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# Earthquake Response of Arch Dams including Hydrodynamic effect using ABAQUS

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**Abstract**

A simple arch dam [1] is analyzed to find responses due to an earthquake, including the hydrodynamic effect of the reservoir water. The simple arch shape dam was modeled as a monolith structure, assuming the linear behavior of dam concrete. The arch dam is modeled with finite elements. The hydrodynamic effect is considered as an added mass of water adhered to the dam's upstream surface [2]. Natural frequencies and mode shapes are computed for the dam without water and the dam with water. Time history analysis of the dam is performed for the Kern County earthquake (1952), Taft component 111 acceleration time history. The added mass of water is calculated according to the Kuo 1982 [2] research paper. Various results containing Cantilever stresses, arch stresses, and deflections are shown and plotted. Analyses are performed with the help of the Abaqus Software.

*Keywords*: Frequency analysis, Responses, Time history analysis, Arch dam, Added mass, Mode shapes.

## 1. Introduction

A Simple arch dam shape from reference [1] is chosen to analyze. This simple shape of the arch dam is easy to model and convenient for applying added mass as nodal inertial masses at the dam's upstream surface. The upstream face of the arch dam is a segment of a circular cylinder contained within radially extending vertical banks enclosing a central angle of 90$^{o,}$ and no vertical curvature is provided to the dam, although actual arch dams have curvature in both vertical and horizontal directions. The dam base and banks are assumed as fixed, i.e., the foundation rock and canyon banks are assumed to be rigid. The simple geometry assumed for the arch dam would not be sufficient for real-life dam analyses, but it is useful to understand hydrodynamic effects in the dynamic analysis of arch dams. Radius, R= 50m, Height of the dam, $H_d$=100m Top width of the dam $B_1$=3.5m, Base width of the dam $B_2$=20m.The hydrodynamic term 'added mass' is taken from [2].

The properties of the concrete of the dam are young's modulus E = 34 GN/m$^2$, Poisson's ratio $\upsilon$ = 0.17, and unit weight of concrete $w_d$ = 2400 kg/m$^3$. The damping ratio for all normal modes of vibration of the dam is assumed to be the same and equal to 5 percent.

## 2. Ground Motion

Acceleration time history of the Kern County earthquake (1952), Taft component 111 is applied in the upstream-downstream direction at the dam base (PGA = 0.18g). No time history was applied in vertical and cross-stream directions.

## 3. Numerical Study

The 3D model of the dam monolith is prepared in AutoCAD 3D, and this 3D model is imported into the ABAQUS Environment as a part. The dam meshes with C3D8: An 8-node linear brick finite element. The property of the concrete is assigned to the dam monolith model.
Westergaard [3] derived his equation for the added mass approach, assuming a completely vertical surface. For such cases, the water mass only acts horizontally (perpendicular to the interacting surface) on the dam surface during a seismic event. Kuo developed a more generalized approach that can be used for arch dams where the contact surface is curved in one or two directions. Water pressure can only develop normal dynamic forces. So, the added mass has to be considered, acting in a perpendicular direction. Hydrodynamic force is considered according to Kuo (1982) [2]. This method is often stated as Generalized Westergaard Added Mass Added masses were applied at the U/S mesh nodes. In ABAQUS, added masses were applied in the interaction module as inertial point masses in the form of $m_{11}$, $m_{22}$, and $m_{33}$ at each mesh node. $m_{11} = \lambda_x m$, $m_{22} = \lambda_y m$, $m_{33} = \lambda_z m$, where m is the mass of the water in the contributing area at a mesh node. Values of $\lambda_x$, $\lambda_y$, $\lambda_z$, and $m_{11}$, $m_{22}$, and $m_{33}$ are found at each mesh node, and values of $m_{11}$, $m_{22}$, and $m_{33}$ are applied at the corresponding nodes.

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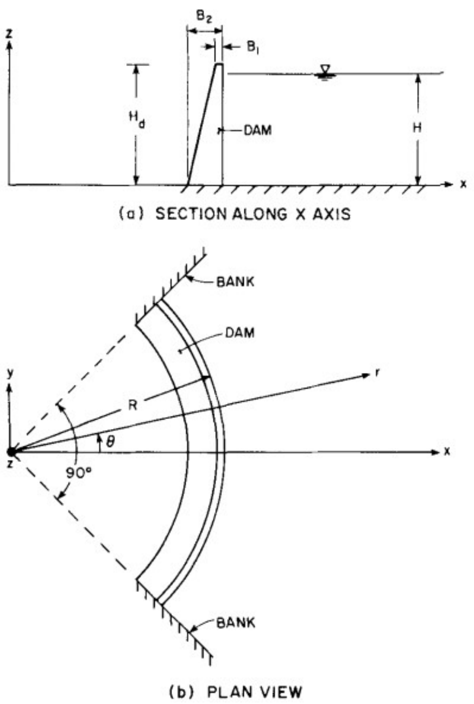



Figure 1: Plan and section of the Arch Dam [1]

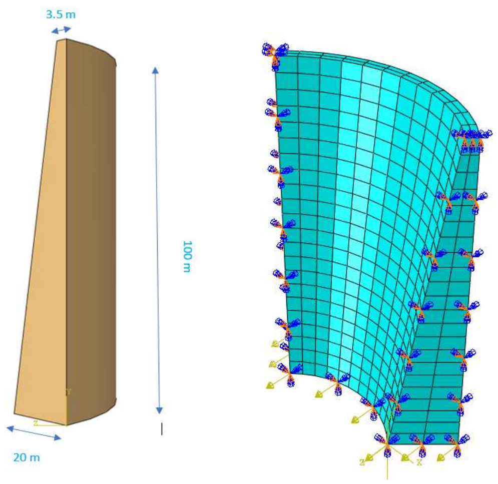



Figure 2: 3D model of the Arch Dam

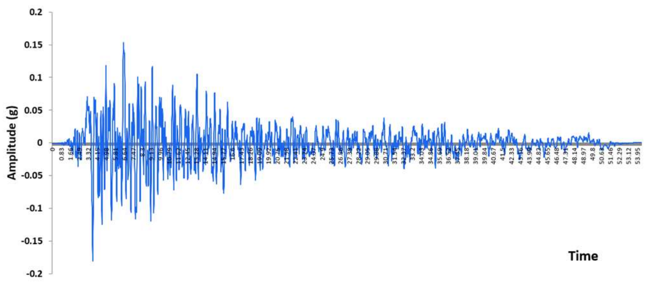



Figure 3: Acceleration time history

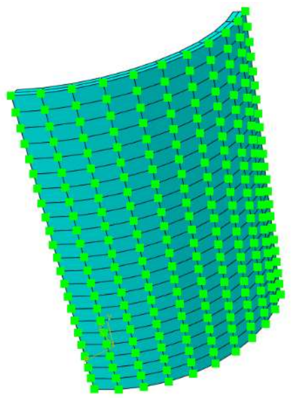


Figure 4: Added mass of water attached to the mesh node points

$$\underline{M}as_i = \alpha_i A_i \lambda_i^T \lambda_i = \alpha_i A_i \begin{pmatrix} \lambda_x^2 & & \text{sym.} \\ \lambda_y\lambda_x & \lambda_y^2 & \\ \lambda_z\lambda_x & \lambda_z\lambda_y & \lambda_z^2 \end{pmatrix}_i$$

$\underline{M}as_i$ is the added-mass matrix associated with node i
$\lambda_i = < \lambda_x \lambda_y \lambda_z >_i$, normal direction cosines at node "i"
$\alpha_i$ = Westergaard pressure coefficient $\frac{7}{8}\rho\sqrt{H_i(H_i - Z_i)}$
α = mass density of the water
$H_i$ = depth of water at the vertical section that includes node "i"
$Z_i$ = Height of node "i" above the base of the dam
Ai = tributary area associated with node i.

Frequency analysis is performed for the dam without water and the dam with water as added mass, and some initial natural frequencies and mode shapes are found. Time history analysis is also performed, and results are shown in tabular and graphical form.

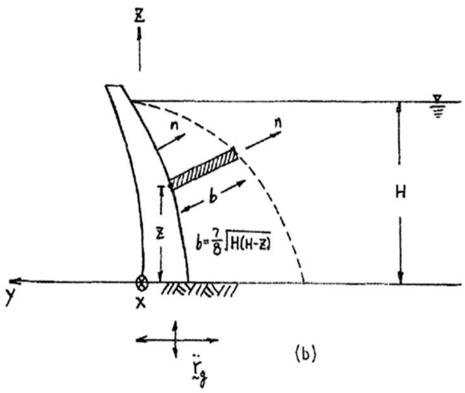
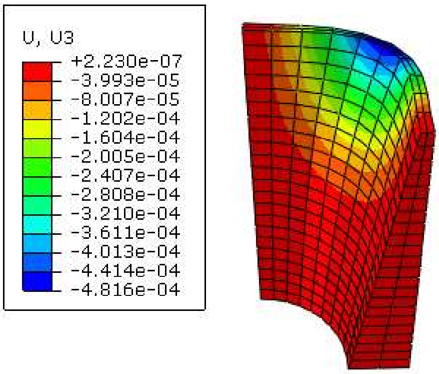


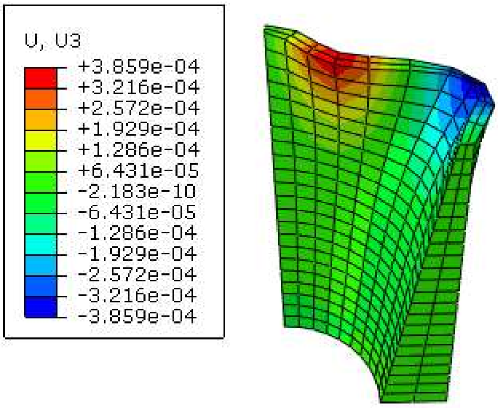

Figure 5: Added mass according to modified Westergaard method [10]

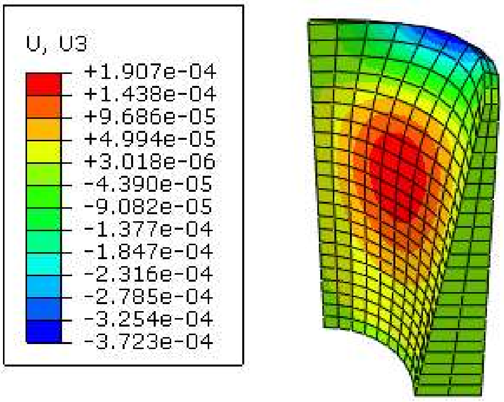
## 4. Results:

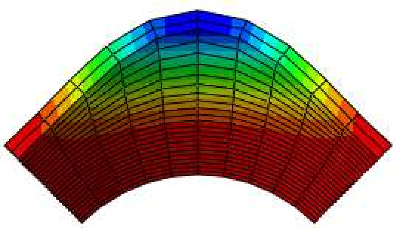
### Natural frequencies and mode shapes

**(a) Dam Without Water**

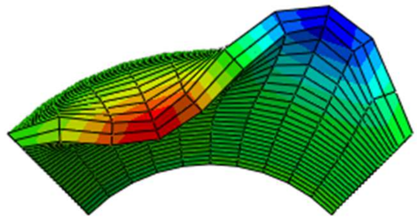


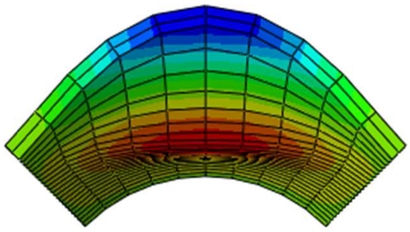



**Mode -1 $\omega_n$ = 11.58 HZ**

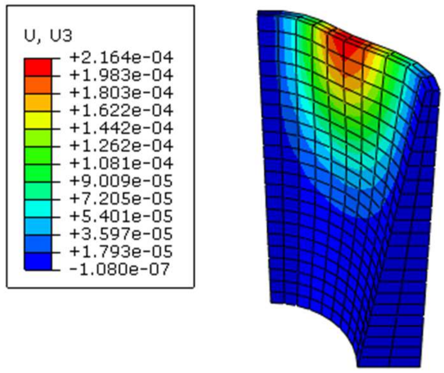


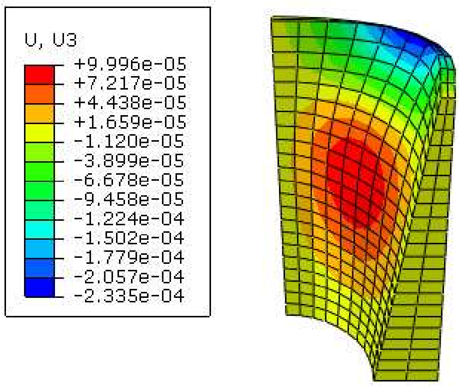
**Mode -2 $\omega_n$ = 13.51 HZ**

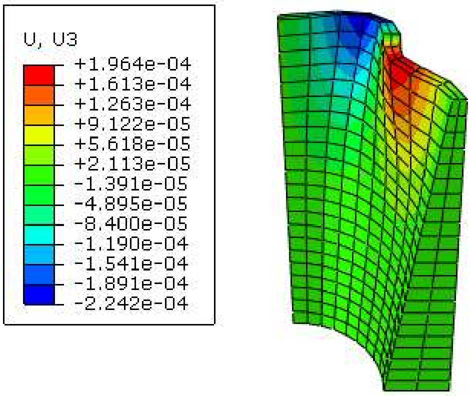


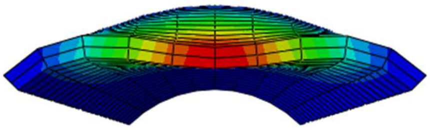
**Mode -3 $\omega_n$ = 14.68 HZ**

**(b) Dam with Water (Water as added mass)**

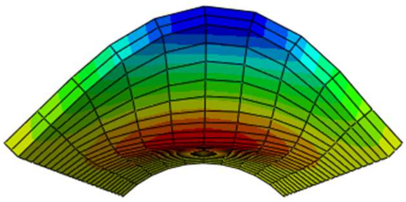


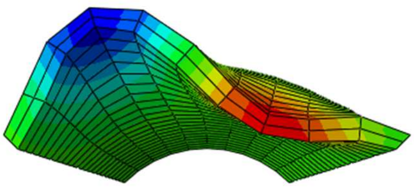


**Mode -1 $\omega_n$ = 6.86 HZ**



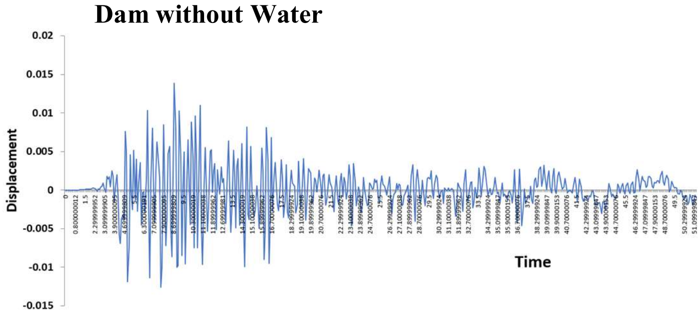
**Mode -2 $\omega_n$ = 8.65 HZ**



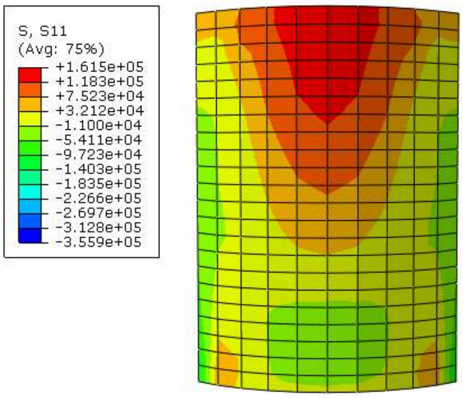
**Mode -3 $\omega_n$ = 8.75 HZ**

**Deflection and Stresses**

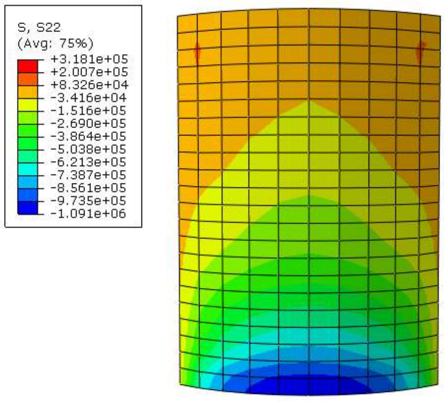
**Dam without Water**




**Deflection of the central top node**

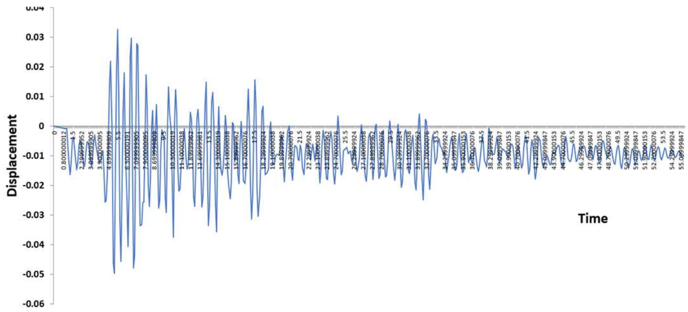



**Arch Stress at 10.5 sec**

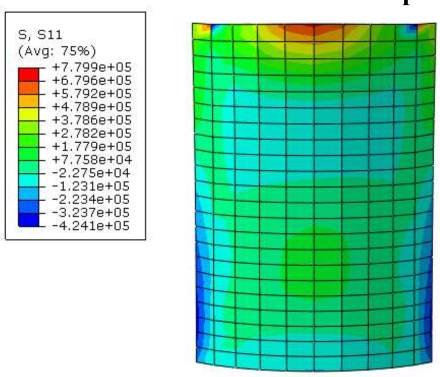



**Cantilever Stress at 10.5 sec**

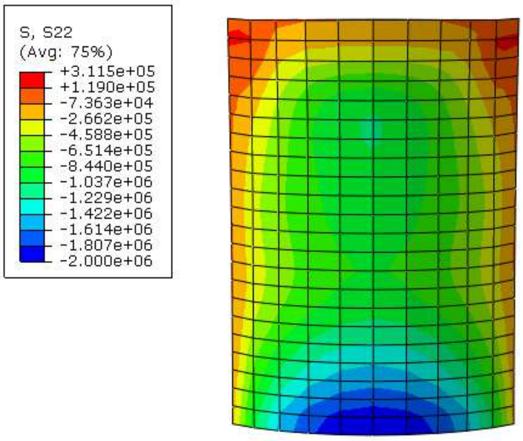
**Dam with Water (Water as added mass)**




**Deflection of the central top node**




**Arch Stress at 10.5 sec**




**Cantilever Stress at 10.5 sec**

## 5. Conclusion

The following conclusions are based on the response results presented in this paper for arch dam-water System of simple geometry. In general, hydrodynamic effects should be considered in analyzing the dynamic response of arch dams. Water in the reservoir causes a decrease in the natural frequencies of the dam; as much as 25 to 40 percent reduction was observed in analysis results. The decrease in a natural frequency depends on the depth of water, mode number, and whether the mode is symmetric or antisymmetric.

Deflection at the top central node and arch stresses at the dam's upstream face are also increased due to the presence of the water. A small increment in the cantilever stresses is also observed at the bottom, but sometimes cantilever stress is decreased due to the presence of water, so no clear relation between the presence of water and cantilever stress can be found.

## Disclosures

Free Access to this article is sponsored by SARL ALPHA CRISTO INDUSTRIAL.

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