An Investigation of The Effects of Explosive Charge in Different Levels on the Dynamic Response of Concrete Arch Dams

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Abstract

Todays, by increasing of the possibility of terrorist attacks, more studies of the behavior of structures, especially dams as massive structures, against explosive charges are needed. Arch dams should be safe against different conditions. Analysis and design of dams not only for conventional loads but also for blast loads could be futuristic. In this paper, 3D numerical model of Karun IV arch dam was modeled using ABAQUS software and dam responses for different levels of explosive masses were investigated. The results for different cases with different levels of explosion show that maximum principal stress and maximum displacement in all cases occurs in front of explosive mass and dam crest, respectively. Analysis showed that in case of explosive mass near to the dam crest, maximum calculated displacement of the crest reaches to 3.12mm.

Keywords: Concrete Arch Dam, Explosive Charge, Air Blast, Dam-reservoir-foundation Interaction.

1. Introduction

Considering the importance of the explosion on structures, especially dam structures as massive structures, in recent years, attempts have been made to study the issues in this regard comprehensively. For the phenomenon of explosion and its effect on the structure, various analytical and laboratory works have been done, pointed out: Woyak in 2002 investigated under water explosion and its effect on submerged structures. In this research, a cylinder was located at a depth of 40 meters, and 60 lb of explosives were located 7.62 meters far from the cylinder [1]. By the year 2006, Sprague et al. studied ship structure exposed to underwater explosion by spectral element-finite element method. They investigated transient response of the finite element model of the ship with 31,000 degrees of freedom [2]. Lai et al. (2007), investigated transient response of spherical shell subjected to underwater explosion. In this paper, the dynamic responses under the submarine explosive charge in sea and air were compared and the effects of the distance on the shell stress time history were presented [3]. Guzas et al. in 2010 studied simulation of structure response due to air blast. In this paper, a steel plate under the 1.36 Kg TNT which was located on 1.52 meters far from the center of the plate was investigated, and the results of the explosion-induced pressure were compared with the equations of the Bulmash and Hopkinson [4]. Zhang et al. in 2014 investigated numerical simulation of damage modes of concrete gravity dam subjected to underwater explosion. In this paper, dynamic response due to underwater explosion at different heights of the dam, from 30 meters to 142 meters were analyzed. The results indicate that increase in explosive height reduces displacement magnitude. On the other hand, the size of the mesh has a significant impact on analysis results [5]. Wang et al. in 2014 studied shock wave scattering and cavitation effects due to underwater explosion near to water free surface [6]. Also, Wang et al. in 2014 investigated damage prediction of Koyna concrete gravity dam (in India) subjected to explosion. The results indicate that because of underwater explosion, 4 types of damage can be resulted: no damage, low damage, moderate damage and high damage. The damage to the dam structure begins from the upstream face and the cavitation effects are observed in the free surface of the reservoir [7].

In this study, according to the studies carried out on the explosion, which most of them was underwater explosion, air blast was applied on a concrete arch dam.

2. Explosion Parameters

An explosion occurs when a large amount of energy is released quickly and suddenly in form of heat and pressure. When an explosion occurs, energy is suddenly released. This release of energy can be divided into two sections of thermal radiation and the emission of waves in the ground and air. The waves that are released in the air are the main reason of destruction of a structure. These waves move faster than the sound speed and hit the structure [8]. Explosion in the air means that the rapid release of gases in the air creates a shock wave. The shock wave propagates radially from the explosion center. In this case, the wave due to the explosion and the reflection waves are in one environment. As shown in Figure 1, the explosion-induced wave is usually exposed to the structure earlier [9].

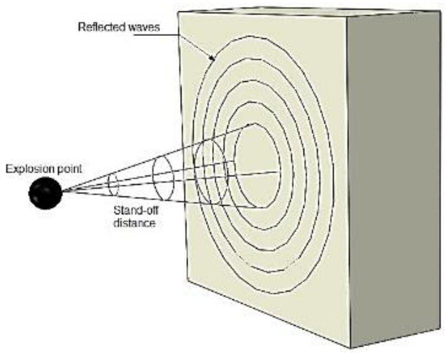


Figure 1- Schematic of air blast

Figure 2 shows the explosion pressure profile in the air, which contains positive and negative phases. As can be seen, within a few milliseconds, atmospheric pressure (P_0) reaches maximum pressure (P_{so}^{+}) and returns to atmospheric pressure for several hundredths of a second, which is defined as the positive phase of the pressure impact. After this phase, a negative phase (P_{so}^{-}) occurs that generates negative pressure over a few hundredths of a second. The negative phase in the design is not very important and is usually neglected [10].

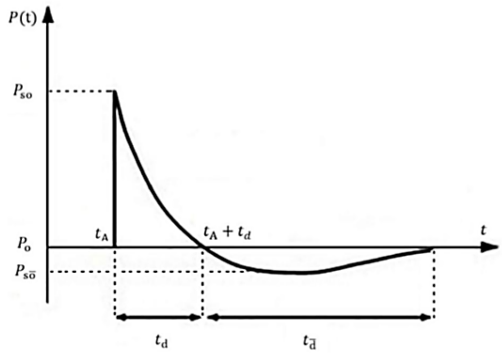


Figure 2- Time history of air blast pressure [11]

Based on the Hopkinson scale, when two explosives with identical materials and identical atmospheric conditions explode, the shock wave effects are expressed as Z:

$$Z = \frac{R}{W^{\frac{1}{3}}} \qquad (1)$$

Where, R, is the distance to explosion center and W, is the explosive mass. The equation is for 1 kg or 1 lb of TNT [4]. The duration of the explosive charge is calculated directly from Kinney and Graham's relation [4]:

$$\frac{t_d}{W^{\frac{1}{3}}} = \frac{980\left[1 + \left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1 + \left(\frac{Z}{0.02}\right)^{3}\right]\left[1 + \left(\frac{Z}{0.74}\right)^{6}\right]\sqrt{1 + \left(\frac{Z}{6.9}\right)^{2}}}$$

In this equation t_d is the duration of the positive phase of the blast profile in a second. P_s, Maximum compression applied directly to the structure due to the explosion, is calculated according to the following equation [4]:

$$P_s = 808P_{atm}\frac{\left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{\left[1+\left(\frac{Z}{0.048}\right)^2\right]\left[1+\left(\frac{Z}{0.32}\right)^2\right]\left[1+\left(\frac{Z}{1.35}\right)^2\right]}} \quad (3)$$

Where P_s is equal to the load applied to the structure in bar and P_{atm}, the atmospheric pressure in bar. Calculating P_s is much easier than P_r. Brode states the relationship between P_s and P_r as follow [4].

$$P_r = P_s\left(2+\frac{6P_s}{P_s+7P_{atm}}\right) \qquad P_s < 6.9\ \text{bar} \quad (4)$$

In equation (4) P_r, is the maximum excess reflected pressure, P_s is excess pressure and P_{atm} is the air pressure. When the excess pressure exceeds 6.9 bar, the air molecules begin to interact with each other and the assumption of ideal gas is not valid. In this case, Brode offered the following relationship [4]:

$$P_r = P_s\left[\frac{0.03851\ P_s}{1+0.0025061\ P_s+4.041\times\ 10^{-7}\ {P_s}^2}+2+\frac{0.004218+0.7011\ P_s+0.001442\ {P_s}^2}{1+0.1160\ P_s+8.086\ 10^{-4}\ {P_s}^2}\right] \quad (5)$$

3. FINITE ELEMENT MODEL

Finite element model of dam-reservoir-foundation of Karun IV was modeled using ABAQUS software. In modeling process, some assumptions were made such as: foundation modeled as a semi-sphere with radius as three times as dam height and reservoir modeled as a prismatic volume with length as three times as dam height. Finite element models of Karun IV are presented in figures 3 to 6. Because three different levels (225m, 115m and 5m from dam base) for explosion materials were considered, three different meshes were used.

In each case, area in front of the explosion point has finer mesh. For the case of explosion near to dam crest (225m from dam base), 45592 hexahedral elements were used. For the cases of explosion near to mid height of the dam (115m from dam base) and near to dam base (5m from dam base), 156706 and 63984 hexahedral elements were used respectively. Foundation and reservoir contains 41131 tetrahedral elements and 258977 tetrahedral acoustic elements.

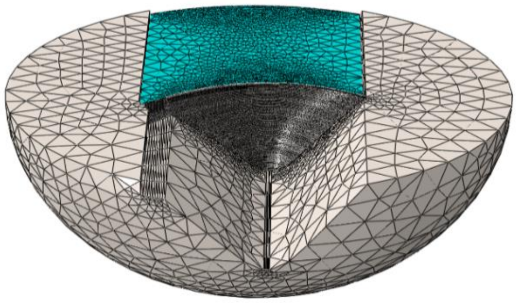


Figure3-finite element model of dam-reservoir-foundation of Karun IV

Figure4-finite element model of Karun IV dam for the case of explosion near to dam crest

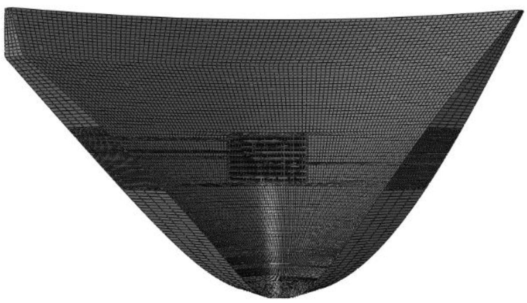


Figure5- finite element model of Karun IV dam for the case of explosion at mid height of the dam

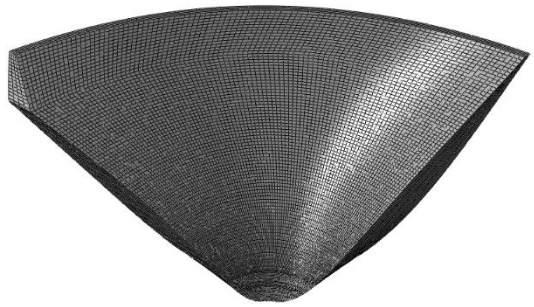


Figure6- finite element model of Karun IV dam for the case of explosion near to dam base

3.1. MATERIAL PROPERTIES

Material properties of Karun IV finite element model are shown in table1. Concrete Damage Plasticity (CDP) model was used for plastic behavior of concrete and damage modeling.

Table1-material properties

Concrete	Static elasticity modulus	24 GPa
	Dynamic elasticity modulus	30 GPa
	Poisson ratio	0.2
	Density	2400 Kg/cm^3
Foundation rock	Elasticity modulus	10 GPa
	Poisson ratio	0.3
	Density	2600 kg/cm^3
Water	Density	1000 kg/cm^3
	Bulk modulus	2.13 GPa

4. RESULTS

In this section, the results of analysis with different explosion levels are presented and compared. The effects of explosions in three different levels (225m, 115m and 5m) are investigated separately. At first, minimum explosive masses which cause damage on dam body for all three levels were calculated. These explosive masses are 1500 kg TNT 2000 kg TNT and 1800 kg TNT for explosion near to dam crest, mid height of the dam and dam base respectively. For all these cases, explosive masses were located at 10 m distance from dam body.

4.1. DISPLACEMENT

Displacement time history for dam crest and the point in front of the explosive mass for all three explosion levels are presented in Figures 7 - 9. As shown in Figure 7 and because in this case the explosive mass is near to the dam crest, displacements for two described points are almost similar and maximum displacement occurs at the same time. The calculated displacement for dam crest and the point in front of the explosive mass, are shown in Figure 8 for the case of explosion in mid height of the dam. Because there is about 115m distance between these two points, 0.44 Sec. time delay between maximum displacements is expectable. Figure 9 illustrates when an explosive mass is near to the dam base, the calculated displacements in dam crest differ significantly with base displacements. In this case, maximum displacement in front of explosive mass occurs at initial time steps but maximum displacement in dam crest occurs after 0.73 s. This time delay is the time which is needed for the explosion wave to transfer to dam crest. In the following time steps, calculated displacements for dam crest show much more magnitudes just because of cantilever behavior of arch dams. Figures represent that maximum displacement for the case of explosive mass near to dam crest occurs and the displacement decreases with lowering the explosion level.

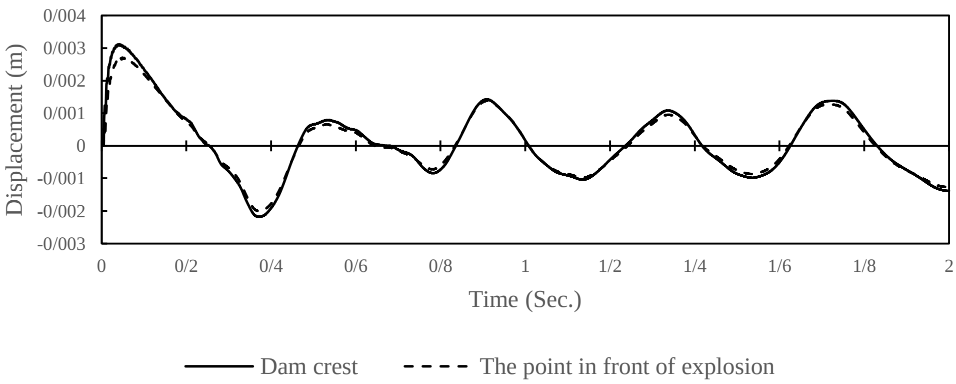


Figure7-time history of displacement for the case of explosion near to dam crest

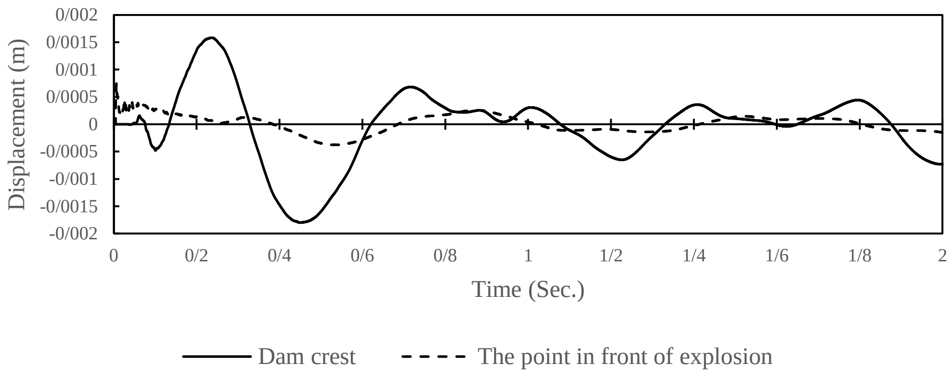


Figure8-time history of displacement for the case of explosion near to mid height of the dam

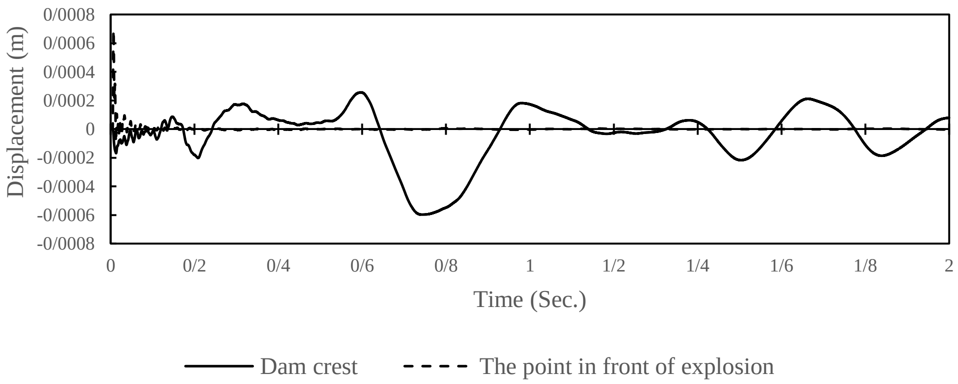
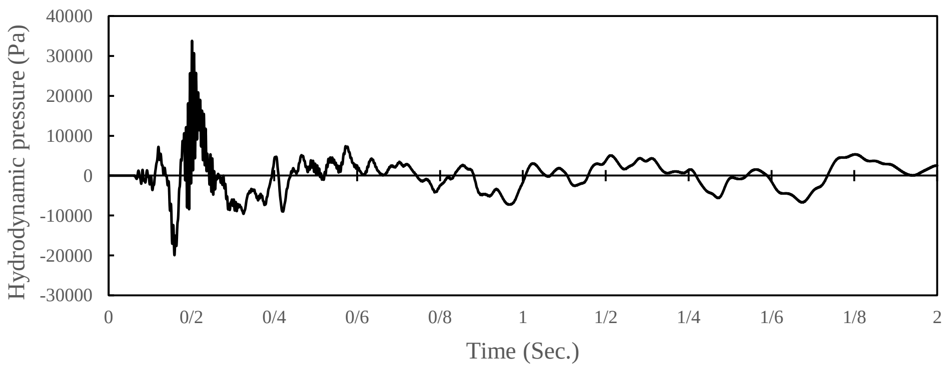


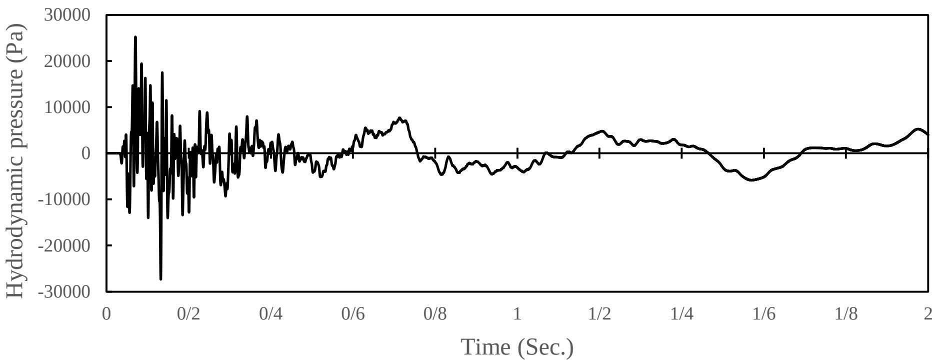
Figure9-time history of displacement for the case of explosion near to dam base

4.2. HYDRODYNAMIC PRESSURE

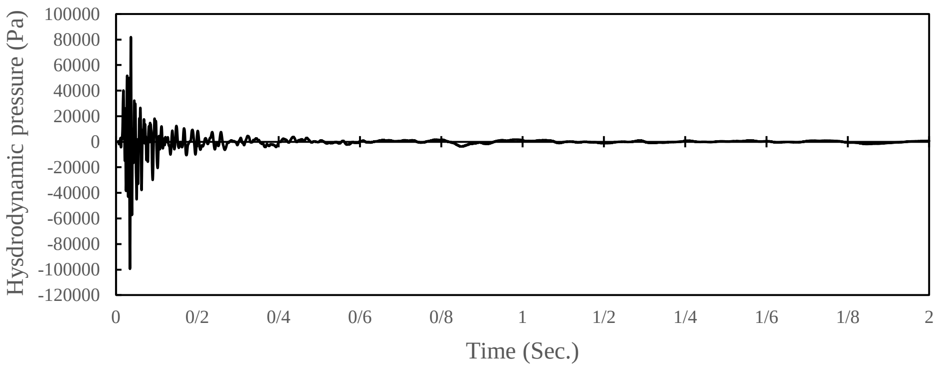
Hydrodynamic pressure time history in dam heel for all three cases (225m, 115m and 5m) are presented in figure 10. As shown in figures, maximum hydrodynamic pressure occurs when explosive mass is near to dam base.



(a)



(b)



(c)

Figure10-time histories of hydrodynamic pressure in dam heel. A) Explosion near to dam crest. B) Explosion at the

4.3. STRESS DISTRIBUTION

Stress distribution contours for three different level of explosive mass at maximum displacement time are presented in figure 11. Maximum stress in the case of explosion near to dam crest is 0.73 MPa and occurs near to dam crest. Maximum stress in the case of explosion at mid height of the dam and near to dam base are 0.18 MPa and 0.038MPa respectively while location of maximum stress in both two cases is in front of explosive mass.

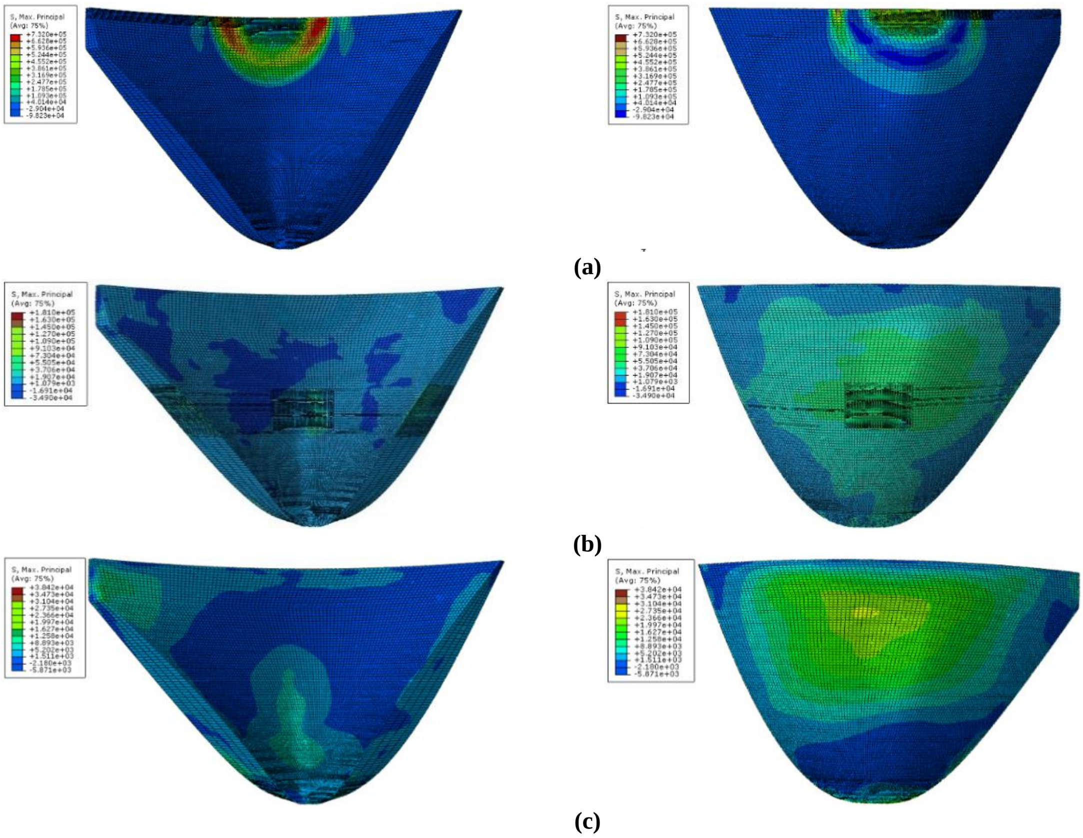


Figure11-stress contours of upstream and downstream of the dam in maximum displacement time. a) Explosion near to dam crest. b) Explosion at the mid height of the dam. c) Explosion near to dam base.

5. CONCLUSIONS

In this paper, 3D nonlinear dam-reservoir-foundation finite element model of Karun IV under air blast in three different levels analyzed using ABAQUS software. Analysis of dam-reservoir-foundation interaction system under blast loading is highly dependent on the mesh sizes. Because finer mesh needs more analysis time, only for areas near to explosive mass finer mesh was chosen. The mesh sensitivity analysis also shows good convergence.

Displacement time history of dam crest and the point in front of explosive mass in all three cases demonstrate that maximum displacement occurs when explosive mass is near to dam crest. It is because of the structural behavior of arch dams. In the case of explosive mass near to the dam crest, the maximum displacement of the crest is 3.12 mm.

Maximum principal stress on dam body locates in the closest point to the explosive mass while maximum displacement locates on the dam crest.

Maximum hydrodynamic pressure in the dam heel occurs in the case of near to dam base explosive mass. In addition, by increasing the level of explosive mass, the occurrence time of the maximum hydrodynamic pressure is postponed more.

6. ACKNOWLEDGMENT

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