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Evaluation of Underwater Blast on Concrete Gravity Dams Using Three-Dimensional Finite-Element Model

S.Saadatfar, A.Zahmatkesh*

Department of Civil Engineering, Ferdows Branch, Islamic Azad University, Ferdows, Iran

ABSTRACT: Dams may undergo the air or underwater blast loading. An underwater explosion can cause significantly more damage to targets in water as compared to an explosion of the same magnitude in the air. It is well known that underwater explosions damage structures of dams by shockwaves and bubble pulsations. This paper studies the effect of the underwater explosion on a concrete gravity dam in different blast locations, with and without considering bubble pulsations. Concrete Damage Plasticity (CDP) is a model that can be used to characterize the constitutive behavior of concrete by introducing scalar damage variables. The results showed that damage was most visible when an explosion occurred in the middle of the reservoir. Damages were significantly higher in the case of bubble impulse dams. According to the results of the damage, bubble pulsation is an explosion in one of the main parts and includes part of blasts energy. Therefore, the amounts of displacement for cases with gas bubble effects were significantly higher than those with an explosion modeled only on the application of shockwaves. The existence of sediments and surface waves can be considered in further studies.

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1- Introduction

Dams are one of the main structures that have contributed to the development of civilization. To meet the societies demand irrigation, power, drinking water, add water recreation spaces, transportation uses and so on, dams with a number of 150 m-300 m high either have been built or under construction. Although dams are so useful in times of peace accidental damage to a high dam with a lot of water in its reservoir can lead to a tragedy in the downstream. Thus because of their significant political and economic benefits, dams are possible targets for terrorist attacks scenarios and wars. Actually, as shown by researchers the risk of a tall concrete dam being subjected to underwater explosion cannot be ignored.

Therefore, damage prediction of dams under blast loads has become critical in civil engineering. Dams may undergo air or underwater blast loading. There is a significant contrast in the wave propagation phenomena between water and air due to their different physical properties. Since an underwater explosion can cause significantly greater damage to targets in water than the same explosion in the air, this study evaluates shock wave propagation characteristics from underwater blasts and the subsequent response and damage of the target [1].

The dynamic response of dam structures subjected to the explosion is crucial to evaluate the antiknock safety of a dam. The subsequent response of the dam subjected to explosion the shock loading involves such complex issues as the explosion, shockwave propagation, structural response, shock wave structure interaction, and so on: this is much more complicated as compared to other loadings, such as static and earthquake loadings. Some researchers have focused on the action of underwater shockwaves on ships: for example, Liang and Tai [2] discussed the response of a float spherical shell to a strong shockwave and the responses of a ship to non-contact underwater blasts. Similarly, Park et al. [3] explained the results of the measurement of naval ship responses to underwater detonation loadings, involving test planning, explosive devices, data decrease, sensor positions, and damage assessments of MSH. Many scholars have undertaken experimental and numerical investigations to model detonation effects on civilian structures [4-8], bridge structures [9-12], plate structures [13, 14], underground structures [15-17] and marine structures [18-20]. However, comparatively little attention has been paid to dam structures under impact loads due to potential risks and high costs of interactions between model components and experimental tests.

One of the most common types of dams is concrete gravity design. The first experimental study on concrete gravity dams under detonation was conducted during the Second World War. A scale model named Möhnewas was used to see whether a big convention bomb could destroy the dam. More studies based on a 1:50 scale model indicated that a Möhne dam could be destroyed if 3000 kg of dynamite were to explode against its inner wall [21]. Many scholars have

Corresponding author, E-mail: Zahmatkesh@ferdowsiau.ac.ir

conducted experiments to determine how concrete dams are affected during strong earthquakes: Zhou and Lin [22] and Lin et al. [23] performed a series of shaking table experiments on models of many concrete gravity dams to find out the seismic failure of concrete gravity dams. The results of Vanadit and Davis [24] on the vulnerability of concrete gravity dams to blasts demonstrate that a dam's crest is weaker than other zones. Lu et al. [25] used the impact of hammers to simulate underwater shock in a gravity dams experiment: Failure modes were analyzed after the hammers struck. However, the maximum impulse pressure was appraised on the basis of the model of the dam's foundation which had no anchorage, and the emergent accelerations were recorded. The effect of foam material as a protective cortex for concrete gravity dams subjected to detonation was studied by Lu et al. [26]: they also provided the damage spectrum to predict the faulted condition of the dam and check high concrete gravity dam damage under a blast shockwave. Six 1:200 scale models were designed and examined under dispensed impact loads. It was clearly seen that the top is a weak zone in concrete dams, so the impact failure initiates with a fracture on the top of the dam.

Before the development of computers and the advancement of numerical techniques, numerical simulation of underwater detonation was difficult to perform because of the limitations to computational ability. However, in recent years, damage prediction of concrete gravity dams under explosion loads has become possible and credible due to numerical simulation. Many complex factors such as large deformations, the fluid-dam interaction, and so on have to be considered to compound various physical processes into a single model system. Eulerian meshes can be used for the analysis, including large transformation without re-meshing; Lagrangian meshes can be used for illiquid materials. Thus a coupled method which combines both Eulerian and Lagrangian approaches-would facilitate the simulation of some problems, including fluid-structure interaction and large metamorphosis [27].

The validity of numerical results is dependent on the mesh size used for analysis: wherever the mesh size is smaller, the answer is more exact. However, the mesh size is also confined by the computer capacity, the dimensions of the model, and the available time for the analysis. Krauthammer and Otani [28] investigated the effect of mesh size, gravity, and static load in the numerical simulation of the boosted concrete structure under the explosion loading. Studies illustrate that the mesh size has a significant effect on the deformation and tension of structures: The propagation of an explosion load can be simulated correctly if the mesh size is 100 mm [29]. Li et al. [30] brought out a 3D dynamic finite element model of a concrete gravity dam and measured damage to the dam and subsequent stress distribution under blast load at the middle high of upstream. Xiang and La [31] probed the elastic behavior of a concrete gravity dam when 4,890 kg TNT was detonated at a distance of 46 m from the dam and water level. According to this study, the dam was subjected to a peak horizontal and vertical acceleration at its upstream bottom location and at its upstream face near the water level respectively.

Yu [32] researched the dynamic response of concrete gravity dams subjected to underwater contact detonation. According to the results, damage is worse when the blast occurs in the water as compared to when it is on the water surface or at the bottom of the reservoir. Linsbauer [33] evaluated the stability of a concrete gravity dam with a crack in its upstream and found an excessive potential of damage for the afflicted structure. Kwak et al. [34] researched the fireball expansion and subsequent shockwave spread from explosives in water and air. Different failure modes of concrete gravity dams exposed to underwater blast have also been studied by Zhang et al. [35]. They also analyzed the influence of the standoff distance, the upstream water level, and the dam height on the antiknock performance of the structure. Wang and Zhang [36] provided a numerical study for predicting the damage of concrete gravity dams subjected to under water explosion: they found concrete gravity dams are seriously vulnerable to shallow water explosions due to a decrease in cavitation effect and an increase in a dam's section thickness in deep explosions. Wang et al. [37] compared the effect of blast loading on concrete gravity dams for air and underwater explosion. Their study shows that damage due to underwater detonations is much more violent than the same amount of charge exploded in the air. Chen et al. [38] deliberated on the influence of the presence of a spillway channel on the damage mode of concrete gravity dams. According to their results, the presence of a spillway tunnel is a reason for more serious damage when an underwater blast occurs. Therefore, it is necessary to consider the effect of the spillway presence in studies.

It is well known that an underwater explosion will damage the dam structure by shockwave and bubble pulsation. When the explosion occurs, 50% of the blast energy is spread by the shockwave and the other 50% is emitted as a gas bubble pulsation [39]. Hence, both the shockwave and bubble impulse can cause damage to a dam. However, in most of the investigations on concrete gravity dams subjected to underwater detonation, the influence of gas bubble pulsation has been neglected. This paper addresses this neglect by comparing the effect of underwater blasts on concrete gravity dams for different locations of explosions, with and without bubble impulse influence. To do so, the non-linear FEM code ABAQUS [40] was employed to simulate and analyze the numerical model.

2- Concrete Material Models

The dynamic behavior of the concrete material subjected to explosion is an intricate non-linear and rate-dependent process. Concrete Damage Plasticity (CDP) is one of the possible constitutive models which can characterize the constitutive behavior of concrete by introducing scalar damage variables [41]. Compressive and tensile behavior of concrete material, as described by CDP, is presented in Figure 1. Two damage variables, tensile damage variable (d_t) and compressive damage variable (d_c), delineate the reduction of elastic stiffness on the strain softening branch of the stress-strain diagram. These damage parameters can take values from zero to one, for no damage material or complete destruction material respectively. The stress-strain relations under uniaxial tension and compression are defined as:

$$\sigma_t = (1-d_t)\times E_0 \times (\varepsilon_t - \tilde{\varepsilon}_t^{pl}) \tag{1}$$

$$\sigma_c = (1-d_c)\times E_0 \times (\varepsilon_c - \tilde{\varepsilon}_c^{pl}) \tag{2}$$

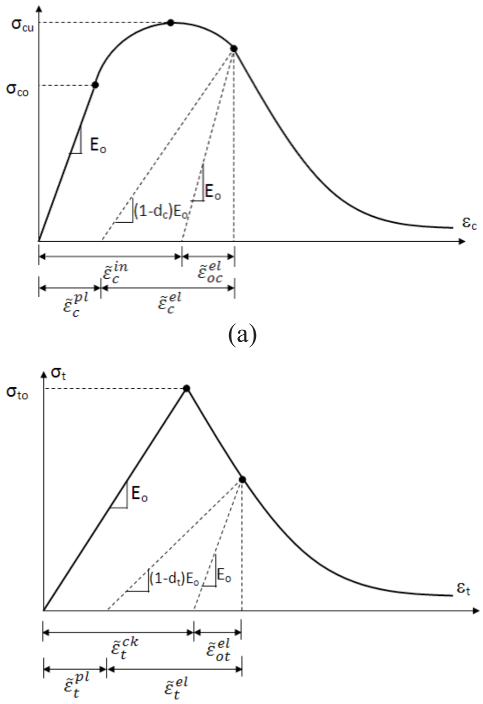


Figure 1. Response of concrete material under axial (a) compressive and (b) tension

E_0, $\tilde{\varepsilon}_c^{in}$, $\tilde{\varepsilon}_c^{pl}$, $\tilde{\varepsilon}_t^{pl}$, $\tilde{\varepsilon}_t^{ck}$, u_t^{pl}, u_t^{ck} are initial elastic stiffness, compressive inelastic strain, compressive plastic strain, tensile plastic strain, cracking strain, plastic displacement, and cracking displacement respectively. Effective tensile cohesion stress ($\overline{\sigma_t}$) and effective compressive cohesion stress ($\overline{\sigma_c}$) are counted by Equations 3 and 4.

$$\overline{\sigma_t} = \frac{\sigma_t}{(1-d_t)} = E_0 \times \left(\varepsilon_t - \tilde{\varepsilon}_t^{pl}\right) \tag{3}$$

$$\overline{\sigma_c} = \frac{\sigma_c}{(1-d_c)} = E_0 \times \left(\varepsilon_c - \tilde{\varepsilon}_c^{pl}\right) \tag{4}$$

Compressive plastic strain, tensile plastic strain, and plastic displacement values are calculated by the following equations:

$$\tilde{\varepsilon}_c^{pl} = \tilde{\varepsilon}_c^{in} - \left(\frac{d_c}{1-d_c}\right) \times \left(\frac{\sigma_c}{E_0}\right) \tag{5}$$

$$\tilde{\varepsilon}_t^{pl} = \tilde{\varepsilon}_t^{ck} - \left(\frac{d_t}{1-d_t}\right) \times \left(\frac{\sigma_t}{E_0}\right) \tag{6}$$

$$u_t^{pl} = u_t^{ck} - \left(\frac{d_t}{1-d_t}\right) \times \left(\frac{\sigma_t \times I_0}{E_0}\right) \tag{7}$$

I_0 the length of the piece, which is considered 1. Tension stiffening is used to model interface behavior and allow simulating strain-softening behavior for cracked concrete: therefore, the definition of tension stiffening in CDP model is necessary. It is possible to specify tension stiffening by post failure stress-strain relation, yield stress-displacement relation, or exerting a fracture energy cracking criterion in ABAQUS.

2- 1- Shockwave propagation and bubble pulsation

Principal material converts into blast gas at about 3000 °C and triggers shock pressure of up to 5 (GPa) during an explosion. The peak overpressure is significantly greater than hydrostatic pressure. The pressure history P(t) of the shockwave starts with rapid increase to peak pressure at a given point, defined by a decaying exponential function [42, 43]:

$$P(t) = P_m \cdot f\left(\frac{t}{\theta}\right) \tag{9}$$

$$P_m = k_1 \times \left(\frac{w^{\frac{1}{3}}}{s}\right)^{1+A} \tag{10}$$

$$\theta = k_2 \times w^{\frac{1}{3}} \times \left(\frac{w^{\frac{1}{3}}}{s}\right)^{B} \tag{11}$$

$$f(\tau) = e^{-\tau} \qquad \tau = \frac{t}{\theta} \le 1 \tag{12}$$

$$f(\tau) = ae^{-a_1\tau} + be^{-b_1\tau} \qquad 1 < \tau = \frac{t}{\theta} \le 7 \tag{13}$$

where P_m is the peak pressure of the shock wave (in MPa), θ is the exponential decay time constant (in ms); w is the weight of the explosive charge (in kg); s is distance between explosive charge and target (in m); k_1, k_2, A and B are constants depending on various explosive charge types with values 52.12, 0.0895, 0.18, and -0.185 respectively; constants a,a1,b and b1 are, again, suggested sequentially to be, 0.8251, 1.1338, 0.1749, and 0.1805.

In order to simulate bubble pulsation, the bubbles' maximum radius R_{max} and the duration T_1 of the pulsation (from the explosion to the first following minimum) can be found using the empirical formula [44, 45]:

$$T_1 = \frac{k_3 \times w^{\frac{1}{3}}}{(H+10.34)^{\frac{5}{6}}} \tag{14}$$

$$R_{max} = \frac{k_4 \times w^{\frac{1}{3}}}{(H+10.34)^{\frac{1}{3}}} \tag{15}$$

For TNT explosions, the constants, depending on explosive material kinds, are k_3=2.11 and k_4=3.5. H is the depth of blast (in m).

3- Water Simulation

In this investigation, water material is simulated by acoustic medium element AC3D8R, where density, under water acoustic wave speed, and bulk modulus are considered as 1025 (kg/m³), 1463 (m/s), and 2140.4 (MPa) respectively.

4- Model Validation

As mentioned, the underwater explosion load was composed of blast shockwave and gas bubble pulsation. The finite element model adopted in this study was validated by two simulations: Shockwave simulation, and shockwave and bubble impulse model.

4- 1- Shock Wave Simulation

One steel plate with 20 mm thickness and 3000 × 3000 mm^2 and rectangular stiffeners 30 mm in thickness and 100 mm in height under three different underwater blast loads were adopted from the Fathallah et al. [46] investigation for this validation. Studies illustrate that the mesh size of 100 mm can correctly simulate wave propagation [30]. So, in this study, a mesh of 100 mm was chosen and the emergent results were compared with the aforementioned paper, which used mesh 75 mm for simulation (Figure 2). Mass density, elastic modulus, Poisson ratio, initial yield stress, and yield stress for steel plate are 7800 (kg/m^3), 3210 (GPa), 0.3, 300 (MPa) and 400 (MPa) respectively: Table 1 shows plastic material properties for steel and Table 2 explains conditions of explosion. Vertical displacements for the center point of the plate in three blast loads are drawn in Figure 3a. The results of this study were compared with the source paper: These are produced in Figure 3, where it can be seen that with mesh size 100 mm, an acceptable response for shock wave propagation model can be reached.

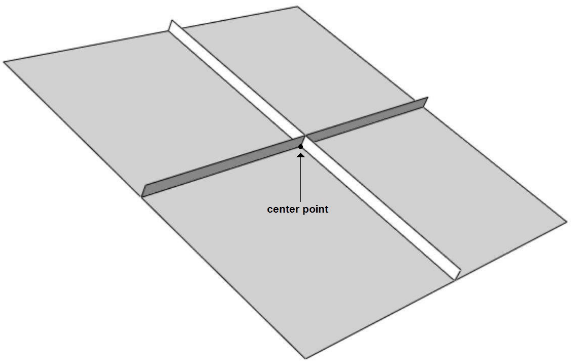


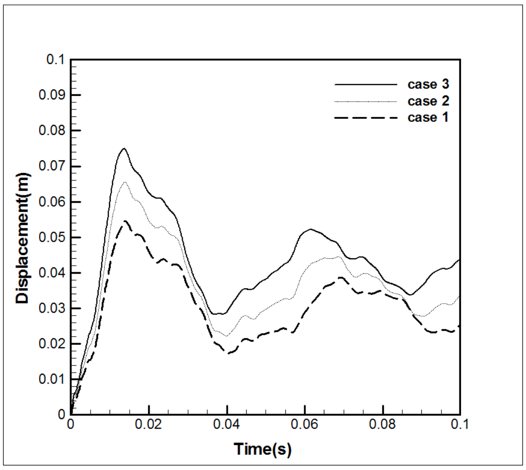
Figure 2. The steel plate for validation

Table 1. Plastic material properties for steel

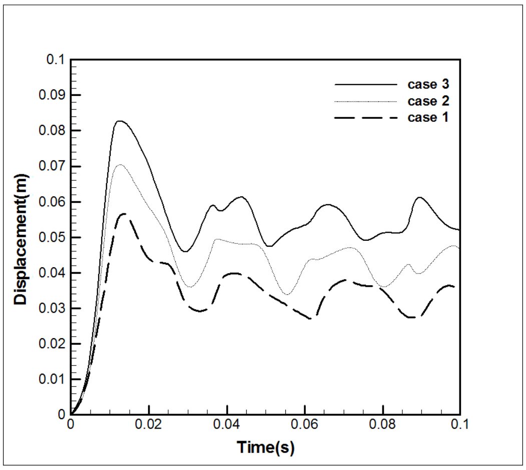
True plastic strain	True stress (Pa)
0.00	300×10^6
0.025	350×10^6
0.100	375×10^6
0.200	394×10^6
0.35	400×10^6

Table 2. Detonation condition

Case no	Pm	R (distance from target)	W (weigh of TNT)
1	14.69 MPa	5m	5kg
2	16.77 MPa	5m	7kg
3	18.52 MPa	5m	9kg



(a)



(b)

Figure 3. Comparing the displacements for center point of the plate. (a) Present work and (b) Fathallah et al. [46].

4- 2- Shock wave and bubble impulse model

In order to verify the effects of the shock wave and bubble impulse, a plate with its properties and shape defined in Table 3 and Figure 4 was adopted from Wang et al. [47] and subjected to an underwater explosion of 0.005 kg TNT at 0.5 m distance from plate. Vertical acceleration of the nodes A1 and A2 were calculated and compared with this study. A1 is located at the origin point of the plate and A2 is located at the bottom of stem bulkhead, as found in Figure 4.

Table 3. Steel material properties

Total mass	Total length	depth	breadth	Distance between bulkheads	All Thicknesses	Number of bulkheads	Mean draft
34.2 kg	2.8 m	0.3 m	0.08 m	0.4 m	0.003 m	6	0.041 m

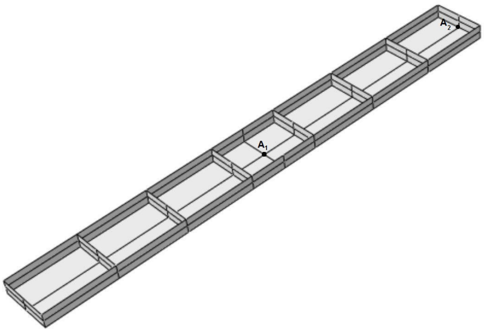


Figure 4. The steel plate adopted for shock wave and bubble pulsation modeling

Mesh size of 100 mm was considered during this study. Results for horizontal acceleration and horizontal velocity, in nodes A1 and A2, were displayed in Figures 5 and 6 sequentially. As found from the results, response of the plate by using mesh of 100 mm is also acceptable: Indeed, for dam explosive analysis caused by increasing model size, the mesh 100 mm is suitable.

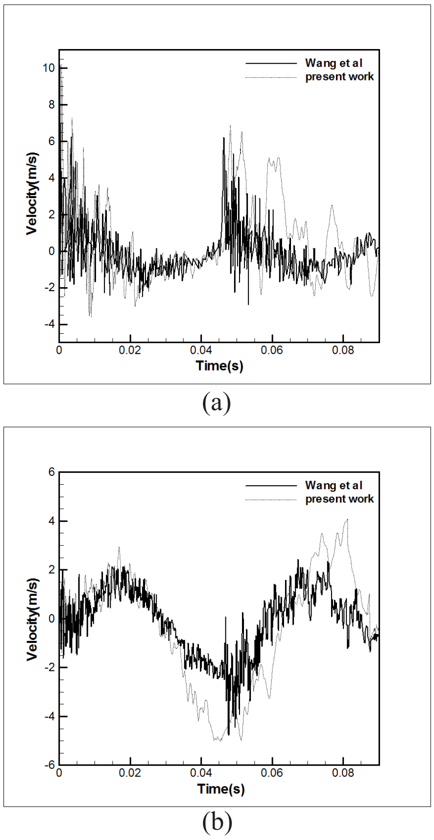


Figure 6. Comparison of Wang et al [46] and present work values of velocity: (a) node A1, (b) node A2

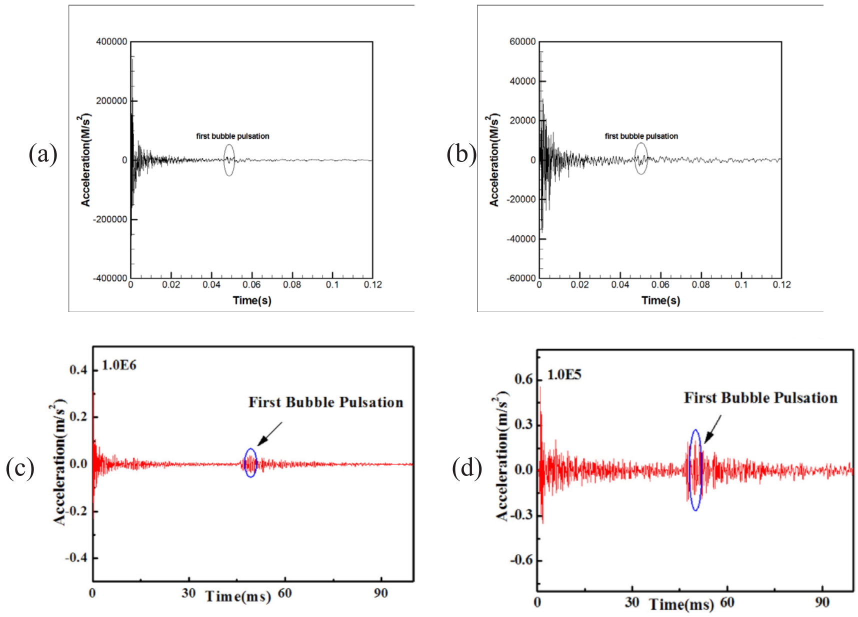


Figure 5. Comparison of the acceleration results for nodes A1 and A2, (a) and (b) results of this study for A1 and A2 respectively, (c) and (d) results of Wang et al paper A1 and A2 respectively

5- Dam simulation

A concrete gravity dam (Figure 7), was adopted in 2D form for frequency analysis to check the accuracy of the dam structure model. The dam's geometric parameters are given in Table 4. Density, Young's modulus, and Poisson ratio for concrete material are 2483 kg/m^3, 22.4 GPa, and 0.20 respectively. These amounts for rock are considered 2660 kg/m3, 68.94 GPa, and 0.33 respectively. First frequency modes for various interactions were computed in Table 5; These indicated that the simulation presented permissible values. The maximum error was observed for the dam with flexible foundation and full reservoir, i.e., about 7.39%.

Table 4. Dams Geometric values (in ft) [48, 49]

b	b_1	b_2	b_3	H_1	H_2	H_3	H_4	H_5
32	16.75	31.57	234	19	14	46	335	300

Table 5. Comparison dams frequency with source data in various conditions

Case no	foundation	Reservoir	Chopra et al.[50]	This model
1	Rigid	Empty	3.1546	3.1406
2	Rigid	Full	2.5189	2.5218
3	flexible	Empty	2.9325	2.8090
4	flexible	Full	2.331	2.5034

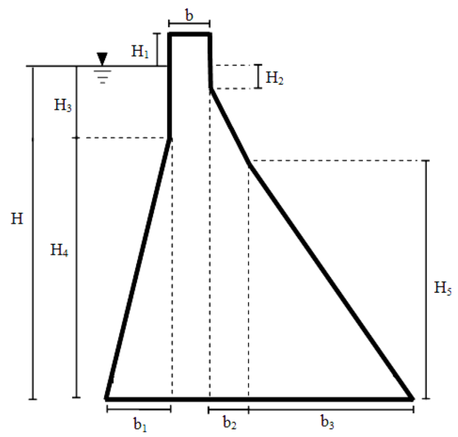


Figure 7. Concrete gravity dam modeled for frequency analysis

6- Parametric analysis

A concrete gravity dam with a height of 75 m, a thickness of 7.5 m, and a width of 15 m and 56.25 m in the crest and heel was adopted for parametric study. Concrete density, Young's modulus, and Poisson ratio were 2750 kg/m^3, 27 GPa and 0.2 respectively. The reservoir depth was considered 70 m and the non-reflecting boundary conditions applied. The mesh size assumed was 100 mm for water at the charge center and 200 mm for the upper part of the dam; these amounts were increased gradually by getting away from the aforementioned zones. Although this paper mainly paid attention to the influence of bubble pulsation for concrete gravity dams subjected to underwater explosion, the effect of the explosion depth and standoff distance were also studied simultaneously.

A 300-kg TNT charge was considered at 5 m, 35 m, and 65 m depth by 5 m stand-off distance. The explosion was modeled using two methods: Simulating explosion shockwave; and simulating both explosion shockwave and bubble impulse. In order to understand the standoff distance effect, another explosion was simulated at 35 m depth by a 7.5 m stand-off distance. The results of the damage, including compressive and tensile damage, are presented in Figures 8 and 9 for a concrete gravity dam subjected to underwater detonation without and with bubble impulse simulation respectively.

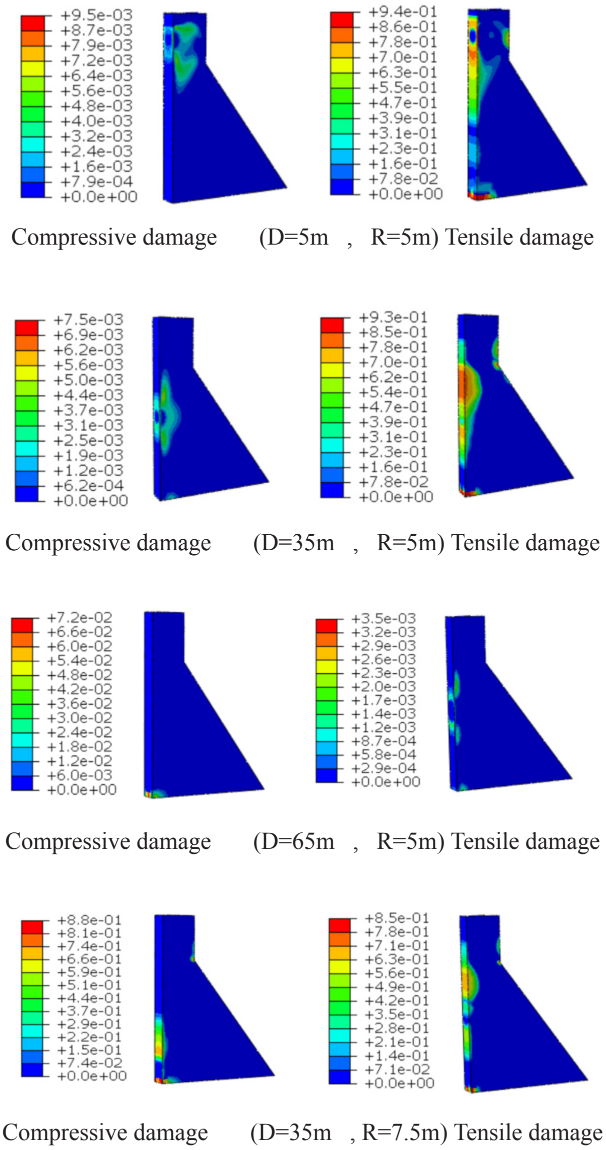


Figure 8. Compressive and tensile damage of dam under explosion shock wave; D is charge depth, R is standoff distance

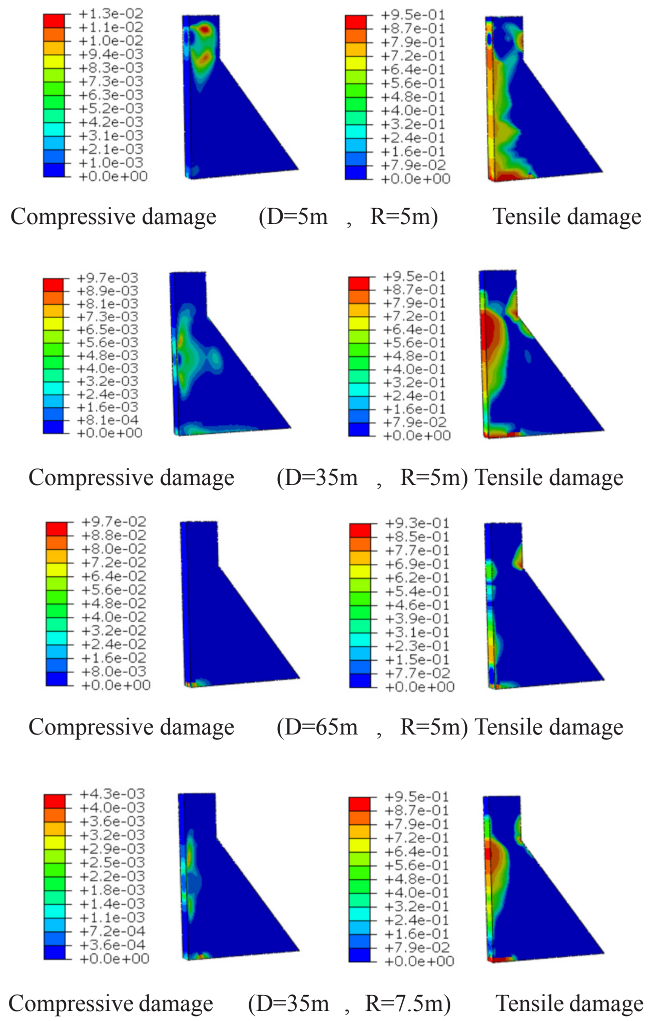


Figure 9. Compressive and tensile damage of dam under both explosion shock wave and bubble impulse; D is charge depth, R is standoff distance

Figure 10 shows the horizontal displacement of crest for four different charge location models with and without gas bubble impulse simulation. When the explosion occurred at a depth of 5 m, the blast load impact was to the upper part of the dam structure: the dam's crest horizontal displacement was positive all throughout the loading. The maximum negative and positive amounts of displacement were seen for both kinds of explosion simulation for 35 m depth by a 5 m stand-off distance. The maximum positive displacement of crest was 0.07 m and 0.04 m respectively, after considering bubble impulse. The maximum negative displacement was -0.005 m and -0.003 m for with and without bubble effect sequentially. According to the results, these amounts decreased by increasing the blast, depth, and standoff distance. All diagrams show that the amount of displacements were significantly higher when the underwater explosion modeled by applying both bubble pulsation and explosion shockwave.

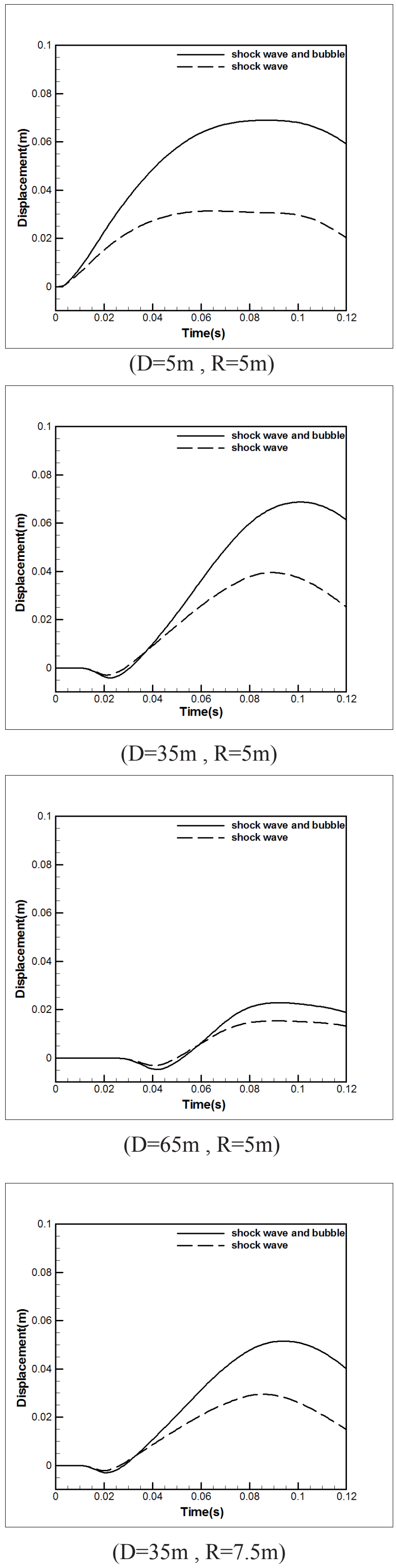


Figure 10. Comparison horizontal displacements of explosion simulating by shock wave and explosion simulating by shock wave and bubble impulse; D is charge depth, R is standoff distance

7- Conclusions

An underwater explosion load includes an explosion shockwave and a gas bubble pulsation. Most of the numerical studies about concrete gravity dams subjected to underwater blast simulated detonation loads by using only an explosion shockwave and neglected the effect of explosion gas bubble impulse. This paper studied numerically the influence of underwater explosion on concrete gravity dams with and without considering bubble impulse effects. A 300 kg TNT charge exploded in 5 m, 35 m, and 65 m depths by 5 m stand-off distance to understand the effect of explosion depth and compare the results of the explosion modeled by blast shockwave with the explosion modeled by considering explosion shockwave and bubble pulsation. In order to research the influence of standoff distance, one other explosion was assumed at a 35 m depth by a 7.5 m stand-off distance. The greatest damage was visible when an explosion occurred in the middle of the reservoir. This was due to the blast load action was exposed to the maximum dam surface, thereby reducing cavitation effects. In high-depth detonation, because of reduced cavitation effect and growth in the dam structure thickness, damage was further decreased. The compressive and tensile damage to the dam in cases which considered bubble impulse was significantly higher than cases which did not. The upstream side of the dam was severely damaged for detonation at a depth of 35 m and a stand-off distance of 5 m when the bubble impulse was considered. Damage occurred mostly in the dam's upstream while tensile damages could be found at the downstream face near the change in the downstream slope. Horizontal displacement results illustrate that while for shallow blasts displacements were positive all through the loading, most displacements occurred with an explosion in the middle of the reservoir by a 5 m stand-off distance. The maximum positive displacement of crest was 0.07 m and 0.04 m for with and without considering bubble impulse respectively. All displacement results for cases considering explosion bubble pulsation were significantly higher than the cases wherein only an explosion shockwave was applied. Therefore, it is necessary to simulate explosions after considering both the explosion shockwave and the bubble impulse in order to study the effects of underwater detonation on concrete gravity dams: The effects of explosion gas bubbles can in no way be neglected.

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