Hydrodynamic Isolation for Concrete Arch Dams

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Abstract

Earthquake is one of the important forces in arch dams design. The hydrodynamic forces resulting from earthquake or shock blast especially in high arc design of concrete dams that their sites are located in high seismic risk , is considerable . For this reason, it seems to use hydrodynamic pressure reducing methods in these types of dams can be more useful. The investigation also indicated to reduce the hydrodynamic pressure due to use the air cushion technique this type of dams, Sometimes even up to 92 percent. Clever use of liquid damper in the vertical seams of concrete arch dams and energy dissipation caused by severe earth movement is another effective method for achieving this goal. Because of the strong ground shaking movements the vertical seams with grout injected torn between the seams, seams opened and are not able to tolerance tensile force and damper mounted between the seams will cause absorption and energy dissipation. There are many other ways that have not been applied practically in any dams yet which is presented in this research text.

Keywords: Hydro-seismic Isolator, High arch dams, Seismic energy dissipation, Fluid damper, Air cushion.

1. Introduction

Earthquake force is one of the important forces designing arch dams which must be applied synchronously in three components of river direction, perpendicular to river direction, and perpendicular to the system of dam- foundation- fountain. It’s quite natural that as the height of the dam increases so does hydrostatic and hydrodynamic forces on top of the dam. Sometimes hydrodynamic pressure exceeds hydrostatic one. Earthquake forces can lead to cracks which in turn are more dangerous compared to those on buildings. A arch dam was designed and performed in one case in form of 2- dimensional arming but this method isn’t economical one due to high expenses. This method has been applied in arch dam of Inguri (USSR) with a height of 271 m. as the role of hydro- seismic force are highlighted in design, the method becomes justified economically and technically to dissipation and separate induction force derived from earthquake and shock. Hall et.al, through a research, have described quake separation of gravity dams as insufficient in regions more susceptible to earthquake and recommended this method for arch dams from which considerable hydrodynamic force derived. Some of earthquake- induced force reduction methods are applicable with performed samples and some others are under analytical and experimental studies and they will provide applied observations and results in case of success. Since dam structure plays a major role in different aspects of human civilization, its destruction will result to demolish civilization. For this the issue of investigation and recognition of quake behavior of high concrete dams particularly the effect of water reservoir on quake response of dam have been considered by researchers. This system contains dam structure and lake behind it. This research aims to introduce different technique of hydro- seismic separations and energy deprivation resulting from earthquake and shock and followed by expressing each advantageous and drawbacks.

2. Interaction of water reservoir and dam body

One of the most intricate issues of structural dynamic is prediction of concrete dams’ behavior at time of earthquake. On the most important cases affecting dams’ response to quake is interaction of water reservoir and dam.

Earthquake creates waves in the lake of dam and liquid inside reservoirs and thus applies pressure over than hydrostatic pressure on the dam and walls of reservoirs which is called hydrodynamic pressure. Interaction of a arch dam with water behind results in period of dam fluctuations to increase. This is because the body may not move without deformation of the water. This fact the water moves along with the dam increases the total moving mass. This added mass increases natural periods of the dam and affects response spectrum and inert forces resulting from the earthquake. This also leads to increased attenuation due to absorption of certain pressure waves on reservoir borders and dissipate waves upward. Methods applied to analyze the interaction of dam and reservoir are three groups: approximate added mass, water oiler formulation, water Lagrange formulation. Generalized Westergaard added hydrodynamic mass model for arch dams. The added-mass representation of dam-water interaction during earthquake ground shaking was first introduced by Westergaard (1933) . In his analysis of a rigid 2-D gravity dam with a vertical upstream face, Westergaard showed that the hydrodynamic pressure exerted on the face of the dam due to the earthquake ground motion is equivalent to the inertia forces of a body of water attached to the dam and moving back and forth with the dam while the rest of reservoir water remains inactive. He suggested a parabolic shape for this body of water with a base width equal to 7/8 of the height , as shown in Fig. 3.A general form of the Westergaard added-mass concept which accounts for the 3D geometry (Clough 1977; Kuo 1982) can be applied to the earthquake analysis of arch dams. The general formulation is based on the same parabolic pressure distribution with depth used by Westergaard (Fig. 3), with the exception that it makes use of the fact that the normal hydrodynamic pressure (Pn) at any point on the curved surface of the dam is proportional to the total normal acceleration.

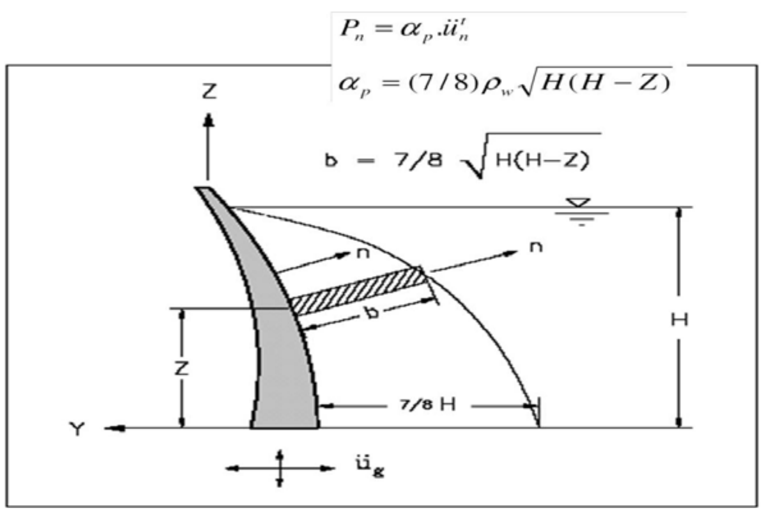


Fig. 1 Generalized Westergaard added hydrodynamic mass model for arch dams.

3. **Air- cushion seismic isolation**

Researchers performed a study on air cushion of concrete dams are mostly from university of Sichuan and Sichuan institute of water and hydroelectric resources in china, Russia and the university of California. A soft layer of As the depth increases, the thickness of this layer increases to make an optimized performance. Hydrodynamic pressure decreases depend on the layer thickness in range of 50-90%. This layer indeed acts as a filter against waves deriving from shock and hydrodynamic pressure. Results indicated that this technic is particularly more efficient where arch dams are high and in site with high hydrodynamic seismic potentiality (Hall & Dowling, 1991). Three phased system of gas- liquid- solid of air chamber is indicated below. Figure 2 shows its performance against explosive wave. Generally, upon increasing width of air chamber, less shake transfer from reservoir to body.

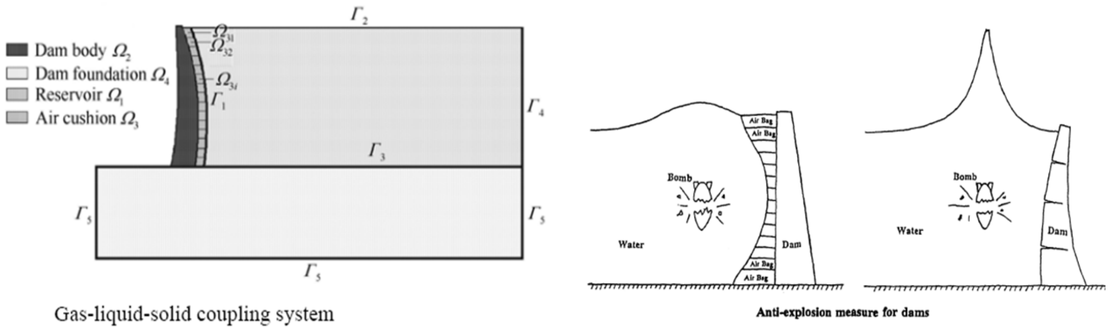
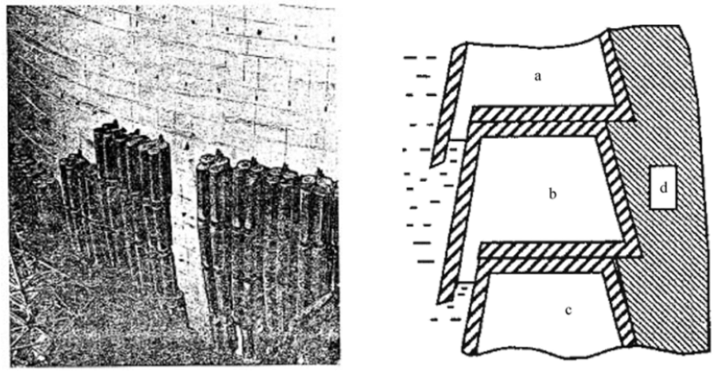


Figure 2 - left) three-phase system of solid - liquid and gas (air cushion) /on the right) air cushions anti-shock system

Through a study in 5 arch dam with various heights, we obtained experiment model under earth agitation for the first three and an analytic model for two last ones. The ratio of hydrodynamic pressure to total seismic burden is approximately 0.5 in dams with 200-300 m height indicating considerable hydrodynamic pressures for this type of dam. For this, the technic is more suitable for arch dams with large heights. Specification of those dams are shown in table 1. Studies on seismic isolation air cushions of dams have been started since 1950 in France and USSR. The first experiment sample of gravity dams Kilvobolouri with a height of 20 m was investigated under explosive shock. Results indicated that the hydrodynamic pressured decreased as 67-88%. Because the created frequency on the dam and wave resulting from shock on the water were high, results weren't applicable for high dams. The air cushion was applied for double arch dam of Chireky with 22 m height with 1100 air chambers of armed concrete and the arch dam of Miately with a height of 186 m with 200 steel air chambers in 1980. Figure 3 shows this. Air cushion has been used designing gravity dam of Mok in Russia with a height of 155 m which resulted in cross section to decrease 9% with large benefits. Figure 3 shows another kind of air layer for top surface of the dam that can be substitute with air chamber. Limitations of air cushion application are including: Certain accessories and equipment will be mounted on top of dam body.Reservoir sediment Figure 4 also shows the effect of the thickness of air cushion layer and the agitation frequency on hydrodynamic pressure of dam top surface. Figure 5 shows small scaled experimental model of arch dam Jinping isolated by means of air cushion.

Table 1 _ effect of hydrodynamic pressure ratio to the total seismic load in 5 dams according to their specification which is previously mentioned in the text.

Dam mass/ added mass	model	Height	Country	Arch dam
1:4.69	Experimental	110	Japan	Shataya
1:2.25	Experimental	113	USA	Monticcello
1:1.34	Experimental	186	Japan	Kurobe4
1:1.087	Analytical	240	China	Ertan
1:0.8	Analytical	278	China	Xiluodu



Gas tank distribution in the Miately arch dam   Concrete air chambers. a, b, c: air chambers; d: dam body

Figure 3 - left) System gas canisters at the upstream dam and right) air supply concrete channel upstream of dam

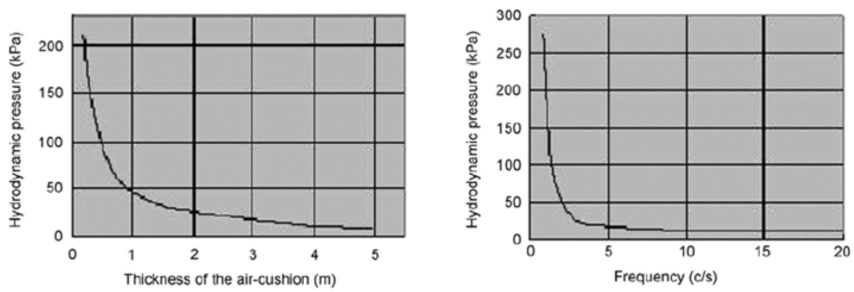


Figure 4 - Effect of excitation frequency on the thickness padding and the pressure upstream of the dam (in order from left to right)

Photo of the experiment model on the shaking table.

Figure 5 - Jinping 1 arch dam vitro model equipped with air cushion

3.1. Results of model analysis of limited components of dam (with air cushion) -reservoir- foundation

Following sections contain dominating equations of dam- reservoir interaction in case of seismic isolation by means of air cushions and mass matrices separation and attenuation and difficulty of system balance equation. Assumptions considered in analytical model are as follow:

The air cushion is considered as continuous layer on top surface.

Conditions of gas inside cushion chamber are the same for ideal chamber.

Gas flow rate isn't considerable in the chamber. The basic equations of air cushion elements are as equation (1). The left side shows the form of Lagrange displacement for the gas inside air cushion. The first elements of mentioned vector are volumetric strain, the second and third are shear strain in two planes indicated by an index. The next three elements show rotation around mentioned indices. K is the Bulk modulus I the right side of square diagonal matrix. Cs and Cr are binding desired shear and torsional parameters, respectively which are considered small for the sake of parameters stability. The first element of right side vector, P, indicates air pressure and the second and third show shear tension and the next three show torsional torque around mentioned axes by means of indices. The involved equation of dynamic balance dominating the reservoir is shown by equation 2. The first term of this equation is resulted from matrix multiplication of reservoir mass by modification rate of nodal pressure vector. The second term indicates the multiplication of the reservoir attenuation matrix by the rate of nodal pressure vector and the second and third is the reservoir difficulty matrix on a nodal pressure vector. The last term in left side is obtained multiplying fluid density in connectivity matrix of gas tank interfacial by nodal acceleration nodal vector. By rewriting it as a matrix and separating it according to relation 3, the first line equation of the system is related to the equation of dynamic balance for dam- foundation- gas and second line is related to the equation of dynamic balance of the reservoir.

$$\begin{Bmatrix} \varepsilon_V \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \\ \theta_x \\ \theta_y \\ \theta_z \end{Bmatrix} = \begin{bmatrix} 1/\boldsymbol{K} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \boldsymbol{C}_s & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \boldsymbol{C}_s & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \boldsymbol{C}_s & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \boldsymbol{C}_r & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \boldsymbol{C}_r & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \boldsymbol{C}_r \end{bmatrix} \begin{Bmatrix} \boldsymbol{p} \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \\ \boldsymbol{M}_x \\ \boldsymbol{M}_y \\ \boldsymbol{M}_z \end{Bmatrix} \tag{1}$$

$$\boldsymbol{M}_{\mathrm{p}}\ddot{\boldsymbol{p}}^{\mathrm{e}} + \boldsymbol{C}_{\mathrm{p}}\dot{\boldsymbol{p}}^{\mathrm{e}} + \boldsymbol{K}_{\mathrm{p}}\boldsymbol{p}^{\mathrm{e}} + \rho\boldsymbol{R}_{\mathrm{p}}\ddot{\boldsymbol{u}} = \boldsymbol{0} \tag{2}$$

$$\begin{bmatrix} \boldsymbol{M}_{\mathrm{s}} & \boldsymbol{0} \\ \rho\boldsymbol{R}_{\mathrm{p}} & \boldsymbol{M}_{\mathrm{p}} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{u}} \\ \ddot{\boldsymbol{p}}^{\mathrm{e}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C}_{\mathrm{s}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{C}_{\mathrm{p}} \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{u}} \\ \dot{\boldsymbol{p}}^{\mathrm{e}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_{\mathrm{s}} & -\boldsymbol{R}_{\mathrm{p}}^{\mathrm{T}} \\ \boldsymbol{0} & \boldsymbol{K}_{\mathrm{p}} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u} \\ \boldsymbol{p}^{\mathrm{e}} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{f} \\ \boldsymbol{0} \end{Bmatrix} \tag{3}$$

Figure 8 shows the model for finite elements of Jinping 1 arch dam and prepared cushion model. For the sake of high efficiency, the cushion model was considered in three different thicknesses in the height of top surface of the dam. Thicknesses are 1, 2 and 3 m bottom- up. After accelerography of the earthquake in 2008 of Vancuan, china with horizontal record of acceleration equal to 3.42 m/s2 on model is shown in two manners with and without hydrodynamic pressure distribution on the dam height. As seen, air cushion plays an effective role to decrease hydrodynamic pressure on dam top surface which is in range of 10-92%.

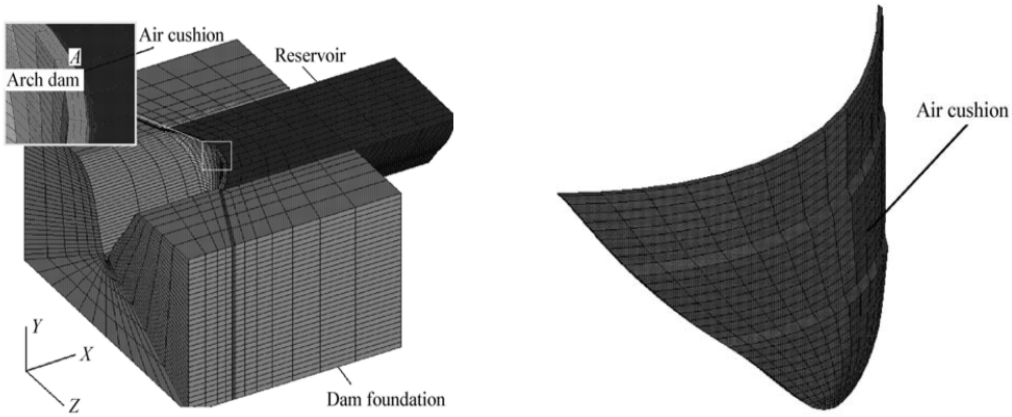


Figure 6 - Finite element model Jinping 1 Dam

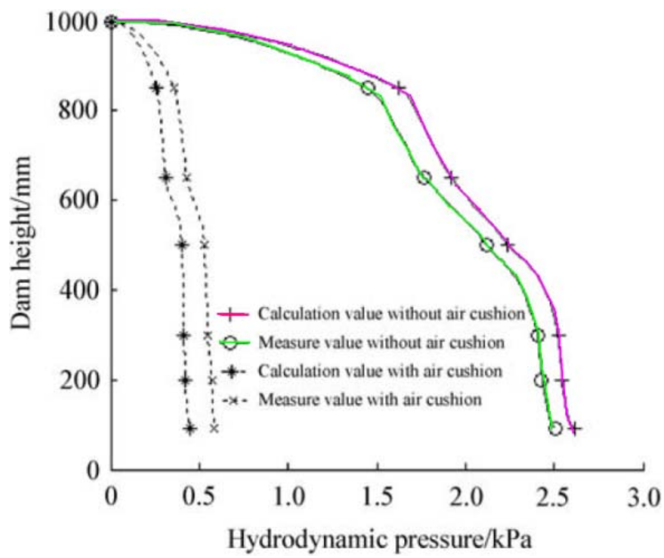


Figure 7 - Results of the finite element model, the distribution of the hydrodynamic pressure on the dam height

4. Conclusions Injection of Air Bubbles

Injection of air bubbles in water which close to concrete dams upstream , is a way to reduce dynamic pressure of water reservoir on dams that has been considered . Dynamic pressures exerted on the dam due to the interaction of the dam and reservoir is increasing the structural response and in result the dam section will be larger and taking concrete in dam will be rise. The idea of injecting air bubbles in the concrete dam-weighted upstream in order to reduce water dynamic pressure on dam body belonging to Savynvf and his colleagues.

5. Dam building using isolated blocks

The idea of this method was introduced by Aminfar et.al (2011). The energy dissipation is through crevices between blocks making the dam which is shown in figure 6. In this method, shear, damper and water stop switches should be placed between cubic pieces. This method is characterized by higher flexibility and energy dissipation. The probability of intension occurrence will be diminished as the period increase. In the case study of this research, the main period of arch dam has been promoted from 0.58 to 4.2 s. authors believe that constructed dams by this method will have proper fulcrum in case of asymmetric leakage because they are of higher flexibility and energy dissipation compared to typical dams. This idea hasn't been applied in a dam so far.

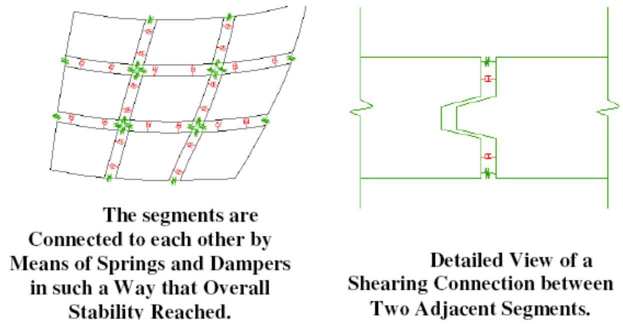


Fig8. Left) blocks connected by a spring and damper & right) shear keys between the blocks

Recently, the damper was used in the Retello dam, Italy. The dampers used in arch dams may produce hysteretic energy dissipation by means of the opening of the contraction joints during strong earthquakes [1]. The related study shows that there are two difficult points in application of dampers to the high dam control.

 Risk of estimation of the contraction joint opening.

According to the typical computation model, all the contraction joints will open, in fact, however, joint opening mainly occurred at one contraction joint in practical earthquakes.

Up to now, three events of contraction joint opening of arch dams occurred, including 2 events (1971, 1944) at the 113 m high Pocaima arch dam, USA, and another one

(1999) at Guguan arch dam (Taiwan, China). According to the analysis results, the maximum opening will occur at the crown; however, practical maximum opening in the three events mentioned above occurred at near the dam abutment.

As a result, if the dampers are installed at each joint, most of them will be no more displacement or energy dissipation; if dampers installed concentrative, it is difficult to estimate where the opening will occur.

5. Conclusions

- Gravity dams' seismic isolation is inefficient in regions with high seismic potentiality and it's recommended to use this technics for arch dams with considerable hydrodynamic force particularly high arch dam.
- Applying the technic of earthquake force dissipation by active control of damper has many complexities and uncertainty.
- Arch concrete dams arming to make them protective against earthquake is not economic.
- Air cushion technic can act as isolator for shocks from explosion in addition to 10-92% isolation of hydrodynamic forces.
- Using logic presumptions can decouple equations of dam- foundation- dam body. Many studies are in hand and this kind of dams are waiting for a clear future with technology and laboratory equipment development, optimized processing, increased potential for modeling multi-phased environments by means of finite element software to make them more strong against hydro-seismic forces and explosive shocks.
- In addition to decrease considerable hydrodynamic force, air cushion technic decrease dam cross section and thereby dam body diminished weight which in turn will be resulted in reduced pressure and tensional maximums on dam body though this technic will face some problems, too.

6. Acknowledgments

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