture

Figure 4: Two situations (a):TPV14 (b):TPV15

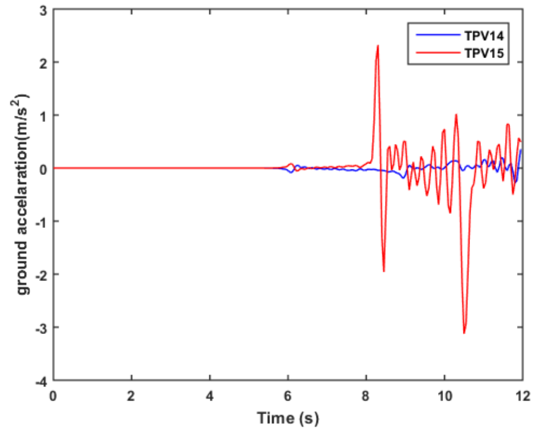


Figure 5: Sation 1

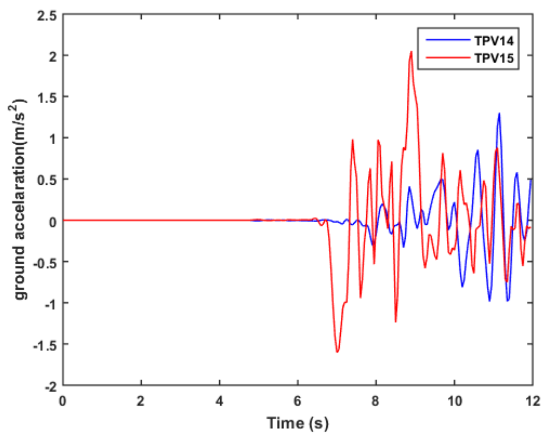


Figure 6: Sation 2

In both stations maximum ground acceleration is more TPV15.

5 Model characteristics

5.1 Concrete Properties

For the simplicity of simulations we considered only density of the concrete and elastic properties for the model.

Property	Units	Dam
Density	$kg.m^{-3}$	2643
Young Modulus	$N.m^{-2}$	31027.10^6
Poisson ratio	–	0.15

5.2 Loads

Gravity Load is applied to the whole model.

Reservoir and dam interactions are considered as hydrostatic interactions. It is applied as a mathematical expression 9810*(168.91-Y).

5.3 Boundary Conditions

The Datum coordinate system is changed from global coordinate system for all the boundary condition.

The bottom part of the dam is fixed with no translations and rotations in any directions and is applied for the nodes.

The abutment sides are fixed with no displacements.

The earthquake boundary condition is applied for the following four cases:

1. Station 1 at tpv14 and tpv15

2. Station 2 at tpv14 and tpv15

These stations are at a branch fault

For the earthquake boundary condition step the bottom fixed boundary condition is deactivated.

5.4 Mesh size

Mesh size is 7m. We considered hexagonal element with 8-nodes (C3D8R).

6 Methodology

We tested the maximum stress on the dam at three different points e1,e2 and e3.
Where e1 being the bottom point at the center of the dam, e2 at the middle part in the same plane and e3 at top part of the dam in the same plane.

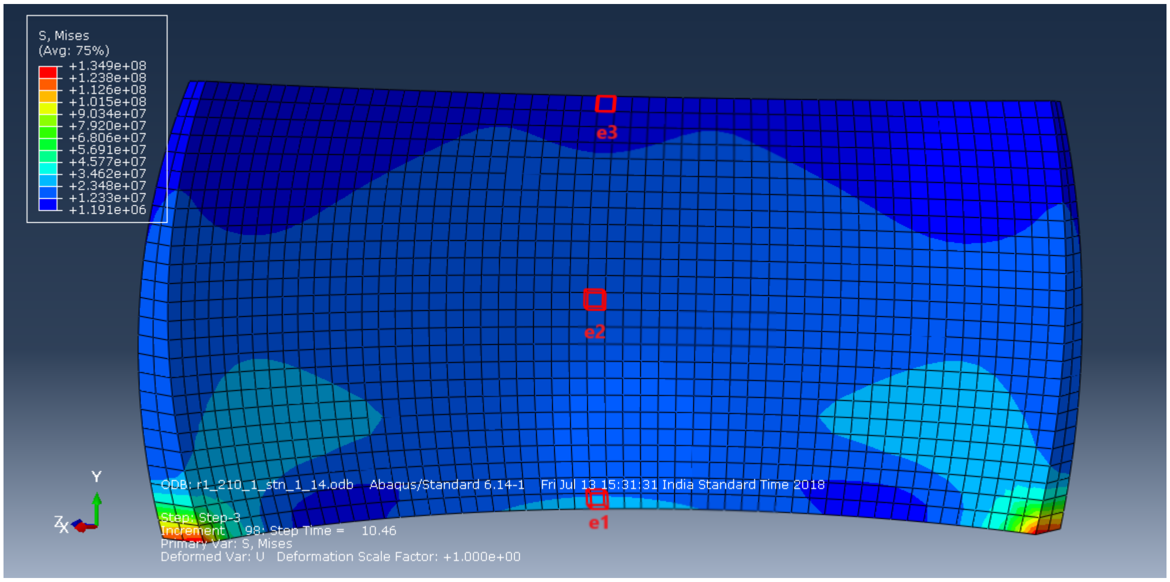


Figure 7: points of consideration for maximum stress

We kept the radius r1 of the plan view arch constant at 210 meters and changed the abutment side arch radius r2 with ratios r1/r2 at 0.8,1 and 1.2

7 Results & Observations

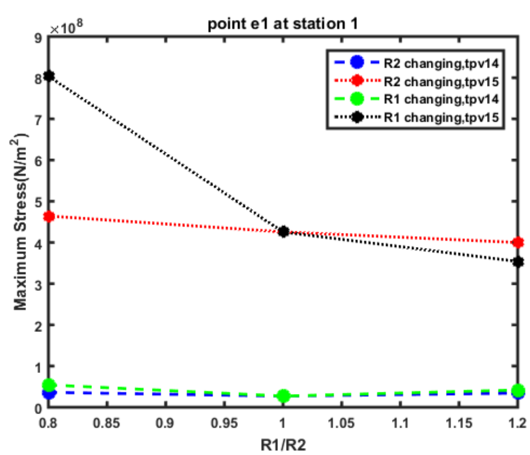


Figure 8: Point e1 at station 1

In TPV15 case as the ratio increases if the radius of plan arch R1 changes the maximum stress decreases for the e1 point. But at the ratio of 0.8, if R1 is less than R2 the maximum stress at the e1 point is higher by 33.31%.
In TPV14 case, the maximum stresses are relatively smaller when R2 is changing in all the ratios, hence it is more preferable than changing the R1 for maximum stresses at e1.

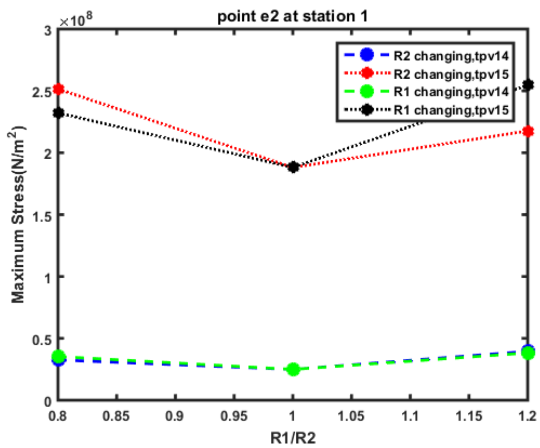


Figure 9: Point e2 at station 1

In TPV15 case at 0.8 ratio the maximum stress is less for R1 changing but as the R1 is increased than R2 the maximum stress becomes more then R2 changing.
In TPV14 case, the opposite trend from the TPV15 case is observed but the percentage of change is lesser at 7.77% and -3.41%.

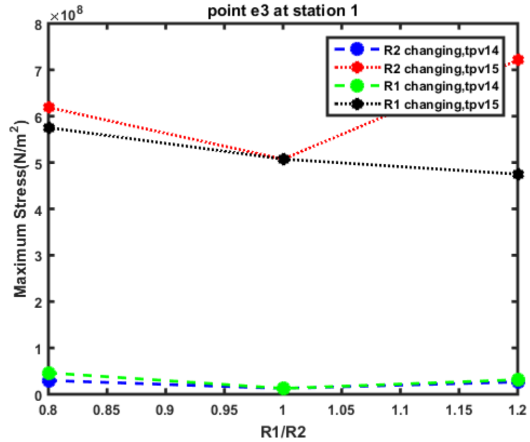


Figure 10: Point e3 at station 1

In TPV15 case the maximum stresses are observed for R2 changing at all ratios than of R1 changing.
In TPV14 case the reverse trend of TPV15 case is observed. Though the percentage difference decreases from 35.66% to 15.10%.

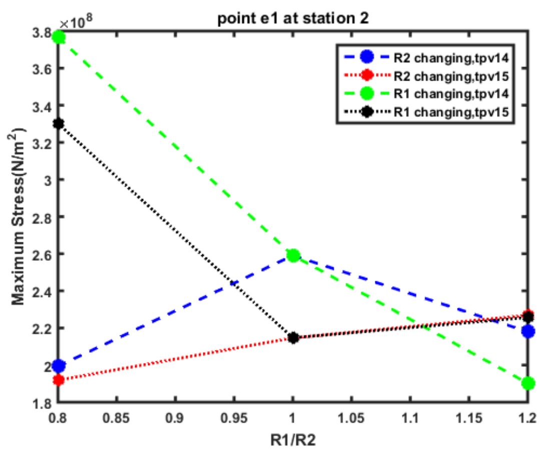


Figure 11: Point e1 at station 2

In this case thought the TPV15 has maximum acceleration, we can see that at point e1 the maximum stresses are relatively higher for TPV14 cases at less ratios when R1 is changing.

At 1.2 ratio, the TPV 15 cases have higher maximum stresses but these are comparatively lesser than at station 1. The difference percentages are shown in the bottom tables for each ratio.

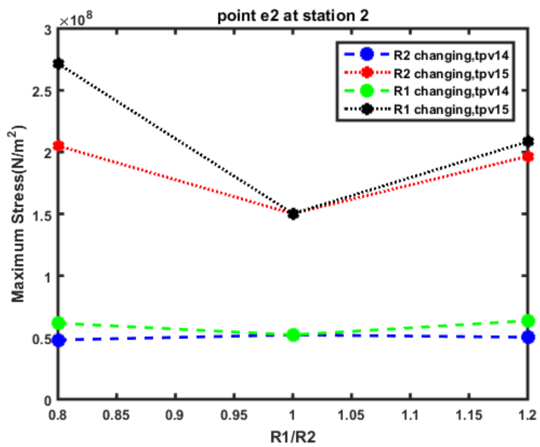


Figure 12: Point e2 at station 2

In TPV15 case, when R1 is changing it has more maximum stresses in all the ratios.
In TPV14 case, the same trend as TPV15 case is observed but at smaller maximum stresses.
In these cases clearly the change in R1 leads in more stresses in all the cases.

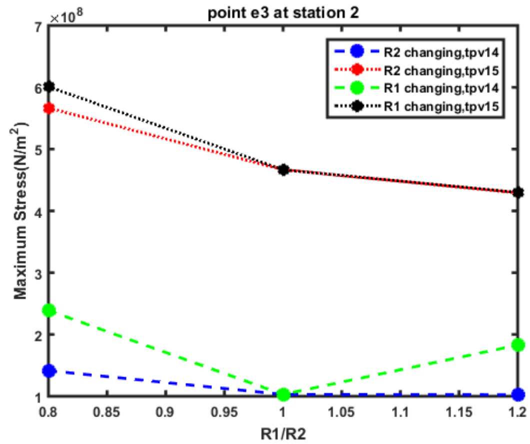


Figure 13: Point e3 at station 2

In TPV15 case, at both the ratios the percentage change is at 5.72% at 0.8 and -0.199% at 1.2. The decrease in the maximum stress if R1 changing is lesses at 1.2 but with more data points a finer result can be observed.
In TPV14 case, clearly if R1 changing it has more stresses at all the ratios.

Percentage change formula :

$$\text{Percentage change} = \frac{(Max.Stress(R1changing) - Max.Stress(R2changing))}{Max.Stress(R1changing)} \times 100$$

	TPV14			TPV15		
R1/R2	**e1**	**e2**	**e3**	**e1**	**e2**	**e3**
0.8	33.31%	7.77%	35.66%	42.22%	-8.229%	-7.58%
1	0%	0%	0%	0%	0%	0%
1.2	17.86%	-3.41%	15.10%	-13.0025%	14.50%	-51.75%

Table 2: At station 1

	TPV14			TPV15		
R1/R2	**e1**	**e2**	**e3**	**e1**	**e2**	**e3**
0.8	47%	22.047%	40.75%	41.908%	24.47%	5.72%
1	0%	0%	0%	0%	0%	0%
1.2	-14.59%	20.977%	43.91%	-0.527%	5.71%	-0.199%

Table 3: At station 2

8 Conclusions

- The percentage change of maximum stress is more at lower ratios (0.8) of R1/R2 mostly for all the points. Since we have considered a branch fault earthquake, where the TPV15 case is the earthquake propagating in branch fault, the maximum stresses are observed there for all the models at all ratios.

- For station 1 with TPV15 dominating TPV15, the point e1 has lesser stresses at higher ratios when both R1 and R2 are changing. For point e2 the stresses are varying with ratios from higher to lower if R2 is changing and the reverse is observed when R1 is changing. For point e3 clearly for all ratios when R2 is changing the maximum stresses are observed.

- For point e1 at both the stations at higher ratios it is experiencing lower maximum stresses.

- For point e2 at both stations the maximum stresses are slightly lower at higher ratios, but this result can be more fine tuned with more data at different ratios.

- For point e3 at higher ratios it is experiencing lower maximum stresses except at some cases where R2 is changing in station 1.

9 Discussions

- The the model we took into considerations are the circular arches at plan view and at abutments. We can consider parabolic equations for

the geometry of the double curvature arch dam. The main difference between circular formulas and parabolic formulas is circular formulas cannot describe the abutment thickening as efficiently as parabolic formulas.
As a result, more concrete volume is used when circular formulas are applied resulting in a more expensive structure.

- Higher order formulas may be used as well, but there are several issues that have to be taken into account. The computational effort and the complexity of the geometry are significantly increased.

- One can design the dam according USBR(United States Bureau of Reclamation) by using the empirical formulas for crown cantilever thickness and the curvature.

- The drift of the elements can be observed and calculated for the elements at different ratios.

10 References

An Interactive Tool for Automatic Predimensioning and Numerical Modeling of Arch Dams
D. J. Vicente, J. San Mauro, F. Salazar and C. M. Baena

Design of Double-Curvature Arch Dams in Terms of Geometric and Stress Constraints by Using Script-Based Finite Element Modelling
Goulas, E.

Design of Double-Curvature Arch Dams Planning, Appraisal, Feasibility Level
U.S. Department of the Interior Bureau of Reclamation Technical Service Center Denver, Colorado

Arch Dams: Designing and Monitoring for Safety
edited by Jose O. Pedro, National laboratory of civil engineering

Seismic analysis of a concrete gravity dam
An example in SIMULIA User Assistance 2017