International Journal of Civil Engineering and
Geo-Environmental

Journal homepage:http://ijceg.ump.edu.my
ISSN:21802742

THE CAVITATION EFFECT ON A CONCRETE GRAVITY DAM RESPONSE DUE TO ROTATIONALCOMPONENT OF EARTHQUAKE

Leila Kalani Sarokolayi[1*], Bahram Navayi Neya[2]

[1]Assistant professor, Tabari University of Babol, Iran
[2]Associate professor, BabolNoshirvani University of Technology, Babol, Iran

ARTICLEINFO

Keywords:
Cavitation
Nonlinear analysis
Rotational component of earthquake
Concrete gravity dam

A B S T R A C T

This paper concentrates on the effect of the rotational components of ground motion during an earthquake on the cavitation phenomena in reservoir of concrete gravity dam. For this purpose, the rotational components of ground motion are created using recorded translational components of ground surface and both translational and rotational components are applied on dam-reservoir system using finite element method. Displacement based formulation is used for both fluid and structural domains, the dynamic equation of motion is solved by Newmark method and the Newton- Raphson modified method is used for consideration of nonlinearity of cavitation in reservoir. To illustrate the rotational components effects on cavitation phenomena, the dam-reservoir system seismic analysis is carried out with and without considering the rotational component of earthquake and the results include the location of cavitation area in the reservoir, the hydrodynamic pressure on dam and the dam crest displacement have been compared with each other. The results indicate that cavitation in reservoirs can occur just during severe ground motion and rotational components of ground motion can change the cavitation location in the reservoir and their hydrodynamic pressure.

1.0 Introduction

During intense seismic excitation, the impounding fluid in the reservoir may separate from the dam and cause forming of micro bubbles and therefore the compressibility and bulk modulus of water is reduced towards zero(Oskoueiet al., 2001;Kalatehand Attarnejad, 2011). When the direction of the ground motion is changed, the micro bubble's region of fluid collapses, and an impact will occur. The formation and collapse of micro bubbles near the reservoir surface is termed as cavitation and it’s one of the sources of nonlinear behavior in the dynamic response analysis of dam–reservoir systems. Cavitation may happen at high speed flow in dam′s spillways, pumps and turbines or is produced due to the elastic wave propagating in the reservoir medium when the severe earthquake occurs and this nonlinearity behavior can complicate the dynamic analysis of dams (El-Aidiand Hall, 1989;Neya 1998). This complexity is increased by consideration both translational and rotational components of ground motion.

First, the possibility of acoustic cavitation forming in the reservoir has been observed in model tests of Koyna dam (Niwaand Clough, 1980). In mentioned experiment, the Koyna dam hydraulic model with height of 27 meters was used and observed the separation between the structural and fluid when absolute pressure of water reduced at vapor pressure. Clough and Chang (1984) have made an analytical study of cavitation for a gravity dam assuming incompressible water. They showed that tensile stresses in the upper part of the dam are increased by 20-40 percent during the impact of the water resulting from collapse of the cavitation bubbles. The increase of tensile stress may cause tensile cracks on the downstream face of dam, where the slope of the dam changes abruptly. Another analytical study has been employed by Zienkiewiczet al. (1983)in which used displacement potential formulation for compressible water. In their research, a bilinear pressure-volume strain relation was used for the water to include cavitation in two dimensional models of gravity dam-reservoir systems. Theyconcluded that cavitation would not alter the maximum stresses of concrete gravity dam significantly but water pressure response was very different depending on whether or not cavitation was included. Various numerical methods have been employed to simulate the cavitation phenomenon in the liquid using pressure, velocity or displacement based finite element formulation (FEM) for the fluid domain(Newton (1980);Zienkiewiczet al. (1983);Fenves and Vargas-Loli (1988);El-Aidiand Hall (1989); Sandberg (1995);Neya (1998); Oskouei andDumanoglu (2001);Kalatehand Attarnejad (2011)). The displacement based Lagrangian formulation formodelingthe fluidmedium was used by Hamdiet al. (1978)and then was employed forseismicanalysis ofdams by many researchers (Ahmadiand Ozaka (1988); El-Aidiand Hall (1989);Neya (1998); Oskoueiet al. (2001);Kalatehand Attarnejad (2011)).El-Aidiand Hall (1989)show that the modeling of cavitation effects using FEM considering classical damping ratios causes spurious oscillation tooccur. To eliminate this effect, they added a small amount of damping to the water domain in their analysis and Fenves and Vargas-Loli (1988) reduced the reservoir damping ratio at the fundamental natural frequency of the system.

Observations of earthquake events have shown that many structural failures and damage are associated to rotational components of ground motions. For example torsional responses of tall buildings in Los Angeles during the San Fernando earthquake in 1971 could be associated to torsional excitation. In recent decades, several researchers such as Bielak (1978),Awadeand Humar (1984), Guptaand Trifunac (1989),Gouland Chopra (1994),Takeo (1998),Ghayamghamianet al. (2009) andSarokolayiet al. (2014a) have shown the importance of the rotational components in the seismic behavior of building structures. Recently, Sarokolayiet al. (2013a) have pointed to the importance of this issue on nonlinear response of concrete gravity dams. In their research, the nonlinear behavior of water reservoiror acoustic cavitation has not been considered. In previous researches, the rotational components of ground motion in analyzes have been produced or measured using various methods.

The kinematics of any point in a medium is ideally expressed in terms of three translational and three rotational components. The current processing of earthquake records provides information only about the three translational components primarily because these are the only components that can be directly measured using standard seismometers. In addition, the effects of ground rotational components on structural response have not been notable. Newmark (1969), Trifunac (1971, 1976, 1982), Li et al.(2004),as well as Lee and Liang(2008) have tried to generate the rotational components of ground motion from translational recorded components using theoretical relations. Kalabet al.(2012a, 2012b)adapted the Russian electrodynamics seismometer named S-5-S for measurement of rotational ground motion which initial results from experimental measurement in Karvina region in2011 with high mining induced seismicity are documented.In the literature, importance of modeling the rotational components of ground motion and its effect on cavitation phenomena is not considered in the evaluating of the seismic response of concrete dams.

In the present study, an improved approach for generation of rotational components of ground motion base on translational components which was proposed by Li et al.(2004) is used. This procedure allows one to include the effect of the relative contributionsof the P and SV waves to calculate time histories of the rotational component. This method is successfully used by authors for nonlinear earthquake evaluation of Pine Flat gravity dam and some water storage tanks (Sarokolayiet al., 2013a; 2013b; 2014b). Then a numerical scheme based on the nonlinear behavior of water reservoir in concrete gravity dam is presented to study the cavitation effect on dam response due to translational and corresponding rotational components of ground motion. The displacement-based formulation is employed for computing dynamic response of concrete gravity dam. The foundation is assumed to be rigid and its interaction with dam and reservoir are not taken into account. In addition, it is also assumed the reservoir water is isotropic, inviscid, irrotational and the behavior of dam is linear.

2.0 Mathematical Formulation

Concrete gravity dam-reservoir systems are three-dimensional structures but are often idealized as two-dimensional section in planes normal to the dam axis. Figure 1 schematically depicts a two-dimensional profile of dam-reservoir system with the associated boundaries, coordinate system and applied loads. The boundary conditions include the wave propagation condition on S_1, the energy absorption by sediment on S_2, dam-reservoir interaction on S_3 and the surface wave condition on S_4 (El-Aidiand Hall (1989);Neya (1998)).

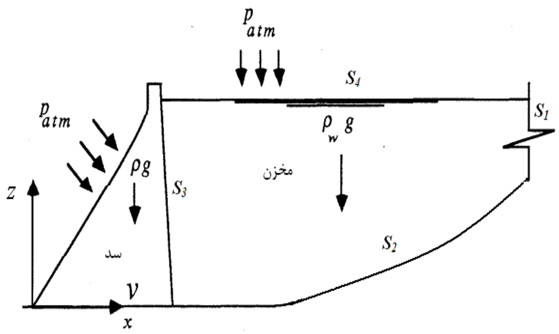


Figure1: The dam-reservoir system, boundaries, coordinate system and applied load

Considering the whole domain of dam-reservoir system based on displacement unknown, Lagrangian-Lagrangian approach, the dynamic equation of motion for coupled system due to ground motion excitation gives rise to the following single matrix equation (El-Aidiand Hall (1989);Neya (1998)).

$$[M]\ddot{U}(t)+[C]\dot{U}(t)+[K]U(t)=P_{eff}(t)+P_s \qquad (1)$$

where $[M]$, $[K]$ and $[C]$ are mass, stiffness and damping matrix of coupled system, $\ddot{U}(t)$, $\dot{U}(t)$ and $U(t)$ are dynamic acceleration, velocity and displacement vector on the nodes of finite element mesh, respectively. P_s is external load vector due to weight and hydrostatic pressure and $P_{eff}(t)$ is also the effective load vector due to earthquake which have obtained using $P_{eff}(t)=-[M]\ddot{U}_g(t)$ where $\ddot{U}_g(t)$ is ground acceleration vector.

The stiffness matrix of coupled system is obtained by assembling the stiffness matrix of reservoir, dam and interface elements. The reservoir fluid element is defined by nine nodes having two degrees of freedom at each node: translation in the nodal x and y directions. This element has four integration points based on Lagrangian reduced integration method (Neya, 1998). The dam solid element is defined by eight nodes having two degrees of freedom at each node: translation in the nodal x and y directions and it has nine integration points. To consider dam-reservoir interaction, the interface elements with zero thickness are used to satisfy displacement boundary conditions between dam and reservoir (on S3). The lumped mass matrix is taken from Hinton et al. (1976) method and damping matrix is obtained by linear combination of mass and stiffness matrixes due to the required accuracy. The details of the described formulation are presented in the worksofNeya (1998), Sarokolayiet al. (2013a) andNavayineya and Shoshpasha (2002).

2.1 Lagrangian formulation of fluid-structure interaction system

The solid elements in FEM analysis are usually as standard elements and their relations are available in references such asClough (1980);Zienkiewiczand Taylor (1977).But about the fluid elements, since introduced by Hamdiet al.(1978), a lot of researches have been done on its formulations. In order to form stiffness matrix of water reservoir in the Lagrangian approach, by writing the relationship between pressure and volumetric strain for two-dimensional fluid element and the use of non-rotating restriction and penalty functionin order to eliminate the spurious modes, α_p , finally, fluid elasticity matrix C_R is obtained as follows (El-Aidiand Hall (1989); Neya (1998)).

$$C_R=\begin{bmatrix} K_w & 0 \\ 0 & \alpha_p \end{bmatrix} \qquad (2)$$

where K_w is the bulk modulus of water and amount of α_p is suggested by Wilson and Khalvati(1983)to ne equal to $100K_w$.

2.2 Cavitation phenomenon

In this research, the displacement-based water model is extended to account water cavitation. It is assumed that the pressure-volume strain relation obeyed the bilinear model as shown in Figure (2) and that the mass distribution throughout the reservoiris uniform. Thus, the nonlinearity is fully contained in the stiffness term loading to straight-forward linearization and solution by the standard Newton-Raphson method (El-Aidiand Hall, 1989).

Cavitation is assumed to initiate when the absolute water pressure drops to the water vapor pressure P_v . The incipience of cavitation is associated with a local sudden drop in the tangent water compressibility K_t from K_w to a much smaller value K_c that lasts as long as the total volume strain exceeds $\varepsilon_v^{\,v}$ in Figure2. The original compressibility, K_w, is regained upon closure of the cavities when the volume strain drops below $\varepsilon_v^{\,v}$.

The special case of $K_c = 0$ implies that cavitated water completely loses its stiffness locally and behaves under its own inertia only (Equations(3) and (4)).

$$P = K_w.\varepsilon_v \qquad P > P_v \qquad (3)$$

$$P = P_v + (\varepsilon_v - \varepsilon_v^v)K_c \qquad P \le P_v \qquad (4)$$

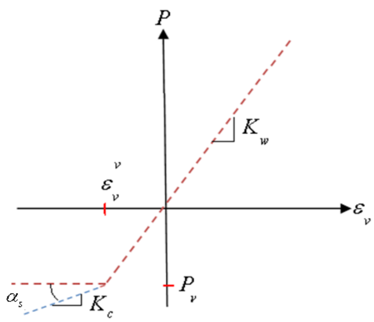


Figure 2: The bilinear model for cavitation

2.3 Rocking component of ground motion

In order to perform 2D seismic analysis of gravity dams, two translational components of ground motion in x and z directions and their related rocking component are used. These motion components are shown in Figure3 by symbols u , w and ϕ_{gy}. In addition for SV wave incidence, the amplitudes of incident wave and reflected P and SVwaves are shown in this Figure 3 by A_S, A_{SP} and A_{SS} and their angles with vertical axes are shown by θ_0 ، θ_1 و θ_2 respectively.

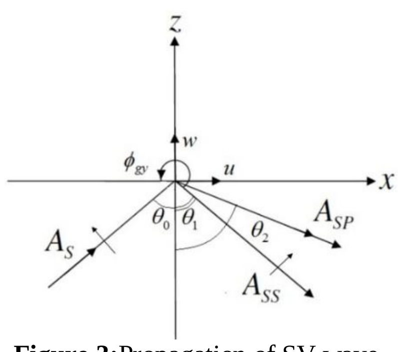


Figure 3: Propagation of SV wave

The rocking component using classical elasticity theory can be written as (Li et al.,2004):

$$\phi_{gy} = \frac{1}{2}\left(\frac{\partial w}{\partial x} - \frac{\partial u}{\partial z}\right) \qquad (5)$$

Using elastic wave propagation theory and the potential functions of wave motion with frequency ω and by imposing the free shear stress condition at the ground surface, the Equation (5) can be rewritten as(Sarokolayiet al., 2013a):

$$\varphi_{gy} = \frac{i\omega}{C_x} w = (1e^{\frac{\pi}{2}i})(\frac{\omega}{C_x})(R_w.e^{i\theta_w}) = (\frac{\omega}{C_x} R_w)(e^{(\frac{\pi}{2}+\theta_w)i}) \qquad (6)$$

where $C_x = \beta / \sin\theta_0$ is the frequency dependent wave velocity and β is the propagation velocity of shear wave.

Equation (6) shows that the rocking component has the amplitude equal to $\frac{\omega}{C_x} R_w$ where R_w is the amplitude of vertical component of ground motion. In addition the phase difference between rocking and vertical ground motion is $\pi / 2$.

Using improved approach developed by Li et al.(2004), by introducing $(x = \sin\theta_0)$ and based on Snell's law, Equations (7) and (8) are used to obtain the angle of incidentwave.

$$G = \frac{2x\sqrt{1-K^2x^2}}{K(1-2x^2)}, \ \theta_0 \prec \theta_C \qquad (7)$$

$$G = -\frac{2x\sqrt{1-K^2x^2}}{iK(1-2x^2)}, \ \theta_0 \succ \theta_C \qquad (8)$$

where $G = w/u$ for rocking component in *x-z* plane due to SV wave; $K = \alpha / \beta$ and $\theta_C = \arcsin(\beta/\alpha)$ is the incident critical angle. α is the propagation velocity of P wave.

Figure4 illustrates the flowchart of calculation for the rotational components of ground motion using translation components.

In Equation (1), to obtain the nodal forces vector due to translational and rotational ground acceleration, $P_{eff}(t)$, the rigid body kinematics theory (Meriam and Kraige, 2012) is used. In this theory the general motion of rigid body can be divided into two translational and rotational motions as shown in Figure 5.

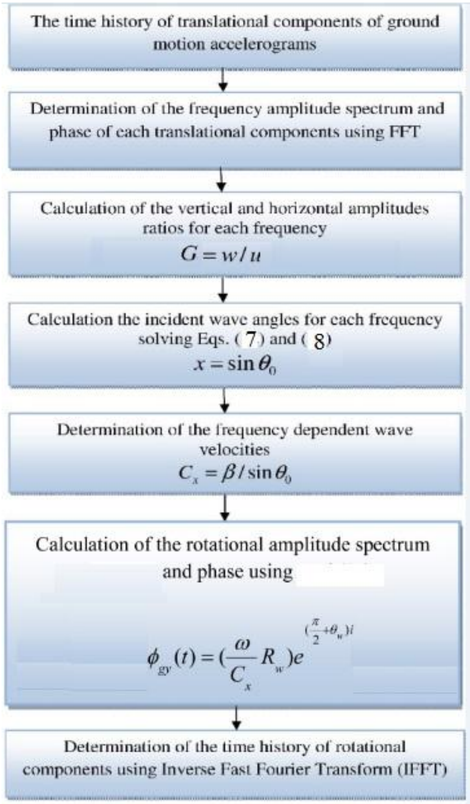


Figure 4: Flowchart of generating rotational component

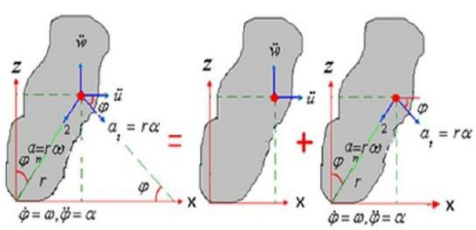


Figure 5: Rigid body motion

In this case:

$$P_{eff}(t) = -[M]\{\ddot{U}_g(t)\} \qquad (9)$$

where:

$$\ddot{U}_g(t) = \begin{Bmatrix} \ddot{u}_g(t) + \ddot{\phi}_{gy}(t)z - \dot{\phi}_{gy}(t)^2 x \\ \ddot{w}_g(t) - (\ddot{\phi}_{gy}(t)x + \dot{\phi}_{gy}(t)^2 z) \end{Bmatrix} \qquad (10)$$

where in Equation (10), $\ddot{u}_g(t)$ and $\ddot{w}_g(t)$ are the time-varying of translational acceleration, $\ddot{\phi}_{gy}(t)$ and $\dot{\phi}_{gy}(t)$ are the time-varying of rotational acceleration and velocity respectively and x, z are coordinates of each node.

2.4 Nonlinear analysis

In this research, the governing equation for dam-reservoir system, Equation (1),is solved by Newmark method. In addition, for nonlinear analysis, the force and energy at joints of finite element mesh are selected for convergence criteria in Newton-Raphson scheme. In these cases, the iterative procedure is terminated when the convergence ratio, f_{norm}, is less than a criterion of tolerance. The parameter of f_{norm} is obtained by:

$$\begin{cases} f_{norm} = \dfrac{|\{R\}_i^k|}{|\{R\}_i|} \\ f_{norm} = \dfrac{|\{R\}_i^k \times \Delta u_i^k|}{|\{R\}_i \times \Delta u_i|} \end{cases} \qquad (11)$$

where $\{R\}_i$ and Δu_i are maximum residual force and displacement change in each time step and $\{R\}_i^k$ and Δu_i^k are maximum residual force and displacement change in iteration k.

3.0 Numerical Result

Based on proposed formulation for calculation of dam-reservoir response under rotational and translational components of ground motion, a computer code have been prepared in Fortran91 by authors.

For this purpose the tallest monolith of the Pine Flat Dam is selected for evaluation of the results.Geometrical characteristics and finite element model of Pine Flat dam-reservoir system are shown in Figure 6 in which maximum water level is 116.2 m and the reservoir's length is considered three times as long as the water level while the Somerfield boundary condition is used for radiation condition in the truncated far end of the reservoir (El-Aidiand Hall (1989);Neya (1998)).

The material properties adopted in the linear analysis are shown in Table 1 (El-Aidiand Hall (1989);Neya (1998)). In this table the Bulk constant, K , is related to elasticity modulus, E, using $K = \dfrac{E}{3(1-2\nu)}$ for same materials. Stiffness proportional damping is assumed with the damping coefficient calibrated to provide $\zeta = 0.05$ for the fundamental mode of the initial linear structure and $\zeta = 0.01$ for the reservoir (Neya, 1998). The bilinear behavior with $\alpha_s = 0$ of water has been employed to considering cavitation effects (Neya, 1998). For nonlinear analysis the tolerance for residual force and residual energy norms are considered 10^{-5} and 10^{-3} respectively.

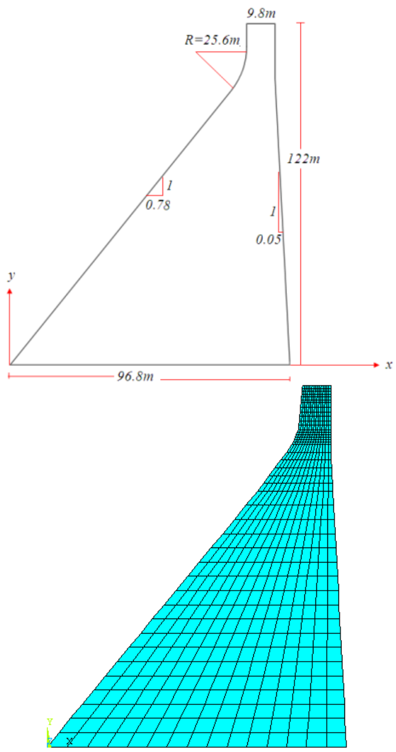


Figure 6: Geometrical and finite element model of Pine flat dam

Table 1: Mechanical characteristics of water and dam material

Material	Concrete	Water
Bulk Modulus $K(MPa)$	12444	**2070**
Absolute vapor pressure $P_v(Pa)$	-	**882**
Poisson's ratio	0.2	**0.0**
Damping ratio	5%	**1%**
Density $\rho(kg/m^3)$	2400	**1000**

3.1 Verification

For validation and verification of used formulation and also FEM code, for calculations that is provided in Fortran 90, results of some special cases are presented in subsections 3.1.1 to3.1.3.

3.1.1 Rotational velocity

In this research time history of rotational velocity about horizontal axis, rocking component, is obtained using improved approach mentioned in section 2.3 and result is compared with recorded data by S-5-S sensor extracted by Kalabet al.(2012a, 2012b)). This sensor is installed in Karvina region in 2011 and initial results from experimental measurement with high mining induced seismicity are documented. Figures 7 and 8 show the time history of translational and rotational velocity recorded by S-5-S sensor(Kalabet al.(2012a; 2012b)) and the rotational velocity time history generated in this research. In addition Figure 9 shows the frequency content spectrum of rotational velocity recorded by S-5-S sensor andpresented research.

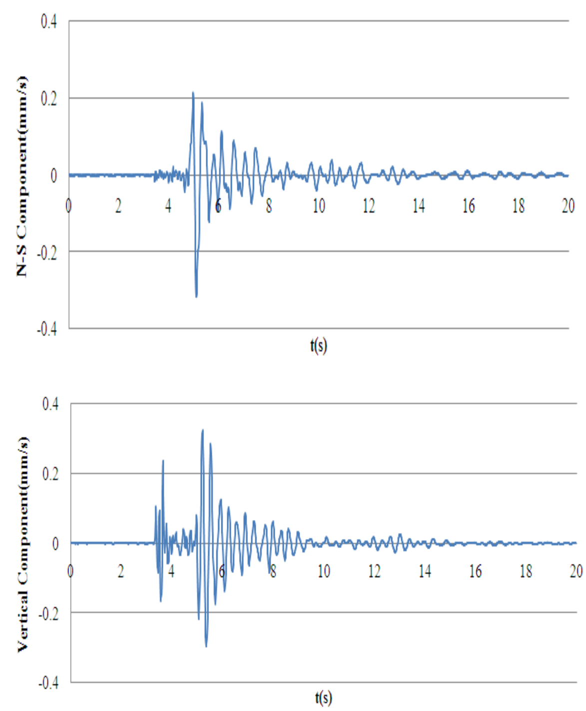


Figure 7: Translational velocity time history recorded by S-5-S sensor(Kalabet al., 2012a; 2012b)

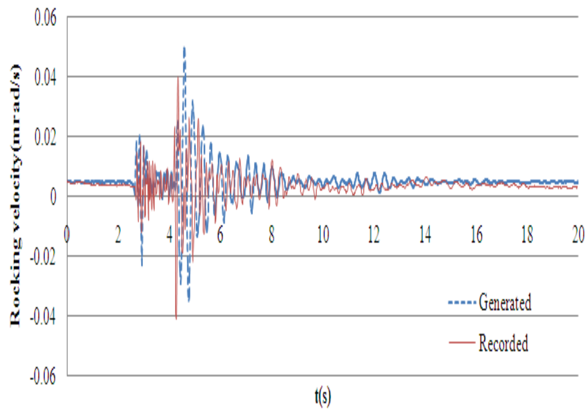


Figure 8: Time history of rotational velocity recorded by S-5-S sensor(Kalabet al.2012a; 2012b) and generated in this research

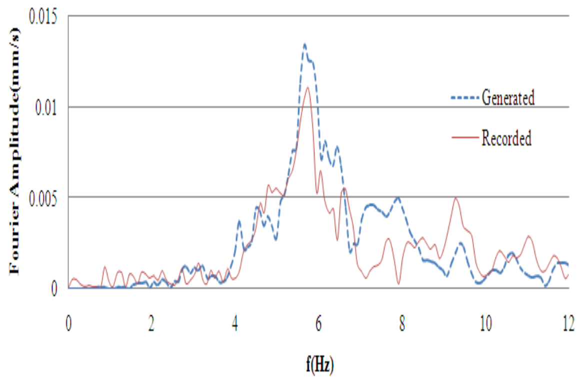


Figure 9: Frequency content spectrum of rotational velocity recorded by S-5-S sensor (Kalabet al.2012a; 2012b) and generated in this research

Obtained results show that the improved approach used in this research, have a good agreement with experimental results so that the correlation coefficient for rotational time history and frequency content spectrum is equal to 0.95 and 0.83 respectively.

3.1.2 Linear analysis of gravity dam

Hydrodynamic pressure on vertical upstream face of gravity dam with 100 meter height under harmonic excitation with peak acceleration of 0.2g is obtained using FEM code and is compared with analytical result of Westergard (1933).Figure 10 shows the obtained results for excitation period of 0.628 second which indicates the accuracy of the FEM modeling of gravity dam-reservoir system. In addition, horizontal displacement of Pine flat gravity dam due to S69E component of Taft 1952 earthquake is obtained using FEM code and is compared with analytical result of Fenves and Chopra (1984) as shown in Figure11.

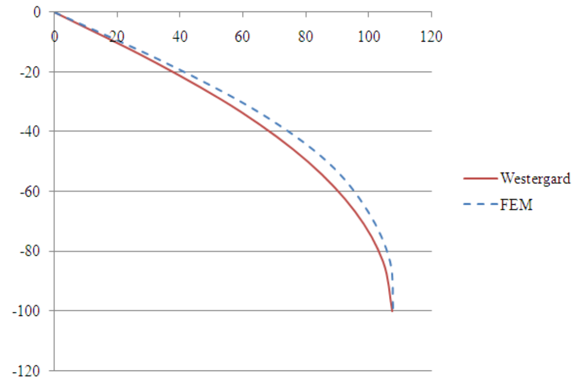


Figure 10: Hydrodynamic pressure on vertical upstream face of a rigid dam, (Westergard, 1933) and this research

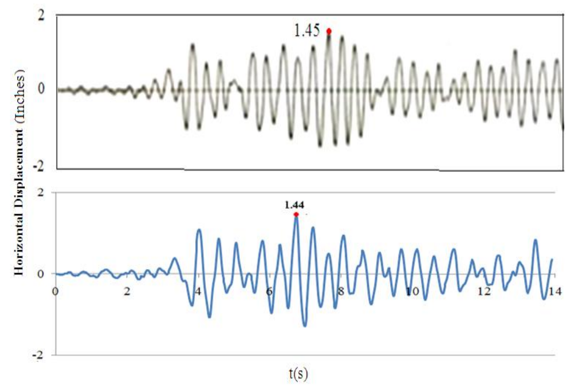


Figure 11: Time history of horizontal displacement of Pine flat dam-reservoir system due to S69E component of Taft earthquake, (Fenves and Chopra, 1984) and this research

3.1.3 Cavitation region

In this research to compare obtained result with other references about cavitation phenomenon (El-Aidiand Hall (1989);Neya (1998);Kalatehand Attarnejad (2011)), analysis of dam-reservoir system due to SFa_g has been done where a_g is the resultant translational acceleration components of Taft 1952 earthquake recorded in School Tunnel Lincoln station and SF is scale factor of a_g. In these analyses, dam behavior is assumed linear because obtained results show that by considering nonlinear behavior of concrete material, the cracking will occur before cavitation phenomenon in the reservoir. The time step obtained is 0.001 using sensitive analysis and are used in all analyses.

The results show that due to translational components of Taft earthquake less than $2.5a_g$, the cavitation phenomenon doesn't occur. For acceleration greater or equal than this amount, cavitation in reservoir starts from element number 1177 according to Figure 12 and during earthquake, cavitated region spreads toward reservoir bottom in upstream face of dam and then near the reservoir surface. These results are confirmed by other researches (El-Aidiand Hall (1989);Neya (1998); Kalatehand Attarnejad (2011)).

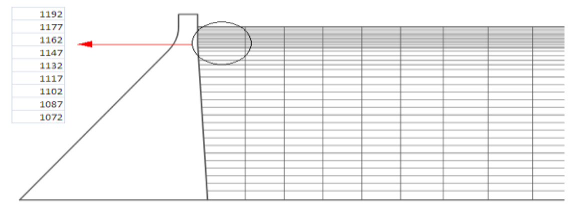


Figure12: Number of reservoir element on upstream face of dam

3.2 Generating the rotational component of earthquake

For S69E and vertical components of Taft 1952 earthquake, the peak ground acceleration are measured $0.179g$ and $0.105g$. Considering shear wave velocity of $V_S = 385.4$ (m/s), $2V_S$, $3V_S$ and $4V_S$, their corresponding rocking component are produced and the maximum rotational acceleration and velocity of them are listed in Table 2. As shown in this table, when the shear wave velocity is increased the maximum rocking acceleration and velocity will be decreased and then the rotational component effects can be neglected.

Table 2: Maximum rotational acceleration and velocity of Taft 1952 earthquake

Shear wave velocity (m/s)	385.4	770.8	1156.2	1541.6
Maximum rocking acceleration $(mrad/s^2)$	15.6	7.8	3.8	1.9
Maximum rocking velocity $(mrad/s)$	-0.04	-0.02	-0.01	-0.005

The predominate frequency of two translational and corresponding rotational component are also obtained as 2.30, 4.40 and 1.0 Hertz respectively. Figures 13 and 14 show the time history of rocking acceleration and its Fourier amplitude spectrum of Taft earthquake with $V_S = 385.4$.

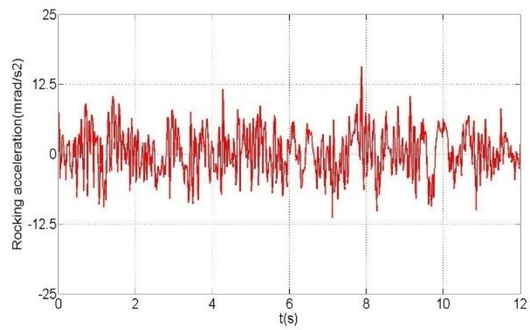


Figure13: Time history of Taft earthquake rocking component with $V_S = 385.4$

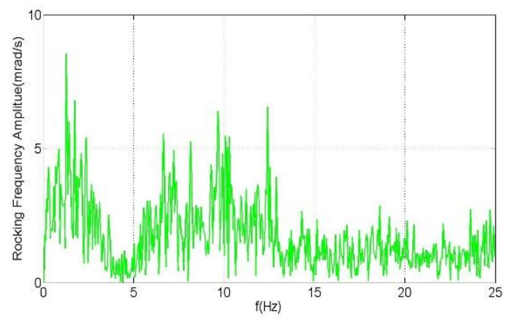


Figure14: Fourier amplitude of Taft earthquake rocking component with $V_S = 385.4$

3.3 The effect of rotational component of earthquake on cavitation

To study the effect of rotational component of earthquake on cavitation, analysis of dam-reservoir system due to SFa_{3g} has been done where a_{3g} is the resultant of all translational and rotational components of Taft earthquake and *SF* is the scale factor of a_{3g} where change from 1 to 5. Results show that due to two translational and their correlated rocking components, *(2C+R)*, of Taft earthquake, the cavitation phenomenon occur due to $2.5a_g$ and higher amounts. The start of cavitation due to *(2C+R)* is from element 1177 and during the earthquake, the cavitated region first spreads toward the reservoir bottom on upstream face of dam and then near the reservoir surface.

The maximum horizontal and vertical displacements of dam crest due to *(2C)* and *(2C+R)* excitations and their normalized response, *NC*, which is obtained by dividing the response due to *(2C+R)* and *(2C)* excitations are summarized in Table 3. Result are related to $SF = 2$, 3, 4 and 5 where due to $SF = 2$, cavitation has not occurred yet and due to higher SF, the cavitation has occurred first near the upstream face of dam and then spread along the reservoir surface.

Results of normalized response, *NC*, in Table 3 show that due to SF gather than 3, the rotational component of earthquake is notplaying an important role and the *NC* is near to 1.

Figure 15 shows the effect of rotational component on dam crest displacement due to $SF = 3$. As shown in this figure, the changes which rotational component creates qualitatively and quantitatively on dam response are less when cavitation occurs. The main reason of this result can be attributed to hydrodynamic pressure change by considering rotational component of earthquake. When the cavitation doesn't occur, the positive and negative hydrodynamic pressure change due to rotational component of earthquake is relatively high but with occurrence of cavitation, the negative hydrodynamic pressure change removed.

Table 3: Maximum displacement of dam crestand its normalized response

Scale Factor	Horizontal Displacement(cm)		Vertical Displacement(cm)	
	2C	*2C+R*	*2C*	*2C+R*
$SF = 2$	4.844	5.667	1.334	1.646
NC	1.167		1.234	
$SF = 3$	7.209	7.111	2.162	2.071
NC	0.986		0.958	
$SF = 4$	10.467	10.371	2.885	2.833
NC	0.991		0.982	
$SF = 5$	11.671	11.531	3.081	3.019
NC	0.988		0.980	

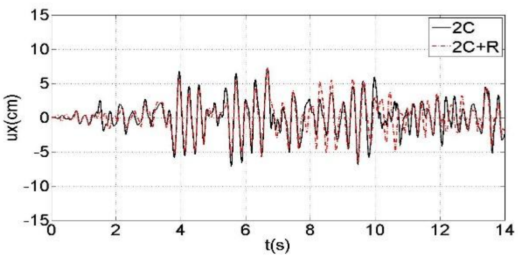


Figure15: Dam crest displacement considering nonlinear behavior of water due to (2C) and (2C+R) excitations of Taft earthquake with $SF = 3$

Figure 16shows the effect of rotational component of Taft earthquake on average hydrodynamic pressure of element number 1177 due to $SF = 3$. As shown in this figure, negative hydrodynamic pressures are the same due to *(2C)* and *(2C+R)* excitations when the cavitation occurs. The maximum positive hydrodynamic pressure for element number 1177 due to *(2C)* and *(2C+R)* excitations are 23.5 and 31 bar respectively.

Figure 17 shows the cavitated region of reservoir due to *(2C)* and *(2C+R)* excitations of Taft earthquake with $SF = 5$ on time $t = 3.545$ second.

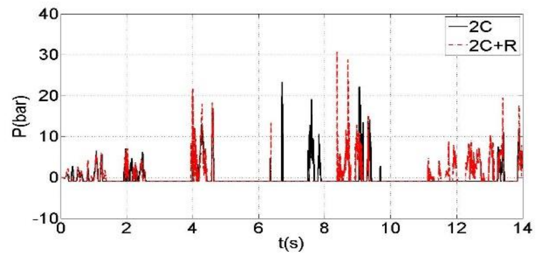
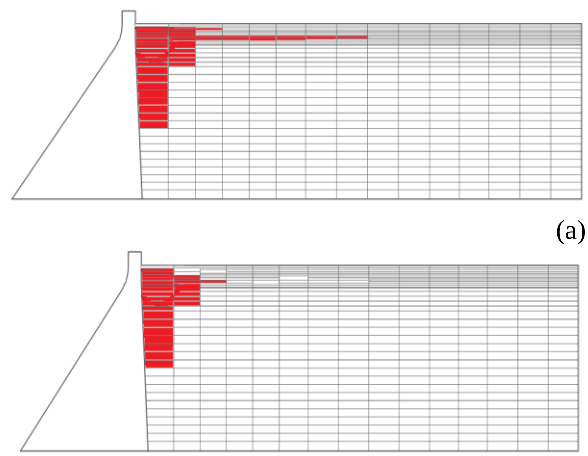


Figure16: Hydrodynamic pressure of element number 1177 due to (2C) and (2C+R) excitations of Taft earthquake with $SF = 3$



(a)

(b)

Figure 17: The cavitated region of reservoir due to (a): (2C) and (b):(2C+R) excitations of Taft earthquake with $SF = 5$

As shown in Figures 16 and 17, the expanding cavitated region near the reservoir surface will be less considering the rotational component of Taft earthquake.

4.0 Conclusions

In this study, the cavitation effect on concrete gravity dam response subjected to two translational components *(2C)* and two translational and their rotational correlated components *(2C+R)* are investigated. Pine Flat concrete gravity dam is chosen for analyses and dam-reservoir interaction is modeled using finite element method and Lagrangian-Lagrangian approach. Nonlinear behavior of water reservoir is idealized using bilinear model and the following conclusions are made:

1- Formulation used to produce the rotational component using corresponding translational components, result acceptable compliance compared with rotation component records.

2- Cavitation in the reservoir occurs under high intensity earthquakes.

3-The changes that the rotation component of ground motion makes in terms of quantity and quality of dam response, will decrease with the occurrence of cavitation. The main cause of this issue is extremely hydrodynamic pressure variations can be explained by considering the effect of rotational component.

4- When the cavitation phenomenon occurs, a dam is less affected by the Earth's rotational acceleration and normalized responses become closer to one.

5-Considering the rotational component of ground motion, expansion of the cavitated region near the reservoir surface become less and toward the upstream face of dam becomes more widespread.

References

Awade, A.M. and Humar, J.L. (1984): Dynamic response of buildings to ground motion. *Canadian Journal of Civil Engineering*, 11:48-56.

Ahmadi, M.T. and Ozaka, Y.A. (1988): simple method for the full-scale 3-D dynamic analysis of arch dams.*Ninth World Conference on Earthquake Engineering* Japan, Tokyo.

Bielak, J. (1978): Dynamic response of nonlinear building foundation system. *Earthquake Engineering ans Structural Dynamic*, 6(1): 17-30.

Clough, R.W. and Chang, C.H. (1984): Seismic cavitation effects on gravity dam. *Numerical methodin coupled system*, John Wiley and Sons: 571-598.

Clough, R.W. (1980): The finite element method after twenty-five years: a personal view. *Computers and Structures*, 12(4): 361-370.

El-Aidi, B. and Hall, J.F. (1989): Nonlinear Earthquake Response of Concrete Gravity Dams, Part. 1: Modeling. *Journal of Earthquake Engineering and Structural Dynamics*, 18 (6): 837-851.

Fenves, G. and Chopra, A.K. (1984): Earthquake analysis of concrete gravity dams including reservoir bottom absorption and dam-water-foundation rock interaction. *Earthquake Engineering and Structural Dynamics*, 12(5): 663-680.

Fenves, G. and Vargas-Loli, L.M. (1988): Nonlinear dynamic analysis of fluid–structure systems.*Journal of Engineering Mechanics*, 114(2): 219–240.

Gupta, V.K. and Trifunac, M.D. (1989): Investigation of buildings response to translational and rotational earthquake excitations”, *Report No. CE 89-02*. Department of Civil Engineering, University of Southern California.

Goul, R.K. and Chopra, A.K. (1994): Dual-level approach for seismic design of asymmetric-plan buildings. ASCE, *Journal of Structural Engineering*, 120(1): 161-179.

Ghayamghamian, M.R., Nouri, G.R., Igel, H. and Tobita, T. (2009): The effect of torsional ground motion on structural response: code recommendation for accidental eccentricity.*Bulletin of the Seismological Society of America*, 99(2B): 1261-1270.

Li, H.-N., Sun, L.-Y. and Wang, S.-Y. (2004): Improved approach for obtaining rotational components of seismic motion.*Nuclear Engineering and Design*, 232(2): 131-137.

Hamdi, M.A., Ousset, Y. and Verchery, G. (1978): A displacement method for the analysis of vibrations of coupled fluid-structure systems.*International Journal for Numerical Methods in Engineering*, 13(1): 139-150.

Hinton, E., Rock, T. and Zienkiewicz, O. (1976): A note on mass lumping and related processes in the finite element method. *Earthquake Engineering and Structural Dynamics*, 4(3): 245-249.

Kalateh, F. and Attarnejad, R. (2011): Finite element simulation of acoustic cavitation in the reservoir and effects on dynamic response of concrete dams.*Journal of Finite element in Analysis and Design*,47(5):543-558.

Sarokolayi, L.K., Neya, B.N. and Amiri, J.V. (2013a): Nonlinear Dynamic Analysis of Concrete Gravity Dams Considering Rotational Component of Ground Motion. *International Journal of Civil Engineering, (IJCE)*, 13(1): 16-29.

Sarokolayi, L.K., Neya, B.N. and Amiri, J.V. and Tavakoli, H.R. (2013b): Seismic Analysis of Elevated Water Storage Tanks Subjected to Six Correlated Ground Motion Components.*Iranian Journal of Energy&Enviroment*, 4 (3) Geo-hazard and Civil Engineering):195-203.

Sarokolayi, L.K., Neya, B.N. and Tavakoli, H.R. (2014a): Dynamic Analysis of Elevated Water Storage Tanks due to Ground Motions Rotational and Translational Components.*Arabian Journal of Science and Engineering*, 39(6): 4391-4403.

Sarokolayi, L.K., Neya, B.N., Tavakoli, H.R. and Amiri, J.V.(2014b): Dynamic Analysis of Elevated Water Storage Tanks due to Ground Motions' Rotational and Translational Components.*Arabian Journal for Science and Engineering*, 38(8):2023-2033.

Kalab, Z., Knejzlik, J. (2012a): Examples of rotational componen records of mining induced seismic events from the Karvina region.*ACTA Geodynamicia and Geomaterialia*, 9(2): 173-178.

Kalab, Z., Knejzlik, J. and Lednicka, M. (2012b): Observation of rotational component in digital data of mining induced seismic events," *Gornictwo*, 7(1): 59-74.

Lee, V.W. and Liang, L. (2008): Rotational components of strong motion earthquakes. *The 14th World Conference on Earthquake Engineering*. Beijing, China.

Meriam, J.L. and Kraige, L.G. (2012): *Engineering mechanics: dynamics*. John Wiley and Sons Incorporated.

Neya, B.N. (1998): *Mathematical Modeling of Concrete Gravity Dams under Earthquake Loading Considering Construction Joints*.Ph.D thesis,Moscow Power Engineering Institute.

Niwa, A. and Clough, R.W. (1980): *Shaking table research on concrete dam models*. Earthquake Engineering Research Center,80/05, University of California, Berkeley, CA.

Newton, R.E. (1980): *Finite element analysis of shock-induced cavitation*". ASCE, Spring Convention: 80–110.

Newmark, N.M. (1969): Torsion in symmetrical buildings. In: *Proceeding of the 4th World Conference on Earthquake* Engineering, 2, Santiago, Chile: A3.19-A3.32.

Navayineya, B. and Shoshpasha, I. (2002): Rock foundation effect on non-linear response of the concrete gravity dams subjected to earthquake.*Swets& Zeitlinger*, Lisse, ISBN 90, 5809-5142.

Sandberg, G. (1995): A new finite element formulation of shock-induced hull cavitation.*Journal of Computer Methods Applied Mechanic Engineering*, 120(1): 33–44.

Takeo, M. (1998): Ground rotational motions recorded in near-source region of earthquakes.*Geophysical Research Letters* 25(6): 789-792.

Trifunac, M.D. (1971): A method for synthesizing realistic strong ground motion.*Bulletin of the Seismological Society of America* 61(6): 1730-1753.

Trifunac, M.D. (1976): Preliminary empirical model for scaling Fourier amplitude spectra of strong ground acceleration in terms of earthquake magnitude, source to station distance and recording site condition.*Bulletin of the Seismological Society of America* 66(4): 1343-1373.

Trifunac, M.D. (1982): A note on rotational components of earthquake motions on ground surface for incident body waves.*Soil Dynamics and Earthquake Engineering,* 1(1): 11-19.

Oskouei, A.V. and Dumanoglu, A.A. (2001): Nonlinear dynamic response of concrete gravity dams: cavitation effect.*Journal of Soil Dynamic and Earthquake Engineering*, 21(2): 99-112.

Wilson, E.L. and Khalvati, M. (1983): Finite elements for the dynamic analysis of fluid-solid systems. *International Journal of Numerical Methods in Engineering*, 19(11):1657–1668.

Westergaard, H.M. (1933): Water pressures on dams during earthquakes.*Transactions of the ASCE*, 98: 418-432.

Zienkiewicz, O.C., Paul, D.K. and Hinton, E. (1983): Cavitation in Fluid Structure Response with particular reference to dams under earthquake loading. *Earthquake Engineering and Structural Dynamics*, 11(4): 463-481.

Zienkiewicz, O.C. and Taylor, R.L. (1977*): The finite element method*. (Vol. 3). London: McGraw-hill.