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Finite Element Analysis of Concrete Arch dams: A Survey

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***Abstract*---- The design and construction of arch dams is based on its ability to withstand various forces of nature that can impact it over the life period. The prior research and present investigation on concrete arch dam reveals that material behavior of arch dam is well known but the geological conditions cannot be predicted and are complex too. Concrete arch dams have a good overload capability and safety records but the dam structure has always been troubled by cracking, deflection, and stresses and strains beyond the acceptable limits which lead to failure issues as other engineering structure. If the factors like foundation, water compressibility, dam water interaction, dam water foundation interaction, wave pressure, TRP etc. subjected to seismic forces if taken into consideration in the analysis and design of concrete arch dam will lead to a stable optimized and a feasible structure and can be functional throughout the life of the structure. The FEM approach is widely used in analyzing and designing of concrete arch dams. This paper presents the review of the researches carried out at various levels focusing mainly on finite element analysis. This review may not cover up entire literature and work published worldwide however we have tried to accommodate most of the literature.**

Keywords ---- arch dam, dynamic analysis, dam water foundation interaction, thermal stresses, wave pressure

I. Introduction

Arch dams utilize its compressive strength to transfer large water loads and other loads by means of arch action [1]. Advanced engineering knowledge is required for analysis and design of arch dams. From last 50 years researchers has been extensively active to improve annunciation of the complex behavior of dam –reservoir system and implement more reliable approaches into codes of practice [2].Since an arch dam carries loads in parts by arch action by transmitting them to the abutments, and it is in contact with foundation and water levels over the height of dam. Arch dam is a statically indeterminate structure. In the event of cracks occurring under the external loads, the arch dam distributes the load between arches and cantilevers and possesses good ultimate load bearing capacity [3]. Thus the effect of dam water foundation system must be considered in analyzing and designing of arch dams *[Hanchen Tan and Anil Chopra 1995]*.

There are number of ways to analyze the arch dams spanning across the valley. *A.Zingini et al. (2013)* states that amongst them the simplest is based upon the assumption that arch ring at various levels are parts of a thin cylinder. In other methods the arch ring is analyzed through the rigorous theory of elasticity ie: theory of arches, finite difference techniques or finite element techniques. In recent past the trend is to employ the FEM technique [4]. The three dimensional static and dynamic analysis of concrete arch dams, should include dam–reservoir-foundation interaction, water compressibility, bottom sediments, nonlinearities originating from the opening or slipping of the vertical contraction joints and the cracking and crushing of the mass concrete, temperature stresses, seepage through dam body, wave pressure etc. [5, 6, 7, 8].All this parameters considered in design leads to a stable structure [9, 10]. This paper focuses on some of the studies related to concrete arch dam by the researchers around the globe. The efforts are being made to incorporate the research review from available literature; however the readers may find additional researches on the same.

II. Earthquake Analysis of Arch dams

The earthquake response analysis of concrete arch dams generally is performed by the standard dynamic FEM *[Binol Varghese et al.2014]*. However, prediction of response of the dam during severe earthquakes is more complex than a typical problem in structural dynamics [12]. The seismic response of the structure is radically influenced by its dynamic interactions with the geological strata and the reservoir water *[**Herzog** 1989]*.

A. Dam-Reservoir- Foundation rock interaction

The concrete is a macroscopic homogenous material. The previous research has shown that the interface between dams, water, and foundation affects the seismic response of concrete arch dams. Cracks that occur in dam concrete are caused due to excessive tensile stresses *[Hanchen Tan and Anil Chopra 1996]*.The FE model of arch dam reveals that due

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to seismic forces the utmost opening of contraction joints is smaller than the allowable openings. Spatial variations in ground motion had considerable control on the computed stresses in the dam [14].The experimental investigations conducted on prototype shows that the cracks are developed in the upper zone of the high arch dams due to tensile stresses [15,16,17,18,19]. Pacoima dam (California, USA) is an example of how a dam can suffer damages in case of strong earthquakes. The cracks in the dam continued horizontally, vertically and along diagonal directions [20,21].

Due to earthquake forces, the cracks in the foundation repeatedly open and closes and this reduces the response of the dam [22].Geological conditions for a dam site is very complicated. Foundation is often composed of complex rock materials and strata. Hence the foundation inhomogenity must be taken into consideration for the safety evaluation of arch dams [23,24,25].

A 3D FE model of arch dam subjected to seismic forces shows that stress response at major parts of arch dam are reduced if the water compressibility is taken into consideration [26].The model that considers water compressibility provides appropriate assessment of the seismic safety of arch dam than the added mass approach. Added mass approach over estimates the stress response at some major parts of dam due to seismic waves [27, 28, 29].

Currently a trend is to provide viscous damping of about 5% to dam and foundation separately which leads to extreme damping in the dam foundation water system and thus underestimates the seismic response of arch dam [6,30,]. *Peng Lin et al. (2014)* developed a DFPA (Dynamic failure process analysis) code .Dams designed through DFPA codes proves to be effective in predicting the failure process of dam and its foundation. *M.A.Hariri Ardebeli et al. (2012)* proposed a method for estimation of crack profiles in the dam body based on ETA (Endurance Time Analysis).This method provides reasonable response in comparison with THA (Time History Analysis).

B. Hydrodynamic pressure

Hydrodynamic forces generated due to seismic waves play an important role in analyzing and designing of arch dams. The earthquake waves generate hydrodynamic forces and waves in the impounded water. Westergaard in 1933 sternly carried out hydrodynamic analysis of the dam considering the dam water interaction [34]. The high magnitude earthquakes could raise the water levels in the reservoir and can cause threat to human life and safety of dam. Higher water levels may lead to damage of the hydraulic structure. Further the surface waves leads to generation of hydrodynamic forces [35].

The weight of the dam and lower water levels inclines the dam structure towards upstream side. As the water levels increases the dam structure inclines downstream. Stress and strains are well within permissible limits during first impounding process [36, 37]. Hydrodynamic forces decrease the displacement in the dam but increases stress response during earthquakes [13]. Water compressibility is more important in opening and closing of contraction joints which reduces seismic stress response in some parts of arch dam [3,39,40,13,43].

Some approaches to understand dam water effects under earthquake loads are Westergaard, Langrangian and Eulers approach *(Sevim et al 2011).* The Author compared the above approaches and states that that the later ones can model dynamic interface between dam water system and considers the water compressibility.

The experimental results shows that due to under water shock waves on concrete arch dam top portion of dam undergo fracture. These cracks appear from upstream to downstream face [42].

III. Model Updating

Ahmet Can Altunisik at al.2016 presented a study on the outcome of 3D FE model updating on linear and non linear seismic response of dam water foundation structure on an existing dam [45]. Dynamic results show that there was approximately 15% to 20% difference among analytical and experimental outcome. The dam was calibrated by varying the material properties of the dam structure to minimize differences.[Baris Sevim et al.2009]. The two models are compared and displacements obtained from updated FE model are smaller than the initial model [1,27].

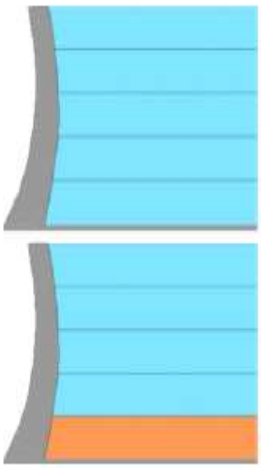
IV. Influence of Reservoir Geometry and Bottom Sediments on Arch Dam

F.Garcia et al.2011 states that the safety of arch dam is largely depends on the geometry of dam. Conventionally the designer would base the shape of the dam through his experience and trial methods [47]. In order to create the geometry of arch dams *Jalal Akbari et at. (2011)* proposed an algorithm based on Hermit Splines method.

J.J. Aznarez et al (2006) proposed a Boundary Element model. This model studies the effect of bottom sediments on dynamic response of arch dams. Hydrodynamic energy becomes imbued due to bottom sediments and thus the damping in the dam water foundation rock system is increased. In the sedimentation process bottom sediments are gradually consolidated due to gravitational force. The properties of bottom sediments vary with respect to depth and are very much varying from the impounded water [48].

Moderately Saturated bottom sediments have limited influence on the geometry of arch dam. In the presence of sediments, frequency response of structure is decreased for incidental P-waves and for rising reservoir water levels (Figure 1 & 2). The author states that, clear relationship between structural response, sediments and geometry of the structure cannot be established for different reservoir levels studied. Further states that accurate modeling must be carried out to establish the relation between the above said parameters in the vicinity [48].

There are two base approaches for 3D analysis of arch dam ie: Added mass and Lagrangian theory. The Brezina arch dam is three dimensionally modeled using these theories. Dam analyzed using first approach proved to be the simplest and cost effective .Further research on arch dams through this approach reports that the coupled frequencies are higher in the dam as compared with actual frequencies. Frequencies estimated by the later approach are not quite exact. The natural frequency of dam system model with water is much below the dam reservoir system without water. But in the way that was not expected, frequency of dam reservoir foundation model are more than the dam foundation rock model (Figure 3).The results shows that the added mass theory is simplest but cannot provide the sloshing effect [39,49].



	Reservoir level
No sediments	5H/5 (full)
	4H/5
	3H/5
	2H/5
	H/5
	0 (empty)
With sediments of thickness H/5	5H/5 (full)
	4H/5
	3H/5
	2H/5
	H/5 (empty)

Figure 1.Reservoir Levels with no sediments and with partial sediments (Source:F.Garcia et al.2014)

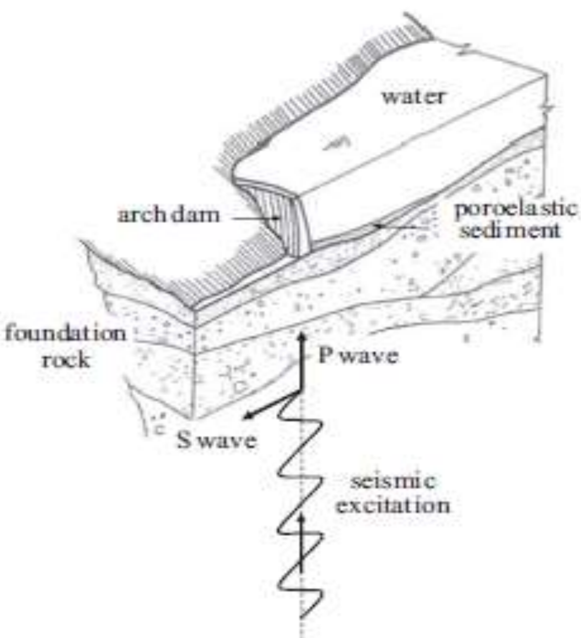


Figure 2.Dam–water–sediment-foundation system (Source:F.Garcia et al.2014)

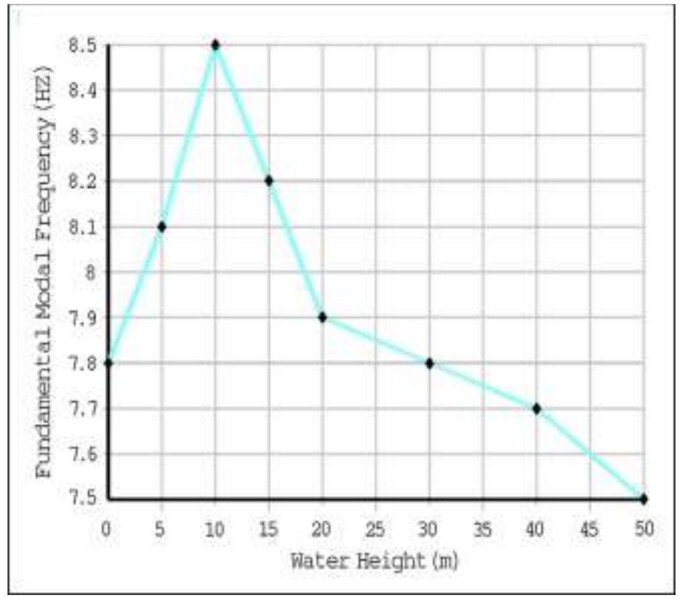


Figure 3. Effect of water levels on the fundamental coupled frequency on dam water foundation system (Source: T.B.Amina et al.2015)

V. Influence of Thermal Variation on arch dams.

Temperature loads play an important role in analyzing and designing of dams, principally when in service under severe temperature variations. After grouting contraction joints, temperature stresses are developed in the huge dam structure due to variation in temperature. In general, temperature distributions within a dam, vary in a nonlinear manner but they are usually approximated by a combination of uniform and linear variations in practical applications. When a temperature change occurs in an arch dam, the resulting volumetric change, if restrained by the dam boundaries, induces thermal stresses in the dam [50]. The researchers across the globe have announced the threat of global warming. The mean temperature on the earth would rise in the coming years. Thus the author has considered the impact of the rise in temperature on the behavior of the structure. [51,52,53].

D.Santillan et al. 2015 states that the thermal variation in the dam concrete throughout the year would increase for the upstream reservoir with full and empty conditions [54]. To study the behavior of dam the loads applied on the structure were the weight of the dam, thermal and hydrostatic loads. Empty, half full and full reservoir water levels were considered for the study. Further the author concluded that the temperature loads in the dam are balanced by the hydrostatic loads. Higher the water levels in the dam, lesser will be warming of the dam body due thermal variation. The rise in the temperature would expand dam concrete and moves the dam crest towards upstream but accordingly the hydrostatic forces pushes the dam downstream [55].Thermal variations were studied on an arch dam in China and is concluded that this phenomenal rise in temperature is observed in the parts of the dam that were sealed later [56].

Huaizhi Su et al.2014 proposed a new technique to reduce the cracks in the dam concrete due to thermal variations. Magnesium Oxide (MgO) if added to concrete that may prevent tensile cracks in dam during cooling period. Cracks are prevented due to expansion of MgO. Further author states that there are three situations to control the dam temperature and to prevent cracks in the dam concrete. The first condition states that Joints in the dam and MgO in concrete should be avoided. Either go for MgO in concrete and do not provide joints. Lastly provide joints as well as MgO in concrete.

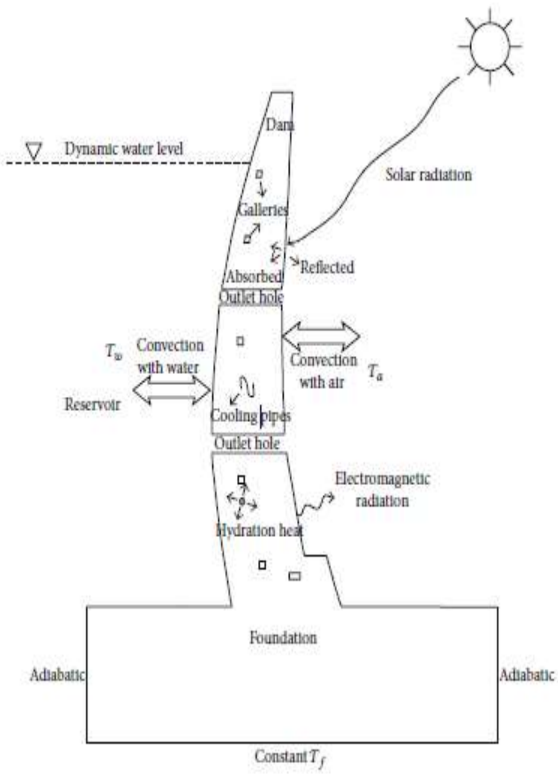


Figure 4: Thermal boundary conditions for arch dams (Source: Qingbin Li et al.2014)

VI. Shape Optimization and Retrofitting of Arch dam

Ahmet Can Altunisik et al. (2015) proposed a study on retrofitting of damaged arch dam .Author carried an experimental investigation on a prototype model in the laboratory. Dynamic forces were applied to a dam water foundation rock model to study its structural behavior. Further the damaged model was retrofitted using high grade concrete and CFRP. After testing the retrofitted model under dynamic loads, the natural frequencies were increased considerably (Figure 5). Thus it is concluded that the strength and stiffness of a retrofitted structure increases [58,59].

Sergio Oliveira et al. (2006) proposed an experimental and numerical investigation on a prototype of arch dam and concluded that the stresses and strains were within the limits. *Jalal Akbari et al. (2011)* proposed an algorithm based technique for optimization of arch dam that works on Hermit Splines approach..

Figure.5. Prototype of dam water foundation system (Source: Ahmet Can Altunisik et al. (2015)

VII. Influence of wave pressure and seepage on arch dams.

Author compared the existing arch dams for seismic induced stresses. The stresses induces in dam are studied with water compressibility measured and water compressibility ignored. Further the effect of water compressibility and reservoir boundary absorption is also neglected. From the results it is concluded that stresses are appreciably underestimated if water compressibility and reservoir absorption neglected as in the case of Monticello Dam (Figure 6). Stresses may be overestimated, as in the case of Morrow Point dam and these discrepancies vary with the location on the dam surface. Thus, water compressibility and reservoir boundary absorption should be included in the arch dam analysis. [60]

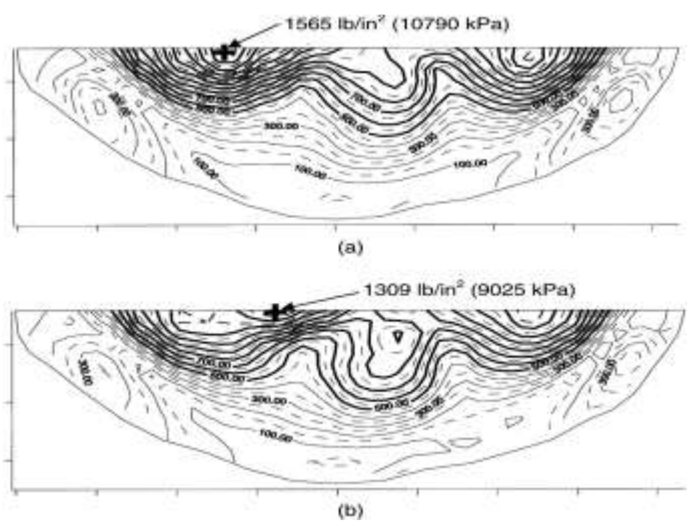


Figure.6. Tensile stresses in Monticello Dam with (a) water compressibility (b) without water compressibility (Image courtesy of Larry K. Nuss)

The pore water pressure in the dams is reduced by providing grouting curtains and drainage holes. Further it reduces seepage through dam body leading to a stable structure [60].

VIII. Concluding Remarks

From the literature review on concrete arch dam, following concluding remarks are made:

a) The upper zone of arch dam is prone to tensile cracks due to earthquake forces [4, 15, 16, 17, 18, 19].

b) Earthquake response of arch dam is reduced due to opening and closing of micro cracks in the foundation [22].

c) Geological condition plays a vital role in the design of arch dam [23, 24, 25].

d)Water compressibility considered in the analysis decreases stress response at key positions and can asses seismic safety of dam [26,27,28,29,39,40,13,43].

e) Analysis of dam through DFPA and ETA codes provide reasonable response in comparison with THA [32,33].

f) During first impounding, the dam inclines towards upstream at low water levels and vice versa [36, 37].

g) Underwater shocks lead to cracks in the top portion of the dam [42].

h) Energy generated by hydrodynamic waves is absorbed by bottom sediments and also raises damping in the dam structure [48].

i) The impact of thermal stresses on dam depends on the reservoir levels in dam. Higher the reservoir levels lesser the thermal stresses [50, 51, 52, 54, 55].

j) Cracks in dam concrete due to thermal variation can be controlled by adding Magnesium Oxide in concrete [57].

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