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Structural response of concrete gravity dams under blast loads

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Abstract. Concrete dams are important structures due to retaining amount of water on their reservoir. So such kind of structures have to be designed against static and dynamic loads. Especially considering on critical importance against blasting threats and environmental safety, dams have to be examined according to the blast loads. This paper aims to investigate structural response of concrete gravity dams under blast loads. For the purpose Sarıyar Concrete Gravity Dam in Turkey is selected for numerical application with its 85 m of reservoir height (H), 255 m of reservoir length (3H), 72 m of bottom and 7 m of top widths. In the study, firstly 3D finite element model of the dam is constituted using ANSYS Workbench software considering dam-reservoir-foundation interaction and a hydrostatic analysis is performed without blast loads. Then, nearly 13 tons TNT explosive are considered 20 m away from downstream of the dam and this is modeled using ANSYS AUTODYN software. After that explicit analyses are performed through 40 milliseconds. Lastly peak pressures obtained from analyses are compared to empirical equations in the literature and UFC 3-340-02 standard which provide unified facilities criteria for structures to resist the effects of accidental explosions. Also analyses' results such as displacements, stresses and strains obtained from both hydrostatic and blasting analysis models are compared to each other. It is highlighted from the study that blasting analysis model has more effective than the only hydrostatic analysis model. So it is highlighted from the study that the design of dams should be included the blast loads.

Keywords: blast load; concrete gravity dam; explicit analysis; structural response; TNT explosive

1. Introduction

Engineering structures are important structures for the humanity so they have to be designed against static and dynamic loads. Especially, some dynamic effects such as blast loading have critical importance on the structural response. Because such kind of loads may cause damages on the structures. In the past few decades, blast loads on structures have become one of the biggest problems all over the world, so precautions against blast load have been being improved. The detonation of the explosive affects the environment including people and structures. In recent years, researchers developed new ways to improve protection against blast effects which are depended on experimental, numerical and empirical methods.

Many empirical equations present the peak overpressure of a blasting related to charge weight size and distance of the detonation (Brode 1955, Henrych 1979, Kinney and Graham 1985). Due to development of computer technology, new software are used to modelling and performing the blast effects on the structures. Detailed structures can be solved with computer analysis programs easily (AUTODYN, LS-DYNA etc.) instead of empirical methods. But in previous years (before computer analysis programs), blast load parameters are solved with equations, so that some researchers investigate and propose empirical equations on blast load parameters. Big structures such as dams, having huge water holding capacity, are critically important; considering its location, disaster risk, construction phase and costs.

Sari *et al.* (2005) studied assessment of modular metal buildings for blast loads. According to the study; resistance of the steel buildings and its components involving exterior walls, floors, steel plates and walls were examined using LS-DYNA software. Wang *et al*. (2008) studied on experimental tests and used the LS-DYNA explicit solver to replicate tests of reinforced concrete slabs subjected to various charge weights of TNT close-in explosions. The numerical model was included slab, air and TNT.

Olmati *et al*. (2013) studied the behaviour of 20 storey steel frame building against blast damage unde different local damage levels and also studied evolution of blast pressures acting on structural elements using computational fluid dynamic (CFD) techniques. Karlos and Solomos (2013), presented a calculation of blast loads for application to structural components. Toy and Sevim (2017) studied a RC wall which was analyzed using explicit solver (AUTODYN) and empirical formulas, besides the results were compared with each other, was subjected TNT explosive. Toy and Sevim (2019) studied the blasting response of a two-storey reinforced concrete (RC) building under different charge weight of TNT explosives. Blasting effect on the structures is included; theory of blast is defined with graphics and tables, explosion is explained with empirical formulas.

Dams have critical importance due to retaining a large amount of water on their reservoirs. So such kind of

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structures have be prevented against dynamic loads such as earthquakes and explosions. Möhne Dam in North Rhine-Westphalia and Edersee Dam in northern were breached by RAF Lancaster Bombers during Second World War in 1943. Bouncing bombs had been constructed to skip over the protective nets that hung in the water and a huge hole was blown into the dam. Many people died due to this bombing. Such kind of situations made the researchers to investigate the blasting response of dams (Url-1, 2019).

Parkes *et al.* (2013) investigated about impact of explosions on embankment dams and levees. In the study it is aimed risk assessment of the dams for blast and post-blast analysis. Afriyie (2014) studied about the effects of explosions on embankment dams. He highlighted from the study that the level of damage caused by an explosive device on an embankment dam depends on the type and amount of explosive as well as the placement of the explosive relative to the dam cross-section. Kalateh (2017) examined the dynamic failure analysis of concrete dams under air blast. In the study the air blast response of the concrete dams including dam-reservoir interaction and acoustic cavitations in the reservoir is investigated.

On the other hand concrete gravity dams have been studied related to earthquake response in the literature. For example, civil engineering chamber published details about mechanical properties of concrete material which is used on construction of Sarıyar Gravity Dam and also involves construction phase of the concrete body. Bayraktar *et al.* (2002) studied the effects of hydrodynamic pressures on the dynamic response of concrete gravity dams for out-of-phase asynchronous ground motion by the Lagrangian approach, and also Sarıyar concrete gravity dam is investigated in this research article. Sesli and Akköse (2015) studied evaluation of sliding stability in concrete gravity dams using multiple wedge analysis of Sarıyar concrete gravity dam, they investigated loading conditions for usual and unusual conditions. Altunisik and Sesli (2015) studied dynamic response of concrete gravity dams using different water modeling approaches: Westergaard, Lagrange and Euler using Finite Element Model Program ANSYS. Sevim (2018) studied the effects of geometrical dimensions of concrete gravity dams on the seismic response considering different base width/dam height ratios. According to this study, a concrete gravity dam with five different L/H ratios, were applied linear time history analysis and solved by using New mark time integration algorithm. Karabulut and Kartal (2019, 2020) examined the seismic response of roller compacted concrete dams including galleries and also considering effect of viscous boundary conditions.

Due to importance of blasting response of dams, in this study, Sarıyar gravity dam (Ankara, Turkey) is preferred to simulate involving the concrete body, valley and the water reservoir which is modelled using Finite Element Model Program (ANSYS Workbench 2019) and the blast analysis is carried out using (ANSYS AUTODYN 2019) in order to investigate the parameters of blast loads.

2. Formulation

2.1 Basic knowledge

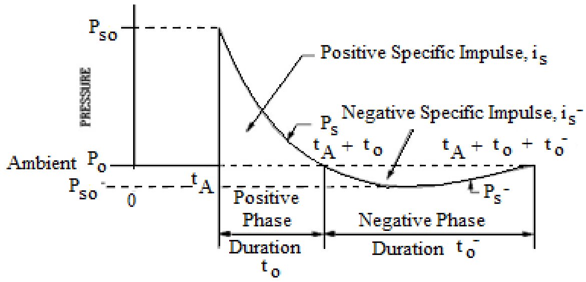


Fig. 1 Time histories of pressures due to explosions (UFC 3- 340-02 2008

The act of explosion can be modeled as a pressure-time graph which is drawn in Fig. 1. According to the graph in Fig. 1, "0" is the start time of the explosion before the shock wave reaches to the structure (t_A) in the millisecond range and subjects (pressure reaches to P_{so} immediately) pressure to the surface; this phase is called positive phase at (t_o) duration. The curve reaches to the ambient pressure at (t_A+t_o), then the pressure decreases and the slope reaches to negative phase (-P_{so}) at (t_o-) duration; this causes negative pressure then the curve reaches back to the ambient pressure at (t_A+t_o+t_o-). At positive phase; a big amount of energy is released and shock wave impacts to the structure that spalling, bending, cracking situations are to be expected. Negative phase means vacuum which pulls debris fragments to explosion source. At the negative phase; the absolute peak negative pressure (-P_{so}) is smaller than the absolute peak positive pressure (P_{so}); on the other hand the negative phase (t_o-) duration is longer than the positive phase (t_A+t_o) duration. Po and duration are related to some important parameters such as charge weight (W), distance (R) from the surface, and type of the material. Generally, duration of the explosion is approximately 2,5~3 milliseconds and value of P_{so} can reach to big overpressures.

2.2 Empirical equations

Blast loads on the structures are calculated considering main parameters of explosion such as charge size of explosive and distance from the structure. According to these two parameters, a scaled distance (z) is defined which is called as Scaling Law. In the literature, Cube Root Scaling Law presented by Hopkinson and Cranz (1914) is the main scaling law (Eq. (1)). In Eq. (1), Z: scaled distance; R: distance between explosive and structure (m); W: charge weight of the explosive (TNT; kg).

$$Z = R/W^{\frac{1}{3}} \tag{1}$$

Some empirical equations are developed considering scaling distance (z) in the literature. Brode (1955) presented equations to calculate the peak overpressure (P_{so}) on the structures of explosions. (Eqs. (2) and (3)).

$$P_{so} = \frac{6{,}7}{Z^3} + 1\ (bar)(P_{so} > 10\ bar) \tag{2}$$

$$P_{so} = \frac{0{,}975}{Z} + \frac{1{,}455}{Z^2} + \frac{5{,}85}{Z^3} - 0{,}019\ (bar) \quad (0{,}1\ bar < P_{so} < 10\ bar) \tag{3}$$

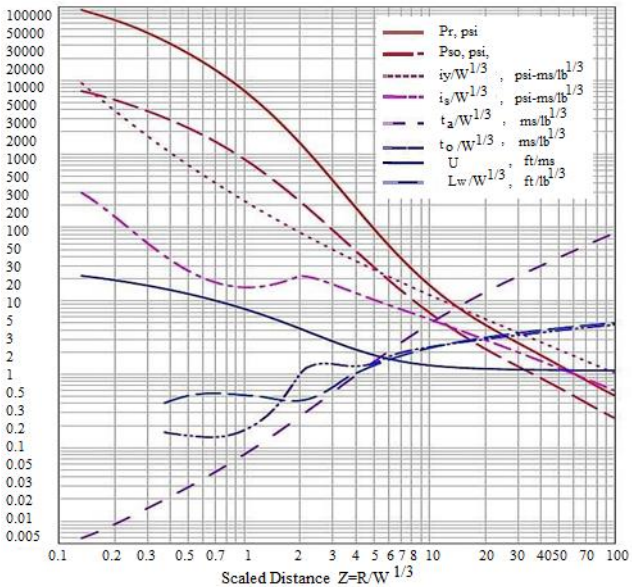


Fig. 2 Parameters of positive phase of TNT charges from free-air bursts (UFC 3- 340-02 2008)

Henrych (1979) proposed peak overpressure (Eqs. (4)-(6)) (P_s) which is same as (Brode 1955)

$$P_{so}=\frac{14{,}072}{Z}+\frac{5{,}54}{Z^2}-\frac{0{,}375}{Z^3}+\frac{0{,}00625}{Z^4}\ (0{,}05\leq Z\leq 0{,}3)\quad(4)$$

$$P_{so}=-\frac{6{,}194}{Z}-\frac{0{,}326}{Z^2}+\frac{2{,}132}{Z^3}\ (0{,}3\leq Z\leq 01)\quad(5)$$

$$P_{so}=\frac{0{,}662}{Z}+\frac{4{,}05}{Z^2}+\frac{3{,}288}{Z^3}(1\leq Z\leq 10)\quad(6)$$

Kinney and Graham (1985) presented an equation (Eq. (7)) to describe the peak pressure given below. In Eq. (7), z is the scaled distance, P_o is the ambient pressure (atmospheric pressure≈1 bar).

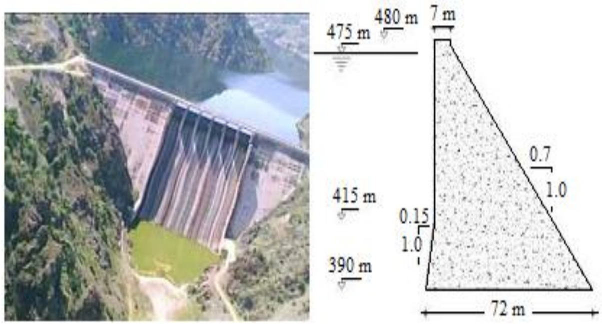
$$P_{so}=P_o\frac{808\left[1+\left(\frac{Z}{4{,}5}\right)^2\right]}{\left\{\left[1+\left(\frac{Z}{0{,}048}\right)^2\right]\left[1+\left(\frac{Z}{0{,}32}\right)^2\right]\left[1+\left(\frac{Z}{1{,}35}\right)^2\right]\right\}^{0{,}5}},(bar)\quad(7)$$

On the other hand, USACE (2008) published unified facilities criteria (UFC) related to structures to resist the effects of accidental explosions. According to UFC 3-340-02, the parameters of the blast load can be read and calculated from the Fig. 2, which depends on scaled distance (Z).

3. Numerical application

3.1 Sarıyar gravity dam and finite element model

In this study, it is aimed to investigate the blasting response of concrete gravity dams. For the purpose Sarıyar Gravity Dam in Ankara in Turkey (see Fig. 3(a)) which is constructed over the River-Sakarya in the year of 1956 for energy production and having approximately 1900 hm³ of reservoir storage, is preferred to simulate. Geometrical properties of the dam is given in Fig. 3(b). As is seen in Fig. 3(b), the dam 85 m of reservoir height (H), 72 m of bottom



(a) An overview (b) Cross-section

Fig. 3 Sarıyar Dam

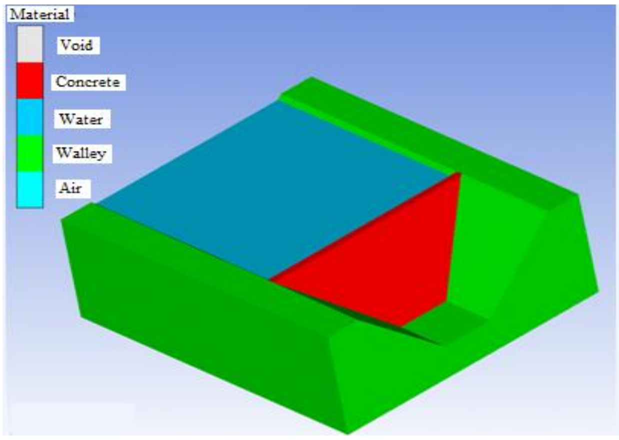


Fig. 4 3D finite element model of Sarıyar gravity dam

and 7 m of top widths (Bayraktar *et al*., 2002). Considering the dimensions given in Fig. 3(b), 3 D finite element model of the dam is constituted (See Fig. 4) using ANSYS Workbench software (2019). 3D finite element model considers also 255 m of reservoir length (3H), and foundation on cross section and downward directions.

The concrete gravity dams carry the loads of their monolithic mass with gravity during their lifespan and hydrostatic force is subjected on the surface by reservoir water and the applied hydrostatic pressure on the concrete body can be shown on the diagram which has been delivered by ANSYS Workbench (2019) (see Fig. 5). According to the diagram; the triangular load distribution is expressed by colors where bottom of the body is expressed by red which refers max pressure and top of the body is expressed by blue that refers min pressure.

Blasting response of the dam is aimed to investigate in this study. So 3D finite element model of the dam is performed using ANSYS AUTODYN software (2019). The software simulates the response of materials to short duration severe loadings from impact, high pressure or explosions. Also it has capabilities complex physical phenomena such as the interaction of fluids and solids. In the study the interface connection between reservoir and dam body has defined as “no separation” and just applied the hydrostatic load on the concrete body. It means that the areas between reservoir and dams are constrained in to normal directions. In Autodyn, 3D solids are considered as Lagrangian elements with 8- nodes and fluids such as dam

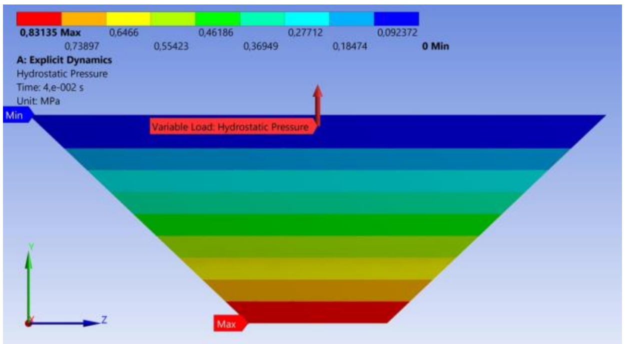


Fig. 5 Applied hydrostatic pressure on the side of the gravity dam

Table 1 The material properties of components used in the modeling (CCE 1955, ANSYS 2019)

Material Component	Material Type	Elasticity Modulus (MPa)	Density (t/m^3)	Compressive Strength (MPa)	Tensile Strength (MPa)
Concrete	C20	28000	2.31	20	2.0
Air	Air	-	1.225×10^{-3}	-	-
Blasting	TNT	-	1.63	-	-

reservoir are allowed as Eulerian elements. In this study, explosion material is selected as 13 tons of TNT placed 20 m in front of the body. Blast modelling is constituted using software, also the explicit analysis of the concrete gravity dam is performed in this software for a duration of 40 milliseconds. The material properties of components are used in the modelling and analysis such as; concrete, air, and TNT are given in Table 1. The compressive strength of the concrete material is chosen as 20 MPa according to the technical report presented by the Chamber of Civil Engineers (CCE 1955) and the material properties are taken into account from ANSYS Workbench library.

The geometric size of the air model is needed for explosive material TNT and blast action. During blast actions the waves of the explosion must take place in the defined air space so that, the interaction between explosive waves and solid model are transferred successfully. The explosive material TNT is modelled and meshed together with air (Euler) model; at first model the explosive material is meshed into (*i.j.k*) pieces. The volume of the explosive is calculated as 2×2×2=8 m^3 and the density of the TNT is 1.63 t/m^3 and the mass of the equivalent TNT is approximately equal to 13 tons. The TNT explosive are considered 20 m away from downstream of the dam on the foundation.

In the study, two types of analysis are performed on finite element model classified as;

- Hydrostatic analysis (only hydrostatic pressure is considered)
- Blasting analysis (both explosion effect and hydrostatic pressure are considered)

The analyses are performed separately in order to consider the parameters on the body such as; pressures, displacements, stresses (von-misses) and strains.

3.2 Gauge points

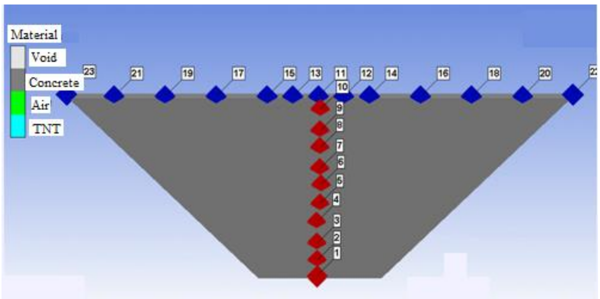


Fig. 6 Plotted gauges on 3D finite element model

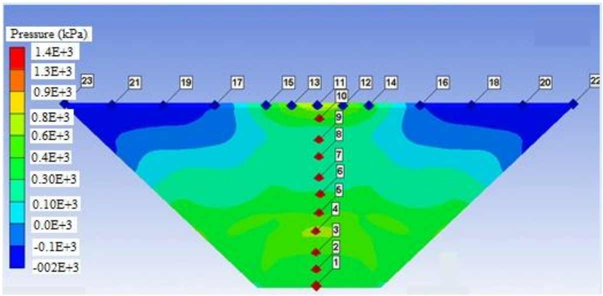


Fig. 7 Maximum applied pressure contour diagram

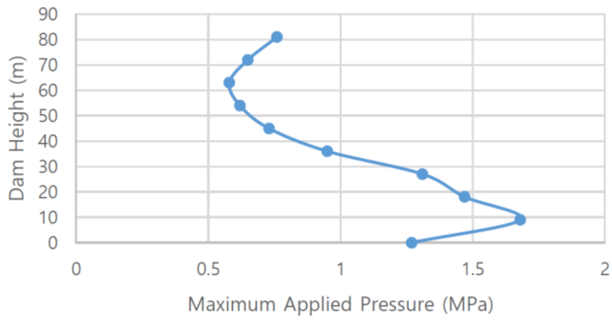


Fig. 8 (a) Dam height - Max applied pressure graph

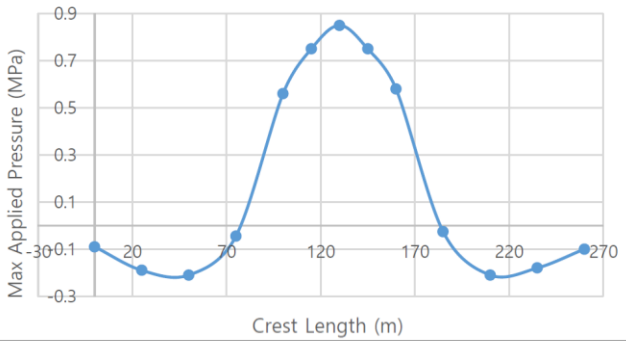


Fig. 8 (b) Crest length - Max. applied pressure graph

Before blasting and hydrostatic analyses, total of 23 gauge points are plotted on the concrete gravity dam, obtaining for the purpose of pressure, displacement, stress and strain results. 10 out of 23 gauges vertically located on the concrete gravity dam while 12 out of 23 gauges located horizontally through the crest as seen in the Fig. 6.

3.3 FEM analyses, results and discussions

After performing explicit finite element analysis

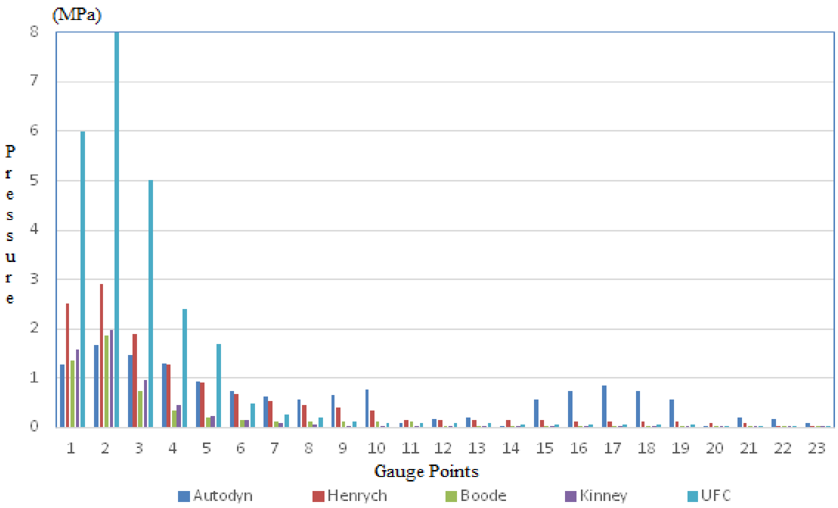


Fig. 9 The comparison of pressure (MPa) parameters

Table 2 Max applied pressures and comparison of the methods (MPa)

Gauges	AUTODYN	Henrych	Brode	Kinney and Graham	UFC 3-340-02
1	1.27	2.52	1.37	1.58	6.00
2	1.68	2.91	1.87	1.98	8.00
3	1.47	1.88	0.73	0.96	5.00
4	1.31	1.27	0.34	0.47	2.40
5	0.95	0.90	0.20	0.24	1.70
6	0.73	0.69	0.15	0.14	0.50
7	0.62	0.55	0.13	0.09	0.25
8	0.58	0.47	0.12	0.06	0.20
9	0.65	0.40	0.11	0.05	0.13
10	0.76	0.35	0.11	0.04	0.09
11	0.09	0.14	0.11	0.04	0.09
12	0.19	0.14	0.03	0.04	0.08
13	0.21	0.14	0.03	0.04	0.08
14	0.45	0.14	0.03	0.03	0.07
15	0.56	0.14	0.03	0.03	0.07
16	0.75	0.12	0.03	0.03	0.07
17	0.85	0.12	0.03	0.03	0.07
18	0.75	0.11	0.02	0.02	0.06
19	0.58	0.11	0.02	0.02	0.06
20	0.26	0.10	0.02	0.02	0.04
21	0.21	0.10	0.02	0.02	0.04
22	0.18	0.02	0.02	0.02	0.02
23	0.10	0.02	0.02	0.02	0.02

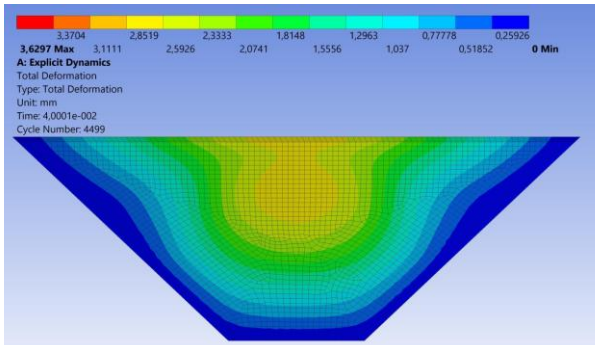


Fig. 10 (a) Displacement contour diagram of the body under hydrostatic analysis

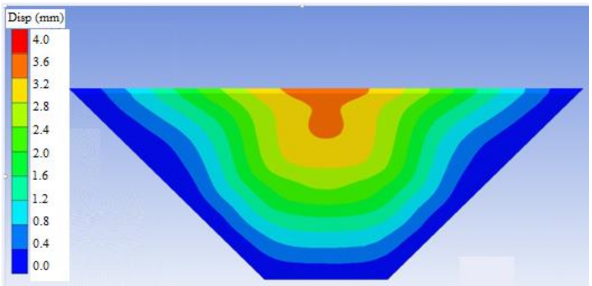


Fig. 10 (b) Displacement contour diagram of the body under blasting analysis

considering explosion; max applied overpressure on the elements of the concrete gravity dam obtained from blasting analysis is demonstrated in Fig. 7. In accordance with Fig. 7, the maximum values are occurred on the gauge number 2 and 3 with max pressure value of 1.68 and 1.47 MPa respectively at X direction. This means; value of overpressure at X direction may not be caused any damage on the surface of the column.

The variation of the pressures, occurring on gauges through concrete body height, is seen in the Fig. 8(a) and through dam crest is seen in Fig. 8(b). According to the Fig. 8(a), the maximum applied pressures on gauges; biggest values are occurred on the gauge number 2 and 3 while the amount of pressure on gauges through dam height decreases upwardly from bottom to the crest. Also as is seen in Fig. 8(b), the pressure graph shows symmetry and in addition to this; on top of the crest; the biggest amount of pressure is occurred at the middle of the crest and decreases through both sides from the middle to the corners.

Maximum applied pressures which are generated by AUTODYN software occurring on gauges are listed in Table 2. Table 2 also includes the pressure results are consisted of proposals by researches through function of scaled distance; AUTODYN Software and UFC3-340-02 standards.

The pressures listed in Table 2 are compared in graph as seen in Fig. 9. According to the Fig. 9, the pressures

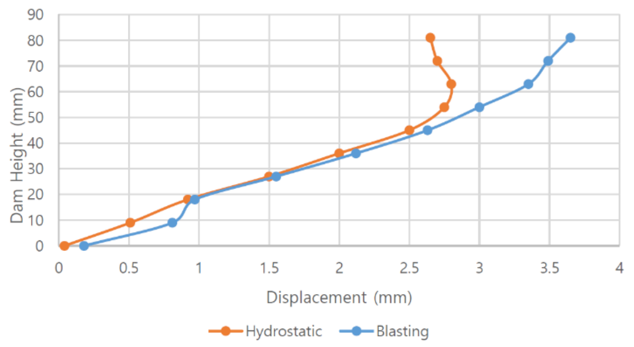


Fig. 11 (a) Maximum displacement changes through dam height

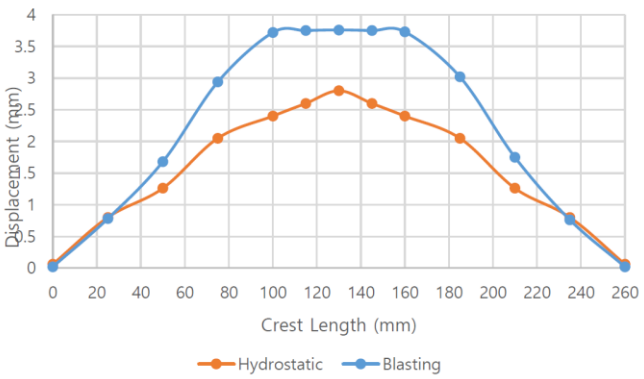


Fig. 11 (b) Maximum displacement changes through crest length

obtaining from different sources on each gauges are compared obviously. For the first 3 gauges; UFC 3-340-02 results shows bigger values when comparing with others on the other and results of AUTODYN Software and researches show compatibility. However the pressure results on gauges (4:23) shows compatibly. The results obtaining from AUTODYN software through crest shows higher results.

Displacement results obtained on downstream-upstream direction both hydrostatic and blasting analyses plotted as contour diagrams and presented in Fig. 10 (a) and (b), respectively. As is seen from Figs. 10 (a) and (b), the maximum displacements are obtained on the middle section of the crest. Also, maximum displacement changes through dam height and crest length obtained both hydrostatic and blasting analyses are plotted in Fig. 11 (a) and (b), respectively. As seen in Fig. 11 (a) and (b), maximum displacement obtained from blasting analyses are nearly %30 bigger than this of hydrostatic analysis. The displacement results obtained from both analyses has symmetry due to symmetry of dam and loads.

The von-misses stresses results obtained from both hydrostatic and blasting analyses plotted as contour diagrams and presented in Fig. 12 (a) and (b), respectively. As is seen Fig. 12 (a) and (b), maximum and minimum stresses are occurred on bottom and top of the dam body. On the other hand, maximum and minimum stress changes through dam height and crest length obtained both hydrostatic and blasting analyses are plotted in Fig. 13 (a) and (b), respectively. When examined Fig. 13 (a), the

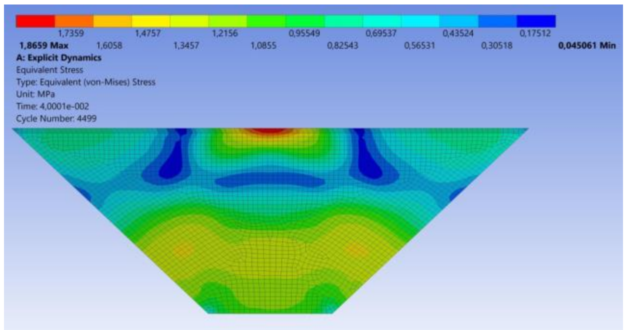


Fig. 12 (a) Stress contour diagram of the body under hydrostatic analysis

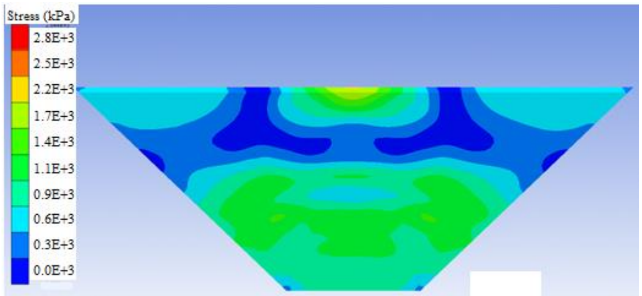


Fig. 12 (b) Stress contour diagram of the body under blasting analysis

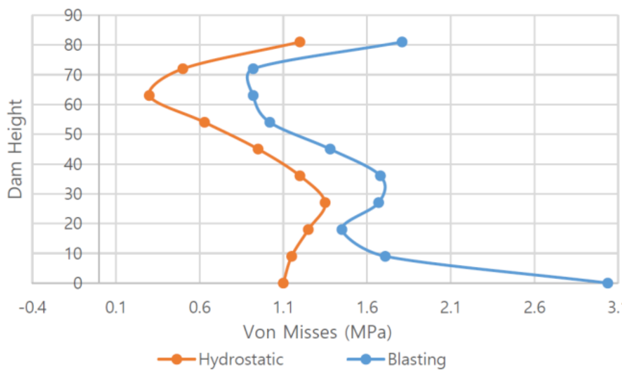


Fig. 13 (a) Von Misses Stress changes through dam height

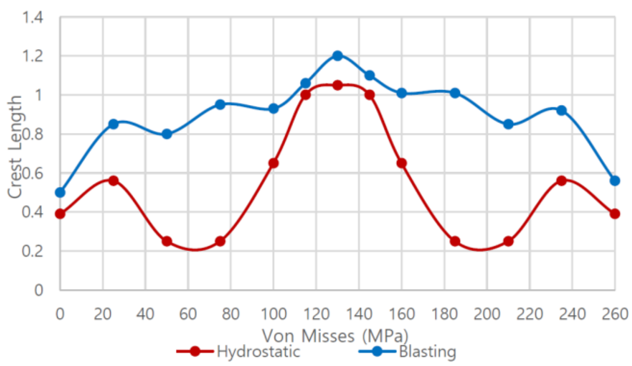


Fig. 13 (b) Von Misses Stress changes through crest length

maximum stresses are obtained 15-20 m away from the bottom and top. Also Fig. 13 (b) shows that the maximum stresses are occurred on the symmetry axis of the dam body. However biggest stresses are obtained from blasting analysis and the ratio is about three times higher than

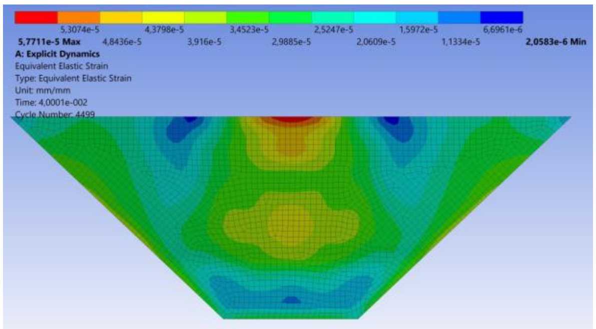


Fig. 14 (a) Strain contour diagram of the body under hydrostatic analysis

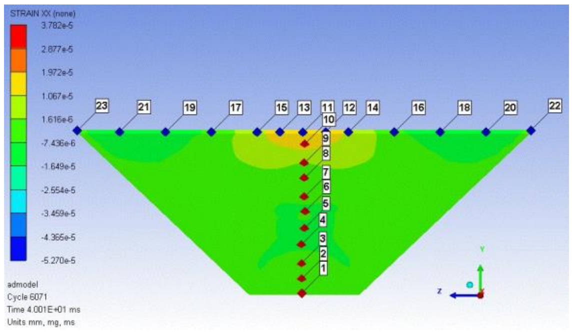


Fig. 14 (b) Strain contour diagram of the body under blasting analysis

hydrostatic analysis at the bottom of the dam. But the stresses obtained at the top of the dam from blasting analysis are nearly two times higher than those of hydrostatic analysis

The elastic strains on the dam body are demonstrated on contour diagrams for both hydrostatic and blasting analyses in Figs. 14 (a) and (b), respectively. As is seen in Fig. 14 that maximum strains are occurred at the mid-part of the crest length of the dam body. Also, the biggest and lowest strain parts show similarity with the displacement diagrams and likewise the values doesn't cause any damage on the concrete dam body or can be negligible. However, maximum strains are obtained from blasting analyses compared to hydrostatic analysis.

4. Conclusions

In this study, structural response of concrete gravity dam under blasting effects is investigated. For the purpose Sarıyar concrete gravity dam is selected for the numerical application. The 3D finite element modelling of the dam is constituted in ANSYS Workbench software, and explicit analyses are performed using ANSYS AUTODYN software. To see the effects of blast loads, two models are performed which one of considers only static analysis of dam including dam-reservoir- foundation interaction and the other one consists of blasting loads as an adding. The main conclusions obtained from the study are followed as;

√ Increasing distance and the charge weight of the explosive affects the scaled distance "Z" which also effects all parameters of blast loading directly considering empirical equations.

√ The AUTODYN results shows the compatibility with the empirical studies such as on gauges (4:23) on the other hand, the results of the UFC 3-340-02 shows compatibility with gauges (1:5).

√ In spite of the small difference between AUTODYN, empirical and UFC 3-340-02, none of the max applied pressures could deface the concrete.

√ Both of pressure and displacement results show that; the amount of explosive charge weight may not cause any crack or failures on the dam body.

√ All section forces such as displacement, stresses and strains obtained blasting analysis are bigger than those of hydrostatic analysis.

√ In case of more charge weight of explosive may cause more damage on the dam body related to scaled distance of explosive from the dam.

√ The blast loads can affect the structural response which should be taken into consideration on the design of dams.

Acknowledgements

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